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COST EFFECTIVE DESIGNS

by

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A Doctoral Thesis submitted in partial fulfilment of the requirements
for the award of Doctor of Philosophy of the
Loughborough University of Technology

December, 1989

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JAYALATH PERERA 1989
DEDICATION

To my wife Nelumnika and my mother
"Do not withhold good from those who deserve it, when it is in your power to act."

Proverbs 3:27, Holy Bible
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ABSTRACT

Different cost effective design methods have been developed to reduce the cost of buildings, of which structural optimum design methods and cost effective designs methods using estimating data, are the most common. However, there is no record of the use of cost effective design methods in practice. Consequently, potential benefits of such methods remain untapped. This research evaluated the cost savings through cost effective design methods, identified difficulties involved in their use and examined favourable conditions for the implementation of such methods in design practice.

The research aimed at investigating whether or not the opinion among practising designers, (structural engineers and architects) that "cost benefits through cost effective designs are insignificant and methods are not practical" is justified. Previous researchers have developed cost effective design methods, but very little has been done to change the opinion of building designers regarding these methods. A proper evaluation of cost effective design methods and a study of the design process are therefore necessary to gain the attention of designers in practice.

The opinion among practising designers is that cost savings through optimum methods are less than 10% of elemental cost and 1% of total building cost. The analysis of cost savings of 22 historical buildings have shown that this is not the case. Optimum design methods using the computer to find the minimum cost from a set of feasible designs were developed for reinforced concrete elements; slabs, beams, columns and independent footing foundations. These optimum methods were applied to the design of 22 historical buildings. More than 10% of elemental cost savings were observed. 2.91% of total building cost can be saved using optimum methods for design of reinforced concrete elements, which is more than 45% of the total design fee of a building. The study proved that for a given building, probabilities of total building cost saving exceeding 1%, 2% and 3% are 0.96, 0.79 and 0.47 respectively.

Design and build contracts provide not only a facility but also an incentive, to designers to use cost effective design methods. On the contrary, percentage fee contracts act as a disincentive. Therefore, the legal procedures in design practice, may sometimes serve as obstacles for the use of cost effective design methods. Furthermore, current design practice lacks motivating factors to designers to use cost effective design methods. Therefore building construction industry may need to pay additional fee to get benefits from cost effective design methods.
This research revealed that main cost information needed for cost effective designs (architectural) is to specify elemental and total cost consequences with respect to changes in design variables such as span and window type. The cost model developed for the design of concrete frames proved that cost information can be provided for design decisions and that cost variations are significant. Responses from architects for the developed cost model concluded that for design decisions factors such as building functional requirements influence more than the cost. Analyses on windows and floor finishes design proved that current design decision making in practice cannot be improved by providing additional cost information related to design decisions. Therefore only a very limited scope exist for cost effective architectural design methods.
DECLARATION

No portion of the research to in this thesis has been submitted in support of an application for another degree or qualification at this or any other university or other institution of learning.
ACKNOWLEDGEMENTS

The research described in this thesis has been completed in the area of building design process as service to clients, architects, structural engineers and quantity surveyors with the help of many.

The author will like to acknowledge help received from the following individuals and organizations.

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May the good Lord reward you all for your labour of Love.

Finally, I thank God the father, Jesus my Lord and brother, and the Holy Ghost for fulfilling the promise, 'I will never leave you nor forsake you'.
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INTRODUCTION

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1.2 MAIN OBJECTIVES OF THE RESEARCH
1.3 WORK UNDERTAKEN
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1.1 BACKGROUND

Cost effective design, manufacturing and management methods are being developed and used in every discipline. The use of economical, productive and efficient design, manufacturing and management methods is of paramount importance for the survival of any organization or industry in competitive markets. As learnt from history, failure to adopt cost effective methods (design, manufacturing, management) sooner or later, lead to closure of an industry or organization. For example, failure to adopt new cost effective shipbuilding methods was one of the main reasons for closure of the British shipbuilding industry (Parkinson 1960).

The construction industry's understanding and application of cost effective design methods has remained largely the same; new methods are being developed in a seeming endless continuum but application in industry has failed to match the development (Lev 1981, Gallagher and Zienkiewicz 1973). Could this under utilization of recently developed cost effective design methods be due to problems in current design practice, not providing proven cost benefits, or the problems associated with developed methods? (Ashworth 1986, Templeman 1983). Had these questions been answered it would have been possible to implement new cost effective design methods into current design practice and to improve the economy of building investments. Adoption of new cost effective methods has been recorded in the building construction industry. Two good examples are the introduction of precast elements in the 50's and the 60's (Brakel 1967) and cost efficient building services design methods in the 70's to reduce energy costs in buildings (Thomas 1971). It would thus seem logical to investigate application of cost effective design methods in practice.

The survey conducted in this research among practising designers concluded that one main reason for not adopting the developed new methods was the low cost benefits from cost effective methods. Designers do not consider new cost effective design methods as offering satisfactory cost savings compared to current design methods. Furthermore, review of literature and discussions with designers revealed that there were problems in current design decision making and design fee (or contracts) methods to accommodate cost effective design methods. Therefore this research is addressed of evaluating the cost benefits and overcoming the problems of implementing cost effective methods in the design process.
1.2 MAIN OBJECTIVES OF THE RESEARCH

From the foregoing background the research described in this thesis was developed.

The main objective being to evaluate the cost benefits of cost effective design methods and to study the difficulties and favourable conditions for the implementation of cost effective design methods.

Reinforced concrete framed buildings were chosen because of its extensive use and dominance as structural material in the author's country. In this research only the cost effective design methods related to the capital cost of buildings were considered. The amount payed by the client (or sum in priced bill of quantity) is considered as the 'cost' in this research.

The research therefore had the following sub-objectives which must be achieved in order to accomplish the overall objective:

(a) to examine cost effective design methods developed in the past;
(b) to identify the reasons for failure of already developed design methods;
(c) to identify the needs and difficulties faced by practising designers;
(d) to develop suitable cost effective design methods to give cost effective designs;
(e) to evaluate the cost benefits of cost effective design methods to the building construction industry, to a given project and accuracy of predicted cost savings; and
(f) to identify the problems and favourable conditions for implementation through a study of the design process.

1.3 WORK UNDERTAKEN

To satisfy these objectives the following work was undertaken:

Firstly, previous research and literature in cost effective design methods for reinforced concrete framed building design were assessed and critically reviewed. The type of design methods developed, relevant design stages for cost effective designs and reasons recognized by others for the failure in practical applications were identified. Requirements to develop new methods to provide practical design solutions and need
to study the design process with respect to cost effective designs also were identified. Reinforced concrete designs at the detail design stage were selected for in depth study since cost effective design methods can provide economical solutions with same building functions.

Secondly, the building design process was investigated for design decision making practice and the involvements of the architect, structural engineer and others in the design process, requirements of the designers for cost effective designs, and practical problems involved in using cost effective design methods were considered. These investigations were conducted through interviews with designers and the literature review. Two sets of interviews were conducted with the aid of questionnaires.

Thirdly, cost effective design methods for design of reinforced concrete slabs, beams, columns and independent footings were developed. Optimum structural design theory and reinforced concrete design methods used by practising designers were used in development of these methods. Necessary steps were taken to overcome problems identified in the literature survey and interviews with designers as well as to give complete practical design solutions.

Fourthly, cost and design data required for cost benefit analyses for use of cost effective design methods were identified and collected from historical buildings. The collected information included design data from drawings and cost data from priced bills of quantities.

Finally, cost savings from cost effective design methods developed for historical buildings were investigated. Cost savings to the building construction industry and to a given project were investigated using statistical theories. Predicted cost savings were judged against minimum cost savings expected by designers. Cost differences in design decisions related to building structure were investigated using a developed cost model. Cost differences of different design options in windows and floor finishes were also investigated.

To undertake the above work and to develop cost effective design methods as well as to calculate cost savings from developed methods and the cost model, computer programs were developed using the Turbo Pascal programming language. Cost savings in historical buildings were analysed according to statistical theories using Statgraphics software.
1.4 MAIN FINDINGS OF THE RESEARCH

On the whole, the work proved that significant cost savings can be achieved in building design using cost effective design methods compared to current design methods.

This study provides new knowledge on potential cost savings in in situ reinforced concrete design of buildings obtained through application of developed cost effective design methods to 22 historical buildings. The study has provided necessary information to predict cost savings in building design together with accuracy (or risk). This study investigated the design process with regard to use of cost effective design methods and favourable conditions and problems which must be overcome to implement new methods were identified.

The main findings of this research were:

1. A total building cost saving of 2.91% can be achieved by using optimum structural design methods for slabs, beams, columns and independent footing foundations in reinforced concrete framed buildings. This was discovered through applications of cost effective design methods to 22 historical buildings. Depending on the size of building a client can save between 45% and 65% of the total design fee in a building.

2. The opinion among practising designers was that cost savings through optimum design methods are less than 10% of elemental cost and 1% of the total cost of a building. This was one of the main reasons for the rejection of new methods by practising designers. This argument was conclusively rejected by the findings of this research.

3. Accuracy (or risk) in predicted cost savings for a given project was measured from the probabilities of predicted cost savings. It was discovered that probabilities of cost saving exceeding 1%, 2% and 3% are 0.96, 0.79 and 0.47 respectively.

4. The cost effective depths of slabs and independent footings were less than the depths used by designers. Therefore optimum methods for slab and footings can be implemented without creating problems to other element designs or to the building. Columns and beams required increase in depths for cost effective design solutions. Depths increases observed in 22 building were not
significant and designers opinion was that these can be accommodated in their designs.

5. Cost effective design methods cannot be put into practice in isolation. Study of the design process proved that design decisions are multidimensional and highly interactive. In building designs, especially architectural design decisions, factors such as building regulations, client's needs, designers experience and choice and available design information influence final design decisions more than the cost. Therefore cost effective design methods should take these into consideration. One way to overcome this is to provide necessary information to the designer to produce cost effective designs as well as leaving final design decisions to the designer.

6. This study revealed that primary use of cost information in briefing and sketch design stages is to produce estimates. A limited use of cost information in decisions related to building size, building shape, grid, and quality of the building was observed. Six architects (out of nine) responded for the developed cost model concluded, even though costs related to design decisions are significant, generally other factors such as building functional requirements influence final design decisions more than the cost. Therefore use of cost effective design methods based on cost concepts do not have potential for practical applications.

7. There are problems in current design contract procedures for implementation of cost effective design methods. The common percentage fee design contracts have a disincentive, thus higher design fee than normal is required to motivate designers to use and to get benefits of cost effective design methods. Design and build contract types have a mechanism to use cost effective design methods, since it can give direct benefits to the contractor.

8. Construction industry's history has evidence of successful application of cost effective design methods; use of precast structural elements and energy saving services and insulation designs are two examples. However, in these cost effective methods, the capital cost of the building was increased and economy was achieved through shorter construction duration or low building cost-in-use.
There are no incentives or benefits to designers motivating them to use the more time resource consuming cost effective design methods to reduce the capital cost of a building such as methods discussed in this research in current design practice.

1.5 GUIDE TO THESIS

The thesis is divided into nine chapters covering the development of the research from the background investigations to final conclusions. Figure 1.1 shows the chapterisation of this thesis. The first section outlines the cost effective design methods developed in the past by others. From the literature survey, problems related to and investigations required for the implementation of cost effective design methods were identified.

To understand the difficulties and favourable conditions for the use of cost effective methods and to establish designers expectations on new cost effective methods, a survey among designers was undertaken.

Cost effective design methods were developed to produce design solutions and to evaluate the cost benefits. Cost and design data of historical buildings was collected to evaluate cost benefits through cost effective design methods.

Finally, an evaluation was made between designers solutions and cost effective design solutions. The problems related to the implementation of methods were established.

Briefly, the thesis constitutes:

Chapter 2 presents a review of optimum structural design methods and cost effective design methods developed based on historical cost data.

Chapter 3 presents detail of design practice and difficulties and favourable conditions for implementation of cost effective design methods. This study was based on the literature review and interviews held with designers in practice.
Chapter 4 presents details of cost effective design methods developed in this research for reinforced concrete slabs, beams, column and independent footings. Development of cost equations, optimum design problems, use of the computer to solve the optimum problems are given in detail.

Chapter 5 gives details of designers' responses to cost effective design methods. This study was held through interviews with designer and details include designers knowledge on new methods, expected cost savings from new methods, needs of designers with respect to cost effective designs.

Chapter 6 gives details of cost and design data collected from historical buildings. The collected data included layout design data of buildings, detail design data of slabs, beams, columns and foundations and cost data from priced bills of quantities.

Chapter 7 gives the cost savings in 22 historical buildings using optimum methods developed in chapter 4. This study predicted cost benefits to the building construction industry in addition to that for a given building.

Chapter 8 gives the details of the developed cost model to show the cost consequences of design decisions in building structure at sketch design stage. Application of the cost model for four historical buildings are given. Analyses on design decisions and cost related to windows and floor finishes were also included.

Chapter 9 concludes the findings of the research by stating conclusions and recommendations for implementation of cost effective design methods. It also recommends further research on cost effective design methods.
Chapter 1
Introduction
Cost effective building design methods have been developed in the recent past for design of building structure as well as other elements. However, cost effective design methods have failed for practical applications (Templeman 1983, Ashworth 1986). What are the main reasons for this failure: problems associated to methods; not providing significant cost savings; or the problems in the design process?

Chapter 2
Cost effective building design methods
What are the main cost effective building design methods? 1. Structural optimum design methods (structural designs). 2. Cost effective design methods based on cost data (mainly for architectural designs).

Chapter 3
The Design process
Building design process was investigated for design decision making, influences on design slabs, beams and columns were developed for design decisions, personnel and their responsibilities, design contract procedures with respect to cost effective designs.

Chapter 4
Cost effective design methods for reinforced concrete elements
Optimum design methods for footings, slabs, beams and columns were developed using optimisation theories. The methods were developed to give complete practical design solutions. The cost of element was used as the objective function and design methods and constraints given in BS8110 were used in the optimum design methods.

Chapter 5
Design decisions and cost effective designs
1. Study of design decision making and use of cost data for decision making.
2. Identification of designers cost data requirements for design decision making process.
3. Expectations of designers on cost effective design methods.

Chapter 6
Cost and design data
1. Identification and collection of cost data required to evaluate the cost benefits of cost effective methods.
2. Identification and collection of design data required for cost benefit analysis from cost effective design methods.

Chapter 7
Cost savings through reinforced concrete optimum design methods
1. Calculation of cost savings of a sample of 22 buildings of which data were collected.
2. Forecast of cost benefits of optimum methods to construction industry & to a given project.

Chapter 8
Cost effective designs using cost information
1. Development and testing of a cost model for cost effective design decisions related to reinforced concrete building structure.
2. Testing of cost information requirements of designer’s related to windows and floor finishes designs to change design decisions.

Chapter 9
Conclusions and recommendations and future research

Figure 1.1 GUIDE TO THESIS
Chapter two

COST EFFECTIVE BUILDING DESIGN METHODS

2.1 INTRODUCTION TO THE SUBJECT
2.2 COST EFFECTIVE DESIGNS BY ASSESSING VARIOUS DESIGN OPTIONS
2.3 OPTIMUM METHODS FOR REINFORCED CONCRETE STRUCTURAL DESIGNS
2.4 EVIDENCE FOR THE USE OF COST EFFECTIVE DESIGN METHODS
2.5 SUMMARY AND CONCLUSIONS
2.1 INTRODUCTION TO THE SUBJECT

2.1.1 History of Economic building design and construction

Economic considerations of building design and construction pervades the long history of building industry. In Britain, more expensive material such as natural stone was gradually replaced by brick which became the dominant structural material. Decorative work with high labour cost such as carving of timber and stone and decorative plaster work largely disappeared giving way to decorative effects using contrasting materials and paints.

Use of prefabricated items can be seen as yet another stage in the economic development of building design and construction. Sometime ago, timber was brought to the building site and was used to make windows, doors roofs etc. Later when factory methods became cheaper, those building elements were pre-fabricated and brought to the building sites. This success led to many other pre-fabricated elements being made from materials such as steel, concrete, aluminium, plastic(PVC) etc. The use of pre-fabricated items are also common in building services.

Today, one of the design team's main responsibilities is to produce designs which satisfy requirements of the client and provide value for money. This does not mean cheapness but 'economy'. Lower standards give lower costs to buildings but do not necessarily improve the economy of a building. The most economical building is one which fulfils the clients requirements at the lowest cost. Therefore the client's requirements and costs need to be considered together.

A vast amount of research has been undertaken during last 3 to 4 decades to provide value for money in building designs, in other words to design buildings to the lowest cost which satisfies the clients requirements, cost effective building design. The research undertaken in cost effective building design to reduce the capital cost can be categorized into two broad categories as given below.

1. Assessment of design options with cost (architectural designs).
2. Structural design optimization methods (structural designs).

These two methods are discussed in sections 2.1.2 and 2.1.3 respectively.
2.1.2 Assessment of design options with cost

Assessment of design options with cost is the most common type of design decision making (architectural) in the construction industry. To make the final design decision, design options are assessed by considering the cost and the requirements such as durability, appearance etc. Therefore design decision making first involves an analysis of design options, secondly a synthesis (suitable types and costs) and finally an evaluation of cost and functional requirements as shown in Figure 2.1. Examples of these design decisions are: making the final decision to select the most suitable site from two or more feasible building sites at the beginning of a project; or to select suitable floor finish type from two or more types of floor finishes at detail design stage. This design decision making process is not simple and judgement based on experience and intuition play an important role.

To make the right design decision, an accurate cost estimate is very important in the economic design decision making process. Therefore over many years a vast number of research projects have been undertaken, mainly in cost models to develop methods for accurate cost estimates (Davis, Belfield & Everest 1977a, Wilson 1982, Reynolds 1978). Further research has been undertaken to understand cost relationships of design variables such as building height, span, etc. (The Wilderness Study Group 1964, Cost Research Panel 1960, Moore and Brandon 1979). In the recent past some researchers have proposed methods of economic designs through value analysis techniques, which is a systematic way of assessing the values of various design options (Dell'Isola 1982, Morton 1987). During last five years, methods have developed, and continued to be, in research for application of expert systems using computers for cost effective building designs (Maher 1984). As a direct result of research undertaken in energy saving to reduce cost-in-use, buildings were designed during the last two decades, to conserve energy.
Figure 2.1 Floor finish design decisions through assessing design options
2.1.3 Structural design optimization

For a given building there are an infinite number of feasible design solutions with different member sizes and spacings for floors, beams and columns. For example, given a loading arrangement of a concrete frame and floors in a building, it is possible to obtain a large number of design solutions with different section sizes for beams, columns and slabs, which satisfy recommendations given in design codes such as BS8110. Methods developed to find the least cost solution from this infinite number of feasible design solutions are known as 'Structural design optimization methods'. The normal method of finding the least cost design solution is by formulating and solving an optimization problem. An optimization problem constitutes an objective function, cost of the structure or weight of the structure together with constraints generally of practical reasons and requirements of design codes such as BS8110. Mathematical procedures such as linear programming with the aid of a computer is generally used to solve optimization problems. Methods have been developed for design optimization of reinforced concrete elements such as slabs, beams, trusses (Chou 1977, Taylor 1985, Prakash, Agrawala and Singh 1988) or for the whole reinforced concrete frame (Clark 1985).

In an assessment of various design options (architectural designs), different costs as well as different qualities such as durability are considered. But structural design optimization methods produce design solutions at lower costs without any change in other qualities.

2.1.4 Summary

The task of today's building design team is to provide value for money and to produce cost effective designs. Cost effective designs to reduce the capital cost of a building can be achieved in two different ways. These are:

1. assessing the feasible design solutions by considering building functions and cost (architectural designs);
2. optimum structural design methods (structural engineer's designs).
2.2 COST EFFECTIVE DESIGNS BY ASSESSING VARIOUS DESIGN OPTIONS

As was discussed in section 2.1.1, one of the main responsibilities of the design team is to provide value for money to the client. This can be expanded further as 'designing a building for requirements in client's brief, of the site, available form of construction, statutory planning rules and to the least cost'. Therefore, as the chief design decision maker, the architect makes a series of design decisions by considering the cost, planning regulations, construction methods, available building materials etc. These design decisions can be quantity related such as building size, plan shape and quality related such as type of materials to be used in the building and standard workmanship required. In the whole design decision making process, three components can be identified (see Figure 2.1). These are:

1. design options (various design decisions available);
2. cost of each design option; and
3. judgement of the designer for clients requirements, available funds and other requirements.

Design options are generated because of availability of different materials and methods of construction. Steel and concrete for structure; timber, aluminium, steel etc. for windows; various types of finishes for walls and floors; different plan shapes; and buildings with different number of storeys are some examples for design options.

To make the design decision which is the most cost effective, cost of various design options are required. For this purpose most designers use traditional methods which are largely techniques of estimating. During the last two to three decades, because of "poor performance of existing cost forecasting methods and on assumption that an improved alternative existed"(Ashworth 1986), a large number of new techniques were developed to provide cost estimates of various design options. Cost modelling is the most common new method developed to forecast the cost of design options. The majority of cost models were computer based and use of statistical theories was very common (Reynolds 1978). Value analysis is another method which not only provides cost information but also has a systematic method to make a judgement for client's needs and the cost (Dell'Isola 1982). Two methods have been developed to produce cost effective designs through value analysis techniques. Expert system is yet another new method developed in the recent past for cost effective building designs. Expert systems provide cost information and expert advice to make a judgement on design options (Maher 1984). A discussion of traditional methods, cost models, value
analysis and expert system methods developed to produce cost effective designs follows.

2.2.1 Traditional methods

Cost effective traditional design methods involve analysis of design options, considering the cost based on available values of design variables such as floor area, building height and the client's requirements. Good descriptions of traditional cost estimating based on design variables are given by Ashworth(1988), Bathurst and Butler(1980) and Seely(1972). Brief descriptions on some of the design decision making by traditional methods are given below.

2.2.1.1 Building size

Building size is the first design decision to be made in any building project. The upper limit is governed by available funds and client's needs. The traditional method calculates the costs of design options by using cost of unit floor area. The cost of unit floor is determined after examining the building quality, size, location, market conditions etc.

2.2.1.2 Plan shape

Plan shape has a significant effect upon the overall cost of a building. The traditional method of making the building more cost effective is by using a low wall to floor ratio. This concept is illustrated by the plan shapes given in Figure 2.2 (Ashworth 1988) in which building 'A' is the most cost effective. Even though square plan shape is the most economical for a building, designers face a number of constraints in real life design: site boundaries; functional requirements of the building such as a narrow layout for a factory building.
2.2.1.3 Height

Tall buildings are more expensive than low-rise buildings. On the other hand single storey buildings are also not cost effective. The traditional design decision method involves experience and the following elements relate to cost of the building height. These are cost of:

1. those which fall as the number of storeys increases (e.g. roofs, foundations);
2. those which rise as the number of storeys increase (e.g. lift installations);
3. those unaffected by height (e.g. floor finishes, internal doors); and
4. those which fall initially and then rise as the number of storeys increase (e.g. exterior enclosure).

The effects of above factors are shown in Figure 2.3 (Flanagan and Norman 1978). There is an increase of cost at five storey level because of requirements of lifts. The cost decreases between 2 to 4 storeys.

2.2.1.4 Storey height

Higher storey heights cost extra money. But sometimes a higher storey height than normal is required due to special reasons such as prestige in hotel lobbies, churches or because of requirements of installations such as heating and air-conditioning ducts. Experience, experimental judgement together with approximate cost guides are used to make this design decision cost effective.
2.2.1.5 Foundations

The traditional method of design decision making is based on known facts such as economical type of foundations. The most economical type of foundation for a reinforced concrete framed building is the independent footing foundation. Even in buildings up to 5 stories, depending on the ground conditions, independent footing foundations could be used. The second cheapest type of foundation is strip or combined footings. Pile foundations are the most expensive and generally raft foundations are more economical than pile foundations. The traditional design method uses cost estimates based on approximate designs to test the economics between a raft foundation and a pile foundation.

2.2.1.6 Frame, floors and stairs

Designers know the cost effective material type for building frames, floors and stairs by experience and published data. For example in Britain steel building frames are more cost effective than in situ concrete building frames because of high labour cost in in situ concrete construction. In Sri Lanka in situ concrete frames are more cost
effective than steel because of cheap labour cost and high cost of steel (steel has to be imported). Designers also receive advice from quantity surveyors to make design decisions related to building frame, floors and stairs.

2.2.2 Cost models

Cost modelling is the most common new method developed for cost estimates. "Any means of estimates can be described as a cost model" (Ashworth 1986) or "all estimating methods can be described as cost models" (Beeston 1987). Many years ago, 'cube method' cost of unit volume was used as a cost guide by designers to make cost forecast as well as for cost advice in design decisions. The cube method proved to be poor at relating design variables and client's requirements to the cost. To overcome this, 'superficial area method', cost of unit floor area was developed and more meaningful cost relationships between cost and design variables were established. James (1954) made a further advancement by introducing 'storey enclosure method' (cost of unit enclosure) which attempted to forecast cost based on a combination of a wall, roof and floor area. Southwell (1971) proposed a method to forecast building cost combining the building's floor area and its perimeter. The above methods are simplistic ways of cost models.

During the last two decades, more advanced cost models were developed for cost effective building designs (optimization models), tender price predictions and to improve the contractors estimating accuracy. The methodology and methods of solutions of cost effective design models are given below.

2.2.2.1 Methodology of design cost models

Wilson (1978) has given the following sequence for optimum design cost models.

1. Define the problem.
2. Identify the independent variables.
3. Derive the objective function.
4. Derive the functional constraints.
5. Test the behaviour of the model.
6. Test the sensitivity of the optimum.
Defining the problem will help to decide factors within and outside the scope of task. Further it will help to identify the level of hierarchy of the design process where cost model will be applicable. The correct identification of independent and dependent variables will often facilitate much easier solutions at optimization stage. The objective function could be to minimize the cost, price, or any other parameter. Functional constraints will take into account the technical, legal and financial constraints on design variables. Cost models must be tested adequately before they are applied to real life projects to produce design solutions. For this testing, different data should be used. It is important to test the optimum solution for sensitivity, to check the changes in the optimum solution for a small change in independent design variable(s). Today, optimum design problems based on cost models can be solved by using a computer.

2.2.2.2 Methods of solutions to cost models

Four methods of solutions to cost models have been described by Ashworth (1986). They are namely, empirical, algorithmic (regression analysis), simulation and heuristics.

(i) **Empirical methods**
Empirical methods are more traditional cost models which are based upon observation, experience and intuition. These cost models are based on data such as descriptions and dimensions in construction works.

(ii) **Algorithmic methods (regression analysis)**
Algorithmic methods use precisely defined procedures to perform calculations. Variables are selected and analysed and the model is constructed. Majority of cost models based on algorithmic methods have used regression analysis techniques (statistical analysis methods).

(iii) **Simulation methods**
A simulation model produces a set of building design alternatives through duplicating the behaviour of the system under investigation by studying the interactions among its components. Simulation does not provide the optimum, but it can give a set of alternatives from which the best can be selected.

(iv) **Heuristics**
Ashworth (1986) defined heuristics methods as a rule of thumb procedure which enables a near optimum solution to be produced once the model has been built.
The heuristic approach can incorporate the proficiency of the expert such as skill, experience, judgement, knowledge, intuition feel, academic background, personality, enthusiasm, hunch and a 'feeling in the back of the head' etc.

2.2.3 Cost data bases

'Data bases' is a new word for structured filing system such as price books and quantity surveyor's historical data file, in computers. Therefore cost data base simply means a structured cost data in a computer. Most cost data bases are used by cost models or by other programs to get information such as elemental costs, total cost or cost per unit area.

A well known data base for building cost information is provided by BCIS (Building Cost Information Service). In 1962 BCIS acted as an information exchange establishment for quantity surveyors and with the development of micro computers in early 1980's BCIS on-line system was established in 1984. BCIS provides cost information on past projects and can be used to price different design alternatives during the design process. Green (1982) has given a description of data bases used at Property Services Agency, U.K. Jaggar (1982) has given details of data base requirements to secure more optimal design and construction solutions in buildings.

2.2.4 Value analysis

Value analysis was developed during 1940's in manufacturing industry in USA. General Electric Company in USA, because of wartime shortages of specific materials, used substitute materials for their designs and found superior performance at lower cost. Value analysis involves answering six cost and functional related questions and a systematic evaluation. These are:

1. what is it? (functional analysis);
2. what does it do? (key question);
3. what is it worth? (least expenditure required to provide the defined function);
4. what does it cost? (to compare with worth);
5. what else will it do?; and
6. what does that cost?
Kelly (1982) has suggested a value analysis method for early building design stage. Morton (1987) has described how to apply value engineering into construction industry. Dell'Isola (1982) has given a comprehensive description of application of value analysis to construction industry to get cost effective designs.

However, to use value analysis professional judgement is very important and accurate cost calculation plays a key role. For the successful application of value analysis, methods answering questions related to cost (above 3, 4 and 6) are important.

2.2.5 Expert systems

An expert system can be defined as "an intelligent computer program that uses knowledge and inference procedure to solve problems that are difficult enough to require significant human expertise for their solution" (Feigenbaum 1981). Maher (1984) has given an expert system HI-RISE, for cost effective preliminary structural designs of high rise buildings. In the HI-RISE system user inputs grid, number of bays in two perpendicular directions, number of storeys and few other design details. The system produces feasible design alternatives and displays graphically together with relative costs and an evaluation of all feasible solutions. The HI-RISE expert system uses a limited knowledge base and development of fully comprehensive knowledge base still remains as an unsolved problem. Difficulty of creating a fully comprehensive data base for the cost effective design system is major set back in applying expert systems to produce cost effective designs.

2.2.6 New estimating methods developed in the past by others for the design process

More than 15 cost models, two value analysis methods and one expert system were recorded in the past for cost effective building designs. Majority of cost models give not only cost advice but claim improved accuracy on cost forecasts during the design process. Table 2.1 shows new cost effective design methods found in literature. Use of elemental cost analysis according to standard form of cost analysis were very common (Holes 1987, Williams 1987, Brown 1987, Reynolds 1978 etc.). For cost forecasting purposes, methods have used statistical theories such as regression analysis (Reynolds 1978, Brandon 1978) and simulation (Brown 1987). Approximately ten
methods have used published unit cost rates for estimates (Moore and Brandon 1979, The Wilderness Study Group 1964, Flanagan and Norman 1978, Avery 1987, Townsend 1982 etc.).

A study on aims and objectives showed that cost models were developed to improve the quantity surveyor's task of design phase cost estimating or cost advice given by the quantity surveyor to the design team (mainly to the architect and the client). No attempt was taken to identify the cost information needs of the chief designer architect, or any other member in the design team to produce cost effective designs. Therefore a study is required to identify cost information requirements of the architect and other members, to improve cost effectiveness of design decision making process.

More than 15 methods were observed for the design of building as one unit during early design stages. However, designers, mainly architects make most cost related design decisions at the detail design stage (see section 3.4.3) and no method was found for this design stage relating to design decision making such as quality of finishes.
Table 2.1 Cost effective design methods developed in the past by others

<table>
<thead>
<tr>
<th>Name</th>
<th>Design stage</th>
<th>Aims and objectives</th>
<th>Design element</th>
<th>Methods of solution</th>
<th>Data used</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moore &amp; Brandon (1979)</td>
<td>Pre-detail design stages.</td>
<td>To identify the effects of major design variables on the cost of an in situ concrete frame building.</td>
<td>Frame and floors.</td>
<td>Interactive modular search through set of feasible design solutions. Frame design according to CP114. Two computer programs: 1. to calculate unit cost rates &amp; quantities in frame and floors; 2. to calculate the cost of finish frame from 1 above.</td>
<td>Pre-determined Eg. square columns from 150 to 600mm</td>
<td>Total cost, floor &amp; roof foundation &amp; frame costs for various bay sizes, length/breadth ratios.</td>
</tr>
<tr>
<td>The Wilderness study group. (1964)</td>
<td>Scheme and outline design</td>
<td>Cost implication of fundamental design variables of storey height, floor loadings column span and number of storeys.</td>
<td>Frame and floors.</td>
<td>Manual calculations. Frame and floor design according to CP114. Graphical representation of cost with fundamental design variables.</td>
<td>Pre-determined fixed data.</td>
<td>16 charts shows the relative costs with design variables. 1. Number of storeys. 2. Storey height. 3. Column spacing. 4. floor loads.</td>
</tr>
<tr>
<td>Flanagan &amp; Norman (1978)</td>
<td>Sketch design stage</td>
<td>1. To find the relationship between price and height</td>
<td>Total building</td>
<td>Analyse of total building price with height.</td>
<td>1. Cost data of 15 offices from journals.</td>
<td>Cost per unit floor area with height. First decrease then increases</td>
</tr>
<tr>
<td>Name</td>
<td>Design stage</td>
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<td>Design element</td>
<td>Methods of solution</td>
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</tr>
</tbody>
</table>
| 4. Brandon (1978)     | Pre-sketch design stages   | 1. To identify two design stages prior to sketch design to determined the design strategy.  
2. To find the cost relationship with shape, height, location etc. | Total building design | 1. An empirical model for lift cost.  
2. Multiple linear regression model for windows design.  
3. A physical evaluation model for the design of frame. | Published data | Cost of various feasible designs by with design variables such as plan shape. |
<p>| 5. Property services Agency (1973) | Any design stage.          | To give improved cost guidance to the designer by taking account of contractors planning methods resources allocation. | Total building design. | Computer based. Asking series of questions for construction and design variables. | User defined | Cost range of possible design alternatives. |
| 6. Avery (1987)       | Pre-detail design stages   | To evaluate future small factory building design.                                  | Total building design. | Graphical representation of cost/m² for various elements such as substructure, external walls, finishes, etc. | PSA schedule of rates | Cost of elements varying with floor area and building types. |</p>
<table>
<thead>
<tr>
<th>Name</th>
<th>Design stage</th>
<th>Aims and objectives</th>
<th>Design element</th>
<th>Methods of solution</th>
<th>Data used</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Holes</td>
<td>Early design stages. designs.</td>
<td>For better planning of the costs of building design.</td>
<td>Total building design.</td>
<td>Use of spreadsheet &amp; computer. Building has considered with elements defined in standard form of elemental cost analysis.</td>
<td>Dimensions.</td>
<td>Resources and cost of the project as a whole can be found.</td>
</tr>
<tr>
<td>8. Weight</td>
<td>Early design stages.</td>
<td>To evaluate variations upon shapes, component choices independently.</td>
<td>Total building design.</td>
<td>By 'partition theorems' which take building as a collection of spaces and zones.</td>
<td>User defined.</td>
<td>This gives cost together with area, length, breadth, number of storeys etc.</td>
</tr>
<tr>
<td>9. Williams</td>
<td>Early design stages.</td>
<td>To demonstrate interrelationship of elements of a building</td>
<td>Total building design.</td>
<td>Use of spreadsheet. Elements are according to standard form of cost analysis. User defined inter relationships between elements.</td>
<td>Data from past priced bills of quantities.</td>
<td>1. Element quantities and unit rates. 2. Cost of various elements for different design decisions.</td>
</tr>
<tr>
<td>10. Brown</td>
<td>Inception design stages.</td>
<td>To predict cost of building services.</td>
<td>Total building design - services</td>
<td>Mote-Carlo simulation method.</td>
<td>BCIS detail Elemental cost cost analysis</td>
<td>A mean properties has been given to 'cost each element:total cost'</td>
</tr>
<tr>
<td>Name</td>
<td>Design stage</td>
<td>Aims and objectives</td>
<td>Design element</td>
<td>Methods of solution</td>
<td>Data used</td>
<td>Results</td>
</tr>
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<td>--------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>12. Reynolds (1978)</td>
<td>Sketch design stages.</td>
<td>For more balance design, according to standard form of cost analysis.</td>
<td>Total building design.</td>
<td>Regression analysis. For defined elements, similar to standard form of cost analysis.</td>
<td>Data from priced bills of past buildings.</td>
<td>Regression cost models for various elements. Cost estimates and design guides.</td>
</tr>
<tr>
<td>Name</td>
<td>Design stage</td>
<td>Aims and objectives</td>
<td>Design element</td>
<td>Methods of solution</td>
<td>Data used</td>
<td>Results</td>
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</tr>
<tr>
<td>14. Davis, Belfield and Everest 1977a, 1977b, 1978a, 1978b, 1978c, 1979a, 1979b.</td>
<td>Initial design stages. Inception,</td>
<td>To give more accurate cost estimates.</td>
<td>Total building, Warehouses, houses, factories flats, hotels etc.</td>
<td>Range of cost per unit area for various elements such as foundation, frame, windows &amp; doors and methods to adjust for building size, location, type of finish etc.</td>
<td>Fixed defined data for 1977 year.</td>
<td>1. Cost per unit area of the building. 2. Total cost of the building.</td>
</tr>
<tr>
<td>16. Russel &amp; Choudhary (1980)</td>
<td>All design stages.</td>
<td>To assist in designing cost effective buildings.</td>
<td>Total building design</td>
<td>Defining the building design as an optimization problem. Cost as the objective function and solved by 'Box complex method'.</td>
<td>User enter data</td>
<td>Minimum cost design for a given design problem.</td>
</tr>
<tr>
<td>17. Bank (1978)</td>
<td>Inception feasibility and sketch design stages</td>
<td>To design buildings with cost effective shapes.</td>
<td>Total building.</td>
<td>Examining length/breadth index and plan/shape index.</td>
<td>Building dimensions length, breadth etc.</td>
<td>Length/breadth index and plan/shape index.</td>
</tr>
<tr>
<td>Name</td>
<td>Design stage</td>
<td>Aims and objectives</td>
<td>Design element</td>
<td>Methods of solution</td>
<td>Data used</td>
<td>Results</td>
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</tr>
<tr>
<td>18. Fallon (1985)</td>
<td>Pre-detail design stages</td>
<td>To produce cost effective single storey steel buildings.</td>
<td>Frame and floors</td>
<td>Graphical representation on relative cost of different types of frames and roofs.</td>
<td>Fixed data.</td>
<td>Relative costs of various feasible designs.</td>
</tr>
<tr>
<td>19. Horridge &amp; Morris (1985)</td>
<td>Preliminary design stages</td>
<td>To produce comparative costs of single story steel frame buildings.</td>
<td>Frame and floors</td>
<td>Graphical representation of cost/m² of various types of frames.</td>
<td>Fixed data.</td>
<td>Cost per unit area of various frames.</td>
</tr>
<tr>
<td>20. Jaggar (1982)</td>
<td>Detail design stage</td>
<td>To produce cost effective design/construction solutions</td>
<td>Total building design</td>
<td>Use of bills of quantities with data base theories.</td>
<td>User defined</td>
<td>Bills of quantities with resource requirements corresponding to cost effective design.</td>
</tr>
<tr>
<td>21. Maher (1984)</td>
<td>Preliminary design stage</td>
<td>To produce and to evaluate feasible structural forms for the building frame.</td>
<td>Frame and floors</td>
<td>Expert system with knowledge base.</td>
<td>Fixed knowledge base and user enter design data, grid, bays storeys etc.</td>
<td>Feasible designs with cost and evaluation of all feasible design solutions</td>
</tr>
</tbody>
</table>
2.2.7 Successes and failures of new methods

Through new methods, better understanding of cost and design decisions were made possible (The Wilderness study group 1964). Further systematic methods were introduced to analyse the cost distribution among elements in a building. Most new methods are computer based and have the ability to produce cost estimate within a very short time, which is very important to modern busy working design offices.

Unfortunately, "cost models have failed almost totally to achieve application in the construction industry" (Ashworth 1986). This failure is not only due to lack of interest from the construction industry but also due to mistakes made by researchers who developed new methods. Ashworth(1986) has discussed some reasons for this failure. Reasons of the failure of new methods to infiltrate into the design practice and possible remedies are discussed below.

2.2.7.1 Understanding the needs of potential users

Almost all the new methods were the methods derived by academics or professionals. Consequently, models were developed for the quantity surveyors day to day work such as to produce estimates (Davis Belfield and Everest 1977a, Reynolds 1978) or for cost control etc. Some methods were developed for the quantity surveyors design phase cost advice task or assumed needs of the architect or structural engineer (Moore and Brandon 1979, The Wilderness study group 1964).

No proper study with respect to development of new methods was undertaken to identify cost information needs of the architect, who is the chief designer or any other member of the design team, except the quantity surveyor. This is one of the main reasons for failure of new methods to fulfil the design team's cost information requirements. Further this has led to inappropriate application of the technique to problems which were not relevant. A way to overcome this is to attempt of a study to identify the cost information needs of the design team.
2.2.7.2 Neglect of value of experience, judgement of professionals in the design team

New methods developed by academics or professionals have very limited or no flexibility to use design team professional experience, intuition and judgement. This has led to lack of co-operation and interest from the senior managers in the industry. Therefore methods should not be developed to override the managers experience and judgement but to exploit and to use it for maximum benefit. An automated cost effective design method based on methods such as cost models, expert system or value analysis seems undesirable. Therefore cost effective methods should provide necessary information leaving the final design decision to the designer. Further a good co-operation between researchers and the industry is required since almost all new methods were developed by academics, and not by professionals in the industry.

2.2.7.3 Implementation of new methods

Ashworth(1986) has identified the fact that 'models did not work' as being the most probable main reason for failure of cost models. This is true for other new methods, value analysis and expert systems. For expert system to give good design solutions there should be a very good knowledge base which is a nearly impossible task to achieve in the case of building designs. This is true for value analysis methods where it is difficult to provide correct answers to 'key'(see section 2.2.4) value analysis questions. The second reason for failure of implementation of new methods into the design practice is general resistance from the professionals to change a method of working. Good performance from new methods for better accuracy, good interaction for design decisions and user friendliness of methods may be able to overcome the above difficulties.

2.2.8 Accuracy of cost estimating methods

A concept suggesting that the accuracy of design phase cost estimates improves with the progress of a design is as shown in Figure 2.4 (Barnes 1974). Further Barnes(1974) suggested +20% to -40% coefficient of variation(CV) at the feasibility design stage and +10% to -20% at the beginning of the detail design stage. However, McCaffer and McCaffery(1981) found through a survey of quantity surveyors forecasting accuracy for 15 schools for four design stages forecast, brief, sketch plan
and detail design of CV's of 17%, 10%, 9% and 6% respectively, which is an improvement on Barnes(1974) suggestions. Interviewing 32 client organizations Greig(1981) found CV's of roughly 6-7% in early design stages and less than 5% prior to tender. Jupp and McMillan(1981) also obtained similar results as Greig(1981) through an opinion survey of 49 quantity surveying practices. Marr(1977) in his 'Standard' for construction cost forecasting proposal, split the design phase into planning, budget, schematic and preliminaries in which corresponding adequate degrees of accuracy are stated as 20-40%, 15-30%, 10-20% and 8-15% reducing 5-10% prior to construction. The above findings can be summarized for 4 design stages, Inception, Feasibility, sketch and outline proposal and details are given in Table 2.2.

Table 2.2 Accuracy of design process cost calculations (coefficient of variations)

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inception</td>
<td>-40 to +20%</td>
<td>17%</td>
<td>6 to 7%</td>
<td>20 to 40%</td>
<td></td>
</tr>
<tr>
<td>Feasibility</td>
<td>10%</td>
<td>6 to 7%</td>
<td>15 to 30%</td>
<td>10 to 20%</td>
<td></td>
</tr>
<tr>
<td>Sketch</td>
<td>9%</td>
<td>6 to 7%</td>
<td>10 to 20%</td>
<td>8 to 15%</td>
<td></td>
</tr>
<tr>
<td>Detail</td>
<td>-20 to +10%</td>
<td>6%</td>
<td>5%</td>
<td>8 to 15%</td>
<td></td>
</tr>
</tbody>
</table>

New methods for design process cost estimates discussed in section 2.2.6 have failed to give a value for accuracy of proposed methods. To test the accuracy of a new method, it needs to be used in practice but there is no evidence of actual use of new methods developed. However, Thorpe(1982) tested the accuracy of McCaffer's(1976) bidding model (tender price prediction model) and found 10% to 19% accuracy, depending on the building type.

The absence of measurement on the accuracy of new methods, has left new methods to be judged for accuracy by examining the method's theory, data used and data analysis in development of the new method. Therefore accuracy of new methods with proven evidence is an unknown factor. Further Beeston(1987) has said that "methods based on in-place quantities seem to have reached the limit of their development with an accuracy insufficient for estimating or for cost advice at design stage".
2.2.9 Summary and conclusions

In summary the following can be stated.

1. New estimating methods or design phase cost advice methods based on cost models, cost data bases and value analysis have been developed to improve existing cost calculations in the design process.

2. New methods such as cost models and data bases have proved that improved cost information within a short time can be provided for the cost calculations in the design process. However accuracy of new methods still remain an unknown factor.

3. Methods have been developed for the quantity surveyors requirements and little or no attention has been given for cost information requirements of the architect, structural engineer and other members of the design team who make final design decisions. Therefore a study is required to identify the cost information needs of designers in the design process on various design decisions.

4. Cost effective design methods should be developed to incorporate factors such as experience and uniqueness of each design problem. Therefore a study is required to understand how designers make design decisions and how cost information could be successfully incorporated to produce cost effective designs.

Figure 2.4 Design progress and accuracy of cost calculations
2.3 OPTIMUM METHODS FOR REINFORCED CONCRETE STRUCTURAL DESIGNS

This section gives details of the optimum methods developed in the past for the design of reinforced concrete elements and roofs. Chapter 4 of this thesis will describe the computer based optimum design methods developed in this research for in situ reinforced concrete slabs, beams, columns and independent footings. Cost savings in 22 historical buildings of which data were collected from the construction industry are given in chapter 7.

