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A STUDY ON DESIGN DATA AND METHODS FOR PLATE-LIKE INJECTION MOULDED THERMOPLASTICS PRODUCTS

by

António Sérgio Duarte Pousada

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

May 1982

© A S D Pousada (1982)
To

Jovita, Ana and Paulo
SUMMARY

Existing methods of designing load-bearing thermoplastics products are based upon the application of Strength of Materials formulae in conjunction with material data (E, v, ...) obtained from simple specimens in standard tests.

In injection moulding the melt flow causes the material to be oriented and consequently to become anisotropic. In this case the application of current design methods may not predict with reasonable accuracy the behaviour of components subjected to complex states of stress.

Recently the concept of testing mouldings having some similarity to parts of real products (subcomponents or pseudo-mouldings) was proposed as a means of generating design data which would tackle the anisotropy pattern without getting into the complexity of anisotropic materials theory.

This work brings this concept afield, and particularly examines in depth the disc subcomponent. Two grades of polypropylene applied in load-bearing products were used for moulding the subcomponents. These were subjected to three flexure tests causing different patterns of stressing: cylindrical bending, and centre loading of the discs supported on the edge and on three points. The latter which was developed in this work has the immediate advantage of overcoming the inherent non-flatness of moulded plates.
Geometric factors of the tests were examined together with the effect of some processing conditions, and the thickness of the discs. The test data were used to predict the behaviour in the centre loading test with edge support for comparison with direct experimental data.

The concept of 'flexural stiffness' involving both modulus and Poisson's ratio was introduced and found suitable as a test datum for designing injection moulded flat plates.

Instrumented impact tests were carried out for estimating the subcomponent toughness properties in terms of processing conditions, thickness, and service temperature. They provide information which should constrain design in parallel with flexural stiffness, though it is not suggested that impact strength of other products can be completely predicted.

Finally some commercial mouldings were examined and tested for assessment of the deflection behaviour of the bases, and comparison of the experimental data with predictions from subcomponents was also done using the concept of flexural stiffness.
ACKNOWLEDGEMENTS

The author is indebted to the Instituto Nacional de Investigação Científica, Lisboa, Portugal, and to his employers the Universidade do Minho, Braga, Portugal, for financing and granting him a study leave in the United Kingdom.

The completion of the work however would not be possible without the help of a number of individuals, namely:

- Mr M J Stevens who accepted to supervise the programme and was exceptionally helpful by his continuous and friendly encouragement, frequent discussions, and organization of external cooperation.

- Dr S Turner and Mr I T Barrie, of ICI Plastics and Petrochemicals Division, who acting as industrial supervisors, arranged for the ICI facilities to be made available whenever necessary and contributed to the project with useful discussions and valuable suggestions.

- Mr D A Hemsley for the suggestions and guidance on the microscopy part of the work.

- Mr C Lines, the most efficient and skilled IPT workshop technician, who manufactured the testing rigs.

- Academic and technical staff of the Institute of Polymer Technology, Department of Mechanical Engineering (Strain Gauge work), and Engineering Design Centre (computation facilities), for their
suggestions and interest on the solution of the diverse problems arising.

- The staff of ICI who helped during the several stays in Welwyn Garden City, and to Mr M J Williams in particular.

The following extra-IPT institutions and organisations contributed to the feasibility of the project:

- Engineering Design Centre, Loughborough University of Technology, for allowing the use of their HP 9845B desk computer to be used in the manipulation of impact test data.

- Mechanical Engineering Department, Loughborough University of Technology, for making possible the utilisation of their strain gauge testing equipment.

- GPG International, Dunstable, for supplying the commercial mouldings used in the terminal part of the work, and, especially

- Imperial Chemical Industries, PLC, Plastics and Petrochemicals Division, Welwyn Garden City, for the invaluable backing of the project, supplying of all the materials required, and allowing the use of their processing and impact testing equipment.

Finally thanks are due to Janet Smith for the fast and neat typing of this thesis.
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$S^*$ - Dimensionless slope
$s$ - Stiffening factor
$T$ - Temperature
$T_{xy}$ - Twisting moment
$t$ - Time
$t$ - Channel width in equation (9.1)
$U$ - Function of $v$
$U$ - Excitation energy in equation (3.34)
$V$ - Volume
$v$ - Velocity
$X$ - Function in equation (3.26)
$x$ - Variable
$x^*$ - Dimensionless overhang
$w$ - Load
$Y$ - Function in equation (3.24)
$y$ - Variable
$Z$ - Distance
$Z$ - Flexural rigidity of beam
$z$ - Variable

$\alpha$ - Angle
$\alpha$ - Material property in equation (2.2)
$\alpha$ - Function in equations (3.30) and (9.1)
$\beta$ - Constant in equation (3.30)
$\gamma_{WR}$ - Shear rate at wall
$\sigma$ - Stress
$\varepsilon$ - Longitudinal strain
\( \dot{\varepsilon} \) - Strain rate

\( \dot{\varepsilon}_c \) - Strain rate in circumferential direction

\( \theta \) - Angle

\( \delta \) - Deflection

\( \dot{\delta} \) - Deflection rate

\( \delta_0 \) - Maximum deflection

\( \xi \) - Fraction of radius increase

**Subscripts**

C - Referring to central loading test
c - Referring to creep
L - Referring to three line test
P - Referring to three point support test
r - Referring to direction
x - Referring to direction
y - Referring to direction
I - Referring to a material
II - Referring to a material
\( \theta \) - Referring to a direction
CHAPTER 1
INTRODUCTION - THERMOPLASTICS IN
ENGINEERING APPLICATIONS

1.1 Plastics as Engineering Materials

For the last hundred years and principally after the commer­cial application of the first synthetic organic polymer, the appli­cation of plastics has been steadily growing as they have been joining and complementing the conventional structural materials such as metals, ceramics, and so on.

This rapid growth of application made the volume consumption of plastics to exceed the volume of the traditional metals, at the beginning of this decade. The reasons for this booming expansion stem from the ability to polymerise, from the forties, onward, polymers which had properties meeting the multiple requirements of modern products, ranging from easy and more energy efficiency process­sability and adequate mechanical properties to resistance to corrosive environments and economic advantage.

The first commodity high-tonnage thermoplastics (polyolefins, styrene polymers and poly (vinyl chloride)) often suffered from certain limitations such as low modulus, strength and creep resis­tance, poor hot strength and heat resistance, amongst others. Incidentally the reinforced thermosets remedy a number of these problems but inherent difficulties in processing as well as unsatisfactory cosmetic, electrical and lubricating properties, limited greatly the application of these materials.
During the fifties however it was possible to polymerise thermoplastic polymers having greatly enhanced mechanical properties and capable of meeting the stringent specifications of high performance and precise engineering components. These specialist plastics are commonly referred to by the term 'engineering plastics' and include materials such as the polyamides, polyesters, polycarbonates and poly(oxymethylene). The properties of the engineering thermoplastics are often improved by the addition of short-glass fibres which increase mostly rigidity, strength, creep resistance and dimensional stability.

Some high tonnage thermoplastics, however, and especially when reinforced, can be successfully used in engineering applications, as is the case of polypropylene.

An interesting account of the development of engineering thermoplastics is given by Deanin (1).

1.2 Injection Moulding in Engineering

The largest processing method to shape engineering components is injection moulding. The process being known in its principles from the last quarter of the nineteenth century, it has proved to be the more adequate to make, for example, the complex shapes which result when products containing an assembly of metal parts is replaced by one or a few plastics parts.

The process which can be used both with thermosets and thermoplastics allows the production of components with very close tolerances.
These are very important in small engineering components where usually the deflections due to loading can easily be kept within acceptable limits.

In larger mouldings where the overall dimensions are several times the thickness, the flow of the melt during the filling stage brings a large number of problems to the designer of plastics products who is usually interested in predicting their stiffness and strength.

The mechanical properties of a polymer depend not only on time and temperature but also, and to a large extent, on such factors as the conditions under which a product has been made. These conditions usually make the material non-isotropic and can contribute to the build-up of internal residual stresses. The departure from the isotropic situation is particularly great in the case of fibre reinforced plastics due to the alignment of the fibres caused by the flow inside the mould.

The problem of designing injection-moulded engineering products attracted the attention of many investigators who have been facing a number of questions from the fundamental understanding of the non-linear-elastic behaviour of plastics, to the establishment of methods for adequately predicting the service performance.

1.3 The Characterisation of Mechanical Properties of Thermoplastics

In spite of the frequent non-isotropy of load-bearing plastics products the characterisation of the mechanical properties does not
usually consider the anisotropy effects resulting from processing and thus the data available for design implicitly assume that the material can be considered as isotropic. This is particularly applicable to the case of unfilled materials, the fibre-reinforced plastics being sometimes considered as composite materials and dealt with accordingly. The following review refers to unfilled materials unless otherwise stated.

The material properties which are defined for the plastics follow the established elastic properties used with metals such as the Young's or elasticity modulus, the shear modulus, and the Poisson's ratio. However the plastics being time dependent, those properties are referred to the loading history. The cases of short term and long term loading are usually considered, and will be briefly analysed in the following sections, as well as aspects related to impact loading.

1.3.1 Short term tests

The short term properties of plastics are usually assessed in testing machines applying a constant rate of deformation.

a) **Tensile test**

The more common of these tests is the tensile test which is standard in different countries such as the UK (2), USA (3), or Germany (4). These standards tend to follow closely the ISO recommendations (5). They specify the dimensions of the test pieces and the way in which the test should be carried out. Given the force-
deflection trace of the test the following material properties can be derived for the displacement rate and test temperature used.

a) The modulus which can be either the Young's modulus - taken as the slope of the tangent to the stress-strain curve at its origin (3), or the secant modulus given by the slope of the straight line from the origin to a point in the curve corresponding to a pre-determined strain, e.g. 0.2% (2). The modulus is a measure of the stiffness of the material describing the relationship between stress and strain prior to the onset of large and permanent deflection.

b) Yield stress and/or stress at break. Some plastics show a peak in the test trace corresponding to the occurrence of localised gross deformation which is known as yield point. The value of the stress at this point depends on the speed of the test and the test temperature. The yield is always associated with ductile behaviour. Other materials do not show a yield point and, especially if they are brittle, a value of the stress at break is used instead. The yield stress and the stress at break give an idea of the strength of the material in the short time.

b) **Bending test**

The flexural three-point bending test is a test method often used for determining the small strain behaviour. It shows some advantages with respect to the tensile test which are (6,7):
the use of specimens easier to obtain
- larger measured deflections for a given strain than in the tensile test.
- the requirement of smaller loads

It has the great disadvantage of the deflection being the average response to strains ranging from the maximum compressive strain to the maximum tensile strain at each section over the whole length of the beam specimen. Nevertheless the test describes better a large number of real life applications where bending occurs. A fairly extensive analysis of this test was made by Heap and Norman (8), and Williams (6) also gave it some thought.

c) Other tests

Compression and shear tests are not very common with plastics, however the information they provide is important for the determination of the compression (in rigour not identical to the tensile modulus) and the shear moduli. The compression test creating a state of plane strain was evaluated by Williams and Ford (9) who used this method, originally used for metals, as a means of determining the behaviour of plastics at high levels of strain. The application of the technique to the examination of polymers at large strains was later done by Williams (10).

Several techniques have been used for determining the shear properties. The current UK standard test method for moulding materials (11) uses a die and punch assembly.
d) **Poisson's ratio**

The Poisson's ratio, sometimes called lateral contraction ratio, is under some conditions the equivalent to the Poisson's ratio function for isotropic materials (7). Bonin et al (12) observed that for some plastics the following relationship holds:

\[ v_c(t) = \frac{E_c(t)}{2 E_c(t)} - 1 \]

where the suffix c refers to the creep test used. This relationship holds exactly for the case of isotropic materials, and was used for indirectly determining the Poisson's ratio.

Direct measurement techniques have been used by other workers (Darlington (13), Benham (14)) who utilised transducer and optical extensometer systems.

1.3.2 **Long term tests**

When plastics are likely to be used over a range of loading times (generally above 100s) and temperatures the values of the material constants obtained from short-time tests are inadequate to describe the product performance.

When the applied stress or strain is maintained over a long period of time the theory of linear viscoelasticity suggests that the stress-strain-time functions are very similar when measurements
are made using either constant load (creep) or constant deformation (stress relaxation) (6). A large quantity of experimental data obtained from creep tests mostly, on grounds of experimental convenience, has been gathered through the years and given in the scientific literature (e.g. Ogorkiewicz (15)) and in the extensive literature published by many leading suppliers of raw materials.

The basic creep data is gathered in the form of strain-log time curves at known levels of stress. These data can be represented by cross-plotting (6) to generate three other types of data which are more useful to the designer:

a) isochronous stress-strain curves, for different times under load.
b) isometric stress-log time curves, for different strains
c) creep-modulus-log time curves, for diverse strains.

Stress relaxation data are not very frequent mainly because for small strains and not very short times isometric curves can be used as design data.

Creep under stress modes other than tension is not as well documented, and some reasons are given for that: creep in compression is similar to creep in tension if the strains are small (16); creep in shear correlates very well with creep in tension (17); and the lateral contraction ratio is only slightly time dependent (18).
1.3.3 Impact tests

The characterisation of plastics materials when subjected to sudden loads is a point which has been associated to a relatively large number of test methods. Brown (19) gives a detailed account of the different current methods and the aspects relative to their standardisation. One of the problems associated with these tests is the impossibility of establishing a set of 'fundamental data' which may be used in design. Another problem is that the several tests using different specimens make impossible to relate the corresponding sets of data. Thus the tests have been applied at will of the users as a means of assessing, for example, the sensitivity of a material to the severity of notches and temperature (e.g. Vincent (20)), or of comparing the relative degree of merit of materials on impact, as is done generally by the raw material suppliers. The application of the impact data in design has been therefore not possible so far.

In recent years the introduction of instrumentation in the impact testers enabling one to obtain a larger amount of information from individual tests brought a new interest to impact testing. These tests that will be discussed in more detail in Chapter 3 are a development of previous standard tests.

1.4 Problems Associated with the Design of Injection-Moulded Products

Most of the designers who get involved with the design of plastics components are only familiar with the methods now very well
established for conventional metallic materials. These methods rely on standard mechanics of materials and make use of material elastic properties such as the moduli, E and G, and the Poisson's ratio (e.g. (21)). Plastics however bring with them a fair number of complexities:

a) Viscoelastic nature of the material
b) Temperature dependence of the properties
c) Anisotropy introduced by the flow which is both directional and through thickness
d) Build-up of residual stresses usually related with the cooling of the mouldings.

The viscoelastic behaviour is possible to be modelled analytically to a lesser or further extent (e.g. Williams (6), or Lockett (22)), but the theory apart from being rather complex for the average designer, lacks support of material data in a large number of commercial polymers. The problem was overcome quite satisfactorily with the 'pseudo-elastic' method which will be reviewed in the next chapter. The method also deals with the problem of variation of the properties with temperature. What the method is unable to cope with is the factors involved in (c) and (d), nor the raw material suppliers are able to supply data representative of such factors.

The result from this is sometimes an inaccurate prediction of the service performance of products from laboratory test data. The deformation predictions based on creep data were generally acceptable,
however, being poor in cases of high degrees of anisotropy, but
the major complaints arose from the prediction of failure.

As a consequence the users of plastics have become suspicious
of the suppliers' data and unable to use them in the most effective
way. The alternatives sometimes taken were the direct testing of
end-products or the imposition of arbitrary constraints on the
materials.

1.5 The Standing of this Work

1.5.1 The role of the raw material suppliers

The situation briefly outlined in the previous paragraph has
greatly concerned raw material suppliers, because the procedures
followed by the material users are both expensive and inefficient.
The past experience of the manufacturers suggested that the clari-
fication of the problem through a better understanding of the ani-
sotropy phenomena would bring subsequent problems on top of a very
expensive upsurge in testing requirements. Imperial Chemical Indus-
tries Limited (ICI) were aware of the problem and came about with a
less conventional approach to the solution of the problem, whose
fundamentals were laid by Stephenson et al (23) in 1979, and is
sometimes designated by 'subcomponent principle'.

1.5.2 The industrial backing of the research

With the industrial support of ICI a preliminary work was under-
taken with the prime objective of establishing the minimum amount of
information needed to predict the stiffness of a moulding subjected
to known loads and made from a given material, in the case a seed tray made from polypropylene. The findings of this work were reported by the author (24) and showed the importance of orientation in the prediction of the deformation behaviour, the inadequacy of traditional test methods for characterising the mechanical performance and also pointed out the need of a new approach to the problem.

On discussion of the results with ICI it was decided to seek a solution to the prediction of stiffness using the subcomponent principle (23) and to make some preliminary work on the stiffness/toughness interdependence so that some information could be generated for the understanding of failure.

As a result of this agreement the objectives of the work were broadly set up and the materials to be used in the programme specified.

1.5.3 Possible practical implications

Apart from the scientific objectives which will be outlined at the end of the next chapter, this work was thought to raise ideas which might be of practical interest to raw material manufacturers who supply customers with material data for design. In general terms these can be outlined as:

i) The programme is likely of showing the necessity for additional, or perhaps different, property data, as well as developing the design methods to be used with them. Thus the raw material
suppliers would be able to provide in the near future customers with a package of more appropriate data and design methods, yielding more reliable predictions of performance.

ii) The introduction of mechanical property data and appropriate design methods to apply these data correctly in respect of deformation under load with a greater degree of accuracy will boost customer's confidence in their own product design predictions.

iii) The acquisition of mechanical property data is time and resource expensive. This research would confirm or otherwise that the existing data programme is correct and sufficient. If inadequacies were demonstrated, then early information and decisions could be important in view of the inevitable and considerable lead time required to remedy those inadequacies.
CHAPTER 2
DESIGN WITH THERMOPLASTICS - A LITERATURE REVIEW

2.1 Design for Stiffness with Creep Data - the Pseudo-Elastic Method

The specifications for engineering plastics parts subject to external loading, from the mechanical point of view may refer to a design stress, a maximum deflection of strain, or even a combination of these. Although detailed viscoelastic models have been developed, the designer with plastics usually looks for simpler methods which can be used with available or readily obtainable data.

The compromise between the non-linear viscoelasticity characteristic of the plastics and the convenience of the elastic models of the established Mechanics of Materials, was embodied in the so-called 'pseudo-elastic method'. This method simply takes the solution of the design problem for an elastic material and replaces the elastic constants by time, stress, temperature, etc., - dependent viscoelastic parameters.

The pseudo-elastic method has been used for long and is well described by Powell (25-27). The fundamentals of its applicability were discussed by Lockett (28) and Williams (6). The convenience and success of the method fully justifies the vast amount of creep data available in the literature and from the leading raw material suppliers.

The design brief for prediction of the load bearing performance of thermoplastics requires information on the following points:
a) Loads and deformations
b) Duration of loads and deformations
c) Service temperature
d) Environmental conditions

The point (a) represents the application of the elastic theory to the product under load. The second point takes into account the time-dependence of the plastics properties and, also, their response to types of loading other than the constant loads which are usually implied in the creep data derivation. The service temperature item refers to the temperature sensitivity of thermoplastics and, finally, the last point is mostly related with the chemical properties of the material.

Once these points are defined the choice of the suitable creep modulus is done as follows (Benham and McCammond (29)).

i) Identify the maximum service temperature under load, $T$, and the maximum (assumed continuous) duration, $t$, for which the maximum load is applied.

ii) Calculate the maximum stress, $\sigma$, in the proposed design.

iii) Identify the relevant creep data for the chosen material and its condition.

iv) Read from the creep data the corresponding creep strain, $\varepsilon(t,T,\sigma)$.

v) Calculate the creep modulus $= \sigma/\varepsilon(t,T,\sigma)$. 
vi) Use this creep modulus in the appropriate formulae of elasticity to predict deflections, deformations, and stability.

Some applications are not of the creep type but involve stress relaxation situations. Stress relaxation data is not so well documented as creep data is but for most practical purposes values from the two sources seldom differ by as much as 10% (6).

It is interesting to notice that most of the raw materials manufacturers who issue 'Design' manuals take this method of design for granted (30-32). It is apparent from these the assumption that the designer usually lacks the expertise of a trained mathematician, is pressed in time, and has no access to means of fast mass calculation.

This method of design generally tends to overdesign the products and hardly takes into account the effects due to processing such as orientation, build-up of residual stresses, formation of weld lines, and so on. Furthermore the design data being generated usually with specimens under uniaxial states of stress, there is a certain degree of uncertainty about how well these data describe bi-axial stress situations such as those occurring in components involving plates and shells.

For meeting these uncertainties the utilisation of design safety factors, sometimes large, is advisable depending on the criticality of the application and the complexity of the component.
2.2 Orientation Effects on Unfilled Thermoplastics

2.2.1 The mechanism of orientation

During the injection of the polymer melt into the mould the molecules which have a large aspect ratio and are only loosely linked to each other by weak Van der Waals' forces are elongated from their random configuration and aligned along a given direction. A model was proposed by Tadmor (33) to describe the final structure of an injection moulding. According to it the filling process is divided into a local flow at the melt front which produces the skin, and the flow behind the melt front which freezes later to give the core of the moulding (Figure 2.1). The material forming

![Diagram](image)

FIGURE 2.1: Schematic representation of the flow pattern in the advancing front between two parallel cold walls (according to Tadmor (33))
the skin is subjected to tensile stress at the melt front which
orient the molecules, the orientation being frozen-off as the
melt solidifies on contacting the mould wall. Meanwhile the melt
in the core is sheared as it flows between the stationary frozen
skins and cools slowly due to the thermal insulation effect of the
skins, allowing more relaxation to occur. If the cooling of the
moulding is fast enough the molecules are frozen in their oriented
state before relaxation to an equilibrium state is possible, and it
is only the core that normally becomes little or not oriented.

A great deal of research work has been put in the study of
moulding structure as the link between processing conditions and
properties. With semi-crystalline polymers two or more regions
of quite distinct morphology can be identified in injection mouldings
and are according to Clark (34):

a) spherulitic core
b) transcrystalline layer
c) skin

The filling of injection mouldings is usually associated with
a diverging flow. This causes a reduction in the flow speed and
associated shear stresses. Glanville (35) observed that as a result
of this the degree of orientation tends to fall as the distance
from the gate increases.
2.2.2 The characterisation of orientation

The alignment of the molecules in preferred directions within the mouldings affects the mechanical properties directionally. The need of generating design data on the magnitude of the anisotropy associated with orientation, and of how to characterise it, was advocated in the late sixties by Darlington and Saunders (36).

The techniques which have been used for assessing the orientation are many and can be broadly classified into direct and indirect methods.

a) Direct methods

The most easily accessible experimental technique that is related to structure is birefringence. Birefringence is related to the way in which polarised light travels through a transparent medium; if the medium is oriented the two rays in which the polarised light beam is divided are slowed in relation to each other, causing the observer to see a combination of colours from the white light spectrum. The method has consequently some shortcomings (37): firstly it is only applicable to transparent materials; secondly it should not be applicable to crystalline materials because the crystallites are intrinsically oriented structures at molecular level; thirdly if the material contains energy elastic residual stresses these will contribute also to birefringence and finally the side-chain orientation may provide significant birefringence without the need for changes in main chain orientation.
The method has nevertheless been used quite widely (e.g. 38-40) and the data obtained have shown that the region of maximum orientation is near the wall (Figure 2.2 (37)).

FIGURE 2.2; Birefringence vs depth in injection-moulded PS (Haworth et al (37))

Another technique for the determination of orientation is the X-ray diffraction used, for example, by Ogorkiewicz (41) for the case of injection moulded polypropylene trays.
b) **Indirect methods**

Characterising orientation by means of the anisotropy of a mechanical property has been seen as a method supplying the designer with more practical data. The determination of the tensile and the flexural moduli have been used. Ogorkiewicz et al. (41) and Pouzada (24) made determinations of the tensile and the flexural moduli respectively in similarly moulded products. They observed that the variation of the moduli followed closely the modified Hearmon equation for the case of cylindrically orthotropic materials (41):

\[
\frac{1}{E_{\theta}} = \frac{\cos^2 \theta}{E_0} + \frac{\sin^2 \theta}{E_{90}} + \left( \frac{4}{E_{45}} - \frac{1}{E_0} - \frac{1}{E_{90}} \right) \sin^2 \theta \cdot \cos^2 \theta \quad (2.1)
\]

where \(\theta\) and the \(E\) subscripts refer to the angle of the axis of the specimen to the direction of flow. The technique was applied by Fujiyama et al. (42) for the case of film-gated square plates injection moulded from several grades of polypropylene.

The measurement of shrinkage or recoverable strain at heat treatment above the softening temperature allows the determination of the relative magnitudes of the orientation both in the in-plane directions and through thickness (43,44).

The determination of the variation of the density through the thickness may also give useful information about the variation of mechanical properties through thickness. Determinations made on polypropylene mouldings (24) showed that the distribution of density
varied strongly with the processing conditions (Figure 2.3).
The distribution of density especially in the case of more ani-

![Graph showing density distribution vs depth in injection moulded PP](image)

FIGURE 2.3: Density distribution vs depth in injection moulded PP (Pouzada (24))

sotropic mouldings agrees well with the observations of Kantz et al (45) who showed that the crystalline structure within the shear or transcrystalline zone is constituted by small, oriented and tightly packed spherulites, whilst in the core the spherulites are bigger but randomly sized.

Fritch (46) reported an interesting technique for visualising the orientation distribution by using transmission electron microscopy to observe the degree of distortion of rubber particles in ABS.
More recently Kent et al (47) proposed the indentation fracture test whereby a ball indenter is compressed against the surface of a glassy moulding (e.g. polystyrene, poly(methyl methacrylate)). The point of first fracture was determined by using the acoustic emissions from the crack and the load at first fracture used as an indicator of the magnitude of the orientation present in the surface layers of the mouldings. The direction of the crack provides information on the direction of the surface orientation.

2.2.3 How complex is the problem of orientation in design?

It is evident from the revision, however brief, made of the orientation aspects in injection mouldings, that even unfilled plastics can have a fair degree of anisotropy in properties due to orientation. This is in some way related with the moduli but there is no conclusive information in this respect because the measurements are taken from specimens where the degree of orientation varies across the thickness, therefore having an averaging effect. Determining how the modulus depends on orientation may prove a task of very great experimental difficulty and surely expensive, and even if it was achievable, to characterise the moulding material in terms of its full anisotropy would entail an extremely complex analysis which would be time and resource-expensive. This may have some academic interest, however designers are looking for a way to deal with the problem of orientation in injection moulding in terms of both their limited time and resources.
2.3 New Trends on Design with Plastics

Standard methods of generating design data have been using simple geometry uniaxial test pieces in which the state of stress is generally simple. A large part of the creep data were derived from samples without orientation obtained by compression moulding or from injection moulded samples where the direction of orientation coincided with the axis of the sample. The data from the former produce design figures underestimating the performance of real life products whilst the latter tend to give an optimistic picture of the capabilities of the material. The data generated in this way, even at a considerable cost, would therefore represent only vaguely the properties of products where the degree of molecular orientation and the pattern of anisotropy of the properties could be very complicated.

The problem arose mainly with the surge of application of glass fibre reinforced thermoplastics in which the anisotropy is governed by a fairly complex distribution of the glass fibres. Stephenson (48) proposed a new practical system of evaluation whereby instead of the classical standard test pieces (either purposely moulded or cut from mouldings used for providing the various stiffness coefficients needed for anisotropic stress analysis), simple mouldings such as discs or plaques were tested directly. This work progressed and complementary information which will be reviewed in the next section published. This attempt was made on grounds of practicality, cost saving, and real representation of complex product properties. This explains, for example,
why most of the work recently published refers to tests with universal testing machines of the Instron type instead of the traditional creep apparatuses. Johnson and Sims (49) also worked along these lines and looked for ways of describing the short time behaviour of plastics subjected to constant loading rates. They showed that for polypropylene and polyethylene a relationship between the rate dependent flexural modulus and the strain and strain rate held and is given by:

\[
E = A \alpha (\delta_0/\dot{\delta})^{\alpha - 1}
\]

where \(A\) and \(\alpha\) are material properties, \(\delta\) is the maximum deflection in the three point bend test and \(\dot{\delta}\) is the deflection rate.

For the two materials analysed the values of the constants are:

<table>
<thead>
<tr>
<th></th>
<th>PP</th>
<th>PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A(\text{GPa.s}^{1-\alpha}))</td>
<td>1.35</td>
<td>0.42</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>0.96</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Attention is also being focussed on the behaviour of panel deflections and stresses, work being reported in progress at this moment (50).

On the impact side Crawford and co-workers (51-54) have been devoting attention to the effect of processing conditions on the
impact strength of mouldings with shapes sufficiently realistic to enable typical moulding situations to be investigated. The results so far available refer to a 'picture frame' moulding containing weld lines and where the flow ratio can be varied. It was shown that the impact strength of the weld line does not vary appreciably but is dependent on the flow ratio which is approximately the same for all the processing conditions studied. Their results also show that the use of 'sample mouldings' to relate injection-moulding conditions to the properties of moulded articles can be achieved successfully and that the production of these mouldings as opposed to moulded specimens highlights many of the apparent contradictions reported when test results are applied to moulded articles.

Finally the design for strength based on the fracture mechanics approach is taking growing importance and documentation on the subject is continuously appearing. One area which is attracting attention at the moment is the design of pipe systems subject to pressure (55).

2.4 The Subcomponent Approach

2.4.1 Introduction

The design of products using standard methods of Mechanics of Materials is based upon the assumption of point properties. When a material is anisotropic this design approach is still possible using appropriate theory which is based upon the definition of the compliance matrix \([A]\) in the generalised Hooke's law
where \([\varepsilon]\) and \([\sigma]\) are the column strain and stress matrices.

In the more general case of a homogeneous elastic body possessing no elastic symmetry in an arbitrarily chosen system of orthogonal coordinates, \(x, y, z\), the number of independent constants necessary to define the compliance matrix is 21.

Dunn and Turner (57) proposed, for overcoming the practical difficulties of fully characterising anisotropy, the use of particular specimens by which upper and lower bounds of properties were defined representing the likely range of properties. They advocated the testing of specimens cut from bars, discs and square plates to define the likely range of variation of the deformation and strength characteristics of short fibre reinforced thermoplastics. The problem with this recommendation and use of three simple mouldings (ASTM tensile bar, edge-gated disc, and flash-gated square plaque) was that however possible it was to define directions of a common property, e.g. \(0^0\) direction or flow direction in the square plaque, it was verified that specimens cut from different points might lead to different results, therefore suggesting that no one specimen could be regarded as superior to the others as a source of a datum, nor can it be said to represent the modulus or the stiffness of the plaque as a whole.
At this point the option of testing the entire moulding presented two advantages: it provided a means of averaging the effects of variation in orientation from point to point - and this is what the moulding in service would do - , reduced the cost of testing by eliminating the need for machined specimens, and by reducing the number of tests required. The disadvantage of testing these wide plates was that they are not ideal specimens for modulus measurement in either tension or flexure (23).

2.4.2 The subcomponent method applied to plates

The first field of application sought for the subcomponent principle was the design of flat plates for stiffness. In a second paper Stephenson and co-workers (58) started the exploitation of the application of the method to design. By observing that the planar anisotropy of low strain properties occurring in planar mouldings of thermoplastics can be often modelled as that of an orthotropic sheet under plane state of stress, they defined the 'mean stiffness' of the orthotropic plate, $\bar{C}$, as

$$\bar{C} = \frac{1}{4} (C_{11} + C_{22} + 2 \bar{C}(45^\circ))$$

(2.4)

where

$$\bar{C}(45^\circ) = \frac{1}{4} (C_{11} + C_{22} + 2 C_{12} + 4 C_{66})$$

(2.5)

and $C_{ij}$ are the elements of the stiffness matrix in the equation
1 and 2 are the subscripts corresponding to the principal directions in an orthotropic plate.