Reinforced concrete optimum design methods vary from each other because of different design variables, objective functions, constraints and methods of analysis. The simplest objective function observed was the volume of main reinforcements and the most complicated was the total cost of a beam which included costs of concrete, formwork, main steel and cost of increasing the building height. Design constraints and methods of analysis given in BS8110, CP110, Indian concrete code and ACI 318 have been used to formulate design optimization problems. Mathematical methods such as linear programming have been used to solve optimization problems. Only a few out of large number of methods developed have filtered to design practice. Therefore design practice has not yet utilized the benefits of reinforced concrete optimum design methods.

Details of design variables, objective functions, constraints and mathematical procedures are discussed. Details of selected optimum methods for reinforced concrete elements, slabs, beams and columns are given. Methods are selected considering relevance to current design practice, to represent different design variables, objective functions, constraints and design practice and to compare cost savings of various methods. Optimum design methods developed for roofs also were discussed. An attempt is made to study reasons for failure of optimum methods to win the acceptance from current design practice.

2.3.1 Optimum design procedure

An optimum method begins with identification of design variables, objective function, and design constraints. These are then transformed into a mathematical problem which is generally solved by using theories in mathematics. Good description of optimum design procedure was given in 'New directions in optimum structural design'
Details of design variables, objective functions, constraints methods and formulation of mathematical problems of optimum methods are given below.

2.3.1.1 Design variables

Design variables of an optimum method consists of geometrical variables such as depth, width of a beam or a column, physical properties such as characteristic strength of concrete ($f_{cu}$) or steel ($f_{y}$) as well as any other quantifiable aspect of the design. For example beam depth was considered as a design variable by virtually all optimum beam design methods (Golding 1988, Cohn and MacRae 1984, Chou 1977). Material strengths of concrete ($f_{cu}$) and steel ($f_{y}$) were considered as constants in majority of methods. In contrast Norman (1964) has considered material strength of concrete ($f_{cu}$) as a design variable.

A variable which is non-continuous and has a set of values is known as a discrete variable. Most of the variables in reinforced concrete design such as reinforcement area, depth of a beam are discrete variables due to practical limitations. Majority of optimum methods overcome this difficulty by assuming discrete variables as continuous variables and making necessary adjustments to the final design solution. Even though this gives an optimum solution, the selected solution can be different from the optimum.

2.3.1.2 Objective function

The objective function is probably the most important feature of structural design optimization as it governs direction of the entire optimum design process. "The objective function, also termed cost or merit function, is the function whose least (or greatest) value is sought in a procedure and constitutes a basis for the selection of one of several alternative acceptable designs" (Gallagher and Zienkiewicz 1973).

The simplest objective function for reinforced concrete design that has been investigated was the volume of longitudinal reinforcements. Rozvany and Cohn (1970) and Krishnamoorthy and Munro (1973) have used volume of longitudinal reinforcements as the objective function. Hill (1966) has used cost of concrete and formwork as the
objective function while Norman(1964) has used only the cost of concrete as the objective function. The cost of concrete and longitudinal reinforcements was used as the objective function by Chou(1977), Brown(1975), Traum(1962) and many others. Friel(1974) has used cost of concrete, main reinforcements, formwork and cost of increasing the building height as the objective function. Satisfying requirements of deflection and bending simultaneously was used as the objective function by Golding(1988). The effects of different objective functions for optimization of reinforced concrete beams were given by Abendroth and Salmon(1986).

2.3.1.3 Constraints and design methods

"A constraint in any class of problem, is a restriction to be satisfied in order for the design to be acceptable. It may take the form of a limitation imposed directly on a variable or group of variables or may represent a limitation on quantities whose dependence on the design variables cannot be stated directly"(Gallagher and Zienkiewicz 1973).

For reinforced concrete design, constraints and design methods depend on the design standard. Constraints such as deflection, serviceability requirements, etc. are given by design codes connected to design variables(e.g. span/depth ratio). It is difficult to solve even with the aid of a computer, a design optimization problem which constitute all the design constraints. Consequently, most optimum design methods constitute only a few design constraints. Therefore requirements of the constraints such as deflection need to be checked for the optimum solution. This method was used by Traum(1963), Norman(1962), Chou(1977), Friel(1974), Cohn and MacRae(1984) and many others.

Design methods given by British standards, American Concrete Institute standards and Indian Concrete Code have been used to develop reinforced concrete optimum design methods. Golding(1988) has used BS8110 design method and Chou (1977) and Friel (1974) while Cohn and MacRae(1984) and many other have used the American Concrete Institute method. Prakash, Agrawala and Singh(1988), Ranganthan and Sahasrabuddhe(1985) and a few others have used Indian concrete code for the design method.
2.3.1.4 Mathematical problem

In algebraic terms of the design optimization problem finally can be written as a mathematical problem. Objective function \( W = f(X_1, X_2, \ldots, X_n) \) of \( n \) design variables subject to constraints

\[
\begin{align*}
g_i(X) &= 0 \quad i \in E \\
g_j(X) &\geq 0 \quad i \in I
\end{align*}
\]

representing equality constraints (E) and inequality constraints (I) on design variables. These equations can be solved by using mathematical methods such as differentiation for simple cases and linear programming, non-linear programming and Lagrangian for more complex optimization problems.

To solve the design optimization problem; Prakash, Agrawala and Singh (1988), Chou (1977) and Friel (1974) have used Lagrangian method and Balaguru (1980), Norman (1964) and Brown (1975) have used differentiation method. To find the optimum design solution Golding (1988) and Ranganthan and Sahasrabuddhe (1985) have used technique of graphical representation of variables and the cost (i.e. graphs). Taylor (1985) has used selection of the least cost from several feasible design solutions as the optimization method.

2.3.1.5 Summary

Quantifiable items in a design such as depth have been used as design variables. In reinforced concrete designs generally design variables are discrete variables. Design methods and constraints given in BS8110, ACI 318 and Indian concrete code have been used in optimum methods. Cost based objective functions are the most common in reinforced concrete optimum methods. To solve optimization problems, Lagrangian differentiation and other mathematical techniques have been used.

2.3.2 Slabs

Four methods have been developed by others for cost effective reinforced concrete slab designs. Only one method (Golding, 1988) follows the design method given in BS8110 while other design methods are according to ACI 318. Only Brown (1975) has given a measure of possible cost savings by a proposed method. Three methods
have used minimization of the cost of concrete and reinforcements as the objective function and Golding(1988) has used satisfying deflection and bending requirements simultaneously as the objective function. Details of the developed optimum methods for slab designs are given below.

A design method for simultaneous design for bending and deflection was developed by Golding(1988). He claimed that this often leads towards the optimum design. The objective function of the method is to satisfy both bending and deflections requirements simultaneously. Therefore, this method is different from conventional optimization methods such as taking reinforcement volume, cost of slab or depth as the objective function. The method uses the equations and constraints in BS8110 and is therefore appropriate to current British design practice. Finally, a series of curves were given for the variables of 'span/(basic span/depth ratio)' and 'bending moment/breadth' to find the optimum depth for a given slab design problem. This depth satisfies both bending and deflection requirements simultaneously as well as often giving an optimum solution. Even though Golding(1988) has claimed that this method often gives an optimum solution no proof has been given for the possible cost savings. Since it only gives a design aid it can be adopted in the design office practice without much difficulty.

A method to find the optimum depth of simply supported one way slabs has been given by Brown(1975). Cost of the slab was considered as the objective function and relative cost of steel and concrete has been used to formulate the objective function. The method uses equations and constraints in American Concrete Institute (ACI 318) code for building requirements. Equation has been given for the optimum thickness of the slab considering flexure only. Therefore shear and deflection requirements need to be checked separately and the optimum thickness may need to be adjusted. The Cost comparison of a one slab design was given as an example. In this design example, the slab depth was first selected from the Table 9a of ACI 318 code for building requirements for reinforced concrete and secondly depth was selected form the proposed optimum method. A 17% cost reduction on second solution over the first solution was observed by Brown(1975).

Methods for optimum design of one way and two way span slabs has been given by Norman(1964). These methods optimize cost as well as quantities such as strength of concrete mixes. Since only variables in concrete have been considered this method gives an optimum solution within the variables of concrete and not a global optimum solution. The method gives an equation to find the optimum depth. There is no prediction of cost savings from this optimum method.
Optimum methods for design of one way, simply supported, one way continuous, two way and flat slabs have been given by Traum(1962). These optimum methods are based on ultimate strength theory according to the requirements of American Concrete Institute (ACI 318) code for building requirements. The cost of a slab was considered as the objective function which constitute cost of concrete and cost of reinforcements. The cost of formwork has been ignored on the assumption that cost of formwork is independent from slab depth. Using simple calculus (differentiation) an equation for optimum reinforcement ratio was given. The reinforcement ratio was used as an independent variable and total cost of the slab has been considered as the dependent variable. The method proved its accuracy and gives the optimum solution for a given loading condition, strengths of concrete and steel and costs of concrete and steel. However, there was no prediction of cost savings possible from the proposed method. Further, the equations given have considered only the requirements of flexure. Therefore optimum depth and reinforcement ratio may be required to adjust to satisfy requirements of shear and deflection.

Table 2.3 gives a comparison of various slab optimum design methods for relevant codes, design principle, objective functions and predicted cost savings. The current design code for reinforced concrete slabs BS8110 has two major slab types: one way span and two way span slabs. Furthermore two way span slabs are divided into nine types. The optimum slab design methods developed in the past did not cover all slab types. Therefore optimum slab design methods to cover all slab types need to be developed.
Table 2.3 Comparison of optimum methods for slabs

<table>
<thead>
<tr>
<th>Method</th>
<th>Design principle</th>
<th>Objective function</th>
<th>Cost savings &amp; Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Golding (1988)</td>
<td>BS8110 design approach</td>
<td>Simultaneous design for deflection and bending.</td>
<td>No value. But easy method to produce more than one solution.</td>
</tr>
<tr>
<td>2. Brown (1975)</td>
<td>ACI 318 Ultimate strength theory.</td>
<td>Minimize cost of slab. Cost = Cost of concrete and reinforcements</td>
<td>17% cost saving. This value is given between selected solution and the optimum.</td>
</tr>
</tbody>
</table>

2.3.3 Beams

Beam is the most analysed structural element for cost effective designs. Therefore beam element claims high number of optimum design methods. This is mainly due to the fact that beams are less complex in design compared to that of slabs or columns, and therefore, it is relatively easy to develop optimum design methods for them. The first optimum method was published by Sawyer (1952). A total of seven methods were found in the literature survey. Except Golding (1988), others have used minimizing cost of the beam as the objective function. The total of seven methods include, one method for BS8110, one method for Indian concrete code and five methods for ACI 318.

Golding (1988) has given a method for simultaneous design for bending and deflection requirements for reinforced concrete beams which claims to often give a cost optimum design solution. A graph was given with two independent variables, 'l/(l/d basic)' and 'Mu/b' (l - span, Mu - bending moment, b - breadth) to find the optimum beam depth. Equations and constraints of this method are according to BS8110. Even though this
method claims to often give a cost optimum solution, no prediction or calculation was
given to demonstrate possible cost savings.

Optimum design methods for singly reinforced, double reinforced and T section beams
have been given by Prakash, Agrawala and Singh(1988). The cost of a beam was
used as the objective function which constitutes costs of concrete and steel. Equations
and constraints in the Indian reinforced concrete design code and Lagrangian method
has been used to find the optimum solution. In this method for a given concrete and
steel prices, concrete and steel strengths and loading conditions, an optimum solution
can be obtained. Further, details on variation of the optimum solution with different
strengths of steel and concrete were also given. There was no calculation to show the
possible cost savings by using the proposed method. Further, no valid reason was
given for neglecting the cost of formwork.

Methods for optimum design of reinforced concrete beams, partially prestressed
concrete beams and prestressed concrete beams have been given by Cohn and
MacRae(1984). These methods have the flexibility to adopt to any desired optimization
goal such as minimizing steel area, concrete volume and the total cost. American
Concrete Institute(ACI 318) building code has been used for design equations and
constraints. A flow chart was given to ease use of the method with examples.
However, no calculation was given to predict possible cost savings.

A comprehensive method for optimum design of T-section beam designs was given by
Chou(1977). This method has used the depth of beam and the reinforcement area as
independent variables. American Concrete Institute(ACI 318) building code for
reinforced concrete design has been used to derive equations and constraints. Details of
the equations and flow chart for computations were given and therefore it is not difficult
to use in spite of the complex mathematics involved. This method included all the
design problems in T-section beam designs. Example has been given to compare the
optimum solution relevant to maximum steel ratio solution and design solution from the
proposed method. A cost saving of 14% was observed between the optimum and the
maximum steel ratio design solutions. Since designers very rarely use maximum steel
ratio design solutions, 14% cost saving does not give a good measurement on possible
cost savings by the method. However this method is not difficult to understand and
due to the flow chart and equations given, it is not difficult to use in practice. A similar
method was given by Balaguru(1980) but the method has additionally considered the
cost of formwork in the objective function.
Table 2.4 Comparison of optimum methods for beams

<table>
<thead>
<tr>
<th>Method</th>
<th>Design principle</th>
<th>Objective function</th>
<th>Cost saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Golding (1988)</td>
<td>BS8110 design approach.</td>
<td>Simultaneous design for bending and deflection</td>
<td>No value</td>
</tr>
<tr>
<td>2. Prakash, Agrawala, &amp; Singh (1983)</td>
<td>Indian reinforced concrete code (CP110) approach</td>
<td>Cost of beam which includes cost of concrete and steel</td>
<td>No value</td>
</tr>
<tr>
<td>3. Cohn &amp; MacRae (1984)</td>
<td>ACI 318 design approach.</td>
<td>Cost of beam which includes cost of concrete and steel.</td>
<td>No value</td>
</tr>
<tr>
<td>4. Chou (1977)</td>
<td>ACI 318 design approach.</td>
<td>Cost of beam which includes cost of concrete and steel.</td>
<td>14% cost saving. This value was between maximum steel area solution and optimum solution.</td>
</tr>
</tbody>
</table>

Friel(1974) has given a method to find the optimum solution for singly reinforced beam sections. The cost of beam was considered as the total of cost of steel, concrete, formwork and increasing the building height. American Concrete Institute(ACI) building code equations and constraints have been used for the formulation of equations for optimum reinforcement area and optimum depth. Loading conditions, breadth of beam and concrete and steel strengths were treated as fixed. Therefore only depth and reinforcements area were considered as variables. No calculation has been given to predict the possible cost savings of this method.
Similar to that of slabs, Norman (1964) has given a method for optimum design of T-section beams. However, this method takes into account the variables in concrete only and therefore does not give a global optimum. Further, there was no calculation to predict the possible cost savings.

Table 2.4 gives a comparison of various methods for design methods, objective functions, constraints, assumptions etc. All beam optimum design methods have considered only a beam section (T, L or rectangular) in the optimum design method. However beams are designed as one unit generally with T-sections in mid spans and rectangular sections at supports. To develop an optimum method to give optimum solutions considering BS8110 design method and beam as one unit need to be developed.

2.3.4 Columns

Only 3 methods have been recorded for optimum design of reinforced concrete column designs. Complex design procedures defined by codes such as BS8110 could be the main reason for this small number of optimum design methods. Methods developed also are not flexible for different material strengths of concrete and steel, bending moments and axial forces and shapes in columns, and generally use fixed curves or graphs to find the optimum solution.

To find optimum design solution for uniaxial bending columns, a method has been given by Prakash, Agrawala and Singh (1988). The method is valid for both circular and rectangular column sections. Graphs with design variables are given to find the optimum design solution for a given column design problem. The first graph shows the comparative cost of rectangular and circular column for given bending 'moment/axial force' ratio. The second graph shows the relative cost of rectangular column for different 'breadth/depth' ratio for given 'bending moment/axial force' ratio. The final graph gives optimum depth contours (curves) for a given ultimate axial force and 'bending moment/axial force' ratio. Using these graphs optimum solution for a given column design problem can be found. However in these graphs strength of concrete and steel, relative cost of steel and concrete were kept fixed. Therefore this optimum design method cannot be used for all column design problems. As a conclusion, it was given that optimum steel percentage lies in the range of 1 to 2 times the minimum permitted by the reinforced concrete design code (1%); the higher value
being for larger 'moment/axial force' and lower 'steel cost/concrete cost' ratio. A similar method was given by Ranganthan and Sahasrabuddhe (1985).

Taylor (1985) has given a method to find acceptable design solutions for given 'n' triplets \((P e_x e_y)1, (P e_x e_y)2, \ldots, (P e_x e_y)n\) of loading condition where \(P\) is the axial force \(e_x\) and \(e_y\) are eccentrics of the axial force in X-X and Y-Y axis respectively. The result can be obtained through an automated computer program for given column dimensions together with reinforcement percentages and cost of concrete, steel and formwork. Finally, the designer can select the most economical solution from the field of feasible design solutions.

Table 2.5 gives a summary of above discussed methods together with cost savings. Optimum column design methods developed are not for design procedure given in BS8110. Therefore optimum column design methods for the design procedure given in BS8110 are need to be developed.

<table>
<thead>
<tr>
<th>Method</th>
<th>Design principle</th>
<th>Objective function</th>
<th>Cost saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Taylor (1985)</td>
<td>ACI 318 design approach</td>
<td>Select the minimum cost solution from field of solutions.</td>
<td>No value</td>
</tr>
</tbody>
</table>

### 2.3.5 Roofs

A literature survey also was conducted to find optimum methods for roofs of reinforced concrete framed buildings. Crawford and Jenkins (1980) have given optimum design method for seven types of steel roofs such as trussed beam, warren girder, universal beam portal, plate girder rafter roofs. These methods have used design methods given in BS449 and cost was considered as the objective function. Optimization procedure given by Box (1965) was used in this method. Reddy, Virupakshuppa and
Jagadish(1986) have given an optimum method for reinforced concrete beam and panel roofs.

In general no methods developed for common types of roofs such as open web girders, built-up steel truss roofs which were encountered in the field survey.

2.3.6 Design practice and optimum methods

Only a few methods out of the vast research output in structural Optimization have filtered into the design practice. Therefore most of the work and optimum design methods in reinforced concrete designs, are still in the academic world only. "The main reason is that very little of optimum methods satisfies the specific needs of its potential users, practising designers" (Templeman 1983). However, cost effective design methods developed based on same theories were put into practice in other disciplines such as air-craft industry (Gallagher & Zienkiewicz 1973).

Reasons for failure of methods to filter to design practice can be identified as: (some were given by Templeman 1983)

1. not assisting in performing designers overall task;
2. difficulty in using computer programs;
3. use of different code of practices;
4. not assisting to speed-up the design process;
5. not addressing the practical design problems;
6. results of optimum methods are not practical and therefore not useful;
7. calculations being unfamiliar due to use of complex mathematics;
8. difficulty in checking the design calculations;
9. possible cost savings were not proved; and
10. no incentive to designers to adopt optimum methods.

Item 1 and 10 in the list are probably the most important. Golding(1988), Agrawala and Singh(1988) have tried to assist the designer to perform his task by providing additional design aids. Most other methods such as Cohn(1965), Cohn and MacRae(1984) and have used mathematical procedure which are unfamiliar to the practising engineer. Majority of optimum methods discussed in this chapter, as results produce non practical values for design variables such as depth or reinforcement area, therefore it is necessary to adjust the optimum solution to satisfy practical limitations. Except for Chou(1977) and Brown(1975) others have failed to give any indication of
potential cost savings, leaving reader or user to experience. This could be a major reason for failure to draw significant attention from design practice. In most cases, optimum methods do not address practical design problems. For example design of reinforced concrete beams involve rectangular and T sections. Friel(1974) addressed only singly reinforced beams while Norman(1964) and Chou(1977) have considered for T section beams only.

Therefore unless methods in future overcome the problems discussed above, the optimum methods will not win acceptance from the design practice.

2.3.7 Summary and conclusions

As a summary, the following can be stated.

1. An optimization problem can be formulated for design of reinforced concrete elements by using design variables, constraints and methods given in design standards. This can be solved by using theories in mathematics.

2. Reinforcement volume, cost of element considering cost of concrete or concrete and reinforcements or concrete, reinforcements and formwork have been used as the objective function. The depth of a slab or beam or reinforcement volume have been used as design variables. Calculus, Lagrangian method, linear programming and other mathematical theories have been used to solve the Optimization problems.

3. Except in two methods(Brown 1975, Chou 1977) other methods have not given value for possible cost saving using proposed methods.

4. Optimum design methods do not include practical constraints on variables and constraints such as deflection or serviceability requirements. Therefore optimum solutions are required to be checked for some design code's requirements and adjustments may be needed.

5. Only a very few methods out of vast research output in structural optimization have filtered into the design practice. This is attributable to many reasons. Lack of incentive to designers to adopt optimum methods, failure of methods to assist designers in performing their overall task and not addressing practical design problems are major considerations.

6. No optimum method have been developed according to BS8110 to produce optimum solutions for practical reinforced concrete design problems. Therefore methods need to be developed for this purpose.
7. Cost savings of optimum methods compared to that of designers solutions still remain an unknown factor which is very important in gaining the acceptance from the construction industry.

2.4 EVIDENCE FOR THE USE OF COST EFFECTIVE DESIGN METHODS

It is important to know whether there is any evidence for the use of cost effective building designs in the history of construction industry. Two good examples are the use of new design methods in buildings services and prefabricated building construction.

Current building services design uses knowledge on new material, cost benefits through analysis of capital costs and costs-in-use, in other words energy costs of buildings. Therefore new buildings are more cost effective compared to buildings constructed 30 years ago (Thomas 1971). Today, prefabricated building construction is common in the construction industry. However, generally a prefabricated concrete structure is more expensive to build than a similar structure of 'traditional' in situ concrete (Brakel 1967). The economical advantages of a shorter construction period and earlier readiness for use often compensate for the higher cost of the prefabricated structure. Therefore depending on the clients needs, location, size of the building etc. a prefabricated building can be more cost effective.

New building services design methods and prefabricated construction methods increase the capital cost of the buildings (Brakel 1967, Thomas 1971). Economical effects are obtained through low costs-in-use of shorter construction period etc. In general design practice design fee is proportional to the capital cost of the building thus the use expensive methods (even though they are cost effective) automatically pays designers an extra design fee. Therefore, methods have faced very minimum or no problems in the implementation. However, there is no evidence for the implementation of cost effective design method which has decreased the capital cost of a building such as methods discussed in this chapter.
2.5 SUMMARY AND CONCLUSIONS

The following can be stated as the summary and conclusions of this chapter.

1. Optimum structural design methods and assessing feasible design solutions considering building functions and cost are the two main methods of cost effective building designs.

2. New cost effective design methods for the design process have been developed using concepts of cost models, data bases, value analysis techniques and expert systems. These methods have proved that cost effectiveness of designs can be improved, but failed to give any prediction about possible cost savings. Further cost forecasting accuracy of new methods is an unknown factor.

3. New cost effective designs/cost advice methods have been developed mainly for the needs or performance functions of the quantity surveyor. Therefore a study is required to identify the cost information requirements of designers mainly the architect and structural engineer. Furthermore it is necessary to study the methods of linking cost information to design decisions and the process of design decision making.

4. Developed optimum structural design methods by others have proved that cost effective structural designs can be produced. However, all the developed methods did not satisfactorily address the practical reinforced concrete design problems. Therefore methods need to be developed to satisfy and to give practical optimum solutions to practical reinforced concrete design problems. (chapter 4)

5. Study of the design process is required to understand personnel and their responsibilities in the design team, design contracts, information used in design decision making for the proper implementation of cost effective design methods (chapter 3).

6. To obtain acceptance from the practising engineers for optimum structural design methods, cost savings through optimum methods compared to normal design office solutions is important. (chapter 7).

7. There is evidence in the history of building construction industry for implementation of cost effective design methods. However, these cost effective methods have increased the capital cost of the building and hence the design fee. There is no evidence for implementation of cost effective design methods which have decreased the capital cost of a building.
Chapter three
THE DESIGN PROCESS

3.1 INTRODUCTION
3.2 INTERVIEWS
3.3 THE PROCESS
3.4 DESIGN DECISION MAKING
3.5 DESIGN CONTRACT PROCEDURES - IS THERE A ROOM FOR COST EFFECTIVE DESIGNS?
3.6 SUMMARY AND CONCLUSIONS
3.1 INTRODUCTION

This chapter gives details of the design process, design stages, design team personnel and their responsibilities, design organization structures, the design making process, use of cost data for design decision making and design contract types. Without a proper knowledge of the design process it is not possible to implement cost effective design methods (discussed in chapter 2). Information on the design process was gathered through interviews and published information.

Three main design stages, briefing, sketch design and detail design were identified as the practical design stages. Four design organization structures were identified in the building construction industry in Sri Lanka. It was found that in private sector design organizations the project director (architect) makes most of the design decisions and has the full responsibility for the design process, while in state organizations responsibility is distributed among design team members. The use of cost data is very low prior to detail design stage and cost data is widely used for decision making at the detail design stage. Percentage fee design contracts serve as negative incentives for cost effective designs and design and build contracts have the highest potential to accommodate cost effective design methods.

In this chapter details and findings of interviews are given. Details of the design process, design stages, personnel and their responsibilities and design organization structures found in the field survey are also examined. The design decision making process, use of information and cost data in the design process are given. Finally, different types of design contracts are discussed for the implementation of cost effective design methods.
3.2 INTERVIEWS

Fifteen interviews were held to collect information related to the design process. A semi structured interview technique was used for this purpose. Careful preparation of questionnaires is important to collect the required information through interviews. Therefore, the questions for the interviews were carefully planned and accurately worded as recommended by Leedy (1974).

The total of fifteen interviewees included seven architects, five structural engineers and three quantity surveyors. The fifteen interviewees included five top level managers (managing director or one of the partners) from private design organizations, two senior architects and two senior structural engineer from state organizations. The personnel interviewed were selected to represent the construction industry in Sri Lanka: five from state organizations; seven from the top 10 private design organizations and three from small to medium private design organizations. These personnel were contacted through formal requests (3 personnel) and informal contacts (12 personnel). Interviews were recorded using audio cassettes and each interview took a minimum of 45 minutes and a maximum of 2 hours.

Through these interviews, design stages, personnel and their responsibilities, design organizations structures, use of cost data and designers views on various types of design contracts and cost effective designs in the design process were identified. Details of questions and summary of the interviews are given below.

3.2.1 Synopsis of the questions

Questions were asked relating to three main design stages (see section 3.3.1), briefing (Inception and feasibility), sketch plan (outline and scheme) and detail design stage. A copy of the questionnaire is attached in the Appendix A. Questions were set to collect the following information.

1. Available design information at various design stages.
2. Personnel involved in different design stages and their responsibilities.
3. Use of cost data in various design stages, their availability, accuracy etc.
4. General problems in the design process.
5. Various types of design contracts and the facilities available for cost effective design methods in design contracts.
3.2.2 Designers Views

Designers views obtained through the interviews can be summarised as given below.

1. All 15 designers said that clients approach designers after completing the briefing design stage (Inception and feasibility). In other words they have made the decision to build. Therefore, most clients come with fairly detailed design brief giving required details such as floor area, number of storeys etc. Consequently, the design process involving outside designers starts at the sketch design stage (outline and scheme).

2. All 15 designers said that the entire design team is formed fully only at detail design stage. Formulation of the full design team earlier than detail design stage is contingent on project size. Designers said that design team consists of a project director (generally an architect), an architect, a structural engineer, an electrical and mechanical engineer, a water supply and sanitation engineer and a quantity surveyor.

3. Involvement in the decision making and responsibility of various members depends on design organization type and its organizational structure. Interviews with all private sector project directors show that most design decisions are made by the project director. In state organizations all members participate in design decision making.

4. Seven architects and three quantity surveyors said that in the design process cost is used in the reverse direction. In other words based on client brief and budget limit, designers have to design the building to meet client's needs. This is true because most clients (especially government) would have completed the feasibility study and have approved budget from the government before engaging designers.

5. Seven architects interviewed use only cost per unit floor area cost information at sketch design stage (outline and scheme). Two quantity surveyor (out of 3) provide elemental cost estimates to the project director (of the design team).

6. The designers response (15 designers) show that design is done without consideration of the accuracy of cost estimates. Variability is attributed to unknown and undecided design parameters. Clients accept this and cost estimates are said to have an accuracy of ±10%. Accurate cost estimates (±5%) are generally prepared when the bills of quantities are made ready at the detail design stage.
7. In the beginning of the sketch plan design stage drawings are produced and submitted for local authority approval. At this stage statement on finishes and services are made.

8. Five structural engineers and seven architects interviewed did not perceive any incentive for cost effective designs. In fact they agreed that there is a disincentive in percentage fee design contracts for cost effective designs. Only few had experience in design and build contracts; however, they believe that probably it is the best type of contract for cost effective design methods.

3.3 THE PROCESS

Details of the design process, design stages, design team personnel and their responsibilities and design organization structures are given. Figure 3.1 shows an overview of the design process, design decisions by various team members at different stages and interactions within the design team and with the client.

3.3.1 Design stages

Royal Institute of British Architects (RIBA) 'Plan of Work' (1973), Wickramasinghe & De Silva (1985) and Sri Lanka Institute of Architects (SLIA 1984) have defined the following design stages.


1. Inception design stage 1. Inception phase
2. Feasibility design stage 2. Feasibility phase
3. Outline design stage 3. Schematic phase
4. Scheme design stage 4. Design development phase
5. Detail design stage 5. Construction document phase

However, interviews with six senior architects (managing director or chief architect), three quantity surveyors and five structural engineers, revealed that there are three main design stages. This agrees with the findings of Mackinder and Marvin (1982). The first design stage involves 'briefing'; where discussions are held with the client for his
Figure 3.1 Personnel and design decisions in the design process
requirements, and study of the technical and financial feasibility of the project is made. The second design stage as 'sketch plan' where general layout of design & statutory authority approvals for the building are obtained. The third design stage is the 'Production of working drawings' where detailed designs and contract documents are produced. Descriptions of these design stages are given in Table 3.1 (RIBA 1973).

<table>
<thead>
<tr>
<th>Terminology in actual practice</th>
<th>Published design stages</th>
<th>Description of work involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Briefing</td>
<td>1. Inception</td>
<td>To prepare general outline of and clients requirements and plan for future work.</td>
</tr>
<tr>
<td></td>
<td>2. Feasibility</td>
<td>To provide the client with an appraisal and recommendation ensuring functional, technical and financial feasibility.</td>
</tr>
<tr>
<td>Sketch plan</td>
<td>3. Outline proposal or scheme design</td>
<td>Client's approval on general layout, design and construction. Complete the client's brief, including planning arrangement, appearance, construction methods, outline specifications and cost and to obtain statutory authority approvals.</td>
</tr>
<tr>
<td></td>
<td>4. Scheme design or design development</td>
<td></td>
</tr>
<tr>
<td>Production of working drawings</td>
<td>5. Detail design</td>
<td>Final design decisions on every matter related to design, specifications, construction methods and specifications.</td>
</tr>
</tbody>
</table>

(source RIBA 'Plan of Work' 1973)

### 3.3.2 Personnel and responsibilities

RIBA (1973) 'plan of work' defined clearly the members of the design team (theoretical) and their responsibilities. SLIA (1984) and Wickramasinghe & De Silva (1985) have also given a good description of personnel in the design team and their responsibilities. Based on these informations, interviews were held with 15 professionals (7 - architects, 3 - quantity surveyors and 5 - structural engineers) to
discuss the responsibilities of the members of the design team. The design team found in practice is as follows:

1. Project director (generally a senior architect);
2. Architect;
3. Structural engineer;
4. Sanitation and water supply engineer;
5. Electrical and Mechanical engineers(s); and
6. Quantity surveyor.

The main design responsibilities of each team member found through interviews and literature are given below.

**Project director**
Project director is responsible to the client for the whole project during design and construction. Through interviews, it was discovered that in all private organizations, the project director is an architect. He is responsible for preparing general layout in sketch plan, getting approvals from statutory authorities, forming the design team with other professionals, producing contract documents and drawings. In all the nine private organizations contacted in the field survey (interviews), it was discovered that the project director is the head of the design organization or one of the main partners. In these private organizations the project director receives the commission for most design contracts because of his reputation and, generally, is totally responsible for the design procedure; which is more than the responsibility defined by RIBA(1980) or SLIA(1984). In state organizations, the project director could be a civil engineer or an architect. The design responsibility of the project director is more distributed among design team members.

**Architect**
In general, there is an architect other than the project director. The main responsibility of the architect is to work closely with the project director at the briefing and sketch design stages and to produce detail architectural design drawings at the production of working drawings stage.

**Structural engineer**
The structural engineer is responsible for advising the project director on technical feasibility of the site and other matters related to structure and for producing structural drawings at the detail design stage.
Quantity surveyor
The main responsibilities of the quantity surveyor are to give cost advice to the project director, to prepare cost estimates and to prepare bills of quantities at the end of the working drawings.

Mechanical, Electrical, sanitation and water engineers
The function of Mechanical, Electrical, sanitation and water engineers are mainly to advice the project manager during sketch design and to perform related designs at the production of working drawings stage.

3.3.3 Design organizations
The design organization structure was studied to understand the authority of various members in the design team. This enabled the study of problems which could arise in the implementation of cost effective design methods. The results given here are based on the answers given to the questions discussed in interviews. Four different design organization structures were identified for which details are given below. Architects have more authority in building design process, especially in private sector. Therefore acceptance and approval of architects for cost effective building design are important for their implementation into practice.

3.3.3.1 Private design organization structure 1
The organization structure shown in Figure 3.2 was identified in most of the top 10 private organizations. Generally, these organizations were established by a senior architect who is normally the managing director or one of the main partners. These directors have a good professional reputation in the construction industry and make most design decisions. Generally, he is the ultimate authority in the design team as well as in the design organization.
3.3.3.2 Private design organization structure 2

A matrix type of organization structure was identified for two (out of 9) private design organizations where engineers and architects have jointly formed the design organization as partners. Even in these organizations, the project director in general is an architect (see Figure 3.3).

3.3.3.3 Private design organization structure 3

Majority of the small design organizations have organization structure similar to that shown in Figure 3.4. Generally, these organizations have been formed by an architect. Other professionals of the design team work on part time basis and in most cases a qualified structural engineer is present in the organization. In Figure 3.4, part time members are shown in italics.
3.3.3.4 Government sector design organization structure

The design organization structure shown in Figure 3.5 was observed in two large state design organizations. Both organizations were established as construction organizations and key positions, such as managing director, are held by an engineer with civil engineering background. In general the project director is directly responsible to the client as well as to the hierarchy of the design organization. A civil engineer acting as the project director is one of the main differences between state and private design organizations.
3.3.4 Summary

Three practising design stages were identified as briefing (inception and feasibility), sketch design (outline and scheme), and detail design stage. The design team consisted of a project director (a senior architect), an architect, a structural engineer, a quantity surveyor, a mechanical/electrical engineer and a water supply and sanitation engineer. In pre-detail design stage the project director makes most of the design decisions with the advice of other team members. In the detail design stage, each member makes design decisions in their respective fields. Four design organization structures were identified in Sri Lanka's construction industry. In the private sector, the project director has higher authority than in state organizations. Generally, architects have high authority in building design process and therefore their acceptance is important for the implementation of cost effective building design methods.

3.4 DESIGN DECISION MAKING

Details of the design decision making process is given in this section. Firstly, the nature of design decisions are discussed. Secondly influential factors such as experience and design information are discussed. Finally, details of use of cost data in the design decision making process is given.

3.4.1 Design problems

Building design problems are often both multidimensional and highly interactive in design functions and user needs. Very rarely does any part of a building serve one purpose. This problem was described by Lawson (1980) for window design as shown in Figure 3.6. As well as letting in daylight and sunlight the window is also usually required to provide a view while retaining privacy and offer natural ventilation. Further window design has to satisfy building regulations. As an interruption in the external wall the window also poses problems of structural stability, heat loss and noise transmission and is thus, arguably, one of the most complex of building elements. Modern science can be used to study each of the many problems of window design with branches of physics, psycho-physics and psychology all being relevant (Figure
3.6). These facts are true for almost all other elements in buildings such as heating system, electrical installations (lights, lifts), doors, partitions etc.

Thomas and Carroll (1979) found that design problems seem structured in terms of subproblems. However subproblems are typically dynamically produced during design, not specifiable at the beginning. Further, they found a crucial aspect of design as specifying goals, and clients do not state all their goals explicitly and probably are not aware of them before interacting with the designer.

![Figure 3.6 Window design problem](image)

**3.4.2 What influences design decisions**

As we identified above, design decision making is a highly complex process. To identify clearly what influences design decisions is also equally complex. Even with the clear identification of influences on design decisions, it is difficult to identify the degree of influence of various factors. Mackinder and Marvin (1982) has identified the following as influencing factors on design decisions.

1. Outside events and agencies and other constraints.
2. Experience.
3. Personal choice and tradition.
3. Recorded design data.
Details of the influences of above factors are discussed below.

3.4.2.1 Outside events and agencies and other constraints

"Instances of the influence of outside events and constraints on the design decision process are relatively easy to pin-point and explain, and hence are readily quantifiable. It is perhaps for this reason that there is a general feeling in the architectural profession that the burden of requirements of building and planning legislation is overwhelming" (Mackinder and Marvin, 1982). Further Mackinder and Marvin (1982), from their research, found that the constraints of site and client requirements are the most dominant factors influencing the early design stages and almost as many design decisions attributed to experience or expediency (no better choice available) as to outside agencies. Effects of outside agencies are beyond the designer's control and appeared to be most significant in the realms of project management.

The main external influences on design decisions can be identified as given below.

1. Time factors
Due to clients needs whole design design and construction program may be very short and the design may have to take that into consideration.

2. Budgets (costs)
Mackinder and Marvin (1982) found that cost constraints are continually present in all designs but generally do not overtly manifest themselves until the detail design stage. More details of cost on design decisions are given in section 3.4.3.

3. Nature of the site
The physical conditions of the site together with clients needs are the greatest obvious influence on the design decisions. Foundation type, plan shape and size are few examples.

4. Clients and users
Constraints of clients and users are not necessarily fixed and generally change with the design progress. Design constraints from clients depend on the type of client and experienced clients needs are more clearer than inexperienced clients.
5. Constraints
Constraints are imposed on the chief designer, architect by other professionals, cost matters by the quantity surveyor, structural matters by the structural engineer. Similarly, any other member of the design team get constraints from other members.

6. Planning and building regulations
Designers often cite planning and building regulations as the reason for design decisions. However, the true extent of their influence is difficult to quantify.

3.4.2.2 Experience

Mackinder and Marvin(1982) have found experience as the most influential factor on design decision making. The most frequent reason for most design decisions is 'experience'. Design decisions based on experience are relatively quicker and with or without no apparent researching before hand.

Experience helps the designer to organize himself to collect necessary information and to make design decisions in an efficient sequence. Experienced designers generally can see the major problems from the outset of the project. Less experienced designers rely more on outside information and tend to discover problems as the design progresses.

Experience on how a building is put together enables the designer to make general assumptions about the form and construction of the building, without reference to a large amounts of external or published information which is time consuming and makes every design project a large scale academic exercise.

Experience of performance is a more straightforward type of information which involves first or second hand knowledge of how a building or an element of a building performs(e.g. roof truss, different finishes, types of doors and window). This type of experience very often used in the detail design stage to make decisions on various types of materials, finishes etc. Mackinder and Marvin(1982) and Marvin(1985) found that designers get this experience by design faults and mistakes made personally rather than from successful designs.
3.4.2.3 Personal choice and tradition

"Research in the cognitive process in design has so far failed to reveal why some designers are better than others at retrieving data and experience in order to make intuitive leaps toward design solutions. It was not rare to discover a design problem or any part of the process which relied entirely on intuitive aspects often appeared more in terms of tradition or office habit when looked at in the context of other work carried out by the office", Mackinder and Marvin(1982).

3.4.2.4 Recorded design data

As professional designers keep, read and use recorded data for building design. Use of new materials, new analysis methods are few examples. Designers use wide range of recorded data both in-house and published. Published data can be identified as building regulations, acts of parliament, official bulletins, price books, journals etc. Further, designers keep in-house records such as client briefs and past design records.

Marvin(1985) found that the average designer uses very little published information during early design stages, inception, feasibility and sketch design stages. During these design stages, designers use their experience on past projects, training(educational and through reading).

3.4.3 Use of cost data in the design process

The primary need for use of cost data in building design is to forecast the probable cost of the project. In the design process the quantity surveyors give cost information to the client, architect and other members of the design team. At the beginning of a project the client makes most cost related decisions such the size and quality of the building. Mackinder and Marvin(1982) found that for the architect's design decision making, the implications of cost constraints are continually present in all design stages but did not overtly manifest themselves until the detailed design decision making stage. Therefore, at the detail design stage cost is often stated as being the prime influence over design decisions. Mackinder and Marvin(1982) observed that cost trimming during the design process is a common cause of 'backtracking' in the design, either because of the clients decision to retract his intentions or because the designers ideas exceed the cost budget.
The level of cost data used by client and others in the design team can be identified as given in Figure 3.7.

Ashworth(1986) has given the following types of cost advice during design process which are generally provided through approximate estimating and cost planning techniques.

1. Budget estimates based on client's brief.
2. Cost advice on different rendering and contractual arrangements.
3. Pre-tender price estimates.
4. Comparative cost advice on alternative design solutions.
5. Elemental target costs for cost planning.

Details of cost advice and cost calculations during the design process are also given by Seeley(1972) and Bathurst & Butler(1980).

Estimating methods are used in early design stages to produce budget estimates, comparative cost of alternative design solutions etc. Various estimating methods are in use in the design process as given below.
1. **Unit method**
In the beginning of a project most clients require preliminary estimates based on very little design information. In this case, units based on type building such as beds for hospitals, cars for car parks are used to produce estimates. Unit cost is obtained from historical data or published data and multiplied for the total number in the proposed building.

2. **Cube method**
In the cube method approximate cost per unit cube is obtained from the historical data and multiplied by the total volume of the proposed building to arrive at an estimate.

3. **Superficial or floor area method**
This is the most common estimating method used in the design process. An estimate for cost of unit floor area is obtained from historical data and adjusted for local conditions, nature of the building etc. Estimate is obtained by multiplying this cost value by the total area of the proposed building.

4. **Approximate quantities**
This is a more reliable method of estimating. Approximate quantities are calculated from the sketch or other design and multiplied by unit rates to get the final estimate.

5. **Elemental cost analysis**
This estimating method uses elemental cost analysis for previous similar projects as a basis for the cost estimate. The cost is calculated on a superficial or floor area basis (as above in 3) but the overall superficial unit cost is broken down into elements and sub-elements.

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**3.4.5 Summary**

It was discovered that all design decisions were both multidimensional and highly interactive. Constraints due to clients needs, building design regulations, designers experience and personal choice and recorded design information influence design decisions. In pre-detail design stages cost data is used only for overall project cost forecast and in detail design stage cost data is used in design decision making only.
3.5 DESIGN CONTRACT PROCEDURES - IS THERE A ROOM FOR COST EFFECTIVE DESIGNS?

Contract procedures and contract agreements are the ultimate governing documents of the design process. Therefore in the process of exploring cost effective design methods and implementations, a study of the limitations and possibilities in contract procedures for cost effective design methods is very important. Study of various Clauses and their legal implications on design and detail comparison on various methods for the design process is outside the scope of this research. Details of various types of design contracts, their basic principles and facility for cost effective design methods are given in this section.

3.5.1 Types of design contracts in building designs

Three main types of design contract agreements in the design process can be identified in Sri Lanka and U.K. building construction industries. These are:

1. percentage fee contracts;
2. lump sum contracts;
3. design and build contracts.

Percentage fee contract is the most common type of contract in the private sector clients in Sri Lanka. Before 1983, public sector organizations also used percentage fee contracts but, due to the 'Treasury circular 850' (Treasury Sri Lanka 1983), public sector organizations were forced to adopt lump sum design contracts. Design and build contracts are not common in Sri Lanka but there is a significant growth in its practice in the recent past.

3.5.2 Percentage fee contracts

Percentage fee contract is the most simple form of design contract in the design process. The architect is responsible for duties defined in 'Standard form of agreement between owner and the client' (Sri Lanka Institute of Architects, SLIA 1980). Fees for this type of contracts are defined in 'Recommended scale of fees and charges' (Sri Lanka Institute of Architects, SLIA 1984) which are given in Table 3.2.
Table 3.2 Design fee for percentage fee contracts

<table>
<thead>
<tr>
<th>TOTAL CONSTRUCTION COST IN THOUSANDS</th>
<th>TOTAL PERCENTAGE FEE</th>
<th>PERCENTAGE OF TOTAL FEE FOR EACH PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New works</td>
<td>Work to existing buildings</td>
</tr>
<tr>
<td>50 to 500</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>500 to 1000</td>
<td>8.5</td>
<td>11</td>
</tr>
<tr>
<td>1000 to 1500</td>
<td>6.5</td>
<td>10</td>
</tr>
</tbody>
</table>

Where

- Phase A - Inception and feasibility (briefing)
- Phase B - Outline and scheme design (sketch)
- Phase C - Detail design
- Phase D - Bidding negotiation and contract agreements
- Phase E - Construction phase

From a study of the contract procedure the following can be stated for percentage fee contracts with respect to cost effective designs:

1. There is no supervision on designers with respect to the design produced. Therefore it is difficult to assess the cost effectiveness of the designs produced.
2. Design fee is based on the final construction cost. Therefore the higher the construction cost the higher the design fee. This is clearly a disincentive for designers to use cost effective design methods.

3.5.3 Lump sum contracts

The lump sum design contract is not a new type of contract. Extensive use of this type of contracts came into Sri Lanka's building construction industry due to treasury circular 850 in 1983. The circular requires state organizations to invite tenders from design organizations for buildings over Rs 10 million (£1 = Rs 60). The following can be stated for this type of design contracts.