The mean stiffness, $\bar{C}$, reduces to $E/(1 - \nu^2)$ for an isotropic material, $E$ being the Young's modulus and $\nu$ the Poisson's ratio. $\bar{C}$ is believed to be a potentially useful parameter for comparing composite systems such as short-glass fibre filled mouldings.

The experimental evaluation of the assumption was made by using a novel test method which measured the bending resistance of a disc specimen in three-'point' flexure along various directions in its plane. By noting that $\bar{C}$ is often approximately the mean of the upper and the lower bound stiffness values for any particular moulding, that is

$$\bar{C} = \frac{C_{11} + C_{22}}{2} \quad (2.7)$$

it was shown that any two stiffnesses evaluated perpendicular to each other will give a reasonable estimate of $\bar{C}$, although the degree of approximation is dependent on the value of the angle of the chosen direction to the principal directions. The effective plate flexural stiffness, $C$, is calculated from the equation (23),

$$C = \frac{L^3}{4bd^3} \left(\frac{W}{\delta}\right) \quad (2.8)$$
where $L$ is the span, 
b the width of the specimen, 
d the mean thickness, and 
$\left(\frac{W}{d}\right)$ the slope of the load/cross head movement trace.

This equation implies that the bending is approximately cylindrical and thus the stiffness calculated from the equation will be a factor $1/(1 - \nu^2)$ greater than that measured on a narrow beam if the material is isotropic.

For determining the mean stiffness of the disc the average of the experimental load/deflection slopes was calculated using the equation

$$C = \left(\frac{W}{\delta}\right) \frac{d^3}{(W/\delta)_k} C_k$$

where $C_k$ is the stiffness of a calibration PMMA specimen, $d$ the thickness of the specimens and $(W/\delta)$ the load-deflection slopes.

For applying the obtained data in deformational design it was proposed that in a number of situations of bending of plates a simple substitution for $C$ (in the isotropic equations) with $C$ would give an adequate approximation for deflection over a range of anisotropies likely in thermoplastics composites.
2.4.3 The future of the subcomponent approach

Further aspects of the test for assessment of anisotropy were discussed by the same authors (59) who feeling the potential of the method however were still concerned about a better means of presenting the results from the tests, and the format that could describe both the mean value and the anisotropy of the property under consideration. It appears that no general solution exists for this problem but a format relating comprehensive short duration tests on subcomponents to limited long term strength and creep information by the use of dimensionless derating factors is believed to provide a direction for progress. The concept of 'derating factor' was introduced by Stephenson (48) who defined it as

$$D(t,T) = \frac{\sigma_D(t,T)}{\sigma_D(t_R, T_R)}$$

where $\sigma_D$ indicates a design stress and the subscript $R$ identifies a reference state.

The introduction of this factor could lead to the condensation of deformational data required for finding values of a design stress. Examples of the application of $D(t,T)$ were presented for the case of reinforced thermoplastics over a range of temperatures and times. The concept was further extended to subcomponents taking as reference the end-gated ASTM tensile bar, and some anisotropy derating factors were derived for various moulding geometries and feeding systems, such as the end-gated plaque, the centre-
gate radial flow, etc.

A preliminary discussion of the subcomponent method for design was recently made by Lockett (60). It is accepted that usual data on the engineering properties of plastics materials provided by material suppliers may lead to a significant discrepancy between design performance and actual product performance. This arises for two reasons: the lack of awareness by engineering designers of the significant differences between plastics and traditional engineering materials, and because the material data supplied may not be representative of the material in a moulded component due to the effects of processing. The use of subcomponents is seen as an approach in which the effects of processing and plastics properties are both handled simultaneously. However Lockett thinks that the method by itself has the problem of leading to new types of design procedure, the details, viability, nature and accuracy of it not having yet been established. It has its shortcomings especially in the case of more complex components which means that a complete replacement of the traditional design methods is not foreseen. However given its attractive features it is possible that traditional design methods could be combined with subcomponent data to produce better designs than either method applied separately.

The number of subcomponents which will be necessary to establish a sound and complete method is likely to be substantial and not fully achievable in the near future. The first moves have been already done in the direction of examining some plane subcomponents and bars.
2.5 **Detailed Objectives of the Research Programme**

The work in this thesis follows the concept of using sub-components for predicting the mechanical behaviour of injection moulded components. Particularly it will be concentrated on an unfilled material, polypropylene, which is a high tonnage material with a large range of applications in load-bearing components.

The objectives of the work can be described as follows:

a) **Assessment of circular disc mouldings as test pieces for predicting the behaviour of plates subjected to flexural bi-axial stressing.**

b) **Investigation of test methods suitable for characterising the bending of injection moulded plates.**

c) **Study of the influence of thickness, gate type, and some moulding conditions in the flexural performance of mouldings.**

d) **Utilisation of instrumented impact tests for relating the failure of injection moulded subcomponents to processing conditions and test piece features.**

e) **Establishment of methods of applying subcomponent data to the design for stiffness of plates.**
CHAPTER 3

THEORETICAL ASPECTS OF THE TESTS WITH SUBCOMPONENTS

Tests with 'bidimensional' specimens such as the circular discs which are going to be used in this investigation are not standard in laboratory testing.

In this chapter a theoretical analysis of the test methods used in the programme is made as well as an extension of some established models to the experimental methods. The study starts with a comparison between the behaviour of similarly loaded linear test pieces (beams) and 'bidimensional' specimens (circular discs) before concentration on aspects completely related to plate-like specimens.

3.1 From Uniaxial Test Pieces to Plates

In most of the plastics products possessing plate-like elements, these are usually connected to other parts of the product which will restrain to a lesser or greater extent the deformation of the plate. For the sake of simplicity the tests in planar subcomponents do not include any kind of edge restraint, e.g. edge fixing, elastic foundation etc. Nevertheless it would be instructive to review how the different types of edge restraint might affect the deflection of a plate. For simplicity again the case of a circular disc is considered and will be compared to beams or
### TABLE 3.1: Deflection of Beams (61)

<table>
<thead>
<tr>
<th>Load Situation</th>
<th>Diagram</th>
<th>Maximum Deflection</th>
<th>Maximum Bend Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrated load, simple support</td>
<td><img src="image" alt="Diagram" /></td>
<td>$\frac{PL}{48EI}$</td>
<td></td>
</tr>
<tr>
<td>Uniformly distributed load, simple support</td>
<td><img src="image" alt="Diagram" /></td>
<td>$\frac{5wL^4}{384EI}$</td>
<td>$\frac{wL^2}{8}$</td>
</tr>
<tr>
<td>Concentrated load, Ends fixed</td>
<td><img src="image" alt="Diagram" /></td>
<td>$\frac{PL^3}{192EI}$</td>
<td>$\frac{PL}{8}$ at middle</td>
</tr>
<tr>
<td>Uniformly distributed load, Ends fixed</td>
<td><img src="image" alt="Diagram" /></td>
<td>$\frac{wL^4}{384EI}$</td>
<td>$\frac{wL^2}{12}$ at middle</td>
</tr>
</tbody>
</table>

### TABLE 3.2: Deflection of circular discs (62)

<table>
<thead>
<tr>
<th>Load situation</th>
<th>Diagram</th>
<th>Maximum Deflection ($v = 0.3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrated load at centre simply supported edge</td>
<td><img src="image" alt="Diagram" /></td>
<td>$0.05 \frac{PR^2}{D}$</td>
</tr>
<tr>
<td>Uniformly distributed load Simply supported edge</td>
<td><img src="image" alt="Diagram" /></td>
<td>$0.063 \frac{wR^4}{D}$</td>
</tr>
<tr>
<td>Concentrated load at centre clamped edge</td>
<td><img src="image" alt="Diagram" /></td>
<td>$\frac{PR^2}{16\pi D}$</td>
</tr>
<tr>
<td>Uniformly distributed load clamped edge</td>
<td><img src="image" alt="Diagram" /></td>
<td>$\frac{wR^4}{64D}$</td>
</tr>
</tbody>
</table>
bars experiencing similar types of loading and constraint, for examining how the degree of edge restraint will affect their deflections.

3.1.1 Deflection

The expressions for the maximum deflection of a loaded beam can be found for example in Roark (61) and are listed in Table 3.1. Corresponding expressions are given by Timoshenko and W Krieger (62) for the case of circular plates and are tabulated in Table 3.2.

From the table 3.1 for beams it can be seen that the deflection due to a load either concentrated (P) or uniformly distributed (w) is differently affected by the edge restraint. In the first case the deflection with fixed edges is only 0.25 of that with simple support, while in the second case the ratio is only 0.2. It is also observable that the deflection due to a uniformly distributed load and of the same magnitude, i.e. \(wL = P\), is smaller than that due to the equivalent concentrated load; the ratio in this case is 0.625 for simply supported beams and 0.5 for beams with fixed ends. This is indeed a good reason for making tests with concentrated loads, however the principal one is the practical difficulty of materialising a uniformly distributed load.

A similar exercise extended to the case of circular discs leads to the following results:

- Effect of edge fixing in case of central concentrated load
  \[= 0.398 \quad (0.25 \text{ for beams})\]
Effect of edge fixing in case of distributed load
= 0.248 (0.2)

Reduction in deflection due to distribution of load
(\( R^2 w = P \)) in simply supported situation = 0.401 (0.625)

Ditto, in fixed edge situation
= 0.25 (0.5)

What is convenient to observe from these basic comparisons is that a prediction of behaviour of plates even if isotropic cannot be readily made in terms of the observation of equivalent effects in beams. Thus while the response to the type loading in the plates is more accentuated in the plates than for beams, the influence of the type of support is smaller for circular plates than for beams.

3.1.2 Distribution of stresses in the cases of beams and discs subjected to concentrated loads

For experimental purposes, it is easier to apply concentrated loads to test pieces rather than uniformly distributed loads. In this section the distribution of the stresses on beams and discs subjected to concentrated and centrally applied loads is compared.

a) Beams

In the case of beams supported at the ends the maximum bending stress, which occurs at the surface, varies linearly from a maximum
at midspan where the load is supposed to be applied.

The maximum bending stress is parallel to the axis of the beam and the stress in the direction perpendicular to it is considered negligible when the beam is narrow.

In Figure 3.1 the maximum stresses (which are proportional to the bending moments by the known relation $\sigma = Mh/2I$) are compared for the cases of beams simply supported and with the ends clamped. It is also shown the shape of the deflection curves in both cases for a similar load. For an equal load the maximum stress in the case of the 'encastré' beam is half of that in the simply supported beam; however the deflection is comparatively much smaller.

b) Discs

In the case of discs centrally loaded there is an overall state of biaxial stress over the disc. The stresses are proportional to the bending moments which are given in the literature (e.g. (63)) for the disc with clamped edge, or readily derived (Section 3.2.2) for the case of a disc simply supported.

The graphic interpretation of the two situations is shown in Figure 3.2 which shows how close the two principal stresses (radial and tangential) are in the region of greater stressing. In the case of clamped edge, this is subjected to a set of stresses which are opposite in sign to those in the middle part of the disc. Furthermore it is worth noting that since the region of high stress is
a) Diagram of maximum bending stress

b) Shape of deflection curve

FIGURE 3.1
a) Simply supported disc

b) Disc with clamped edge

FIGURE 3.2
small, in the case of non-uniform properties, the stiffness in this load situation is mainly representative of the properties in this area.

3.2 How to Test Discs and Which Real Situations they Represent

Following the introduction of the subcomponent principle some methods of testing them were already suggested and they are fundamentally four

- Tests with square plates
  1) Plate flexure in three lines
  2) Plate torsion

- Tests with circular discs
  3) Disc flexure in three lines
  4) Central loading of the disc

3.2.1 Cylindrical bending/tests

The tests (1) and (3) cause a situation of 'cylindrical bending' in the specimens, this being closer to the theoretical idealisation in the case of flexure of square plaques. This test which for convenience will be referred to in the thesis as the 'three line test' imposes on to the specimen a state of stress which is biaxial in nature (63). In fact the two principal curvatures in the plate at the loading line (Figure 3.3) are:
and the unit bending moments are

\[ M_x = 2 C D \]
\[ M_y = 2 v C D \]
\[ T_{xy} = 0 \]

(3.2)
D being the flexural rigidity \( \frac{E h^3}{12 (1 - v^2)} \) and \( h \) the thickness.

The resulting stresses in the plate are \( 6/h^2 \) times the unit moments. Thus the three line test on a square plaque is equivalent to a uniformly distributed moment, \( 2CD \), acting in the sides parallel to the loading line and also a somewhat smaller moment in the perpendicular direction. The existence of these 'reactive' moments will keep the sides straight by avoiding the anticlastic effect due to the Poisson's ratio effect.

This test has the advantage of being very simple to be carried out, however it does not represent typical service situations.

### 3.2.2 Central loading test

The central loading test of a disc, (4), is a situation closer to reality where usually transverse loads are applied to the components. This type of loading applies to the specimen a state of biaxial stress where the principal stresses are nearly identical, differently from the previous test where one of the stresses is usually less than 50% of the major stress. The principal stresses are in the radial and in the circumferential directions and are given in polar coordinates by (62):

\[
\sigma_r = \frac{12 M_r}{h^3} Z
\]

\[
\sigma_\theta = \frac{12 M_\theta}{h^3} Z
\]
where \( Z \) is the distance to the mid-plane of the plate of thickness, \( h \), and radius, \( R \).

Given the deflection function, \( \delta \), for an applied load \( W \),

\[
\delta = -\frac{W}{16 \pi D} \left( \frac{3 + \nu}{1 + \nu} (R^2 - r^2) + 2 r^2 \log \frac{r}{R} \right) \quad (3.4)
\]

and the expressions of the moments

\[
M_r = -D \left( \frac{3 \delta}{3 r^2} + \nu \left( \frac{1}{r} \frac{\delta}{\delta r} + \frac{1}{r^2} \frac{3 \delta}{\delta r^2} \right) \right) \quad (3.5)
\]

\[
M_\theta = -D \left( \nu \frac{3 \delta}{3 r^2} + \frac{1}{r} \frac{\delta}{\delta r} + \frac{1}{r^2} \frac{3 \delta}{\delta r^2} \right)
\]

the expressions for \( \sigma_r \) and \( \sigma_\theta \) can be found considering that \( \frac{\partial \delta}{\partial \theta} = \frac{\partial^2 \delta}{\partial \theta^2} = 0 \) because \( \delta \) is a function of \( r \) only. For \( Z = \frac{h}{2} \) is obtained after taking derivatives of \( \delta \) with respect to \( r \), first

\[
M_r = -\frac{W}{8 \pi} \left( 3 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} + \nu \left( 1 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} \right) \right) \quad (3.6)
\]

\[
M_\theta = -\frac{W}{8 \pi} \left( \nu \left( 3 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} \right) + 1 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} \right)
\]

and then

\[
\sigma_r = -\frac{3 W}{4 \pi h^2} \left( 3 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} + \nu \left( 1 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} \right) \right) \quad (3.7)
\]

\[
\sigma_\theta = -\frac{3 W}{4 \pi h^2} \left( 1 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} + \nu \left( 3 - \frac{3 + \nu}{1 + \nu} + 2 \log \frac{r}{R} \right) \right)
\]
For polypropylene $\nu \approx 0.45$ and at a small distance from the loading central point, say 5 mm, and a support radius $R = 55$ mm results

$$\sigma_r = 1.660 \frac{W}{h^2}$$

$$\sigma_\theta = 1.923 \frac{W}{h^2}$$

which is a difference of about 16%.

The distribution of the principal stresses $\sigma_r$ and $\sigma_\theta$ along the radius of a circular disc with the edges free and loaded at the centre by a concentrated load was already shown in Figure 3.2(a).

### 3.2.3 Plaque torsion test

The plate torsion test, 2), was used (64) for representing the shear properties of the material. In fact this test reproduces the pure uniform twist of a plate giving a value of the effective plate shear modulus, $G$. This can be calculated from the load displacement curve using the relationship:

$$G = \frac{3}{8} \frac{L^2}{\delta} \left( \frac{W}{\delta} \right)$$

(3.8)

where: $L$ - diagonal length of the plate

$\delta$ - relative displacement of adjacent corners

$\frac{W}{\delta}$ - slope of the load/displacement trace.
In this work the torsional properties have not yet been considered and therefore this point will not be pursued further. Nevertheless its interest is great because one of the points which concerns designers of products like trays or crates is their twisting rigidity.

3.2.4 Three point support test

One intrinsic problem of 'plane' injection mouldings is that some degree of warpage is always present. This will bring a problem to the testing of mouldings in the three line test and the central load test. In fact even if the specimens are bent very slightly, the first movement of the machine crosshead at the beginning of the test will be used for 'flattening' the specimen. In the force/displacement graph this feature is shown by an initial transition zone with a very small slope and extending until the plate 'sits' perfectly on the supports.

A means of overcoming this problem is to adopt a type of test which is 'insensitive' to the lack of perfect flatness. Such test can consist of supporting the specimen on three points and central loading it. This test which will be referred to as the 'three point support test' was developed during the course of this work and has the additional advantage of simulating more closely a full biaxial stress situation than the three line test.
3.3 Analytical Modelling of the Test Methods

3.3.1 Three line test

For the derivation of an analytical expression for the three line test it will be assumed that the material is isotropic and linear elastic. For the purpose of this research it is only necessary to establish a relationship between the load applied to a circular disc and the corresponding deflection.

The geometry of the test is shown in Figure 3.4 where a circular disc is simply supported on two parallel linear supports.
and loaded with a parallel and uniformly distributed force applied at midspan, of total magnitude \( W \).

The maximum deflection which takes place at midspan is given by the following expression of the method of moment of areas (21):

\[
\delta = \frac{1 - \nu^2}{E} \int_0^{R-A} \frac{Mx}{I} \, dx.
\]  

(3.9)

where \( (1 - \nu^2) \) is the stiffening effect due to the plate geometry, and

for \( 0 \leq x \leq R-A \), \( M = \frac{Wx}{2} \)

\[
I = \frac{h^3}{12} 2 \sqrt{(2R(x+A)-(x+A)^2)},
\]

\[
E = \text{flexural modulus (Pa)}
\]

\[
R = \text{radius of disc (m)}
\]

\[
W = \text{total applied load (N)}
\]

\[
h = \text{thickness (m)}
\]

\[
A = \text{overhanging length (m)}
\]

\[
\nu = \text{lateral contraction ratio}
\]

Substituting the expressions of \( M \) and \( I \) into the equation (3.9), after simplification is obtained

\[
\delta = \frac{3W(1 - \nu^2)}{Eh^3} \int_0^{R-A} \frac{x^2}{\sqrt{(2R(x+A)-(x+A)^2)}} \, dx
\]  

(3.10)
The definite integral can be calculated analytically (65) leading to

\[
\delta = \frac{3W (1 - v^2)}{Eh^3} \left[ - \frac{x + 3(R-A)}{2} \sqrt{2R(x+A) - (x+A)^2} + \frac{3R^2 - 4RA + 2A^2}{2} \sin^{-1} \frac{R-A}{R} \right]_0^{R-A} \tag{3.11}
\]

and finally, after calculation

\[
\delta = \frac{3W (1 - v^2)}{Eh^3} ((R-A) (-2R + \frac{3}{2} \sqrt{2RA - A^2}) + \frac{3R^2 - 4RA + 2A^2}{2} \sin^{-1} \frac{R-A}{R}) \tag{3.12}
\]

Hence, recalling the definition of flexural stiffness of a plate:

\[
C = \frac{E}{1 - v^2} \tag{3.13}
\]

the following expression for the deflection of the circular plate in the three line test may be obtained:

\[
\delta = \frac{3W}{Ch^3} f(A,R) \tag{3.14}
\]

where \(f(A,R)\) is the function of the radius and the span length (or the overhanging length \(A = (2R-L)/2\)), inside brackets in equation
(3.12), which takes into account the geometric in-plane arrangements of the test.

3.3.2 Central loading test

The maximum deflection of a simply supported circular disc on a ring of equal radius and centrally loaded by a force $W$ is given in the literature (62):

$$\delta = \frac{3W(1 - \nu^2)}{4E \pi h^3} \frac{3 + \nu}{1 + \nu} R^2$$

(3.15)

In terms of the flexural stiffness it becomes

$$\delta = \frac{3W}{4\pi Ch^3} \frac{3 + \nu}{1 + \nu} R^2$$

(3.16)

3.3.3 Three point support test

The problem of the transverse flexure of elastic plates supported at several points was considered by Bassali (66) who derived explicit formulae for the deflection at any point of the plate. The maximum deflection of a circular plate supported at three points regularly distributed along the periphery circumference, and centrally loaded is given by the following expression:

$$\delta = \frac{3W(1 - \nu^2)}{4 \pi h^3 E} R^2 \left(\frac{8}{(1-\nu)(3+\nu)} (2 \log - \frac{\pi}{27} (1+\nu)(\pi + 3\sqrt{3})) + \frac{2}{K(K+1)}\right)$$

(3.17)
where \( K = \frac{3 + \nu}{\nu + 1} \).

Calling the expression of \( \nu \) inside brackets by \( B(\nu) \) and considering the flexural stiffness this equation becomes

\[
\delta = \frac{3W}{4\pi Ch^3} B(\nu) R^2
\]  

(3.18)

### 3.3.4 Relations between the flexural tests

The previously indicated formulae (3.14), (3.16) and (3.18) for the flexural tests are utilised for deriving the flexural stiffness of the specimens and also allow for a direct comparison between the different data.

From the tests is obtained a curve which relates directly force and displacement. In most of the cases this curve can be approximated by a straight line whose slope \( dW/dZ \) is given by the ratio \( W/\delta \). In the case of mechanical springs this ratio is called 'stiffness of the spring'; however in the present context such designation could lead to avoidable confusion with the modulus, \( E \), or even the ratio \( E/(1-\nu^2) \) which are also called stiffnesses. Thus the ratio \( W/\delta \) will be referred to as the 'slope', \( S \).

The flexural stiffness, \( C \), is obtained in each test by the following functions of the applicable slope:

i) Three line test:

\[
C = \frac{3f(A,R)}{h^3} S_L
\]
ii) Central loading test:

\[ C = \frac{3}{4\pi h^3} \frac{R^2}{(1 + \nu)^3} Sc \]  

\[ (3.19) \]

iii) Three point support test:

\[ C = \frac{3R^2}{4\pi h^3} B(\nu) Sp \]

In these circumstances the slope of any of the tests can readily be expressed in terms of any of the other slopes if an adequate value is adopted for \( \nu \). Thus, for example, the slope of the central loading test is related to the other two by:

\[ Sc = \frac{4\pi}{3} \frac{1 + \nu}{3 + \nu} \cdot \frac{f(A,R)}{R^2} SL \]  

\[ (3.20) \]

and

\[ Sc = \frac{1}{3} \frac{1 + \nu}{3 + \nu} B(\nu) Sp \]  

\[ (3.21) \]

3.4 The Problem of Large Deflections

According to Timoshenko (62) the application of formulae like that in equation (3.15) is only valid when the deflection is small in comparison with the thickness of the plate. When the deflection becomes larger the assumption that the strain in the middle plane of the plate is negligible does not apply because it will become stretched like a membrane and in that state can carry part of the load like a curved membrane. A catalogue of results had been derived
for the case of steel plates which have a Poisson's ratio of 0.3, the formulae being compiled in textbooks dealing with the subject. However a number of plastics used in structural applications have a lateral contraction ratio higher than 0.3 and for these an expression for the large deflections is not available. Therefore it appears opportune to derive the equation of large deflections for materials with \( v \neq 0.3 \). In this section the situation of central loading of simply supported disc will be dealt with.

The method used gives an approximate solution for the problem, is based on the application of the strain energy method, and follows the derivation path followed by Timoshenko (62).

The deflection of a simply supported disc with a load \( W \) concentrated at the centre \( (r = 0) \) is given by

\[
\delta = \delta_0 \left(1 - \frac{r^2}{R^2} + 2 U \frac{r^2}{R^2} \log \frac{R}{r}\right)
\]  

(3.22)

where

\[
U = \frac{1 + \nu}{3 + \nu}
\]

\( \delta_0 \) = maximum deflection

\( R \) = radius of the disc

This equation holds rigorously for a plate with small deflections.

The stress function \( f \), defining the tensile forces per unit length applied to the plate is governed by the differential equation
Differentiating the function $\delta$ (Equation 3.22) and substituting in equation (3.23) is obtained

$$\frac{d}{dr} \left( \frac{1}{r} \frac{df}{dr} + \frac{d^2f}{dr^2} \right) = Ar + Br \log \frac{r}{R} + C^* r \log^2 \frac{r}{R}$$

(3.24)

where

$$A = (U - 1)^2 Y$$
$$B = 4U (U - 1) Y$$
$$C^* = 4U^2 Y$$
$$Y = -\frac{2 \delta_0 Eh}{R^4}$$

After some manipulation and integration (detail calculations are shown in Appendix 1) the following form results

$$\frac{df}{dr} = \frac{D^*}{4} r^3 + \frac{E^*}{4} r^3 (\log \frac{r}{R} - \frac{1}{4}) + \frac{C^*}{4} r^3 \left( \frac{1}{16} - \frac{\log \frac{r}{R}}{4} + \frac{\log^2 \frac{r}{R}}{2} \right)$$

$$+ \frac{C_1}{2} r + \frac{C_2}{r}$$

(3.25)

where $C_1, C_2$ - constants of integration.
\[ D^* = \frac{A}{2} - \frac{B}{4} + \frac{C^*}{4} \]

\[ E^* = \frac{B}{2} - \frac{C^*}{2} \]

Two conditions implying that:

i) The disc boundary can have a free radial displacement

\[ \left( \frac{1}{r} \frac{df}{dr} \right)_{r=R} = 0 \]

ii) The in-plane force at the centre has finite value

\[ \left( \frac{df}{dr} \right)_{r=0} = 0 \]

allow the calculation of the constants of integration

\[ C_1 = \left( \frac{E^*}{4} - D^* - \frac{C^*}{16} \right) \frac{R^2}{2} \]

\[ C_2 = 0 \]

Then the deflection equation can be calculated from the equation

\[ \int_0^R X \frac{d\phi}{dr} r \, dr = 0 \]

where \( X = D \frac{d}{dr} (\Delta \delta) - \psi - \frac{1}{r} \frac{df}{dr} \frac{d\delta}{dr} \)
\[ \phi = 1 - \frac{r^2}{R^2} + 2U \frac{r^2}{R^2} \log \frac{r}{R} \]

\[ \Delta \delta = \frac{1}{r} \frac{d\delta}{dr} + \frac{d^2\delta}{dr^2} \]

and \[ \psi = \frac{W}{2\pi r} \]

After some more manipulation of the results the following expression is obtained for the deflection function

\[
\frac{2}{R^2} \int_0^R \left( B_0 r^5 + B_1 r^3 + B_2 r^5 + B_3 r^5 \log \frac{r}{R} + B_4 r^5 \log^2 \frac{r}{R} + B_5 r^5 \log^3 \frac{r}{R} + B_6 r^5 \log^4 \frac{r}{R} \right) \, dr = 0
\]

(3.27)

where \( B_0 = (U - 1) A_0 \)
\( B_1 = -(U - 1) A_1 \)
\( B_2 = -(U - 1) A_2 \)
\( B_3 = 2U A_0 \)
\( B_4 = -2 U A_1 - (U - 1) A_3 \)
\( B_5 = -2 U A_3 \)
\( B_6 = -2 U A_2 - (U - 1) A_4 \)
\( B_7 = -2 U A_4 - (U - 1) A_5 \)
\( B_8 = -2 U A_5 - (U - 1) A_6 \)
\( B_9 = -2 U A_6 \)

and \( A_0 = 4 U D H - \frac{W}{2\pi} \)
\[ A_1 = (U - 1) \frac{C_1}{2} H \]

\[ A_2 = \left(\frac{D^*}{4} - \frac{E^*}{16} + \frac{C^*}{64}\right) \frac{U - 1}{64} H \]

\[ A_3 = C_1 U H \]

\[ A_4 = \left(\frac{D^*}{2} + \frac{E^*}{8} - \frac{C^*}{32}\right) U - \frac{E^*}{4} + \frac{C^*}{16} H \]

\[ A_5 = \left(\frac{E^*}{2} - \frac{C^*}{8}\right) H \]

\[ A_6 = \frac{C^*}{4} U H \]

and \[ H = \frac{2}{R^2} \delta_0 \]

The definite integral in (3.27) can be calculated using the solution:

\[
\int_0^R r^m \log^n r \frac{dr}{R} = \frac{(-1)^n n!}{(m+1)(m+1)!} R^{m+1}
\]  

Then after a somewhat lengthy manipulation which is described in Appendix 1, one gets the final equation as

\[
\frac{\delta_0}{h} + \frac{5(1 - v^2)}{U} B^* \left(\frac{\delta_0}{h}\right)^3 = \frac{3(1 - v^2)}{4 U \pi} \frac{W R^2}{Eh^4}
\]  

(3.29)
where $B^*$ is a function of the coefficients $B_i$.

The calculation of the equation (3.29) which is of the form

$$\left(\frac{\delta}{R} + \alpha \left(\frac{\delta}{R}\right)^3\right) = B \frac{W R^2}{E h^2} \quad (3.30)$$

can be readily done for different values of the lateral contraction ratio using a computer. This was done with a Basic computer programme which is also enclosed in Appendix I, as well as a list of values of the coefficients $\alpha$ and $B$ for typical values of $v$.

For the case of PP which was the material mostly used in the experimental work, $v = 0.45$. For this value of $v$ the equation (3.29) becomes

$$\frac{\delta}{R} + 0.226 \left(\frac{\delta}{R}\right)^3 = 0.453 \frac{W R^2}{E h^4} \quad (3.31)$$

If the flexural stiffness is taken instead of $E$ the alternative equation results

$$\frac{\delta}{R} + 0.226 \left(\frac{\delta}{R}\right)^3 = 0.568 \frac{W R^2}{C h^4} \quad (3.32)$$

In Figure 3.5 is shown how the actual deflection calculated using the large deflection equation varies with respect to the small strain equation which does not consider the membrane stresses. It is...
Disc diameter 100 mm
thickness 3 mm
E = 2.2 GPa

FIGURE 3.5
observed for a deflection of the order of half the thickness the departure between the 'membrane' deflection and the 'elastic' deflection is 5%, and 15% for deflections of the order of thickness. There is however an interesting point about this: if the designer does not consider the membrane stress problem at all and is interested in the stiffness of the plate only then his predictions will be conservative from the point of view of deflection.

3.5 The Subcomponent as a Means of Assessing the Toughness

Impact loading (or abuse) is a common cause of failure of plastics products and usually a cause of concern insofar that the type of failure tends to be brittle. The brittle behaviour can be induced by sharp notching specimens and testing them at slow speeds. This has been the approach from the Fracture Mechanics point of view and a number of tests have been already standardised using specimens of defined configuration such as the sing-edge-notch test piece (SEN) or the compact tension test piece (CTS). With plastics however the preferred method of assessing the brittleness of materials is by impact testing.

Very broadly the impact tests are divided into pendulum and drop weight impact tests. The pendulum ones are indeed the more popular and a Fracture Mechanics analysis for brittle failure has already been done (67). The toughness of the material was quantified in terms of a critical strain energy release rate, $G_c$. This is in turn related to the stress intensity factor $K_{IC}$ of the material by
for the case of plane stress. Nevertheless the results obtained with this test refer to the properties of the material in a specimen and hardly can be extended to complete products.

3.5.1 Instrumented falling weight tests

Drop weight tests were revived in recent years due to the possibility of instrumentation allowing for the absorbed energy at fracture being measured. These tests offer the attraction of enabling one to test complete mouldings as opposed to sample pieces. The instrumentation of the tests has been developed during the last 15 years or so. Practical advantages have been assigned to this type of test as being (68)

1. Sample preparation is reduced to a minimum since whole mouldings or specimens roughly cut from the whole can be tested.

2. The number of specimens required for a given material evaluation is reduced since each specimen tested fails and the details of each failure are recorded.

3. The distinction between brittle and ductile behaviour is more clearly defined than in other tests since yielding of the material can be observed from the load-deflection details for each specimen.

4. The test will show the weak directions in a component, and failure will occur in these directions.

$K_{IC}^2 = \frac{E}{G_C}$ (3.33)
5. Whole mouldings with different geometries can be tested to assess the effect of corners, ribs etc. as well as the size of a component.

3.5.2 Impact data presentation

The instrumented test produces a curve which generally shows the variation of the force exerted by the impactor upon the specimen, but there are systems such as that described by Wnuk et al. (69) where the recorded variable is the acceleration of the impactor. Nevertheless the actual interpretation of the test data as a means of describing toughness has been usually dependent on the researcher's judgement after analysing in detail their own equipment performance. A number of uncertainties are associated with the test and the need is strongly felt for standardisation of data. A system of data presentation was recently put forward by Gutteridge and Turner (70) who not only consider the falling weight test but also the other principal tests: Charpy, Izod and tensile. The impact data should be presented as a function of the test temperature, $T$, the notch geometry, $N$, the straining rate, $\dot{\varepsilon}$, and the excitation energy, $U$. The consideration of molecular orientation and texture which depends on the fabrication method and the processing conditions should also be included in the impact data. Thus in the simplest case, the impact datum, $I$, would relate to the above parameters by a relation like

$$I = f(T, N, \dot{\varepsilon}, U) \ g(P_i)$$  \hspace{1cm} (3.34)
3.5.3 Instrumented falling weight machine specifications

The basic specifications for an instrumented impact test can be listed as (71):

a) be a small-scale test
b) produce quick and reliable results
c) be simple in design and easy of operation
d) permit full-speed tests to be performed even on brittle materials
e) allow for testing samples of a wide range of size and shape
f) the loading pattern should be as close to practical conditions as possible (i.e. biaxial impact loading).

Most of the falling weight (FW) instrumented machines derive from the standard FW tester, where the impactor was fitted with a pressure/force transducer and its weight increased so that sufficient kinetic energy will be available at the impact to ensure fracture. The transducer is connected to a transient recorder and to an oscilloscope which will display the load-time curve. In some of the apparatuses this information can be transferred to a computer where the salient load-deflection details are worked out. This type of machine has been used by a number of researchers (69,71-75) however others have used servohydraulic actuated machines where the impactor is fixed and the specimen pushed towards it (75,76).

The impactor has in most cases, a hemispherical head, but some authors (71,72) advocate the use of a flat headed impactor. According to these the use of this type of head will avoid the 'drawing'
of the material around the head, however the different pattern of stressing induced by it is not considered and also to what extent it will affect the failure of the specimens. This point has not been argued by other researchers.

The majority of the machines use the sample clamped to its support and Wnuk et al (69) even claim that this is fundamental for guaranteeing the reproducibility of the results. It appears, however not to be the opinion of Minkhorst et al (72), and Hooley and Williams (68) who used the specimen simply supported on its edge.

The effect of strain rate on the results was reported by Torres (77) and Wnuk (69), but it appears that some trend exists on fixing the impact speed at about 4 m/s.

The radius of the impactor was examined by Tryson et al (76) but the work appeared a little inconclusive insofar as different materials (PC and PMMA) produced very different results.

3.5.4 Energy considerations in the FW test

The determination of the energy absorbed during the impact can be done considering the energy balance of the kinetic energy at the moment of the impact

\[ E_0 = \frac{1}{2} m v_o^2 \]  

(3.35)

and the energy remaining in the impactor after the rupture of the specimen

\[ E_n = \frac{1}{2} m v_n^2 \]  

(3.36)
Thus the energy absorbed during the impact is

\[ E_b = \frac{1}{2} m (v_o^2 - v_n^2) \]  

(3.37)

where \( m \) - mass of the striking impactor (kg)

\( v_o, v_n \) - initial and final speeds of the impactor (m/s)

The value of \( v_o \) can be estimated by the known relation

\[ v_o = \sqrt{2 gh} \]  

(3.38)

where

\( g \) - acceleration due to gravity (9.81 m/s²)

\( h \) - height from which the tup is dropped (m)

For the determination of \( v_n \) the relationship between the variation of velocity and the impulse applies

\[ m(v_o - v_n) = \int_{t_o}^{t_n} F(t) \, dt \]  

(3.39)

By solving this equation with respect to \( v_n \) is obtained

\[ v_n = -\frac{1}{m} \int_{t_o}^{t_n} F(t) \, dt + v_o \]  

(3.40)

The integral \( \int_{t_o}^{t_n} F(t) \, dt \) is given by the area under the force-time (= deflection) obtained in the test, which can be represented by \( A \). Thus the equation (3.40) can be rewritten as
\[ v_n = - \frac{1}{m} A + v_0 \]  

(3.41)

By combining this equation with equation (3.41) an expression is obtained for the energy absorbed during the impact as a function of the mass of the impactor, \( m \), its velocity at the moment of impact, \( v_0 \), and the area under the experimental curve, \( A \),

\[ E_b = \frac{1}{2} m (v_0^2 - (v_0 - \frac{1}{m} A)^2) \]

This expression after simplification leads to

\[ E_b = A (v_0 - \frac{A}{2m}) \]  

(3.42)

and can also be expressed in terms of the maximum energy at impact, by recalling the equation (3.35):

\[ E_b = A v_0 \left(1 - \frac{A v_0}{4E_0}\right) \]  

(3.43)

In order to minimise the effect of the reduction of velocity during the impact authors such as Casiraghi (74) recommend that the energy at the moment of impact should be at least three times that required for breaking the specimen. The argument however did not receive particular attention from other researchers for whom the specification of an amount of energy 'well in excess' of that required for breaking the specimen is considered enough.
3.5.5 Interpretation of test data

It was already referred to that for the pendulum tests a Fracture Mechanics analysis had been developed in recent years for the case of plastics. The analysis for the case of brittle materials is a straightforward application of the linear elastic fracture mechanics (LEFM). The problem of the ductile failure involving large plastic deformation, which is the case of most engineering thermoplastics, involves greater complexities which it was suggested might be overcome by other FM approaches such as the integral J concept (Plati and Williams (67)) or the specific surface energy approach (Newmann and Williams (78)). The problems of interpretation of the data are nevertheless great and many, which might explain the lack of information in this field.

The situation gets worse when biaxial stress situations such as that in the FW test are considered. No attempt appears to have been done on the systematic interpretation of the behaviour in Fracture Mechanics terms. The results so far are usually shown as the energy required for the fracture of the samples however this value depends on a fairly great number of test variables.

In this work an instrumented FW machine was used but it is felt that the interpretation of data in terms of Fracture Mechanics is out of the scope and the time scale of the programme. The data obtained will only hold for comparative purposes within tests in similar conditions. This information is nevertheless important for the designer as it can guide him for an adequate selection of
materials, say, in terms of service temperature, design of sections in critical regions, convenient positioning of gates, optimisation of weld lines, and so on.
CHAPTER 4
EXPERIMENTAL METHODS

4.1 Design of Equipment

Circular discs being not standard test pieces for which testing equipment is fitted with off-the-shelf accessories, and as non-standard tests were used in this work, special pieces of equipment had to be designed for use with the universal testing machine Instron floor Model TT-CM available at the IPT. The test rigs were designed for performing the three flexural tests, which were referred to in the previous chapter, based upon the utilisation of a 100 kgf load cell. In all the tests the load cell is used in compression.

4.1.1 Three line test rig

This rig is composed of a base (see Figure 4.1) which is screwed directly on to the load cell. The base has a diametral slot in which two sliding linear supports can move allowing for the change of the span in the test. A loading bar is attached to a rigid extension bar which is fixed to the crosshead bar of the machine. The loading bar is aligned with the axis of the load cell and can be set parallel to the two sliding supports. The supports and the loading bar have the radius of the loading edge equal to 4 mm corresponding to the recommendations of BS 2782 (79) for three point bending tests on plastic bars. Detail drawings of this rig are included in Appendix 2.
4.1.2 Central loading test rig

In the central loading test the specimen is required to be supported along its periphery. The rig designed for this test was also intended for testing the discs having a clamped edge however this test was not pursued in the work.

The loading of the specimens is done by a loading nose with radius 40 mm (Figure 4.2). It is a fairly large radius chosen for reducing the indentation at the loading 'point'. The effect of the radius of the loading nose in the results of the test was analysed by Dunn and Williams (80) who also discussed other points involved in the central loading of circular plastic plates.

The initial requirement for the rig being useable in tests with clamped edge discs made the manipulation of the specimens not as easy
FIGURE 4.2

- Extension bar
- Loading nose
- Support ring (interchangeable)
- Base
as in other designs where the support is only a ring with external diameter identical to the diameter of the specimen (e.g. Hooley and Turner (81)). The design adopted allows for the testing of samples with different diameters by using appropriate exchangeable support rings. Detail drawings are available in Appendix 2.

4.1.3 Three-point support test rig

The rig for the novel three point support test uses part of the components used for the preceding rig. The only modification (see Figure 4.3) is the replacement of the support ring by a plate where spherical headed supports can be positioned in three basic configurations chosen for the samples used in the test programme.
a) **Rig specifications:**

For the design of the rig the following specifications were set:

i) The loading nose of the edge support test should be used.

ii) The contact stresses in the support points should be of the same level as those in the loading point.

iii) The positioning of the circular discs should be easy and quick.

iv) The deflections to be considered in the tests are small in comparison with the thickness of the samples.

These specifications have practical implications in the results of the test which will be discussed next.

b) **Determination of the radius of the point supports:**

The specification (ii) can be expressed by means of the maximum Hertz contact stress which is given (82) with reference to Figure 4.4 by

\[ p_{\text{max}} = \frac{3w}{2 \pi a^2} \]  \hspace{1cm} (4.1)

The radius of the area of contact, \( a \), is given by
where:

\( w \) = contact force (N)

\( 2a \) = diameter of the area of contact (m)

\( \nu \) = lateral contraction ratio

\( E_I \) = modulus of elasticity (for steel = 210 GPa)

\( E_{II} \) = modulus of elasticity (for PP = 2 GPa)

\( d \) = diameter of sphere head support

In this case the maximum pressure at the loading nose is:

\[
 p_{\text{max}} = \frac{3w}{2 \pi a_1^2} 
\]  

(4.3)

and at each support

\[
 p_{\text{max}} = \frac{3 \frac{W}{3}}{2 \pi a_2^2} 
\]  

(4.4)
Equating (4.3) to (4.4) results

\[ a_2^2 = \frac{a_1^2}{3} \]  \hspace{1cm} (4.5)

Using the formula (4.2) \( a_1 \) and \( a_2 \) are expressed in terms of the parameters known for the test:

\[
a_1 = \sqrt[3]{\frac{3w}{6}} \left(1 - v^2\right) \left(\frac{1}{E_I} + \frac{1}{E_{II}}\right) d_1 \]  \hspace{1cm} (4.6)

\[
a_2 = \sqrt[3]{\frac{3w}{6}} \left(1 - v^2\right) \left(\frac{1}{E_I} + \frac{1}{E_{II}}\right) d_2
\]

By substitution of \( a_1 \) and \( a_2 \) in equation (4.5) and raising both members to the power 1.5 is obtained

\[
\frac{3w}{8 \times 3} \left(1 - v^2\right) \left(\frac{1}{E_I} + \frac{1}{E_{II}}\right) d_2 = \frac{1}{31.5} \left(\frac{3w}{6} \left(1 - v^2\right) \left(\frac{1}{E_I} + \frac{1}{E_{II}}\right) d_1\right)
\]

resulting after simplification

\[
\frac{d_2}{3} = \frac{d_1}{31.5}
\]

or

\[
d_2 = \frac{d_1}{\sqrt{3}} \]  \hspace{1cm} (4.7)
Thus, if the diameter of the loading nose is \( d_1 = 80 \) mm then the diameter of the supports will be

\[
d_2 = \frac{80}{\sqrt{3}} = 46 \text{ mm}
\]

c) Variation of the span diameter with deflection

Since the supports have a finite diameter when a deflection is applied to the plane specimen the span diameter (locus of the support centres) will shorten and the specimen actually will move downwards. For the following analysis it will be assumed that the surface will deflect according to a spherical shape.

When a deflection of value \( \delta \) is applied, if a cross-section is made passing through the line of loading and the centre of one of the supports the geometrical configuration shown in Figure 4.5 will be obtained.

Considering the system of rectangular coordinates \( Oxz \) shown in the figure, the equation of the circle of the radius \( R_0 \) (support) is

\[
x^2 + z^2 = R_0^2
\]

and the equation of the deflected surface line is

\[
(x - \frac{L}{2})^2 + (z - Z)^2 = R^2
\]
From geometry considerations it results that the ordinate of the centre of the deflected surface is

\[ Z = R_0 + R - \delta \]  \hspace{1cm} (4.10)

and considering the angle \( \alpha \)

\[ \sin \alpha = \frac{x_0}{R_0} = \frac{L - x_0}{R} \]  \hspace{1cm} (4.11)

Since the spheres of radii \( R \) and \( R_0 \) are tangent at a point \( P(x_0, z_0) \) the tangents to both circles at that point are common, that
is:

- For the support and from differentiation of (4.8)

\[
\frac{dz}{dx}_{x=x_0, z=z_0} = -\frac{x_0}{z_0}
\]  

(4.12)

- For the surface, after differentiation of (4.9)

\[
\frac{dz}{dz}_{x=x_0, z=z_0} = \frac{-\left(x_0 - \frac{L}{2}\right)}{z_0 - z}
\]  

(4.13)

Hence, from (4.12) and (4.13) after replacing \( Z \) by \( (4.10) \) results

\[
\frac{x_0}{z_0} = \frac{x_0 - \frac{L}{2}}{z_0 - R - R + \delta}
\]

or

\[
\frac{z_0}{x_0} = \frac{R_0 + R - \delta}{L/2}
\]  

(4.14)

Finally the equations (4.11),(4.14) and a third one obtained by ascertaining the coordinates \((x_0, z_0)\) in equation (4.8)

\[
x_0^2 + z_0^2 = R_0^2
\]  

(4.15)

enable to determine the decrease \( x_0 \) in the span radius.
Substituting in (4.15) the value of \( z_0 \) obtained from (4.14) and that of \( R \) obtained from (4.11), results

\[
x_0^2 + \left( \frac{R_0 \frac{L}{Z} - \delta x_0}{L} \right)^2 - R_0^2 = 0.
\]

which after rearrangement and simplification leads to

\[
\left( \frac{L}{Z} \right)^2 + \delta^2 x_0^2 - \delta R_0 L x_0 = 0
\]

(4.16)

This second-order equation has a trivial solution \( x_0 = 0 \) which does not apply, and another which is

\[
x_0 = \frac{\delta R_0}{L + \frac{L}{4} \delta^2}
\]

(4.17)

For small values of \( \delta \) compared with \( L/2 \) this expression shows that the decrease in span is proportional both to the deflection \( \delta \) and the radius of the support \( R_0 \). In the case of the experimental work done the deflections are of the order of 1 mm. Thus the decrease in span radius due to loading is for one of the geometries used:

Given \( R_0 = 23 \text{ mm} \)

\( L = 92 \text{ mm} \)

\( \delta = 1 \text{ mm} \)

\[
x_0 = \frac{1 \times 23}{92 + \frac{12}{92}} = 0.9995 \text{ mm}
\]

which is a reduction marginally above 2%.
d) Dependence of the deflection equation on the span

The load-deflection equation for the three point support test, (3.24), introduced in Section 3.6.3 shows that the deflection is proportional to the load and the span radius squared

\[ \delta = KwR^2 \quad (4.18) \]

when the radius \( R \) is decreased by a fraction \( \xi \) due to a deflection, \( \delta \), its new value is

\[ R' = R(1 - \xi) \quad (4.19) \]

Then, the load actually required for producing that deflection is higher than that predicted by equation (4.18) which assumes a constant \( R \). Let the new load be \( w' \), then

\[ \delta = Kw'R'^2 \]

or

\[ \delta = Kw'R^2(1 - \xi)^2 \quad (4.20) \]

Dividing (4.20) by (4.18) is obtained

\[ \frac{w'}{w} = \frac{1}{(1 - \xi)^2} \]

or

\[ w' = w(1 + \frac{\xi}{1 - \xi})^2 \quad (4.21) \]
The relation shows that if the span is reduced by, say, 2% then the force actually required for causing a given deflection needs to be about 4% higher.

These facts are important if large scale deflections are to be considered in the bending of circular discs. If the diameter of the supports is large, the reduction in span diameter is also large and, therefore, the apparent increase in stiffness observed in the tests should be accounted for by the membrane stresses (already discussed in Section 3.7) and the reduction in span diameter. The practical implication is that the diameter of the supports should be kept to the minimum compatible with indentation effects when large deflections are to be considered.

4.1.4 Rig for testing complete mouldings

For the terminal part of the work commercial mouldings were tested. These were boxes of different sizes and configurations, and it was decided to test them in the Instron by applying a concentrated load at the centre of the boxes.

For these tests a rig was prepared consisting of a frame attached to the base of the Instron and allowing for the boxes being supported along the periphery of their bases, or in 4 points near their corners. Provision was also made for using the compression 100 kgf load cell from the loading side by attaching it to the crosshead (Figure 4.6).
Detail drawings of this rig are enclosed in Appendix 2.

4.2 Moulding Programme

The moulding of the samples for the work was carried out at the Plastics Division (now Petrochemicals and Plastics Division) of Imperial Chemical Industries PLC, Welwyn Garden City, in two stages. During the first stage one type of moulding only - the edge gated disc with 113 mm diameter - was produced in two thicknesses, over a range of processing conditions and using two materials. In the second stage three types of mouldings were used differing in gate system. The materials used in the first stage were two injection moulding grades of polypropylene:

i) Polypropylene homopolymer, ICI Propathene GSM 10

ii) Ethylene-propylene copolymer, ICI Propathene GWM 101.

In the second stage only the copolymer was used.
4.2.1 Material properties

The basic properties of the two grades of polypropylene which were supplied in granules, according to the manufacturers (83) are those listed in Table 4.1. These materials were selected because they have different melt flow indices and the copolymer is one of the more used materials being applied in cases where rigidity, appearance, and impact properties are desirable. A great number of applications are load bearing, therefore it was considered as being representative and worthwhile to use it in this type of investigation.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>GWM 101 Grade</th>
<th>GSM 10 Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (mean)</td>
<td>kg/m³</td>
<td>9.05</td>
<td>9.05</td>
</tr>
<tr>
<td>Melt Flow Index</td>
<td>g/10 min, 230°C, 2.16Kgf</td>
<td>4.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Tensile yield stress (ASTM D638-64)</td>
<td>MPa</td>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>Flexural modulus (ASTM D790-66)</td>
<td>GPa</td>
<td>1.38</td>
<td>1.51</td>
</tr>
<tr>
<td>Drop impact strength (BS 2782:306B at 23°C with 1.5 mm spec)</td>
<td>J</td>
<td>15.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Softening temperature (BS 2782: 102)</td>
<td>°C</td>
<td>147</td>
<td>148</td>
</tr>
<tr>
<td>Heat distortion temp. (ASTM D648-72 at 455 kPa)</td>
<td>°C</td>
<td>100</td>
<td>105</td>
</tr>
</tbody>
</table>
During the timespan of the programme two batches of the nominally same GWM 101 ethylene copolymer were used. Their batch codes are:

Batch I:    EF 12/393
Batch II:   ED1 AZ1D

4.2.2 Moulding equipment

For the moulding of the samples two injection moulding machines were used: a Daniels 350-120 (with shot capacity of 200 grammes and plasticating rate of 75 kg/hr) and an Ankerwerk 36-150 with similar processing capabilities. The first machine was used for the first stage of the programme and part of the second (when some mouldings were remoulded for checking the repeatability of properties of different batches of the same grade of material).

The moulds used were two, both being of the two plate and single impression type. Both have a recess where different inserts featuring distinct cavities can be used. In the first mould the following inserts were used:

i) 115 mm diameter, 1.5 mm deep cavity with edge gate
ii) 115 mm diameter, 3 mm deep cavity with edge gate
iii) 89 mm diameter, 3 mm deep cavity with double edge gate

A schematic drawing of this mould and inserts is shown in Figure 4.7 (overleaf).
a) MOULD FOR EDGE AND DOUBLE-GATED DISCS

b) EDGE-GATED INSERT AND MOULDING

c) DOUBLE-GATED MOULDING INSERT

FIGURE 4.7
The second mould also allows for the use of several inserts. The following cavities were used with this mould for central gated discs (see Figure 4.8):

iv) 100 mm diameter, 1.5 mm depth
v) 100 mm diameter, 3 mm depth

The cooling system of the moulds is very simple consisting only of two parallel water lines in each plate of the mould.
The moulds were usually temperature controlled by a circulating water unit. This however did not have refrigerating capabilities, therefore the minimum achievable mould temperature was determined by the thermal balance of the melt heat input and the mains water output, and radiation and convection to the atmosphere.

4.2.3 Moulding conditions

Four sets of processing conditions shown in Table 4.2 were utilised. They are thought to represent a range of processing conditions in which commercial practice will lie.

TABLE 4.2
Processing Conditions

<table>
<thead>
<tr>
<th>Temperatures (°C)</th>
<th>Injection speed</th>
<th>Identification Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back end to nozzle</td>
<td>Circulating Water</td>
<td></td>
</tr>
<tr>
<td>180 - 190 - 205 - 210</td>
<td>20</td>
<td>Slow</td>
</tr>
<tr>
<td>200 - 210 - 225 - 230</td>
<td>20</td>
<td>Fast</td>
</tr>
<tr>
<td>200 - 210 - 225 - 230</td>
<td>80</td>
<td>Fast</td>
</tr>
<tr>
<td>250 - 260 - 275 - 280</td>
<td>80</td>
<td>Fast</td>
</tr>
</tbody>
</table>

The injection pressure and hold-on pressure as well as the moulding cycle were selected so that warpage-free mouldings could be obtained. The cycle times and the pressures are detailed in Table 4.3, which also show the moulding codes in a
three figure code meaning

- First letter (E, C, D) - gate type: edge, central, or double edge gate
- Digit (1, 3) - thickness: 1 for 1.5 mm, 3 for 3 mm
- Second letter (A to D) - processing condition according to Table 4.2

TABLE 4.3
Moulding Cycles and Pressures

<table>
<thead>
<tr>
<th>Moulding</th>
<th>Cycle Time (s)</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inj + Hold on</td>
<td>Cooling</td>
</tr>
<tr>
<td>Edge Gated (EG)</td>
<td>E1A</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>E1B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E1C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E1D</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E3A</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>E3B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E3C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E3D</td>
<td></td>
</tr>
<tr>
<td>Central Gated (CG)</td>
<td>C1B</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>C1C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3B</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>C3C</td>
<td>40</td>
</tr>
<tr>
<td>Double Edge Gated (DG)</td>
<td>D3B</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>D3C</td>
<td>40</td>
</tr>
</tbody>
</table>

After injection the mouldings were allowed to cool without piling. Piling after demoulding would have the effect of annealing the material therefore affecting the properties of the mouldings. In the case of
CG discs the differential cooling caused by the great mass of the sprue would produce gross warpage of the mouldings, especially those at higher temperatures. To prevent this they were cooled between two steel plates, before removal of the sprue.

4.2.4 Control of moulding

The mouldings actually taken for testing were taken only after steady thermal conditions were reached in the mould. After this the mouldings were produced at a constant rate and periodically their weight was checked and the mould temperature measured by thermocouple.

4.3 Utilisation of Resistance Strain-Gauges for Measuring Lateral Contraction Ratios

For the determination of υ of plastics materials, the most commonly reported method uses contact extensometers (e.g. Benham and McCawond (14), Darlington (36)). The utilisation of these extensometers brings along some problems.

i) A very careful specimen machining preparation is necessary

ii) The extensometers are complex pieces of equipment requiring a convenient degree of expertise for proper utilisation

iii) Their price tends to be expensive

As an alternative it was therefore decided to use resistance strain gauges. These are very well established with metals, but their application to plastics has been limited by the large strains sometimes
observed and the difficulty of bonding them to some materials, namely the polyolefines. Nevertheless in recent years strain gauges capable of coping with large deflections and improved adhesives made the application of the technique possible.

In the case of a material with cylindrical orthotropy such as occurs in centre gated injection mouldings, two contraction ratios are defined in the plane of the plate using polar coordinates (Figure 4.9)

\[
v_{r\theta} = -\frac{\varepsilon_\theta}{\varepsilon_r}
\]

(4.21)

determined in a specimen cut in the radial direction (A)

\[
v_{\theta r} = -\frac{\varepsilon_r}{\varepsilon_\theta}
\]

(4.22)
determined in a specimen cut perpendicularly to the radius (B). \( \varepsilon_r \) is the strain measured in the direction \( r \) of the specimens, while \( \varepsilon_\theta \) is the strain measured in the direction \( \theta \). It should be noted that the values of \( \varepsilon_r \) and \( \varepsilon_\theta \) are not identical in equations (4.21) and (4.22).

If the material is elastic the following relationship between the Young's moduli and the lateral contraction ratios apply (62)

\[
E_\theta \varepsilon_{r\theta} = E_r \varepsilon_{\theta r}
\]  

(4.23)

where \( E_\theta \) and \( E_r \) are the moduli measured in the two principal directions.

For measuring the ratios of a material with this kind of anisotropy strips should be cut in the two principal directions. Given the dimensions of the strain gauges which are recommended for polypropylene, strips 10 mm wide should be used. Ideally the length of the specimen bars would be ten times the width. Limitations in the moulding size however can dictate a choice of smaller length.

For the measurement of \( \nu \) two resistance strain gauges at right angles should be used, or alternatively a 90° rosette. For determining the strains a half bridge arrangement (Figure 4.10) was chosen. For the actual testing a Universal Testing Machine Instron was used at a 0.5 mm/min crosshead speed. Simple resistance foil strain gauges TML type GFLA-3 were used. The strain/length is
3 mm, the gauge resistance $120 \pm 0.3\Omega$ and the gauge factor 2.13, and are usable up to 3% strain in tension.

The adhesive recommended for this application is a fast curing CN (cyano acrylate) adhesive which sets in 1 minute under finger pressure.

The surface preparation prior to bonding is essential for obtaining good results. The following operations were performed:

i) Degreasing of surface with Freon TF. Isopropyl alcohol is an alternative solvent degreaser.

ii) Abrading of the surface to be bonded using a 400 -grit abrasive paper.

iii) Application of gauge layout lines

iv) Surface neutralizing. MM Neutralizer 5 was used

v) Bonding of strain gauges and terminals. TML-CN adhesive was used.
The strain gauges are available with the leads already attached. The connecting terminals (laminated with rubber sheet), TML-TFY-2S type, are soldered to the gauge leads prior to bonding.

The dummy gauges are fitted in test pieces identical to that being tested.

For the determination of the strains an electronic digital strain bridge TQ model E31 was used. This is a multichannel bridge enabling the quick reading of the strain in each of the two strain gauges in the specimen.

After fixing the specimen in one of the Instron grips the bridge is balanced. The second grip is then tightened on and the position of the crosshead of the machine adjusted for compensating any strain introduced during the operation until the balance of the bridge is restored.

The loading is then applied in steps of 5N which for 3 mm-thick polypropylene specimens corresponds to longitudinal strains of 0.07% approximately.

The layout of the strain gauges is shown in Figure 4.11.
4.4 Observation of Structures by Microscopy

Semicrystalline plastics such as polypropylene are optically anisotropic materials insofar as their molecules are organised in preferential directions at the level of crystalline structures, spherulites. When light is transmitted through this type of medium it travels as two beams which are plane polarised in mutually perpendicular directions. Optically these media are characterised by two different indices of refraction and thus are birefringent.

When a birefringent specimen is observed between two polarising plates with axes of polarisation at right angles, i.e. in the position of complete light extinction some features related with the structure and the morphology of the material can be observed. This principle is widely used in the microscopic observation of plastics materials.

The light polarising microscope is basically an ordinary light microscope with certain accessories added and with the optical components constructed from strain-free glass for avoiding spurious sources of (strain) birefringence. The characteristic accessories used in the polarising microscope are:

- the polariser which is placed somewhere below the specimen
- the analyser placed above the specimen
- a rotating specimen stage
- slots for the insertion of compensating devices

For the observation of plastics in this microscope 10-20 μm thick sections must be microtomed and mounted in glass slides with
a suitable mounting liquid. This liquid for the case of PP may be Balsam oil or Euparal oil which have refraction indices close to those of PP.

The sectioning of the specimens across the thickness of the mouldings was done in 10-15 mm long samples, previously sawn off from the complete mouldings, using a Leitz microtome. The microscopy observations were done with a Zeiss Universal light polarising microscope using low power magnification to allow a complete view of the structure through thickness being seen. The photography of the relevant sections was done with an automatic Zeiss MC 63 camera using black and white Ilford FP4 film.

4.5 Tests at Constant Strain Rate

Introduction

In recent years the constant strain rate tests have known increasing popularity resulting from the availability of testing machines which are easy to operate, allow quick testing and produce data which have proved useful from the practical point of view.

In this programme these tests were used throughout in place of the 'traditional' creep tests. A point which usually arouses some concern is which crosshead speed, and therefore which strain rate should be used. This point was considered in this work as described and discussed in Chapter 5 (Results) and 6 (Discussion). From the observations made resulted that a generally suitable testing rate could be 5 mm/min which was used for the majority of tests.
The tests on the circular discs at constant strain rate were the three flexure tests introduced in the previous chapter: three line, central loading, three point support. The tests on complete commercial mouldings were also done for practical convenience with the 5 mm/min crosshead speed and are reported separately in Chapter 9.

4.5.1 Three line tests

Theoretical aspects of this test were already discussed in Section 3.6.1. Being a test to a fair extent mentioned in the literature (23, 48, 58, 59, 81, 84) it was analysed in greater detail than the other two. Several aspects were looked at in the testing schedule:

i) Repeatability of the bending behaviour

ii) Assessment of the influence of any residual warpage on measured stiffness

iii) Utilisation of the test for evaluation of the pattern of flexural anisotropy of unfilled materials

iv) Dependence of the measured stiffness on the crosshead speed

v) Variation of the stiffness with span

Thus, 9 samples from each of the 8 edge gated GWM 101 moulding lots were tested at a displacement rate of 5 mm/min, and with a nominal span of 90 mm (for construction reasons it was in fact 90.5 mm). The samples were tested with the face to the injection-machine barrel up, and also upside down. They were also tested at different angular positions as defined in Figure 4.12:
FIGURE 4.12: Arrangement for Measuring Stiffness

The degree of variability of the tests being established, the influence of the crosshead speed and the span (i.e. the strain rate in other words) was assessed by testing a smaller number of 5 to 7 samples at the combination of crosshead rates and spans shown in Table 4.4.

TABLE 4.4
Schedule for Three Line Bending of EG discs

<table>
<thead>
<tr>
<th>Span (mm)</th>
<th>Crosshead speed (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>60</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>X</td>
</tr>
</tbody>
</table>

(a) These tests were also done in GSM 10 mouldings.
The tests with the other types of mouldings (CG discs and DG discs) were done at 5mm/min and spans of 65 and 55 mm respectively, these being initially chosen for maintaining a similar span/radius ratio.

The interpretation of test data and derivation of results is described in the next chapter prior to the listing of results.

4.5.2 Central loading test

This is also a common test for circular plates. In this work it was carried out with the disc supported along its periphery and with the edge free to rotate, thus reproducing the situation of simple support edge. A constant crosshead rate of 5 mm/min was used and the tests were done in 7 samples from each set of mouldings.

4.5.3 Three point support test

This test was presumably used for the first time in the testing of plastic plates in this programme. Some conceptual aspects related to the test were introduced and discussed in earlier sections 3.6.3 and 4.1.3.

For ease of location of the test pieces the supports were designed in a way such that the points of support were inside the periphery of the discs and not along it as the mathematical model of Bassali (66) describes. By doing so the specimens will appear stiffer due to the restraining effect of the overhanging rim of the disc. The analytical derivation of the influence of the over-
hang length did not appear to be cost effective, the alternative being pursued consisted of experimentally assessing that effect. The procedure (see Section 5.3.3c) consisted of starting from a large diameter disc (250 mm in diameter) and measuring successively the apparent stiffness of discs of decreasing diameter cut from the initial one.