1. A competitive bidding system among design organizations.
2. Preparation of detail design brief by the client with the aid of buildings department, Sri Lanka.
3. Evaluation of various designs by a committee of professionals to assess the design cost, designs produced and methods of design and other factors such as design organization reputation.

4. Due to competitive bidding and evaluation by a professional committee on the proposed designs, this contract agreements has a better opportunity for cost effective designs than percentage fee contracts.

3.5.4 Design and build contracts

Design and build contracts have the mechanism required for cost effective building designs. This contract type is known from its present form of several decades of history (Turner 1986). There is a more direct and strong contract agreement and communication link between the client and the contractor than percentage and lump sum design contracts. In design and build contracts, the contractor is responsible for both design and construction and, generally, cost is a lump sum as a package deal. Characteristics of design and build contracts are as given below.

1. The contractor is totally responsible for design and construction of the building. Depending on the design and build contract, contractor could employ an architect, a structural engineer for the design work. However, in this case there is no direct contract or communication between such designer and the client.

2. The client provides a brief to the contractor. This may be simply the need of the client or a comprehensive description prepared by an specialist such as an architect. The contractor can get involved with the project as early as in inception and feasibility design stage or late as the detail design stage. There is no possibility for the contractor to get involved later than details design stage because in that case there is no design and build contract.

3. Generally, in design and build contracts client and contractor agree on a fixed sum based on statements on the outstanding parts of the design.

4. Use of any cost effective design method is directly beneficial to the contractor. Therefore design and build contracts have the highest potential to use cost effective design methods. However, if design work is given as a contract to a design organization the case is similar to a lump sum design contract. In both cases if contractor recognize the possibility of cost saving through optimum methods he can ask desingers to use cost effective design mehtods.
Designers have legal liabilities for their responsibility for designs. Hudson's 'Building and Engineering Contracts' (Wallace 1970) has given the following as the legal design duties of the design team.

1. To advice and consult with the client (not as a lawyer) as to any limitation which may exist as to the use of the land to be built on, either (inter alia) by planning legislation, restrictive covenants, or the rights of adjoining owners or the public over the land, or by statutes and by-laws affecting the works to be executed.

2. To examine the site, sub-soil, and surrounding or to make arrangements for such an examination, including advising on the need for the employment of specialist or consultants.

3. To consult with and advise the client as to the proposed work.

4. To prepare sketch plans and specifications, having regard to all the conditions known to exist and to submit them to the employer for approval, with an estimate of the probable cost, if requested.

5. To elaborate and, if necessary, modify or amend the sketch plans, and then, if so instructed, to prepare drawings and a specification of the work to be carried out as a first step in the preparation of contract documents including advising on the need for the employment of any specialists or consultants.

6. To consult with and advise the client as to the form of contract to be used (including whether or not to use bills of quantities) and as to the necessity or otherwise of employing a quantity surveyor (engineers usually do not employ an independent quantity surveyor) to prepare bills and carry out the usual valuation services during the currency of the contract.

7. To bring contract documents to their final state before inviting tenders, with or without the assistance of quantity surveyors and structural engineers, including the obtaining of detailed quotations from and arrangement of delivery dates with any nominated sub-contractors or suppliers whose work may have to be ready or available at an early stage of the main contractor's work.

From these, it is clear that designers do not have a legal duty to produce cost effective designs. However, many court cases have been recorded for bad designs such as improper foundations, damp penetration through windows and foundations. In few court cases designers were held responsible for inaccurate cost forecastings. In the court case of Nye Sauders and Partners v. Alan E. Bristow, 1987 (Crone 1989) court
of appeal found that designer (architect) failed to warn of the inaccuracy of the initial cost estimate of £238000 and to compare with sketch plan estimate of £440000. Architect failed to warn on inflation in initial estimate and the court rejected the architects claim for the design fee of £15581.59. Therefore designers are legally liable to produce accurate cost forecasts in building designs. However, there is no legal duty to produce cost effective designs. More details on various legal liabilities in the design process is given by Crones(1989).

3.5.6 Summary and conclusions

Percentage fee, lump sum and design and build contracts are the three main types of design contracts. Percentage fee design contracts have negative incentives for cost effective designs and therefore are not suitable for implementing cost effective design methods. Lump sum design contracts have mixed properties for cost effective design while design and build contracts possess the highest potential for cost effective designs. From the legal point of view, designers do not have a duty to design buildings cost effectively.
3.6 SUMMARY AND CONCLUSIONS

The following can be stated as the summary and conclusions of this chapter.

1. Three practising design stages are briefing, sketch plan and detail design stage. The design team consists of a project director, an architect, a structural engineer, a quantity surveyor, a mechanical and an electrical engineer and a water supply and sanitation engineer. In pre-detail design stages, the project director makes most design decisions and in the detail design stage each member makes design decisions related to their respective fields.

2. The project director exercises more authority in private sector design organizations than in state design organizations.

3. Design decisions are both multidimensional and highly interactive. Building regulations, constraints form clients needs, experience, designers choice, design information influence design decisions. Therefore cost effective design methods should take these into consideration.

4. In pre-detail design stages cost data is used primarily to forecast the total building cost. Interviews with professionals in the building construction industry revealed that in the design process, cost is used in reverse direction. In other words, buildings are designed for the given cost rather than costing the designed buildings. Cost data is widely used at the detail design stage for the design decision making process. Therefore detail design stage is the best design stage to use cost effective methods. It is important to identify cost information required for detail design decision making.

5. Out of the three design contracts, percentage fee, lump sum and design and build contracts, design and build contracts have the highest potential to implement cost effective design methods.
Chapter four

COST EFFECTIVE DESIGN METHODS FOR REINFORCED CONCRETE ELEMENTS

4.1 INTRODUCTION
4.2 OPTIMUM METHOD FOR SLABS
4.3 OPTIMUM METHOD FOR BEAMS
4.4 OPTIMUM METHOD FOR COLUMNS
4.5 OPTIMUM METHOD FOR INDEPENDENT FOOTINGS
4.6 SUMMARY AND CONCLUSIONS
4.1 INTRODUCTION

Optimum design methods for reinforced concrete slabs, beams, short columns and independent footing foundations were developed and details are given in this chapter. Design methods follow the procedures given in BS8110. The methods developed in the past by others, which were discussed in section 2.3, gave incomplete design solutions. Therefore, necessary steps were taken in the development of optimum design methods to give complete design solutions to normal reinforced concrete design problems of above mentioned elements. Chapter 7 of this thesis gives the details of cost savings of the methods developed in this chapter, for 22 historical reinforced concrete buildings.

Each design method and optimum method was tested with three case studies obtained from published information and from the data collected from the building construction industry. The developed methods gave satisfactory close results as given by published information or data obtained from the industry. For slabs, beams and independent footings graph of depth and cost proved that least cost solution or optimum solution is well within the range or depths proposed by the methods. For columns, various sizes proposed and the cost proved that the least cost solution is well within the maximum and minimum sizes proposed by the method. Sensitivity studies of optimum solutions for price variations of concrete, formwork and steel showed that the optimum solution depends on concrete and steel prices and very weakly on formwork price. However, for price variation of less than ±20% of concrete, steel and formwork prices, change of optimum solution was negligible.

Details of the developed optimum method for slabs are given. This includes details of cost equations for different types of slabs, design method according to BS8110, the slab design optimization problem and the method of solving it and computer programs. Testing of the design method, the optimum method, and a sensitivity study of the optimum solution for price variations of concrete, formwork and steel were also conducted. Similar details for beams, columns and independent footings are given. Finally, a summary of this chapter is given at the end.

The cost equations developed were validated by cost data for 22 building projects collected in this research. Design methods and the optimum methods were tested with published data and design problems of two projects for which full design calculations were collected.
4.2 OPTIMUM METHOD FOR SLABS

A computer based optimum design method was developed for the design of reinforced concrete slabs. Detail structural drawings can be produced from the optimum design solutions given by the method. This is an advancement compared to six slab optimum design methods developed by others (discussed in section 2.3.2), as those methods often give incomplete design solutions.

The computer based slab optimum design method produced the optimum solution within 3 seconds of computer time using IBM system 2 model 30 computer. The design method was tested with published information as well as information collected from the building construction industry and close values in design solutions were observed. A sensitivity study of the optimum solution for price variations in concrete, formwork and steel was held. The sensitivity study proved that the optimum solution is independent from formwork price, but dependent on variations in concrete and steel prices.

Design methods given in BS8110 depend on slab type therefore, slab types are discussed. Different cost equations according to the recommendations of SMM6 of RICS(1979) were developed depending on slab type. A brief description of normal reinforced concrete slab design method (according to BS8110) is given. The slab design optimization problem, design constraints, solving method of the optimization problem, computer programs, testing of design optimum method and a sensitivity study of the optimum method for price variations are given in detail.

4.2.1 Types of slabs

The design procedure given in BS8110 for slabs, recommend the identification of the slab type. The slab type is identified by examining slab dimensions, support conditions, continuity over supports etc. Different slab types given in BS8110 are:

A. One way span slabs;
B. Two way span slabs;
   B.1 Interior panels ($NS = 0, \ NL = 0$);
   B.2 One short edge discontinuous ($NS = 1, \ NL = 0$);
   B.3 One long edge discontinuous ($NS = 0, \ NL = 1$);
   B.4 Two adjacent edges discontinuous ($NS = 1, \ NL = 1$);
   B.5 Two short edges discontinuous ($NS = 2, \ NL = 0$);
B.6 Two long edges discontinuous \((Ns = 0, \ NL = 2)\);
B.7 Three edges discontinuous (one long edge continuous)
\((Ns = 2, \ NL = 1)\);
B.8 Three edges discontinuous (one short edge continuous)
\((Ns = 1, \ NL = 2)\); and
B.9 Four edges discontinuous \((Ns = 2, \ NL = 2)\).

Therefore, it may be necessary to develop different optimum methods for each slab type in order to cover all slab types. However, a careful examination on two way span slabs revealed that, they can be uniquely identified from the number of discontinuous short edges \((Ns)\) and the number of discontinuous long edges \((NL)\). Therefore, in this research, two optimum methods, one for one way span slabs and one for two way span slabs, were developed and different types of two way span slabs were taken into account by values of \(Ns\) and \(NL\).

### 4.2.2 Cost equations for different slab types

Any prediction of cost savings or optimum design solution based on cost depends on the accuracy of the cost equation. Optimum methods developed in the past have used different cost equations based on various assumptions. They were simple addition of cost of concrete and cost of steel etc. (Freil 1974, Chou 1977). To develop an accurate cost equation for reinforced concrete slabs, the recommendations of Standard Method of Measurement (SMM6, RICS 1979) should be used. SMM6 of RICS(1979) has given the following rules for the preparation of bills of quantities for reinforced concrete in situ slabs.

1. Volume of concrete calculated according to the geometry without any reduction for reinforcements.
2. Reinforcement total weight for each diameter.
3. Formwork area together with the slope.

The following symbols have been used to formulate cost equations for slabs.

\[
\begin{align*}
Cc &= \text{cost of concrete per unit volume} \\
Cs &= \text{cost of reinforcement per unit weight} \\
Cf &= \text{cost of formwork per unit area} \\
Asb &= \text{area of bottom reinforcement per unit length. Suffix x or y denotes the direction.} \\
Ast &= \text{area of top reinforcement per unit length. Suffix x or y denotes the direction.}
\end{align*}
\]
Asn = minimum permissible reinforcement area required.
lx = length of panel in X direction
ly = length of panel in Y direction
h = overall thickness of the slab.
Ns = number of discontinuous short edges
NL = number of discontinuous long edges

Case 1. One way span slabs less than 3 continuous spans
The case of one way span slabs with less than 3 continuous spans was not considered since very few slabs fall into this category.

Case 2. One way span slabs continuous over 3 spans or more
For the simplicity of this research a middle panel was considered for the cost equation as shown in Figure 4.1.

Figure 4.1 One way span continuous slab

A. Cost of concrete
volume of concrete = h.lx.ly
cost of concrete = Cc.h.lx.ly

B. Cost of formwork
cost of formwork = Cf.lx.ly
C. Cost of reinforcements

One major problem in the development of a cost equation for reinforcements in a slab is curtailment of reinforcements. Generally in slab design simplified curtailment for main reinforcements according to clause 3.12.10.3 of BS8110 are used (see Figure 4.2).

According to Figure 4.2,

\[
\text{total volume of reinforcements} = 0.4A_{sbx}.l_x.l_y + 0.6A_{sbx}.0.6l_x.l_y + 2[0.5A_{stx}.0.3l_x.l_y + 0.5A_{stx}.0.15l_x.l_y] + A_{sn}.l_y.l_x + 2A_{sn}.0.31x.l_y \\
= l_x.l_y[0.76A_{sbx} + 0.45A_{stx} + 1.6A_{sn}]
\]

total weight of reinforcements = \( p \cdot l_x.l_y[0.76A_{sbx} + 0.45A_{stx} + 1.6A_{sn}] \)

where,

\( p = \) density of steel

cost of reinforcements = \( C_s \cdot p \cdot l_x.l_y[0.76A_{sbx} + 0.45A_{stx} + 1.6A_{sn}] \) ..4.3

cost of slab = cost of concrete + cost of reinforcement + cost of formwork

\[
= C_c.l_x.l_y + C_f.l_x.l_y + C_s.p.l_x.l_y[0.76A_{sbx} + 0.45A_{stx} + 1.6A_{sn}] \]

..4.4

Case 3. Two way span interior panels

A. Cost of concrete.

Similar to above,

cost of concrete = \( C_c.l_x.l_y \) ..4.1

B. Cost of Formwork

cost of formwork = \( C_f.l_x.l_y \) ..4.2
C. Cost of reinforcement.

For the design purpose BS8110 divides two way span slabs into middle and edge strips as shown in Figure 4.3.

![Figure 4.3 Division of slab into middle and edge strips](image)

BS8110 recommends reinforcement for flexure to be provided for middle strips and minimum reinforcements (0.12%) for edge strips. But during the data collection from drawings of actual projects in this research, no such variation was observed. This was discussed with structural engineers in practice, and the following reasons were given for design practice without strips.

1. Provision of different reinforcement bars or spacing required high supervision at sites;
2. Possibility of providing wrong bar spacing;
3. Complexity of drawings; and
4. Cost saving by providing different spacings is negligible.

Consequently, these strips have been ignored in formulation of cost equations for two way span slabs. As discussed for one way span slabs, in general slab designs, reinforcements are curtailed according to the simplified rules of clause 3.12.10.3 of BS8110 (see Figure 4.4). In two way span slabs, reinforcements are required to be provided in both directions at middle spans and as well as over supports (see Figure 4.5).
Considering Figure 4.4 and Figure 4.5 the following cost equations for reinforcements of two way span slabs were derived.

1. \( N_s = 0, \ N_l = 0 \)
   \[
   \text{cost} = C_{sp} \cdot l_x \cdot l_y [(0.76A_{xp} + 0.76A_{yp}) + 0.225(A_{1p} + A_{2p} + A_{3p} + A_{4p}) + 1.2A_{snp}] \quad \ldots \quad 4.5
   \]

2. \( N_s = 0, \ N_l = 1 \)
   \[
   \text{cost} = C_{sp} \cdot l_x \cdot l_y [(0.82A_{xp} + 0.76A_{yp}) + 0.225(A_{1p} + A_{2p} + A_{3p} + 0.49A_{4p}) + 1.01A_{snp}] \quad \ldots \quad 4.6
   \]

3. \( N_s = 0, \ N_l = 2 \)
   \[
   \text{cost} = C_{sp} \cdot l_x \cdot l_y [(0.88A_{xp} + 0.76A_{yp}) + 0.225(A_{1p} + A_{2p} + 0.49A_{3p} + 0.49A_{4p}) + 0.82A_{snp}] \quad \ldots \quad 4.7
   \]
4. \( N_s = 1, N_L = 0 \)
\[
\text{cost} = C_{sp} \times l_x \times l_y [(0.76 A_{sp} + 0.82 A_{yp}) + 0.225 (A_{1p} + 0.49 A_{2p} + A_{3p} + A_{4p}) + 1.01 A_{snp}] \quad . . 4.8
\]

5. \( N_s = 1, N_L = 1 \)
\[
\text{cost} = C_{sp} \times l_x \times l_y [(0.82 A_{sp} + 0.82 A_{yp}) + 0.225 (A_{1p} + 0.49 A_{2p} + A_{3p} + A_{4p}) + 1.01 A_{snp}] \quad . . 4.9
\]

6. \( N_s = 1, N_L = 2 \)
\[
\text{cost} = C_{sp} \times l_x \times l_y [(0.88 A_{sp} + 0.82 A_{yp}) + 0.225 (A_{1p} + 0.49 A_{2p} + 0.49 A_{3p} + 0.49 A_{4p}) + 0.63 A_{snp}] \quad . . 4.10
\]

7. \( N_s = 2, N_L = 0 \)
\[
\text{cost} = C_{sp} \times l_x \times l_y [(0.76 A_{sp} + 0.88 A_{yp}) + 0.225 (0.49 A_{1p} + 0.49 A_{2p} + A_{3p} + A_{4p}) + 0.82 A_{snp}] \quad . . 4.11
\]

8. \( N_s = 2, N_L = 1 \)
\[
\text{cost} = C_{sp} \times l_x \times l_y [(0.82 A_{sp} + 0.88 A_{yp}) + 0.225 (0.49 A_{1p} + 0.49 A_{2p} + 0.49 A_{3p} + A_{4p}) + 0.63 A_{snp}] \quad . . 4.12
\]

9. \( N_s = 2, N_L = 2 \)
\[
\text{cost} = C_{sp} \times l_x \times l_y [(0.88 A_{sp} + 0.88 A_{yp}) + 0.225 (0.49 A_{1p} + 0.49 A_{2p} + 0.49 A_{3p} + 0.49 A_{4p}) + 0.44 A_{snp}] \quad . . 4.13
\]

Total cost of slab = cost of concrete (eqn. 4.1) + cost of formwork (eqn. 4.2) + cost of reinforcements (eqn. 4.4 to eqn. 4.13) . . 4.14

The accuracy of the above equations were tested with actual reinforced concrete slab cost data from 22 building projects. Table 4.1 shows the accuracy of estimates based on above equations and actual cost values. OPEN ACCESS II spreadsheet software and Turbo Pascal computer program were used for this analysis. The results proved that the equations above satisfactorily represent the cost of in situ reinforced concrete slabs. Errors in percentage cost components are shown in Table 4.1.

e.g. error of concrete cost
\[
= \frac{\text{(cost percentage of concrete from BOQ)} - \text{(cost percentage of concrete from equation)}}{\text{Cost percentage of concrete from BOQ}}
\]

81
Table 4.1 Cost analysis of slabs from equations and BOQs*

<table>
<thead>
<tr>
<th></th>
<th>Concrete</th>
<th>Formwork</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Standard mean error analysis</td>
<td>Mean Error</td>
<td>0.53</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>5.69</td>
<td>4.2</td>
</tr>
<tr>
<td>2. Absolute mean error analysis</td>
<td>Mean error</td>
<td>4.69</td>
<td>3.73</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>3.07</td>
<td>2.45</td>
</tr>
</tbody>
</table>

*BOQ reads bills of quantities

4.2.3 Slab designs according to BS8110

The design procedure given in BS8110 was used in the optimum slab design method. Detail design methods of reinforced concrete one way and two way span slabs are given in Appendix C.1. The method given satisfy conditions in BS8110 and the manual for design of reinforced concrete structures of Institute of Structural Engineers (1985), London. The procedure given in Appendix C.1 can be summarized as follows.

1. Input slab design problem short span (lx), long span (ly), slab depth, type of slab, edge restrain conditions, concrete and steel material strengths and dead and imposed loads (C.1.1).
2. Calculate design loads, bending moments, shear forces according to BS8110 (C.1.2).
3. Provide reinforcement areas according to available bar diameters and practical bar spaces (C.1.3).
4. Satisfy the serviceability requirements such as deflection, crack control etc (C.1.4 & C.1.5).

4.2.4 Methodology for optimum slab designs

The optimum slab design problem with an objective function and constraints can be defined as given below.

**Objective function**
Minimize total cost of the slab = cost of concrete (eqn.4.1) + cost of formwork (eqn.4.2) + cost of reinforcements (eqn.4.4 to eqn.4.13)
Constraints
1. Deflection Span/depth ≤ Allowable span/depth = f(reinforcement ratio, slab thickness)
2. Crack control - maximum spacing between bars = f(effective depth, maximum value of 300mm)
3. Shear stress ≤ allowable shear stress = f(reinforcement ratio, slab thickness, concrete material strength)
4. Minimum reinforcement area (100As/bd) ≥ 0.13
5. Maximum reinforcement area (100As/bd) ≤ 4

Methods developed in the past (see section 2.3), have used mathematical optimization methods to solve problems. Majid (1974), Kirsh (1981) and Gallagher & Zienkiewicz (1973) have discussed various methods such as linear programming for different optimization problems. Computers have been used only as a tool to solve mathematical problems (Cohn and MacRae 1984, Taylor 1985). In the proposed method, the computer was used to find the minimum cost solution from a set of feasible design solutions. Because of the high speed of calculations by a computer, 21 design solutions and their costs, were obtained in less than 5 seconds using IBM system 2 model 30 computer. Therefore, instead of complex mathematical procedures, the computer was used to find the least cost design solution, in other words the optimum solution. The steps involved in the detail procedure of the optimum method are given below and the flow chart is shown in Figure 4.6.

The feasible design solutions were obtained by varying the slab thickness from 100mm to 200mm in steps of 5mm. A minimum slab thickness of 100mm was selected because it is difficult to construct slabs with lesser thicknesses. Further slabs thicknesses for the 22 buildings of which data were collected, were between 100mm and 200mm.

Step 1  Input the design problem, type of slab, short span(lx), long span(ly), imposed and dead loads and material strengths of concrete(fcu) and steel(fy).
Step 2  Design the slab for slab thickness of 100mm according to the method given in Appendix C.1. Calculate the total cost of the slab using cost equations given in section 4.2.2 of this thesis. If there is no feasible solution for the selected depth, set the cost of slab to infinity. Record the cost and depth.
Step 3  Repeat the procedure in step 2 for increases of slab thickness by 5mm to a maximum of 200mm. This will give 21 feasible design solutions from 100mm to 200mm of slab thickness.
Step 1
Input the design problem lx, ly, fcu, fy, gk and qk or n, Ns, NL and type of slab (one way or two way span).

Step 2
Set slab thickness h = 100mm

Step 2
1. Find the bending moments and shear forces. m1, m2, m3, m4, mx and my and SF.
2. Design the slab for flexure and provide reinforcements from to Table C.1 (i.e. As1p, As2p, As3p, As4p, Asxp and Asyp).
3. Check for maximum spacing of bars SP1, SP2, SP3, SP4, SPx and SPy. If required increase the reinforcement area to satisfy the cracking requirements.

Step 3
No

Step 2
Deflection requirements are satisfactory?

Yes

No

Step 2
Shear requirements are satisfactory?

Yes

Step 4
Calculate the cost

Record the cost and h.

Step 3
h ≥ 200mm

Yes

h = h + 5

No

Step 4
Select the minimum cost and corresponding thickness

Step 5
1. Find the bending moments and shear forces. m1, m2, m3, m4, mx and my and SF.
2. Design the slab for flexure and provide reinforcements from to Table C.1 (i.e. As1p, As2p, As3p, As4p, Asxp and Asyp).
3. Check for maximum spacing of bars SP1, SP2, SP3, SP4, SPx and SPy. If required increase the reinforcement area to satisfy the requirements.

Calculate the optimum cost

Step 6
Print the optimum solution

STOP

Figure 4.6 Optimum design method for slabs
Step 4 Select the minimum cost slab and its thickness.
Step 5 Design the slab according to the method described in step 2.
Step 6 - Print the design solution in step 4 as the optimum design solution for the given problem.

4.2.5 Computer programs for slabs

Three computer programs were developed using the Turbo Pascal language: slab design method in Appendix C.1; slab optimum design method (Figure 4.6); and to test the optimum slab design method. Turbo Pascal was selected as the programming language due to following reasons.

1. Facility to structure the programs with procedures and units.
2. High speed due to advanced compiler.
3. Facility to use IBM personal computers which are the most common types of computers in design offices.

Details of three computer programs, program functions, data input and output results are given in Table 4.2. The IBM system 2 model 30 was used to run programs. Programs have the facility to enter data through the keyboard using VDU or to read from a text file created by spread sheet, wordprocess software or an editor such as EDLIN.

4.2.6 Optimum slab design method testing

The accuracy of optimum slab design programs was tested in 3 different ways. These are:

1. for design methodology;
2. optimum solution; and
3. sensitivity of the optimum solution.

Details of the analyses are given below.
<table>
<thead>
<tr>
<th>Program function</th>
<th>Data Input</th>
<th>Results (Output)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Program 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. To find the design solution of a slab according to BS8110.</td>
<td>1.1. Type of slab i.e. one way span two way span. Ns and NL 1.2. Design loads n or gk and qk. 1.3. Slab dimensions lx, ly and h. 1.4. Material strengths fcu and fy.</td>
<td>1. Reinforcement area requirements. Asx, Asy, As1, As2, As3, As4, Asn. 2. Results of the deflection requirements. 3. Results of the shear requirements.</td>
</tr>
<tr>
<td>1.1 Reinforcement requirements in different locations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 To check and satisfy deflection requirements.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 To check and satisfy shear requirements.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 To check and satisfy crack control requirements.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Program 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. To find the optimum design solution for a given slab.</td>
<td>2.1 Design information as in 1 above. 2.2 Price rates of concrete formwork and steel.</td>
<td>1. Optimum design solution. i.e least cost design solution. Asx, Asy, As1, As2, As3, As4, Asn, cost and thickness. 2. Cost , Asx, As3 and thickness for each solution.</td>
</tr>
<tr>
<td>2.1 To find set of feasible design solutions for thickness of 100mm to 200mm in steps 5mm for the procedure defined in 1 above.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 To find the cost of each design solution above 2.1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3 To find the minimum cost solution.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Program 3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. To study the sensitivity of the optimum solution for price variations in concrete formwork and steel.</td>
<td>3.1 Design information as in 1 above. 3.2 Price rates as in 2.2 above.</td>
<td>1. Optimum design solutions for price variations of concrete, formwork and steel.</td>
</tr>
</tbody>
</table>
### Table 4.3 Methodology testing with three case studies - slabs

<table>
<thead>
<tr>
<th>Problem</th>
<th>Results</th>
<th>Given solution</th>
<th>Method's solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Kong &amp; Evans (1987)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab details</td>
<td>Design problem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness 180 mm</td>
<td>Mid moment kNm</td>
<td>24.7</td>
<td>24.7</td>
</tr>
<tr>
<td>Load 12.96 kN/m²</td>
<td>Support kNm</td>
<td>24.7</td>
<td>24.7</td>
</tr>
<tr>
<td>Short span 5.5 m</td>
<td>Effective depth mm</td>
<td>154</td>
<td>160</td>
</tr>
<tr>
<td>Long span 14.0 m</td>
<td>Asx mm²</td>
<td>523</td>
<td>436</td>
</tr>
<tr>
<td>f̄cu = 20 N/mm²</td>
<td>As3 mm²</td>
<td>523</td>
<td>436</td>
</tr>
<tr>
<td>fy = 410 N/mm²</td>
<td>Allowable span/depth</td>
<td>37.5</td>
<td>35.9</td>
</tr>
<tr>
<td>One way span slab</td>
<td>Shear stress N/mm²</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>2. Design organization 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab details</td>
<td>Design problem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness 100 mm</td>
<td>Mid moment kNm</td>
<td>2.28</td>
<td>2.20</td>
</tr>
<tr>
<td>Load 10.43 kN/m²</td>
<td>Support kNm</td>
<td>3.06</td>
<td>3.09</td>
</tr>
<tr>
<td>Short span 2.5 m</td>
<td>Effective depth in mm</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Long span 2.5 m</td>
<td>Asx mm²</td>
<td>354</td>
<td>357</td>
</tr>
<tr>
<td>f̄cu = 20</td>
<td>As3 mm²</td>
<td>354</td>
<td>357</td>
</tr>
<tr>
<td>fy = 410</td>
<td>Asy mm²</td>
<td>354</td>
<td>357</td>
</tr>
<tr>
<td>Two way restrained slab. Two adjacent edges discontinuous.</td>
<td>Allowable span/depth</td>
<td>33.5</td>
<td>52.0</td>
</tr>
<tr>
<td></td>
<td>Shear stress N/mm²</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>3. Design organization 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab details</td>
<td>Design problem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness 125 mm</td>
<td>Mid moment X kNm</td>
<td>8.73</td>
<td>9.12</td>
</tr>
<tr>
<td>Load 9.34 kN/m²</td>
<td>Support X kNm</td>
<td>11.68</td>
<td>12.16</td>
</tr>
<tr>
<td>Short span 4.0 m</td>
<td>Mid moment Y kNm</td>
<td>7.02</td>
<td>6.77</td>
</tr>
<tr>
<td>Long span 6.35 m</td>
<td>Support Y kNm</td>
<td>5.23</td>
<td>5.08</td>
</tr>
<tr>
<td>f̄cu = 20 N/mm²</td>
<td>Effective depth mm</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>fy = 410 N/mm²</td>
<td>Asx mm²</td>
<td>349</td>
<td>261</td>
</tr>
<tr>
<td>Two way restrained slab. Two adjacent edges discontinuous.</td>
<td>As3 mm²</td>
<td>392</td>
<td>327</td>
</tr>
<tr>
<td></td>
<td>Asy mm²</td>
<td>349</td>
<td>261</td>
</tr>
<tr>
<td></td>
<td>As1 mm²</td>
<td>349</td>
<td>327</td>
</tr>
<tr>
<td></td>
<td>Allowable span/depth</td>
<td>52.0</td>
<td>51.74</td>
</tr>
<tr>
<td></td>
<td>Shear stress N/mm²</td>
<td>0.22</td>
<td>0.23</td>
</tr>
</tbody>
</table>

#### 4.2.6.1 Design methodology of slabs

The design methodology was tested with one published design solution given by Kong and Evans (1987) and design solutions of two projects obtained from two design organizations in Sri Lanka. The test hypothesis being that if the method is accurate (for
a given loading condition) it should give same or close values for bending moments, reinforcement areas, 'span/depth' ratios (deflection requirement) and shear stress. Table 4.3 gives the results of analysis.

The above (Table 4.3) analysis shows that developed method gives the same bending moments as in given solutions. The main reason for deviation in reinforcement areas was that the proposed method calculated the steel areas by using equations given in BS8110 and design methods have used design charts given in part 3 of BS8110 (or Part 2 of CP110). Close values were observed for allowable 'span/depth' ratios and shear stress.

4.2.6.2 Optimum slab design solution

The accuracy of the optimum design method was tested with three case studies of problems given in Table 4.4, by comparing the cost and the depth of feasible design solutions. Figure 4.7 shows the graph of thickness vs slab cost for three case studies. Three case studies have proved that there is a minimum cost solution, and the optimum depth is between 100mm and 200mm.

Table 4.4 Design problems to test the optimum method - slabs

<table>
<thead>
<tr>
<th>Details of the problem</th>
<th>Slab 1</th>
<th>Slab 2</th>
<th>Slab 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thickness in mm</td>
<td>180</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>2. Slab type 1 - One way span</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2 - Two way span</td>
<td>Ns = 1</td>
<td>Ns = 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NL = 1</td>
<td>NL = 1</td>
</tr>
<tr>
<td>3. Short span Lx in m</td>
<td>5.5</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>4. Long span Ly in m</td>
<td>14.0</td>
<td>6.35</td>
<td>6.35</td>
</tr>
<tr>
<td>5. fcu N/mm²</td>
<td>40</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>6. fy N/mm²</td>
<td>460</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td>7. Designed load n in kN/m²</td>
<td>12.96</td>
<td>9.34</td>
<td>20.00</td>
</tr>
<tr>
<td>8. Concrete price Rs/m³</td>
<td>1700</td>
<td>1395</td>
<td>1395</td>
</tr>
<tr>
<td>9. Formwork price Rs/m²</td>
<td>141</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>10. Steel price Rs/kg</td>
<td>19.0</td>
<td>16.0</td>
<td>16.0</td>
</tr>
<tr>
<td><strong>Optimum solution</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Optimum depth mm</td>
<td>130</td>
<td>105</td>
<td>135</td>
</tr>
<tr>
<td>2. Asxp mm²/m</td>
<td>808</td>
<td>327</td>
<td>651</td>
</tr>
<tr>
<td>3. Asyp mm²/m</td>
<td>942</td>
<td>491</td>
<td>942</td>
</tr>
</tbody>
</table>
The optimum slab thicknesses are: 130mm for slab 1; 105mm for slab 2 and 135mm for slab 3. Therefore, all optimum slab thicknesses are well within the limits of 100mm and 200mm. For slabs 1 and 2 thickness less than the optimum were not feasible because of deflection requirements. This agrees with Golding's (1988) findings that the cost optimum slabs are those which satisfy both deflection and bending requirements at the lowest possible depth. For slab 3, feasible design solutions can be found for thickness more than 105mm, but least cost thickness is 135mm. Cost and slab thickness graphs for the three slabs are shown in Figure 4.7. The shape of the graph for slab 3 is similar to that given by Brown (1975).

![Figure 4.7 Slab thickness vs Cost](image)

**Figure 4.7 Slab thickness vs Cost**

### 4.2.6.3 Sensitivity analysis of the optimum solution

Sensitivity of the optimum solution was studied for the price variation of concrete, formwork and steel. The price was changed for each item from -50% to +50% in steps of 5%. Figure 4.8a shows the variation of optimum solutions with individual price fluctuation of concrete, steel and formwork. It is evident from the Figure 4.8a that optimum solution is independent from formwork price and generally remain unchanged for concrete and steel price variations up to ±20%. Furthermore, Figure 4.8b shows the variations of the optimum solution with Cc/Cs ratio change and uniform price inflation on all three cost items (concrete, steel and formwork). It is clear from Figure 4.8b that optimum solution is dependent on Cc/Cs ratio and independent from uniform price inflation.
Figure 4.8a Price variance vs optimum slab depth
Figure 4.8b Dependability of slab optimum depth on inflation & Cc/Cs ratio
In general estimating practice, cost rates of concrete, reinforcements and formwork vary with slab thickness (Wessex 1988), therefore, to find the optimum solution for slab design problem, different rates, depending on the slab thickness may have to be used. However, sensitivity analysis proved that the optimum solution does not change for Cc/Cs ratio (or price) variations up to ±20%, therefore a single price rate can be used to find the optimum solution. Generally price variations in different section sizes are less than ±20% (Wessex 1988).

4.2.7 Summary

Cost equations for different types of one way span and two way span slabs were developed according to the recommendations of SMM6 of RICS (1979). These cost equations were tested from the cost data of past projects and found to be satisfactory. Equations developed were as follows: one equation for cost of concrete; one equation for cost of formwork; and ten equations for cost of reinforcements.

An optimum slab design method was developed considering minimizing the cost of slab as the objective function and deflection, crack control, minimum and maximum steel ratios, shear requirements as constraints. With the aid of a computer, selecting the minimum cost solution from a field of feasible design solutions was used to solve the optimum slab design problem.

The optimum design method was tested for the design methodology, selection of the least cost solution and sensitivity of the optimum solution for price variations of concrete, steel and formwork. The design method was tested with 3 case studies and satisfactory results were observed. Graphs of cost and slab depth for the field of design solutions obtained proved that the least cost solution was well within the depths proposed by the method (100mm to 200mm). The optimum depth was found to be independent from formwork price but depend on concrete and steel prices. However, optimum solution remained unchanged for Cc/Cs ratio (or price) variations up to ±20%. Therefore single price rates can be used to find optimum solutions provided that variation in Cc/Cs ratio is less than ±20% within the project.
4.3 OPTIMUM METHOD FOR BEAMS

A computer based optimum design method for reinforced concrete beams was developed. The method has the facility to design both rectangular and T beam sections. The beam design optimum method gives design solutions with reinforcement area together with bar sizes for mid spans and supports. Further, checks for deflection and shear are built into the optimum design method. Therefore, design solution produced is complete and detailed structural drawings can be produced from the optimum design solution. The seven beam design methods developed by others, (section 2.3) failed to give full design solutions. The facility to obtain a full design solution is an advantage of the new method compared to other methods developed in the past. The method produces a set of feasible design solutions for a given problem and the optimum cost solution is obtained from this field of feasible design solutions.

The proposed optimum beam design method gives optimum solution for a given beam design problem in less than 5 seconds using IBM system 2 model 30 computer. When the design method was tested with published information as well as two design solutions obtained from the industry, satisfactory results were observed. The optimum design methodology was tested with 3 case studies. A sensitivity study revealed that the optimum solution depends on price variations of concrete and steel. Dependability of the optimum solution on formwork price variations was negligible.

Details of the cost equation for concrete beams are given. The beam cost equation was developed according to the rules given in SMM6 of RICS(1979). A summary of the reinforced concrete beam design method of BS8110, which was used in the optimum method is given. Details of the optimum method developed and its testing for accuracy are given. Assumptions made in the development of the cost equation was validated from cost data of 22 building projects. The reinforced concrete beam design method was tested from two complete design calculations of two projects collected in this research and published information.

4.3.1 Cost equation for beams

An optimum method based on minimizing cost as the objective function and predicted cost savings depends on the accuracy of the cost equation. SMM6 of RICS(1979) has given similar rules as in slabs, which were discussed in section 4.2.2, for costing of
reinforced concrete beams. In addition to symbols given in section 4.2.2 the following symbols were used.

- Asb - area of bottom reinforcements
- Ast - area of top reinforcements
- L - span of beam
- hf - thickness of the flange
- bw - web thickness

It was assumed that there is only a negligible difference in cost of shear links between the optimum design and another acceptable design solution. Therefore, the cost of shear links was ignored in the development of a cost equation for reinforced concrete beams. Figure 4.9 was considered for the formulation of the cost equation for a unit length of a beam.

![Beam Section](image_url)

**Figure 4.9 Beam Section**

(A. Cost of concrete

cost of concrete = Cc.D.bw ..4.15

B. Cost of formwork

cost of formwork = Cf[ bw + 2(D- hf)] ..4.16

C. Cost of reinforcements

Similar to slabs, one major problem in the development of a cost equation for reinforcements in a beam is the curtailment of reinforcements. According to the design methods given in BS8110 reinforcements could be curtailed considering the shape and values of bending moments diagram or according to simplified curtailment rules given in clause 3.12.10.2 of BS8110. Therefore, two equations were considered for the cost of reinforcements. They are:
1. cost equation without any curtailment for main reinforcements; and
2. cost equations based on simplified curtailment according to clause 3.12.10.2 of BS8110.

Figure 4.10 shows curtailment of main reinforcements according to simplified rules.

![Diagram of beam reinforcement details for simplified rules]

Figure 4.10 Beam reinforcement details for simplified rules

Cost of reinforcements without curtailment

\[ = Cs \cdot p \cdot L \cdot [ Asb + Ast ] \] .. 4.17

Cost of reinforcements according to simplified curtailment

\[ = Cs \cdot p \cdot L \cdot [ 0.79 Asb + 0.52 Ast ] \] .. 4.18

Table 4.5 shows the results of cost analysis of 22 building projects from priced bills of quantities and costs based on the two equations above.

<table>
<thead>
<tr>
<th>Table 4.5 Cost analysis of components in beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error in percentage of cost components</td>
</tr>
<tr>
<td>Concrete</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>1. Cost equation without curtailment</td>
</tr>
<tr>
<td>Mean error</td>
</tr>
<tr>
<td>Standard deviation</td>
</tr>
<tr>
<td>Absolute mean error</td>
</tr>
<tr>
<td>Standard deviation</td>
</tr>
<tr>
<td>2. Cost equation with curtailment</td>
</tr>
<tr>
<td>Mean error</td>
</tr>
<tr>
<td>Standard deviation</td>
</tr>
<tr>
<td>Absolute mean error</td>
</tr>
<tr>
<td>Standard deviation</td>
</tr>
</tbody>
</table>
It is difficult to make a decision to select a cost equation from the results shown in Table 4.5. Both equations have used same basis for cost of concrete and formwork. Therefore, the only variable is the cost of reinforcements. Since the cost equation without curtailment showed lesser variability for cost of reinforcements, equation without any curtailments for main reinforcements was selected. Thus the following equation can be given for the cost of beams.

\[
\text{Cost of beam} = Cc \cdot D \cdot bw + Cf[bw + 2(D-hf)] + Cs \cdot p \cdot [Asb + Ast] \quad \ldots 4.19
\]

4.3.2 Beam designs according to BS8110

The beam design method according to BS8110 are given in detail in Appendix C.2. These design methods were used in beam optimum methods. The procedure in Appendix C.2 can be summarized as follows.

1. Input beam design problem, section type span (L), geometry of the section (D, bw, hf), material strengths of concrete and steel, bending moments and shear forces.
2. Calculate the reinforcements areas required from the procedure given in C.2.2 and C.2.3 and provide reinforcements area from Table C.2.
3. Check serviceability requirements such as deflection, crack control etc.

4.3.3 Optimum method for beams

Beam design optimization problem can be defined as given below.

**Objective function**

Minimize total cost of beam

\[
= \text{cost of concrete(eqn.4.15)} + \text{cost of formwork(eqn. 4.16)} + \text{cost of reinforcements(eqn.4.17)}
\]

**Constraints**

1. Deflection, "span/depth" ratio \( \leq \text{allowable ratio} \)
   \( = f(\text{tension and compression reinforcements}) \)
2. Crack control, maximum spacing between bars
3. Minimum reinforcement ratio \((100As/bd) \geq 0.13\)
4. Maximum reinforcement ratio \((100As/bd) \leq 4\)
Similar to slab design optimization problem, a computer was used to solve the above beam design optimization problem. Unlike in slabs, it is difficult to define predetermined range for the beam depth. This difficulty was overcome by selecting the initial depth, 150mm less than the balance design depth \( \sqrt{(BM/0.156bfcu)} \). Details of this optimization procedure are given in Figure 4.11 and the steps involved are outlined below.

**Step 1** Input the bending moments of sections 1-1, 2-2 and 3-3 (see Figure 4.10), material strengths of concrete and steel, span, web thickness, flange width, price rate of concrete, steel and formwork.

**Step 2** Calculate the balance design depths \( d_{1b}, d_{2b} \) and \( d_{3b} \) from the equation of \( \sqrt{(BM/0.156bfcu)} \) for sections 1-1, 2-2 and 3-3.

**Step 3** Select the minimum of \( d_{1b}, d_{2b} \) and \( d_{3b} \) as \( d_i \). Adjust \( d_i \) to the nearest 25mm from the equation \( D_i = \text{INT}(D_i/25).25 \). Set the initial depth \( D_i \) to \( (D_i - 150) \). If the total depth including the cover is less than 225mm set the total initial depth to 225mm.

**Step 4** Calculate \( A_{s1}, A_{s2} \) and \( A_{s3} \) from methods in Appendix C.2 and provide \( A_{s1p}, A_{s2p} \) and \( A_{s3p} \) from Table C.2.

**Step 5** Calculate the cost of the beam and record the cost and beam depth. If there is no feasible design solution set the cost to infinity.

**Step 6** Repeat step 4 and step 5 for increase of depth by 25mm for 50 cycles. This will give 50 design solutions for a given beam design problem.

**Step 7** Select the minimum cost and corresponding beam depth.

**Step 8** Redesign the beam for the depth in step 7.

**Step 9** Print the results as the optimum solution.
**Step 1**
Input BM1, BM2, BM3, fcu, fy, b, L, bw, hf, Cc, Cf and Cs.

**Step 2 and 3**
\[
\begin{align*}
  d_{1b} &= \sqrt{BM1/0.156b.fcu} \\
  d_{2b} &= \sqrt{BM2/0.156bw.fcu} \\
  d_{3b} &= \sqrt{BM3/0.156bw.fcu} \\
  d_i &= \text{minimum of } d_{1b}, d_{2b}, d_{3b} \\
  D_i &= d_i + 45\text{mm} \\
  D_i &= \text{Int}(D_i/25).25 - 150\text{mm} \\
\text{If } D_i < 225\text{mm then } D_i &= 225\text{mm}
\end{align*}
\]

**Step 4**
Calculate the reinforcement area requirements sections 1-1, 2-2 and 3-3 according to the method given in Appendix C.2. Provide reinforcements for sections 1-1, 2-2 and 3-3 from the Table C.2

**Step 4**
Are deflection requirements satisfactory?

**Step 5**
Calculate the cost of the beam from the cost equation 4.18.

**Step 5**
Record the cost and the depth

**Step 6**
Is \( D > D_i + 25x50 \)?

**Step 7**
Find the minimum cost and corresponding depth

**Step 8**
Calculate the reinforcement area requirements sections 1-1, 2-2 and 3-3 according to the method given in Appendix C.2. Provide reinforcements for sections 1-1, 2-2 and 3-3 from the Table C.2

**Step 9**
Print the results as the optimum solution

Figure 4.11 Optimum design procedure for beams

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The optimum method selects the initial depth less than the balance depth. Consequently, the method produces design solutions of depths corresponding to both double and singly reinforced sections.

4.3.4 Computer programs for beams

Three computer programs were developed using the Turbo Pascal: for reinforced concrete beam design method (see section 4.3.2); the optimum design method (see Figure 4.11); and to test the sensitivity of the optimum solution for price variations. Program functions, data input and results are given in Table 4.6. The program developed for the optimum beam designs, produced optimum solutions for beam design problems in less than 3 seconds using IBM system 2 model 30 computer.

4.3.5 Testing of the optimum beam design method

The accuracy of optimum design programs and methodology were tested for 3 different criteria. They are:

1. for design methodology;
2. optimum solution; and
3. sensitivity of the optimum solution.

Details of the analysis are given below.

4.3.5.1 Design methodology of beams

The beam design methodology was tested with one published design solution given by Kong and Evans(1987) and design data of two projects obtained from two design organizations in Sri Lanka. Design problems were selected such that problems 1 and 3 have higher bending moments in 2 to 5 storey building frames. The design problem 2 has average values for bending moments in 2 to 5 storey building frames. Table 4.7 gives test results of the accuracy of design methodology analyses.
Table 4.6 Computer programs for beams

<table>
<thead>
<tr>
<th>Program function</th>
<th>Data Input</th>
<th>Results (Output)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Program 1</strong></td>
<td>1.1. Input bending moments M1, M2 and M3</td>
<td>1. Reinforcement area requirements. As1, As2, As3, Asn.</td>
</tr>
<tr>
<td>1. To find the design solution of a beam according to BS8110.</td>
<td>1.2. Beam dimensions b, bw hf and d.</td>
<td>2. Results of the deflection requirements.</td>
</tr>
<tr>
<td>1.1 Reinforcement requirements in different locations.</td>
<td>1.4. Material strengths fcu and fy.</td>
<td></td>
</tr>
<tr>
<td>1.2 To check and satisfy deflection requirements.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Program 2</strong></td>
<td>2.1 Design information as in 1 above.</td>
<td>1. Optimum design solution. i.e least cost design solution. As1, As2, As3, cost and depth.</td>
</tr>
<tr>
<td>2. To find the optimum design solution for a given beam.</td>
<td>2.2 Price rates of concrete formwork and steel.</td>
<td>2. Cost, As1, As2 and thickness for each solution.</td>
</tr>
<tr>
<td>2.1 To find 50 feasible design solutions for various depths.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 To find the cost of each design solution above 2.1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3 To find the minimum cost solution.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Program 3</strong></td>
<td>3.1 Design information as in 1 above.</td>
<td>1. Optimum design solutions for price variations of concrete, formwork and steel.</td>
</tr>
<tr>
<td>3. To study the sensitivity of the optimum solution for price variations in concrete formwork and steel.</td>
<td>3.2 Price rates as in 2.2 above.</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.7 Design methodology testing for beams

<table>
<thead>
<tr>
<th>Problem</th>
<th>Design</th>
<th>Results</th>
<th>Given solution</th>
<th>Methods solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kong and Evans (1987)</td>
<td>D = 550 mm, bw = 350 mm, b = 1330 mm</td>
<td>BM1 = 522 kNm, BM2 = 520 kNm, BM3 = 203 kNm, hf = 180 mm, Cc = 1700 Rs/m³, Cf = 141 Rs/m², fcu = 40 N/mm², Cs = 19 Rs/kg, fy = 460 N/mm²</td>
<td>As1r mm² 2775</td>
<td>3181</td>
</tr>
<tr>
<td>2. Design organization 1</td>
<td>D = 575 mm, bw = 300 mm, b = 300 mm</td>
<td>BM1 = 180 kNm, BM2 = 194 kNm, BM3 = 159 kNm, hf = 125 mm, Cc = 1395 Rs/m³, Cf = 102 Rs/m², fcu = 20 N/mm², Cs = 16 Rs/kg, fy = 410 N/mm²</td>
<td>As1r mm² 1054</td>
<td>1119</td>
</tr>
<tr>
<td>3. Design organization 2</td>
<td>D = 650 mm, bw = 300 mm, b = 900 mm</td>
<td>BM1 = 431 kNm, BM2 = 444 kNm, BM3 = 88 kNm, hf = 100 mm, Cc = 1385 Rs/m³, Cf = 102 Rs/m², fcu = 20 N/mm², Cs = 16 Rs/kg, fy = 410 N/mm²</td>
<td>As1r mm² 2124</td>
<td>2196</td>
</tr>
</tbody>
</table>

The following symbols have been used in the Table 4.7.
- **D** depth of beam (mm)
- **bw** web width (mm)
The developed method gave the same values for reinforcement area requirements for As1r, As2r and As3r. Therefore there is no difference between normal design calculation procedures and the computer based method developed. However, minor variations were observed in the provided reinforcement areas As1p, As2p and As3p, mainly due to the use of Table C.2 given Appendix C.2. Satisfactorily close values were also observed for allowable span/depth ratio (deflection requirements).

4.3.5.2 Optimum beam design solution

To be an accurate optimum design method, the optimum beam design method discussed in section 4.3.3, should provide a minimum cost solution, within the values of depths selected. One way to prove this is to study the graph of depth and cost. Figure 4.12 shows the graphs of depth and cost for 3 beams given in Table 4.7. Figure 4.12 proved that the minimum cost solution is well within the range of depths selected for 3 beams studied.

The three curves shown in Figure 4.12 have similar parabolic shapes. The rate of change in cost is higher for depths less than the optimum.
4.3.5.3 Sensitivity of the optimum beam solution

Prices of concrete, formwork and steel depend on factors such as beam section area, bar diameters, height of beam etc. (Wessex 1988) as well as market conditions, type of project etc. Therefore, a sensitivity study of the optimum solution was conducted for price fluctuations of concrete, formwork and steel. Prices were varied from -50% to +50% in steps of 5%. Figure 4.13a shows the dependability of the optimum depth on individual price variations of concrete, steel and formwork for beams given Table 4.7. From Figure 4.13a, it is evident that the optimum depth remain unchanged for price variation within ±20%, but beyond ±20% the optimum depth changes for concrete and steel price variations. Also, Figure 4.13a revealed that the optimum solution depends weakly on formwork price. Furthermore, Figure 4.13b shows the dependability of the optimum solution on Cc/Cs ratio and uniform price inflation. It is evident from Figure 4.13b that Cc/Cs ratio is more important than values of cost rates which agrees with Chou's (1977) equations for optimum depths. Therefore if the variation of Cc/Cs ratio in one project is less than ±20% single price rates can be used to find the optimum solution of all beams.

The optimum depth remained unchanged for beams 1 and 2 for formwork price variations up to ±50%. In all three beams, optimum depth was changed due to price variations of concrete and steel. Highest dependability was observed for steel price variations.
Figure 4.13a Price variations vs optimum depth in beams
Figure 4.13b Dependability of optimum beam depth on inflation and Cc/Cs ratio
4.3.6 Summary

A cost equation for the middle span of a beam was developed according to SMM6 of RICS(1979). This equation was tested with cost data for 22 building projects and satisfactory results were observed.

The optimum beam design methodology was developed with minimization of cost of the beam as objective function and deflection, crack control, maximum and minimum steel ratios as constraints. The optimization problem was solved by using the computer to produce fifty feasible design solutions and their costs; the least cost solution being selected as the optimum solution.

The design methodology was tested with three case studies obtained from the industry and published information. The proposed method gave same results for the reinforcement area requirements and deflection requirements, thus accuracy and compatibility of the proposed design method were proved. The optimum method was tested with 3 case studies and optimum depths were well within the range of depths considered. Further, graphs for cost and depth showed a parabolic relationship. A sensitivity study on optimum solution proved that optimum depth generally remains unchanged for Cc/Cs ratio (or price) fluctuations within ±20%. But, price fluctuations of more than ±20% for concrete and steel optimum depth changed considerably. Generally, optimum depth remains unchanged for price fluctuations of formwork.

4.4 OPTIMUM METHOD FOR COLUMNS

A computer based optimum design method was developed for reinforced concrete columns. Three column optimum design methods developed by others (see section 2.3.4) cannot be used for all column design problems, because of fixed values in costs and material strengths of concrete and steel. However, the developed method can give optimum design solutions for any short column design problem. The proposed method produces 38 feasible design solutions and the minimum cost solution is obtained from this field of feasible design solutions as the cost optimum solution.
The computer based optimum method gave the optimum solution approximately in 90 seconds using IBM system 2 model 30 computer. Predetermined section sizes were used to produce feasible design solutions. The optimum solutions for three case studies were obtained within the range of sections used. From the sensitivity study on price variations, it was established that optimum solution is generally independent for price fluctuations up to ±50%.

Details of cost equation for columns according to SMM6 of RICS(1979) are given. Details of design of reinforced concrete columns to BS8110 are discussed. Details of the optimization problem, constraints and computer programs developed are given. Assumptions in the cost equation was validated from cost data of 22 building projects collected in this research. Assumptions made on the design methodology and the optimum method were validated from complete design details of two projects collected in this research and published information.

4.4.1 Cost equation for columns

SMM6 of RICS(1979) gives rules for costing reinforced concrete columns. These are similar to those given for beams and slabs discussed in 4.2.2 and 4.3.1 of this thesis. Details given in Figure 4.14 and symbols given below, in addition to those given in 4.2.2 and 4.3.1, have been used in the cost equation.

![Column section](image)

**Figure 4.14** Column section

symbols

- $A_s$: main reinforcement area
- $H$: total height
- $b$: column breadth

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4.4.2 Column designs according to BS8110

The column design method given in BS8110 was used in column optimum design method. The design method of reinforced concrete short rectangular columns according to BS8110 is given in Appendix C.3. Other types of columns were not studied in this research. The procedure given in Appendix C.3 can be summarised as follows.

1. Input column design problem, column height (L), column breadth (b), depth (h), bending moments Mx, My, axial load (N) and material strengths of concrete and steel (fcu and fy).

2. Calculate the reinforcement requirements given in C.3. Provide reinforcements from Table C.3.

4.4.3 Optimum design method for columns

The optimum column design problem can be defined as given below.

Objective function
Minimize the cost of column =
- cost of concrete (eqn. 4.20) + cost of formwork (eqn. 4.21)
  + cost of steel (eqn. 4.22)

Constraints
1. Minimum reinforcements area, 100As/bd ≥ 0.4
2. Maximum reinforcement area, 100As/bd ≤ 6.0
Similar to slab and beam optimization problems, the computer was used to solve the column optimization design problem. It is difficult to determine initial depth or breadth for the optimum method because of the complexity in column design. This difficulty was overcome by using depths and breadths given in Table 4.8. Each column was designed and costed for all section sizes, and least cost solution was selected as the optimum solution. IBM system 2 model 30 computer took approximately 90 seconds (15 seconds using IBM system 2 model 80) to produce the optimum solution. Iterative design procedure given in Appendix C.3 was the main reason for this slow speed.

Column section
For a column both breadth \((b)\) and depth \((h)\) can be varied. This adds to complexity of any optimum method. Therefore in this research, depth and breadth were obtained from the values given in Table 4.8. By varying depth and breadth independently (given in Table 4.8), 38 different column sections were considered for each column. These values were decided through a study of breadths and depth of columns of 22 building projects.

<table>
<thead>
<tr>
<th>Depth</th>
<th>225</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>600</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breadth</td>
<td>225</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>400</td>
<td>450</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The logic and the optimum method is shown in Figure 4.15 and details are given below.

Step 1 Input the axial force \((N)\), bending moments \(M_x, M_y\) and material strengths of concrete \((f_{cu})\) and steel \((f_y)\) and prices of concrete \((C_c)\), formwork \((C_f)\) and steel \((C_s)\).

Step 2 Design the column for the smallest cross section (i.e 225mmX225mm) according to the method given in Appendix C.3. Calculate the cost of the design solution. If there is no feasible design solution set the cost to infinity. Record the cost, column breadth \((b)\) and depth \((h)\).

Step 3 Select the next cross section from the Table 4.8. Repeat the procedure in step 2 for this section. Repeat this process for all possible cross sections shown in Table 4.8.

Step 4 Select the minimum cost solution. Redesign the column for the breadth and depth corresponding to minimum cost.

Step 5 Print the results in step 4 as optimum solution.
Step 1
Input N, Mx, My, fcu, fy, Cc, Cf and Cs

Step 2
Design the column according to the methods given in Appendix C.3 for the column of 225mmX225mm.

Step 2
Is there is a feasible design solution

Step 2
Cost = α

Step 2
Yes
Calculate the cost of the column for equation 4.23

Step 2
Record the cost, breadth and depth of column

Step 2
Are dept h = 700 and breadth = 450?

Step 4
Yes
Select the minimum cost and corresponding depth and breadth of the column

Step 4
Design the column according to the methods given in Appendix C.3.

Step 5
Print the results

STOP

Figure 4.15 Optimum design method for columns
4.4.4 Computer programs

Three computer programs were developed using the Turbo Pascal programming language for the column design method (Appendix C.3), the optimum method discussed in 4.4.3 and to check the sensitivity of the optimum solution for price fluctuations of concrete, steel and formwork. Table 4.9 gives details of program functions, input data and results.

4.4.5 Testing of the optimum method for columns

The accuracy of optimum design programs and methodology were tested for 3 different criteria including:

1. for design methodology;
2. optimum solution;
3. sensitivity of the optimum solution.

Details of the above analysis are given below.

4.4.5.1 Design methodology of columns

The design methodology was tested with one published design solution given by Kong & Evans (1987) and two column design solutions obtained from two design organizations in Sri Lanka. Table 4.10 gives details of the problems, given solutions and solution obtained from the proposed method. For column 1 and 3 close results were obtained for reinforcement requirements. For column 2 reinforcement requirements, CP110 minimum requirement 1% has been used by the design office and the proposed method has used BS8110 requirement which is 0.4%.
<table>
<thead>
<tr>
<th>Program function</th>
<th>Data Input</th>
<th>Results (Output)</th>
</tr>
</thead>
</table>
| **Program 1**    | 1. Input bending moments Mx, My  
1.1 To find reinforcement requirements according to BS8110.  
1.2 To check and satisfy minimum and maximum reinforcement requirements. | 1. Reinforcement area requirements |
| **Program 2**    | 2. To find the optimum design solution for a column section.  
2.1 To find 38 feasible design solutions for various column sections.  
2.2 To find the cost of each design solution in above 2.1.  
2.3 To find the minimum cost solution from above 2.1. | 1. Optimum design solution i.e. least cost.  
2. Cost of design solution. |
| **Program 3**    | 3. To study the sensitivity of the optimum solution for price variation in concrete, steel and formwork. | 1. Optimum design solutions for price variations of concrete, steel and formwork. |

Table 4.9: Computer programs for columns.
Table 4.10 Methodology testing for columns

<table>
<thead>
<tr>
<th>Design problem</th>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mx kNm</td>
<td>107.0</td>
<td>40.13</td>
<td>194.06</td>
</tr>
<tr>
<td>My kNm</td>
<td>0.0</td>
<td>6.53</td>
<td>0.00</td>
</tr>
<tr>
<td>N kN</td>
<td>1982</td>
<td>435</td>
<td>639</td>
</tr>
<tr>
<td>L m</td>
<td>4.0</td>
<td>3.2</td>
<td>2.65</td>
</tr>
<tr>
<td>b mm</td>
<td>380</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>h mm</td>
<td>380</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>fcu N/mm²</td>
<td>40</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>fy N/mm²</td>
<td>460</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td>Cc Rs/m³</td>
<td>1700</td>
<td>1395</td>
<td>1385</td>
</tr>
<tr>
<td>Cf Rs/m²</td>
<td>141</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>Cs Rs/kg</td>
<td>19.0</td>
<td>16.0</td>
<td>16.0</td>
</tr>
</tbody>
</table>

**Designed solution**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As required</td>
<td>578</td>
<td>1115</td>
<td>1890</td>
</tr>
<tr>
<td>As provided</td>
<td>1960</td>
<td>1482</td>
<td>1960</td>
</tr>
</tbody>
</table>

**Methods solution**

<p>| | | | |</p>
<table>
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<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>As required</td>
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<td>309</td>
<td>1007</td>
</tr>
<tr>
<td>As provided</td>
<td>678</td>
<td>452</td>
<td>1884</td>
</tr>
</tbody>
</table>

4.4.5.2 Optimum column solution

For the optimum column design method to be valid and useful, for a given column design problem, there should be a minimum cost solution within the section sizes suggested by Table 4.8. Since a column has two basic independent variables breadth (b) and depth (h), one way to study the cost variation on different solutions is through a table of cost and different sections (Table 4.11). Table 4.11 gives design solutions for problems given in Table 4.10 and least cost solutions, in other words, optimum solution are shown in 'bold letters'. Optimum solutions are within the smallest and largest cost sections given in Table 4.8. Therefore, proposed method can be used to find the optimum solution for a given column design problem.
<table>
<thead>
<tr>
<th>b</th>
<th>h</th>
<th>As mm²</th>
<th>Cost Rs</th>
<th>Column 2 As mm²</th>
<th>Cost Rs</th>
<th>Column 3 As mm²</th>
<th>Cost Rs</th>
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</thead>
<tbody>
<tr>
<td>225</td>
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<td>1884</td>
<td>2094</td>
<td>1884</td>
<td>1752</td>
</tr>
</tbody>
</table>
4.4.5.3 Sensitivity of the optimum solution

The dependence of the optimum solution on price variations for concrete, formwork and steel were investigated. Prices were varied from -50% to +50% in step of 5%. The optimum solution of all three design problems defined in Table 4.10 remained unchanged for price fluctuations studied. Therefore, single price rates of concrete, steel and formwork can be used to find the cost of all feasible design solutions as well as the optimum solution.

4.4.6 Summary

A cost equation for columns was developed according to SMM6 of RICS(1979). An optimum column design method was developed considering minimizing the cost of column as the objective function and minimum and maximum steel requirements as constraints. A number of design solutions were produced for 38 column cross sections and the least cost solution was selected as the optimum solution. The computer was used to produce 38 feasible design solutions as well as to select the least cost solution.

The design methodology was tested with 3 case studies. Satisfactory close results were observed for reinforcement requirements for 2 cases. The optimum method was tested with 3 case studies, and for all three cases, optimum solution was well within the minimum and maximum cross sections suggested by the method. A sensitivity study on the optimum solution proved that optimum design solution remain unchanged for price fluctuations up to ±50% for concrete, formwork and steel.
4.5 OPTIMUM METHOD FOR INDEPENDENT FOOTINGS

A computer based optimum design method was developed for independent footing foundations. Literature review found no method for optimum design of reinforced concrete footings. Direct search method as in column optimum design method, was used to find the optimum solution from a field of design solutions. Footing plan dimensions, bending moments, material strengths of concrete (f_{cu}) and steel (f_{y}) and prices of concrete, steel and formwork are the design information required by the method.

The developed computer based method gave the optimum solution for a given footing design problem in 5 seconds using IBM system 2 model 30 computer. The design method, cost equations and optimum method were tested with information published and collected from the industry, and satisfactorily close results were observed. A sensitivity analysis of the optimum solution revealed that this solution generally depends on the concrete and steel prices.

Details of cost equations for independent footings according to SMM6 of RICS (1979) are given. Design method of reinforced concrete footings according to BS8110 are discussed. Details of column optimum design method and testing of computer programs are given. Assumptions made in the design methodology were validated from design details of one project obtained from a design organization in Sri Lanka and published information.

4.5.1 Cost equation for footings

SMM6 of RICS (1979) gives rules for costing of reinforced concrete independent footings. They are similar to those given for slabs and beams. Details in Figure 4.16 and symbols given below, in addition to those given for slabs and beams were used in cost equations.
Figure 4.16 Independent footing with reinforcements

Asx bottom reinforcement per unit length in short span bending
Asy bottom reinforcement per unit length in long span bending
Asxt top reinforcement per unit length in short span bending
Asyt top reinforcement per unit length in long span bending
Lx short span
Ly long span

A. Cost of concrete
\[
\text{cost of concrete} = Cc \cdot Lx \cdot Ly \quad \ldots 4.24
\]

B. Cost of formwork
\[
\text{cost of formwork} = 2Cf \cdot h \cdot (Lx + Ly) \quad \ldots 4.25
\]

C. Cost of reinforcements
\[
\text{cost of reinforcements} = Cs \cdot p \cdot Lx \cdot Ly (Asx + Asy + Asxt + Asyt) \quad \ldots 4.26
\]

Total cost = \[
Cc \cdot Lx \cdot Ly + Cs \cdot p \cdot Lx \cdot Ly (Asx + Asy + Asxt + Asyt) + 2Cf \cdot h \cdot (Lx + Ly) \quad \ldots 4.27
\]
4.5.2 Footing designs according to BS8110

Design of rectangular plan shape independent footings according to BS8110 are given in Appendix C.4. This design method was used in the optimum independent footing method. Other types of foundations were not studied in this research. Details in Appendix C.4 can be summarised as follows.

1. Input the design problem, section sizes Lx, Ly, h, bending moments Mx and My and material strengths of concrete and steel.
2. Calculate the reinforcement requirements from the procedures given in Appendix C.4.1.
3. Check the shear strength requirements according to C.4.2.
4. Check for serviceability requirements such as crack control.

4.5.3 Optimum method for independent footings

The optimum independent footing design problem can be defined as given below.

Objective function
Minimize the cost of footing = cost of concrete (eqn. 4.24) + cost of formwork (eqn. 4.25) + cost of steel (eqn. 4.26)

Constraints
1. Minimum reinforcements area, 100As/bd ≥ 0.13
2. Maximum reinforcement area, 100As/bd ≤ 4.0
3. Critical shear stress ≤ allowable shear stress
4. Punching shear stress ≤ allowable shear stress
   (allowable shear stress - see Appendix C.1.5)

A flow chart for the optimum method developed is shown in Figure 4.17 and details are given below.

Step 1 Input the bending moments Mx, My, axial force N, material strengths of concrete (fcu) and steel (fy), price rates of concrete, steel and formwork.
Step 2 Calculate the balance depths for bending dbx, dby from the equation depth = \( \sqrt{(M/0.156bfu)} \).
Step 3 Select the minimum of dbx and dby as Di. Adjust Di to the nearest 10mm from the equation Di = INT(Di/10).10. Set the initial depth 'Di' to Di-100. If the Di is less than 100mm set Di to 100mm.
Step 1
Input Mx, My, N, fcu, fy, Cc, Cf and Cs.

Step 2 and step 3
Calculate Mdx, Mdy from equations in C.4.
dbx = \sqrt{(Mdx/0.1561x)} fcu
dby = \sqrt{(Mdy/0.1561y)} fcu
di = minimum of dbx and dby
Di = di + 40
Di = Int(Di/10) 10 - 100mm
If Di < 100mm then Di = 100mm

Step 4
Calculate the reinforcement area requirements Asx, Asy, Asxt, Asyt according to the method given in Appendix C.4. Provide reinforcements using Table C.1. Check for crack control requirements. If required increase the reinforcement area.

Step 5
Are shear and punching shear requirements satisfactory?

Step 6
Cost = a
Calculate the cost of the footing from the cost equation 4.27.
Record the cost and the depth

Step 7
D > Di + 10X40
Find the minimum cost and corresponding depth.

Step 8
Calculate the reinforcement area requirements Asx, Asy, Asxt, Asyt according to the method given in Appendix C.4. Provide reinforcements using Table C.1. Check for crack control requirements. If required increase the reinforcement area.

Step 9
Print the results as the optimum solution

STOP

Figure 4.17 Optimum design procedure for independent footings
Step 4 Calculate the reinforcement requirements form the methods given in Appendix C.4.1.

Step 5 Check for shear strength and serviceability requirements.

Step 6 Calculate the cost and record this together with depth. If shear and serviceability requirements are not satisfactory set the cost to infinity.

Step 7 Increase the depth by 10mm. Repeat step 4, step 5 and step 6. Repeat this procedure for 40 cycles by increasing the depth by 10mm each time.

Step 8 Select the minimum cost and corresponding depth.

Step 9 Repeat step 4, step 5 and step 6.

4.5.4 Computer programs for independent footings

Three computer programs were developed using the Turbo Pascal: independent footing design method (Appendix C.4); the optimum design method discussed in section 4.5.3; and to study the sensitivity of the optimum design solution for price variations in concrete, steel and formwork. The optimum design program produced the optimum solution for a given footing design problem in less than 3 seconds using IBM system 2 model 30 personal computer. Details of computer programs, program functions, data input and results are shown in the Table 4.12.

4.5.5 Testing of the optimum method

The accuracy of optimum design programs and methodology were tested for 3 different criteria including:

1. for design methodology;
2. optimum solution;
3. sensitivity of the optimum solution.

Details of the analysis are given below.

4.5.5.1 Design methodology for footings

The design methodology was tested with one design solution obtained from a design organisation in Sri Lanka and another published design solution given by Mosely and Bungey(1987). The developed method's accuracy was tested by comparing the given solutions with solutions obtained from the proposed method. Table 4.13 gives the details of this analysis.
<table>
<thead>
<tr>
<th>Program function</th>
<th>Data Input</th>
<th>Results (Output)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Program 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. To find the design solution of a footing according to BS8110.</td>
<td>1.1 Input bending moments Mx, My and axial loads.</td>
<td>1. Reinforcement area requirements</td>
</tr>
<tr>
<td>1.1 To find reinforcement requirements in an independent footing.</td>
<td>1.2 Footing dimensions lx, ly and depth</td>
<td></td>
</tr>
<tr>
<td>1.2 To check and satisfy minimum and maximum reinforcement requirements.</td>
<td>1.3 Material strengths of concrete and steel.</td>
<td></td>
</tr>
<tr>
<td>1.3 To check and satisfy shear requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2. Program 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. To find the optimum design solutions for a given footing.</td>
<td>2.1 Design information as in above 1.</td>
<td>1. Optimum design solution i.e. least cost design solution.</td>
</tr>
<tr>
<td>2.1 To find 40 feasible design solutions for various footing depths.</td>
<td>2.2 Price rates of concrete, formwork and steel.</td>
<td>2. Cost of each design solution.</td>
</tr>
<tr>
<td>2.2 To find the cost of each design solution in above 2.1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3 To find the minimum cost solution from 2.2 above.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3. Program 3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. To study the sensitivity of the optimum solution for price variations in concrete, formwork and steel.</td>
<td>3.1 Design information as in above.</td>
<td>1. Optimum design solution for price variations of concrete, steel and formwork.</td>
</tr>
<tr>
<td></td>
<td>3.2 Price rates as in 2.2 above.</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.13 Design methodology testing for independent footings

<table>
<thead>
<tr>
<th>Problem</th>
<th>Results</th>
<th>Given</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mosely &amp; Bungey (1987)</td>
<td>Mux kNm</td>
<td>504</td>
<td>504</td>
</tr>
<tr>
<td></td>
<td>Muy kNm</td>
<td>504</td>
<td>504</td>
</tr>
<tr>
<td>Mx = 0 kNm</td>
<td>Asx required</td>
<td>911</td>
<td>867</td>
</tr>
<tr>
<td>My = 0 kNm</td>
<td>Asy required</td>
<td>911</td>
<td>867</td>
</tr>
<tr>
<td>N = 1960 kN</td>
<td>Asx provided</td>
<td>1010</td>
<td>942</td>
</tr>
<tr>
<td>lx = 2.8 m</td>
<td>Asy provided</td>
<td>1010</td>
<td>942</td>
</tr>
<tr>
<td>ly = 2.8 m</td>
<td>Punching shear</td>
<td>0.25</td>
<td>0.32</td>
</tr>
<tr>
<td>h = 600mm</td>
<td>Shear</td>
<td>0.24</td>
<td>0.32</td>
</tr>
<tr>
<td>fcu = 20 N/mm²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fy = 460 N/mm²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Design organization</td>
<td>Mux kNm</td>
<td>505.6</td>
<td>521.7</td>
</tr>
<tr>
<td>Mx = 0 kNm</td>
<td>Muy kNm</td>
<td>505.6</td>
<td>521.7</td>
</tr>
<tr>
<td>My = 0 kNm</td>
<td>Asx required</td>
<td>889</td>
<td>904</td>
</tr>
<tr>
<td>N = 1426 kN</td>
<td>Asy required</td>
<td>889</td>
<td>904</td>
</tr>
<tr>
<td>lx = 3.5 m</td>
<td>Asx provided</td>
<td>910</td>
<td>942</td>
</tr>
<tr>
<td>ly = 3.5 m</td>
<td>Asy provided</td>
<td>910</td>
<td>942</td>
</tr>
<tr>
<td>h = 600mm</td>
<td>Punching shear</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>fcu = 20 N/mm²</td>
<td>Shear</td>
<td>0.30</td>
<td>0.27</td>
</tr>
<tr>
<td>fy = 410 N/mm²</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The above analysis shows that the proposed method gives the same results for design moments, reinforcement requirements and shear stresses as in the original designs.

4.5.5.2 Optimum solution for footings

To be an accurate optimum design method, the proposed method should give the least cost solution within the depth range selected by the method. This was studied for design problems shown in Table 4.14.
Table 4.14 Design problems for footing optimum method

<table>
<thead>
<tr>
<th></th>
<th>Problem 1</th>
<th>Problem 2</th>
<th>Problem 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mx kNm</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>My kNm</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>N kN</td>
<td>1960</td>
<td>1426</td>
<td>1426</td>
</tr>
<tr>
<td>lx m</td>
<td>2.8</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>ly m</td>
<td>2.8</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>fcu N/mm²</td>
<td>35</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>fy N/mm²</td>
<td>460</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td>Cc Rs/m³</td>
<td>1700</td>
<td>1395</td>
<td>1395</td>
</tr>
<tr>
<td>Cf Rs/m²</td>
<td>141</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>Cs Rs/kg</td>
<td>19</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Optimum solution

<table>
<thead>
<tr>
<th></th>
<th>Problem 1</th>
<th>Problem 2</th>
<th>Problem 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum depth mm</td>
<td>370</td>
<td>400</td>
<td>390</td>
</tr>
<tr>
<td>Asx provided mm²/m</td>
<td>2011</td>
<td>1436</td>
<td>1676</td>
</tr>
<tr>
<td>Asy provided mm²/m</td>
<td>2001</td>
<td>1436</td>
<td>1676</td>
</tr>
</tbody>
</table>

Optimum depths for the 3 cases given were well within the range of depths considered in this method is as shown below.

<table>
<thead>
<tr>
<th>Optimum depth</th>
<th>Feasible range of depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>370mm</td>
<td>330 to 570mm</td>
</tr>
<tr>
<td>400mm</td>
<td>330 to 570mm</td>
</tr>
<tr>
<td>390mm</td>
<td>350 to 570mm</td>
</tr>
</tbody>
</table>

Further graph of cost vs depth shows the nature of relationship between cost and depth as shown in Figure 4.18. Therefore, the proposed method can be used to find the optimum solution satisfactorily.
The sensitivity of the optimum solution was studied for price fluctuations of concrete, formwork and steel. Prices were varied -50% to +50% in steps of 5%. Figure 4.19a shows dependence of the optimum depth of footings given in Table 4.14 for individual price variations of concrete, steel and formwork. Except for footing 3 optimum solution remained unchanged up to ±30% price variations. Generally, the optimum depth remained unchanged for formwork price variations. However, optimum depth was changed considerably for price variations of more than ±30% of concrete and steel. Furthermore, Figure 4.19b shows the dependability of the optimum solution on Cc/Cs ratio and uniform price inflation on concrete, steel and formwork. It is evident from Figure 4.19b that Cc/Cs ratio is the most important factor when dealing with different price rates. Since the optimum solution remained unchanged for Cc/Cs ratio (or price) variations up to ±30%, single price rates for concrete, formwork and steel can be used to find optimum design solutions.
Figure 4.19a Price variations vs optimum footing thickness
Figure 4.19b Dependability of optimum footing depth on uniform inflation and Cc/Cs ratio
4.5.6 Summary

A cost equation for independent footings was developed according to SMM6 of RICS(1979).

An optimum independent footing design method was developed considering minimizing the cost of independent footings using objective function and punching shear, critical shear, minimum and maximum steel ratios as constraints. The optimization problem was solved by using the computer to produce 40 feasible design solutions and their costs and to select the least cost solution as the optimum solution.

The design methodology was tested with 2 case studies obtained from the industry and published information. Similar values were observed for reinforcement area requirements and shear stresses. The optimum design method was tested with 3 case studies. For all three design problems optimum depth was found to be well within the limits of depths considered by the method. The sensitivity study of the optimum solution revealed that, for two cases optimum depth remained unchanged for Cc/Cs ratio (or price) variations up to ±30%. However, optimum depth changed considerably for price variation more than ±30% for concrete and steel. The optimum depth generally remained unchanged for formwork price variations.

4.6 CONSTRUCTION OF OPTIMUM DESIGNS

In the application of optimum designs into practice, criteria other than design methods need to be considered. Finding of all related factors, problems and their solutions is another area need deep investigations. Among these criteria author believe the following as the most important.

1. Contractors pricing methods.
2. Buildability.

Since optimum methods developed in this research are computer based requirements of contractors pricing methods and buildability can be accommodated without difficulty. For example, if optimum methods produce different depths for beams, since contractor has to use different formwork for each beam cost can rise and cost saving may not achieve. This can be easily avoided by finding the single optimum depth for all beams. Similarly buildability such as good spacing between reinforcement bars can be achieved by introducing a constrain for bar spacing.
4.7 SUMMARY AND CONCLUSIONS

Cost equations for slabs, beams, columns and independent footings were developed according to the requirements of SMM6 of RICS(1979). Equations for slabs and beams were compared with cost distributions obtained through cost data analysis of 22 building projects. Both proposed equations and analysis of cost data of past projects gave the same cost distributions for concrete, formwork and steel.

Design methods used(according to BS8110) were tested with 3 case studies for slabs, beams and columns and 2 case studies for independent footings. Satisfactorily close values for reinforcement requirements, deflections requirements and shear requirements were observed.

Optimum methods for slabs, beams, columns and independent footings were developed considering minimizing cost of the element as well as the objective function and shear, deflection and maximum and minimum steel ratios as constraints. The optimum design problems were solved by using the computer to produce a set of feasible design solutions and their cost and to select the least cost solution as the optimum solution. Optimum methods were tested with 3 case studies for each element. For all these cases, the optimum solution was well within the limits of depths or section sizes considered by the method. Further graphs such as cost and depth proved the accuracy of the optimum methods.

Sensitivity studies on the optimum solutions revealed that the optimum solution generally remain unchanged up to ±20% Cc/Cs ratio (or price) variations. The optimum solution is independent of the formwork price variations. However, for slabs, beams, and independent footings optimum solutions were changed considerably for price variations of more than ±20% for concrete and steel. Since optimum solution is independent for up to ±20% Cc/Cs ratio (or price) variations, single price rates for concrete, formwork and steel can be used to find the optimum solutions (without considering different rates for various sections sizes).
Chapter five

DESIGN DECISIONS AND COST EFFECTIVE DESIGNS

5.1 INTRODUCTION
5.2 INTERVIEWS
5.3 FOUNDATION DESIGNS
5.4 FRAME AND UPPER FLOOR DESIGNS
5.5 ROOF
5.6 EXTERNAL AND INTERNAL WALLS
5.7 DOORS AND WINDOWS
5.8 FINISHES
5.9 OTHER ELEMENTS
5.10 SUMMARY AND CONCLUSIONS
5.1 INTRODUCTION

In chapter 2 of this thesis stages in the design process, personnel involved and various contract agreements with respect to cost effective design methods were discussed. Furthermore, in chapter 3, methods developed in the past for cost effective designs were described and chapter 4 discussed the details of cost effective design methods developed in this research for reinforced concrete elements. This chapter gives the details of interviews held to collect information on detail design decisions in building design, use of cost information in design decision making, and designers' response to cost effective design methods. A total of fifteen interviews were held with seven architects, six structural engineers and two quantity surveyors.

The interviews revealed that designers do not use cost information for design decisions in the briefing stage. Thus, no significant opportunity exists for cost effective design methods at the beginning of a building design. Important design decisions related to frame and floors, such as grid are made during sketch design stage. Provision of cost information related to design decisions showing cost consequences of design variables with respect to elemental cost and total cost can improve the cost effectiveness of current design decision making practice. Personnel interviewed agreed that structural optimum methods, such as methods developed in chapter 4 can be implemented in practice. However, the designers concept was that those methods should facilitate for more than 10% saving in elemental cost or 1% saving in total cost of building. Quality related design such as type of doors and windows, type of finishes are decided from the beginning of building design, however this is subject to variations due to cost overruns, clients change of mind, etc. A system which can show the cost consequences of design decisions related to quality may be able to improve the cost effectiveness of design decision making practice.

Details of the interviews and the questions used are given. Responses of the designers on design decisions and cost effective design methods, use of cost information for design decisions related to foundation, frame and upper floors, doors and windows, walls and finishes are also detailed. The chapter ends with conclusions and a summary.
5.2 INTERVIEWS

In chapter 2 cost effective design methods by structural design optimization and assessment of design options with cost consideration were discussed. Furthermore, it was discovered that most cost effective design methods have failed to have any practical application in the building construction industry. Therefore, it is important to study the expectations of practising designers regarding cost effective design methods; cost saving, favourable conditions for implementation, obstacles for implementation, and to integrate cost effective methods with design decisions.

Clearly, the information required need to be collected from the personnel in the building construction industry. For this purpose a structured questionnaire or interviews can be used as suggested by Leedy (1974) and Oppenheim (1966). To collect information through a questionnaire, possible answers need to be known beforehand. But it was difficult to get enough information to prepare a detailed questionnaire. In this circumstance, interviews were preferred to the questionnaire method. Therefore, a semi-structured interview method (interviews with a questionnaire) was used. The questionnaire used for the interviews is attached to Appendix B. A total of fifteen interviews were held with seven architects, six structural engineers and two quantity surveyors. Interviews were recorded on audio cassettes and each interview session lasted between 1 hour and 2 and half hours.

5.3 FOUNDATION DESIGNS

Foundation design decisions, use of cost information for design decision making and integration of cost effective design methods into design practice are discussed. Detailed discussions with structural engineers were held and architects were questioned on their involvements in foundation design decision making. It was discovered that in foundation design decision making, technical considerations such as ground conditions, column loads and bending moments were the most important. Designers give very little consideration to cost in foundation designs.

Synopsis of the questions discussed, foundation design decisions, responses of designers on cost effective design methods such as method developed in section 4.5 are given in detail.
Figure 5.1 Foundation design decision making
5.3.1 Synopsis of questions on foundation design

The questionnaire used for the interviews is given in Appendix B. Synopsis of questions related to foundation designs are as follows:

1. information collection during three design stages (see section 3.3.1 for design stages);
2. decision making between different feasible types of foundations;
3. use of cost data for foundation design decision making;
4. knowledge on cost effective foundation design methods and designers expectations from such methods; and
5. favourable conditions and difficulties for the implementation of cost effective foundation design methods into practice.

5.3.2 Foundation design decisions

Six structural engineers and seven architects said that during briefing stage (inception and feasibility) design information is mainly collected by a walk over inspection, knowledge of the locality, information from near by construction sites etc. (see Figure 5.1). Generally, decision on the type of foundation (pile, raft, independent footing) for the building can be made from this study. At this design stage depth of site investigation, a test pit, few bore holes etc. is recommended and the nature of site investigation depends on factors such as the type of foundation, size of project, nature of top soil etc.

A detailed study of the type of foundation selected at briefing stage, is made during sketch design stage (outline and scheme). This study is performed by the structural engineer and loads and moments on the foundation, site investigation details, safety factors of different types of foundations are used to make design decisions. According to designers interviewed cost information is very rarely used to make design decisions at sketch design stage. The design produced at this stage is only approximate and details are passed to the project director for the preparation of sketch design stage report(s).
5.3.3 Cost effective foundation designs

Questions were raised with designers such as expectations on cost effective foundation design methods. Details of the answers provided are given below.

1. Knowledge of designer on cost effective foundation design methods
   All six structural engineers interviewed were not aware of satisfactory and proven cost effective design methods for foundations designs. A few said good load analysis method based on methods such as finite element analysis, can give economical solutions, but highlighted the need of a computer for such methods. Most of the structural engineers believe that cost savings from cost effective methods so far developed, cannot be significant.

2. Expected cost savings from cost effective foundation design methods
   All six structural engineers said that they expect at least 10% of foundation cost savings or 1% of total building cost saving from cost effective foundation design methods. It is interesting that the answers given were in percentages, even though questions were asked in amounts. The designers expectations on cost savings were examined using a historical project as an illustration. Total building cost was Rs 20 million and the total foundation cost was Rs 1.2 million. The answers suggested in the questionnaire were in Rs values, but designers answered in percentages with respect to the foundation cost as well as to the total cost of the building.

3. Professional responsibility to design for minimum possible cost
   Two (out of six) structural engineers and three architects believe that designing for the minimum possible cost is a designer's professional responsibility. If there are proven cost effective design methods, the designers are willing to use those methods.

4. Lack of incentive to designers to use cost effective design methods
   According to the respondents there is no incentive for the use of cost effective design methods. Rather, in percentage fee design contracts, there is a disincentive. Six respondents said design and build contracts provide the best incentive for the use of cost effective design methods.
5. **Design duration**

Three engineers said that time limitations is a major obstacle to the use of cost effective design methods. The total design duration in some projects were only few months (2 or 3 months). Consequently, according to three engineers there isn't enough time, not only to consider cost effective design methods, but also, for a proper structural analysis and design. Therefore, most engineers produce designs with high safety factors without a proper structural analysis and design.

6. **Cost**

All the designers said that, especially at the pre-detail design stages technical factors such as ground conditions, construction difficulties in different types of foundations, loads and bending moments influence the final design decisions more than the cost. However, especially when both a pile foundation as well a raft foundation is feasible, cost estimates based on approximate designs are used to make the final design decision. This situation arises in less than 10% of the total foundation designs.

7. **Design stages**

In pre detail design stages, there is no significant room for cost effective designs due to inadequate use of cost information for design decisions. However, the optimum design method developed in section 4.5 can be used to produce cost effective foundations, since it provides economy with same structural functions.

### 5.3.4 Conclusions

In foundation design decisions making in pre-detail design stages, technical requirements such as ground conditions, building size, etc. are the most important. Therefore, it is difficult to improve the cost effectiveness of foundation design in pre-detail design stages. In detail design stage, structural design optimum methods discussed in section 4.5 could be used to produce cost effective designs. However, methods should show cost savings of more than 10% of elemental cost or 1% of total building cost.
5.4 FRAME AND UPPER FLOOR DESIGNS

The project director (architect) makes most of the design decisions on frame and upper floors while the structural engineer plays an advisory role (see Figure 5.2). However, during detail design stage, the structural engineer works independently and finally produces structural drawings for construction. Cost yardstick, cost/m² is the only cost data used for frame and upper floor design decisions. The structural engineers and the architects interviewed said that cost information connected to design decisions, such as grid, can improve the cost effectiveness of present designs during sketch (outline and scheme) design stage. Structural designs at the detail design stage is the responsibility of the structural engineer and he/she has an opportunity to implement cost effective methods such as methods discussed in sections 4.2, 4.3 and 4.4. Most structural engineers felt that, if cost effective design methods for detail design stage prove more than 10% saving in elemental cost or 1% saving in total building cost, methods should be integrated into design practice.

5.4.1 Synopsis of questions for frame and upper floor designs

The questions asked with respect to frame and upper floor design are given below. The full questionnaire used is attached in Appendix B.

1. Design decisions in frame and upper floor designs.
2. Different design decisions made by the architect and the structural engineer.
3. Use of cost information for design decision making.
4. Designers' knowledge of cost effective designs in frame and upper floors.
5. Favourable conditions and difficulties in implementing cost effective frame and upper floor design methods.

5.4.2 Frame and upper floor design decisions

From interviews with six structural engineers and seven architects, based on questions discussed in section 5.4.1 design decisions, important factors in decision making and architects and structural engineers involvements were identified. Table 5.1 gives a summary and Figure 5.2 shows the design decisions making process in frame and upper floors.
Inception and Feasibility design stages

1. Clients space requirements of the building.
2. Funds available.

Outline and Scheme design stage

1. Functional requirements of the building.
2. Site conditions
3. Local authority regulations.

Detail Design Stage

1. Area of the building together with the shape.
2. Number of storeys.
3. Storey height/s.

Project Manager decides following.

- Architect produces layout plans of the building
- Structural Engineer carries out following.
  - Analysis of the frame and floors for loads. This gives axial forces, bending moments and shear forces.
  - Detail design of each member for reinforcements.
  - Produce structural drawings for construction.

- Structural Engineer advises on following.
  - Structural stability.
  - Economy of various grid patterns.
  - Compatibility with the foundation.

Figure 5.2 Frame and upper floor design decision making
The design decisions related to frame and floors are discussed below.

5.4.2.1 Briefing design stage

The following are the design decisions related to frame and upper floors during sketch design stage (inception and feasibility):

1. area of the building together with the shape;
2. number of storeys or height of the building; and
3. storey height(s).

The following were identified as the influential factors for the design decisions identified above.

1. **Who is the decision maker, the architect or the structural engineer?**
   
   Both structural engineers and architects (project director) are involved in design decision making. However, the project director (architect) makes the final design decisions considering the functional requirements, funds available, etc. (see Table 5.1) while the structural engineer plays an advisory role.
2. **Client's requirements**

The project director collects client requirements through discussions and the client's brief. Depending on these requirements, area of the building, number of storeys, storey height(s) are decided. Most architects experience show that degree of contribution from the client varies considerably. Presence of a person with experience in building with the client (or client organization) leads to precise definitive client requirements.

3. **Available funds**

Most clients come to designers with an upper limit of the funds available. Therefore, total area of the building, number of storeys and storey height(s) are decided from consideration of available funds. Superficial floor areas cost based on a historical project(s) (cost/m²) is used for design decision making.

4. **Functional requirements of the building**

The building shape, area of the building and storey height(s) depend on functional requirements of the building. For example, designers said that, for a factory building, a narrow building may be required.

5. **Site conditions**

Site conditions also can influence design decisions. For example, due to weak ground conditions a pile foundation may be required even for a 2 storey building. In this situation number of storeys may increase to reduce the plan area, and thus the cost of the foundation.

6. **Local authority regulations**

Local authority regulations govern the total height of buildings, distances from the road, window areas, etc. and thus influence design decisions.