The tests were done with two different span diameters 95 and 82 mm. The problem of the influence of the large radius of the supports was not experimentally examined because as discussed in Chapter 3, it will only arise when large deflections are imposed on the specimens.

4.5.4 Tests with PMMA

It was desired to assure that the differences eventually observed between the results of the various tests with injection mouldings were only due to the specimen characteristics and not to the test methods themselves. Poly(methylmethacrylate) (PMMA) is known to be a material which when obtained by casting is highly isotropic and approximately elastic for short time loads producing small deflections. Thus it was decided to perform the three flexural tests on discs cut from ICI Perspex cast acrylic sheet of 3 mm thickness.
4.6 Impact Tests

The instrumented falling weight impact tests were done at ICI using their own developed instrumented machines Mk I (68,81) and Mk II. The Mk I machine is shown in Figure 4.9 and was coupled to a Commodore PET personal computer. The details of the equipment are shown in the figure.

For the tests at sub-room temperature the specimens were cooled in a Dewar flask with a mixture of methanol and solid CO₂. The tests with specimens at room temperature were generally done with dry specimens in the Mk II equipment. This is a more developed version of the initial machine with a greater degree of automation and fitted with an environmental cabinet for temperature conditioning of the samples, however the basic principles of operation and data produced are identical. It was thought that the room temperature tests not being carried out with wetted specimens, the results could be misleading, therefore for two sets of mouldings tests at room temperature were done with both dry and wetted specimens.

The impact tests were done only with GWM 101 discs according to schedule shown in Table 4.5, nearly 1 month after moulding.

For the test the subcomponents were placed on the support which is an annular ring of 50 mm diameter. The weight attached to the impactor, about 100N, is released from a height such that the velocity at impact is known (5 m/s in the Mk I and 4.43 m/s in the Mk II). A force transducer connected to the impactor which has a
FIGURE 4.9: ICI Instrumented Falling Weight Impact Equipment
TABLE 4.5

Schedule for Impact Testing of GWM 101 Discs

<table>
<thead>
<tr>
<th>Lot</th>
<th>Test Temperature (°C)</th>
<th>Room temperature</th>
<th>Wet</th>
<th>Dry</th>
<th>10</th>
<th>0</th>
<th>-10</th>
<th>-20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1A</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>E1B</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>E1C</td>
<td></td>
<td></td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
</tr>
<tr>
<td>E1D</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>E3A</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>E3B</td>
<td></td>
<td></td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
</tr>
<tr>
<td>E3C</td>
<td></td>
<td></td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
<td>XY</td>
</tr>
<tr>
<td>E3D</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>C1B</td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>C1C</td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>C3B</td>
<td></td>
<td></td>
<td>Y</td>
<td>YZ</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>C3C</td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>D3B</td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>D3C</td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Notes:  
X - samples moulded from material batch I  
Y - samples moulded from material batch II  
Z - tests also done 48 hr and 295 days after moulding

12 mm radius nose gives a record of the load on the specimen during the time it is deformed by the impactor. This information is stored and displayed in an oscilloscope as a load-time curve. This information also can be fed into the computer which after analysis and computation of the data prints the salient load deflection details.
This chapter includes the numerical results obtained in the experimental work, their discussion being left for the next three chapters.

5.1 Repeatability of the Test Pieces

The consistency of the mouldings was assessed by checking the individual weight of each moulding after degating and de-flashing. The analysis was done on the EG discs moulded in GMM 101 during the first stage of the moulding programme. Each lot of mouldings was constituted by 60 mouldings with the exception of lot E1C (refer to Section 4.2.3) for the key to identification codes) with only 45 mouldings.

The mouldings were taken only after the machine reached stable working conditions, coarsely assessed by checking of the cavity surface temperature. The statistical analysis (only for standard deviation and average) is shown in Table 5.1. In Figures 5.1 and 5.2 is shown how the shot weight varied in each case and also the weight distribution histograms for each of the lots.

5.2 General Moulding Characteristics

The characterisation of the remaining mouldings (GWM 101 from Batch II, and GSM 10) was made in terms of the average weight and dimensions (diameter and thickness). Some EG discs were moulded
FIGURE 5.1
TABLE 5.1
GWM 101 Mouldings (Batch I)

<table>
<thead>
<tr>
<th>Identification Code</th>
<th>Thickness (mm)</th>
<th>Weight</th>
<th></th>
<th></th>
<th>No. of Mouldings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average (g)</td>
<td>Std.Dev. (g)</td>
<td>Coeff. of Variation (%) (a)</td>
<td></td>
</tr>
<tr>
<td>E1A</td>
<td>1.56</td>
<td>14.152</td>
<td>0.009</td>
<td>0.06</td>
<td>60</td>
</tr>
<tr>
<td>E1B</td>
<td>1.55</td>
<td>14.173</td>
<td>0.007</td>
<td>0.05</td>
<td>60</td>
</tr>
<tr>
<td>E1C</td>
<td>1.55</td>
<td>14.149</td>
<td>0.009</td>
<td>0.06</td>
<td>45</td>
</tr>
<tr>
<td>E1D</td>
<td>1.54</td>
<td>14.020</td>
<td>0.080</td>
<td>0.57</td>
<td>60</td>
</tr>
<tr>
<td>E3A</td>
<td>3.06</td>
<td>27.667</td>
<td>0.044</td>
<td>0.16</td>
<td>60</td>
</tr>
<tr>
<td>E3B</td>
<td>3.08</td>
<td>27.963</td>
<td>0.083</td>
<td>0.30</td>
<td>60</td>
</tr>
<tr>
<td>E3C</td>
<td>3.10</td>
<td>28.132</td>
<td>0.037</td>
<td>0.13</td>
<td>60</td>
</tr>
<tr>
<td>E3D</td>
<td>3.07</td>
<td>27.885</td>
<td>0.044</td>
<td>0.16</td>
<td>60</td>
</tr>
</tbody>
</table>

(a) Coefficient of variation = \( \frac{\text{Standard deviation}}{\text{average}} \times 100 \text{ (%)} \)

in GWM 101 Batch II. All GSM 10 discs were edge gated. The data corresponding to these mouldings are shown in Table 5.2.
## TABLE 5.2
General Characteristics of Mouldings

<table>
<thead>
<tr>
<th>Materials</th>
<th>Identification Code</th>
<th>Thickness (mm)</th>
<th>Average Weight (g)</th>
<th>Diameter (mm)</th>
<th>Lot Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWM 101 Batch II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1B II</td>
<td>1.57</td>
<td>14.19</td>
<td></td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>E3B II</td>
<td>2.96</td>
<td>26.76</td>
<td>113</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>E3C II</td>
<td>2.92</td>
<td>26.30</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>C1B</td>
<td>1.62</td>
<td>11.26</td>
<td></td>
<td></td>
<td>70</td>
</tr>
<tr>
<td>C1C</td>
<td>1.63</td>
<td>11.24</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>C3B</td>
<td>3.10</td>
<td>21.78</td>
<td></td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>C3C</td>
<td>3.05</td>
<td>21.39</td>
<td></td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>D3B</td>
<td>3.20</td>
<td>16.80</td>
<td>89</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>D3C</td>
<td>3.13</td>
<td>16.37</td>
<td></td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>GSM 10</td>
<td>E1B H</td>
<td>1.57</td>
<td>14.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E1C H</td>
<td>1.57</td>
<td>14.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E1D H</td>
<td>1.56</td>
<td>14.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E3A H</td>
<td>3.07</td>
<td>27.66</td>
<td>113</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>E3B H</td>
<td>3.06</td>
<td>27.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E3C H</td>
<td>3.05</td>
<td>27.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E3D H</td>
<td>3.05</td>
<td>24.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3 Constant Strain Rate Tests

5.3.1 Three line test

a) Sample calculation of slope

The following example is included to show how the raw data from the test were worked out to produce the information to be dealt with in the discussion. Thus, the method of calculation being shown the results to be included will consist only of processed data.

For the constant strain rate tests the machine variables are:

- Crosshead speed, CH (mm/min)
- Paper chart speed, PC (mm/min)
- Full scale load, FS (kgf) over 242 mm

On the trace of the test (Figure 5.3), after drawing the relevant tangent line, its slope is calculated from a force interval, F, and a distance interval, D as follows:

\[ \text{Slope} = \frac{\text{Force}}{\text{Deflection}} \quad (N/m) \]

\[ \text{Force} = \frac{F(mm)}{242} \times 9.81 \times FS \ (kgf) \quad (N) \]

\[ \text{Deflection} = \frac{D(mm)}{1000} \times \frac{CH}{FS} \quad (m) \]

In the example shown in the figure, corresponding to the disc number 3 from Lot E3C tested in the flow direction is

\[ CH = 5 \text{ mm/min} \]
Then

\[
\text{Deflection} = \frac{50}{1000} \times \frac{0.5}{20} = 1.25 \times 10^{-3} \text{ m}
\]

\[
\text{Force} = \frac{154}{242} \times 9.81 \times 5 = 31.2 \text{ N}
\]

and finally

\[
\text{Slope} = \frac{31.2}{1.25 \times 10^{-3}} = 24971 \text{ N/m}
\]
A typical example of the data collected for a set of mouldings from a given lot at specific testing conditions is shown in Table 5.3.

TABLE 5.3

<table>
<thead>
<tr>
<th>Lot identification</th>
<th>E3C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span: 90.5 mm</td>
<td></td>
</tr>
<tr>
<td>Crosshead speed:</td>
<td>5 mm/min</td>
</tr>
<tr>
<td>Paper chart speed:</td>
<td>200 mm/min</td>
</tr>
<tr>
<td>Full scale load:</td>
<td>5 kgf</td>
</tr>
<tr>
<td>Distance Interval:</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test piece Number</th>
<th>Force Interval F (mm)</th>
<th>Slope (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>154</td>
<td>24 971</td>
</tr>
<tr>
<td>8</td>
<td>151</td>
<td>24 484</td>
</tr>
<tr>
<td>18</td>
<td>149.5</td>
<td>24 241</td>
</tr>
<tr>
<td>28</td>
<td>155.5</td>
<td>25 214</td>
</tr>
<tr>
<td>36</td>
<td>152</td>
<td>24 247</td>
</tr>
<tr>
<td>43</td>
<td>151.5</td>
<td>24 566</td>
</tr>
<tr>
<td>47</td>
<td>152</td>
<td>24 647</td>
</tr>
<tr>
<td>52</td>
<td>152.5</td>
<td>24 728</td>
</tr>
<tr>
<td>55</td>
<td>151</td>
<td>24 482</td>
</tr>
</tbody>
</table>

Average: 24 665 N/m
Standard deviation: 286 N/m

b) Repeatability of results:

The repeatability of the test was assessed using a span of 90.5 mm and a crosshead speed of 5 mm/min, with sets of 9 samples random chosen from each lot. The tests were done at different angles of positioning (Figure 4.8, Chapter 4). The assessing parameter was
the coefficient of variation and the results obtained are shown in Table 5.4.

TABLE 5.4  
Coefficient of Variation of Three Line Test Results

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Coefficient of variation (%) for test at</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
<td>30°</td>
<td>45°</td>
<td>60°</td>
<td>90°</td>
</tr>
<tr>
<td>E1A</td>
<td>1.1</td>
<td>1.5</td>
<td>-</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>E1B</td>
<td>1.0</td>
<td>0.9</td>
<td>-</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>E1C</td>
<td>0.9</td>
<td>0.9</td>
<td>-</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>E1D</td>
<td>0.8</td>
<td>1.9</td>
<td>1.7</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>E3A</td>
<td>1.1</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>E3B</td>
<td>1.4</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>E3C</td>
<td>1.2</td>
<td>-</td>
<td>0.9</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>E3D</td>
<td>0.8</td>
<td>1.1</td>
<td>0.9</td>
<td>1.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

c) Variation of the slope with the position angle (EG discs):

For some of the moulding lots tests were done at different angles to the main direction of flow (position angle). The angles chosen are indicated as well as the obtained slopes in Table 5.5.

d) Test speed:

Three different test speeds were considered: 0.5, 5 and 20 mm/min and its influence observed on the stiffness of 3 mm thick EG discs, with a span of 90.5 mm. The data in Table 5.6 was obtained by averaging the slopes in directions 0° and 90° (mean slope).
TABLE 5.5

Variation of Slope with Angle of Position

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Slope (kN/m)</th>
<th>0°</th>
<th>30°</th>
<th>45°</th>
<th>60°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1A</td>
<td></td>
<td>3.09</td>
<td>3.07</td>
<td></td>
<td>3.27</td>
<td>3.43</td>
</tr>
<tr>
<td>E1D</td>
<td></td>
<td>2.96</td>
<td>3.09</td>
<td>3.05</td>
<td>3.04</td>
<td>3.05</td>
</tr>
<tr>
<td>E3B</td>
<td></td>
<td>22.7</td>
<td>22.2</td>
<td>21.9</td>
<td>22.2</td>
<td>22.5</td>
</tr>
<tr>
<td>E3D</td>
<td></td>
<td>23.7</td>
<td>24.3</td>
<td>23.5</td>
<td>24.4</td>
<td>24.0</td>
</tr>
</tbody>
</table>

TABLE 5.6

Variation of Mean Slope with Test Speed

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Mean Slope (kN/m)</th>
<th>0.5 mm/min</th>
<th>5 mm/min</th>
<th>20 mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3A</td>
<td></td>
<td>19.2</td>
<td>22.1</td>
<td>23.3</td>
</tr>
<tr>
<td>E3B</td>
<td></td>
<td>19.8</td>
<td>22.6</td>
<td>24.1</td>
</tr>
<tr>
<td>E3C</td>
<td></td>
<td>22.2</td>
<td>25.0</td>
<td>26.2</td>
</tr>
<tr>
<td>E3D</td>
<td></td>
<td>21.4</td>
<td>23.8</td>
<td>25.9</td>
</tr>
</tbody>
</table>

e) Influence of span:

Three different spans were considered: 90.5, 70 and 60 mm. Smaller spans were not used because in that case the influence of the shear stresses would start to account significantly for the total deflection. The results in Table 5.7 were obtained at a crosshead speed of 5 mm/min, five samples being used at each condition.
### TABLE 5.7
Variation of Slope with Span

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Mean Slope (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60 mm</td>
</tr>
<tr>
<td>E1A</td>
<td>13.1</td>
</tr>
<tr>
<td>E1B</td>
<td>12.1</td>
</tr>
<tr>
<td>E1C</td>
<td>13.1</td>
</tr>
<tr>
<td>E1D</td>
<td>12.0</td>
</tr>
<tr>
<td>E3A</td>
<td>83.3</td>
</tr>
<tr>
<td>E3B</td>
<td>86.4</td>
</tr>
<tr>
<td>E3C</td>
<td>96.0</td>
</tr>
<tr>
<td>E3D</td>
<td>91.9</td>
</tr>
</tbody>
</table>

f) **Effect of material batch:**

Some EG discs were moulded in both batches of the GWM 101 copolymer and the results of the three line tests are listed in Table 5.8 for span of 70 mm.

### TABLE 5.8
Dependence of Slope on Material Batch

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Mean Slope (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch I</td>
</tr>
<tr>
<td>E1C</td>
<td>7.58</td>
</tr>
<tr>
<td>E3B</td>
<td>53.2</td>
</tr>
<tr>
<td>E3C</td>
<td>59.2</td>
</tr>
</tbody>
</table>
g) **Tests with a different material grade:**

A number of GSM 10 polypropylene homopolymer mouldings were moulded upon request and tested with a span of 90.5 mm and a crosshead speed of 5 mm/min. The values of the mean slope shown in Table 5.9 were obtained, from tests on 7 specimens from each lot.

**TABLE 5.9**

*Flexural Test on GSM 10 Discs*

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Mean Slope (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1B&lt;sub&gt;H&lt;/sub&gt;</td>
<td>4.45</td>
</tr>
<tr>
<td>E1C&lt;sub&gt;H&lt;/sub&gt;</td>
<td>4.80</td>
</tr>
<tr>
<td>E1D&lt;sub&gt;H&lt;/sub&gt;</td>
<td>4.10</td>
</tr>
<tr>
<td>E3A&lt;sub&gt;H&lt;/sub&gt;</td>
<td>28.02</td>
</tr>
<tr>
<td>E3B&lt;sub&gt;H&lt;/sub&gt;</td>
<td>28.58</td>
</tr>
<tr>
<td>E3C&lt;sub&gt;H&lt;/sub&gt;</td>
<td>27.03</td>
</tr>
<tr>
<td>E3D&lt;sub&gt;H&lt;/sub&gt;</td>
<td>27.37</td>
</tr>
</tbody>
</table>

h) **Tests with centre-gated discs:**

The tests with CG discs were done using a span of 65 mm and a crosshead speed of 5 mm/min. The discs were tested with the sprue side of the mouldings facing downwards. The determination of slope in the inverse position gave higher values in the case of thin discs (C1's) and lower for the thick ones (C3's). These variations were of the order of 10% and mean that the mouldings being
not perfectly flat have concavities in opposite directions. The results obtained are shown in Table 5.10.

### TABLE 5.10
Tests with Centre-Gated Discs

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Slope (kN/m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>C1B</td>
<td>8.29</td>
<td>0.24</td>
</tr>
<tr>
<td>C1C</td>
<td>8.51</td>
<td>0.32</td>
</tr>
<tr>
<td>C3B</td>
<td>59.7</td>
<td>0.79</td>
</tr>
<tr>
<td>C3C</td>
<td>58.0</td>
<td>1.39</td>
</tr>
</tbody>
</table>

1) **Tests with double-gated discs:**

For the tests with DG discs a span support of 55 mm was used and a crosshead speed of 5 mm/min. The discs were tested in two positions perpendicular to each other: with supports parallel to the weld line (along weld position), and perpendicular to this line (across weld position). The results are listed in Table 5.11.

### TABLE 5.11
Tests with Double-Gated Discs

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Position</th>
<th>Slope (kN/m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std. Dev.</td>
<td></td>
</tr>
<tr>
<td>D3B</td>
<td>Along weld</td>
<td>84.3</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>Across weld</td>
<td>87.2</td>
<td>2.67</td>
</tr>
<tr>
<td>D3C</td>
<td>Along weld</td>
<td>83.0</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td>Across weld</td>
<td>92.0</td>
<td>1.23</td>
</tr>
</tbody>
</table>
5.3.2 Centre loading tests

The discs were supported along the periphery thus reproducing the conditions of simple support and freedom of the edge to move radially and rotate. The crosshead speed used was 5 mm/min. In the case of CG discs the tests were done with the sprue-side face down. The results obtained are shown in Table 5.12 which includes all the types of mouldings moulded in GWM 101 Batch II and homopolymer GSM 10. The size of the copolymer samples was 7 and 5-7 in the case of homopolymer.

5.3.3 Three point support tests

a) Influence of the positioning:

The assessment of the influence of the relative location of the supports in the case of the EG and DG discs, involving non-symmetric flow, was made by testing one of the EG thick disc lots and the DG discs. The results obtained from 7 samples are listed in the Table 5.13.

b) Results with the different types of disc:

The results shown in Table 5.14 were obtained with a sample size of 7 specimens.

c) Effect of overhang:

The effect of the overhanging length on the measured slope was studied by testing circular discs cut from a large circular moulding (Φ 250 mm) of GWM 101, and obtaining successively smaller
<table>
<thead>
<tr>
<th>Material</th>
<th>Lot Identification</th>
<th>Slope (kN/m)</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td><strong>E1C</strong></td>
<td></td>
<td>4.10</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>E3B</strong></td>
<td></td>
<td>24.98</td>
<td>0.68</td>
</tr>
<tr>
<td><strong>E3C</strong></td>
<td></td>
<td>24.18</td>
<td>0.73</td>
</tr>
<tr>
<td><strong>C1B</strong></td>
<td></td>
<td>4.83</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>C1C</strong></td>
<td></td>
<td>5.58</td>
<td>0.37</td>
</tr>
<tr>
<td><strong>C3B</strong></td>
<td></td>
<td>36.35</td>
<td>0.31</td>
</tr>
<tr>
<td><strong>C3C</strong></td>
<td></td>
<td>36.80</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>D3B</strong></td>
<td></td>
<td>46.30</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>D3C</strong></td>
<td></td>
<td>48.01</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>E1B_H</strong></td>
<td></td>
<td>4.81</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>E1C_H</strong></td>
<td></td>
<td>5.19</td>
<td>0.29</td>
</tr>
<tr>
<td><strong>E1D_H</strong></td>
<td></td>
<td>5.41</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>E3A_H</strong></td>
<td></td>
<td>33.85</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>E3B_H</strong></td>
<td></td>
<td>36.21</td>
<td>2.48</td>
</tr>
<tr>
<td><strong>E3C_H</strong></td>
<td></td>
<td>32.00</td>
<td>2.33</td>
</tr>
<tr>
<td><strong>E3D_H</strong></td>
<td></td>
<td>35.72</td>
<td>0.93</td>
</tr>
</tbody>
</table>
### TABLE 5.13
Influence of the Relative Position

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Position</th>
<th>Relative Rotation</th>
<th>Slope (kN/m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Std. Dev.</td>
<td></td>
</tr>
<tr>
<td>E3C</td>
<td>Gate on support</td>
<td>0°</td>
<td>29.63</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°</td>
<td>28.95</td>
<td>0.49</td>
</tr>
<tr>
<td>D3B</td>
<td>Gate on support</td>
<td>0°</td>
<td>62.43</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30°</td>
<td>62.68</td>
<td>0.28</td>
</tr>
<tr>
<td>D3C</td>
<td>Gate on support</td>
<td>0°</td>
<td>63.93</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Weld on support</td>
<td>30°</td>
<td>64.04</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>15°</td>
<td>63.90</td>
<td>0.69</td>
</tr>
</tbody>
</table>

### TABLE 5.14
General Results of 3 Point Support Test

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Support Diameter (mm)</th>
<th>Slope (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1C</td>
<td></td>
<td>4.89</td>
</tr>
<tr>
<td>E3B</td>
<td></td>
<td>29.29</td>
</tr>
<tr>
<td>E3C</td>
<td></td>
<td>29.49</td>
</tr>
<tr>
<td>C1B</td>
<td></td>
<td>6.63</td>
</tr>
<tr>
<td>C1C</td>
<td>82</td>
<td>7.59</td>
</tr>
<tr>
<td>C2B</td>
<td></td>
<td>45.11</td>
</tr>
<tr>
<td>C3C</td>
<td></td>
<td>45.05</td>
</tr>
<tr>
<td>D3B</td>
<td>69</td>
<td>62.55</td>
</tr>
<tr>
<td>D3C</td>
<td></td>
<td>63.95</td>
</tr>
</tbody>
</table>
test pieces. The tests were done using two different support diameters. The results obtained in both cases are shown in Table 5.15.

**TABLE 5.15**

Overhang Effect

<table>
<thead>
<tr>
<th>Support diameter (mm)</th>
<th>Disc Diameter (mm)</th>
<th>Overhang length (mm)</th>
<th>Slope (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>250</td>
<td>77</td>
<td>27.73</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>52</td>
<td>27.32</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>27</td>
<td>25.13</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>17</td>
<td>23.67</td>
</tr>
<tr>
<td></td>
<td>113</td>
<td>8.5</td>
<td>21.32</td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>0</td>
<td>18.20</td>
</tr>
<tr>
<td>82</td>
<td>250</td>
<td>84</td>
<td>38.48</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>59</td>
<td>37.57</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>39</td>
<td>36.32</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>24</td>
<td>33.81</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>9</td>
<td>29.43</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>0</td>
<td>23.64</td>
</tr>
</tbody>
</table>

5.3.4 Tests with PMMA

The three flexural tests were performed on cast acrylic sheet discs of 2.95 mm thickness.

The experimental results were obtained using a crosshead speed of 5 mm/min and test parameters shown in Table 5.16.
TABLE 5.16
Flexural Tests with PMMA

<table>
<thead>
<tr>
<th>Test</th>
<th>Disc Diameter (mm)</th>
<th>Test Parameter</th>
<th>Slope (kN/m)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three line</td>
<td>115</td>
<td>70 mm span</td>
<td>124.8</td>
<td></td>
</tr>
<tr>
<td>Central loading</td>
<td>115</td>
<td></td>
<td>50.5</td>
<td></td>
</tr>
<tr>
<td>Three point support</td>
<td>115 96</td>
<td>95 mm point diameter</td>
<td>60.5 51.2</td>
<td>Overhang 9.5 mm Overhang nil</td>
</tr>
</tbody>
</table>

5.4 Poisson Ratio Measurements

The lateral contraction ratio tests were done with test pieces cut from GWM 101 edge gated discs and from GSM 10 trays centre gated at the rectangular base with dimensions 375 x 245 (mm) and thickness of 3.3 mm.

The test with GSM 10 were done with bars cut in the radial direction and in the direction perpendicular to it. Those with GWM 101 were done with bars cut along the diameter passing through the edge gate. The results obtained are shown in Table 5.17. The lateral contraction ratio is calculated as the slope of the best line fitting the experimental points.
<table>
<thead>
<tr>
<th>Material</th>
<th>Processing Condition Code</th>
<th>Direction of Specimen</th>
<th>Strain Longitudinal (µε)</th>
<th>Transversal (µε)</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP homo-</td>
<td>D (Tray 3.5mm)</td>
<td>Across flow</td>
<td>1180</td>
<td>530</td>
<td>0.456</td>
</tr>
<tr>
<td>polymer</td>
<td></td>
<td>2410</td>
<td>1090</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSM 10</td>
<td></td>
<td>3550</td>
<td>1610</td>
<td></td>
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</tr>
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<td>4940</td>
<td>2250</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Along flow</td>
<td>1230</td>
<td>590</td>
<td>0.440</td>
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<td></td>
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<td>3900</td>
<td>1790</td>
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</tr>
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<td></td>
<td></td>
<td>5330</td>
<td>2390</td>
<td></td>
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</tr>
<tr>
<td>PP co-</td>
<td>A (Tray 3.5mm)</td>
<td>Across flow</td>
<td>800</td>
<td>450</td>
<td>0.471</td>
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<tr>
<td>polymer</td>
<td></td>
<td>1670</td>
<td>870</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSM 10</td>
<td></td>
<td>2650</td>
<td>1340</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3600</td>
<td>1770</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Along flow</td>
<td>780</td>
<td>360</td>
<td>0.410</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1730</td>
<td>760</td>
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</tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PP co-</td>
<td>A (Disc 3 mm)</td>
<td>Along flow</td>
<td>700</td>
<td>300</td>
<td>0.458</td>
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<td>2540</td>
<td>1130</td>
<td></td>
<td></td>
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<td>Along flow</td>
<td>805</td>
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<td>0.415</td>
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<td></td>
<td>1300</td>
<td>560</td>
<td></td>
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</tr>
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<td></td>
<td>1870</td>
<td>800</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>2350</td>
<td>990</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>Along flow</td>
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<td></td>
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<td>960</td>
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<td></td>
<td></td>
<td>2580</td>
<td>1220</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Along flow</td>
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<td>350</td>
<td>0.553</td>
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<tr>
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<td>1350</td>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1875</td>
<td>985</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td>2370</td>
<td>1270</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.5 Impact Test Data

5.5.1 Raw data

The impact test data were worked out by an in-line computer which, using an ICI-developed package, interpreted the curve 'impact force-time' of each test, such as the one shown in Figure 5.4.

In the computer output the results are shown in terms of force-deflection, which derives from the computer package assuming that the speed during impact varies very little and thus the deflection is proportional to time.

The output of the computer is of the form shown in Figure 5.5 and gives information on:

a) Identification of the sample tested; for the purpose of this programme: lot reference, sample number, and test temperature.

b) GRAD - slope of the load/deflection curve (N/mm \(\equiv\) kN/m)

c) P/YF - maximum force during the test (N)

d) P/YD - deflection corresponding to the point P/YF (mm)

e) P/YE - energy absorbed up to the maximum force point (Nm \(\equiv\) J)

f) FD - deflection at the point of rupture (mm)

g) FE - total energy absorbed during the test (Nm \(\equiv\) J)

h) FAIL TYPE - identification of the type of failure, decided by the operator by inspection of the shape of the curve shown in the oscilloscope, prior to the computer analysis.
### FIGURE 5.4

**PPGWMI01 CENTRE-GATED DISC 3mm LOT G [OFFSET IMPACT]**

<table>
<thead>
<tr>
<th>TEST NO</th>
<th>DETAILS</th>
<th>N/mm</th>
<th>N</th>
<th>mm</th>
<th>mm</th>
<th>Nm</th>
<th>Nm</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0281.23</td>
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<td>633.6</td>
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<td>3.74</td>
<td>16.3</td>
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</tr>
<tr>
<td>2</td>
<td>0235.</td>
<td>615</td>
<td>2052</td>
<td>14.9</td>
<td>20.2</td>
<td>23.3</td>
<td>48.3</td>
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</tr>
<tr>
<td>3</td>
<td>0177.</td>
<td>274</td>
<td>1504</td>
<td>7.57</td>
<td>4.86</td>
<td>9.23</td>
<td>6.21</td>
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</tr>
<tr>
<td>4</td>
<td>0055.</td>
<td>329</td>
<td>2852</td>
<td>14.7</td>
<td>20.3</td>
<td>25.2</td>
<td>41.2</td>
<td>D</td>
</tr>
<tr>
<td>5</td>
<td>0035.</td>
<td>325</td>
<td>2754</td>
<td>12.9</td>
<td>15.9</td>
<td>14.5</td>
<td>18.5</td>
<td>B/D</td>
</tr>
<tr>
<td>6</td>
<td>0019.</td>
<td>319</td>
<td>2160</td>
<td>16.5</td>
<td>3.41</td>
<td>12.2</td>
<td>11.4</td>
<td>B</td>
</tr>
<tr>
<td>7</td>
<td>0070.</td>
<td>330</td>
<td>2852</td>
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<td>20.7</td>
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<td>43.0</td>
<td>D</td>
</tr>
<tr>
<td>8</td>
<td>0145.</td>
<td>322</td>
<td>2352</td>
<td>15.1</td>
<td>20.6</td>
<td>17.7</td>
<td>25.6</td>
<td>D/B</td>
</tr>
<tr>
<td>9</td>
<td>0125.</td>
<td>327</td>
<td>2371</td>
<td>14.7</td>
<td>20.5</td>
<td>24.3</td>
<td>48.6</td>
<td>B</td>
</tr>
<tr>
<td>10</td>
<td>0115.</td>
<td>204</td>
<td>1172</td>
<td>6.88</td>
<td>3.65</td>
<td>8.59</td>
<td>4.74</td>
<td>B</td>
</tr>
</tbody>
</table>

**Note:** LOT G ≠ C3C

### FIGURE 5.5

Output of in-line PET computer
5.5.2 Derivation of results

All the PET data were later recorded in a 9845B Hewlett-Packard computer, and statistically examined in terms of average and standard deviation. The computer programme used (in BASIC) is appended in Appendix 3, and was named 'DISC'. In this programme provision was also made for obtaining graphics showing the variation of the several test variables as a function of the test temperature. These graphs are of the type shown in Figure 5.6 in which are represented the average points and the standard deviation.
deviation. It is also noted that the identification codes for the lots are different from those used now, which intend to provide a more systematic and complete information. Whenever necessary the equivalence between the identification code shown and that adopted in this work is indicated.

5.5.3 Tests with edge-gated discs

The tests with EG discs were done on 10 random chosen specimens from each lot at each of the five testing temperatures. These specimens were moulded in GWM 101 from batch I. Tests were however done in some mouldings from batch II.

The results corresponding to these mouldings are included in Appendix 4. In Table 5.18 is given one example of these results with indication of how they are presented.

5.5.4 Tests with centre-gated discs and double-gated discs

The results of the tests with CG and DG discs are listed in Appendix 4. The tests with CG discs consisted of impacting the specimens far from the sprue point (see Section 8.5) while in the case of DG discs they were impacted on the weld line.

5.6 Microscopy Observations

All types of mouldings were sectioned for observation of the structure. The microphotographs are included in the discussion chapters when referred to.
TABLE 5.18
Instrumented Impact Falling Weight Test Results
Lot E3C

<table>
<thead>
<tr>
<th>GRAD (kN/m)</th>
<th>P/YF (N)</th>
<th>P/YD (mm)</th>
<th>P/YE (J)</th>
<th>FD (mm)</th>
<th>FE (J)</th>
<th>TEST TEMP (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>438 (1)</td>
<td>2099.8</td>
<td>6.2</td>
<td>6.73</td>
<td>7.5</td>
<td>8.2</td>
<td>-20</td>
</tr>
<tr>
<td>54</td>
<td>890.4</td>
<td>2.1</td>
<td>4.73</td>
<td>2.0</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>438</td>
<td>2847.6</td>
<td>9.4</td>
<td>13.02</td>
<td>11.5</td>
<td>15.0</td>
<td>-10</td>
</tr>
<tr>
<td>56</td>
<td>877.8</td>
<td>2.7</td>
<td>5.43</td>
<td>1.3</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>411</td>
<td>2732.3</td>
<td>9.9</td>
<td>14.48</td>
<td>12.3</td>
<td>17.8</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>805.3</td>
<td>3.1</td>
<td>6.14</td>
<td>1.8</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>379</td>
<td>2846.5</td>
<td>11.6</td>
<td>16.95</td>
<td>15.4</td>
<td>25.3</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>29.6</td>
<td>0.3</td>
<td>1.00</td>
<td>1.7</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>330</td>
<td>2707.2</td>
<td>12.8</td>
<td>18.67</td>
<td>22.8</td>
<td>37.4</td>
<td>23 (2)</td>
</tr>
<tr>
<td>3</td>
<td>306.5</td>
<td>1.8</td>
<td>4.31</td>
<td>5.0</td>
<td>10.6</td>
<td></td>
</tr>
</tbody>
</table>

Note (1): The first number is the average and the second the standard deviation, calculated from 10 specimens

(2): In Appendix this temperature is incorrectly shown as 20°C
CHAPTER 6

INFLUENCE OF THE FLEXURAL TEST VARIABLES

The discussion of the experimental results which were collected in Chapter 5 will be split in three different parts/chapters. The first will be concerned with aspects specific to the tests used, analyses the influence of the parameters capable of being varied in each test, and makes a comparison of the various test data. The second will concentrate on aspects related to the test specimens themselves such as the influence of the processing conditions, moulding gating, and so on. Finally the third part will deal exclusively with the analysis of the impact test results.

6.1 Repeatability of the Tests

The information which is collected from the flexural tests with circular subcomponents derives from the interpretation of the slope of a straight line fitting the force-deflection trace of the testing machine for small deflections (of the order of 40% of the thickness for minimising the effect of the membrane stresses). This procedure is obviously prone to experimental error. An additional source of error is the fact that the mouldings can have different degrees of warpage arising mostly from the cooling; this warpage, even if slight, causes the test trace to have an initial random shaped portion corresponding to the 'settling' of the sample in the supports (this applies to the three line test
and to the central loading test. From the results shown in Table 5.4 dealing with the coefficient of variation of the 'hand-calculated' slopes for various sets of mouldings can be observed that this parameter of repeatability has an acceptable value around 1.2%. It is substantially higher than the specimen coefficient of variation (relating to the weight) but this does not take into consideration the non-flatness effects.

No suggestion of a correlation between the coefficient of variation and the processing conditions was observed.

The results which were presented correspond to EG discs in the three line test, but it was observed that for the other tests and moulding types the coefficient of variation was similar.

6.2 Three Line Tests

6.2.1 Influence of the test speed

Three different speeds were considered: 0.5, 5 and 20 mm/min and their influence observed on the flexural stiffness of the 3 mm thick EG discs, keeping constant the span of 90 mm.

The flexural stiffness was calculated from the test data using the Equation 3.14 from Chapter 3:

\[ C = \frac{3 f(A, R)}{h^3} S_L \]

For a span of 90.5 mm and the disc dimensions the value of \( f(A, R) \) is \( 584.2 \times 10^{-6} \, \text{m}^2 \). The values of the slope \( S_L \) were given in
Table 5.6, and the moulding thicknesses listed in Table 5.1. The resulting values for the flexural stiffness are graphically represented in Figure 6.1.

![Graph showing the flexural stiffness as a function of crosshead speed.](image)

**FIGURE 6.1**

It is observed that as the test speed increases the rate of increase of the flexural stiffness is rapidly attenuated. Thus, it appears that if a standard test speed of 5 mm/min, or
even higher, is adopted it will be representative of a fairly large range of rates of straining.

6.2.2 Influence of the span

For the assessment of the influence of the span, three different spans were chosen for testing the discs: 60, 70 and 90.5 mm. The calculated flexural stiffness, as shown in Table 6.1, decreases when the span length is increased. This variation can be

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Thickness (mm)</th>
<th>Flexural Stiffness (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>60 mm span</td>
</tr>
<tr>
<td>E1 A</td>
<td>1.56</td>
<td>1.671</td>
</tr>
<tr>
<td>E1 B</td>
<td>1.55</td>
<td>1.581</td>
</tr>
<tr>
<td>E1 C</td>
<td>1.55</td>
<td>1.703</td>
</tr>
<tr>
<td>E1 D</td>
<td>1.54</td>
<td>1.600</td>
</tr>
<tr>
<td>E3 A</td>
<td>3.06</td>
<td>1.410</td>
</tr>
<tr>
<td>E3 B</td>
<td>3.08</td>
<td>1.434</td>
</tr>
<tr>
<td>E3 C</td>
<td>3.10</td>
<td>1.564</td>
</tr>
<tr>
<td>E3 D</td>
<td>3.07</td>
<td>1.540</td>
</tr>
</tbody>
</table>

due partly to the effect of the dependence of strain rate on span, and also to the increasing influence of the shear stresses when the span is reduced. The latter were not taken into account in
the derivation of equation 3.12. The variation is bigger in the case of thin mouldings where the stiffness varies almost linearly with the span. For the thick mouldings the stiffness varies less at smaller spans.

6.2.3 Effect of strain rate

The variation of the two parameters analysed in the two previous sections are alternative ways of changing the strain rate of the test.

If the bent disc in the three line test is approximated by a flexed beam supported in two points and loaded at the centre, the maximum tensile stress, occurring at the surface, is given by:

\[ \sigma = \frac{M}{Z} \]  \hspace{1cm} (6.1)

where: \( M \) = bending moment (Nm)
\( Z \) = flexural rigidity, \( I/y \) (m³)
\( I \) = moment of inertia (m⁴)
\( y = \frac{h}{2} \), \( h \) being the thickness (m)

The maximum longitudinal strain occurring at the point of maximum tensile stress is:

\[ \varepsilon_x = \frac{Y}{R} \]  \hspace{1cm} (6.2)
where the radius of curvature $R$ is

$$ R = \frac{EI}{M} \quad (6.3) $$

Thus

$$ e_x = \frac{h M}{2EI} \quad (6.4) $$

and considering the following expressions for $M$ and $I$,

$$ M = \frac{FL}{4} \quad (6.5) $$

$$ I = \frac{bh^3}{12} \quad (6.6) $$

with $F$ = applied force (N),

$L$ = span (m),

$b$ = beam breadth (m)

is obtained

$$ e_x = \frac{3FL}{2Ebh^2} \quad (6.7) $$

In a linear-elastic situation the force, $F$, is proportional to the deflection, the maximum being reached at the point of application of the load and given by

$$ \delta = \frac{FL^3}{4Eb^3} \quad (6.8) $$

Combining the expressions (6.7) and (6.8) the following relationship is obtained
\[
\varepsilon_x = \frac{6 \, h}{L^2} \delta
\]  
(6.9)

By taking derivatives of both members of (6.9) with respect to the time a relationship results between the strain rate, \( \dot{\varepsilon}_x \), and the displacement rate (or crosshead speed), \( \dot{\delta} \),

\[
\dot{\varepsilon}_x = \frac{6 \, h}{L^2} \dot{\delta}
\]  
(6.10)

This expression means that for a linear elastic beam in bending, the strain rate is proportional to the crosshead speed and the thickness, and inversely proportional to the square of the span length.

In this way the experimental values referred to in the previous sections can be directly compared as tabulated in Table 6.2.

The analysis of the results, particularly those concerning the thick discs, where the study was more complete, show that the stiffness values obtained by reducing the span from the 90.5 mm value used for the variation of crosshead speed, are above those obtained for this last span, even when the approximate shear rate \( \dot{\varepsilon}_x \) was higher. It appears therefore that for injection mouldings such as those used for these tests, factors other than the actual variation of strain rate are contributing for the increasing of the measured value of the flexural stiffness. The contribution of the growing shear stresses (when the span is reduced) may be a part of the explanation but for the geometry used they contribute very little for the overall deflection. Other factors may be related to the particular characteristics of the injected-moulding test pieces.
### TABLE 6.2
Variation of $C$ with $\dot{\varepsilon}_x$

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Span (mm)</th>
<th>Crosshead Speed (mm/min)</th>
<th>$\delta$ (m/s) $\times 10^6$</th>
<th>$\dot{\varepsilon}$ (s$^{-1}$) $\times 10^6$</th>
<th>$C$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3A</td>
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<td>19</td>
<td>1.14</td>
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<td>83</td>
<td>187</td>
<td>1.31</td>
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<td>333</td>
<td>747</td>
<td>1.38</td>
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<td>1.41</td>
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<tr>
<td>E3C</td>
<td>90.5</td>
<td>0.5</td>
<td>8</td>
<td>19</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>90.5</td>
<td>5</td>
<td>83</td>
<td>189</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td>90.5</td>
<td>20</td>
<td>333</td>
<td>757</td>
<td>1.50</td>
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<tr>
<td></td>
<td>60</td>
<td>5</td>
<td>83</td>
<td>430</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>5</td>
<td>83</td>
<td>317</td>
<td>1.54</td>
</tr>
<tr>
<td>E3D</td>
<td>90.5</td>
<td>0.5</td>
<td>8</td>
<td>19</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>90.5</td>
<td>5</td>
<td>83</td>
<td>188</td>
<td>1.40</td>
</tr>
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<td></td>
<td>90.5</td>
<td>20</td>
<td>333</td>
<td>750</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>5</td>
<td>83</td>
<td>427</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>5</td>
<td>83</td>
<td>314</td>
<td>1.54</td>
</tr>
<tr>
<td>E1A</td>
<td>60</td>
<td>5</td>
<td>83</td>
<td>217</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td></td>
<td>159</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>90.5</td>
<td></td>
<td></td>
<td>95</td>
<td>1.46</td>
</tr>
<tr>
<td>E1B</td>
<td>60</td>
<td>5</td>
<td>83</td>
<td>215</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td></td>
<td>158</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>90.5</td>
<td></td>
<td></td>
<td>95</td>
<td>1.42</td>
</tr>
<tr>
<td>E1C</td>
<td>90.5</td>
<td>5</td>
<td>83</td>
<td>95</td>
<td>1.42</td>
</tr>
<tr>
<td>E1D</td>
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<td>5</td>
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<td>214</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td></td>
<td>157</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>90.5</td>
<td></td>
<td></td>
<td>94</td>
<td>1.40</td>
</tr>
</tbody>
</table>
6.3 Three Point Support Tests

As was already pointed out the three point support test is not a test which had been used for determining mechanical properties, and in that respect can be considered novel. Its introduction in this work was mainly seen as a means of overcoming the unavoidable warpage of injection-moulded planar specimens regardless of the care which might have been put on getting the better processing conditions.

6.3.1 The problem of overhanging

The mathematical model for the three point support test (66) is based upon the assumption that the circular disc is supported along its circumference. For practical reasons the supports were designed to be located inside the circle. This caused the specimens to appear over stiff due to the restraining effect of the rim of material outside the circumference of the supports (overhang).

It was felt that a mathematical analysis of the stiffening effect of the overhanging rim would not be cost and time effective, therefore the decision was for determining experimentally the magnitude of such effect. Tests were both done in cast PMMA discs and in injection-moulded GWM 101 ethylene propylene copolymer discs of large diameter.

In order to make a comparison possible the results were reduced to dimensionless form:
Slope \( S + \frac{S}{S_0} = S^* \)

where \( S_0 \) is the slope corresponding to the test without overhanging.

Overhang \( \Delta R + \frac{\Delta R}{D} = x^* \)

where \( D \) is the support point diameter.

The experimental results so recalculated (Table 6.3) were plotted in Figure 6.2 which shows the data from the tests with 96 and 82 mm support diameter for PP and with 96 mm support for PMMA.

**TABLE 6.3**
Overhang Effect on Three Point Support Tests

<table>
<thead>
<tr>
<th>( \frac{\Delta R}{D} ) (1)</th>
<th>( \frac{S}{S_0} )</th>
<th>Error % ((3)-(2) \times 100 )</th>
<th>Support Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental (2)</td>
<td>Eqn. 6.11 (3)</td>
<td>(2) x 100</td>
<td></td>
</tr>
<tr>
<td>0.089</td>
<td>1.17</td>
<td>1.180</td>
<td>0.8</td>
</tr>
<tr>
<td>0.099</td>
<td>1.181</td>
<td>1.197</td>
<td>1.3</td>
</tr>
<tr>
<td>0.110</td>
<td>1.245</td>
<td>1.214</td>
<td>-2.5</td>
</tr>
<tr>
<td>0.177</td>
<td>1.301</td>
<td>1.304</td>
<td>0.3</td>
</tr>
<tr>
<td>0.281</td>
<td>1.381</td>
<td>1.404</td>
<td>1.6</td>
</tr>
<tr>
<td>0.293</td>
<td>1.430</td>
<td>1.413</td>
<td>-1.2</td>
</tr>
<tr>
<td>0.476</td>
<td>1.536</td>
<td>1.506</td>
<td>-2.0</td>
</tr>
<tr>
<td>0.542</td>
<td>1.561</td>
<td>1.526</td>
<td>1.6</td>
</tr>
<tr>
<td>0.720</td>
<td>1.589</td>
<td>1.559</td>
<td>-1.9</td>
</tr>
<tr>
<td>0.802</td>
<td>1.524</td>
<td>1.568</td>
<td>1.7</td>
</tr>
<tr>
<td>1.024</td>
<td>1.623</td>
<td>1.581</td>
<td>-2.6</td>
</tr>
</tbody>
</table>
It is apparent that for an overhang of about 50% of the support diameter the stiffening effect starts to stabilise. Nevertheless, points beyond these are of reduced or nil practical interest. A reasonable approximation to the experimental points was found to be given by the empirical expression

\[ S^* = 0.59 \left( 1 - e^{-4.1 x^*} \right) + 1 \]  

(6.11)

which fits all the experimental data within less 2.5% error (see Table 6.3).
Thus from the expression (6.11) a correcting factor can be set for the experimental results obtained with discs over-hanging from the supports.

Given the overhang length \( \Delta R \), the support diameter, \( D \), and the measured slope, \( S \), the value of the slope corresponding to the disc of diameter equal to the diameter support is, from

\[
\frac{S}{S_0} = 0.59 \left(1 - e^{-4.1 \frac{\Delta R}{D}} \right) + 1
\]

obtained by

\[
S_0 = \frac{1}{0.59 \left(1 - e^{-4.1 \frac{\Delta R}{D}} \right) + 1}
\]

(6.12)

6.4 Centre Loading Tests

The centre loading tests, more than any of the others, showed the influence of the membrane stresses which was analysed in Chapter 3. These stresses start to play an important role for deflections of the order of 40% of the plate thickness. When the membrane stresses are important the force-deflection curves appear concave and the slope has to be determined by tracing a tangent to the initial position of the curve and calculating the tangent slope. Nevertheless, as was shown in Table 5.12, the repeatability of the results was well in line with the other tests.
6.5 Comparison of the Different Test Data

It was shown in Chapter 3 that all the three tests carried out with circular subcomponents are likely to yield data which can be used in design of planar products. All the tests enable the determination of the value of a parameter, the flexural stiffness, which contains in itself information concerning the stiffness of the material, the lateral contraction ratios, and anisotropy effects. In the case of an isotropic material the flexural stiffness is given by the ratio $E/(1 - \nu^2)$.

6.5.1 Experimental aspects

The three tests are all straightforward to be carried out with only the requirement of a more careful positioning required for the three line test (Figures 6.3 and 6.4 show aspects of the three line and the three point support tests).

The traces which are obtained with the injection moulded specimens are however different. Due to the warpage (even small) of the discs, in the three line and in the central loading tests there is an initial part of the load deflection curve which roughly corresponds to the 'accommodation' of that warpage before the specimen becomes fully 'committed' to the test. Thus an initial curved zone, more or less long depending on the degree of warpage, is identifiable, and for the derivation of the data the tracing of a tangent is required (Figures 6.5 and 6.6 illustrate the situation for thin and thick discs).
FIGURE 6.3: Three line test

FIGURE 6.4: Three point support test showing the overhanging of the disc and alignment of this with support
FIGURE 6.5: Tests with a thin EG disc (C1B)

FIGURE 6.6: Tests with a thick EG disc (E3B)
In the case of the three point test, the warpage is automatically tackled and therefore in its trace a straight line is obtained as from the beginning of the test.

This feature is potentially interesting especially where automatic testing is concerned.

6.5.2 The question of the Poisson's ratio

Both the three point support and the central loading tests require some suitable assumption to be made about the value of $v$, due to the fact that the expressions of the flexural stiffness, $C$, contain functions of that parameter. The values of these functions however only vary slightly over the range of values of the lateral contraction ratio of the material.

For example, in the case of PP (Table 6.4) if we assume the ratio $v$ to vary, say, between 0.43 and 0.47, the function $B(v)$ appearing in the three point support equation varies less than 0.9% and that in the central loading test only 1.7%.

This fact appears to support the assumption that an estimate of 0.45 for the lateral contraction ratio of PP is perfectly acceptable in design. The assumption was nevertheless supported by some experimental work which pointed out that value. Furthermore, as will be observed in the next chapter, variations due to processing conditions alone, for example, are likely to cause bigger variations.
TABLE 6.4
Variation of the Functions $B(v)$ and $\frac{1+v}{3+v}$

<table>
<thead>
<tr>
<th>$v$</th>
<th>$B(v)$ (1)</th>
<th>$\frac{1+v}{3+v}$ (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>3.366</td>
<td>0.412</td>
</tr>
<tr>
<td>0.41</td>
<td>3.370</td>
<td>0.413</td>
</tr>
<tr>
<td>0.42</td>
<td>3.375</td>
<td>0.415</td>
</tr>
<tr>
<td>0.43</td>
<td>3.380</td>
<td>0.417</td>
</tr>
<tr>
<td>0.44</td>
<td>3.386</td>
<td>0.419</td>
</tr>
<tr>
<td>0.45</td>
<td>3.393</td>
<td>0.420</td>
</tr>
<tr>
<td>0.46</td>
<td>3.401</td>
<td>0.422</td>
</tr>
<tr>
<td>0.47</td>
<td>3.409</td>
<td>0.424</td>
</tr>
<tr>
<td>0.48</td>
<td>3.419</td>
<td>0.425</td>
</tr>
<tr>
<td>0.49</td>
<td>3.429</td>
<td>0.427</td>
</tr>
<tr>
<td>0.50</td>
<td>3.440</td>
<td>0.429</td>
</tr>
</tbody>
</table>

(1) In Equation (3.18)
(2) In Equation (3.15)

6.5.3 How equivalent are the data?

Before embarking on the full programme involving a large range of mouldings in the three tests an experimental check was done on the equivalence of data obtained with the three flexural tests.

Cast acrylic sheets are known for their great degree of homogeneity, isotropy and linear elasticity in the short time. The value of 0.41 for the Poisson's ratio of this material is established (e.g. (85)).
Thus the raw data shown in Table 5.16 lead to the following values of the flexural stiffness in Table 6.5. These figures compare quite well to each other showing only a difference of 1.5% with respect to the average value.

**TABLE 6.5**

**Flexural Stiffness of PMMA**

<table>
<thead>
<tr>
<th>Test</th>
<th>Flexural Stiffness (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 line</td>
<td>3.87</td>
</tr>
<tr>
<td>Central loading</td>
<td>3.76</td>
</tr>
<tr>
<td>3 point support</td>
<td>3.70</td>
</tr>
</tbody>
</table>
CHAPTER 7

ASSESSMENT OF THE CIRCULAR DISC AS A SUBCOMPONENT

In the previous chapter the analysis was made of the factors directly related to the flexural tests regardless of the inherent characteristics of the test pieces. In this chapter aspects related to the test pieces themselves will be discussed, such as the material batch, the processing conditions, the type of mouldings etc. Also a first insight will be made into the potentiality of the subcomponent method in design.

7.1 Influence of the Material Batch

The variation of mechanical properties within different grades of the same polymer is easily understandable, however one is not able to say by how much the change of batch within the same grade of material is likely to affect the mechanical properties of mouldings made with the same processing conditions.

The point arose due to the fact that during the moulding programme it was necessary to use two different batches of the same grade of material, ICI's PP GWM 101.

The study was done with EG discs considering two thicknesses and two processing conditions. From the data recorded in Tables 5.1, 5.2 and 5.8 the results shown in Table 7.1 are obtainable, referring to three line tests. They show that the second batch of the material tends to produce stiffer mouldings, especially when a warm mould is used (mouldings C). In this case the increase in
mean stiffness, \( \bar{C} \), is of the order of 5% while for mouldings from a cooler mould the increase is only about 1%.

As pointed out before for this experiment the same machine, processing conditions and operator were used. Therefore the results show that a quite significant range of variation is likely to be expected within a given commercial moulding.

7.2 Influence of the Processing Conditions

The effect of the processing conditions on the flexural stiffness is not the same in thin as in thick mouldings (EG discs considered in this discussion). The data from three line tests at 90 mm span were taken as a basis of comparison.

7.2.1 Thick mouldings

The thick mouldings which were produced almost at the lower boundary of the processing window (low melt and mould temperatures,
slow injection speed) showed the lowest \( C \). Then, as the melt and the mould temperatures were increased the stiffness increased as well. However when the melt temperature was increased even further the stiffness dropped as is shown in Figure 7.1. This reduction appears to be caused by the different structures of the material, which are photographed in Figure 7.2. In fact the samples E3D and E3C have a similar coarse structure but the magnitude of the skin (S) and the transcrystalline (T) layers are
different, being comparatively small in E3D. The transcrystalline layer or shear zone corresponds to the region of the moulding where greater orientation is created due to the higher shear stresses during filling. If the cooling is fast, for example, due to a lower melt or mould temperature, this orientation is frozen-in. In a previous work with polypropylene mouldings of identical thickness (24) it was shown that this oriented transcrystalline layer has a somewhat higher density, (Figure 7.3). The higher
density implies usually a greater stiffness, and consequently the outer layers will be on average stiffer than the core.

In bending, the outer layers of the specimen are those which predominantly contribute for the stiffness and this explains the increase of the stiffness of the moulding E3C in comparison with E3D, as these two mouldings have similar core structure.

The other two mouldings have a different finer core structure derived from the shortest time available for the melt before falling temperature prevents further crystallisation. This will induce an overall lower degree of crystallinity and consequently lower density and lower stiffness. The smaller skin shear zone in E3A in comparison with E3B explains the lower stiffness of the former with respect to the latter by the same reasons given previously.

7.2.2 Thin mouldings

In the case of thin mouldings there is a peak of stiffness at the processing conditions which determined the previous stiffer discs. However the mouldings corresponding to the lower processing temperatures showed an increase of stiffness (Figure 7.4).

The analysis of the structures of these mouldings (Figure 7.5) show that at the lowest processing temperatures (E1A) there is a sharp increase in the thickness of the skin this surely accounting for the higher stiffness of these mouldings. The thin mouldings in contrast with the thick mouldings show a very sharp transition between
the skin and the core, a transcrystalline layer being not apparent. It is also noticed that in these thin mouldings α-form spherulites do not occur. They are clearly visible in the boundary of skin and shear zones of mouldings E3C and E3D (Figure 7.2).

7.3 Influence of the Thickness

In the previous section it was verified that mouldings with different thicknesses and moulded at the same processing conditions have quite different structures. Therefore it is expected that the corresponding mechanical properties will also be different. This point is illustrated in Table 7.2 where the mean stiffnesses of thin and thick discs (measured in the three line test with 90.5 mm span) are compared.
TABLE 7.2
Variation of Mean Stiffness \( \left( \frac{E}{1-\nu^2} = A \frac{w}{\delta h^3} \right) \) with thickness.

<table>
<thead>
<tr>
<th>Processing Condition Code</th>
<th>Mean Stiffness (GPa)</th>
<th>Thin Moulding</th>
<th>Thick Moulding</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.462</td>
<td>1.310</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.415</td>
<td>1.315</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1.492</td>
<td>1.427</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1.399</td>
<td>1.399</td>
<td></td>
</tr>
</tbody>
</table>

It is seen that the thin mouldings are generally stiffer than the similarly processed thick mouldings, the bigger variation taking place for the conditions leading to higher degree of anisotropy.

The effect observed with centre gated discs however is different: in this case the thick discs are stiffer than the thin ones (see Table 7.3, next section). The differences in stiffness are however less important than in the case of EG discs. No immediate explanation is foreseen for this difference which may probably be related to the different patterns of orientation in the two types of mouldings. This point will be further discussed in Section 7.5.

However if the data from the other two tests is used instead of those from the three line test the same trend of variation is observed for all types of gating (Tables 7.4 and 7.5).
7.4 Influence of the Material

The PP homopolymer GSM 10 is a stiffer flowing grade than the copolymer GWM 101. The mean stiffnesses in the three line test were calculated for the different processing conditions, which were identical to those used for the copolymer. The results are shown in graphical form in Figure 7.6 which shows that the trend of variation of the flexural stiffness is different from the copolymer in the case of thick mouldings. This suggests that different materials might react differently to the
same variation in processing conditions. Another important observation is the great change in the flexural stiffness caused by the variation of thickness, this change being much bigger than in the case of the easier flowing copolymer.

7.5 Gating and Orientation

The effect of the type of gate used shows differently depending on the type of test utilised. The following discussion is based on data obtained with mouldings in GWM 101 from batch II.

7.5.1 Three line test

In Table 7.3 are indicated the flexural stiffnesses of the various types of disc.

The EG discs are the stiffest in cylindrical bending (the situation created in this test) whilst the CG-thin discs and the DG discs are comparatively less stiff. The reason for this difference cannot be attributed to the different strain rates in each test because with the exception of the thin discs they lie in the region where it affects little the flexural stiffness (Section 6.2.3). Therefore the orientation effects related to the different patterns of flow may provide an explanation.

In the case of CG discs, the radial orientation is important in comparison to the circumferential orientation, especially in the case of thin discs where the faster cooling prevents relaxation. A rough estimate of the relative magnitude of the orientation can
TABLE 7.3

Flexural Stiffness of Circular Discs in the Three Line Test

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Thickness (mm)</th>
<th>Flexural Stiffness (GPa)</th>
<th>Test Span (mm)</th>
<th>Approx. ( \varepsilon ) (10^{-6}s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1C</td>
<td>1.57</td>
<td>1.672 (a)</td>
<td></td>
<td>305</td>
</tr>
<tr>
<td>E3B</td>
<td>2.96</td>
<td>1.425</td>
<td>70</td>
<td>610</td>
</tr>
<tr>
<td>E3C</td>
<td>2.92</td>
<td>1.606</td>
<td></td>
<td>610</td>
</tr>
<tr>
<td>C1B</td>
<td>1.62</td>
<td>1.370</td>
<td></td>
<td>350</td>
</tr>
<tr>
<td>C1C</td>
<td>1.63</td>
<td>1.381</td>
<td></td>
<td>350</td>
</tr>
<tr>
<td>C3B</td>
<td>3.10</td>
<td>1.408</td>
<td>65</td>
<td>710</td>
</tr>
<tr>
<td>C3C</td>
<td>3.05</td>
<td>1.436</td>
<td></td>
<td>710</td>
</tr>
<tr>
<td>D3B</td>
<td>3.20</td>
<td>1.249 (a)</td>
<td>55</td>
<td>990</td>
</tr>
<tr>
<td>D3C</td>
<td>3.13</td>
<td>1.283</td>
<td></td>
<td>990</td>
</tr>
</tbody>
</table>

Note: (a) Mean stiffness

be made in terms of the average deformation rates.

Considering a melt being injected into a circular cavity of thickness, \( h \), at a constant volumetric flow rate, \( Q \), and assuming isothermal conditions and steady-state flow:

a) The extensional deformation rate in the circumferential direction, \( \varepsilon_c \), is at any time, \( t \), after the injection begins

\[
\varepsilon_c = \frac{dR}{dt} \frac{1}{R} \quad (7.1)
\]

As \( Qt = V = \pi R^2 h \) \( (7.2) \)

then

\[
R^2 = \frac{Qt}{\pi h}
\]
and
\[ \frac{dR}{dt} = \frac{Q}{2\pi Rh} \] (7.3)

Entering with the expression of \( \frac{dR}{dt} \) (7.3) in (7.1) results
\[ \dot{\varepsilon}_c = \frac{Q}{2\pi R^3h} \] (7.4)

b) For the flow through a constant rectangular section of width \( t \), the shear rate at the wall is
\[ \dot{\gamma}_{WR} = \frac{6Q}{7h^2} \] (7.5)

If the divergence of the flow is ignored in the plane of the spreading disc:
\[ t = 2\pi R \] (7.6)

and thus, approximately
\[ \dot{\gamma}_{WR} = \frac{3Q}{\pi h^2R} \] (7.7)

The extensional deformation rate, \( \dot{\varepsilon}_c \), is associated to the orientation in the circumferential direction, and the shear rate \( \dot{\gamma}_{WR} \) to the radial orientation. Hence the circumferential orientation would be proportional to \( 1/R^2 \) and the radial orientation is proportional to \( 1/R \).
This crude analysis shows that the circumferential deformation rate decreases more quickly than the radial shear rate. Near the gate however the temperature is higher due to the great mass of the sprue nearby, Figure 7.7, and also to the effect of shear heating, which helps the relaxation of orientation.

In the EG discs the sprue is far from the moulding and consequently the orientation is more likely to be frozen-in than in the case of CG discs.

Also the shear induced orientation is largely surface dominated because the shear stresses are higher at the cavity wall while the elongational orientation is more averaged out over the thickness of the discs, and during cooling the core region at any radius has more time to relax.
This seems to suggest that the overall level of orientation in the EG discs is higher than in the other two types of discs, especially in the case of thin discs, which will be therefore stiffer. Also for equal filling times, the flow length and so the mean velocity are greater in the EG discs.

The visual observation of DG discs shows a neat weld line along the diameter perpendicular to the line through the gates. It was already observed that the degree of flexural anisotropy of these discs depends substantially on the mould temperature: when a cold mould is used (D3B) the degree of anisotropy compares to that of the EG mouldings which is around 1.04. The degree of anisotropy is given by the ratio between the slopes in two mutually perpendicular directions. However when a warm mould is used a very definite anisotropy ratio of 1.11 was determined. This fact may be explained by the contrary effects of the weld line and the orientation: more quickly cooled mouldings have a higher orientation leading to higher stiffness, but, on the other hand, a weaker knitting line is likely to be formed. In the case of warm mould discs, the weld line is less critical but the degree of orientation is lower. So the evidence appears to be that in the case of double gating the effect of mould temperature on orientation is more important than its effect on the stiffness due to the presence of the weld line. In fact, in both mouldings the observation of structure in the weld zone did not show any discontinuity in the structure, as shown in Figures 8.26 and 8.27 (next chapter) with microphotographs taken from a disc moulded with a cold mould (D3B).
7.5.2. Central loading test

The tests with the discs supported by a circular ring lead generally to higher values of the flexural stiffness (Table 7.4)

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Flexural Stiffness (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1C</td>
<td>1.921</td>
</tr>
<tr>
<td>E3B</td>
<td>1.747</td>
</tr>
<tr>
<td>E3C</td>
<td>1.761</td>
</tr>
<tr>
<td>C1B</td>
<td>1.613</td>
</tr>
<tr>
<td>C1C</td>
<td>1.830</td>
</tr>
<tr>
<td>C3B</td>
<td>1.733</td>
</tr>
<tr>
<td>C3C</td>
<td>1.842</td>
</tr>
<tr>
<td>D3B</td>
<td>1.589</td>
</tr>
<tr>
<td>D3C</td>
<td>1.761</td>
</tr>
</tbody>
</table>

than the three line tests.