Considering the above factors it is clear that the influence of the cost on design decisions is very low during briefing design stage. Therefore, no significant opportunity exists for cost effective designs during briefing design stage.
5.4.2.2 Sketch design stage

The following design decisions are made during sketch (outline and scheme) design stage jointly by the project director (architect) and the structural engineer.

1. Grid pattern, i.e. short span, long span and number of spans in each direction.
2. Columns and beams layout.

The architects and the structural engineers interviewed said that the above decisions are made jointly but with different design responsibilities. The role of the structural engineer is advisory and concern structural stability, economy of selected variables such as long and short span values and compatibility with the foundation. The project director makes the final decisions, and for that, most of the professionals interviewed consider the following as important:

1. functional requirements of the building; and
2. advice of the structural engineer (see section 5.4.2.1 for details).

5.4.2.3 Detail design stage

Both the structural engineer and the architect work independently during detail design stage. The structural engineer carries out the following in the detail design stage.

1. An analysis of the frame and floors for loads. This gives bending moments, axial loads, shear forces etc.
2. Detail design of each member, columns, beams, stair cases, lift shafts, floors etc.

Three engineers stated frankly that, sometimes, proper analysis is not carried out in some projects. The following two main reasons were given.

1. Low design fee due to competitive bidding for small number of jobs. At present design fee vary from a low of 3% to a high of 10%.
2. Limited and short design durations. Most Clients want to finish designs as soon as possible. This leads to designs without proper analyses but with higher safety margins.

The only communication between the structural engineer and the project director (architect) during this design stage is on minor changes such as those in beam depth or column section etc.
5.4.3 Cost effective design of frame and upper floors

Discussions were held with the architects and the structural engineers to identify the needs of cost information to design decisions cost effective at three design stages, briefing, sketch and detail stage. Details of the answers given are discussed below.

5.4.3.1 Briefing design stage

It was understood from the discussions that it is extremely difficult to improve the current design practice at briefing (inception and feasibility) design stage due to the following reasons.

1. As has been discussed in section 3.4.3 designers very rarely use cost data for design decisions, thus cost considerations are not relevant.
2. The design decision made at briefing stage is not sufficient for any consideration of cost effective designs.

5.4.3.2 Sketch design stage

The sketch (outline and scheme) design stage has a room for cost effective designs because important design decisions are made and also cost information related to design decisions can be provided. One major set-back is that the project director (architect) has to make design decisions considering functional and structural requirements of the building and cost considerations. Two questions regarding cost effective designs were discussed with architects and structural engineers. Results of the answers and the questions are discussed below.

1. Question was discussed on the possibility of accommodating information showing cost variations with grid patterns (short span and long span) for reinforced frame designs. Table 5.2 gives the results of answers to the question by architects and structural engineers.

<table>
<thead>
<tr>
<th></th>
<th>No Possibility</th>
<th>Could be</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architects</td>
<td>0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Engineers</td>
<td>0</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
The results clearly indicate that if there is a proper system to show cost information connected to design decisions it is possible to improve design decisions related to the grid. The structural engineers felt that there is limited possibility because architects give a high weight to functional requirements. On the other hand, most architects said that if the cost information are available, directly related to design decisions, using a simple system, and if the cost variations are significant, it is possible to accommodate it into current design decision making practice. Most of the architects welcome such facility.

2. A question was discussed to test the knowledge of designers on cost variations with grid variation. The results of the answers given to the question of the optimum range for spans (short and long spans) are given in Table 5.3

<table>
<thead>
<tr>
<th></th>
<th>Not known</th>
<th>4 to 5 metres</th>
<th>4 to 6 metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architect</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Engineer</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

Most of the architects said that they are not sure of the optimum range for spans. Further, all the structural engineers said that optimum range is 4 to 6 metres, but nobody was able to tell the pattern of variation within 4 to 6 metres. Most of the architects said that if information is available on cost variation with spans, it is possible to accommodate such information in design of buildings as functional requirements are integrated into design decision making.

5.4.3.3 Detail design stage

Detail designs, such as reinforcements for beams, take place during detail design stage. Generally the structural engineer has total freedom to decide changes to depths and breadths required. In most cases, during sketch design stage, the project director and the structural engineer jointly decide feasible depths and breadths for beams. Architects prefer and demand for uniform beam depth in a floor, to eliminate or to hide beams or to have shallow beam depths for special areas such as entrance lobbies. In some buildings, services such as air-conditioning or heating ducts demand shallow depths for beams. Almost all the structural engineers and the architects interviewed said that, when required, it is possible to accommodate required depths for beams in most buildings without much problem. They are aware of optimum design methods for beams, but
think that the benefits devisable from them cannot be significant. However, if benefits are more than 10% of elemental cost they will consider using the methods in design practice. Similar to foundation designs, cost benefits expected were discussed using a historical project as illustration. The benefits were examined in monetary values but designers gave answers in percentages of elemental and project cost. Further, they said benefits have to be judged, not only by beams costs, but also with respect to the total building cost.

Detail design of columns are very similar to that of beams. But most structural engineers did not know any optimum method for cost effective column designs.

5.4.3.4 Slabs

Design of slabs is undertaken during detail design stage and it is responsibility of the structural engineer. According to the structural engineers the most critical design criteria is deflection. Therefore, depth is generally selected to meet deflection requirements. Interesting answers were given to the question of cost effective slab designs. One engineer generally takes at least 125mm thickness even for small spans such as 3 meters. His reason was that, for smaller depths, very close spacing of reinforcements is required due to crack control criteria which lead for higher cost. The example below illustrates the logic of this argument.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Effective depth</th>
<th>Maximum spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>100mm</td>
<td>75mm</td>
<td>225mm</td>
</tr>
<tr>
<td>125mm</td>
<td>100mm</td>
<td>300mm</td>
</tr>
</tbody>
</table>

Most of Structural Engineers were aware of optimum methods for reinforced concrete slab designs published in journals but said that benefits cannot be significant. The least cost benefit required to consider cost effective design method for practical applications was discussed. Four engineers expected at least 10% elemental cost saving while two engineers said at least 5% elemental cost saving. Further the cost saving have to be judged with respect to benefits to the total project. If benefits are more than 1% of total project cost then cost effective methods could be used. Therefore, a study is required to evaluate the cost benefits of optimum design methods for reinforced concrete slabs to test if designers expectations can be achieved.
5.4.4 Conclusions

At the briefing design stage decisions are not detailed enough to require in depth cost information to aid cost effective design decisions. During sketch design stage providing cost information related to design decisions such as grid can improve the cost effectiveness of design decisions. However, such information should be simple, and should show cost consequences with respect to the elemental cost as well as total cost of the building. Cost effective methods developed for the detail design stage can be implemented into design practice. However, the designers opinion was that methods should show more than 10% elemental cost savings or 1% of total building cost saving.

5.5 ROOF

Both the structural engineers and the project director (architect) are involved in roof designs. Design of a roof involves two key design decisions. They are; to select a suitable roofing material and the type of roof structure. Four issues were raised with designers and they are as follows:

1. information available in three design stages (briefing, sketch and detail design stages);
2. design stages and final design decisions;
3. designers' knowledge on various roof types; and
4. possibilities of improving the cost effectiveness of roof designs.

Table 5.4 gives a summary of the answers to the above questions. Details of the answers are given below.
Table 5.4 Designers & roof designs

<table>
<thead>
<tr>
<th>Inception &amp; feasibility stages</th>
<th>Outline and scheme stages</th>
<th>Detail design stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Information</td>
<td>1. Column and beam layout</td>
<td>Details relevant to details designs</td>
</tr>
<tr>
<td>1. Size, number of storeys et.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Type of building</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 2. Design decisions           | 1. Type of roofing material | 1. Detail design of roof structure |
| An idea of roof type          | 2. Type of roof structure  | 2. Details of roofing material |

| 3. Possibilities of cost effective designs | No | To select economical roof structure | Use of optimum methods |

5.5.1 Roof design decisions

The project director (architect) makes most of the decisions relevant to roof design. The structural engineer advises the project director especially to select a roof structure. The project director first selects a suitable type of roofing material and then selects a type of roof structure. Designers have vague idea about the roof during briefing design stage. Generally, the type of roofing material and type of structure is decided during sketch design stage. These facts were discovered during discussions based on question (1) and (2) given in section 5.5 (see Figure 5.3).

Hardly any estimating data is used for roof design decisions. Most of the designers said that, for buildings with more than three storeys, cost of the roof is not significant. In answering the question on economical roofs, designers judgment was that steel truss structures are suitable for most buildings. This judgment was said to be based on experience but without any proven cost data. Therefore, a study is necessary to analyse the most economical roof for various spans.
Figure 5.3 Roof design decision making
5.5.2 Cost Effective Roof Designs

It is possible to improve the cost effectiveness of roof designs in selecting of a roof structure in sketch design stage. The roofing material is decided by considering the durability, the roof shape, requirements and the cost. Therefore, there seems to be no significant scope for improving the cost effectiveness of selecting a roofing material.

5.6 EXTERNAL AND INTERNAL WALLS

Design decision on external and internal walls are made by the project director (architect). According to the designers, these two elements are relatively insignificant in modern buildings, especially in offices. This was confirmed by cost analysis conducted in this research which gave 4.15% mean value of external walls and 1.21% mean value for internal walls relative to the total cost of the building (see section 6.2.5, Table 6.1). Generally, wall types are decided during detail design stage and only an idea is available during sketch and briefing design stages.

In Sri Lanka, three types of materials are available for walls. They are:

1. ordinary bricks;
2. wirecut bricks; and
3. cement sand blocks.

Wirecut bricks are used for decorative finish, therefore, only ordinary bricks and cement sand blocks can be substituted for each other. All six architects said that blocks are cheaper but three architects prefer bricks because of its flexibility for infilling and finish. Two architects said that clients are also involved in making the final decision.

A question was asked on the cost difference required to change architects choice on types of material selected for walls. Five architects said that if the cost difference is more than 25%, they are willing to consider a change. Further most designers said that an accurate cost information is not available to them for making proper design decisions.
5.7 DOORS AND WINDOWS

Doors and windows give quality and character to buildings. Both the project director (architect) and the client jointly make design decisions connected to doors and windows. The project director specifies suitable types while the quantity surveyor gives costs relevant to each type. Through discussions with the client, the project director finally decides the type of doors and windows. Figure 5.4 gives the design decisions, and involvement of the project director and the client in design decision making.

Due to the design and cost significance (Table 6.1 chapter 6) of doors and windows, consideration is given to them from briefing stage. Type of doors and windows are confirmed during sketch design through discussions with the client. Detail designs and specifications such as sizes, manufacturer etc. are made during the detail design stage.

5.7.1 Cost effective doors and windows designs

Two questions were discussed with respect to cost effective doors and windows designs. These are:

1. cost difference required to change the selected type; and
2. how the cost information showing cost of various types influence on design decisions.

Table 5.5 shows the results of the answers to the first question.

<table>
<thead>
<tr>
<th>No change</th>
<th>Change if elemental cost difference is more than</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10% 25% 50%</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>No change</td>
<td>Change if total building cost difference is more than</td>
</tr>
<tr>
<td></td>
<td>1% 2% 3%</td>
</tr>
<tr>
<td>2</td>
<td>1 2 2</td>
</tr>
</tbody>
</table>

The Table 5.5 proves that if the cost difference is significant selected types could be changed. This change is not always done but in most cases, four architects consider it as necessary. Two architects said that they will not change the selected type for reason of high cost because other factors such as durability, quality etc. are much more
important than cost. Table 5.6 gives the results of the answers given to the second question.

<table>
<thead>
<tr>
<th>No, judgement by experience is enough</th>
<th>System could help</th>
<th>Yes, we need that information</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Most of the architects said that a system which can tell cost of various types during sketch design stage will improve the cost effectiveness of design decisions. Therefore a study is required to check the requirements given in Table 5.5 to decide whether the provision of cost information related to design decisions can improve the cost effectiveness of current windows and doors design decision making practice.

5.7.2 Conclusions

Designers need cost information to show the cost consequences of their design decisions with respect to elemental costs and the total building cost. Therefore a study is required to test whether cost differences between design options in doors and windows are more than designers expectations.
Figure 5.4 Doors and Windows design decision making
5.8 FINISHES

Finishes are subjected to various changes during building design process. Through discussions, it was understood that most designers use finishes as a buffer for cost overruns. Cost analysis given in Table 6.1 (see chapter 6) shows mean cost of 15.5% of the total cost of the building for finishes. Finishes are ultimately visible to building user. Thus, they greatly contribute to the quality of the building.

5.8.1 Finishes design decisions

Similar to doors and windows, the client is involved in the final design decision on finishes. Finishes is one of the elements that the project director (architect) discusses with the client from the inception design stage to the detail design stage. Both the architect and the client have good ideas of finishes anticipated during briefing design stage. This is confirmed during sketch design stage. During detail design stage, final design on finishes is carried out. Further, finishes could change during detail design stage due to cost overruns. The Figure 5.5 shows the design decisions involved and, architects and clients involvement on finishes designs.

5.8.2 Cost effective finishes designs

Three questions were discussed with the architects with respect to cost effective finishes designs. These are:

1. method and information used to select the type of finishes;
2. cost difference required to change the selected type; and
3. whether cost information showing cost of various types of finishes will help to improve the cost effectiveness of finishes designs.

Results of the answers to above questions are given in Table 5.7.
### Table 5.7 Designers and finishes design

<table>
<thead>
<tr>
<th>Inception and feasibility design stages</th>
<th>Outline and scheme design stages</th>
<th>Detail design stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Information available</td>
<td>1. Client preferences</td>
<td>1. Accurate cost estimates</td>
</tr>
<tr>
<td></td>
<td>2. Approximate cost of various finishes.</td>
<td>2. Details of costs of various elements</td>
</tr>
<tr>
<td></td>
<td>3. Available funds.</td>
<td></td>
</tr>
<tr>
<td>2. Cost difference required to change selection</td>
<td>1. Change if elemental cost difference is more than 50%</td>
<td>1. Change to accommodate cost overruns.</td>
</tr>
<tr>
<td></td>
<td>2. No change at any cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Change if total cost difference is more 2%</td>
<td></td>
</tr>
<tr>
<td>3. Effect of structured cost data on finishes design</td>
<td>1. No cost is not important</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Yes could help</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Yes we need that information</td>
<td></td>
</tr>
</tbody>
</table>

#### 5.8.3 Conclusions

Designers need cost information to show the cost consequences of their design decisions with respect to the elemental cost and the total building cost. Therefore, a study is required to test whether cost differences between design options in finishes are more than designers expectations.
Figure 5.5  Finishes design decision making
5.9 OTHER ELEMENTS

Elements other than those discussed above, which includes services, external work, plumbing, fittings and furniture etc. have higher complexity in design. This is mainly due to factors such as reliability, safety and many other factors that have to be considered in designs. Therefore potentials for cost effective designs of these elements are much more limited than for the elements discussed. Cost analysis in Table 6.1 shows that the total cost of these elements is less than 20%. Consequently, study of elements other than those discussed above, were not considered in this research.

5.10 SUMMARY AND CONCLUSIONS

The following conclusions can be given for the use of cost effective design methods in current design practice.

1. There is only a nominal use of cost information in foundation, frame and upper floor design decision making in briefing stage. Therefore there is no significant scope to use cost effective design methods for building structure design in briefing stage.

2. Cost information related to frames can be incorporated in sketch design stage decision making. Information is required to show the cost consequences of design variables with respect to building structure elemental cost and the total building cost. Therefore, a test should be carried out to check whether there are significant cost variations attributed to the design variables in sketch design stage.

3. Optimum structural design methods such as methods given in chapter 4, can be used to produce cost effective designs during detail design stage. However, designers will implement such methods into current design practice only if the methods can show cost saving more than 10% of the elemental cost or 1% of the total building cost. Therefore, analyses should be made to evaluate cost savings of structural cost effective design methods.

4. There are disincentives in current design practice to use cost effective design methods because of unfavorable design contract types (percentage fee
contracts), short design durations, lack of monetary benefits for extra time consuming design work. Therefore, the building construction industry should identify these difficulties and appropriate actions should be taken to overcome the unfavorable conditions. Design and build contracts serve an incentive for implementing cost effective design methods.

5. Cost information relevant to design decisions related to the quality of the building can improve the cost effectiveness of design decision making practice. A study should be made to check the variations of the cost between design options for the designers cost difference requirements.
Chapter six

COST AND DESIGN DATA

6.1 INTRODUCTION
6.2 COST DATA COLLECTION
6.3 DESIGN DATA COLLECTION
6.4 SUMMARY
6.1 INTRODUCTION

This chapter gives the details of data collected in this research from design drawings and priced bills of quantities. The data was collected to produce optimum designs for buildings already designed using methods developed in chapter 4 of this thesis. A total of 22 building design data and cost data of 32 buildings were collected. The collected design data included reinforced design details of slabs, beams, columns and independent footings and general building details of plans, elevations, layouts of beams and columns etc. Cost data of unit price rates of concrete, formwork and steel and elemental costs of building were also collected.

6.2 COST DATA COLLECTION

6.2.1 Project information

General project information collected was similar to that defined in RICS (1969) 'Standard Form Of Cost Analysis' of buildings. The details of data collected are given below.

1. Project details
   A project name was defined because data was collected with the agreement that they will not be identified from the real name of the building. Details of project location, the client, the consultant and the contractor were collected for each building. A brief description of the project which includes, type of foundation, roof type, finishes and fittings was included.

2. Contract document information
   The tender data, the type of contract between the client and designer, client and contractor, project total, project overheads and profits were collected.
6.2.2 Unit cost rates

One of the main objectives of this research is to evaluate cost differences between cost effective design solutions and designer's solutions. The optimum structural design methods developed for slabs, beams, columns, and independent footings (chapter 4) need unit cost rates of concrete, formwork and steel to find optimum solutions. Further cost unit rates of windows and finishes are required for analyses of cost differences in design options. Therefore unit cost rates were collected and details are given below.

1. Unit cost rates of reinforced concrete elements
Unit cost rates of concrete (Rs/m3), formwork (Rs/m2), and steel (Rs/kg) were collected separately for independent footing foundations, slabs, beams and columns. The unit cost rates depend on sections size, location of the element. Generally, first floor level units rates of the most common element (highest cost) were collected. Data related to types (or grade) of concrete, formwork, steel are also collected.

2. Unit cost rates of other elements
Unit cost rates of other elements such as windows, doors, finishes were also collected in this research. Unit cost rates depend on type of material, location of the element in the building etc. Therefore cost rates at first floor level were collected with a brief description. These unit rates were used in cost difference analyses of different feasible design options (see chapter 8).

6.2.3 Elemental costs

To evaluate elemental and total cost benefits from cost effective design methods, elemental costs such as foundations, doors, windows, finishes etc., are required. Further, cost details in priced bills of quantities are too detailed for cost saving analyses. Therefore project cost details were collected as elemental costs. In breaking building cost into elements, the Standard Form of Cost Analysis (RICS 1979) was considered. However, variations were required for sub-elements to suit the objectives of this research. Details are discussed below.
1. Design elements

Slabs, beams, columns and footings are designed as separate elements and cost effective methods were developed for above elements separately (chapter 4). Therefore costs of these elements were required separately to calculate cost benefits from developed cost effective design methods. In Standard Form Of Cost Analysis (RICS 1969) beams and columns are considered as one element, but in this research beams and columns were treated as two separate elements. Costs of above elements at each floor level were collected separately. Further costs of concrete, formwork and steel were collected for reinforced concrete elements separately. Cost component of concrete, formwork and steel were used to validate cost equations developed in chapter 4.

2. Doors and Windows

Standard form of cost analysis has windows and external doors and internal doors as two elements. However, for design purpose doors and windows are treated as two elements. Therefore cost data of windows and doors were collected as two separate elements. Windows and doors elemental costs were collected with area, description of types together with unit cost rates.

Therefore, elements considered in this research were different from Standard Form of Cost Analysis and full list of elements considered are given below.

<table>
<thead>
<tr>
<th>Main element</th>
<th>Element</th>
<th>Sub element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>Level 2</td>
<td>Level 3</td>
</tr>
<tr>
<td>A. Foundation</td>
<td>A.1</td>
<td>A.2.1 Concrete</td>
</tr>
<tr>
<td></td>
<td>A.1.1</td>
<td>A.2.2 Formwork</td>
</tr>
<tr>
<td></td>
<td>A.1.2</td>
<td>A.2.3 Steel</td>
</tr>
<tr>
<td></td>
<td>A.1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A.2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A.2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A.2.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A.3</td>
<td></td>
</tr>
<tr>
<td>B. Structure</td>
<td>B.1</td>
<td>B.1.1 Concrete</td>
</tr>
<tr>
<td></td>
<td>B.1.1</td>
<td>B.1.2 Formwork</td>
</tr>
<tr>
<td></td>
<td>B.1.2</td>
<td>B.1.3 Steel</td>
</tr>
<tr>
<td></td>
<td>B.1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.2.2</td>
<td></td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>B.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.3.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.3.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.7</td>
<td></td>
</tr>
</tbody>
</table>
C. Bricklayer
C.1 Foundation
C.2 External walls
C.3 Internal walls

E. Steel work
E.1 Roof steel work
E.2 Other steel work

F. Carpenter
F.1 Roof structure
F.2 Ceiling
F.3 Others

G. Joiner
G.1 Doors
G.2 Windows
G.3 Ironmonger

H. Roof and roof plumber
H.1 Roofing material
H.2 Roof plumbing

I. Plumber
I.1 Water supply
I.2 Waste water
I.3 Sewerage works
I.4 Sanitary fittings
I.5 Others
I.6 Drainer

J. Finishes
J.1 Wall finishes
J.2 Floor finishes
J.3 Bathroom and toilet finishes
J.4 Others

L. Paint
L.1 Walls
L.2 Doors
L.3 Windows
L.4 Others

M. Electrical fittings
M.1 Electrical fittings

N. External work
N.1 External work

P. Money provisions
P.1 Money provisions

Q. Preliminaries
Q.1 Preliminaries

R. Contingencies
R.1 Contingencies
6.2.4 Problems encountered in cost data collection

Problems were encountered in cost data collection from historical projects. The details are discussed below.

1. Permission to extract information
   It was difficult to convince many consultants to give cost data for this research purpose. This was the case with all private sector organizations. However, it was relatively easy to get information from government organizations. The main reason given by private consultants was that they have a legal bond (mainly to the contractor) not to give cost information to a third party. However, after a few visits as well as through informal contacts, many consultants agreed to give priced bills of quantities to extract information. Further a promise was given to consultants that details will be treated as confidential and use only for the research analysis purposes.

2. Different formats of bills of quantities
   There was no uniformity in bills of quantities prepared by consultants in Sri Lanka. State organizations and few private design organizations use more structured bills of quantities according to standard method of measurements (SMM6, RICS 1979).

3. Poor record keeping
   In some organizations it was difficult to trace priced bills of quantities of past projects. This was the case with one large state organization and few private organizations. In one state organization bills of quantities were in regional offices with different offices who were in charged of projects. However, in one large state organization and some private sector organizations satisfactory record keeping was observed.

4. Lack of interest from the people in the building construction industry
   It was difficult to convince, especially senior managers to give required information. A good response was received from the quantity surveyors in practice.
5. Units

Some bills of quantities were in imperial units. Therefore it was required to convert unit cost rates into metric units. Because of this different units, it took extra time to extract information from bills of quantities.

Table 6.1 Elemental cost percentages in reinforced concrete framed buildings

<table>
<thead>
<tr>
<th>Element</th>
<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Foundation</td>
<td>11.81</td>
<td>24.90</td>
<td>3.45</td>
<td>53.0</td>
</tr>
<tr>
<td>2. Structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Beams</td>
<td>8.14</td>
<td>18.13</td>
<td>3.34</td>
<td>46.8</td>
</tr>
<tr>
<td>b. Columns</td>
<td>5.34</td>
<td>9.66</td>
<td>1.28</td>
<td>40.6</td>
</tr>
<tr>
<td>c. Slabs</td>
<td>10.50</td>
<td>17.97</td>
<td>5.82</td>
<td>29.62</td>
</tr>
<tr>
<td>d. Others</td>
<td>2.16</td>
<td>5.70</td>
<td>0.20</td>
<td>70.4</td>
</tr>
<tr>
<td>e. Pre-cast elements</td>
<td>0.60</td>
<td>9.20</td>
<td>0.00</td>
<td>352.6</td>
</tr>
<tr>
<td>3. Roof</td>
<td>10.11</td>
<td>25.93</td>
<td>1.78</td>
<td>68.2</td>
</tr>
<tr>
<td>4. Walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Internal walls</td>
<td>1.21</td>
<td>3.42</td>
<td>0.60</td>
<td>79.3</td>
</tr>
<tr>
<td>b. External walls</td>
<td>4.15</td>
<td>8.31</td>
<td>1.46</td>
<td>49.1</td>
</tr>
<tr>
<td>5. Doors and Windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Doors</td>
<td>3.75</td>
<td>9.04</td>
<td>1.67</td>
<td>55.2</td>
</tr>
<tr>
<td>b. Windows</td>
<td>7.70</td>
<td>18.34</td>
<td>1.47</td>
<td>65.4</td>
</tr>
<tr>
<td>6. Services</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Electrical fittings</td>
<td>6.02</td>
<td>13.27</td>
<td>2.01</td>
<td>69.2</td>
</tr>
<tr>
<td>b. Water &amp; others</td>
<td>3.19</td>
<td>8.13</td>
<td>1.78</td>
<td>67.9</td>
</tr>
<tr>
<td>7. Finishes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Floor finishes</td>
<td>4.61</td>
<td>14.39</td>
<td>1.90</td>
<td>75.4</td>
</tr>
<tr>
<td>b. Wall finishes</td>
<td>8.52</td>
<td>15.94</td>
<td>3.18</td>
<td>34.6</td>
</tr>
<tr>
<td>c. Ceiling &amp; others</td>
<td>2.34</td>
<td>10.45</td>
<td>0.00</td>
<td>136.4</td>
</tr>
<tr>
<td>8. External work</td>
<td>4.92</td>
<td>19.33</td>
<td>0.00</td>
<td>113.0</td>
</tr>
<tr>
<td>9. Preliminaries</td>
<td>0.45</td>
<td>2.69</td>
<td>0.00</td>
<td>191.2</td>
</tr>
<tr>
<td>10. Money provisions</td>
<td>2.25</td>
<td>18.27</td>
<td>0.00</td>
<td>210.1</td>
</tr>
<tr>
<td>11. Contingencies</td>
<td>2.22</td>
<td>9.14</td>
<td>0.00</td>
<td>150.7</td>
</tr>
</tbody>
</table>
6.2.5 Elemental costs of reinforced concrete buildings

Cost component analysis of elements was conducted to identify cost significances of different building elements. Table 6.1 shows cost percentages of building elements derived from an analysis of costs of 32 reinforced concrete framed historical buildings. Table 6.1 shows that structure of average building costs 36% (Foundation 11.81%, beams 8.14%, columns 5.34% and slabs 10.60%) of the total cost of the building. Therefore cost savings through optimum design methods of slabs, beams, columns and footings can give significant cost savings compared to the total cost of a building. Windows, floor finishes and wall finishes also show high cost percentage therefore it is worth analysing cost effective design methods for windows and finishes design.

![Costs of different building elements](Image)

**Figure 6.1 Costs of different building elements**

6.3 DESIGN DATA COLLECTION

Design data of independent footings, slabs, beams and columns of 22 reinforced concrete historical projects were collected. The details include section sizes, material strengths of concrete and steel, reinforcement details etc. The required design data was identified to produce cost effective solutions using optimum methods developed in chapter 4 of this thesis. Details of the data collected are given below.
6.3.1 General project details

The project plan together with overall dimensions, grid details (spans two directions), number of storeys, storey height(s), type of columns and foundations were collected for each project. An example is shown in Figure 6.2. All design dimensions were collected in metric units.

![Diagram of project layout]

- Storey number 0-1 1-2
- Storey height 3.0 3.49
- C1, C2, C3... - Column types
- F1, F2, F3 - Foundation types
- Number of storeys = 2
- Project name - MTT

Figure 6.2 General project details

6.3.2 Independent footing foundations

Details of the most common 2 independent footings were collected for each project. Details include type of concrete (grade), type of reinforcements, reinforcement details and sections sizes. An example of details collected for one independent footing is given below (Figure 6.3).
6.3.3 Beams

Details of most common one longitudinal and one cross beam were collected. The details included reinforcement details, section sizes, concrete grade, reinforcement type etc. The most common beams were identified from the beam layout in a floor (see Figure 6.4), and example of details collected for one beam is shown in Figure 6.5.
For the project shown in Figure 6.4 details of FB1 and FB9 were collected and details collected for FB1 are shown in Figure 6.5 below.

![Diagram of beam design](image)

Concrete grade = 20N/mm²  
Reinforcements fy = 410N/mm²  
Cover = 20 mm

Figure 6.5 Data collected for beams

### 6.3.4 Columns

Design details of the two most common columns for each project were collected. Details of one column in a project is given in Figure 6.6.

![Diagram of column design](image)

Concrete grade = 20N/mm²  
Reinforcements fy = 410N/mm²  
Cover = 25mm

Figure 6.6 Columns details collected for one column
6.3.5 Slabs

Design details of the two most common slabs were collected for each project. Details of one slab in a project is given in Figure 6.7.

Concrete grade = 20N/mm²
Reinforcements fy = 410N/mm²
cover = 20mm
Thickness = 150mm

Bottom Reinforcements
X direction Y direction
Y10 - 225 Y10 - 225

Top reinforcements
1 2 3 4
Y10-300 Y10-300 Y10-300 Y10-300

Secondary reinforcements
R6 - 200

Figure 6.7 Data collected for a slab

6.3.6 Total project design information

The total structural design details of two projects were collected from two design organizations. The collected details include:
1. structural analysis details, bending moments, shear forces, load analysis etc.; and
2. complete structural details (set of structural drawings).

6.3.7 Problems encountered in data collection from drawings

Similar problems in collecting data from priced bills of quantities (see section 6.2.4) were encountered in data collection from drawings. Permission to extract data from drawings was the most difficult.
6.4 SUMMARY

Cost data which includes unit cost rates of reinforced concrete elements, elemental costs such as foundations, beams, windows, finishes were collected for 32 historical building projects. Design details which include section sizes, reinforcement details were collected from 22 historical buildings. Full design and cost data, including priced bills of quantities and structural drawings of two projects were collected. The Cost analysis of elements of 32 buildings of which data were collected showed 36% cost for the building structure, 7.7% for windows and 4.61% for floor finishes thus proved the importance of studying of cost effective design methods related those elements.
Chapter seven

COST SAVINGS THROUGH REINFORCED CONCRETE OPTIMUM DESIGN METHODS

7.1 INTRODUCTION
7.2 DATA FOR COST SAVING ANALYSES
7.3 MODIFIED OPTIMUM METHODS
7.4 COST SAVINGS IN REINFORCED CONCRETE DESIGNS
7.5 DESIGNERS' EXPECTATIONS AND ACTUAL COST SAVINGS OF THE OPTIMUM METHODS
7.6 COMPARISON OF OPTIMUM DESIGN SOLUTIONS AND DESIGNERS' SOLUTIONS
7.7 SUMMARY AND CONCLUSIONS
7.1 INTRODUCTION

This chapter gives the details of the cost savings on 22 building projects for the optimum methods developed in chapter 4. Cost data from priced bills of quantities and design details from structural drawings of 22 buildings were collected from the construction industry. This analyses revealed that average cost savings through optimum methods for four reinforced concrete elements, slabs, beams, columns and independent footings of the buildings designed by normal design procedure are more than 10% of the elemental cost (with 95% confidence). Furthermore, it was discovered that total of 2.22% of the total cost of buildings can be saved using optimum methods for slabs, beams and columns and total of 2.91% of the total cost of buildings can be saved by using optimum methods for slabs, beams, columns and independent footings. These cost savings are equal to a minimum of 34% and maximum of 65% of design fee of a building project. For a given project probabilities of cost saving exceeding 1%, 2% of the total building cost are 0.96 and 0.79 respectively.

Firstly, details of data used for cost saving analyses of slabs, beams, columns and footings are given. Secondly, modifications made to adjust the optimum methods discussed in chapter 4 for the data collected are given. Thirdly, details of cost savings analyses of the four elements of 22 buildings are given. Fourthly, details of tests of cost savings for designers' expectations discussed in chapter 5 are given. Finally, changes demanded by optimum methods are given by comparing optimum and design solutions.
7.2 DATA FOR COST SAVING ANALYSES

Design data extracted from structural drawings and cost data obtained from priced bills of quantities were used for this analyses. Details of the data collected were given in chapter 6. A total of 22 building data for slabs, beams and columns and 12 building data for independent footings was used for the analyses. Details of data used for the analyses for slabs, beams, columns and independent footings are given separately.

7.2.1 Slabs

For each building the most common two slab panels in the first floor were considered. Table 7.1 gives an example of a data set used in a building. Cost data was collected from priced bills of quantities and design data was collected from structural drawings of buildings (see chapter 6).

Table 7.1 Data for cost saving analysis of slabs

<table>
<thead>
<tr>
<th>Slab no</th>
<th>lx (m)</th>
<th>ly (m)</th>
<th>h (mm)</th>
<th>Ns</th>
<th>NI</th>
<th>NP</th>
<th>TNP</th>
<th>qk (kN/m2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.9</td>
<td>5.5</td>
<td>125</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>14</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>5.5</td>
<td>125</td>
<td>1</td>
<td>1</td>
<td>12</td>
<td>14</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Details of slab panels

Where,
- qk - imposed load used or provided according to the type of building.
- NP - number of panels in each category of slab (NP1 - slab1, NP2 - slab2)
- TNP - total number of panels considered (NP = NP1 + NP2).
- lx, ly, Asx, Asy etc. as defined in section 4.2.
7.2.2 Beams

An example of data used for the cost saving analysis in beams are given in Table 7.2. For each building the most common longitudinal and cross beams were selected.

Table 7.2 Data for beam cost saving analysis

<table>
<thead>
<tr>
<th>Project name : MTC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>fcu = 20N/mm²</td>
</tr>
<tr>
<td>fy = 410N/mm²</td>
</tr>
<tr>
<td>Cc = 1700.0 Rs/m³</td>
</tr>
<tr>
<td>Cf = 141.0 Rs/m²</td>
</tr>
<tr>
<td>Cs = 19.3 Rs/kg</td>
</tr>
<tr>
<td>Beam cost = Rs 2 633 270</td>
</tr>
<tr>
<td>Total building cost = Rs 22 618 301.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam no</th>
<th>D (mm)</th>
<th>bw (mm)</th>
<th>b (mm)</th>
<th>hf (mm)</th>
<th>L (m)</th>
<th>BL (m)</th>
<th>TBL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600</td>
<td>250</td>
<td>600</td>
<td>160</td>
<td>5.0</td>
<td>240</td>
<td>580</td>
</tr>
<tr>
<td>2</td>
<td>750</td>
<td>450</td>
<td>1850</td>
<td>160</td>
<td>10.0</td>
<td>340</td>
<td>580</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam no</th>
<th>As1 (mm²)</th>
<th>As2 (mm²)</th>
<th>As3 (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>402</td>
<td>402</td>
<td>402</td>
</tr>
<tr>
<td>2</td>
<td>3435</td>
<td>3926</td>
<td>3926</td>
</tr>
</tbody>
</table>

where,

BL - length of longitudinal or cross beams
TBL - total length of beams considered
D, bw, b, As1, As2 etc. as defined in section 4.3.

7.2.3 Columns

An example of data used for the cost saving analysis in columns are given in Table 7.3. For each project the most common two columns were selected.
Table 7.3 Data for column cost saving analysis

<table>
<thead>
<tr>
<th>Project name : MTC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>fcu = 20N/mm²</td>
</tr>
<tr>
<td>fy = 410N/mm²</td>
</tr>
<tr>
<td>Cc = 1700.0 Rs/m³</td>
</tr>
<tr>
<td>Cf = 141.0 Rs/m²</td>
</tr>
<tr>
<td>Cs = 19.3 Rs/kg</td>
</tr>
<tr>
<td>Column cost = Rs 1,376,833</td>
</tr>
<tr>
<td>Total building cost = Rs 22,618,301.15</td>
</tr>
</tbody>
</table>

Details of columns

<table>
<thead>
<tr>
<th>Column no</th>
<th>b (mm)</th>
<th>h (mm)</th>
<th>H (m)</th>
<th>N</th>
<th>NC</th>
<th>TNC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450</td>
<td>450</td>
<td>3.3</td>
<td>1458</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
<td>450</td>
<td>3.3</td>
<td>801</td>
<td>12</td>
<td>21</td>
</tr>
</tbody>
</table>

Details of reinforcements

<table>
<thead>
<tr>
<th>Column no</th>
<th>As (mm²)</th>
<th>Asx (mm²)</th>
<th>Asy (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5880</td>
<td>3920</td>
<td>3920</td>
</tr>
<tr>
<td>2</td>
<td>7840</td>
<td>4900</td>
<td>4900</td>
</tr>
</tbody>
</table>

where,

NC - number of columns in each category
TNC - total number of columns considered
As - total reinforcement area provided
Asx - reinforcement area in X-X axis bending
Asy - reinforcement area in Y-Y axis bending
H, b, h etc. as defined in section 4.4.

7.2.4 Independent footings

An example of data used for the cost saving analysis in independent footings are given in Table 7.4. For each project the most common two independent footings were selected.
Table 7.4 Data for independent footing cost saving analysis

| Project name : BCN |
|-------------------|-----------------|
| $f_{cu} = 20N/mm^2$ | $f_y = 410N/mm^2$ |
| $C_c = 506.0$ Rs/m$^3$ | $C_f = 46.8$ Rs/m$^2$ |
| Foundation cost = Rs $156469.5$ | Total building cost = Rs $5 584 223.1$ |

Details of independent footings

<table>
<thead>
<tr>
<th>Footing no</th>
<th>$l_x$ (m)</th>
<th>$l_y$ (m)</th>
<th>$h$ (mm)</th>
<th>$b_c$ (mm)</th>
<th>$h_c$ (mm)</th>
<th>$N$ (kN)</th>
<th>NF</th>
<th>TNF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.05</td>
<td>3.05</td>
<td>600</td>
<td>300</td>
<td>375</td>
<td>2065</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>2.44</td>
<td>2.44</td>
<td>450</td>
<td>300</td>
<td>375</td>
<td>1152</td>
<td>12</td>
<td>30</td>
</tr>
</tbody>
</table>

Details of reinforcements

<table>
<thead>
<tr>
<th>Footing no</th>
<th>$A_{sx}$ (mm$^2$/m)</th>
<th>$A_{sy}$ (mm$^2$/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1436</td>
<td>1436</td>
</tr>
<tr>
<td>2</td>
<td>1131</td>
<td>1131</td>
</tr>
</tbody>
</table>

where,

NF - number of footing in each category
TNF - total number of footings

$A_{sx}$, $A_{sy}$, $l_x$, $l_y$, $h$ etc. as defined in section 4.5

7.3 MODIFIED OPTIMUM METHODS

Optimum methods developed for slabs, beams, columns and independent footings discussed in chapter 4 were used to find the cost savings of above elements. However, modifications were required for the developed computer programs to be suited for the data collected in this research. Details of the modifications made are given below. Facility to calculate the cost savings of optimum methods compared to that of used design solutions are also added to the optimum method Turbo Pascal computer programs.

7.3.1 Design load for slabs

The optimum method discussed in section 4.2 for reinforced concrete in situ slabs need the design load $'n'$ $(n = 1.4g_k + 1.6q_k)$ to find the optimum design solution. Except for two projects where full design information was collected, for most other projects it was not possible to collect the design load used. Therefore design load for those
projects was calculated by using the imposed load \( q_k \) given in drawings or from BS6399:Part 1 (depending on building type) and assuming the dead loads as given below. These values were decided after examining the dead loads used in the two projects where full design calculations were obtained. The values used for dead loads due to partitions and finishes are higher than the values used in normal building designs (see Table 7.5). Therefore, optimum solutions were capable of carrying more load than designed, thus real cost savings possible can be higher and will not be less than predicted in this research.

\[
\begin{align*}
\text{Partitions} &= 1.0 \text{ kN/m}^2 \\
\text{Finishes} &= 1.21 \text{ kN/m}^2 \text{ (assumed 25mm cement sand rendering & 15mm soffit plaster)} \\
\text{Self weight} &= \frac{h}{1000} \times 23.6 \text{ kN/m}^2 \text{ (concrete density = 23.6 kN/m}^3) \\
\text{Total dead load}(g_k) &= 2.21 + \frac{h}{1000} \times 23.6 \text{ kN/m}^2 \\
\text{Design load (n)} &= 1.4(2.21 + \frac{h}{1000} \times 23.6) + 1.6q_k
\end{align*}
\]

Example
- \( q_k = 2.5 \text{ kN/m}^2 \) for general offices
- \( h = 125 \text{mm} \)
- \( n = 11.2 \text{ kN/m}^2 \)

7.3.2 Bending moments in beams

To use the optimum methods developed in section 4.3 for beams, bending moment values of sections 1-1, 2-2 and 3-3 (according to Figure 4.10) are required. But it was not possible to collect the bending moment values for the above sections. Therefore bending moments were calculated using provided reinforcement areas from the procedure shown in Figure 7.1. The procedure shown in Figure 7.1 was repeated for the sections 1-1, 2-2 and 3-3 separately. The Turbo Pascal routine was added to the optimum design program developed in section 4.3 to calculate the bending moments. This procedure always calculates equal or higher bending moments than used in designs (see Table 7.5). Therefore optimum solutions are valid for higher moments than present in the building. This avoided over estimation of cost savings through optimum methods developed.
7.3.3 Axial load and bending moments in columns

To use the optimum method developed in section 4.4 for columns, axial load and the bending moments on axis X-X and Y-Y are required. Axial loads and bending moments of columns were not collected (see data collection chapter 6). Therefore axial load and bending moments were calculated as given below.

7.3.3.1 Axial load of columns

Axial load on column = \( \Sigma (\text{load from slabs above} + \text{loads from beams} + \text{self weight of column} + \text{loads from the roof}) \)

load from slabs = (load carrying area of the column) \( \times \) (design load)

Design load calculated for slabs were used to calculate the loads from slab and beams, and self weight of the column was calculated using the concrete density and section parameters. Loads from the roof were calculated as in slabs BS6399:Part 1.
START

Read \( N, b, h, f_{cu}, f_y, A_{xd}, A_{yd} \)

\[ M_{ux} = 5 \text{kNm} \]

Design the column using the procedure given in Appendix C.3 and provide reinforcements (\( A_{xp} \)).

Is \( A_{xd} \leq A_{xp} \) ?

Yes: \( M_{uy} = 5 \text{kNm} \)

Design the column using the procedure given in Appendix C.3 and provide reinforcements (\( A_{xyp} \)).

Is \( A_{yd} \leq A_{xyp} \) ?

Yes: Get \( \beta \) from Table 3.24 of BS8110

\[ M_x = M_{ux} + \frac{\beta(h - 42.5)}{(b - 42.5)} M_{ux} \]
\[ M_y = M_{uy} + \frac{\beta(b - 42.5)}{(h - 42.5)} M_{uy} \]

Record \( M_x \) and \( M_y \)

STOP

Figure 7.2 Procedure to calculate design bending moments in columns
7.3.3.2 Bending moments of columns

Bending moments on axis X-X and Y-Y of columns were calculated separately using the procedure given in Figure 7.2. Therefore, it is possible for values of axial forces and bending moments to be different from values used in designs. However, validation test held using values of two projects showed satisfactorily close results (see Table 7.5).

7.3.4 Axial load and bending moments in independent footings

Similar to that of columns axial loads and bending moments of independent footing foundations was not possible to collect in the data collection (chapter 6). Axial load on independent footings were calculated from the same procedure given for columns. Bending moments were calculated from the procedure shown in Figure 7.3. This procedure was repeated for axes X-X and Y-Y separately.

![Figure 7.3 Procedure to calculate design bending moments in an independent footing section](image

START

Read Asd, h, fcu, Lx, Ly, N

BM = 5 kNm

Design the section for the procedure given in appendix C.4 (according to BS8110) and provide reinforcements (Asp).