In the case of CG discs it has been already pointed out that the orientation is predominantly radial and that a certain degree of circumferential orientation is also likely, especially further from the gate.

In this test the principal stresses occur in the radial and in the circumferential directions which are precisely those corresponding to the orientation. Thus, this is the situation in which the material is more effectively used, and therefore a higher value of the flexural stiffness can be understandably accepted.
7.5.3 Three point support test

The three point support test creates in the middle of the test piece a state of stress which resembles the situation in the central loading test. Thus similar values for the stiffness measured in this test would be expected, and were in fact obtained. Table 7.5 shows how the flexural stiffness was calculated.

TABLE 7.5

Flexural Stiffness of Circular Discs in Three Point Support Test

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Slope S (kN/m)</th>
<th>Corrected Slope $S_0$ (kN/m)</th>
<th>Flexural Stiffness $C_p$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1C</td>
<td>4.89</td>
<td>4.15</td>
<td>1.999</td>
</tr>
<tr>
<td>E3B</td>
<td>29.29</td>
<td>24.83</td>
<td>1.787</td>
</tr>
<tr>
<td>E3C</td>
<td>29.64</td>
<td>25.13</td>
<td>1.884</td>
</tr>
<tr>
<td>C1B</td>
<td>6.63</td>
<td>5.46</td>
<td>1.749</td>
</tr>
<tr>
<td>C1C</td>
<td>7.17</td>
<td>5.90</td>
<td>1.864</td>
</tr>
<tr>
<td>C3B</td>
<td>45.11</td>
<td>37.16</td>
<td>1.699</td>
</tr>
<tr>
<td>C3C</td>
<td>45.05</td>
<td>37.11</td>
<td>1.781</td>
</tr>
<tr>
<td>D3B</td>
<td>62.55</td>
<td>49.47</td>
<td>1.456</td>
</tr>
<tr>
<td>D3C</td>
<td>63.95</td>
<td>50.58</td>
<td>1.590</td>
</tr>
</tbody>
</table>

by determining first the value of the slope corrected for the effect of overhanging with equation 6.12.

The results obtained with this test compare very well with those obtained with the central loading test mentioned in the previous paragraph. Thus the comments made to those results apply in this case.
7.6 How Important is Orientation?

The data obtained when mouldings with different types of gate were tested in tests governed by a principal bending stress, such as the cylindrical bending test, or in full bi-axial tests such as the central loading or the three point support tests, suggest that in the design activity attention should be devoted not only to the likely flow of the melt during filling but also to which kind of design data more realistically represents the service situation. In other terms this is equivalent to saying that in injection moulding design orientation must be taken into account.

The results discussed so far seem to show that the traditional approach to design based upon point and material properties is very unlikely to predict accurately the performance of injection moulded components, so great is the variation in that performance due to factors such as processing, material, and so on.

By using subcomponents which are more realistic test pieces in tests representing more closely actual loading situations, it will be possible to derive design data which eventually lead to better design.

These design data are unlikely to be the usual material properties due to the almost unbearable complexities arising from the inherent complex anisotropy of injection mouldings which becomes even more complicated in the case of reinforced mouldings. The different patterns of anisotropy affect the performance as has been discussed. The situation is well contrasted by recalling again the results obtained with 'isotropic' PMMA discs (Section 6.6.3), a case where
the principle of well defined material properties \((E, \nu)\) holds without problems regardless of the loading situation.

The range of orientation effects can be experimentally determined by considering a suitable and representative range of processing conditions. This has been partially attempted in this work for a particular type and grade of material. This idea brings afield the concept of 'derating factor' which was recommended for subcomponents by Stephenson (48); The derating factors will be referred to a test and subcomponent datum which will be eventually agreed as standard.

7.7 Applying Subcomponent Data in Design

The three line test and the three point support test, due to particular advantages, are being considered as potential generators of data for the prediction of the deflection behaviour of plates and, possibly, components containing plate-like parts.

Before getting involved with more complex practical situations, an assessment of these two methods can be made by comparing how the two sets of respective data can be used for predicting the flexural behaviour of the same mouldings in the edge support test.

The method used for making the predictions was introduced in the Section 3.6.4 of Chapter 3. A distinction is now convenient to be made between the flexural stiffnesses derived from each test, which will be designated by \(C_L\) and \(C_P\) respectively for the three line test and the three point support test. These stiffnesses were calculated and tabulated in Tables 7.3 and 7.4, respectively.
Considering a value of \( v = 0.45 \), the results shown in Table 7.6 are obtained considering that the slope in the central loading test relates to the flexural stiffness by the expression

\[
S = \frac{4 \pi h^3}{3R^2} \frac{1 + v}{3 + v} C
\]

From the results shown it is clear that the three line test data overestimates the deflection by a margin of error averaging nearly 20%. From the design point of view these estimates are quite conservative but lead to an incomplete exploitation of the capabilities of the material.

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Experimental Slope - Central load test (kN/m)</th>
<th>Prediction based on:</th>
<th>3 line test</th>
<th>3 point test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope (kN/m)</td>
<td>Error (%)</td>
<td>Slope (kN/m)</td>
<td>Error (%)</td>
</tr>
<tr>
<td>E1C</td>
<td>4.10</td>
<td>3.57</td>
<td>-13.0</td>
<td>4.27</td>
</tr>
<tr>
<td>E3B</td>
<td>24.98</td>
<td>20.38</td>
<td>-18.4</td>
<td>25.56</td>
</tr>
<tr>
<td>E3C</td>
<td>24.18</td>
<td>22.05</td>
<td>-8.8</td>
<td>25.87</td>
</tr>
<tr>
<td>C1B</td>
<td>4.83</td>
<td>4.10</td>
<td>-15.1</td>
<td>5.24</td>
</tr>
<tr>
<td>C1C</td>
<td>5.58</td>
<td>4.21</td>
<td>-24.5</td>
<td>5.68</td>
</tr>
<tr>
<td>C3B</td>
<td>36.35</td>
<td>29.54</td>
<td>-18.7</td>
<td>35.64</td>
</tr>
<tr>
<td>C3C</td>
<td>36.80</td>
<td>28.69</td>
<td>-22.0</td>
<td>35.58</td>
</tr>
<tr>
<td>D3B</td>
<td>46.30</td>
<td>36.39</td>
<td>-21.4</td>
<td>42.42</td>
</tr>
<tr>
<td>D3C</td>
<td>48.01</td>
<td>34.98</td>
<td>-27.1</td>
<td>43.35</td>
</tr>
</tbody>
</table>
The three point support test data give much closer predictions generally in line with the errors introduced by the experimental factors of the methods and the theoretical simplifications. This shows the great potential of the three point support test in that the design of plate-like components subjected to biaxial stress situations is concerned. This situation is on the other hand the more common for such components.

An aspect which has to be considered in applying the three point support test is the possibility of localised indentation or crushing at the supports in the case of high testing loads. This point can be overcome by designing sufficiently large radius which can keep the maximum contact Hertz-stress below the compressive yielding stress of the material, as happened in the rig used in this work. However making the support radii too large may introduce another source of error which is the variation of support span which increases the measured stiffness if the deflection is too large. This point was analysed in more general terms in Section 4.1.3 where it was concluded that for the geometry used if the deflections are small (say 1 mm) the reduction in diameter is of the order of 2% and the increase in slope (w/δ) not higher than 4%. Nevertheless in the experimental curves obtained during testing noticeable departure from linearity was not observed for small deflections.

Concluding it appears that for design, the utilisation of a flexural stiffness obtained by testing a suitable subcomponent may bring to the design of plates, where the factor $E/(1 - \nu^2)$ usually
appears, an attractive degree of simplification and improved accuracy on the prediction of stiffness.
CHAPTER 8

IMPACT BEHAVIOUR OF CIRCULAR SUBCOMPONENTS

The impact tests are gathering at present renewed interest arising from the fact that instrumentation has been developed giving the possibility of generating quickly large amounts of information.

In this work the impact testing programme was undertaken for establishing the influence of several factors on the impact performance of subcomponents, for examining the behaviour of the used material over a range of temperatures, and for seeking a possible link between impact and 'static' data.

All this information is of potential interest to the designer insofar as the subcomponents contain features present in commercial mouldings, and specifications related to impact are usually present in the design activity.

A theoretically based analysis could not be made but the qualitative information gathered will provide an indication of tracks worthwhile of further investigation and work.

8.1 The Different Types of Impact Failure

In the falling weight impact test the following types of failure are identifiable (Figure 8.1):

a) Ductile
b) Ductile-brittle
c) Brittle-ductile

The types (a), (d) and (e) are easily identifiable. The first is characterised by a large deflection and yielding before break, the second by the low energy required for break, the failure taking place without any trace of yielding, and the last by the characteristic shape of the curve suggesting that the cracking takes place in steps.

The two intermediate types (b) and (c) used to be distinguished by the conjunction of the shape of the trace and the aspect of the failed specimen. In the first case the curve presents usually a peak followed by a short post-yielding period, and the broken specimen shows signs of important whitening. In the second case however the brittle behaviour is more accentuated, and there is not a recognisable post-yielding portion of the curve. Some whitening, a characteristic of ductile behaviour in PP is nevertheless observable.

With the PP mouldings all the types of failure were observed, the ductile failures taking place generally at room temperature, and the brittle ones mostly at sub-zero temperatures. The initiation-propagation failures were observed only in the case of DG discs.

8.2 Repeatability of the Test

The repeatability of the tests at room temperature is particularly good especially in the case of EG discs as shown in Figure 8.2 for the
mouldings E3C. When the temperature is dropped the tendency for brittleness increases and the modes of failure vary as is illustrated for the same mouldings in Figure 8.3 referring to tests at 0°C, (see next page).

The tests with other types of mouldings (CG) where the impact was applied offset from the sprue point, showed a poorer degree of repeatability especially at room temperatures as shown in Figure 8.4, for specimens C3C.

![Diagram showing force vs time for mouldings tested at different temperatures](image-url)
Figure 8.1
FIGURE 8.2: Mouldings E3C tested at 23°C

FIGURE 8.3: Mouldings E3C tested at 0°C
8.3 The Impact Test Data

As mentioned already in Chapter 5, the data of impact tests were worked out by an in-line computer using the record of the force-time plot from a transient recorder.

The ICI package used for the interpretation of the curve determined:

a) The points corresponding to the maximum force in the test and to the subsequent nil force, assuming a constant impactor speed.

b) The areas under the curve from the origin to the point of maximum force, and to the break point.

c) The gradient of the rising portion of the curve.

The five data values calculated within the points (a) and (b) have been generally accepted by the researchers using the equipment and the package without major criticism, however the gradient figure (c) has been open to some doubts arising mostly from the fact that the rising portion of the curve has not a regular form. Therefore the gradient figures which will be quoted in this chapter should be envisaged with some reservation and in some cases seen mostly as a matter of record.

One point that usually attracts interest is to establish how 'ductile' a given failure is, this being especially true in the cases of the curves intermediate between the ductile and the brittle types.
It appeared convenient to adopt as a measure of the amount of ductility, the difference between the total energy absorbed in the impact, \( FE \), and the energy absorbed up to the maximum force point, \( P/YE \). This difference for convenience will be designated as the 'ductile energy' in the subsequent discussion, and using the ICI data nomenclature is:

\[
DE = FE - P/YE
\]

### 8.4 Tests with EG Discs

The tests with EG discs covered the range of four processing conditions, and were done for the two thicknesses over the five test temperatures from \(-20^\circ C\) up to the room temperature, \(23^\circ C\).

For the discussion the average results only are going to be considered. In the illustrative diagrams the symbology shown in Table 8.1 is used for representing the processing conditions.

#### TABLE 8.1

Symbols for Processing Conditions

<table>
<thead>
<tr>
<th>Processing Conditions Code</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>○</td>
</tr>
<tr>
<td>B</td>
<td>○</td>
</tr>
<tr>
<td>C</td>
<td>●</td>
</tr>
<tr>
<td>D</td>
<td>●</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td></td>
</tr>
<tr>
<td>Break</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td></td>
</tr>
<tr>
<td>□</td>
<td></td>
</tr>
</tbody>
</table>
It must also be pointed out that in many cases the standard deviation of the results is greater or identical to the actual difference between the average points represented. This fact justifies the drawing of a single line for all processing conditions signifying the trend of variation of the function with the variation of test temperature.

8.4.1 Tests with thin discs

With the reservations already made in Section 8.3 about the determination of the gradient, it was observed that the stiffness in impact of the mouldings which, in some way, will be proportional to the gradient, varied substantially with the temperature, Figure 8.5. Thus, at the lowest test temperature (-20°C) the stiffness of

![Graph: Thin Discs-Dependence of Impact Gradient on Temperature]
the moulding was about 30% higher than at room temperature. Also the discs moulded at lower temperatures were around 10% stiffer than those moulded at higher temperatures. The stiffness of the mouldings varies little in the range from -10 to 10°C however showing appreciable variations outside this region.

The thin discs showed a remarkable brittleness even at room temperature. This is well illustrated in Figures 8.6 and 8.7 which show a variation of the deflection and the energy at yield/peak and at break. Nevertheless it was possible to verify that the mouldings produced with higher temperatures (C and D) were more brittle than those moulded at lower temperatures. The 'ductile energy' remained roughly constant up to nearly the room temperature, signifying a consistent brittleness, and it was only at this temperature that a slight increase of this parameter was observed.

Finally the maximum force increased only very slightly with the test temperature (Figure 8.8). This fact appears to be consistent with the quasi-monotony of the other test data.

8.4.2 Tests with thick discs

The gradient was nearly constant up to 0°C for the case of thick discs (Figure 8.9). At this temperature a substantial drop takes place suggesting a definite change in behaviour at the mouldings. Above this temperature the influence of the processing conditions appears to affect very little the stiffness in impact.
FIGURE 8.6: Thin discs - dependence of deformation on temperature

FIGURE 8.7: Thin discs - dependence of impact absorbed energy on temperature
FIGURE 8.8: Thin discs – dependence of maximum force on temperature

FIGURE 8.9: Thick discs – dependence of impact gradient on temperature
The change in behaviour at about 0°C is also shown in the curves for deflection behaviour (Figure 8.10) and absorbed energies (Figure 8.11). This is particularly evident in the curve of the 'ductile energy' which is superimposed to the other two energy curves on Figure 8.11: up to nearly 0°C the DE curve is nearly horizontal corresponding to the brittle behaviour of the mouldings, but from this temperature on the degree of ductility increases steadily with the increase of temperature, and this is shown by the positive slope of the DE curve.

The peak force shows little variation with the temperature especially for temperatures above -10°C (Figure 8.12). Below this temperature the force required for rupture is substantially lower. When the temperature rises above -10°C the peak force decreases very slightly with the increase of temperature.

![Graph showing the dependence of deflection on temperature](image-url)
FIGURE 8.11: Thick discs - dependence of impact absorbed energies on temperature

FIGURE 8.12: Thick discs - dependence of maximum force on temperature
For the thin discs the trend of variation of the force was clearly different (Figure 8.8), the variation was almost negligible up to room temperature where a small increase was observed, this appearing to be the opposite of what happens with the thick discs.

8.4.3 The existence of a critical temperature

Especially with the thick discs a change in behaviour from brittle to ductile is observed around 0°C for the GWM 101 PP copolymer. This was observed by examination of the fractured specimens or by observation of the energy curves (Figure 8.11). It is interesting to note that the thinner mouldings tend to be much more brittle in impact even at room temperature.

8.5 Tests with Centre-Gated Discs

The original idea for testing CG discs was to impact the specimens at the centre where the sprue is located. However, the preliminary tests showed that with this type of loading all the specimens broke in a very brittle manner even at room temperature, for that requiring only a very small amount of energy. For example for the thick discs E3B, the fracture energy at room temperature was 0.5J when the impact was on the sprue point while the average values when the striking point was offset from the centre were 33J. This means that, as one would expect, the sprue is a very weak point in the moulding and hardly representative of the whole moulding in
terms of toughness. Hence the decision was to make the impact tests on CG with the offset arrangement shown in Figure 8.13.

![Test Arrangement for CG Discs](image)

**FIGURE 8.13:** Test Arrangement for CG Discs

### 8.5.1 Tests with thin discs

The features observed in the case of edge gated discs were observed again in the CG discs when impacted offset from the sprue. Figures 8.14 and 8.15 illustrate that. It can be noted that the discs moulded with warm moulds are more brittle than those moulded
FIGURE 8.14: CG Thin discs - dependence of impact gradient on temperature

FIGURE 8.15: Thin discs - dependence of ductile energy on temperature
with a cold mould, when tested at room temperature. An explanation for this can be found in the coarser core structure of the mouldings obtained with a warm mould (Figure 8.16).

The maximum force in the test takes place at the onset of the fracture and is little dependent on the moulding conditions and the test temperatures (Figure 8.17)

---

**FIGURE 8.17:** Thin discs - dependence of maximum force on temperature

8.5.2 Tests with thick discs

The behaviour of thick CG discs is similar to the EG ones discussed in a previous Section (8.4.2). The curves of variation
a) Structure of Moulding ClB

b) Structure of Moulding ClC

FIGURE 8.16:
of gradient (Figure 8.18), ductile energy (Figure 8.19) and peak force (Figure 8.20) can be seen to be identical to those obtained for the EG discs. It is interesting to note that, at room temperature, as well as the thin discs, the thick discs moulded with a warm mould are also more brittle. Here again the different structures of the core (Figures 8.21 and 8.22) can account for the variation of impact resistance: when the mould temperature is higher the spherulites can grow bigger and therefore the coarser structure will be more impact sensitive insofar as the interspherulitic larger regions act as flaws which are potential nucleators of cracks.

8.5.3 Effect of ageing

The limited study done on the effect of ageing on the impact properties was done over a period of three decades of time: the tests at room temperature were done after 48 hours, one month and 10 months after moulding.

The results show mainly an embrittlement, and some stiffening of the mouldings. These effects are quantified in terms of the fracture and ductile energies, and also the impact gradient as shown in Table 8.2.

These results agree with the expectations from the post-moulding secondary crystallization that polypropylene undergoes at room temperature which is just above its glass transition temperature.
FIGURE 8.17: Thin discs - dependence of maximum force on temperature

FIGURE 8.18: Thick discs - dependence of impact gradient on temperature
FIGURE 8.19: Thick discs - dependence of ductile energy on temperature

FIGURE 8.20: Thick discs - dependence of maximum impact force in temperature
FIGURE 8.21: Structure and Moulding C3B

FIGURE 8.22: Structure of Moulding C3C
TABLE 8.2
Variation of Impact Properties of Subcomponents

<table>
<thead>
<tr>
<th>After moulding time s</th>
<th>Gradient (kN/m)</th>
<th>Displacement at yield (mm)</th>
<th>Fracture energy (J)</th>
<th>Ductile energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7 x 10^5 (48h)</td>
<td>284</td>
<td>14.0</td>
<td>34.0</td>
<td>16.3</td>
</tr>
<tr>
<td>2.6 x 10^6 (1 month)</td>
<td>304</td>
<td>12.5</td>
<td>25.8</td>
<td>10.7</td>
</tr>
<tr>
<td>2.6 x 10^7 (10 months)</td>
<td>326</td>
<td>14.0</td>
<td>31.1</td>
<td>12.4</td>
</tr>
</tbody>
</table>

8.5.4 Effect of methanol wetting

The great increase in the fracture energy at room temperature was at a moment suggested to be derived from the fact that the tests on mouldings at room temperature were done with dry specimens, instead of wet in methanol and solid CO₂, the procedure for the other test temperatures.

The assessment of this effect was done with thick CG discs C3C and thin EG discs E1C. In both cases only a small increase in toughness (as measured by the FE) was noted when the discs were previously immersed in methanol. Some of the data obtained is compared in Table 8.3 with those obtained with dry mouldings. The variation in the properties nevertheless is very small and rather smaller than the typical variation of results with this type of test. Possibly more interesting is the analysis of the standard
TABLE 8.3

Effect of Methanol Wetting in Impact

<table>
<thead>
<tr>
<th>Property</th>
<th>CG thick discs</th>
<th>EG thin discs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>Gradient (kN/m)</td>
<td>304 (a)</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>41 (b)</td>
<td>9</td>
</tr>
<tr>
<td>Defl. at yield (mm)</td>
<td>12.5</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Fracture energy (J)</td>
<td>25.8</td>
<td>27.7</td>
</tr>
<tr>
<td></td>
<td>16.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Notes: (a) Average value
(b) Standard deviation

deviation of the results. In the case of thick CG discs for example when wet, the scatter of the results is much smaller: take the fracture energy standard deviation which is 16J for the dry discs and only 4J for the wet ones. This fact may be due to the lubricating effect caused by the liquid. When hit by the hemispherical nose the specimen undergoes a certain amount of drawing before breaking, This effect was observed and pointed out by Mooij (63). On drawing the higher the coefficient of friction between the nose and the material, the higher is the tendency for a less energy demanding fracture and less deformation before rupture. As might be expected this effect is not observed with thin discs which being brittle draw very little before breaking. Thus wetting with methanol leads to little or no reduction in the scatter of results.
8.6 Tests with Double-Gated Discs

When the DG discs are impacted offset from the weld line running through the diameter perpendicular to the gates line, the behaviour is very similar to that already analysed for EG and CG discs impacted far from the sprue. Thus, for the DG mouldings it was opted to evaluate the influence of the weld line on the impact behaviour when the specimens are struck on it.

In a great number of cases the test pieces cracked in the so called 'initiation-propagation' mode (IP). These failures are characterised by a force-deflection trace with a number of peaks, the higher being not necessarily the first (Figure 8.23).
The incidence of this type of failure increases as the test temperature is decreased, as shown in Table 8.4 for the two types of DG discs. In these failures the test pieces shatter in every direction instead of splitting in two along the weld line (brittle failures) which is supposedly the weakest line in the moulding. The failure along the weld line occurs more often at higher test temperatures, and the graph of the test is of the brittle type.

The energy required for breaking the DG discs with an on-weld blow is much less than that necessary for breaking similar thickness discs with impacts far from critical points. Impacting a weld line is nearly as bad as striking a sprue point: when the failure occurs along the weld line the energy required is little higher than that required for breaking a CG disc impacted on sprue. The failures which are of the brittle type require an amount of energy only marginally higher than for the IP failure.

TABLE 8.4
Failure Modes of Double-gated Discs

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>Failure Mode</th>
<th>Number of samples failing @ Test Temp(°C) of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-20</td>
</tr>
<tr>
<td>D3B</td>
<td>Brittle I-P</td>
<td>-</td>
</tr>
<tr>
<td>D3C</td>
<td>Brittle I-P</td>
<td>2</td>
</tr>
</tbody>
</table>
The force corresponding to the first peak in the IP failures increases with the test temperature and the same happens with the fracture energy (Figures 8.24 and 8.25).

**FIGURE 8.24:** Double-gated discs - dependence of peak force on temperature

**FIGURE 8.25:** Double-gated discs - dependence of failure energy on temperature
The higher mould temperature appears to improve slightly the toughness (FE) at lower temperatures of testing (Figure 8.25), however given the great scatter of the results it does not appear correct to draw definitive conclusions from the number of results available.

It is interesting to mention that in spite of the weld line being visually identifiable in the mouldings, a microphotograph of the section does not show any discontinuity in the structure, this suggesting that the weld is after all a 'good' weld (Figures 8.26 and 8.27).

FIGURE 8.26: Section of a DG disc far from the weld
8.7 Variation of Toughness with Gating

The comparison of the impact resistance dependence on the type of gating can be based on the fracture energy as a measure of toughness, and on the peak force as a measure of strength on impact.

For making the comparison the results obtained at room temperature with thick mouldings are tabulated in Table 8.5. The tests on CG discs refer to impact offset the sprue, and those on DG discs to impact upon the weld.

The results shown suggest that if the impact is applied away from weak points such as weld lines and gating points, the toughness and the impact strength of the mouldings are not particularly affected by the type of the gate. The mould temperature however affects the toughness in all types of mouldings, mouldings obtained with cooler moulds being tougher than those where the melt cooling was
slower. The singular zones such as gate points and weld lines produce a great reduction in toughness and impact strength when hit.

TABLE 8.5

<table>
<thead>
<tr>
<th>Disc Type</th>
<th>Relative Mould Temperature</th>
<th>Fracture Energy (J)</th>
<th>Peak Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EG</td>
<td>Cold</td>
<td>37</td>
<td>2.74</td>
</tr>
<tr>
<td></td>
<td>Warm</td>
<td>31</td>
<td>2.65</td>
</tr>
<tr>
<td>CG (a)</td>
<td>Cold</td>
<td>33</td>
<td>2.75</td>
</tr>
<tr>
<td></td>
<td>Warm</td>
<td>31</td>
<td>2.43</td>
</tr>
<tr>
<td>DG (b)</td>
<td>Cold</td>
<td>9</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>Warm</td>
<td>6</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Notes:  
(a) Offset impact  
(b) Impact on weld

8.8 Is a Relationship Possible Between Impact and 'Static' Tests?

Given the possibility of instrumented impact tests producing plots of the type generated with tensile testing machines, an attempt was made to find out if a relationship would hold between the two types of data.

As the diameters of the supports are different in the two tests, for similar mouldings a comparison between the two sets of load-
deflection data can be made by comparing a factor involving only the material properties, stiffness and lateral contraction ratio.

For the central loading test this factor \((W/\delta) (R_o^2/h^3)\) is related to the flexural stiffness by the following relation derived from the expression for the deflection in the test (equation 3.23):

\[
\left(\frac{W}{\delta}\right) \left(\frac{R_o^2}{h^3}\right) = 4 \pi C \frac{1 + \nu}{3(1 + \nu)}
\]

The radii of the supports are 56 mm for the 'static' central loading tests in the tensile testing machine, and 25 mm for the impact ones. The results obtained are shown in Table 8.6 and refer to samples from mouldings made of PP copolymer of batch I.

<table>
<thead>
<tr>
<th>Lot Identification</th>
<th>'Static' Test</th>
<th>'Impact' Test</th>
<th>Ratio (4)/(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope (kN/m)</td>
<td>(W/\delta)(R_o^2/h^3) (GPa)</td>
<td>Gradient (kN/m)</td>
</tr>
<tr>
<td>E1D</td>
<td>4.95</td>
<td>4.10</td>
<td>177</td>
</tr>
<tr>
<td>E1C</td>
<td>5.03</td>
<td>4.09</td>
<td>187</td>
</tr>
<tr>
<td>E1B</td>
<td>4.62</td>
<td>3.76</td>
<td>185</td>
</tr>
<tr>
<td>E1A</td>
<td>4.98</td>
<td>3.97</td>
<td>193</td>
</tr>
<tr>
<td>E3D</td>
<td>31.8</td>
<td>3.33</td>
<td>327</td>
</tr>
<tr>
<td>E3C</td>
<td>30.6</td>
<td>3.11</td>
<td>330</td>
</tr>
<tr>
<td>E3B</td>
<td>27.2</td>
<td>2.82</td>
<td>322</td>
</tr>
<tr>
<td>E3A</td>
<td>27.7</td>
<td>2.92</td>
<td>319</td>
</tr>
</tbody>
</table>
The results suggest that a relationship between the data from the two tests cannot be made upon this basis. In fact whilst the factor \((W/\delta)/(R_o^2/h^3)\), in impact for thick discs, was roughly 2.4 times the 'static' value, in the case of thin discs it could be as high as eight times greater. Whereas in the 'static' tests the effect of processing conditions and disc thickness on stiffness is modest, in the impact test disc thickness has a major effect.

A clear explanation for this large difference does not emerge from the information gathered so far, however some possible causes can be suggested:

a) Method of determining the slope \(W/\delta\) in the impact test - this can be part of the explanation but is very unlikely to explain a difference as big as that observed.

b) Influence of the membrane stresses - in the impact test the failure takes place usually at large deflections compared with the thickness. In that case the membrane stresses make the material appear stiffer than it actually is. This may explain the higher impact stiffness of the thin discs in comparison with the thick ones.

c) Influence of the overhanging length in the impact test - this suggestion however does not appear likely insofar as the impact results seemed to be independent of the size of the specimen. (The energies absorbed by the discs of different diameters when struck offset from critical zones were nearly identical). It may happen that the overhang, as observed in the three point
test results discussion, stiffens the disc, however if this was true the effect should be higher in the case of thick discs than in the thinner ones.
CHAPTER 9
TESTS WITH COMMERCIAL MOULDINGS - A CASE STUDY

The subcomponent principle is based upon the idea that the laboratory test pieces should reproduce closely the commercial moulding features. Thus further industrial support was sought within this work in order that a small selection of commercial polypropylene mouldings (trays, boxes, lids) should be made available to obtain evidence on structure and properties experienced, in practice. In order to keep to a minimum the number of new variables being introduced, a similar material was desired and the mouldings chosen should have unperforated flat bases of circular or rectangular shape.

9.1 Description of the Commercial Mouldings

Three types of commercial mouldings were made available by GPG International, Dunstable. They are basically rectangular trays and boxes with different wall configurations which will cause different degrees of base constraint. An overall view of the mouldings is shown in Figure 9.1.

They were moulded in two different grades of ICI Propathene copolymer of propylene-ethylene in powder form:

GW 601M - which is equivalent to GWM 101 in granule form used for the moulding of the discs
GW 701M - a stiffer flowing grade which has somewhat reduced mechanical properties but better impact performance.

The basic properties of these two grades are shown in Table 9.1, which contains raw material supplier data (75).

The GW 601M mouldings were supplied in natural colour and according to the moulders their manufacturing characteristics and processing conditions are:
TABLE 9.1

Properties of commercial moulding materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>GW 601M</th>
<th>GW 701M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>0.905</td>
<td>0.905</td>
</tr>
<tr>
<td>Melt flow index</td>
<td>g/10 min, 190°C, 10 Kgf</td>
<td>22.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Tensile yield stress (ASTM D638-64T (2 in/min))</td>
<td>MPa</td>
<td>29.0</td>
<td>22.8</td>
</tr>
<tr>
<td>Flexural modulus (ASTM D790-66)</td>
<td>GPa</td>
<td>1.38</td>
<td>1.0</td>
</tr>
<tr>
<td>Drop Impact Strength at 23°C (BS 2782: 306B)</td>
<td>J</td>
<td>15.1</td>
<td>23.3</td>
</tr>
<tr>
<td>Softening temperature (BS 2782: 102D)</td>
<td>°C</td>
<td>147</td>
<td>143</td>
</tr>
</tbody>
</table>

a) Sunblest tray (Figure 9.1(a)) characteristics:
   - Moulding weight = 440 g
   - Base thickness = 2.1 mm
   - Base dimensions = 214 x 418 (mm)
   - Sprue gated at the centre of the base

Processing:
   - Melt temperature = 235°C
   - Mould temperature = 47°C
   - Cycle time = 50 seconds
b) Rat cage (Figure 9.1(b)) characteristics
- Moulding weight 1220 g
- Base thickness = 3.2 mm
- Base dimensions 257 x 447 (mm)
- Sprue gated at the centre of the base
Process:
- Melt temperature 250°C
- Coolant (chilled water) temperature 7°C
- Cycle time 58 seconds

The GW 701M mouldings were coloured tan and the characteristics and processing conditions are:

c) Eurobox (Figure 9.1(c)) characteristics:
- Moulding weight 2.45 kg
- Base thickness 2.7 mm
- Base dimensions 340 x 540 (mm)
- Injection with four hot runners near the corners of the base
Process:
- Melt temperature 255°C
- Mould temperature = 30°C
- Cycle time 70.5 seconds

9.2 Testing Programme
9.2.1 Objectives

The testing programme with the commercial mouldings aimed at the following objectives:
a) Determination of the overall base stiffness by centrally loading it with a concentrated load.

b) Determination of the degree of edge restraint caused by the walls on the base.

c) Cutting of circular discs from the base of the mouldings for determination of the flexural stiffness.

d) Observation of the structure of the mouldings by polarised light microscopy.

9.2.2 Testing aspects

The tests implied in the points (a), (b) and (c) of the previous section were done in the IPT Universal Testing Machine INSTRON, fitted with the specially designed test rigs already referred to in Chapter 4.

The cutting of circular discs was done using a bench-model bandsaw and the finishing done by grinding.

In spite of the bases of the mouldings being capable of withstanding fairly large deflections, the bending tests were only taken to relatively small deflections and of the order of magnitude of the base thicknesses.

The results to be obtained were not expected to produce very accurate correlations because:

a) the bases were not perfectly flat in the case of the rat cage.
b) The Eurobox base is deliberately domed for increasing the base stiffness when the box is loaded.

c) The Sunblest tray base has some perforations.

9.3 Analytical Solutions

Analytical solutions are known for the cases of rectangular plates simply supported along the edges, and with the edges built-in (or clamped).

Due to the restraining caused by the walls it was expected that the actual deflection of the bases of the mouldings would lie between the two extreme cases represented by the simple support and the clamping. The non-flatness of the bases however may bring membrane effects.

9.3.1 Deflection of a rectangular plate

The deflection of rectangular plates depends on their length/breadth ratio. In general the expression of the deflection in the case of central load is of the form (56):

\[ \delta = \frac{\alpha w a^2}{D} \]  

(9.1)

where \( \alpha \) = function of the b/a ratio

\( a \) = shortest dimension of base

\( b \) = longest dimension of base
\( w = \text{applied load} \)

\( D = \text{flexural rigidity } (Eh^3/(1 - \nu^2) \text{ for isotropic materials}) \)

Timoshenko and Woinosky-Krieger (56) give the values for the parameter \( a \) in several edge-constraint situations. These are reproduced in Table 9.2 for the cases of simple support and edge clamping.

**TABLE 9.2**

Tabulation of \( a \) for two edge fixing cases.

<table>
<thead>
<tr>
<th>( b/a )</th>
<th>Clamped edge</th>
<th>Simple support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>5.60 ((x \times 10^{-3}))</td>
<td>11.60 ((x \times 10^{-3}))</td>
</tr>
<tr>
<td>1.2</td>
<td>6.47</td>
<td>13.53</td>
</tr>
<tr>
<td>1.4</td>
<td>6.91</td>
<td>14.84</td>
</tr>
<tr>
<td>1.6</td>
<td>7.12</td>
<td>15.70</td>
</tr>
<tr>
<td>1.8</td>
<td>7.20</td>
<td>16.20</td>
</tr>
<tr>
<td>2.0</td>
<td>7.22</td>
<td>16.51</td>
</tr>
<tr>
<td>( \infty )</td>
<td>7.25</td>
<td>16.95</td>
</tr>
</tbody>
</table>

**9.3.2 Degree of edge constraint**

For the cases within this study the values of \( a \) for both clamped edge and simple support were interpolated from Table 9.2 and are shown in Table 9.3 which also shows the 'stiffening factor' due to the edge clamping. This factor which is a measure of the degree of edge constraint is defined as the ratio of the measured stiffnesses in the situations of clamped edge and simply supported base. For identical plates this ratio is given by:
TABLE 9.3
Factor $\alpha$ for the moulding base geometries

<table>
<thead>
<tr>
<th>Moulding</th>
<th>Base Dimensions (mm)</th>
<th>b/a</th>
<th>$\alpha_{\text{simple}}$</th>
<th>$\alpha_{\text{clamp}}$</th>
<th>Stiffening factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunblest</td>
<td>214x418</td>
<td>1.953</td>
<td>16.44x10^{-3}</td>
<td>7.215x10^{-3}</td>
<td>2.28</td>
</tr>
<tr>
<td>Rat cage</td>
<td>257x447</td>
<td>1.739</td>
<td>16.05</td>
<td>7.176</td>
<td>2.24</td>
</tr>
<tr>
<td>Eurobox</td>
<td>340x540</td>
<td>1.588</td>
<td>15.65</td>
<td>7.111</td>
<td>2.20</td>
</tr>
</tbody>
</table>

$$s = \frac{(w/\delta)_{\text{clamp}}}{(w/\delta)_{\text{simple}}} = \frac{\alpha_{\text{simple}}}{\alpha_{\text{clamp}}}$$  \hspace{1cm} (9.2)

9.4 Tests on Complete Mouldings

The tests on complete mouldings were done with the mouldings supported by a rectangular frame with dimensions similar to those of the base. An aspect of this test is shown in Figure 9.2 for the case of the Eurobox.

In order to assess the effect of the effectiveness of the support another test was done whereby the mouldings were supported in four points (materialised by bolt heads) located near the corners of the base. An aspect of this test is shown for the Sunblest tray in Figure 9.3.

It was verified that the dimensions of the frame itself were not critical for the results because the mouldings have a built-in base support which is schematically shown in Figures 9.4 and 9.5.
FIGURE 9.2: Test with box supported on base

FIGURE 9.3 Test with tray supported on 4 corners
FIGURE 9.4: Base of Sunblest Tray

FIGURE 9.5: Base of "rat cage"
for the Sunblest tray and the rat cage. The geometry of these bases were in fact considered the actual bases for calculation, the remnant being considered already part of the wall.

The 'four point test' as stated before, had only a marginal interest and no additional information was foreseen from it. Furthermore the lack of an immediate simple analytical model for this loading situation rendered the test less interesting than it might appear at the first sight.

The tests were done on the 6 mouldings which were supplied and the scatter of results examined. The loading was done at the displacement rate of 5 mm/min already used with the discs. The slope of the force-deflection trace of the test was determined for small deflections less than half of the thickness.

9.4.1 Tests on Sunblest trays

The shape of the load-deflection curve is similar to that obtained with the circular discs showing the effect of the membrane stresses when the deflection is greater than about half thickness.

The results obtained with these trays are shown in Table 9.4. It is immediately apparent that the type of support does not make a big difference in the results which seems to be due to great stiffening effect of the wall.
TABLE 9.4
Tests with Sunblest trays

<table>
<thead>
<tr>
<th>Test</th>
<th>Tray Number</th>
<th>Slope Results (kN/m)</th>
<th>Average (kN/m)</th>
<th>Std. Deviation (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Four point</td>
<td>4</td>
<td>4.38</td>
<td>4.44</td>
<td>0.27 (6%)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>4.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td>4</td>
<td></td>
<td>4.41</td>
<td>0.15 (3.4%)</td>
</tr>
<tr>
<td>support</td>
<td>5</td>
<td>4.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9.4.2 Tests on rat cages

The comments made for the Sunblest tray apply in this case. The results with these mouldings are shown in Table 9.5. It is evident that the degree of repeatability in this case is smaller than in the previous case which can be attributed to the lesser degree of flatness of the base.
TABLE 9.5

Tests on rat cages

<table>
<thead>
<tr>
<th>Test</th>
<th>Moulding Number</th>
<th>Results (kN/m)</th>
<th>Average (kN/m)</th>
<th>Std. Deviation (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four Point</td>
<td>1</td>
<td>7.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8.51</td>
<td>8.41</td>
<td>1.04 (12.3%)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>9.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge support</td>
<td>1</td>
<td>7.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>8.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9.08</td>
<td>8.90</td>
<td>0.67 (7.5%)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>9.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9.4.3 Tests on Euroboxes

As already mentioned the Euroboxes have a domed base which is schematically shown in section in Figure 9.6. The load deflection curve has consequently a shape different from those already reported on. The curve shows (Figure 9.7) an initial part (up to about 2 mm deflection) which is representative of the peculiar configuration of the base. For a deflection of about 2 mm the curve flattens and a large deflection takes place at a force-deflection rate significantly smaller. This appears to be caused by the 'collapse' of the dome which is transformed into a concave plate whose deflection will
FIGURE 9.6: Section of base of Eurobox

FIGURE 9.7
be greatly governed by membrane forces. The third part of the curve when the force starts rising again corresponds to this last configuration. The results shown in Table 9.6 correspond to slopes measured in the first part of the curve.

Table 9.6
Tests on Euroboxes

<table>
<thead>
<tr>
<th>Test</th>
<th>Box Number</th>
<th>Slope Results (kN/m)</th>
<th>Average (kN/m)</th>
<th>Std. Deviation (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four point</td>
<td>1</td>
<td>2.66</td>
<td>2.25</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.16</td>
<td>2.54</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge support</td>
<td>1</td>
<td>2.93</td>
<td>2.51</td>
<td>2.43</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.19</td>
<td>2.58</td>
<td>2.47</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A fact which is apparent in the tests with these mouldings and also with the other two types is the comparatively poor degree of repeatability of the results, especially in the cases where the bases are far from perfectly flat (Eurobox and rat cage).
9.5 Tests on the Bases of the Mouldings

The bases of some mouldings were sawn off for assessing the degree of edge constraint caused by the walls and wall ribbing. The results obtained are listed in Table 9.7 and show already the effect of edge constraint due to the walls, when compared to those obtained with the complete boxes (Tables 9.4 to 9.6).

### Table 9.7

Tests on moulding bases

<table>
<thead>
<tr>
<th>Moulding Type</th>
<th>Slope (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunblest tray</td>
<td>3.61</td>
</tr>
<tr>
<td>Rat cage</td>
<td>7.93</td>
</tr>
<tr>
<td>Eurobox</td>
<td>1.13</td>
</tr>
</tbody>
</table>

9.6 Degree of Edge Constraint

If the results obtained in the 'edge support' tests where the mouldings were supported around the edge of the base are compared with those obtained with the sawn off bases the degree of edge constraint due to the wall and wall ribbing can be estimated and compared with the theoretical clamped case already referred to in Section 9.3.

The degree of edge restraint, or stiffening factor $s$, was defined in Section 9.3. Thus the previous experimental data with
complete mouldings and sawn off bases allow for the determination of the stiffening effect of the moulding walls which is:

\[ s = \frac{(W/δ)_{\text{moulding}}}{(W/δ)_{\text{base}}} \]

In Table 9.8 are shown the resulting values which are also compared to the values corresponding to the situation of maximum stiffening (clamped edge). It can be observed that the experimental values, as determined, are quite far from the perfectly clamped situation.

**TABLE 9.8**

Experimental Stiffening Factors

<table>
<thead>
<tr>
<th>Moulding Type</th>
<th>Slope (kN/m)</th>
<th>Experimental s</th>
<th>Clamped Edge s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complete Moulding</td>
<td>Base</td>
<td></td>
</tr>
<tr>
<td>Sunblest</td>
<td>4.41</td>
<td>3.61</td>
<td>1.22</td>
</tr>
<tr>
<td>Rat cage</td>
<td>8.90</td>
<td>7.93</td>
<td>1.12</td>
</tr>
<tr>
<td>Eurobox</td>
<td>2.52</td>
<td>1.71</td>
<td>1.47</td>
</tr>
</tbody>
</table>

The more severe restraint takes place with the Euroboxes whilst the rat cage walls cause a somewhat reduced stiffening.
9.7 Tests on Discs Cut from the Bases

9.7.1 Objectives

Discs were cut from the base of the mouldings in order to assess in commercial products effects such as:

a) Influence of the gate
b) Dependence of properties on distance from gate
c) Effect of weld lines

In the discs cut from the Sunblest tray and the rat cage the two first aspects were analysed, while the large four-point gated Euroboxes allowed the examination of the weld line effects.

9.7.2 Weld lines in Eurobox

In the Eurobox mouldings two or probably three different types of welds can be identified as sketched in Figure 9.8: the primary weld line which is the first to occur and results from the encounter of the radial flows from two adjacent gates has a limited length, vanishing when the radial flow is transformed into a roughly parallel flow along the major dimension of the base. The two parallel flows originating from the two pairs of closer gates eventually meet near the edges of the base defining the secondary weld line. The filling finally ends when the converging fronts meet roughly at the centre of the base. Here a very poor quality weld appears due to the low temperature of the melt at that moment and possibly the back pressure of the entrapped air. On observation of the boxes, most of the mouldings showed a very imperfect welding at that point.
FIGURE 9.8: Formation of weld lines on base of Eurobox

I) - primary weld line
II) - secondary weld line
III) - final weld line

9.7.3 Layouts for cutting of discs

The layout of the positioning of the discs cut from the bases is shown in Figure 9.9 for the three different bases.

9.7.4 Flexural test results

The discs, 96 mm in diameter, were tested in the three point support test with the 96 mm support diameter. The results both in terms of slope and flexural stiffness are shown in Table 9.9. For the calculation of the flexural stiffness it was assumed that the lateral contraction ratio was 0.45.
(a) Sunblest tray base

(b) Rat cage base

(c) Eurobox base

FIGURE 9.9
### TABLE 9.9

Three point support data and results

<table>
<thead>
<tr>
<th>Moulding</th>
<th>Disc characterisation</th>
<th>Slope (kN/m)</th>
<th>Stiffness (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Dist from gate (mm)</td>
<td>Thickness (mm)</td>
</tr>
<tr>
<td>Eurobox</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>160</td>
<td>3.26</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>60</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>60</td>
<td>3.23</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>110</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Rat cage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>150</td>
<td>2.14</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>50</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>Sunblest tray</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If the average and standard deviation of the results for each moulding are calculated, it is verified that the small and thicker mouldings (Sunblest tray and rat cage) produce more repeatable results (Table 9.10) whilst those obtained for the bigger Eurobox vary quite a lot from moulding to moulding.
TABLE 9.10
Comparison of repeatability of results (kN/m)

<table>
<thead>
<tr>
<th>Moulding Type</th>
<th>Average Thickness (mm)</th>
<th>Moulding 1</th>
<th>Moulding 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std. Devn.</td>
<td>Average</td>
</tr>
<tr>
<td>Eurobox</td>
<td>2.7</td>
<td>1.305</td>
<td>0.069</td>
</tr>
<tr>
<td>Rat cage</td>
<td>3.2</td>
<td>1.946</td>
<td>0.085</td>
</tr>
<tr>
<td>Sunblest tray</td>
<td>2.1</td>
<td>1.953</td>
<td>0.013</td>
</tr>
</tbody>
</table>

9.8 Analysis of Results

9.8.1 Variation of stiffness with distance from the gate

The results obtained with the rat cages which are the thickest mouldings with a regular base show that the flexural stiffness decreases as the distance from the gate increases (Figure 9.10). The results obtained with the Sunblest trays are rather inconclusive. The rat cage results are in accord with the expected decrease of the orientation with the increasing distance from the gate.

The results with the Eurobox also show a greater stiffness of the discs cut near the gates (2 and 3).

9.8.2 Effect of the weld lines

The discs cut in the zones containing the weld lines (1 and 4 for primary welds, 5 and 9 for secondary, and 7 for the final weld line) did not show any clear indication of their influence on stiffness.
A drop in stiffness was noticeable with respect to the stiffness of discs cut near the gates (2 and 3) however discs without welds (6 and 8) cut far from the gates and between the formation of welds I and II showed a stiffness only marginally higher than those containing a weld line. In that the weld III, the final one, is concerned conclusions do not appear possible because while in one moulding the stiffness was the lowest, in the other it was apparently higher than that of the other discs with welds.
What appears clearer now is that the welds generally have a small influence upon the flexural stiffness for the polypropylene copolymer. A section made through the weld III did not show any discontinuity on the structure.

9.8.3 Observation of structures

The sections on the GW 601M mouldings (rat cage and Sunblest tray) bear some resemblance with those made on discs. Both have sizeable skins especially the Sunblest trays. (Figure 9.11). These skins are highly oriented which shows by the wrinkling after sectioning and that is clearly visible in the microphotographs. The same is observed in the rat cage section. (Figure 9.11) which shows a skin and transcryalline zone bigger than that obtained with the thick discs. The skin is also highly oriented.

The Eurobox section refers to a different grade of material, reportedly stiffer flowing. The skin in this moulding is very small and the transcryalline zone is also not very differentiable from the large core.

9.9 Comparison with Subcomponent Data

The flexural stiffness of the GW 601M mouldings obtained in the three point support test can be compared with data obtained with GW 101 subcomponents as they are nominally the same material.

The stiffness of the thinner moulding (average 1.94 GPa) compares quite well with the stiffness of thin edge gated discs, which
a) Rat cage

b) Sunblest tray

c) Eurobox

FIGURE 9.4
is marginally higher (2.00 GPa). The stiffness of thin CG discs is lower (1.86 GPa).

The thicker rat cages have a flexural stiffness (average 1.94 GPa) a little higher than that observed with thick mouldings (EG or CG), the variation being between 3 and 11% depending on the subcomponents which are taken as reference.

A fact that appears relevant at this moment is that the commercial mouldings have a higher degree of orientation which may be responsible for the higher flexural stiffness.

The thinner subcomponents which were produced represent better the products than the thicker discs. The major difference observed in the thick subcomponents is associated with the comparatively little anisotropy and orientation of the structure in comparison with commercial products.

9.10 Predicting the Stiffness Using Disc Data

The slope of the deflection curve of a rectangular plate is given (see Section 9.3) by

$$\frac{W}{\delta} = \frac{D}{\alpha a^2}$$

If the flexural stiffness is used instead of the flexural rigidity, D, the previous expression becomes:
\[
\frac{W}{\delta} = \frac{Ch^3}{12a^2}
\]

where \( \alpha \) is the factor related to the degree of edge fixing.

a) Eurobox:

For the Eurobox the value of \( \alpha \) for the simple support case is 15.65 \( \times \) 10\(^{-3} \) and the experimentally determined factor of stiffening is 1.47. Thus, the applicable value of \( \alpha \) is

\[
\alpha = 15.65 \times 10^{-3}/1.47
= 10.64 \times 10^{-3}
\]

and as

\[
\begin{align*}
h &= 2.7 \text{ mm} \\
a &= 0.340 \text{ m} \\
C &= 1.44 \text{ GPa}
\end{align*}
\]

(Table 9.10, from data obtained with cut off discs from Moulding 2),
then

\[
\frac{W}{\delta} = \frac{1.44 \times 10^9 \times (2.7 \times 10^{-3})^3}{12 \times 10.64 \times 10^{-3} \times 0.34^2}
= 1.920 \text{ N/m}
\]

The measured slope was 2.52 kN/m which means that the prediction based upon the experimental \( \alpha \) is 24% below. This result suggests that the degree of edge fixing is higher than indicated by the method used
where, for example, the effect of the doming was not eliminated. If the prediction assumes that the base is simply supported and free to move then the predicted slope is

\[
\frac{W}{\delta} = \frac{1.44 \times 10^9 \times 0.0027^3}{12 \times 15.65 \times 10^{-3} \times 0.34^2}
\]

\[= 1.31 \text{ kN/m}\]

and the actual degree of fixing, \( s \), is

\[s = \frac{2.52}{1.31}\]

\[= 1.92 \quad (87\% \text{ clamping})\]

b) Rat cage:

In this case

\[\alpha_{\text{simple}} = 16.05 \times 10^{-3}\]

\[s_{\text{expmtl}} = 1.12\]

\[\therefore \quad \alpha = \frac{16.05 \times 10^{-3}/1.12}{1.12} = 14.28 \times 10^{-3}\]

\[h = 3.2 \text{ mm}\]

\[a = 0.257 \text{ m}\]

\[C = 1.93 \text{ GPa (from Table 9.10)}\]
Thus

\[
\frac{W}{\delta} = \frac{1.93 \times 10^9 \times 0.0032^3}{12 \times 14.28 \times 10^{-3} \times 0.257^2}
\]

\[= 5.59 \times 10^3 \text{ N/m} \]

The measured slope was 8.9 kN/m and thus the error in the prediction is around 37% below, which again means that the experimentally determined factor of stiffening was too low. This is in fact, with respect to the slope of a simply supported base, and considering that

\[
\frac{W}{\delta_{\text{simple}}} = \frac{1.93 \times 10^9 \times 0.0032^3}{12 \times 16.05 \times 10^{-3} \times 0.257^2}
\]

\[= 4.97 \times 10^3 \text{ N/m} , \]

\[s = \frac{8.9}{4.97} \]

\[= 1.79 \quad (80\% \text{ clamping}) \]

\[c). \quad \text{Sunblest tray:} \]

Finally for the smaller moulding

\[\alpha_{\text{simple}} = 16.44 \times 10^{-3} \]

\[s_{\text{expmtl}} = 1.22 \]

\[\therefore \quad \alpha = 16.44 \times 10^{-3}/1.22 = 13.48 \times 10^{-3} \]
Thus

\[
\frac{W}{\delta} = \frac{1.94 \times 10^3 \times 0.0021^3}{12 \times 13.48 \times 10^{-3} \times 0.214^2}
\]

\[= 2425 \text{ N/m}\]

The error with respect to the actual value of 4.41 kN/m is rather high, 45%. Then, calculating the effective stiffening factor as before, it is obtained

\[
\frac{W}{\delta, \text{ simple}} = \frac{1.94 \times 10^3 \times 0.0021^3}{12 \times 16.44 \times 10^{-3} \times 0.214^2}
\]

\[= 1.99 \times 10^3 \text{ N/m}\]

\[s = \frac{4.41}{1.99} = 2.21 \quad (97\% \text{ clamping})\]

This value corresponds to a very high degree of restraining, as the clamped-edge-situation factor is 2.28.

9.11 Some Practical Implications

All the previous results indicate that the degree of edge fixing of the base of the mouldings is fairly high being closer to the clamped edge case than to the simply supported case with the edges free to move. The high stiffening is due not only to the
effect of the wall but also to built-in features such as the doming of the base or its bowing upwards.

For the mouldings now analysed it can be said that the average values for the factor $\alpha$ in the formulae of deflection of rectangular plates are around half the factor for the simply supported case or alternatively 80-90\% of the clamped-edge-case factor.

The degree of repeatability of the commercial mouldings was not comparable to the laboratory subcomponents and the variation from moulding to moulding usually higher than 5\%.

The subcomponent flexural stiffness data generated with mouldings with thickness similar to that of the commercial products are lower than the measured $C$ of discs cut from the boxes. The difference is around 6\% for the longer flow path edge-gated discs and 11\% for the smaller centre-gated discs. However it was interesting to note that data from subcomponents with similar skin/core proportions (thin discs) are closer to the commercial moulding properties. This aspect raises the question of which proportions and processing conditions will be better appropriated for producing representative subcomponents. The limited evidence so far seems to point out more to a flow path/thickness ratio rather than to an absolute thickness criterion.

Nevertheless the results show the potential of the subcomponent method for predicting stiffness of products whose deformation behaviour is mostly dependent of a plate-like element. The route to follow is likely to contain steps such as:
a) Selection of a representative flexural stiffness value decided on the basis of processing conditions, dimensions and thickness of the plate/product.

b) Calculation of an adequate stiffening factor. The right selection appears to lie, for most commercial boxes, near to the clamped edge situation.

c) Utilisation of standard formulae of the Theory of Plates where the flexural rigidity \( D = \frac{Eh^3}{12} (1 - \nu^2) \) is replaced by a function of the flexural stiffness \( C \) \( D = \frac{Ch^3}{12} \).
The conclusions of the work reported herein can be divided into three major areas:

- Assessment of the bending tests used for the characterisation of flexure behaviour of circular discs

- Influence of specimen related aspects on stiffness, and appropriateness of stiffness data for predicting the deformation behaviour of products containing plate-like elements

- Utilisation of instrumented impact tests for assessing the toughness of a material and its dependence on moulding conditions and dimension effects.

a) Assessment of Bending Tests

1. Flexure tests on 'Bi-dimensional' specimens are appropriate for describing the bending behaviour of injection-moulded products where anisotropy effects and biaxial stressing make the analysis by the theory of anisotropic plates very difficult, if not impossible in practical terms.

2. The flexure tests allow for the determination of a flexural stiffness which is a function of the material stiffnesses and lateral contraction ratios \( E/(1-\nu^2) \) in the case of isotropic materials. It can be used as a datum in the design for stiffness of plate-like elements.
3. A new flexure test designated as three point support test, was introduced, and proved to be promising for subcomponents of circular shape. The test correlates well with other established tests in the case of isotropic materials and has the advantage of overcoming the intrinsic lack of perfect flatness of injection-moulded plates, by producing a linear test trace as from the beginning of loading.

In fact, a shortcoming of the centre loading and the three line tests is their traces showing always a variable initial zone corresponding to the settling of the specimens. Thus the reproducible linearity of the three point support test trace makes this test potentially applicable in programmes involving automatic systems of testing.

4. The flexure tests are sensitive to the overall orientation of the unfilled polypropylene mouldings. However the expected anisotropy in specimens such as the edge-gated disc is not detectable by the three line test which is supposed to be sensitive to the variation of stiffness with the direction in the plane of flat mouldings.

5. The measured flexural stiffness of circular injection-moulded specimens depends on the type of state of stress which is imposed upon them. When this type of data is used for predicting the deflection of plates subjected to a full biaxial state of stress the data from the three line test, which has
been favoured for some time in the literature, gives a figure of about 15% less than the measured value. The predictions based upon the three point support test data are within the order of magnitude of the experimental error and approximations made on modelling the tests.

b) Material and Moulding Effects

6. Significant variation of mechanical properties of end-products are likely within different batches of the same raw material grade.

7. In the case of the materials used, the flexural stiffness of injection-moulded subcomponents depends on processing conditions and thickness. In thin mouldings (thickness below 2 mm) it appears mostly controlled by the variation of the skin thickness, while in thicker mouldings a combination of skin thickness and core structure will be the relevant factor. However the proportions of skin and core fractions are very different in the two cases. The observed variation of the flexural stiffness within a supposedly typical range of processing conditions was of the order of 5 to 7% of the average value of the flexural stiffness.

8. The effects of gating on properties are mainly on direction and degree of orientation produced. In the case of subcomponents containing a weld line they showed some anisotropy of flexural
stiffness. However this was not determined by the possible weakening effect of the weld line, but by orientation derived effects. The influence of the weld is likely to be important only when the weld is of very poor quality.

9. In commercial mouldings the degree of orientation and the flexural stiffness are higher than those obtained in laboratory subcomponents of similar thickness. This being attributable to larger flow lengths and faster production cycles. Nevertheless it is possible to estimate within reasonable limits the deflection of large plates using data obtained from edge-gated or centre-gated laboratory subcomponents.

c) Impact and Toughness Aspects

10. The impact behaviour of subcomponents is more dependent on the thickness than on the size or on the processing conditions. Thinner mouldings are more brittle.

11. For a given material a brittle/ductile transition of the impact behaviour can be observed by comparing the curves of variation of the total energy absorbed in the test and the energy up to the maximum-force-in-the-test point. At temperatures above the transition these curves diverge, and below it are parallel and fairly close to each other.

12. Singularities in the mouldings such as weld lines and gate points are very weak points on impact if struck directly. However if
the impact is offset, the toughness is independent of the type of gating. Thus the offset impact is useful for assessing overall impact behaviour but the designer must treat the singularities individually.

13. As a final conclusion, the use of subcomponents (or pseudo-mouldings) appears to have great potential for describing the deflection behaviour of injection mouldings products, however, non-conventional methods of test and new material data have to be considered.
RECOMMENDATIONS FOR FURTHER WORK

1. An immediate point arising from the observations done with commercial mouldings is the study of the size effect on the flexural stiffness. This work was partly started during this programme and a mould was designed and partially manufactured.

2. The influence of Poisson's ratio on stiffness was suggested in the work. A more systematic study of the dependence of this datum on processing conditions and moulding characteristics is likely to increase the accuracy of the prediction of deformation especially when using models involving assumptions of the value of the ratio.

3. The study of glass-fibre-reinforced mouldings is already being done by other workers, however the study of the behaviour of plates containing some kind of ribbing or holes (the current commercial practice) apparently has not yet been undertaken. Also a study of deflection of box-type products should be envisaged in order to establish more precisely the degree of edge constraint on the base.

4. Finally it appears that the study of subcomponents as a means of analysing the twisting properties of plates (or shear properties) should receive immediate attention, especially as the
torsional behaviour of trays and shallow boxes is commercially important but difficult to predict.
REFERENCES


APPENDIX 1

DERIVATION OF EQUATION OF LARGE DEFORMATIONS OF

A SIMPLY SUPPORTED PLATE

a) Detail calculations
b) Computer programme for determining the coefficients of the equation
c) List of results for typical values of the Possion ratio
d) Computer programme for predicting the force-deflection curve of a circular plate
e) Results for the case of polypropylene discs
(a) DETAIL CALCULATIONS
1. Derivation of equation (3.25)

By integrating once equation (3.24):

\[
\frac{d}{dr} \left( \frac{1}{r} \frac{df}{dr} + \frac{d^2 f}{dr^2} \right) = Ar + Br \log \frac{r}{R} + C*r \log^2 \frac{r}{R} \tag{3.24}
\]

results

\[
\frac{1}{r} \frac{df}{dr} + \frac{d^2 f}{dr^2} = \frac{Ar^2}{2} + \frac{Br^2}{2} \left( \log \frac{r}{R} - \frac{1}{2} \right) + \frac{C* r^2}{4} \left( 2 \log^2 \frac{r}{R} - 2 \log \frac{r}{R} + 1 \right) + C_1
\]

where \( C_1 \) is a constant of integration.

(Asterisks (*) are used with \( C, D \) and \( E \) for distinguishing from the symbols for flexural stiffness, flexural rigidity, and Young's modulus, respectively).

Multiplying both members of (a) by \( r \), one gets

\[
\frac{df}{dr} + r \frac{d^2 f}{dr^2} = \frac{Ar^3}{2} + \frac{Br^3}{2} \left( \log \frac{r}{R} - \frac{1}{2} \right) + \frac{C* r^3}{4} \left( 2 \log^2 \frac{r}{R} - 2 \log \frac{r}{R} + 1 \right) + C_1 \tag{b}
\]

But

\[
\frac{df}{dr} + r \frac{d^2 f}{dr^2} = \frac{d}{dr} \left( r \frac{df}{dr} \right)
\]

Thus

\[
r \frac{df}{dr} = \int \left( \frac{A}{2} - \frac{B}{4} + \frac{C*}{4} \right) r^3 + \left( \frac{B}{2} - \frac{C*}{2} \right) \frac{r^3}{r} \log \frac{r}{R} + \frac{C*}{2} \frac{r^3}{r} \log \frac{r}{R} + C_1 \frac{r}{r} \right) \, dr
\]

\[
+ \frac{C*}{2} \frac{r^3}{r} \log \frac{r}{R} + C_1 r
\]

(c)
By making

\[ D^* = \frac{A}{2} - \frac{B}{4} + \frac{C^*}{4} \]  \hspace{1cm} (d)

and

\[ E^* = \frac{B}{2} - \frac{C^*}{2} \]  \hspace{1cm} (e)

it is obtained

\[ r \frac{df}{dr} = \int (D^* r^3 + E^* r^3 \log \frac{r}{R} + \frac{C^*}{2} r^3 \log^2 \frac{r}{R} + C_1 r) \, dr \]  \hspace{1cm} (f)

and, after calculation of the integral

\[ r \frac{df}{dr} = \frac{D^*}{4} r^4 + \frac{E^*}{4} r^4 \left( \log \frac{r}{R} - \frac{1}{4} \right) + \frac{C^*}{4} r^4 \left( \frac{1}{16} - \frac{\log \frac{r}{R}}{4} \right) \]

\[ + \frac{\log^2 \frac{r}{R}}{2} \right) + \frac{C_1 r^2}{2} + C_2 \]  \hspace{1cm} (g)

where \( C_2 \) is a second constant of integration.