Is Asd ≤ Asp

No

BM = BM + 2

Yes

Record the value of BM

STOP

Figure 7.3 Procedure to calculate design bending moments in an independent footing section.
Table 7.5 Analysis between calculated and design values for loads and bending moments

<table>
<thead>
<tr>
<th>SLABS</th>
<th>Design load used k/Nm²</th>
<th>Calculated load kN/m²</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project 1 Slab 1</td>
<td>10.37</td>
<td>10.43</td>
<td>-0.58</td>
</tr>
<tr>
<td>Slab 2</td>
<td>10.37</td>
<td>10.43</td>
<td>-0.58</td>
</tr>
<tr>
<td>Project 2 Slab 1</td>
<td>10.72</td>
<td>11.19</td>
<td>-4.38</td>
</tr>
<tr>
<td>Slab 2</td>
<td>10.72</td>
<td>11.19</td>
<td>-4.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BEAMS</th>
<th>Designed moment (kNm)</th>
<th>Calculated moment (kNm)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1 section 1-1</td>
<td>429.0</td>
<td>431.0</td>
<td>-0.46</td>
</tr>
<tr>
<td>Beam 1 section 2-2</td>
<td>444.4</td>
<td>485.0</td>
<td>-9.14</td>
</tr>
<tr>
<td>Beam 1 section 3-3</td>
<td>88.3</td>
<td>195.0</td>
<td>-120.84</td>
</tr>
<tr>
<td>Beam 2 section 1-1</td>
<td>180.0</td>
<td>197.0</td>
<td>-9.44</td>
</tr>
<tr>
<td>Beam 2 section 2-2</td>
<td>194.3</td>
<td>245.0</td>
<td>-26.09</td>
</tr>
<tr>
<td>Beam 2 section 3-3</td>
<td>159.4</td>
<td>165.0</td>
<td>-3.51</td>
</tr>
<tr>
<td>Beam 3 section 1-1</td>
<td>164.3</td>
<td>181.0</td>
<td>-10.16</td>
</tr>
<tr>
<td>Beam 3 section 2-2</td>
<td>257.2</td>
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<td>-14.70</td>
</tr>
<tr>
<td>Beam 4 section 1-1</td>
<td>236.0</td>
<td>241.0</td>
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</tr>
<tr>
<td>Beam 4 section 2-2</td>
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<td>225.0</td>
<td>-10.84</td>
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</table>

<table>
<thead>
<tr>
<th>COLUMNS</th>
<th>Designed load kN</th>
<th>Calculated load kN</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>618</td>
<td>640</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
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<td></td>
<td>304</td>
<td>365</td>
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<tr>
<td>Column 2</td>
<td>659</td>
<td>630</td>
<td>4.40</td>
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<tr>
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<td></td>
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<td>95</td>
</tr>
<tr>
<td></td>
<td>107</td>
<td>213</td>
<td>-99.06</td>
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<tr>
<td>Column 3</td>
<td>547</td>
<td>540</td>
<td>1.28</td>
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<td></td>
<td></td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>107</td>
<td>213</td>
<td>-99.06</td>
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<tr>
<td>Column 4</td>
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<td>-5.83</td>
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<td>110</td>
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<td></td>
<td></td>
<td></td>
<td>-37.50</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>INDEPENDENT FOOTINGS</th>
<th>Designed load kN</th>
<th>Calculated load kN</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footing 1</td>
<td>1426</td>
<td>1560</td>
<td>-9.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>457</td>
<td>505</td>
<td>-10.50</td>
</tr>
<tr>
<td>Footing 2</td>
<td>1500</td>
<td>1430</td>
<td>4.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
7.3.5 Validation of loads, axial loads and bending moments

To validate the slab design loads, bending moments for beams, axial and bending moments in columns and footings, comparison was made between values used in actual designs (from two projects) and values calculated from procedures discussed above. Table 7.5 shows the results of this analysis. Results proved that satisfactorily close values from the procedure used, thus validity of those to calculate design loads, bending moments and axial loads.

7.4 COST SAVINGS IN REINFORCED CONCRETE DESIGNS

Cost savings of 22 buildings were studied. This revealed that mean cost savings of 10.10% for slabs, 7.78% for beams, 7.33% for columns and 8.43% for independent footings from the elemental cost. Further it was discovered that cost savings with respect to total cost of building of 1.13% for slabs, 0.70% for beams, 0.46% for columns and 0.41% for independent footings. Average total cost savings of total building cost were 2.22% excluding footings and 2.91% with footings.

Firstly, details of principle of cost saving calculations are given. Secondly details of elemental cost savings of the buildings studied are given. Thirdly cost savings with respect to total building cost of the 22 building studied are given.

7.4.1 Principle of cost saving calculations

Cost saving of an element was calculated as the cost difference between the designed solution and the cost of the optimum solution. For each element the most common two types of members in a building were considered. In other words, the most common two slab panels for slabs, the most common longitudinal and cross beams for beams, the most common two types of columns for columns and the most common two types of footings for independent footing foundations. Weighted cost savings for the elements were calculated as the total of the weighted cost savings of the two members considered.
Percentage of cost savings = \[
\frac{\text{cost of design solution} - \text{cost of optimum solution}}{\text{cost of design solution}} \times 100
\] \hspace{1cm} (7.3)

Weighted cost saving was calculated as given below.

- \(CS_i\) - cost savings of \(i^{th}\) member
- \(NM_i\) - number of members of \(i^{th}\) member (for slabs, columns and independent footings) or total length of \(i^{th}\) member (for beams)
- \(TNM\) - total number of members (for slabs, columns and footings) or total length of members
- \(n\) - number of members considered

\[
\text{weighted cost saving} = \sum_{i=1}^{n} \frac{CS_i \times NM_i}{TNM}
\] \hspace{1cm} (7.4)

Cost savings through optimum design methods with respect to total building cost was calculated from the equations given below.

\[
\text{cost savings with respect to total cost of building} = \frac{(\text{weighted cost saving}) \times (\text{total cost of element})}{\text{total cost of building}}
\] \hspace{1cm} (7.5)

### 7.4.2 Elemental cost savings

Elemental cost savings with respect to total elemental cost of 22 buildings for slabs, beams and columns and the cost saving of 12 buildings for independent footings are given in Table 7.6.

In cost saving calculations, to find optimum solutions in a project single price rates for concrete, steel and formwork were used. To use single price rates to give true optimums variations in \(C_c/C_s\) need to be less than \(\pm20\%\) (see chapter 4). Therefore maximum, minimum and variation percentage of \(C_c/C_s\) ration were calculated as given in Table 7.6. The variations observed for all 22 projects were less than \(\pm20\%\). Therefore, the use of single price rates for concrete, steel and formwork to find optimum solutions is justified.
<table>
<thead>
<tr>
<th>Project</th>
<th>Percentage of elemental cost saving</th>
<th>Cc/Cs ratio</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slabs</td>
<td>Beams</td>
<td>Columns</td>
<td>Footings</td>
</tr>
<tr>
<td>CSM</td>
<td>1.81</td>
<td>12.03</td>
<td>11.10</td>
<td>-</td>
</tr>
<tr>
<td>GPPS</td>
<td>12.84</td>
<td>3.49</td>
<td>1.01</td>
<td>14.68</td>
</tr>
<tr>
<td>MTC2</td>
<td>5.08</td>
<td>11.62</td>
<td>14.49</td>
<td>-</td>
</tr>
<tr>
<td>BCN</td>
<td>10.99</td>
<td>3.90</td>
<td>31.44</td>
<td>7.44</td>
</tr>
<tr>
<td>NLDB</td>
<td>16.78</td>
<td>9.89</td>
<td>3.03</td>
<td>-</td>
</tr>
<tr>
<td>MHS</td>
<td>10.07</td>
<td>11.32</td>
<td>8.77</td>
<td>-</td>
</tr>
<tr>
<td>SLA</td>
<td>11.72</td>
<td>19.91</td>
<td>0.01</td>
<td>10.41</td>
</tr>
<tr>
<td>BTTP</td>
<td>1.28</td>
<td>9.75</td>
<td>6.01</td>
<td>1.00</td>
</tr>
<tr>
<td>MTT</td>
<td>7.41</td>
<td>5.81</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
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<td>6.24</td>
<td>2.09</td>
<td>6.47</td>
</tr>
<tr>
<td>MTC1</td>
<td>3.59</td>
<td>9.81</td>
<td>11.92</td>
<td>-</td>
</tr>
<tr>
<td>ASIR</td>
<td>12.62</td>
<td>1.73</td>
<td>5.66</td>
<td>-</td>
</tr>
<tr>
<td>CSMS</td>
<td>12.26</td>
<td>3.00</td>
<td>9.16</td>
<td>-</td>
</tr>
<tr>
<td>DPH</td>
<td>14.92</td>
<td>10.66</td>
<td>10.10</td>
<td>10.89</td>
</tr>
<tr>
<td>DMK</td>
<td>4.62</td>
<td>2.98</td>
<td>11.05</td>
<td>2.25</td>
</tr>
<tr>
<td>PCB</td>
<td>0.00</td>
<td>7.16</td>
<td>1.01</td>
<td>-</td>
</tr>
<tr>
<td>ACBA</td>
<td>1.20</td>
<td>10.33</td>
<td>13.20</td>
<td>-</td>
</tr>
<tr>
<td>DQB</td>
<td>20.69</td>
<td>6.27</td>
<td>2.01</td>
<td>21.61</td>
</tr>
<tr>
<td>DME</td>
<td>27.12</td>
<td>3.42</td>
<td>0.03</td>
<td>15.48</td>
</tr>
<tr>
<td>DWH</td>
<td>8.19</td>
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<td>4.56</td>
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<tr>
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<td>1.89</td>
<td>0.00</td>
<td>5.11</td>
</tr>
<tr>
<td>Mean</td>
<td>10.10</td>
<td>7.78</td>
<td>7.33</td>
<td>8.43</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>6.86</td>
<td>4.94</td>
<td>7.46</td>
<td>6.47</td>
</tr>
</tbody>
</table>
7.4.3 Cost savings with respect to total building cost

Total cost savings with respect to total building cost are given in Table 7.7.

Table 7.7 Cost savings with respect to total building cost

<table>
<thead>
<tr>
<th>Project</th>
<th>Total building cost saving %</th>
<th>Total cost saving %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slabs</td>
<td>Beams</td>
</tr>
<tr>
<td>CSM</td>
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</tr>
<tr>
<td>GPPS</td>
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<td>0.63</td>
</tr>
<tr>
<td>MTC2</td>
<td>0.60</td>
<td>1.44</td>
</tr>
<tr>
<td>BCN</td>
<td>1.23</td>
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</tr>
<tr>
<td>NLDB</td>
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<td>MTT</td>
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<td>0.42</td>
</tr>
<tr>
<td>ASIR</td>
<td>1.19</td>
<td>0.15</td>
</tr>
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<td>Mean</td>
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</tr>
<tr>
<td>Standard deviation</td>
<td>0.80</td>
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</tr>
</tbody>
</table>
7.5 DESIGNERS’ EXPECTATIONS AND ACTUAL COST SAVINGS OF THE OPTIMUM METHODS

Through the interviews discussed in chapter 5 it was discovered that the practical designers expect approximately more than 10% elemental cost savings from optimum methods. Six structural engineers and seven architects interviewed considered that if the cost savings are more than 10% they will consider the optimum methods for implementation. Further they said that if the cost savings are more than 1% from the total building cost they will consider optimum methods for implementation. Therefore it is important to check the cost savings given in Table 7.6 and Table 7.7 for the above requirements. Furthermore, cost savings need to be checked from two different angles as highlighted in the two questions given below.

1. What are the cost benefits through optimum methods to the building construction industry as a whole?

2. What are the cost benefits through optimum methods for a given project?

It was discovered that elemental cost savings of slabs, beams, columns and footings of (in the whole construction industry) total building designed are more than 10% (with 95% confidence). Further it was discovered that total of 2.22% for slabs, beams and columns and 2.91% for slabs, beams, columns and footings of the total cost building can be saved using optimum methods. This cost savings are equal to a minimum of 34% and maximum of 65% of the total design cost (designed fee paid by clients). Probabilities in a given project for elemental cost saving exceeding 10% are 0.51 for slabs, 0.33 for beams, 0.36 for columns and 0.41 for independent footings. There is more than 0.95 probability for total cost saving to exceed 1% and more than 0.75 probability to exceed to 2% of the total cost of a given project.

Firstly, probability distributions of cost savings are given. Secondly, details of the analyses of cost savings in the total buildings designed are given. Thirdly, cost savings were compared with the design fees and charges. Finally, details of the forecasting probabilities on cost savings for a given project are given.

7.5.1 Distribution patterns of cost savings

Any prediction on a random variable depends on its frequency distribution pattern and therefore it is important to identify the correct frequency distribution pattern. Frequency distribution pattern of cost saving of 44 (2X22 projects) slabs, beams columns and 24
(2X12 projects) independent footings showed a normal probability distribution pattern. This conclusion was made after examining the results of Chi-square test with 5% risk factor. These tests were held using Statgraphics 2.1 software in IBM system 2 model 30 personal computer. Corresponding probability distributions for elemental cost savings of slabs, beams, columns and independent footings are given in Figure 7.4 to Figure 7.7.

![Normal probability distribution curves for slab cost savings](image)

**Figure 7.4** Normal probability distribution curves for slab cost savings

![Normal probability distribution curves for beam cost savings](image)

**Figure 7.5** Normal probability distribution curves for beam cost savings
7.5.2 Testing of Elemental cost savings

Through the interviews with designers it was discovered that designers expect at least 10% cost saving from optimum methods (chapter 5). Therefore it is necessary to test whether the average elemental cost savings of the total buildings designed ($\mu$) is more than 10%. Details of this test using statistical theories are given below. Two alternatives of the test (test hypothesis) is symbolically as follows:

$$H_0 : \mu \geq 10.00\% \quad (\mu \text{ is more than } 10\%)$$
$$H_1 : \mu < 10.00\% \quad (\mu \text{ is less than } 10\%)$$

In statistics this type of test is known as 'One-Sided Lower-tail Alternatives' and further details are given by Neter, Wasserman and Whitmore (1988) or any other standard statistical book. Figure 7.8 shows this test for 5% risk ($\alpha = 0.05$) for the sample mean distribution.
Standard variable $Z$ in statistics is defined as

$$Z = \frac{\bar{X} - \mu_0}{S(\bar{X})}$$  \hspace{1cm} \text{... 7.6}$$

where,

- $\bar{X}$ - sample mean (Eg. for slabs $\bar{X} = 10.10$)
- $S(\bar{X})$ - standard deviation of $\frac{\bar{X}}{\sqrt{\text{sample size}}}$
  (Eg. for slabs $S(\bar{X}) = 6.86/\sqrt{22}$)

The sampling distribution of $\bar{X}$ and of its standardized equivalent $z$, are approximately normal (Neter, Wasserman and Whitmore 1988). As the lower-tail area of the sampling distribution in Figure 7.8 is to be 0.05, the action limit 'A' must correspond to the 5th percentile of the standard normal distribution, that is $z(0.05) = -1.645$ on the $z$ scale. The appropriate decision rule for the test hypothesis is therefore as follows:

- If $z \geq -1.645$, conclude $H_0$
- If $z < -1.645$, conclude $H_1$

For slabs,

$$\bar{X} = 10.10$$

$$S(\bar{X}) = \frac{6.86}{\sqrt{22}} = 1.463$$

$$Z = \frac{(10.10 - 10.0)}{1.463} = 0.068 > -1.645 \text{ Hence } H_0 \text{ is valid.}$$

Similar tests were held for beams, columns and independent footings and details are given in Table 7.8. It is clear from the Table 7.8 that except for beams elemental cost...
savings for the other elements elemental cost savings are more than 10% with 5% risk factor. Therefore elemental cost savings in slabs, columns and independent footings satisfy the designers requirement (with 95% confidence). Further analysis revealed that for beams Ho is valid for average cost savings of 9.5% which is very close to the 10% requirement. Therefore as conclusion it can be stated that cost savings of slabs, beams, columns and independent footings through optimum methods satisfy designers requirements.

<table>
<thead>
<tr>
<th>Element</th>
<th>$\bar{X}$</th>
<th>$S{\bar{X}}$</th>
<th>$\frac{(\bar{X} - \mu_0)}{S{\bar{X}}}$</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab</td>
<td>10.10</td>
<td>1.46</td>
<td>0.068</td>
<td>Ho</td>
</tr>
<tr>
<td>Beam</td>
<td>7.78</td>
<td>1.05</td>
<td>-2.106</td>
<td>H1</td>
</tr>
<tr>
<td>Column</td>
<td>7.33</td>
<td>1.67</td>
<td>-1.601</td>
<td>Ho</td>
</tr>
<tr>
<td>Footing</td>
<td>8.43</td>
<td>1.87</td>
<td>-0.842</td>
<td>Ho</td>
</tr>
</tbody>
</table>

7.5.3 Testing of total cost savings

It is necessary to test whether average elemental cost savings compare to the total building cost is more than 1% (designers requirement, chapter 5). Similar to 7.5.2 tests were held according to statistical theories and results are given in Table 7.9. Two tests (hypothesis) symbolically are as follows:

$Ho : \mu \geq 1.00\%$

$H1 : \mu < 1.00\%$

It is clear from Table 7.9 that except for slabs for other 3 elements the average cost savings of the buildings designed is less than 1.00% (with 5% risk). Therefore except for slabs, other elements do not satisfy designers requirements of 1.00% cost savings compared to total building cost. In this situation it is important to calculate the maximum mean total cost savings for which Ho is valid. This was calculated from the method given below.

For Ho to be valid:

$$\frac{(\bar{X} - \mu_0)}{S\{\bar{X}\}} \geq -1.645$$

$$\mu \leq \bar{X} + 1.645S\{\bar{X}\}$$
This gives following values for maximum mean total cost savings where Ho is valid. Therefore it is building construction industry's responsibility to accept or to reject whether the given cost savings are satisfactory or not.

<table>
<thead>
<tr>
<th>Element</th>
<th>Maximum mean cost saving % for Ho is valid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slabs</td>
<td>1.41</td>
</tr>
<tr>
<td>Beams</td>
<td>0.86</td>
</tr>
<tr>
<td>Columns</td>
<td>0.67</td>
</tr>
<tr>
<td>Independent footings</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Table 7.9 Test for total cost savings for designers expectations

<table>
<thead>
<tr>
<th>Element</th>
<th>$\bar{X}$</th>
<th>$S(\bar{X})$</th>
<th>$((\bar{X} - \mu)/S{\bar{X}}$</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab</td>
<td>1.13</td>
<td>0.171</td>
<td>0.764</td>
<td>Ho</td>
</tr>
<tr>
<td>Beam</td>
<td>0.70</td>
<td>0.100</td>
<td>-2.992</td>
<td>H1</td>
</tr>
<tr>
<td>Column</td>
<td>0.46</td>
<td>0.127</td>
<td>-4.235</td>
<td>H1</td>
</tr>
<tr>
<td>Footing</td>
<td>0.41</td>
<td>0.124</td>
<td>-4.753</td>
<td>H1</td>
</tr>
</tbody>
</table>

7.5.4 Total building cost savings

Total building cost savings mean values for frame and floors (Slabs + Beams + Columns) and total structure (slabs + beams + columns + footings) were given in Table 7.7.

<table>
<thead>
<tr>
<th></th>
<th>Frame and floors</th>
<th>Frame, floors and footings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.22%</td>
<td>2.91%</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.97%</td>
<td>1.12%</td>
</tr>
</tbody>
</table>

Maximum mean cost saving for which Ho is valid, was calculated and the result is as follows:

<table>
<thead>
<tr>
<th></th>
<th>Frame and floors</th>
<th>Frame, floors and footings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum mean cost saving for which Ho is valid</td>
<td>2.56%</td>
<td>3.44%</td>
</tr>
</tbody>
</table>

Table 7.10 shows the recommended total design fee (architectural and structural) for new buildings and possible cost savings through optimum methods on structural design at the detail design stage. The design fees given in Table 7.10 were obtained from 'Conditions of engagement and recommended scale of professional fees and charges' by Sri Lanka Institute of Architects (SLIA 1984). Table 7.10 shows that between 45%
to 65% equivalent to total design cost can be saved in a reinforced concrete frame building project by adopting optimum design methods for the design reinforced concrete elements. This proved that the time has come for the building construction industry to consider seriously improvement in cost effectiveness in reinforced concrete designs.

Table 7.10 Design fees and cost savings in buildings

<table>
<thead>
<tr>
<th>Total construction cost in millions</th>
<th>Total percentage of design fee</th>
<th>Total percentage cost saving from total cost</th>
<th>Total percentage cost saving from total design fee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Floors</td>
<td>Frame Floors Floors Foundation</td>
<td>Frame Floors Floors Foundation</td>
<td>Frame Floors Floors Foundation</td>
</tr>
<tr>
<td>Rs 1.5m to 10m</td>
<td>6.5</td>
<td>2.22</td>
<td>2.91</td>
</tr>
<tr>
<td>Rs 10m to 100m</td>
<td>5.5</td>
<td>2.22</td>
<td>2.91</td>
</tr>
<tr>
<td>Rs 100m to 300m</td>
<td>4.5</td>
<td>2.22</td>
<td>2.91</td>
</tr>
<tr>
<td>over Rs 300m</td>
<td>Negotiate fee</td>
<td>2.22</td>
<td>2.91</td>
</tr>
</tbody>
</table>

7.5.5 Probabilities of cost savings in a given project

Through the interviews with six structural engineers, discussed in chapter 5 it was discovered that engineers expect at least 10% cost savings from optimum methods. In this aspect a structural engineer may be interested to know the probability of cost saving exceeding 10% for a given project or the project he is dealing with now. This can be predicted by using figures 7.4, 7.5, 7.6 and 7.7. For example, Figure 7.4(a) shows the probability density function for slab cost saving and area under the curve between 5% and α (see Figure 7.9) gives the probability of cost saving exceeding 5%. Similar tests were held for other elements also and Table 7.11 gives the results. Table 7.12 shows probabilities for total building cost savings.

Figure 7.10 shows how the probability vary with elemental cost savings in the region of 0% to 20%. This shows that probability of cost saving from the elemental cost decrease gradually(approximately linear) in the region 0% to 20% cost savings. However, probability of cost saving from the total building cost decrease very rapidly in the region of 0.00% to 1.50% for beams, columns and independent footings and for slabs decreases approximately linearly in the region of 0.00% to 2.5%. Figure 7.11 shows how probabilities vary with cost savings form the total building cost of all elements together. This shows that slabs, beams, columns and footings together shows
more than 0.80 probability up to 2.00% cost saving and thereafter probability decreases gradually up to 4.5% cost saving. For slabs, beams and columns together shows more than 0.90 probability up to 1.00% cost saving and thereafter probability decreases gradually to zero up to 3.5% cost saving.

Table 7.11 Probability of elemental cost saving exceeding given values

<table>
<thead>
<tr>
<th>Element</th>
<th>Probability of exceeding the given value</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elemental cost saving</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>0.5%</td>
<td>0.75%</td>
</tr>
<tr>
<td>Slab</td>
<td>0.77</td>
<td>0.65</td>
<td>0.51</td>
<td></td>
<td>0.79</td>
<td>0.68</td>
</tr>
<tr>
<td>Beam</td>
<td>0.71</td>
<td>0.52</td>
<td>0.33</td>
<td></td>
<td>0.66</td>
<td>0.54</td>
</tr>
<tr>
<td>Column</td>
<td>0.62</td>
<td>0.49</td>
<td>0.36</td>
<td></td>
<td>0.47</td>
<td>0.31</td>
</tr>
<tr>
<td>Independent</td>
<td>0.70</td>
<td>0.56</td>
<td>0.41</td>
<td></td>
<td>0.42</td>
<td>0.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Probability of total building cost saving exceeding given value</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab+Beam+Column</td>
<td>Probability of total cost saving exceeding given value</td>
<td>0.5%</td>
<td>0.75%</td>
<td>1.00%</td>
<td>1.25%</td>
<td>1.50%</td>
</tr>
<tr>
<td>Slab+Beam+Column+Footing</td>
<td>Probability of total cost saving exceeding given value</td>
<td>0.96</td>
<td>0.93</td>
<td>0.90</td>
<td>0.85</td>
<td>0.77</td>
</tr>
<tr>
<td>Footing</td>
<td>0.99</td>
<td>0.97</td>
<td>0.96</td>
<td>0.94</td>
<td>0.90</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Figure 7.9 Probability of cost saving exceeding 5% for slabs
(a) Elemental cost saving

(b) Total cost savings of elements

Figure 7.10 Elemental cost saving vs Probability
7.6 COMPARISON OF OPTIMUM DESIGN SOLUTIONS AND DESIGNERS' SOLUTIONS

7.6.1 Section dimensions

A study was held to compare dimensions and reinforcement ratios of elements from optimum methods and designers' solutions. This facilitates to study of the design changes demanded by the optimum design methods.

It was observed that for slabs optimum depths are less than designed depths while for beams optimum depths are generally higher than designed depths. Generally, for columns optimum breadths are lesser than designed breadths but optimum depths are higher than designed depths. Optimum depths of independent footings are less than designed depths.
7.6.1.1 Slab thicknesses

Figure 7.12 shows designed depths and optimum depths for slabs studied. It is clear from Figure 7.12 that optimum depths are lesser than the depths used by designers in practice. Study of the failure criteria (deflection, bending or shear) of optimum designs revealed that generally the optimum depth is the lowest depth which satisfies the deflection requirements. This result agreed with findings given by Golding (1988). Figure 7.13 shows the variability of designed depths and optimum depths with shorter spans. Best fitting curves in Figure 7.13 were drawn using Cricket Graph software in Apple Macintosh personal computer.

7.6.1.2 Beam depths

Figure 7.14 shows optimum and design depths for the 44 beams studied. Figure 7.15 shows how the optimum depth and design depth are related to the span and Figure 7.16 shows how optimum depths and designed depths related to bending moments at sections 1-1 (mid span) and 2-2 (at support). Best fitting curves in Figure 7.15 and Figure 7.16 were drawn by Cricket Graph software using Apple Macintosh personal computer. It is clear from Figure 7.14, Figure 7.15 and Figure 7.16 that the optimum depth is generally higher than the designed depth. This means that in order to accommodate optimum depths in reinforced concrete buildings it may be necessary to increase the building floor height. There is no doubt that increase in floor height will increase the total cost of the building. Therefore as Friel (1974) suggested it may be necessary to include a cost factor to take into account of cost increasing the building height.

The additional cost in increasing the building height is complex due to its connection to various elements in a building such as finishes, internal walls and partitions etc. Further additional cost of above elements depend on type of ceiling, type of partitions (some partitions do cover the full floor height), type of finishes etc.
Figure 7.12 Designed and optimum depths of slabs

Figure 7.13 Short span Vs designed and optimum depths
Figure 7.14 Designed and optimum depths of beams

Figure 7.15 Span Vs optimum and designed depths
Figure 7.16 Bending moments Vs depth of beams

7.6.1.3 Column depths and breadths

It is clear from Figure 7.17 that generally optimum breadths are less than designed breadths. But optimum depths of columns are higher than designed depths (Figure 7.18). Ranganthan and Sahasrabuddhe(1985) have observed that optimum breadth is the minimum possible breadth. But according to Figure 7.17 that in some cases the optimum breadths are higher than the designed breadths (next higher breadth in most cases). This is because that Ranganthan and Sahasrabuddhe(1985) have ignored practical limitations such as possible reinforcement areas for columns. But this research has used and provided practical reinforcement areas for any design solution.
Figure 7.17 Optimum and designed column breadths

Figure 7.18 Optimum and designed column depths

7.6.1.4 Footing depths

Figure 7.19 shows optimum and design depths for the 24 independent footings studied. Figure 7.20 shows how the optimum and the designed depths are related to bending moments. It is clear from both Figure 7.19 and Figure 7.20 that optimum depths are lesser than designed depths.
7.6.2 Reinforcement ratios

Study was conducted to compare reinforcement ratios of designed solutions and optimum solutions.

No particular relationship was observed between optimum and designed steel ratios for slabs. For beams, generally optimum steel ratio was less than designed steel ratio and optimum steel ratio at mid span was singly reinforced and at supports for few cases optimum steel ratio was double reinforced. For columns optimum steel ratio was less than designed steel ratio and lies between 0.4% and 2.0%. The optimum steel ratio was generally higher than the designed steel ratio for independent footings.
7.6.2.1 Slabs

Figure 7.21 shows that optimum reinforcement ratio for slabs lies in between 0.2% and 0.5%. Optimum steel ratio did not show a relationship to designed steel ratio and optimum steel ratio was less, higher and equal to designed steel ratio.

![Figure 7.21 Optimum and designed reinforcement ratios of slabs](image)

7.6.2.2 Beams

Figure 7.22 and Figure 7.23 showed that optimum steel ratios are less than steel ratios used by designers. From the equations given in clause 3.4.4.4 of BS8110 it is possible to calculate the maximum singly steel ratio ($0.23 \frac{f_{cu}}{f_y}$) for a given steel and concrete strengths. In the case of 20N/mm² concrete strength ($f_{cu}$) and 410N/mm² steel strength ($f_y$) the maximum singly reinforcement ratio is 1.13%. Figure 7.22 for section 1-1 shows that the optimum steel ratio is always singly reinforced. This result agreed with observations made by Chou (1977). However in Figure 7.23 for section 2-2 (or section 3-3) shows that for more that 9 beams (more than 20% of beams) optimum solution is double reinforced. This is different to the findings given by Chou (1977). Main reason for this is that in this research beam was considered with three sections and Chou (1977)'s method is only for one section.
7.6.2.3 Columns

Figure 7.24 shows that optimum reinforcement ratios are less than designed reinforcement ratios. Further in most cases optimum reinforcement ratio is within the region of 0.40% (minimum according to BS8110) to 2.00%. This observation is agreed with observations (1.0% and 2.0%, 1% is minimum according to CP110) made by Prakash, Agrawala and Singh (1988) and Ranganthan and Sahasrabuddhe (1985).
7.6.2.4 Independent footings

Figure 7.25 shows that for independent footings the optimum steel ratios are higher than the steel ratios used by designers.
7.7 SUMMARY AND CONCLUSIONS

As summary and conclusions the following can be stated.

1. It was discovered that for sample of 22 buildings use of optimum methods has a mean elemental cost savings of 10.10% for slabs, 7.78% for beams, 7.33% for columns and 8.43% for independent footing foundations from the elemental cost.

2. It was discovered the for the 22 buildings studied, use of optimum methods can save a total of 1.13% for slabs, 0.70% for beams, 0.46% for columns and 0.41% for independent foundations from the total building cost.

3. Statistical analysis proved that average elemental cost savings of the total buildings designed is more than 10% from the elemental cost (with 95% confidence) for slabs beams, columns and independent footings. Therefore this disproved the common concept among practising engineers that cost savings through optimum methods are less than 10% of the elemental costs.

4. Statistical analysis proved that cost saving from optimum slab design method is more than 1% of total building cost. Therefore this disproved the common concept among practising engineers that cost savings from optimum methods are less than 1% of the total building cost. However, cost savings of beams, columns and independent footings cost savings were less than 1% of the building cost but they were more than 0.4% of the total building cost.

5. A total of 2.22% of the total cost buildings designed can be saved by use of optimum methods for slabs, beams and columns and a total of 2.91% can be saved from the total cost of buildings designed by use of optimum methods for slabs, beams, columns and independent footing foundations.

6. A minimum of 34% and maximum of 49% of the total design fee can be saved by use of optimum methods for slabs, beams and columns and minimum of 45% and maximum of 65% of the total design fee can be saved by using optimum methods for slabs, beams, columns and independent footings. This proved that efficiency of the detail designs, reinforced concrete element design can be improved significantly. Therefore the time has come for the building construction industry to implement optimum methods into practice.

7. Probabilities of elemental cost savings(of the elemental cost ) exceeding 10% for slabs, beams, columns and independent footings are 0.51, 0.33, 0.36 and 0.41 respectively. Probabilities of total cost savings from the total buildings cost (slabs, beams, columns and footings together) exceeding 1.00%, 2.00% and 3.00% are 0.96 and 0.47 respectively. Therefore according to
statistical theories 2% cost saving of the total building cost can be saved for a given building.

8. Optimum slab thickness is generally less than the slab thickness used by designers. Optimum beam depths are higher than designed beam depths. Optimum column depths are higher than designed column depths. For independent footings optimum depths are less than depths used by designers. Therefore optimum methods of slabs, independent footings and columns can be accommodated into normal building designs without much problems. The depth increases demanded by optimum beam solutions were not significant and according to the opinion of designers (discussed in chapter 5) increases in depths can be accommodated.

9. The sections sizes with respect to span, bending moments etc. showed high randomness. Therefore each designer has chosen section sizes to satisfy deflection, to design as singly reinforced sections etc. Since there is no relationship between optimum solutions with span, bending moments etc. simple graphical design aid cannot produce optimum solutions. Therefore designers need to be helped by a tool such as the computer to produce cost effective designs.
Chapter eight

COST EFFECTIVE DESIGNS USING COST INFORMATION

8.1 INTRODUCTION
8.2 COST EFFECTIVE DESIGNS OF THE STRUCTURE IN PRE DETAIL DESIGN STAGES
8.3 WINDOWS AND FLOOR FINISHES DESIGN
8.4 SUMMARY AND CONCLUSIONS
8.1 INTRODUCTION

Design decisions and related cost information for design of building structure, windows and floor finishes were investigated (architectural designs). Designers' cost information requirements with respect to cost effective designs were identified through interviews with 15 personnel in the building construction industry (chapter 5). The main cost information requirements related to design decisions are cost consequences with changes of design variables. Thus cost consequences for changes in design variables related to the building structure were investigated by a cost model. Changes in cost in windows and floor finishes designs also were investigated.

The cost changes with design variables in building structure depend on building shape, size of the building, selected values of short and long spans etc. The cost changes observed were significant therefore, provision of cost information related to building structure can improve building design decision making with respect to cost. However, majority of architects responses on the cost model was that other criteria such as building functional requirements influence the final decision more than cost. The cost differences for various design options in windows and floor finishes fell below the expectations of the designers. Therefore it is unlikely to improve the current design decision making practice through cost effective methods for window and floor finishes designs.

Details of the cost model developed and application to four historical buildings are given in section 8.2. Details of the analyses of windows and floor finishes are given in section 8.3.

8.2 COST EFFECTIVE DESIGNS OF THE STRUCTURE IN PRE DETAIL DESIGN STAGES

Cost information related design decisions to building structure were investigated in chapter 5. A cost model was developed to provide cost information requirements identified. The cost model was developed based on approximate design procedures according to the recommendations given in BS8110, and cost equations developed in this research (see chapter 4). The developed cost model was applied to four historical buildings and cost variations for design variables were observed.
The cost model proved that cost information related design decisions can be provided. The cost variations with design variables were significant. Therefore use of such information could improve cost effective design decision making procedure. Similar cost models have been developed by others in the past (Moore and Brandon 1979, The Wilderness study Group 1964). However those models did not show elemental and total building cost consequences related to design decisions.

The cost model was developed using the Turbo Pascal computer programming language. IBM system 2 model 30 computer took more than 8 minutes to produce cost information for the developed model.

8.2.1 Cost information requirements in building structure design decisions

Details of design decisions related to the building structure, important factors in the design decision making and the architect's and structural engineer's involvements were discussed in section 5.4.1 of this thesis. Design decisions (see section 5.4.1) related to the building structure are given in Table 8.1.

<table>
<thead>
<tr>
<th>Table 8.1 Design decisions related to the building structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inception and feasible design stages</td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Design decisions</td>
</tr>
<tr>
<td>1. Area of the building</td>
</tr>
<tr>
<td>a. length</td>
</tr>
<tr>
<td>b. breadth</td>
</tr>
<tr>
<td>2. Plan shape</td>
</tr>
<tr>
<td>3. Total building height</td>
</tr>
<tr>
<td>a. number of storeys</td>
</tr>
<tr>
<td>b. storey height(s)</td>
</tr>
<tr>
<td>Important factors for design decisions</td>
</tr>
<tr>
<td>2. Client's needs</td>
</tr>
<tr>
<td>3. Available funds for the buildings</td>
</tr>
<tr>
<td>4. Building regulations</td>
</tr>
</tbody>
</table>
Design decisions in inception and feasible design stages are determined based on cost estimates calculated mainly from cost per unit floor area or elemental cost analysis. Through the interviews discussed in section 5.4.3, it was clear that design decisions in inception and feasible design stages are determined by considering functional requirements, clients needs and building regulations more than the cost. Therefore, there is no significant room for cost data to incorporate in the design decision making process during inception and feasible design stages.

Short span(lx), long span(ly) and column and beam layout are decided during outline and scheme (sketch) design stages. Seven architects and six structural engineers interviewed (discussed in section 5.4.3.2) said that cost information related to design decisions is useful for cost effective designs. Architects said that as they consider functional requirements, cost relationships with the design variables also can be incorporated in final design decisions related to building structure. Furthermore, architects and structural engineers said that the cost is required to be judged in two angles with respect to design decisions. These are:

1. relationship between design decisions and the elemental cost (cost of building structure only);
2. relationship between design decisions and the total building cost.

Therefore a cost model was developed based on approximate reinforced concrete design procedure according to BS8110, to give above mentioned cost requirements. The developed cost model can give relationships between the design decisions and the elemental cost of the building structure and the total cost of the building related to design decisions such as short span(lx) and long span(ly).

8.2.2 A cost model for the design decisions in the building structure

A cost model for the design of reinforced concrete building structure, slabs, beams, columns and independent footing foundations was developed, based on design procedures and cost equations given in chapter 4 of this thesis. The developed cost model is valid for rectangular framed buildings with more than 2 spans in each direction, short span (lx) and long span (ly) as shown in Figure 8.1.

The following parameters were treated as independent design variables in the cost model for reinforced building structure:
1. short span lx;
2. long span ly;
3. total length of building in short span direction Tlx;
4. total length of building in long span direction Tly;
5. unit cost rates of concrete Cc, formwork Cf, and steel Cs;
6. material strengths of concrete fcu, and steel fy;
7. number of storeys NOS.

Therefore, the total cost of the building structure

\[ = f(lx, ly, Tlx, Tly, Cc, Cf, Cs, fcu, fy, NOS) \] ... 8.1

The cost of unit floor area of the building structure

\[ = \frac{\text{Total cost of the building structure}}{Tlx \cdot Tly} \] ... 8.2

Three main steps were taken in the development of the cost model. Firstly, elemental sizes of slabs, beams, columns and independent footings used by designers in historical buildings were studied. Secondly, the general design and costing procedures were developed using design methods and cost equations developed in chapter 4 of this thesis. Finally, the cost model was tested for accuracy to represent reinforced concrete buildings with four historical projects.

\[ \text{Nss} = \frac{Tlx}{lx} \]
\[ \text{Nls} = \frac{Tly}{ly} \]
8.2.2.1 Element sizes

Reinforced concrete element sizes of 22 historical buildings, mainly the depth were investigated with variables such as span in chapter 7. These relationships of elemental sizes were integrated into the cost model of frame and floors. Figure 7.13 shows slab depth variations with short span and Figure 7.15 shows the beam depth with span. Considering these figures, depending on short span and long span element sizes were integrated into the cost model as shown in Table 8.2 and Table 8.3. A minimum thickness of 400mm was used for independent footing foundations in two storey buildings and footing thickness was increased by 50mm for each additional floor.

Table 8.2 Slab and beam sizes for the cost model

<table>
<thead>
<tr>
<th>Span or short span (m)</th>
<th>Slab depth (mm)</th>
<th>Beam depth (mm)</th>
<th>Beam breadth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 3.0</td>
<td>100</td>
<td>225</td>
<td>225</td>
</tr>
<tr>
<td>3.0 to 3.5</td>
<td>115</td>
<td>300</td>
<td>225</td>
</tr>
<tr>
<td>3.5 to 4.0</td>
<td>125</td>
<td>350</td>
<td>225</td>
</tr>
<tr>
<td>4.0 to 4.5</td>
<td>140</td>
<td>400</td>
<td>250</td>
</tr>
<tr>
<td>4.5 to 5.0</td>
<td>150</td>
<td>400</td>
<td>250</td>
</tr>
<tr>
<td>5.0 to 6.0</td>
<td>160</td>
<td>450</td>
<td>250</td>
</tr>
<tr>
<td>6.0 to 7.0</td>
<td>175</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>7.0 to 8.0</td>
<td>200</td>
<td>550</td>
<td>300</td>
</tr>
<tr>
<td>8.0 to 10.0</td>
<td>-</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>10.0 to 12.0</td>
<td>-</td>
<td>700</td>
<td>400</td>
</tr>
<tr>
<td>above 12.0</td>
<td>-</td>
<td>1000</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 8.3 Breadths and depths of columns and independent footings

<table>
<thead>
<tr>
<th>Short span (m)</th>
<th>Breadth (mm)</th>
<th>Long span (m)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Column</td>
<td>Footings (lx)</td>
<td>Column</td>
</tr>
<tr>
<td>less than 3.0</td>
<td>225</td>
<td>1000</td>
<td>less than 4.0</td>
</tr>
<tr>
<td>3.0 to 3.5</td>
<td>250</td>
<td>1200</td>
<td>4.0 to 5.0</td>
</tr>
<tr>
<td>3.5 to 4.0</td>
<td>300</td>
<td>1200</td>
<td>5.0 to 6.0</td>
</tr>
<tr>
<td>4.0 to 4.5</td>
<td>350</td>
<td>1500</td>
<td>6.0 to 8.0</td>
</tr>
<tr>
<td>4.5 to 5.0</td>
<td>400</td>
<td>1500</td>
<td>8.0 to 10.0</td>
</tr>
<tr>
<td>5.0 to 6.0</td>
<td>450</td>
<td>2000</td>
<td>10.0 to 12.0</td>
</tr>
<tr>
<td>6.0 to 7.0</td>
<td>500</td>
<td>2500</td>
<td>more than 12.0</td>
</tr>
<tr>
<td>more than 7.0</td>
<td>600</td>
<td>2500</td>
<td></td>
</tr>
</tbody>
</table>
8.2.2.2 Design and costing procedure for slabs

The slab design procedure given in section 4.2.3 was included to design slabs in the cost model. Cost equations developed in section 4.2.2 were used to estimate the cost of slabs. Four types of slab panels (see section 4.2.1) are present in the cost model shown in Figure 8.1. The total cost of slabs can be written in terms of number of short spans (Nss) and long spans (Nls) as given below.

<table>
<thead>
<tr>
<th>Type of slab panel</th>
<th>Number of panels in Figure 8.1</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. All edges continuous</td>
<td>(Nss -2)X(Nls -2)</td>
<td>eqn.8.3XNOP</td>
</tr>
<tr>
<td></td>
<td>Ns = 0, Ni = 0</td>
<td></td>
</tr>
<tr>
<td>2. One short edge discontinuous</td>
<td>(Nss -2)X2</td>
<td>eqn.8.4XNOP</td>
</tr>
<tr>
<td></td>
<td>Ns = 1, Ni = 0</td>
<td></td>
</tr>
<tr>
<td>3. One long edge discontinuous</td>
<td>(Nls -2)X2</td>
<td>eqn.8.5XNOP</td>
</tr>
<tr>
<td></td>
<td>Ns = 0, Ni = 0</td>
<td></td>
</tr>
<tr>
<td>4. Two adjacent edges discontinuous</td>
<td>4</td>
<td>eqn.8.6XNOP</td>
</tr>
<tr>
<td></td>
<td>Ns = 1, Ni = 1</td>
<td></td>
</tr>
</tbody>
</table>

Equations 8.3, 8.4, 8.5 and 8.6 are as given below.

All edges continuous slab panel  
Ns = 0, Ni = 0.
Slab panel cost = Cs.p.lx.ly[ 0.76(Asxp + Asyp) + 0.225(As1p + As2p + As3p + As4p) + 1.2Asnp] + Cc.h.Lx.ly + Cf.lx.ly .... 8.3

One short edge discontinuous  
Ns = 1, Ni = 0.
Slab panel cost = Cs.p.lx.ly[ (0.76Asxp + 0.82Asyp) + 0.225(As1p + As2p + 0.49As3p + As4p) + 1.01Asnp] + Cc.h.Lx.ly + Cf.lx.ly .... 8.4

One long edge discontinuous  
Ns = 0, Ni = 1.
Slab panel cost = Cs.p.lx.ly[ (0.82Asxp + 0.76Asyp) + 0.225(As1p + As2p + As3p + 0.49As4p) + 1.01Asnp] + Cc.h.Lx.ly + Cf.lx.ly .... 8.5

Two adjacent edges discontinuous  
Ns = 1, Ni = 1.
Slab panel cost = Cs.p.lx.ly[ 0.82(Asxp + Asyp) + 0.225(As1p + As2p + 0.49As3p + 0.49As4p) + 1.2Asnp] + Cc.h.Lx.ly + Cf.lx.ly .... 8.6
The design load 'n' is required for the slab design procedure given in section 4.2.3. The design load 'n' was calculated from equation 8.7 (see 7.3.1 for details).

\[ n = 1.4(2.21 + h/1000.23.6) + 1.6qk \]  

where,

- \( h \) - slab thickness in mm
- \( qk \) - imposed load from BS6399:Part 1 (1984) depending on the building type

8.2.2.3 Design and costing procedure for beams

The beam design procedure given in section 4.3.2 was included to design beams in the cost model. Reinforced concrete cost equations developed in section 4.3.1 were used to calculate the cost of beams. As given in the equation 4.19 (chapter 4) the unit length cost of a beam:

\[ = Cc.D.bw + Cf[bw + 2(D - hf)] + Cs.p.(Asb + Ast) \]  

Table 8.4 Bending moments and shear forces of beams in the cost model

<table>
<thead>
<tr>
<th>Slab position</th>
<th>Moment</th>
<th>Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>At outer support</td>
<td>0</td>
<td>0.45F</td>
</tr>
<tr>
<td>Near middle of end span</td>
<td>0.09F1</td>
<td>-</td>
</tr>
<tr>
<td>At first interior support</td>
<td>-0.11F1</td>
<td>0.6F</td>
</tr>
<tr>
<td>At middle of interior span</td>
<td>0.07F1</td>
<td>-</td>
</tr>
<tr>
<td>At interior support</td>
<td>-0.08F1</td>
<td>0.55F</td>
</tr>
</tbody>
</table>

where,

- \( 1 \) - effective span
- \( F \) - the total design ultimate load (1.4Gk + 1.6Qk)
Therefore,

Total cost of beams = \( \sum ( \text{cost of short span beams} + \text{cost of long span beams} ) \)

cost of short span beams
\[ = 2(\text{cost of short span end beam}) + \sum (\text{cost of short span middle beams}) \]
\[ = 2(\text{cost of short span end beam}) + (\text{Nss} - 1)(\text{cost of short middle span beam}) \]

... 8.9

Similarly,

cost of long axis beams
\[ = 2(\text{cost of long span end beam}) + \sum (\text{cost of long span middle beams}) \]
\[ = 2(\text{cost of long span end beam}) + (\text{Nls} - 1)(\text{cost of long middle span beam}) \]

... 8.10
8.2.2.4 Design and costing procedure for columns

The column design procedure given in section 4.4.2 was integrated into column design in the cost model. The reinforced column cost equation given in section 4.4.1 was used to calculate the cost of columns. Four types of columns considered in the cost model were as shown in Figure 8.3.

![Diagram of column types](image)

**Figure 8.3 Types of columns in the cost model**

<table>
<thead>
<tr>
<th>Type of column</th>
<th>Number of columns in the cost model</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 - corner column</td>
<td>4</td>
</tr>
<tr>
<td>C2 - end column long span</td>
<td>2(Nls - 1)</td>
</tr>
<tr>
<td>C3 - end column short span</td>
<td>2(Nss - 1)</td>
</tr>
<tr>
<td>C4 - middle column</td>
<td>(Nls -1)(Nls -1)</td>
</tr>
</tbody>
</table>

Cost of reinforcements was increased by 10% to take into account shear links. 10% is an approximation calculated through the analysis of cost data of shear links of columns in 22 buildings, where data was collected.

Total cost of columns

\[
\text{Total cost of columns} = [Cc.h.b.l + Cf.2(b + h).l][4 + 2(Nls -1) + 2(Nss -1) + (Nls -1)(Nss -1)] + 1.1Cs.p.l[4As1 + 2As2(Nls -1) + 2As3(Nss -1) + As4(Nss -1)(Nls-1)]
\]

... 8.11
The axial load of a column was calculated as the load on shaded area of each column as shown in Figure 8.3. The axial load was reduced depending on number of storeys as recommended in BS6399: Part 1 (Table 8.5).

### Table 8.5 Reduction in imposed floor loads

<table>
<thead>
<tr>
<th>Number of floors including roof supported by the member</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5-10</th>
<th>over 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction of imposed load on floors</td>
<td>0</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Bending moments in columns were calculated using sub-frames according to clause 3.2.1.2.5 of BS8110 (see Figure 8.4).

![Figure 8.4 sub-frames for column bending moment calculations](image)

(a) End column  
(b) Middle column

where  

- I - second moment of area of an element (beam or column)  
- l - effective length of the element (beam or column)

**Figure 8.4 sub-frames for column bending moment calculations**

\[
B_{BD} = \frac{I_{BD}}{\sum(I/l)} OBM \quad \text{... 8.12}
\]

\[
B_{BE} = \frac{I_{BE}}{\sum(I/l)} OBM \quad \text{... 8.13}
\]

Equations 8.12 and 8.13 were used to find bending moment in axis X-X and Y-Y of columns. The out of balance moment at 'B' was calculated according to the recommendation of clause 3.2.1.2 of BS8110.
8.2.2.5 Design and costing procedure for independent footings

The independent footing design procedure given in section 4.5.2 was included for independent footing design in the cost model. The independent footing cost equation given in section 4.5.1 was used to calculate the cost of footings. Four types of independent footings were considered in the cost model as shown in Figure 8.5.

![Diagram of independent footings](image)

**Figure 8.5 Types of independent footings in the cost model**

<table>
<thead>
<tr>
<th>Type of independent footing</th>
<th>Number of footings in the cost model</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 - corner footing</td>
<td>4</td>
</tr>
<tr>
<td>F2 - end footing long span</td>
<td>2((Nls - 1))</td>
</tr>
<tr>
<td>F3 - end footing short span</td>
<td>2((Nss - 1))</td>
</tr>
<tr>
<td>F4 - middle footing</td>
<td>((Nls -1)X(Nss -1))</td>
</tr>
</tbody>
</table>

Cost of an independent footing

\[ = Cc.lxf.lyf + Cs.p.lxf.lyf(Asx + Asy + Asxt + Asyt) + 2Cf.h.(lxf +lyf) \quad ... \quad 8.14 \]

The total cost of independent footings

\[ = 4(\text{cost of F1}) + 2(Nls -1)(\text{cost of F2}) + 2(Nss -1)(\text{cost of F3}) + (Nls -1)(Nss -1)(\text{cost of F4}) \quad ... \quad 8.15 \]

Axial loads on independent footings were calculated using the same procedure as in columns. Bending moments on independent footings were used as half of columns at first floor level.
8.2.3 Validation of the cost model

The cost model was tested with four case studies. The elemental costs of slabs, beams, columns and independent footings and total structural cost from the cost model and priced bills of quantities were compared. The results of this analysis is given in Table 8.6 below.

Table 8.6 Comparison of model estimates and values form BOQ

<table>
<thead>
<tr>
<th>Cost Rs/m2</th>
<th>Project</th>
<th>MTC1</th>
<th>ASC</th>
<th>SLA</th>
<th>DQB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total slab cost</td>
<td>Model</td>
<td>1718</td>
<td>834</td>
<td>831</td>
<td>2433</td>
</tr>
<tr>
<td></td>
<td>BOQ*</td>
<td>1380</td>
<td>854</td>
<td>660</td>
<td>1982</td>
</tr>
<tr>
<td>Percentage error</td>
<td></td>
<td>-24.0</td>
<td>2.3</td>
<td>-25.9</td>
<td>-22.8</td>
</tr>
<tr>
<td>Total beam cost</td>
<td>Model</td>
<td>1178</td>
<td>442</td>
<td>511</td>
<td>2313</td>
</tr>
<tr>
<td></td>
<td>BOQ*</td>
<td>1036</td>
<td>389</td>
<td>429</td>
<td>2287</td>
</tr>
<tr>
<td>Percentage error</td>
<td></td>
<td>-13.7</td>
<td>-13.6</td>
<td>-19.1</td>
<td>-1.1</td>
</tr>
<tr>
<td>Total column cost</td>
<td>Model</td>
<td>349</td>
<td>182</td>
<td>197</td>
<td>1131</td>
</tr>
<tr>
<td></td>
<td>BOQ*</td>
<td>612</td>
<td>364</td>
<td>307</td>
<td>856</td>
</tr>
<tr>
<td>Percentage error</td>
<td></td>
<td>43.0</td>
<td>50.0</td>
<td>35.8</td>
<td>-32.13</td>
</tr>
<tr>
<td>Total foundation cost</td>
<td>Model</td>
<td>-</td>
<td>108</td>
<td>116</td>
<td>298</td>
</tr>
<tr>
<td></td>
<td>BOQ*</td>
<td>-</td>
<td>214</td>
<td>168</td>
<td>367</td>
</tr>
<tr>
<td>Percentage error</td>
<td></td>
<td>-</td>
<td>49.5</td>
<td>30.9</td>
<td>18.9</td>
</tr>
<tr>
<td>Total project cost</td>
<td>Model</td>
<td>3245</td>
<td>1566</td>
<td>1655</td>
<td>6175</td>
</tr>
<tr>
<td></td>
<td>BOQ*</td>
<td>3028</td>
<td>1821</td>
<td>1564</td>
<td>5492</td>
</tr>
<tr>
<td>Percentage error</td>
<td></td>
<td>-7.16</td>
<td>14.0</td>
<td>-5.82</td>
<td>-12.44</td>
</tr>
</tbody>
</table>

* BOQ reads bills of quantities (priced)

The cost model has given an error less than 14.0% (coefficient of variation 35%). The developed cost model is relevant for the sketch design stage. Section 2.3.7 of this thesis discussed the accuracy of design process cost forecastings and past research suggested accuracy of 6% to 20% (coefficient of variation) for sketch design stage. Therefore the developed cost model does not offer an improvement for cost forecasting accuracy. However, the cost model adequately represented the cost of projects through an approximate design procedure. Since the error is less than 14% the cost model can be used to investigate and to predict cost consequences of design decisions such as variations in spans, number of storeys etc.
High inaccuracies in elemental cost are mainly due to unique characters of each building which are almost impossible to accommodate in one single cost model. For example, in the building MTC1 slab opening for staircases and entrance lobbies has reduced the building slab cost more than in the model. Further model selected 160mm for slab depth while depth used is 175mm, which could be a more economical slab. Buildings DQB and ASC contain more columns and footings than in the model because of additional spans provided for corridors. Therefore as Beeston (1987) suggested, it is difficult to develop a cost model to improve the accuracy of cost forecasts in the design process.

8.2.4 Application of the cost model for real projects

The developed cost model design of reinforced concrete structure was applied for four historical buildings to study the cost variations with design variables. The selected grid in buildings, short span lx and long span ly were changed by ±2m in steps of 0.5m, and cost variations were observed. During span variations, the overall dimensions of the building were kept close to the original values through considering integer values for number of spans.

Cost savings through variations of short and long spans depend on the building shape, original values of short and long spans, number of storeys etc. Therefore, details of cost savings on each building are discussed separately. Summary of observations on application of the cost model on four projects are given at the end.

8.2.4.1 Building MTC1

The building MTC1 is a square, three storey technical college building. The building consists of offices for the administration and academic staff, lecture rooms and laboratories. The plan together with the grid is shown in Figure 8.6.
Elemental cost savings through span changes are shown in Figure 8.7 and total project cost savings are shown in Figure 8.8. It is clear from Figure 8.7 and Figure 8.8 that decrease in short or long results in cost savings and increases cost extra money. Cost savings possible through decrease of spans are significant considering the total project cost: 0.6% for 0.5m; 1.75% 1m; 3.3% for 1.5m; and 4.6% for 2.0m.

Figure 8.9 shows the elemental cost variation of slabs, beams, columns and foundation with span. Both slabs and beams costs increase with short or long span increase but change in cost of columns and foundations were negligible.
Figure 8.7 Elemental cost savings of MTC1

Figure 8.8 Total project cost savings of MTC1
8.2.4.2 Building SLA

The building SLA is narrow, long, two storey residential quarters for army personnel. The building has 9 spans in the long direction and two spans in short direction as shown in Figure 8.10.

Percentage cost savings for short and long span changes of elemental cost and total project cost are given in Figure 8.11 and Figure 8.12 respectively. Decrease in short span increases the cost while decrease in long span decrease the cost. Therefore cost
savings of the building SLA is different from building MTC1. Main reason for this cost variation difference is that Building SLA is a narrow long building while MTC1 is a square building. Furthermore, elemental costs shown in Figure 8.13 shows a rapid decrease in cost of beams with increase of short span and rapid increase of beam cost with increase of long span.

Figure 8.11 Elemental cost savings of SLA

Figure 8.12 Total project cost savings of SLA
8.2.4.3 Building ASC

The building ASC is a rectangular (nearly a square), two storey office and shopping complex, plan as shown in Figure 8.15.
Figure 8.15 - Plan of building ASC

Figure 8.16 shows elemental cost savings and Figure 8.17 shows total cost savings of project ASC. Maximum cost savings occurs when spans decrease by 1 to 1.5m, suggesting that optimum span is around 3m which agrees with the opinion of structural engineers interviewed (see chapter 5).
8.2.4.4 Building DQB

The building DQB is a six storey, residential quarters for doctors working in a city hospital, and plan is shown in Figure 8.18. The building DQB is a narrow long
building, similar to building SLA. Cost changes are also similar to SLA due to the same reasons discussed for SLA.

Figure 8.18 Plan of building DQB

Figure 8.19 Elemental cost savings of DQB
8.2.4.5 Summary on project cost savings by change of spans

The cost model satisfactorily produced the cost informations requirements (see section 8.2.1) related to short span and long span design decisions. Cost savings through change of spans depend on shape of the buildings as well as the original values of short span (lx) and long span (ly). For building MTC1, SLA and DQB original short span was more than 5.0m and higher cost savings than building SLA (original span 4.6) was observed.

8.2.4 Designers' response for the cost model

The cost consequences observed for projects MTC1 and DQB were complied into a questionnaire (see Appendix D) and was sent to 40 architects by post (in U.K). The projects MTC1 and DQB were selected; to represent different shapes of buildings (MTC1 - square, DQB - narrow long), and to represent different cost saving patterns with long and short span variations. A total of nine replies were received. Six architects have stated that they will not change any design variable related to the building structure based on cost because always other factors such as building functional requirements are more important. Three architects have replied indicating changes to design variables, but have stated that other criteria may influence more than
the cost and final decision may not change because of cost. This concludes that there is not much scope for cost effective design methods developed based on cost data related for architectural design decisions. Therefore it is not feasible to develop cost effective design methods even with new methods such as expert systems, value analysis etc. because simply, cost is not relevant to design decisions.

8.2.5 Summary and conclusions

As conclusions the following can be stated.

1. It is possible to give cost information required by designers for design decisions related to the building structure, thus cost effectiveness of building design could be improved.

2. Cost savings through changes of short and long span depend on building shape, original values of short span and long span, in other words unique for a building. Therefore cost information for design decisions should be provided by a system which includes above parameters.

3. Decreasing a span (short or long) by 0.5m to 2.0m between 0.6% to 7.6% of the total cost of a building can be saved. Further it costs between 0.5% to 9% of total building cost to increase a span between 0.5m to 2.0m. These results proved the cost vary with design variables. Therefore design decisions based using cost information related design decisions are more cost effective than the designs form current design practice.

4. Architects response for the developed cost model proved that cost effective design methods developed based on cost data has limited scope for practical applications because for architectural design decisions other factors such as building functional requirements influence more than cost for final decisions.

8.3 WINDOWS AND FLOOR FINISHES DESIGN

Analyses on windows and floor finishes design decisions, designers cost information requirements and expected cost differences to change the selected type were conducted. Cost information related to design decisions were identified through interviews (see chapter 5).
8.3.1 Cost information for windows and floor finishes designs

As a summary cost information required related to windows and floor finishes are as follows:

1. what is the cost of selected type? (e.g. 1st class timber for windows);
2. what are the costs of other types? (e.g. costs of aluminium and 2nd class timber for windows);
3. what are the elemental cost differences between the selected type and other types?
4. what are the total cost differences between the selected type and other types?

Provision of above cost information will give the facility to the designer to make a cost effective design decision using his experience and judgement to incorporate user requirements, and qualities such as durability. In this process most of the difficulties identified in section 2.3.7 can be overcome.

8.3.2 Designers' expectations and cost information

The prime aim of this research is to evaluate cost effective design methods for practical applications. Unless a new method provides information required by designers and necessary cost differences between design options, there will be no change in the building design decision making process. Windows and floor finishes design decisions, the designer can select the next superior type (at a higher cost) or next inferior type (at a lower cost). Therefore, four questions related to cost information were asked from the designers (see interview, chapter 5):

1. the elemental cost difference required to change the selected type to next inferior type;
2. the total cost difference required to change the selected type to next inferior type;
3. the elemental cost difference required to change the selected type to next superior type; and
4. the total cost difference required to change the selected type to next superior type;

The answers given by seven senior architects to above questions (see interviews in chapter 5) are given in Table 8.7.
Table 8.7 Cost differences expected by designers for window and floor finishes

<table>
<thead>
<tr>
<th></th>
<th>Windows</th>
<th>Floor finishes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Elemental cost difference required to change to next inferior type</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>2. Total cost difference required to change to next inferior type</td>
<td>3%</td>
<td>2.00%</td>
</tr>
<tr>
<td>3. Elemental cost difference required to change to next superior type</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>4. Total cost difference required to change to next superior type</td>
<td>3%</td>
<td>2.00%</td>
</tr>
</tbody>
</table>

Therefore, cost differences of various design decisions were tested for the values given in Table 8.7 and details are given in sections 8.3.3. and 8.3.4.

8.3.3 Window designs

Change of windows types for the next higher and next lower for 32 historical building projects were investigated. Types of windows were selected after considering the suitability and availability of substituting each other. Types of windows considered were:

1. aluminium windows;
2. 1st class timber windows; and
3. 2nd class timber windows.

Table 8.8 shows the cost differences between the selected type and other suitable types of windows of 32 historical buildings. Cost differences were calculated using cost ratios obtained form the window unit rates given in 'Building Schedule of Rates' (BSR, Central Engineering Consultancy Bureau, Sri Lanka, 1987).
### Table 8.8 Cost differences of types windows types in historical buildings

<table>
<thead>
<tr>
<th>Project</th>
<th>Total project cost</th>
<th>Window element cost</th>
<th>Selected window type</th>
<th>Window type change</th>
<th>Next lower</th>
<th>Next higher</th>
<th>Percentage cost difference lower</th>
<th>Percentage total cost difference lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTCI</td>
<td>9,717 120</td>
<td>237 096</td>
<td>1st class timber</td>
<td>2nd class timber</td>
<td>Aluminium</td>
<td>21.94</td>
<td>83.10</td>
<td>0.54</td>
</tr>
<tr>
<td>CSM</td>
<td>18,254 698</td>
<td>1,065 000</td>
<td>Aluminium</td>
<td>1st class timber</td>
<td>None</td>
<td>44.50</td>
<td>-</td>
<td>2.60</td>
</tr>
<tr>
<td>SCA</td>
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<td>Window type change</td>
<td>Percentage cost difference lower</td>
<td>Percentage cost difference higher</td>
<td>Percentage total cost difference lower</td>
<td>Percentage total cost difference higher</td>
</tr>
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<td>3.49</td>
<td>-</td>
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<td>83.10</td>
<td>1.21</td>
<td>4.59</td>
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<td>-</td>
<td>5.28</td>
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<td>186 112</td>
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<td>83.10</td>
<td>0.57</td>
<td>2.16</td>
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<td>83.10</td>
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<td>4.29</td>
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<td>2nd class timber</td>
<td>21.94</td>
<td>83.10</td>
<td>1.75</td>
<td>6.64</td>
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<tr>
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<td>74 115</td>
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<td>2nd class timber</td>
<td>21.94</td>
<td>83.10</td>
<td>1.51</td>
<td>5.73</td>
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<td></td>
<td></td>
<td></td>
<td>26.88</td>
<td>83.10</td>
<td>1.66</td>
<td>3.71</td>
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<td></td>
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<td>9.47</td>
<td>0.0</td>
<td>1.70</td>
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</table>
As given in Table 8.7 to change the selected window type based on cost, designers expect 50% elemental cost difference or 3% of total building cost. Therefore, by testing results shown in Table 8.8, a conclusion on whether providing cost information for window design decisions will improve cost effectiveness of designs can be made. Therefore, test hypotheses are:

**Test 1**

H0 : \( \mu \geq 50\% \) (To change to next inferior type)

H1 : \( \mu < 50\% \) (No change)

or

H0 : \( Z \geq -1.65 \) (Z scale)

or

\[
\frac{(\bar{X} - \mu)}{S(\bar{X})} \geq -1.645
\]

**Test 2**

H0 : \( \mu \leq 50\% \) (To change to next superior type)

H1 : \( \mu > 50\% \) (No change)

or

\[
\frac{(\bar{X} - \mu)}{S(\bar{X})} \leq 1.645
\]

where, \( \mu \) = average cost difference between selected type and another suitable type.

The above tests can be made using statistical theories and details of a similar test was discussed in section 7.5.2. Similar tests were held for the total building cost differences and results are shown in Table 8.9.

<table>
<thead>
<tr>
<th>Table 8.9 Test on cost information in window designs</th>
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<tbody>
<tr>
<td>( \bar{X} )</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>1. To change to next inferior type (based on elemental cost difference)</td>
</tr>
<tr>
<td>2. To change to next superior type (based on elemental cost difference)</td>
</tr>
<tr>
<td>3. To change to next inferior type (based on total cost difference)</td>
</tr>
<tr>
<td>4. To change to next superior type (based on total cost difference)</td>
</tr>
</tbody>
</table>

The above analysis proved that providing cost information related to cost consequences on window design decisions will not change the decisions based on cost.
8.3.4 Floor finishes designs

Change of floor finish type for the next higher, and next lower for 32 historical buildings were investigated. Five types of floor finishes were investigated as possible to substitute for each other. These types were:

1. cement sand rendering;
2. clay tiles;
3. terra-cotta tiles;
4. PVC tiles;
5. terrazzo tiles.

Table 8.10 shows the cost differences between the selected type and other suitable types of floor finishes of 32 historical buildings. The cost differences were calculated using the ratios calculated form unit floor finishes rates given in 'Building Schedule of Rates' (Central Engineering Consultancy Bureau, Sri Lanka, 1987).

As given in Table 8.7 to change the selected floor finish type on cost, designers expect 50% elemental cost difference or 2.0% total building cost difference. Similar tests as for windows were conducted and results of the test for the above requirements are given in Table 8.11.

| Table 8.11 Test on cost information in floor finishes designs |
|---------------------|-----|---------------------|---------------------|---------------------|
| 1. To change to next inferior type |
| based on elemental cost difference |
| 15.24 | 4.23 |
| 2. To change to next superior type |
| based on elemental cost difference |
| 162.5 | 16.02 |
| 3. To change to next inferior type |
| based on total cost difference |
| 0.83 | 0.24 |
| 4. To change to next superior type |
| based on total cost difference |
| 3.73 | 0.44 |

The above analysis proved that providing cost information related to cost consequences on floor finishes design decisions will not change the final decisions based on cost.
<table>
<thead>
<tr>
<th>Project</th>
<th>Total project cost</th>
<th>Floor finish element cost</th>
<th>Selected floor finish type</th>
<th>Floor finish type change</th>
<th>Percentage cost difference lower</th>
<th>Percentage cost difference higher</th>
<th>Percentage total cost difference lower</th>
<th>Percentage total cost difference higher</th>
</tr>
</thead>
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<td>9 717 120</td>
<td>7 610 099</td>
<td>Terrazzo</td>
<td>PVC tiles</td>
<td>8.14</td>
<td>3.07</td>
<td>0.64</td>
<td>0.24</td>
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<td>1 211 565</td>
<td>PVC + Terrazzo</td>
<td>PVC</td>
<td>0.42</td>
<td>0.0</td>
<td>0.03</td>
<td>0.0</td>
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<td>Cement sand</td>
<td>Clay tiles</td>
<td>-</td>
<td>221.4</td>
<td>-</td>
<td>4.48</td>
</tr>
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<td>59 887</td>
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<td>Clay tiles</td>
<td>-</td>
<td>221.4</td>
<td>-</td>
<td>3.85</td>
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<td>Clay tiles</td>
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<td>-</td>
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<td>Clay tiles</td>
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<td>1.13</td>
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<td>-</td>
<td>4.2</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
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Table 8.10 Cost differences of different types of floor finishes for historical buildings (cont.)

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<td>15.24</td>
<td>162.51</td>
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<td>12.52</td>
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8.4 SUMMARY AND CONCLUSIONS

The developed cost model for the design of building structure successfully provided the information related to design decisions. The main cost information requirements were the cost changes in elemental cost and total building cost for changes in design variables such as short span and long span. The developed cost model proved that cost changes with design variables depend on building size, shape of building, selected values of short and long span etc. Therefore, to predict cost consequences related to design decisions need to be provided by a system which can represent the unique characters of buildings as considered in the developed cost model. Between 0.6% and 7.6% of the total cost of building vary with changes in a span (long or short) by 0.5m to 2.0m, thus proving the significant cost variation related to design decisions. Therefore design decisions based on the cost model developed in this research can be more cost effective than design decisions made from the current practice. However, architects' response for the cost model proved that for final design decisions (architectural) more than the cost other factors such as building functional requirements are more important. Therefore there is not much scope to develop cost effective design methods for architectural design decisions based on cost information.

Analyses on selection of windows and floor finishes types proved that providing relevant cost information related design decisions cannot improve the current design decision making practice with respect to the cost. This is because results of the analyses proved that cost differences related to design decisions are less than the differences expected by designers. Therefore, architectural design decision making practice, especially that related to the quality of the building cannot be improved by providing relevant cost information to design decisions.
Chapter nine

CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

9.1 DISCUSSION
9.2 CONCLUSIONS
9.3 RECOMMENDATIONS
9.4 FUTURE RESEARCH
9.1 DISCUSSION

This research set out to evaluate the cost savings of cost effective design methods, to identify difficulties involved in their use and to examine favourable conditions for the implementation of methods in design practice. To achieve this the whole subject of cost effective design methods was first reviewed.

The concept of cost effective building design pervades in the long history of building construction. Until the recent past, economic building design methods were limited to replacing one material with another more cost effective material such as replacement of natural stone by brick in Britain. After the second world war new developments with technology and theories were discovered and used with no exception in building designs. Cost effective design methods were developed mainly for the building structure designs using simple theories such as differentiation (calculus) as well as complex theories such as linear programming, finite elements theory. Unfortunately, however, in construction industry these methods remained in the academic world while similar methods based on the same theories were put into practice in other disciplines such as air-craft industry (chapter 2). The reasons put forward for this lack of use of new methods related to the methods themselves. However judgement from the practising designer's angle and design practice as a whole were yet to be reckoned. Therefore, cost effective design methods were investigated from the angle of design practice (chapter 5) and evaluated cost benefits by applying to historical buildings (chapter 7). These two steps were considered necessary for the implementation of cost effective design methods.

There was a problem knowing what the specific needs of practising designers with respect to cost effective designs were. This was resolved by interviewing designers on cost effective design methods for their knowledge, technical problems in using such methods, the cost benefits expected, and design decisions and relevance of putting such methods into practice (chapter 5). The designers' opinion was that structural design methods developed cannot offer cost savings more than 10% of elemental cost or 1% of total building cost. Even though designers knew about structural optimum design methods, on the basis of above assumption they haven't shown any interest in studying and using them. On the other hand people who developed cost effective methods (mainly academics) have done very little to change this concept. Therefore a proper evaluation of cost benefits from optimum methods was required.
9.2 CONCLUSIONS

9.2.1 Benefits of cost effective design methods

Application of optimum design methods for 22 historical buildings showed mean cost savings in slabs, beams, columns and independent footings of 10.10%, 7.78%, 7.33% and 8.43% respectively. These values suggested that only cost savings in slabs shows more than 10% elemental cost saving, which is the designer’s minimum cost saving requirement. However, according to statistics, a judgement cannot be made without analysing the mean with standard deviation. Analyses using statistical theories proved that elemental costs of total buildings designed are more than 10% (with 95% confidence). Therefore this study disproved the common opinion among practising designers regarding the cost benefits from optimum design methods. Total building cost savings from optimum method for slabs, beams, columns and independent footings were 1.13%, 0.70%, 0.46% and 0.41% respectively. Statistical analysis proved that cost savings are more than 1% of the total building cost for slabs (with 95% confidence). Therefore this study rejected the opinion of practising designers that cost savings are less than 1% of the total project cost for reinforced concrete elements.

Sample of 22 historical buildings showed a mean total building cost saving of 2.91% from the use of optimum methods to building structure designs (foundation, slabs, beams and columns). This study proved that depending on size of the building cost saving between 45% to 65% equivalent to the design fee can be saved by using optimum design methods for slabs, beams, columns and independent footings at the detail design stage. Probabilities of total building cost saving exceeding 1%, 2% and 3% were more than 0.96, 0.79, and 0.47 respectively. Therefore this study has proved that the time has come for the building construction industry to improve the cost effectiveness of designs in detail design stage.

Cost savings can be achieved by using builddability concepts which take into account contractors pricing methods. Therefore unless optimum methods take builddability concepts into considerations, there could be an extra cost instead of cost saving.

9.2.2 Practical cost effective design methods

From literature it was recognized that the main reason for under utilization of new methods is that "very little of them satisfies the specific needs of its potential users, practising designers" (Templeman 1983). Therefore study of methods and needs of
practising designers are important for application of cost effective design methods in current design practice.

Technical problems associated to the method themselves were highlighted as reasons for failure of new design methods application in current design practice (Templeman 1983, Ashworth 1986). The main reasons were the use of complex mathematics which gives difficulties in understanding for practising designers, less practical design solutions for design variables such as beam depths, reinforcement area etc. and incomplete design solutions leaving user to perform some design checks required by design codes such as BS8110. This led to an investigation of whether cost effective design solutions can be produced using design methods familiar to practising designers. The computer was used to produce and to give a set of feasible design solutions and their costs using normal design methods used in current practice. This method gave practical and complete design solutions to reinforced concrete designs as well as eliminating difficulties in understanding.

This study produced optimum beam design considering a beam as one unit. Previous research (Chou 1977, Golding 1988, Brown 1974) proved that optimum beam design solutions always as singly reinforced. They have made this conclusion based on developed optimum methods for a section in a beam. This study proved that generally optimum beam's mid span is singly reinforced while in some beams, supports could be double reinforced. Therefore this study has proved that to obtain the true optimum a reinforced concrete element (beam) should be considered as one unit.

9.2.3 Current design practice and cost effective design methods

The current design contract procedure is not geared to exploit the benefits of new cost effective design methods. The common percentage fee design contract procedure discourages designers from using cost effective design techniques. In percentage fee contracts final payment to the designer is made as a percentage of the total tender sum (tender sum from the contractor). Therefore use of optimum design methods not only demand more time for designs but also reduce the design fee. Lump sum design contracts are awarded through a competitive bidding system (tendering for designs). Sometime to get design contacts designers put low design fee which acts as a barrier to use cost effective design methods. However, in lump sum design contracts designers can suggest the use of expensive cost effective design methods which the tender committee or the client can consider. A project management system can play an
important role to advise the client. Therefore lump sum design contracts have a better facility to use cost effective design methods than percentage fee design contracts. Design and build contracts have a mechanism to accommodate cost effective design methods, because cost savings are directly beneficial to the contractor. Even though designers are legally responsible for giving reasonably accurate cost forecasts, they are not responsible to producing cost effective designs.

Comparison between designers' solutions and optimum solutions showed the reasons for cost savings observed. For slabs, designers have provided higher depths than the optimum depths (Figure 7.13). Interviews revealed that slab depths are selected to meet deflection criteria and analysis proved that used depths in historical buildings were more than for deflection requirements. Selection of depths showed randomness (no relationship with span) which has led for expensive slabs compared to optimum slabs. For beams and columns optimum depths were higher than depths used by designers and proved less reinforcement ratios than used by designers are more economical. A high randomness was observed for beam depths from the analysis of beam depths with span and bending moments. Similar patterns as for slabs were observed for independent footings. A comparison between optimum and designers' solutions proved that simple graphical representation design aid (e.g. for slabs, span vs optimum depth) cannot produce more economical solutions. Therefore designers need to be helped by a tool such as the computer to produce cost effective designs.

Application of cost effective design methods (architectural designs) to a large extend depends on the use of cost information in design decision making. Literature review and interviews with practising designers proved that in pre detail design stages, mainly for architectural design decisions use of cost data is very limited. This proved that scope of applying cost effective design methods for many pre detail architectural designs are very limited. The main cost information need of architectural design decisions is to highlight cost consequences between design options. This leaves designers to make the final decisions considering the cost, the clients needs, building regulations etc. This proved irrelevant, hence the failure of cost effective design methods developed based on estimating data.

Application of cost effective design concept into architectural design decision making was tested for design decisions related to building structure, windows and floor finishes. Elemental and total building cost consequences in design decisions related to the building structure were produced for four historical buildings. However, responses from the architects were that even though cost model produced significant
cost information, for final design decisions other factors such as building functional requirements were more influential. The cost differences observed for windows and floor finishes were less than cost differences expected by designers to change their selected types on cost alone. Therefore, there is not much scope in using or developing cost effective design methods for architectural design decision making.

9.2.4 Implementation of cost effective design methods

The current design practice lacks motivation factors or incentive schemes (higher design fee) to designers to use cost effective design methods. Few designers responded that it is the designer's professional responsibility to produce designs for the minimum possible cost. Therefore the building construction industry needs to understand the cost benefits and requirements to pay extra payments to designers to use cost effective design methods.

Is there any evidence in the history of construction industry for the use of cost effective design methods? The answer is Yes! Two examples are the use of cost effective services design and the use of pre cast concrete methods. Prefabricated concrete structure is more expensive to build than a similar structure of 'traditional' in situ concrete structure and economy is achieved through shorter construction period (Brakel 1967). New services design methods uses expensive material for insulation and economy is due to low energy costs in building use. Therefore, even though building construction industry has evidence for use of new cost effective methods in all the occasions the capital cost of the building has increased and hence the design fee. There is no evidence for the use of cost effective design methods which reduced the capital cost of the building such as methods described in this thesis.
9.3 RECOMMENDATIONS

The main aim of cost effective design methods is to improve the efficiency of building designs and to provide efficient investments to building clients. Based on findings of this research to implement cost effective design methods; an incentive scheme to designers (or higher design fees), creating an awareness among large clients and professionals in project management organizations are recommended. Further research results proved that there is not much scope in developing cost effective design methods for architectural design decisions.

9.3.1 An incentive scheme to designers

An incentive scheme is recommended for structural design work. An extra payment is required due to need of computers, to pay for new software, extra design time and to motivate designers to use new cost effective design methods. What is the extra payment required for designs? To answer the above question further research is required. However, designers, clients and project managers can use predicted cost savings to decide on reasonable additional fee required to use cost effective designs.

9.3.2 Clients

Large clients who design their own buildings such as developers, building department in Sri Lanka can implement structural optimum design methods without much difficulty. Therefore to draw attention from large clients to use cost effective design methods is recommended.

9.3.3 Professional organizations

The study proved that more than 45% equivalent to the design fee can be saved by using optimum structural design methods for reinforced concrete framed buildings. Professional organizations such as institute of architects, institute of civil engineers are the organizations who give guides for design fees, design contracts etc. Therefore it is recommended to professional organizations to review the current contracts and design fees in design practice and to include necessary recommendations in their publications to accommodate cost effective designs.
9.3.4 Contract types

Design and build contract types have a mechanism to employ cost effective design methods. Therefore it is recommended to those who engaged in design and build contracts to use these cost effective structural design methods.

9.3.5 Cost effective design methods for architectural designs

This research revealed that to improve cost effectiveness of architectural design decisions are practically not feasible with current design practice. Therefore there is no scope of developing cost effective design methods using cost data even with new methods such as expert systems, value analysis etc.

9.4 FURTHER RESEARCH

Many cost effective design methods have been developed in the past using new theories such as finite elements theory, linear programming etc. For the implementation of new design methods cost benefits compared to current design methods are very important. This study investigated cost saving of cost effective design methods developed for reinforced concrete framed buildings. Steel structures are the most investigated type of structure for optimum designs and therefore an investigation of cost savings from optimum methods compared to designers' solutions is another research requirement for the implementation of optimum methods developed.

As discussed above, steel structures are the most investigated structures for cost effective designs. More than 700 research works have been published between 1972 and 1980 for optimum steel design methods (Lev 1981). As was identified in this research one of the major problems is cost effective design methods developed for steel structures was the use of complex mathematics such as linear programming, finite elements theory etc. Furthermore, optimum design method's solutions sometimes need to be modified to suit practical limitations such as available section sizes, lengths etc. One way to overcome this difficulty is by selecting elements (e.g. beams) from a data base of available sizes, lengths etc., to use design software to produce feasible design solutions, an estimating program (software) to calculate the cost feasible
solutions and another program to find the least cost design solutions (see Figure 9.1). The process may look time consuming even with a computer, but a similar principle used in this research proved that with modern computers (such as IBM system 2 model 30, model 50 etc.) this can be achieved within a reasonable time (in other words feasible for investigation).

Modification required to facilitate cost effective design methods through already developed design software (e.g. Software for BS8110 designs) need to be investigated. As this research suggested with some modifications to existing design software, can produce cost effective designs.

To recommend suitable payments for the use of cost effective design methods is another area need to be investigated. Extra design time required may depend on building size building shape etc. Therefore detailed investigation is required to make proper recommendations for additional design fees for the use of cost effective design methods.

Market testing of the designs from optimum methods need to be investigated. Optimum designs need to be produced parallel to normal design methods and should be priced by contractor/s. This will take into account of factors such as contractors pricing methods, buildability etc. and more refined values for cost saving can be achieved.
Analyse the frame for bending moments and shear forces

Select smallest beam section size from the data base for beam section properties

Attempt to design all longitudinal beams with the same section size. Use the steel design software.

Is the selected beam size can be used for all longitudinal beams?

Yes

Use estimating system to cost the longitudinal beams.

Record the cost and beam properties.

No

Cost of beams = \( \alpha \)

Select the next larger section of the data base

Selected beam section is the largest in the data base of beam sizes

Yes

Select the minimum cost beam section as the optimum solution for the longitudinal beams

Stop

Data base for steel beam sections sizes. Section dimensions such as depth, breadth length, moment of areas etc. together with coding to link estimating and design software.

Steel design software for BS449 requirements

Figure 9.1 Optimum steel beam design procedure
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STRUCTURAL OPTIMUM DESIGNS


FURTHER READING


APPENDIXES

Appendix A  DESIGNER'S QUESTIONNAIRE 1
Appendix B  DESIGNER'S QUESTIONNAIRE 2
Appendix C  DESIGN OF REINFORCED CONCRETE ELEMENTS
Appendix D  DESIGNER'S QUESTIONNAIRE BASED ON COST MODEL RESULTS
APPENDIX A

DESIGNER'S QUESTIONNAIRE 1

The questionnaire given here was used for the interviews. The questionnaire was used only as guide and many occasions important factors came out were discussed. A total of fifteen interviews were held with seven senior architects, five senior structural engineers and three quantity surveyors. Each interview took between 45 minutes and 2 hours and were recorded using audio cassettes.

QUESTIONNAIRE

The questionnaire is set to study the design decisions making in the design process, use of cost information in design decision making, design organization structures and to investigate to improve the cost effectiveness of design process. Please answer the questions with past example whenever possible.

A. BRIEFING DESIGN STAGE

A.1 What are the available design information at briefing (inception and feasibility) design stage? Please discuss with an example.
   (a) Floor area
   (b) Number of storeys
   (c) Type of finishes for floors, walls etc.
   (d) Type of doors and windows
   (e) .........................

A.2 How do you collect design information at briefing design stage?
   (a) Client's brief
   (b) Through discussions
   (c) Visits to site, existing clients building such present office etc.
   (d) .............................
A.3 What are the cost data available and used at briefing design stage?
   (a) Available funds for the building
   (b) Cost per unit floor area (Rs/m², Rs/ft², etc.)
   (c) Costs of similar projects
   (d) ..............................

A.4 How do you use cost data for building design decisions?
   (a) Building size
   (b) Quality of finishes and fittings
   (c) ..............................

A.5 What are the problems especially connected to cost information?
   (a) Availability of cost data
   (b) Accuracy of cost data.

A.6 What is your judgment on accuracy of cost forecasts?

A.7 Who are the personnel involved at briefing design stage?
   (a) Project director
   (b) Structural engineer
   (c) Quantity surveyor
   (d) .........................

A.8 What the responsibilities of the personnel involved at briefing design stage?
   (a) Project director
   (b) Structural engineer
   (c) Quantity surveyor
   (d) .........................

A.9 What is the design team structure at briefing design stage?
B. SKETCH DESIGN STAGE

B.1 What are the available design information and level of design at sketch (scheme and outline) design stage? Please discuss with an example.
(a) Sketches of plans, elevations etc.
(b) Definite type of finishes for floors, walls etc. (e.g. terrazzo for floors)
(d) Definite type of doors and windows (e.g. aluminium windows etc.)
(e) ..........................

B.2 How do you collect design information at sketch design stage?
(a) Through discussions based on sketches
(b) Visits to site, existing clients building such present office etc.
(c) ............................

B.3 What are the cost data available and used at briefing design stage?
(a) Elemental costs
(b) Cost per unit floor area (Rs/m², Rs/ft², etc.)
(c) Costs of similar projects
(d) ..........................  

B.4 How do you incorporate cost data for building design decisions at sketch design stage?
 (a) ..........................

B.5 What are the problems especially connected to cost information?
(a) Availability of cost data
(b) Accuracy of cost data.

B.6 What are the general design problems your face at sketch design stage?
(a) Foundation design problems
(b) Cost overruns
(c) Clients change of mind
(d) ..........................

B.7 How do you forecast building cost at sketch design stage?
(a) Cost per unit floor area
(b) Elemental cost analysis of similar projects
(c) Approximate quantities estimate
B. 8 What is your judgment on accuracy of cost forecasts during sketch design stage?

B. 9 Who are the personnel involved at sketch design stage?
   (a) Project director
   (b) Structural engineer
   (c) Quantity surveyor
   (d) .................

B. 9 What the responsibilities of the personnel involved at sketch design stage?
   (a) Project director
   (b) Structural engineer
   (c) Quantity surveyor
   (d) ..................

B. 10 What is the design team structure at sketch design stage?

C. DETAIL DESIGN STAGE

C.1 What are main design work at detail design stage?
   (a) Detail design of building structure (foundations, slabs, beams, etc.)
   (b) Detail design of finishes, doors, windows etc.
   (c) ............................

C.2 What are the general problems your face at detail design stage?
   (a) Cost overruns
   (b) Changes from the client
   (c) .........................

C.3 How do you forecast building cost at detail design stage?
   (a) Pricing the bills of quantities using your own rates
   (b) Pricing the bills of quantities using published rates
   (c) ..........................

C.4 What is your judgment on accuracy of cost forecasts during detail design stage?
C.5 Who are the personnel involved at detail design stage?
(a) Project director
(b) Structural engineer
(c) Quantity surveyor
(d) ....................

C.6 What are the responsibilities of the personnel involved at detail design stage?
(a) Project director
(b) Structural engineer
(c) Quantity surveyor
(d) ....................

C.7 What is the design team structure at detail design stage?

D. COST EFFECTIVE DESIGNS

In the recent past methods have been developed to improve the cost effective of design decisions. Methods have been developed to give cost relationship with design decisions such as building size, quality of finishes, number of storey etc. Further methods have been developed to produce optimum structural design. These methods especially structural optimum design methods can provide economical solutions, thus improve the efficiency of building investments. Some cost effective design effective design methods can lower the capital cost of the building.

D.1 What type of design contracts you use (experience)?
(a) Percentage fee design contracts
(b) Lump sum design contracts (through competitive bidding)
(c) Design and build contracts
(d) .........................

D.2 Do you think that your can use cost effective design methods which can lower the capital cost in above contract types?

D.3 What are provisions in present design contract types to accommodate cost effective designs which can take more design time and resources such as computers?
(a) ..................
APPENDIX B

DESIGNERS' QUESTIONNAIRE 2

The questionnaire given here was for the interviews. These interviews were held to collect information related to detail design decisions related to foundations, frame and upper floors, roof, windows and doors and finishes. Designers were interviewed for their knowledge and expected cost savings from cost effective designs methods. Further discussion were held to investigate the detail design decisions of above elements in briefing, sketch and detail design stages.

QUESTIONNAIRE

This questionnaire is set to understand the detail design decision related to building elements such as foundations, frame, slabs, finishes, doors and windows, roof etc. Further questions related cost effective design methods are also included. Whenever possible please answer the questions with your past experience.

Questions are structured for three design stages, briefing (inception and feasibility), sketch (outline and scheme) and detail design.

A. FOUNDATION DESIGNS

Briefing design stage foundation designs

A.1 What are the available information related to foundations at the briefing design stage (inception and feasibility) ? - discuss.
   (a) Soil bearing pressure
   (b) Type of soil strata
   (c) Depth of bed rock
   (d) Depth of water table

A.2 How do you collect above information at the briefing design stage ?
   (a) Experience of past of the same locality
   (b) Walk over inspection
   (c) Site tests
A.3 Do you recommend a suitable type of foundation in briefing design stage such as
   (a) Pile foundation 
   (b) Raft foundation 
   (c) Independent footing foundation. 
   (d) Strip foundation etc.

A.4 On what basis do you recommend a suitable type of foundation in briefing design 
   stage ? 
   (a) Experience, considering size of building knowledge of locality etc. 
   (c) Approximate column loads and pressure of the building. 
   (d) Cost of each type of foundation 

Sketch design stage foundation designs

A.5 What are the additional information do you collect during sketch (scheme and 
   outline) design stage for foundation designs ? 
   (a) Soil bearing pressure 
   (b) other soil mechanics properties such as settlements 
   (c) Accurate column loads etc. 

A.6 How do collect above information in A.5 ? 
   (a) Site investigation (bore holes etc.) 
   (b) Information from near by sites. 

A.7 What are the design decisions you make at sketch design stage with respect to 
   foundation designs ? 
   (a) Detail study on feasible type(s) decided at briefing design stage 
   (b) Investigation of suitable types etc. 

A.8 How do you make design decisions related to foundations at sketch design stage ? 
   (a) Technical parameters such as soil bearing pressure, settlements, column 
      loads etc. 
   (b) Cost of feasible types of foundations
A.9 What are the cost data you use at sketch design stage for foundation design decisions?
   (a) Unit rates of concrete, steel, pile costs etc.
   (b) Historical data (data of past similar projects)

A.10 How do you perform cost calculations of feasible foundation types?
   (a) Approximate designs
   (b) Past designs and past cost data (cost data of past projects)

Detail design stage

A.11 Discuss the detail design stage foundations designs
   (a) Detail design of selected type in sketch design stage
   (b) Changes possible for the selected type etc.

Cost effective foundation designs

A.12 Do you know any cost effective foundation design method?
   (a) Structural analysis methods such as methods based on finite elements theory etc.
   (b) Optimum reinforced concrete design methods for foundation types such as independent footings, raft foundations etc.

A.13 If you know any cost effective design methods do you use those methods in your normal foundation design work?
   Yes - Goto questions A.14
   No - Goto question A.15.

A.14 Please give details on cost effective foundation methods you use.
   (a) Analysis methods e.g. finite elements theory
   (b) Optimum structural design methods
   (c) Methods based on cost information

A.15 What are the reasons for not using cost effective design methods you know, discuss.
   (a) Cost saving possible through cost effective methods are not significant
   (b) Practical limitation such as lack of design time available, need of computers etc.
A.16 What is the minimum cost saving you expect from optimum concrete design methods developed for detail design of reinforced concrete foundations such as independent footings? You may consider the details given as an illustration.

Assume that you are designing a four story office complex of Rs 20 million and foundation cost is Rs 1.2 million.

<table>
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<td>&lt;50 000</td>
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A.17 What are the practical difficulties in implementing (or using) cost effective design methods for foundations designs?
(a) No incentive (no additional design fee)
(b) Actually negative incentive in percentage fee design contracts.
(c) Opposition for other members of the design team considering the safety of the new methods, unseen, unfamiliar design calculations etc.
(d) Additional design time requirements
(e) Requirements of computer, computer software etc.

A.18 What are the changes required to implement cost effective design methods in practice?
(a) A project management system to convince clients to give additional design fee.
(b) Use of design and build contracts.

B. BEAMS, COLUMNS AND FLOORS DESIGNS

Briefing design stage

B.1 What are the design decision you make during briefing design stage (inception and feasibility design stage)?
(a) Building floor area (building size)
(b) Building shape together with some sketches
(c) Number of storeys, storey height.
(d) column grid etc. - discuss
B.2 How do you make above design decisions?
(a) clients requirements
(b) available site
(c) suitable structural forms
(d) available funds
(e) using approximate cost guides
(f) using past experience
(g) using historical data of past projects (both cost and design data).

Sketch design stage

B.3 What are the design decisions you make during sketch design stage (inception and feasibility design stage)?
(a) column grid
(b) beam layout,
(c) type of floor - discuss

B.4 How do you make above design decisions?
(a) clients requirements
(b) building shape, size
(c) structural forms
(e) using approximate cost guides
(f) using past experience
(g) using historical data of past projects (both cost and design data).

B.5 Do you need additional cost information to make above design decisions cost effective?
-discuss

B.6 If a system is developed for cost information related to design decisions, do you think that it will be useful for the above design decision making?

B.7 What are the practical limitations you see for the development and implementation of a cost information system discussed in above B.4?
-discuss
Detail design stage

B.8 Do you know optimum design methods for detail design of reinforced concrete slabs?

B.9 Do you have any experience of using cost effective (optimum methods) methods for design of reinforced concrete slabs?

B.10 If you know any optimum method for reinforced concrete slab design what are reasons for not using them?
   (a) methods are not practical
   (b) cost savings cannot be significant
   (c) need extra design time, computer, software etc.

B.11 What is the minimum cost saving you expect from reinforced concrete slab design method before implementing in current design practice?
   You may consider the example given as an illustration.
   Assume that you are designing a four storey office building of which total cost is Rs 20 million. The total cost slabs is 2.0 million.

<table>
<thead>
<tr>
<th>Minimum cost saving</th>
<th>10 000</th>
<th>20 000</th>
<th>50 000</th>
<th>100 000</th>
<th>200 000</th>
<th>500 000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Should be more than</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B.12 Do you know optimum design methods for detail design of reinforced concrete beams?

B.13 Do you have any experience of using cost effective (optimum methods) methods for design or reinforced concrete beams?

B.14 If you know any optimum method for reinforced concrete beams design what are reasons for not using them?
   (a) methods are not practical
   (b) cost savings cannot be significant
   (c) need extra design time, computer, software etc.
B.15 What is the minimum cost saving you expect from reinforced concrete beam design method before implementing into current design practice? You may consider the example given as an illustration. Assume that you are designing a four storey office building of which total cost is Rs 20 million. The total cost slabs is 1.5 million.

| Minimum cost saving should be more than |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| <10 000         | 10 000          | 20 000          | 50 000          | 100 000         | 200 000         |

B.16 Do you know optimum design methods for detail design of reinforced concrete columns?

B.17 Do you have any experience of using cost effective (optimum methods) methods for design of reinforced concrete columns?

B.18 If you know any optimum method for reinforced concrete column design what are reasons for not using them?
   (a) methods are not practical
   (b) cost savings cannot be significant
   (c) need extra design time, computer, software etc.

B.19 What is the minimum cost saving you expect from reinforced concrete column design method before implementing in current design practice? You may consider the example given as an illustration. Assume that you are designing a four storey office building of which total cost is Rs 20 million. The total cost slabs is 0.5 million.

| Minimum cost saving should be more than |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| <10 000         | 10 000          | 20 000          | 50 000          | 100 000         | 200 000         |

B.20 What are the practical difficulties in implementing optimum design methods for slabs, beams and columns in current practice?
   (a) Extra design time required
   (b) no incentive
   (c) actually negative incentive in some design contracts such as percentage fee design contracts.
(d) need of additional facilities such as computers, software.  
(e) need to know new design methods etc.

B.21 Do you think that you can accommodate changes demand by optimum design methods?  
(a) Higher or lower beam depths  
(b) Higher or lower slab depths  
(c) Higher or smaller columns sizes

C. ROOF

Briefing design stage

C.1 What are the design decisions you make during briefing design stage related to roof?  
(a) Only idea about the roof type  
(b) Type of roof structure  
(c) Type of roofing material

C.2 How do you make design decisions related to the roof in briefing design stage?  
(a) Using experience to suit the building  
(b) Using cost guides of different roofs

Sketch design stage

C.3 What are the design decisions you make during sketch design stage related to roof?  
(a) Development of the idea of briefing design stage  
(b) Type of roof structure  
(c) Type of roofing material

C.4 How do you make design decisions related to roof in sketch design stage?  
(a) Using experience to suit the building  
(b) Using cost guides of different roofs
Detail design stage

C.5 What are the design decisions at the detail design stage related to roof - discuss

C.6 How do you think cost is related to various types of roofs given below.
0 - cheapest 1 - second cheapest 2 - third cheapest X - not suitable

<table>
<thead>
<tr>
<th>Span</th>
<th>Steel trusses</th>
<th>Steel open girders</th>
<th>Timber trusses</th>
<th>Concrete beams</th>
<th>Concrete flat roofs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 - 7.5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5 - 10 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 - 15 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 - 20 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 - 25 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 - 30 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 m &gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C.7 Do you know any optimum (cost effective) design method for roof design.

C.8 What is minimum cost saving that you expect from cost effective roof structure design method before its implementation in current design practice
You may consider the example given below as an illustration
Total cost of four storey office building is Rs 20 million and cost of roof structure is 0.5 million.

<table>
<thead>
<tr>
<th>Cost saving should be more than</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10 000</td>
</tr>
</tbody>
</table>

285
D. EXTERNAL AND INTERNAL WALLS

D.1 At what design stage do you design external and internal walls?
(a) Briefing design stage
(b) Sketch design stage
(c) Detail design stage

D.2 How do you decide on type of external and internal wall?
(a) Building functional requirements
(b) Cost considerations
(c) Clients preferences

D.3 What is the cost difference required for you to change the selected external wall type to a cheaper suitable type? - discuss
You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of external walls is Rs 200 000.

<table>
<thead>
<tr>
<th>Change if cost difference is more than</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 000</td>
</tr>
</tbody>
</table>

D.4 What is the cost difference required for you to change the selected external wall type to an expensive suitable type? - discuss
You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of external walls is Rs 200 000.

<table>
<thead>
<tr>
<th>Change if cost difference is less than</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 000</td>
</tr>
</tbody>
</table>

D.5 What is the cost difference required for you to change the selected internal wall type to a cheaper suitable type? - discuss
You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of internal walls is Rs 250 000.
D.6 What is the cost difference required for you to change the selected internal wall type to a expensive suitable type? - discuss

You may consider the example given below as an illustration. Consider that you are designing a four storey office building of which total cost is Rs 20 million and total cost of internal walls is Rs 250,000.

<table>
<thead>
<tr>
<th>Change if cost difference is more than</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
</tr>
<tr>
<td>20,000</td>
</tr>
<tr>
<td>30,000</td>
</tr>
<tr>
<td>40,000</td>
</tr>
<tr>
<td>50,000</td>
</tr>
<tr>
<td>100,000</td>
</tr>
</tbody>
</table>

E. JOINER

Windows

E.1 At what design stage do you design types of doors and windows for a building?
(a) Briefing design stage
(b) Sketch design stage
(c) Detail design stage

E.2 How do you decide on types of doors and windows?
(a) Building functional requirements
(b) Cost considerations
(c) Clients preferences
E.3 What is the cost difference required you for to change the selected window type to a cheaper suitable type? - discuss

You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of windows is Rs 1.2 million.

<table>
<thead>
<tr>
<th>Change if cost difference is more than</th>
<th>10 000</th>
<th>20 000</th>
<th>50 000</th>
<th>100 000</th>
<th>250 000</th>
<th>500 000</th>
</tr>
</thead>
</table>

E.4 What is the cost difference required for you to change the selected window type to an expensive suitable type? - discuss

You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of windows is Rs 1.2 million.

<table>
<thead>
<tr>
<th>Change if cost difference is less than</th>
<th>10 000</th>
<th>20 000</th>
<th>50 000</th>
<th>100 000</th>
<th>250 000</th>
<th>500 000</th>
</tr>
</thead>
</table>

E.5 What is the cost difference required for you to change the selected doors type to a cheaper suitable type? - discuss

You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of doors is Rs 300 000.

<table>
<thead>
<tr>
<th>Change if cost difference is more than</th>
<th>10 000</th>
<th>20 000</th>
<th>30 000</th>
<th>50 000</th>
<th>100 000</th>
<th>150 000</th>
</tr>
</thead>
</table>
E.6 What is the cost difference required for you to change the selected doors type to an expensive suitable type? - discuss
You may consider the example given below as an illustration. Consider that you are designing a four storey office building of which total cost is Rs 20 million and total cost of doors is Rs 300,000.

<table>
<thead>
<tr>
<th>Change if cost difference is less than 100,000</th>
<th>10,000</th>
<th>20,000</th>
<th>30,000</th>
<th>50,000</th>
<th>100,000</th>
<th>150,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F. FINISHES

Floor finishes

F.1 At what design stage do you design types of floor and wall finishes for a building?
(a) Briefing design stage
(b) Sketch design stage
(c) Detail design stage

F.2 How do you decide on types of floor and wall finishes?
(a) Building functional requirements
(b) Cost considerations
(c) Clients preferences

F.3 What is the cost difference required for you to change the selected floor finish type to a cheaper suitable type? - discuss
You may consider the example given below as an illustration. Consider that you are designing a four storey office building of which total cost is Rs 20 million and total cost of floor finishes is Rs 700,000.

<table>
<thead>
<tr>
<th>Change if cost difference is more than 200,000</th>
<th>10,000</th>
<th>20,000</th>
<th>50,000</th>
<th>100,000</th>
<th>200,000</th>
<th>300,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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F.4 What is the cost difference required you to change from the selected floor finishes type to a expensive suitable type? - discuss
You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of floor finishes is Rs 700 000.

<table>
<thead>
<tr>
<th>Change if cost difference is less than</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 000</td>
</tr>
<tr>
<td>20 000</td>
</tr>
<tr>
<td>50 000</td>
</tr>
<tr>
<td>100 000</td>
</tr>
<tr>
<td>200 000</td>
</tr>
<tr>
<td>300 000</td>
</tr>
</tbody>
</table>

F.5 What is the cost difference required for you to change the selected wall finish type to a cheaper suitable type? - discuss
You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of wall finishes is Rs 500 000.

<table>
<thead>
<tr>
<th>Change if cost difference is more than</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 000</td>
</tr>
<tr>
<td>20 000</td>
</tr>
<tr>
<td>50 000</td>
</tr>
<tr>
<td>100 000</td>
</tr>
<tr>
<td>150 000</td>
</tr>
<tr>
<td>200 000</td>
</tr>
</tbody>
</table>

F.6 What is the cost difference required for you to change the selected wall finishes type to a expensive suitable type? - discuss
You may consider the example given below as an illustration. Consider that your are designing a four storey office building of which total cost is Rs 20 million and total cost of wall finishes is Rs 500 000.

<table>
<thead>
<tr>
<th>Change if cost difference is less than</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 000</td>
</tr>
<tr>
<td>20 000</td>
</tr>
<tr>
<td>50 000</td>
</tr>
<tr>
<td>100 000</td>
</tr>
<tr>
<td>150 000</td>
</tr>
<tr>
<td>200 000</td>
</tr>
</tbody>
</table>
APPENDIX C

DESIGN OF REINFORCED CONCRETE ELEMENTS

Reinforced concrete design procedures for slabs, beams, short columns and independent footings are given here. The procedures given here were used in the reinforced concrete optimum design methods given in chapter 4 of this thesis. The design methods discussed satisfy BS8110 and Institute of structural engineers manual for reinforced concrete designs (1985).

C. 1 REINFORCED CONCRETE SLAB DESIGNS

Design procedure for reinforced concrete slabs, both one-way span continuous over 3 spans and two-way span restrained slabs are given here. The details include evaluation of loads for slabs, detail calculation of reinforcements, shear checks, deflection checks etc. The design method described here was used to formulate the optimum reinforced concrete slab design method in section 4.2 of this thesis.

C. 1.1 Loads on slabs

BS6399:Part 1 has given following loads for reinforced concrete slabs.

A. Imposed load (qk)

<table>
<thead>
<tr>
<th>Building category</th>
<th>Load kN/m2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. General offices</td>
<td>2.5</td>
</tr>
<tr>
<td>2. Storages spaces in offices</td>
<td>5.0</td>
</tr>
<tr>
<td>3. Computer rooms in offices</td>
<td>3.5</td>
</tr>
<tr>
<td>4. Shops</td>
<td>4.0</td>
</tr>
<tr>
<td>5. Hotels</td>
<td>5.0</td>
</tr>
</tbody>
</table>

B. Dead load (gk)

Following data were used for dead load calculations.

- Concrete density = 24kN/m3
- Finishes and partitions = 2.5kN/m2
BS8110 defines the design load slabs as follows.

Design load \( n = 1.4g_k + 1.6q_k \) \[C.1\]
where \( g_k \) = characteristic dead load
\( q_k \) = characteristic imposed load.

C.1.2 Bending moments in slabs

Case 1 One way span slabs

For one way span slabs bending moments can be calculated according to clause 3.5.2.4 of BS8110. In this case Table 3.6 of BS8110 gives bending moment coefficients.

<table>
<thead>
<tr>
<th>Moment</th>
<th>Near middle</th>
<th>At first interior</th>
<th>At middle of interior spans</th>
<th>A interior</th>
</tr>
</thead>
<tbody>
<tr>
<td>At outer support of end span</td>
<td>0</td>
<td>0.09F1</td>
<td>-0.11F1</td>
<td>0.07F1</td>
</tr>
<tr>
<td>Near middle at outer support</td>
<td>0.45F</td>
<td>0.6F</td>
<td></td>
<td>0.55F</td>
</tr>
</tbody>
</table>

where,

\( F \) is the total design ultimate load \( (1.4G_k + 1.6Q_k) \)
\( l \) is the span.

Case 2 Two way span slabs

For two way span restrained slabs BS8110 has given following equations to calculate the bending moments.

\[ m_{sx} = \beta_{sx}n_lx^2 \] \[C.2\]
\[ m_{sy} = \beta_{sy}n_ly^2 \] \[C.3\]

Where \( \beta_{sx} \) and \( \beta_{sy} \) can be obtain form Table 3.15 of BS8110 or from the following equations.

\[ \beta = (24 + 2Nd + 1.5Nd^2) \] \[C.4\]
\[ \gamma = \frac{2}{9}[3 - \sqrt{18.1x/ly} \{\sqrt{(\beta_y + \beta_1)} + \sqrt{(\beta_y + \beta_2)}\}] \] \[C.5\]
\[ \gamma = \sqrt{(\beta_x + \beta_3)} + \sqrt{(\beta_y + \beta_4)} \] \[C.6\]

where,

\( Nd \) = number of discontinues edges
\( \beta_1, \beta_2 = 4/3\beta_y \) for continuous edge
= 0 for discontinues edge
\( \beta_3, \beta_4 = 4/3\beta_x \) for continuous edge
= 0 for discontinuous edge

Figures C.1 illustrate the bending moments and respective coefficients. Figure C.2 gives the procedure to calculate bending moment coefficients and bending moments.
Figure C.1 Moments & coefficients in slabs
START

Input the following
1. Design load n
2. Number of discontinous short edges \( N_S \)
3. Number of discontinous long edges \( N_L \)
4. Input \( l_x, l_y \)

\[ N_d = N_S + N_L \]
\[ \beta_y = \frac{(24 + 2N_d + 1.5N_d^2)}{1000} \]

1. Case of \( N_S = 0 \) then
   \[ \beta_1 = \frac{4}{3}\beta_y, \quad \beta_2 = \frac{4}{3}\beta_y \]
2. Case of \( N_S = 1 \) then
   \[ \beta_1 = \frac{4}{3}\beta_y, \quad \beta_2 = 0 \]
3. Case of \( N_S = 2 \) then
   \[ \beta_1 = 0, \quad \beta_2 = 0 \]

\[ m_1 = \beta_1 n l_x^2; \quad m_2 = \beta_2 n l_x^2; \quad m_y = \beta_y n l_x^2 \]
\[ \gamma = \frac{2}{9}[3 - \sqrt{18}] \frac{l_y}{l_x} \{\sqrt{(\beta_y + \beta_1) + \sqrt{(\beta_y + \beta_2)}}\]}

1. Case of \( N_L = 0 \) then
   \[ \beta_x = \frac{\gamma}{4(1 + 4/3)}; \quad \beta_3 = 4/3\beta_x; \quad \beta_4 = 4/3\beta_x \]
2. Case of \( N_L = 1 \) then
   \[ \beta_x = \frac{\gamma}{\sqrt{(1+4/3)}}; \quad \beta_3 = 4/3\beta_x; \quad \beta_4 = 0 \]
3. Case of \( N_L = 2 \) then
   \[ \beta_x = \frac{\gamma}{4}; \quad \beta_3 = 0; \quad \beta_4 = 0; \]

\[ m_x = \beta_x n l_x^2; \quad m_3 = \beta_3 n l_x^2; \quad m_4 = \beta_4 n l_x^2 \]

STOP

Figure C.2  Procedure to calculate bending moments in two way span slabs
Get values of bending moment (BM), shear force, slab thickness, Ix, ly, fcu, fy, etc.

\[ d = h - 25 \]
\[ d1 = 25 \]
\[ K = \frac{BM}{bd^2 f_{cu}} \]

\[ Z = d[0.5 + \sqrt{(0.25 - \frac{K}{0.9})}] \]
\[ x = \frac{(d - Z)}{0.45} \]
\[ As = \frac{BM}{0.87f_y Z} \]

**If Yes**

\[ K < 0.156 \]
\[ Asl = \frac{(K - 0.156)f_{cu} bd^2}{0.87f_y (d - d1)} \]
\[ As = \frac{0.156f_{cu} bd^2}{0.87f_y Z} + Asl \]

If Yes, provide As from Table C.1 which is just higher than As. Record As and bar spacing (SP).

**If No**

\[ As/ bd < 0.0013 \]
\[ As = 0.0013bd \]

Provide As from Table C.1 which is just higher than As. Record bar spacing. If Yes, provide As just higher value from Table C.1. Record bar spacing.

Print As as the result

**STOP**

*Figure C.3 Procedure to provide reinforcement*
C.1.3 Reinforcement area calculations

BS8110 recommend same procedure as beams for the calculations of the required reinforcement area for slabs. Therefore design procedure given in clause 3.4.4.4 of BS8110 can be used. Alternatively, BS8110 suggests to use design charts in Part 3. For the calculation procedure unit width of the slab was used.

Calculation procedure as a summary is shown in Figure C.4 flow chart and details are given below. Symbols defined in clause 3.4.4.3 of BS8110 were used for the design calculations. These are:

- $A_s$ - area of tension reinforcements;
- $A_s'$ - area of compression reinforcements;
- $b$ - width (=1000mm in metric);
- $d$ - effective depth of tension reinforcements;
- $d'$ - effective depth of compression reinforcements;
- $M$ - design ultimate moment of resistance;
- $x$ - depth to neutral axis;
- $z$ - lever arm;
- $f_{cu}$ - ultimate concrete strength;
- $f_y$ - ultimate steel strength; and
- $h$ - slab thickness;

Following assumptions were made for the calculations.

1. No redistribution of moments.
2. 10mm or higher bar diameter for main reinforcements. Institute of structural engineers manual minimum bar diameter is 10mm.
3. General assumptions in BS8110.
4. Cover = 20mm.

\[
d = h - 20 - 10/2 = h - 25 \tag{C.7}
\]

\[
K' = 0.156 \quad (\text{No redistribution})
\]

\[
K = \frac{M}{bd^2f_{cu}} \tag{C.8}
\]
Case 1 \( K \leq K' \)

\[
z = d \left( 0.5 + \sqrt{0.25 - \frac{K}{0.9}} \right)
\]

but \( z \leq 0.95d \)

\[
x = \frac{(d - z)}{0.45}
\]

\[
As = \frac{M}{0.87f_y z}
\]

\[..C.9\]

### Table C.1 Reinforcement areas for slabs

<table>
<thead>
<tr>
<th>Area (mm²)</th>
<th>Bar diameter (mm)</th>
<th>Bar spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>261</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td>280</td>
<td>10</td>
<td>280</td>
</tr>
<tr>
<td>302</td>
<td>10</td>
<td>260</td>
</tr>
<tr>
<td>327</td>
<td>10</td>
<td>240</td>
</tr>
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<td>357</td>
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<td>561</td>
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<td>160</td>
</tr>
<tr>
<td>1436</td>
<td>16</td>
<td>140</td>
</tr>
<tr>
<td>1676</td>
<td>16</td>
<td>120</td>
</tr>
<tr>
<td>2011</td>
<td>16</td>
<td>100</td>
</tr>
</tbody>
</table>

Case 2 \( K > K' \)

\[
z = d \left( 0.5 + \sqrt{0.25 - \frac{K'}{0.9}} \right)
\]

\( K' = 0.156 \)

Therefore;

\[
z = 0.7768d;
\]

\[
x = \frac{(d - z)}{0.45}
\]

\[
As' = \left( K - K' \right) f_{cu} b d^2 / 0.87f_y (d - d')
\]

\[..C.10\]
\[ As = K'_{cu} b d^2 / 0.87 f_y z + As' \] ..C.11

Provide reinforcement area just higher than required from Table C.1.

C.1.4 Deflection of slabs

Deflection of slabs has to be checked according to clause 3.5.7 of BS8110.

\[ f_s = \frac{5}{8} f_y \frac{A_{s_{bx\text{req}}}}{A_{s_{bx\text{prov}}}} \] ..C.12

Modification factor = 0.55 + \frac{(477 - f_s)}{120(0.9 + \frac{M_{x}}{bd^2})} ..C.13

Therefore

\[ \frac{\text{span}}{\text{depth}} = 26X(\text{modification factor}) \] ..C.14

C.1.5 Shear check of slabs

BS8110 gives coefficients and the following equations to calculate the shear stress in two span slabs. Calculations of shear forces of one way span slabs was given above (C.1.2).

\[ V = \beta n_1 \quad \text{sy} \quad \text{vy} \quad x \] ..C.15

\[ V = \beta n_1 \quad \text{sx} \quad \text{vx} \quad x \] ..C.16

Coefficients of \( \beta_{vy} \) and \( \beta_{vx} \) are given in Table 3.16 of BS8110. For slabs deflection and flexure are the most critical design criteria and therefore for simplicity of calculations maximum values in Table 3.16 of BS8110 were used in this research. The values used are given below.
Maximum shear stress allowable in BS8110 is:

\[ v = 0.8\sqrt{f_{cu}} \text{ or } 5\text{N/mm}^2 \text{ whichever is the lesser.} \]

Shear stress \( v = \frac{V}{bd} \)

Therefore,

\[ v \leq 0.8\sqrt{f_{cu}} \text{ or } 5\text{N/mm}^2 \text{ whichever is lesser} \]

C.1.6 Maximum and minimum reinforcement requirements

Clause 3.12.5.3 of BS8110 requires minimum of 0.13\% of bh (for \( f_y = 460, 410 \) N/mm\(^2\)) reinforcements for slabs. Clause 3.12.6 of BS8110 specify maximum steel ratio of 4\% of bh for slabs.

C.1.7 Maximum and minimum distance between bars

The restriction on maximum distance between bars are intended for controlling crack width (clause 3.12.11.2 of BS8110) and apply only to tension bars. Maximum spacing between bars \( \leq 3d \) or 300mm whichever is lesser. (Institute of Structural engineers manual 1985). The above requirements was checked before providing the reinforcement in design procedure given above (see Figure C.3).
C.2 REINFORCED CONCRETE BEAM DESIGN

The general beam arrangement shown in Figure C.4. The design procedure given here for beams satisfy:

(a) BS8110 design requirements; and
(b) Institute of structural engineers manual (1985)

The symbols used are as follows.

As area of tension reinforcement
As' area of compression reinforcement
b with or effective width of the section or flange in the compression zone
bw average web width of a flanged beam
d effective depth of tension reinforcement
d' effective depth of compression reinforcement
hf thickness of the flange
M design ultimate resistance moment
x depth to the neutral axis
\( \beta_b \) the ratio

(moment at the section after redistribution)
(moment at the section before redistribution)

C.2.1 Reinforcement design in rectangular section

Procedure given below was used to calculate the required reinforcement areas in rectangular beam sections (2-2 and 3-3).

Clause 3.4.4.4 of BS8110 gives the equations to calculate the reinforcement areas. Detailed description of use of equations are given by Kong and Evans (1987).

\[ K' = 0.156 \text{ where redistribution does not exceed } 10\% \; ; \text{ or} \]

\[ K' = 0.402(\beta - 0.40) - 0.18(\beta - 0.45) \text{ where redistribution exceed } 10\% \]

\[ K = \frac{M}{b d f c u} \]

..C.8
Case 1. If $K \leq K'$, compression reinforcement is not required and:

$$z = d \{ 0.5 + \sqrt{0.25 - \frac{K}{0.9}} \} \text{ but not greater than } 0.95d$$

$$x = \frac{(d - z)}{0.45}$$

$$As = \frac{M}{0.87fy}$$

Figure C.4 Reinforced concrete beam
Case 2. If $K > K'$, compression reinforcement is required and:

\[ z = d \left( 0.5 + \sqrt{0.25 \left( \frac{K'}{0.9} \right)} \right) \]
\[ x = \frac{(d - z)}{0.45} \]

assuming redistribution is less than 10%.

$K' = 0.156$, therefore

\[ z = 0.7769d \]
\[ x = 0.4958d \]
\[ As' = \frac{(K - 0.156)fcubd^2}{0.87f(d-d')} \]
\[ As = \frac{0.156fcubd^2}{0.87fz} + As' \]

The above equations gives the required $As$ and $As'$ values. Provide reinforcements from Table C.2 just higher than $As$ or $As'$ required.

C.2.2 Flange beam sections

Design and flange sections are more complicated than rectangular sections because the neutral axis could lie inside or outside the flange. Consequently, additional check is required to find the position of neutral axis before calculating reinforcement requirements. The simplified procedure given Kong and Evans (1987) was used for reinforcement area calculations. The method used is given below.

If the neutral axis in flange, $x/d$ ratio $\leq hf/d$; and
If the neutral axis is outside flange $x/d$ ratio $> hf/d$.

In the quick design method given by Kong and Evans (1987) the $x/d$ ratio in not checked explicitly. Instead, two simplifying assumptions are made:

(a) The depth of the BS8110 rectangular stress block in not less than the flange thickness, i.e. $0.9x \geq hf$. (If in fact $0.9x < hf$, then the design errors slightly on the sage side.)

(b) The compressive force in the web below the flange (shaded area in Figure C.5) is neglected.
The forces in the beam section are then as shown in Figure C.5, where the steel stress $f_s$ depends on $x/d$ ratio. For $f_y = 460\, \text{N/mm}^2$ (or $f_y = 410\, \text{N/mm}^2$), $f_s = 0.87f_y$, provided $x/d$ ratio does not exceed 0.64. Hence

$$M = 0.87f_yA_s[ d - \frac{hf}{2}]$$  .. C.21

where $(d-hf/2)$ is take as the lever arm. If $x/d$ exceed 0.64, then the steel stress $f_s$ is less than the design strength, and the moment capacity of the flange is given by

$$M_u = 0.45f_{cub}hf[ d - \frac{hf}{2}]$$  .. C.22

**Case 1** $M \leq M_u$ then

$$A_s = \frac{M}{0.87f_y[ d - hf/2]}$$  .. C.23

**Case 2** $M > M_u$

Procedure given in Institute of structural engineers was used and details are given below.

The ultimate resistance moment of the flange $M_{u_f}$:

$$M_{u_f} = 0.45f_{cu}(b - bw)hf( d - 0.5hf)$$  .. C.24

$$K_f = \frac{(M - M_{u_f})}{f_{cub}wd}$$  .. C.25

If $K_f \leq 0.156$ then

$$A_s = \frac{M_{u_f}}{0.87f_y(d - 0.5hf)} + \frac{(M - M_{u_f})}{0.87f_z}$$  .. C.26
where,
\[ K = \frac{M}{bf_{cu}} \quad \text{and} \]
\[ z = d\left(0.5 + \sqrt{\frac{0.25 - K}{0.9}}\right) \quad \text{but not greater than 0.95d} \]

If \( K_f > 0.156 \) then
\[ Asf = \frac{Muf}{0.87f(d - 0.5h_f)} \]
\[ Asw = \frac{(M - Muf)}{0.87fz} \]
\[ As = Asf + Asw \]

Provide reinforcement area \( (A_{s,\text{pro}}) \) from Table C.2 just higher than \( A_s \) calculated.

### C.2.3 Beam deflection check

Table 3.10 of BS8110 gives the basic span depth ratio for deflection check as given below.

<table>
<thead>
<tr>
<th>Support condition</th>
<th>Rectangular section</th>
<th>Flanged beams with ( bw/b \leq 0.3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cantilever</td>
<td>7</td>
<td>5.6</td>
</tr>
<tr>
<td>Simply supported</td>
<td>20</td>
<td>16.0</td>
</tr>
<tr>
<td>Continuous</td>
<td>26</td>
<td>20.8</td>
</tr>
</tbody>
</table>

The above factors should be modified according to tension and compression reinforcements.

Modification factor for tension reinforcements:
\[ = 0.55 + \frac{477 - fs}{120(0.9 + \frac{M}{bd^2})} \leq 2.0 \]

where,
\[ fs = \frac{5f_yA_{s,\text{req}}}{8A_{s,\text{pro}}} \times \frac{1}{\beta_b} \]

Modification factor for compression reinforcements:
Therefore deflection check is (for continuous beams):
\[ \frac{1}{2} \leq 26(\text{Modifications factor tension})(\text{Modification factor for compression}) \]

..C.32

Table C.2 Reinforcement areas for beams

<table>
<thead>
<tr>
<th>Area mm²</th>
<th>Diameter(s)</th>
<th>Number of bars</th>
<th>Area mm²</th>
<th>Diameter(s)</th>
<th>Number of bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>226</td>
<td>12</td>
<td>2</td>
<td>1570</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>329</td>
<td>12</td>
<td>3</td>
<td>1673</td>
<td>25, 16</td>
<td>3, 1</td>
</tr>
<tr>
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<td>16</td>
<td>2</td>
<td>1786</td>
<td>25, 20</td>
<td>3, 1</td>
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<td>1963</td>
<td>25</td>
<td>4</td>
</tr>
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<td>12</td>
<td>5</td>
<td>2164</td>
<td>25, 16</td>
<td>4, 1</td>
</tr>
<tr>
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<td>3</td>
<td>2453</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>628</td>
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<td>2</td>
<td>2726</td>
<td>32, 20</td>
<td>3, 1</td>
</tr>
<tr>
<td>741</td>
<td>20, 12</td>
<td>2, 1</td>
<td>2944</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>804</td>
<td>16</td>
<td>4</td>
<td>3080</td>
<td>32, 25</td>
<td>2, 3</td>
</tr>
<tr>
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<td>1, 2</td>
<td>3216</td>
<td>32</td>
<td>4</td>
</tr>
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<td>3435</td>
<td>25</td>
<td>7</td>
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<td>32</td>
<td>5</td>
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<td>32, 25</td>
<td>5, 1</td>
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<td>2, 2</td>
<td>5628</td>
<td>32</td>
<td>7</td>
</tr>
<tr>
<td>1472</td>
<td>25</td>
<td>3</td>
<td>6432</td>
<td>32</td>
<td>8</td>
</tr>
</tbody>
</table>

C.2.4 Minimum area of main reinforcement

Clause 3.12.5 of BS8110 gives the minimum steel area requirements for beams. These are:

(a) **Rectangular beams**: the tension steel area \( A_s \) should not be less than \( 0.13\% \) of \( bD \) where \( b \) is the beam width and \( D \) the overall depth. (The Institute of structural engineers (1985) recommend a minimum of 0.2%).
(b) **Flanged beams (web in tension):** The minimum percentage depend on the ratio of the web width \( bw \) to the effective flange width \( b \). If \( bw/b < 0.4 \), the minimum is 0.18% \( bwD \), if \( bw/b \geq 0.4 \) the minimum is 0.13% \( bwD \). (The Institute of structural engineers (1985) recommend a minimum of 0.2%\( bD \) for both cases).

(c) **Flanged beams (flange in tension over a continuous support):** 0.26% of \( bwD \) for T-beams; 0.2% of \( bwD \) for L-beams.

C.2.5 **Maximum areas of main reinforcement**

Clause 3.12.6 gives the maximum steel area for beams. As nor \( As' \) should exceed 4% of \( bD \).

C.3 **DESIGN METHOD FOR SHORT COLUMNS**

C.3.1 **Columns subject to uniaxial bending**

Generally, reinforced concrete design of columns are more complex than slabs and beams. In this research the computer was used to produce design solutions. Therefore iterative design procedure given by Hulse and Mosley (1987) was used. Details of this design procedure is given below. The method can be used only for rectangular and for symmetrical arrangement of reinforcement (see Figure C.6).

![Figure C.6 Column stress and strains under a moment and a axial force](image_url)
Form the strain diagram strains of reinforcements \( \varepsilon_s \) and \( \varepsilon_{sc} \) can be calculated as given below:

\[
\varepsilon_s = \frac{0.0035(x - d')}{x} \quad \text{..C.33}
\]

\[
\varepsilon_{sc} = \frac{0.0035(d - x)}{x} \quad \text{..C.34}
\]

Axial load capacity of the section is given by the equation:

\[
N_u = f_{bkx} + A's_{fc} - A's_f \quad \text{..C.35}
\]

For symmetrical arrangement of reinforcement:

\[
A's' = A's \quad \text{(Figure C.6)} = A's/2 \quad \text{..C.36}
\]

where,

\[
A's = \text{total reinforcement area provided}
\]

\[
N_u = f_{bkx} + A's/2(f_{sc} - f_s) \quad \text{..C.37}
\]

\( f_{sc} \) - compression steel stress

\( f_s \) - tension steel stress

Therefore

\[
A's = \frac{2[Nu - kfx]}{(f_{sc} - f_s)} \quad \text{..C.38}
\]

Similarly the ultimate moment capacity of the section is given by equation:

\[
M_u = kfx \left(\frac{h - kx}{2}\right) + A's_{fc} \left(\frac{h}{2} - d'\right) + A's_f \left(\frac{h}{2}\right) \quad \text{..C.39}
\]

\[
A's' = A's = A's/2 \quad d = h - d' \quad \text{..C.40}
\]

Therefore,

\[
A's = \frac{2[Mu - kfx(h - kx)/2]}{[(h/2 - d')(f_{sc} + f_s)]} \quad \text{..C.41}
\]

If it is possible to find the position of the neutral axis \( x \) depth which gives the same answer for the steel area \( A's \) in above two equations then required steel area can be found. The simplest method to find \( x \) is by iteration using the computer. A procedure to find \( A's \) through iteration method is shown in Figure C.7.
C.3.2 Columns subjected to bi-axial bending

BS8110 gives a simplified method to design columns subjected to bi-axial bending. Firstly critical bending axis is determined. Secondly, effective bending moment on critical axis is calculated. Finally the column is design as uni-axial bending column form the procedure given above.

1. Critical bending axis is X-X if:
   \[
   \frac{M_x}{h'} \geq \frac{M_y}{b'}
   \]
   Design moment \( M_{x}' = M_x + \beta \frac{h'M_y}{b'} \)  \( ..C.42 \)

2. Critical bending axis is Y-Y if:
   \[
   \frac{M_x}{h'} < \frac{M_y}{b'}
   \]
   Design moment \( M_{y}' = M_y + \beta \frac{b'M_x}{h'} \)  \( ..C.43 \)

where,
\[
\beta = 0.3 + \frac{7}{6} \left(0.6 - \frac{Nu}{bhf_{cu}}\right) \]  \( ..C.44 \)

Provide reinforcement area (As prov) just higher than As from Table C.3

C.3.3 Minimum reinforcement area in columns

The total area \( A_{sc} \) of the longitudinal bars should not be less than 0.4\% of the cross-sectional area of the column (Clause 3.12.5 of BS8110)

C.3.4 Maximum reinforcement area in columns

The longitudinal bar area should not exceed 6\% of the cross-sectional area of a vertically cast column, nor 8\% of that of a horizontally coat column, except that at laps of reinforcement bars the limit may be increased to 10\% (Clause 3.12.6 of BS8110).
I Input fcu, fy, b, h, d, d', d1, N, M, k

Iterate x form (d1 +1) to 2.33d

Is
x < 0.9d

Yes

Calculate the compression and tension steel stresses
\[ \varepsilon_s = \frac{0.0035(x - d')}{x} \]
\[ \varepsilon_{sc} = \frac{0.0035(d - x)}{x} \]

Calculate the steel area As
\[ As = 2\left[ \frac{Nu - kfx}{(fsc - fs)} \right] \]

Calculate the moment of resistance from
\[ Mu = kfx\frac{(h - kx)}{2} + As'fsc\left(\frac{h}{2} - d'\right) + Asfs\left(\frac{h}{2}\right) \]

No
(M - Mu)/M*100 \leq 2

Yes

Iterate x from d1 to 0.9d

Calculate the compression and tension steel stresses
\[ \varepsilon_s = \frac{0.0035(x - d')}{x} \]
\[ \varepsilon_{sc} = \frac{0.0035(d - x)}{x} \]

Calculate the steel area As
\[ As = 2\left[ \frac{Mu - kfx(h - kx)/2}{[(h/2 - d')(fsc + fs)]} \right] \]

Calculate the axial force
\[ Nu = fbks + As/2(fsc - fs) \]

Yes
(N - Nu)/N*100 \leq 2

No

Stop

Print the steel area As

Figure C.7 Column reinforcement area calculation procedure
### Table C.3 Reinforcement area for columns

<table>
<thead>
<tr>
<th>Area mm²</th>
<th>Diameter(s) mm</th>
<th>Number of bars</th>
<th>Area mm²</th>
<th>Diameter(s) mm</th>
<th>Number of bars</th>
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</thead>
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<td>4, 4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### C.4 INDEPENDENT FOOTINGS

Design of independent footings first involves of finding bending moments in critical sections as shown in Figure C.8.

Bending moments and shear forces (including punching shear) can be calculated using structural analysis theory. Details of this analysis given by Mosley and Bungey (1987).

#### C.4.1 Reinforcement areas

Independent footing is design using the same procedure for slabs.
C.4.2 Shear

Shear checks are made using the same procedure as for slabs. However, there are two requirements to be satisfied:

(a) Critical shear, 1.5d distance from the face of the column;
(b) Punching shear (see Figure C.8).

C.4.3 Other requirements

Other requirements such as crack control also same as for slabs.

---

Figure C.8 - Critical sections for footing design
APPENDIX D

DESIGNER'S QUESTIONNAIRE BASED ON COST MODEL RESULTS

The questionnaire given here was used for the postal survey among 40 architects in U.K. A total of nine replies were received. The questionnaire is based on results of two projects obtained by applying the developed cost model.

QUESTIONNAIRE

A. INTRODUCTION OF THE COST MODEL

Building cost model for the design of reinforced concrete frame structure building was developed to give cost information related selection of the grid, in other words, spans in two perpendicular directions (see Figure D.1). The cost model was developed considering the following as design variables.

1. Short span lx.
2. Long span ly.
3. Total length of the building in short span direction Tlx.
4. Total length of the building in long span direction Tly.
5. Unit cost rates of concrete Cc, formwork Cf, and steel Cs.
7. Number of storeys NOS.

B. APPLICATION OF THE COST MODEL TO PROJECT 1

The project 1 is a three storey technical college building (see Figure D.2) which consists of lecture rooms, laboratories and offices for the staff. The total cost of building is £3 million and total cost of the structure is £1 million. Imagine that you have selected spans shown in Figure D.2 during sketch design stage (outline and scheme).
Figure D.1 Plan of building in cost model

Nss = Tlx/lx

Nsl = Tly/ly

Figure D 2 Plan layout of project 1
QUESTIONS

QB.1 Figure D.3 shows the elemental cost consequences of the building for changes in spans (obtained from the cost model). Based on information shown in Figure D.3 will you change the selected spans (6.0m)?

<table>
<thead>
<tr>
<th>Yes</th>
<th>Goto question QB.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>Goto question QB.6</td>
</tr>
</tbody>
</table>

QB.2 Will you change both short and long spans?

<table>
<thead>
<tr>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
</tr>
</tbody>
</table>

QB.3 What are the values of short and long span do you select now?

<table>
<thead>
<tr>
<th>Short span</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
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<tbody>
<tr>
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</table>

Goto question QB.4  Goto question QB.5
QB.4 Reason/s for the selection of a lesser span
1. Cost savings are significant and span less than 6.0m can be incorporated in the technical college building

2. Any other reason ........................................

QB.5 Reasons for selection of a higher span
1. Cost increase is not significant compare to the higher span possible for the building which will give more space for lecture rooms and laboratories.

2. Any other reason ........................................

QB.6 Selected span need not to be changed due the following reason/s.
1. Cost changes are not significant

2. Functional requirements are more important than the cost

3. Other reasons (please specify)

QB.7 Figure D.4 shows the total building cost consequences of the building for changes in spans (obtained from the cost model). Based on information shown in Figure D.4 will you change the selected spans (6.0m)?

<table>
<thead>
<tr>
<th>Yes</th>
<th>Goto question QB.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>Goto question QB.12</td>
</tr>
</tbody>
</table>
Figure D.4 Total building cost changes with spans - project 1

QB.8 Will you change both sport and long spans?

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

QB.9 What are the values of short and long span do you select now?

<table>
<thead>
<tr>
<th>Short span</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long span</td>
<td>4.0</td>
<td>4.5</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.5</td>
<td>7.0</td>
<td>7.5</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Goto question QB.10  Goto question QB.11

QB.10 Reason/s for the selection of a lesser span

1. Cost savings are significant and span less than 6.0m can be incorporated in the technical college building design.

2. Any other reason. ..........................................

..........................................................

..........................................................

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QB.11 Reasons for selection of a higher span

1. Cost increase is not significant compare to the higher span possible for the building which will give more space for lecture rooms and laboratories.

2. Any other reason .................................................................................................................................

QB.12 Selected span need not to be changed due the following reason/s.

1. Cost changes are not significant

2. Functional requirements are more important than the cost

3. Other reasons (please specify)

C. APPLICATION OF THE COST MODEL TO PROJECT 2

The project 2 is a six storey doctors quarters (married and single) building (see Figure D.5) for a city hospital. The total cost building is £2 million and total cost the structure is £0.6 million. Imagine that you have selected spans shown in Figure D.5 during sketch design stage.

![Plan layout of project 2](image-url)
QUESTIONS

QC.1 Figure D.6 shows the elemental cost consequences of the building for changes in spans (obtained from the cost model). Based on information shown in Figure D.6 will you change the selected spans?

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goto question QC.2</td>
<td>Goto question QC.6</td>
</tr>
</tbody>
</table>

Figure D.6 Elemental cost changes with spans - project 2

QC.2 Will you change both sport and long spans?

| Yes | No |

QC.3 What are the values of short and long span do you select now?

<table>
<thead>
<tr>
<th>Short span</th>
<th>2.2</th>
<th>2.7</th>
<th>3.2</th>
<th>3.7</th>
<th>4.2</th>
<th>4.7</th>
<th>5.2</th>
<th>5.7</th>
<th>6.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long span</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.5</td>
<td>7.0</td>
<td>7.5</td>
</tr>
</tbody>
</table>

| Goto question QC.4 | Goto question QC.5 |

318
QC. 4  Reason/s for the selection of a lesser span
1. Cost savings are significant and span less or more than (4.2 or 5.5) can be incorporated

2. Any other reason. ............................................
   ........................................................................
   ........................................................................

QC. 5  Reasons for selection of a higher span
1. Cost increase or decrease is not significant compare to the higher spans possible for the building which will give more space.

2. Any other reason  ........................................................................
   ........................................................................
   ........................................................................

QC. 6  Selected span need not to be changed due the following reason/s.
1. Cost changes are not significant

2. Functional requirements are more important than the cost

3. Other reasons (please specify)

QC. 7  Figure D.7 show the total cost consequences of the building for changes in spans (obtained from the cost model). Based on information shown in Figure D.7 will you change the selected spans ?

<table>
<thead>
<tr>
<th>Yes</th>
<th>Goto question QC.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>Goto question QC.12</td>
</tr>
</tbody>
</table>
QC.8 Will you change both sport and long spans?

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
</table>

QC.9 What are the values of short and long span do you select now?

<table>
<thead>
<tr>
<th>Short span</th>
<th>2.2</th>
<th>2.7</th>
<th>3.2</th>
<th>3.7</th>
<th>4.2</th>
<th>4.7</th>
<th>5.2</th>
<th>5.7</th>
<th>6.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long span</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.5</td>
<td>7.0</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Goto question QC.10  Goto question QC.11

QC.10 Reason/s for the selection of a lesser span

1. Cost savings are significant and span less than (5.5 or 4.2) can be incorporated.

2. Any other reason. ........................................

..........................................................
QC.11 Reasons for selection of a higher span

1. Cost increase is not significant compare to the higher span possible for the building which will give more space.

2. Any other reason ..........................................................................................................................

QC.12 Selected span need not to be changed due the following reason/s.

1. Cost changes are not significant

2. Functional requirements are more important than the cost

3. Other reasons (please specify)

QD.1 Please write your comments for providing cost information as given above for design decisions.

Positives..............................................................................................................................

Negatives..........................................................................................................................

QD.2 Please write your name and address (optional)

........................................................................................................................................

........................................................................................................................................