Then, by dividing both members of (g) by \( r \), it results

\[ \frac{df}{dr} = \frac{D^* r^3}{4} + \frac{E^*}{4} r^3 \left( \log \frac{r}{R} - \frac{1}{4} \right) + \frac{C^*}{4} r^3 \left( \frac{1}{16} - \frac{\log \frac{r}{R}}{4} \right) \]

\[ + \frac{\log^2 \frac{r}{R}}{2} \right) + \frac{C_1 r}{2} + \frac{C_2}{r} \]  \hspace{1cm} (3.25)
2) **Calculation of the constants of integration $C_1$ and $C_2$**

The boundary conditions being

i) $(\frac{1}{r} \frac{df}{dr})_{r=\infty} = 0$

ii) $(\frac{df}{dr})_{r=0} = 0$

it results after making $r=R$ and $r=0$ in the corresponding equations obtained from (3.25)

\[
\frac{D^*}{4} R^2 + \frac{E^*}{4} R^2 (\frac{1}{4}) + \frac{C^*}{4} R^2 (\frac{1}{16}) + \frac{C_1}{2} + \frac{C_2}{R} = 0 \tag{h}
\]

and

\[
\frac{D^*}{4} 0 + \frac{E^*}{4} 0 + \ldots + \frac{C_2}{0} = 0 \tag{i}
\]

Thus the second condition (i) leads to

\[C_2 = 0\]

and (h) to

\[C_1 = \frac{R^2}{2} (\frac{E^*}{4} - \frac{D^*}{4} - \frac{C^*}{16}) \tag{j}\]
3) **Derivation of equation (3.27)**

It is started with the calculation of the functions \(X\) and \(\phi\) in equation (3.26):

\[
\int_0^R X \frac{d\delta}{dr} r \, dr = 0 \quad (3.26)
\]

\(X\) is given (62) by

\[
X = D \frac{d}{dr} (\Delta \delta) - \psi - \frac{1}{r} \frac{df}{dr} \frac{d\Delta \delta}{dr} \quad (k)
\]

As

\[
\Delta \delta = \frac{1}{r} \frac{d\delta}{dr} + \frac{d^2 \delta}{dr^2}
\]

and

\[
\delta = \delta_0 (1 - \frac{r^2}{R^2} + 2 \frac{U r^2}{R^2} \log \frac{r}{R}) \quad (3.22)
\]

it results after making

\[
H = \frac{2 \delta_0}{R^2} \quad (4)
\]

\[
\frac{d\delta}{dr} = H r (U - 1 + 2 U \log \frac{r}{R}) \quad (m)
\]

and

\[
\frac{d^2 \delta}{dr^2} = H (3 U - 1 + 2 U \log \frac{r}{R}) \quad (n)
\]
Then

\[ \Delta \delta = \frac{1}{r} H \left( U - 1 + 2U \log \frac{r}{R} \right) + H \left( 3U - 1 + 2U \log \frac{r}{R} \right) \]

\[ = H \left( 4U - 2 + 4U \log \frac{r}{R} \right) \]

and by differentiation

\[ \frac{d}{dr} (\Delta \delta) = H \frac{4U}{r} \]  

(0)

Therefore, recalling the expressions for \( \frac{df}{dr} \) (3.25), and \( \frac{d\delta}{dr} \) (m), equation (k) becomes after considering that (62)

\[ \psi = \frac{W}{2\pi r} \]

\[ X = DH \frac{4U}{r} - \frac{W}{2\pi r} - \frac{1}{r} \left( \frac{D^* r^3}{4} + \frac{E^*}{4} r^3 \log \frac{r}{R} - \frac{E^*}{16} r^3 + \frac{C^*}{64} r^3 \right) \]

\[ - \frac{C^*}{16} r^3 \log \frac{r}{R} \]

\[ + \frac{C^*}{8} r^2 \log^2 \frac{r}{R} + \frac{C_1}{2} (Hr \left( U - 1 + 2U \log \frac{r}{R} \right)) \]

The simplification of this expression leads successively to

\[ X = \frac{A_0}{r} - \left( \frac{C_1}{2} (U-1) r + \left( \frac{D^*}{4} - \frac{E^*}{16} + \frac{C^*}{64} \right) (U-1) r^3 + C_1 U r \log \frac{r}{R} \right) \]

\[ + \left( \frac{E^*}{4} - \frac{C^*}{16} (U-1) \right) r^3 \log \frac{r}{R} \]

\[ + \left( \frac{E^*}{4} - \frac{C^*}{16} (U-1) \right) r^3 \log^2 \frac{r}{R} + \frac{C^*}{8} 2U r^3 \log^3 \frac{r}{R} \]

\[ + \left( \frac{C^*}{8} (U-1) + \left( \frac{E^*}{4} - \frac{C^*}{16} \right) 2U \right) r^3 \log^2 \frac{r}{R} + \frac{C^*}{8} 2U r^3 \log^3 \frac{r}{R} \]
The constants $A_i$ ($i = 0, 1, \ldots, 6$) are given in the main test.

Now, considering that (62)

$$\phi = (1 - \frac{r^2}{R^2} + 2U \frac{r^2}{R^2} \log \frac{r}{R})$$

it is obtained

$$\frac{d\phi}{dr} = \frac{2r}{R^2}(U - 1 + 2U \log \frac{r}{R})$$

and, finally, by replacing (p) and (q) into (k)

$$\int_0^R \left( \frac{A_0}{r} - A_1 r + \ldots + A_6 r^3 \log^3 \frac{r}{R} \right) \frac{2r}{R^2}(U - 1 + 2U \log \frac{r}{R}) r \, dr = 0$$

By calculating the expression under the sign of integral it is finally obtained (equation 3.27)

$$\frac{2}{R^2} \int_0^R \left( B_0 r + B_1 r^3 + B_2 r^5 + B_3 r \log \frac{r}{R} + B_4 r^3 \log \frac{r}{R} + B_5 r^3 \log^2 \frac{r}{R} + B_6 r^5 \log \frac{r}{R} + B_7 r^5 \log^2 \frac{r}{R} + B_8 r^5 \log^3 \frac{r}{R} + B_9 r^5 \log^4 \frac{r}{R} \right) \, dr$$

(3.27)
where the constants $B_i$ ($i = 0, 1, \ldots, 9$) are given in the main test.

4) **Solution of the definite integral (3.28)**

A solution of the integral $\int r^m \log^n r \, dr$ is given by (65)

$$\int r^m \log^n r \, dr = \frac{n! (-1)^n}{m+1} r^{m+1} \sum_{i=0}^{n} \frac{(- \log r)^i}{i! (m+1)^{n-i}};$$

Therefore the definite integral will be

$$\int_0^R r^m \log^n r \, dr = \frac{n! (-1)^n}{m+1} \left[ R^{m+1} \left( \frac{1}{0! (m+1)^n} + \sum_{i=1}^{n} \frac{(- \log R)^i}{i! (m+1)^{n-i}} \right) \right] - o^{m+1} (...) \tag{r}$$

All the terms of the series in equation (r) but the first are null ($\log 1 = 0$). Then, the solution of the definite integral becomes

$$\int_0^R r^m \log^n r \, dr = \frac{n! (-1)^n R^{m+1}}{(m+1)^{n+1}}$$  \hspace{1cm} (3.28)

5) **Derivation of equation (3.30)**

The integration of equation (3.27) using the solution (3.28) leads to
\[
\frac{2}{\R^2} \left[ B_0 \frac{\R^2}{2} + B_1 \frac{\R^4}{4} + B_2 \frac{\R^6}{6} + B_3 \left( -\frac{\R^2}{4} \right) + B_4 \left( -\frac{\R^4}{16} \right) \right] + B_5 \frac{\R^4}{2^5} + B_6 \left( -\frac{\R^6}{6^2} \right) + B_7 \left( \frac{\R^6}{3 \times 6^2} \right) + B_8 \left( -\frac{\R^6}{6^3} \right) + B_9 \frac{\R^6}{9 \times 6^2} = 0
\]

and, after rearranging

\[
B_0 - \frac{B_3}{3} - \frac{B_1}{2} \R^2 - \frac{B_2}{3} \R^4 \frac{B_4}{8} R^2 + \frac{B_5}{16} R^2 + \frac{B_6}{16} R^4 + B_7 \frac{R^4}{54} - \frac{B_8}{108} R^4 + \frac{B_9}{162} R^4 = 0
\]

\( B_1, B_4 \) and \( B_5 \) are functions of \( \frac{R^2}{2} \), and all the \( B_i \) are in turn functions of \( H = \frac{2 \delta_0}{R^2} \) and \( Y = \frac{2 \delta_0 E h}{R^4} \).

For calculation purposes it is convenient to re-define the coefficients \( A_i \) and \( B_i \) independently of \( R, H \) and \( Y \). This was done for the organisation of the computer programme in the next section.

Thus if the expression containing the coefficients \( B_i \) (but \( B_0 \) and \( B_3 \)) independently of \( H \) and \( Y \) is called \( B^* \), the equation (s) becomes

\[
B_0 - \frac{B_3}{2} + R^4 H Y B^* = 0
\]
and by replacing backwards the several functions by their values:

\[-4 U D H + \frac{W}{Z\pi} + R^4 H Y B^* = 0\]

Noting that \(D = \frac{Eh^3}{12 (1 - \nu^2)}\),

\[-\frac{4 Eh^3}{12 (1 - \nu^2)} \frac{2\delta_o}{R^2} U + \frac{W}{Z\pi} + R^4 \left(-\frac{2\delta_o^2 Eh}{R^4}\right) \frac{2\delta_o}{R^2} B^* = 0\]

Multiplying both members by \(\frac{3(1 - \nu^2)R^2}{2U Eh^4}\), simplifying and rearranging

\[
\frac{\delta_o}{H} + \delta(1 - \nu^2) B^* \left(\frac{\delta_o}{H}\right)^3 = \frac{3(1 - \nu^2)}{4U \pi H} \frac{WR^2}{Eh^4} \tag{3.29}
\]

or, in a simplified form

\[
\frac{\delta_o}{H} + \alpha \left(\frac{\delta_o}{H}\right)^3 = \beta \frac{WR^2}{Eh^4} \tag{3.30}
\]
(b) BASIC COMPUTER PROGRAMME
100 ! A.S.D.POUZADA - PROGRAMME TITLE > PLATE - BASIC
110 !
120 ! THIS PROGRAMME CALCULATES THE COEFFICIENTS OF THE EQUATION
130 ! FOR LARGE DEFLECTIONS OF A SIMPLY SUPPORTED CIRCULAR PLATE
140 ! SUBJECTED TO A CONCENTRATED CENTRAL LOAD
150 !
160 PRINT ' You have two options:
170 PRINT ' (S) Equation for a given value of Poisson ratio'
180 PRINT ' (M) Equations for a range of values of u'
190 PRINT
200 !
210 Z=0
220 INPUT 'Which option (S/M) ',A$
230 IF A$='M' THEN 260
240 INPUT 'N = ',N
250 GOTO 290
260 INPUT 'Range of values of u (min, max,increment)',N1,N2,S
270 !
280 FOR N=N1 TO N2 STEP S
290 U=(1+N)/(3+N)
300 A=(U-1)^2
310 B=4*U*(U-1)
320 C=4*U*U
330 D=A/2-B/4+C/4
340 E=B/2-C/2
350 Cl=E/4-D-C/16
360 A1=Cl/2*(U-1)
370 A2=(D/4-E/16+C/64)*(U-1)
380 A3=Cl*U
390 A4=U*(D/2+E/8-C/32)-E/4+C/16
400 A5=(-C/8+E*U/2)
410 A6=C*U/4
420 Y=U-1
430 B1=-A1*Y
440 B2=-A2*Y
450 B4=-2*A1*U-A3*Y
460 B5=-2*A3*U
470 B6=-2*A2*U-A4*Y
480 B7=-2*A4*U-A5*Y
490 B8=-2*A5*U-A6*Y
500 B9=-2*A6*U
500  \[ B_9 = -2A_6U \]
510  \[ B = B_1/4 + B_2/3 - B_4/16 + B_5/32 - B_6/18 + B_7/108 + B_8/162 \]
520  \[ A = 6(1-N^2)B/U \]
530  \[ B = 3(1-N^2)/4U/PI \]
540  \[ I \]
550  \[ \text{IF } Z=1 \text{ THEN 640} \]
560  \[ \text{IF } A$='S' \text{ THEN 580} \]
570  \[ Z=1 \]
580  \[ \text{PRINTLIN(5)} \]
590  \[ \text{PRINT ' Equation of max deflection, } Wo, \text{ of a centrally loaded disc' } \]
600  \[ \text{PRINT ' of radius, } a, \text{ and thickness, } h, ' \]
610  \[ \text{PRINT ' considering the membrane stresses' } \]
620  \[ \text{PRINTLIN(3)} \]
630  \[ \text{IF } A$='M' \text{ THEN 650} \]
640  \[ \text{PRINT LIN(2)} \]
650  \[ \text{PRINT ' Poisson ratio } = 'N \]
660  \[ \text{PRINT} \]
670  \[ \text{PRINTUSING ' } Wo/h + .##### * (Wo/h)^3 = .##### *P*a^2/E/h^4', \]
\[ A,B \]
680  \[ \text{IF } A$='S' \text{ THEN 700} \]
690  \[ \text{NEXT N} \]
700  \[ \text{PRINTLIN(7)} \]
710  \[ \text{I} \]
720  \[ \text{PRINT' For re-running the programme type EXECUTE'} \]
730  \[ \text{END} \]
(c) LIST OF EQUATIONS FOR TYPICAL VALUES OF $\nu$
You have two options:
(S) Equation for a given value of Poisson ratio
(M) Equations for a range of values of \( u \)

Which option (S/M) S
\[ N = 0.45 \]

Equation of max deflection, \( W_o \), of a centrally loaded disc of radius, \( a \), and thickness, \( h \), considering the membrane stresses

\[
\frac{W_o}{h} + 0.2262 \left( \frac{W_o}{h} \right)^3 = 0.4530 \left( \frac{P}{a} \right)^2 \left( \frac{a^2}{E_h} \right)^4
\]

For re-running the programme type EXECUTE

> EXECUTE

You have two options:
(S) Equation for a given value of Poisson ratio
(M) Equations for a range of values of \( u \)

Which option (S/M) M
Range of values of \( u \) (min, max, increment): 0.3, 0.39, 0.01
Equation of max deflection, \( W_0 \), of a centrally loaded disc of radius, \( a \), and thickness, \( h \), considering the membrane stresses.

\[
\begin{align*}
\text{Poisson ratio} &= 0.3 \\
\frac{W_0}{h} + 0.2722 \times (\frac{W_0}{h})^3 &= 0.5515 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.31 \\
\frac{W_0}{h} + 0.2693 \times (\frac{W_0}{h})^3 &= 0.5452 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.32 \\
\frac{W_0}{h} + 0.2664 \times (\frac{W_0}{h})^3 &= 0.5390 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.33 \\
\frac{W_0}{h} + 0.2635 \times (\frac{W_0}{h})^3 &= 0.5326 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.34 \\
\frac{W_0}{h} + 0.2605 \times (\frac{W_0}{h})^3 &= 0.5263 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.35 \\
\frac{W_0}{h} + 0.2575 \times (\frac{W_0}{h})^3 &= 0.5198 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.36 \\
\frac{W_0}{h} + 0.2545 \times (\frac{W_0}{h})^3 &= 0.5134 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.37 \\
\frac{W_0}{h} + 0.2515 \times (\frac{W_0}{h})^3 &= 0.5069 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.38 \\
\frac{W_0}{h} + 0.2484 \times (\frac{W_0}{h})^3 &= 0.5003 \times \frac{P \times a^2}{E \times h^4} \\

\text{Poisson ratio} &= 0.39 \\
\frac{W_0}{h} + 0.2453 \times (\frac{W_0}{h})^3 &= 0.4937 \times \frac{P \times a^2}{E \times h^4}
\end{align*}
\]
Poisson ratio = .4

\( \frac{W_0}{h} + .2422 \times (\frac{W_0}{h})^3 = .4870 \times P^a2/E/h^4 \)

Poisson ratio = .41

\( \frac{W_0}{h} + .2391 \times (\frac{W_0}{h})^3 = .4803 \times P^a2/E/h^4 \)

Poisson ratio = .42

\( \frac{W_0}{h} + .2359 \times (\frac{W_0}{h})^3 = .4735 \times P^a2/E/h^4 \)

Poisson ratio = .43

\( \frac{W_0}{h} + .2327 \times (\frac{W_0}{h})^3 = .4667 \times P^a2/E/h^4 \)

Poisson ratio = .44

\( \frac{W_0}{h} + .2295 \times (\frac{W_0}{h})^3 = .4599 \times P^a2/E/h^4 \)

Poisson ratio = .45

\( \frac{W_0}{h} + .2262 \times (\frac{W_0}{h})^3 = .4530 \times P^a2/E/h^4 \)

Poisson ratio = .46

\( \frac{W_0}{h} + .2229 \times (\frac{W_0}{h})^3 = .4460 \times P^a2/E/h^4 \)

Poisson ratio = .47

\( \frac{W_0}{h} + .2196 \times (\frac{W_0}{h})^3 = .4391 \times P^a2/E/h^4 \)

Poisson ratio = .48

\( \frac{W_0}{h} + .2163 \times (\frac{W_0}{h})^3 = .4320 \times P^a2/E/h^4 \)

Poisson ratio = .49

\( \frac{W_0}{h} + .2129 \times (\frac{W_0}{h})^3 = .4249 \times P^a2/E/h^4 \)

Poisson ratio = .5

\( \frac{W_0}{h} + .2095 \times (\frac{W_0}{h})^3 = .4178 \times P^a2/E/h^4 \)
d) COMPUTER PROGRAMME FOR PREDICTING
THE FORCE-DEFLECTION CURVE OF A
CIRCULAR PLATE
100 ! A.S.D.POUZADA - PROGRAMME TITLE > MEMBRANE - BASICV
110 !
120 ! THIS PROGRAMME CALCULATES THE DEFLECTIONS OF A CIRCULAR PLATE
130 ! SUBJECTED TO A CONCENTRATED CENTRAL LOAD CONSIDERING
140 ! a) THAT MEMBRANE STRESSES ARE NEGLECTED
150 ! b) MEMBRANE STRESSES
160 !
170 DIM E(200), M(200), P(200)
180 PRINTLIN(5)
190 PRINT 'Poisson ratio = 0.45'
200 !
210 INPUT 'Maximum load (N) = '; Q
220 INPUT 'Load point interval (N) = '; S
230 INPUT 'Diameter (mm) = '; D
240 R = D * 1E-3 / 2
250 INPUT 'Thickness (mm) = '; H
260 H = H * 1E-3
270 INPUT 'Flex Modulus (GPa) = '; E
280 E = E * 1E9
290 !
300 DEFFNE(P) = 0.568 * R * R / E / H ^ 4 * P
310 DEFFNM(X) = X + 0.226 * X ^ 3 - FNE(P)
320 !
330 ! CALCULATION AND PRINTOUT OF RELATIVE DEFLECTIONS
340 !
350 PRINTLIN(5)
360 PRINT
370 PRINT
380 PRINT
390 PRINT
400 PRINT
410 PRINT
420 PRINT
430 I = 0
440 FOR P = S TO Q STEP S
450 I = I + 1
460 P(I) = P
470 IF FNE(P) > = 1.5 THEN 690
480 A = 0
490 B = FNE(P)
500 IF (FNM(A) * FNM(B) <= 0 THEN 520
265

510 GOTO 1130
520 IF ((B-A)/2)<=1E-6 THEN 590
530 C=(B+A)/2
540 IF (FNM(C)*FN(A))<=0 THEN 570
550 A=C
560 GOTO 520
570 B=C
580 GOTO 520
590 C=(B+A)/2
600 E(I)=FNE(P)
610 M(I)=C
620 X=(E(I)-M(I))/E(I)*100
630 IF (INT(I/4)-I/4)<0 THEN 670
640 PRINTUSING '###.##  ###.##  ###.##  #.## %',
   P(I),E(I),M(I),X
650 IF (INT(I/20)-I/20)<0 THEN 670
660 PRINT
670 NEXT P
680 GOTO 730
690 I=I-1
700 PRINTLIN(2)
710 PRINT 'Programme designed for limiting max defl to 1.5*h'
720 PRINT
730 PRINT'
740 !
750 ! PLOT OF THE SHAPE OF THE CURVES USING THE TERMINAL
760 !
770 PRINTLIN(2)
780 INPUT 'SCALE FACTOR (<1.1 FOR D=100)',X
790 F=X/E(I)
800 PRINTLIN(3)
810 PRINT 'FORCE (N)'
820 PRINT
830 FOR J=I TO 1 STEP -2
840 IF (INT(J/5)-J/5)<0 THEN 860
850 PRINTUSING'###.##',P(J):
860 IF INT(E(J)-M(J))*F*70)<1 THEN 890
870 PRINTTAB(M(J)*F*70);'M';SPA((E(J)-M(J))*F*70);'E'
880 GOTO 900
890 PRINTTAB(E(J)*F*70);'E'
900 NEXT J
910 ' !
920 FOR J=1 TO INT(E(I)*F*70)+1
930 PRINT ' - ;
940 NEXT J
950 PRINT
960 FOR J=0 TO E(I) STEP .1
970 PRINTTAB(J*F*70);'!';
980 NEXT J
990 PRINT
1000 '!
1010 K=E(I)/.1
1020 IF K>7 THEN 1070
1030 FOR J=0 TO E(I) STEP .1
1040 PRINTTAB(J*F*70);J;
1050 NEXT J
1060 GOTO 1100
1070 FOR J=0 TO E(I) STEP .2
1080 PRINTTAB(J*F*70);J;
1090 NEXT J
1100 PRINT
1110 PRINT
1120 PRINTTAB(E(I)*F*60);'W/h'
1130 '!
1140 PRINTLIN(5)
1150 END
e) RESULTS FOR THE CASE OF

POLYPROPYLENE DISCS
Poisson ratio = 0.45
Maximum load (N) = 5
Load point interval (N) = .1
Diameter (mm) = 113
Thickness (mm) = 1.5
Flex Modulus (GPa) = 1.8

<table>
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<th>FORCE (N)</th>
<th>RELATIVE DEFLECTION ( W/h )</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>ELASTIC</td>
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<tr>
<td>0.40</td>
<td>.0796</td>
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<tr>
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<td>.2388</td>
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<td>.3184</td>
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<td>.3980</td>
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<td>2.40</td>
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<td>2.80</td>
<td>.5571</td>
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<tr>
<td>3.20</td>
<td>.6367</td>
</tr>
<tr>
<td>3.60</td>
<td>.7163</td>
</tr>
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<td>4.00</td>
<td>.7959</td>
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<td>4.40</td>
<td>.8755</td>
</tr>
<tr>
<td>4.80</td>
<td>.9351</td>
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FORCE (N)

5.0

4.0

3.0

2.0

1.0

E E E

E E E

E E E

E E E

E E E

E E E

E E E

E E E

E E E

E E E

E E E

0 .2 .4 .6 .8 w/h
Poisson ratio = 0.45  
Maximum load (N) = 50  
Load point interval (N) = 1  
Diameter (mm) = 113  
Thickness (mm) = 3  
Flex Modulus (GPa) = 1.8

<table>
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<tr>
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<td>0.3394</td>
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<td>(.2)</td>
<td>(.3)</td>
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</table>

\(W/h\)
APPENDIX 2

DRAWINGS OF TEST RIGS FOR THE INSTRON

1. Three line and centre loading test rigs
2. Three point support test rig
3. Box and crate testing rig

(See drawings in back cover folder)
APPENDIX 3

COMPUTER PROGRAMME FOR

IMPACT TEST DATA
10 1 READ #1,1
20 1 PRINT #1:1(*) ,Data(*)
30  OPTIONBASE 1
40  DIM Y[25],X2S[25],Data(5,10,8),N(5)
50  COM Ra(30,5),Rb(30,4),Avg(5,6),Dev(5,6)
60  INPUT "Date?",Date$
70  ASSIGN #2 TO "PRCE"
80  READ #2,1
90  READ #2;N,Ra(*),Rb(*)  ! Processing records
100  PRINTER IS 16
110  PRINT PAGE.
120  GO$UB Space
130  PRINT "THIS PROGRAMME COMPILES AND DISPLAYS DATA GENERATED IN"
140  PRINT "INSTRUMENTED IMPACT TESTING AT I.C.I."
150  PRINT
160  Mat$="Propathene Gm 101"
170  PRINT "MATERIAL : " ; Mat$
180  PRINT "DO YOU WANT ?"
190  PRINT " INPUT DATA ? (1)"
200  PRINT " READ DATA ? (2)"
210  PRINT " READ RESULTS ? (3)"
220  PRINT " STOP ? (4)"
230  INPUT X
240  IF X=4 THEN End
250  PRINT PAGE
260  !
270  PRINT "PROCESSING AND DATAFILE RECORDS"
280  PRINT "-----------------------------"
290  PRINT " IMPACT DATA ON CIRCULAR DISCS"
300  PRINT " Moulding Temperatures
310  PRINT " Disc moulding Data File"
320  PRINT " Mould temperature Injection moulded speed Type Dia Thick file no.
330  PRINT "-----------------------------"
340  PRINT 
350  PRINT
360  FOR I=1 TO M
370  PRINT USING 380:Kc$(I,1),Ra(I,3),Ra(I,4),Rb$(I,3),Rb$(I,2),Ra(I,1),Ra(I,2),Rb$(I,4),I
380  IMAGE X,6A,3X,3D,4X,2D,4A,4A,3X,11A,X,3D,3X,D,DD,4X,5A,2X,2D
390  NEXT I
400  PRINT "-----------------------------"
410  PRINT
420  IF X<>1 THEN 740
430  Z$="Y"
440  INPUT "Want odd new processing data? (Y/N)" ,Z$
450  IF Z$<"Y" THEN 740
460  !
470  M=M+1
480  PRINT PAGE
490  INPUT "Date of moulding, e.g. 1ST. 50",H$(i,1)
500  INPUT "Disc type - CentreGated;Edge Gated;DoubleGated",Jb$(i,2)
510 INPUT "Disc Diameter (mm)";Ra(1,1)
520 INPUT "Disc Thickness (mm)";Ra(1,2)
530 INPUT "Injection Temperature";Ra(1,3)
540 INPUT "Mold Temperature";Ra(1,4)
550 INPUT "Injection Speed - Fast; Slow";Rs$(1,3)
560 INPUT "Name of Datafile";Rs$(1,4)
570 PRINT PAGE
580 PRINT "Date of moulding";Rs$(1,1)
590 PRINT "Disc type";Rs$(1,2)
600 PRINT "Disc Diameter (mm)";Ra(1,1)
610 PRINT "Disc Thickness (mm)";Ra(1,2)
620 PRINT "Inject Temperature";Ra(1,3)
630 PRINT "Mould Temperature";Ra(1,4)
640 PRINT "Injection Speed";Rs$(1,3)
650 PRINT "Name of Datafile";Rs$(1,4)
660 PRINT
670 INPUT "All OK? (Y/N)";Z$
680 IF Z$<"Y" THEN 480
690 PRINT "Create Datafile and press CONT"
700 PAUSE
710 READ #2,1
720 PRINT #2,1;M,Ra(*),Rs$(*)
730 GOTO 270
740 INPUT "Which Test Temperature?";R
750 ASSIGN #1 TO Rs$(1,4)
760 READ #1,1
770 READ #1;R(*),Date(*)
780 ON X GOTO Input,Read,Results,End
790 !
800 Input: 1
810 !
820 PRINT "Which Test Temperature?"
830 INPUT T
840 I=(20+1)/10+1
850 PRINT "How many samples?"
860 INPUT N(1)
870 PRINT
880 PRINT "Input Data Set";I;"C"
890 PRINT
900 FOR J=1 TO I(1)
910 PRINT "Sample";J
920 INPUT Data(I,J,1),Data(I,J,2),Data(I,J,3),Data(I,J,4),Data(I,J,5),Data(I,J,6),Data(I,J,7),Data(I,J,8)
930 GOTO 1670
940 !
950 GRAPHICS
960 CSIZE 0.7,5,8/15
970 SCALL -5,100,-5,5
980 SCALE 0,3
990 LABEL 1,0
1000 MOVE -5,0
1010 LCWK 1
1020 LABEL Data(I,J,1);Data(I,J,2);Data(I,J,3);Data(I,J,4);Data(I,J,5)
1030 ;Data(I,J,6);Data(I,J,7);Data(I,J,8)
1040 SLEEP
1050 PAUSE
1060 GCLEAR
1070 !
1080 FOR K=1 TO T
1090 PRINT USING 1110;Data(I,K,1);Data(I,K,2);Data(I,K,3);Data(I,K,4)
1100 ;Data(I,K,5);Data(I,K,6);Data(I,K,7);Data(I,K,8)
1110 NEXT K
1120 IMAGE DDD,X,3D,X,4D ,X,DD.DD,X,DD.D,X,DD.D,X,DD.D,X,D
1130 Z$="Y"
1140 IF Z$<>"Y" THEN 910
1150 NEXT J
1160 Z$="Y"
1170 INPUT "Other test temperature? (Y/N)" ,Z$
1180 IF Z$<>"Y" THEN 100
1190 GOTO Input
1200 !
1210 Data: !
1220 !
1230 READ #1,1
1240 READ #1;N(*),Data(*)
1250 PRINT "SYSTEM BUSY"
1260 FOR I=1 TO 5
1270 !
1280 ! Statistical calculations
1290 !
1300 FOR K=2 TO 8
1310 Avg(I,K)=0
1320 Dev(I,K)=0
1330 FOR J=1 TO N(I)
1340 Avg(I,K)=Avg(I,K)+Data(I,J,K)
1350 Dev(I,K)=Lev(I,K)+Data(I,J,K)^2
1360 NEXT J
1370 Avg(I,K)=Avg(I,K)/N(I)
1380 Dev(I,K)=SQR((Dev(I,K)-Avg(I,K)^2*N(I))/(N(I)-1))
1390 NEXT K
1400 NEXT I
1410 RETURN
1420 !
1430 Read: !
1440 !
1450 GOSUB Data
1460 G=16
1470 INPUT "PRINTER IS ?",Q
1480 PRINT "PRINTER IS Q"
1490 GOSUB Space
1500 PRINT Date$
1510 FOR I=1 TO 5
1520 IF Data(I,1,1)=0 THEN 1860
1530 GOSUB Space
1540 PRINT "MATERIAL: "; Mat$  
1550 PRINT
1560 PRINT
1570 PRINT RT$(F,2); " injection moulded disc: "; Ra(R,1); " mm Dia."; Ra(R,2); " mm Thick"
1580 PRINT
1590 PRINT "PROCESSING CONDITIONS"
1600 PRINT
1610 PRINT "Melt Temp Mould Temp Inj Speed"
1620 PRINT
1630 PRINT USING 1640; Ra(R,3), Ra(R,4), Rb$(R,3)
1640 IMAGE 3X, 3D, 9X, 2D, 5X, 4A
1650 PRINT
1660 T=10*1-30
1670 PRINT
1680 PRINT "TESTING RESULTS AT ";T;"C"
1690 PRINT
1700 PRINT "SAMPLE GRAD P/YF P/YD P/YE FL FE F"
1710 PRINT "NO N/mm N mm N mm N mm T YF $"
1720 PRINT
1730 FOR J=1 TO N(I)
1740 PRINT USING 1770; Data(I,J,1); Data(I,J,2); Data(I,J,3); Data(I,J,4); Data(I,J,5); Data(I,J,6); Data(I,J,7)
1750 NEXT J
1760 PRINT
1770 IMAGE 3X, 3D, 5X, 3D, 3X, 5X, 3D, 3X, 3X, 3D, 3X, 3D, 5X, 3D, 5X
1780 IMAGE 3X, 3D, 5X, 3D, 3X, 3D, 3X, 3D, 3X, 3D, 3X, 3D, 3X, 3D
1790 IMAGE 3X, 3D, 5X, 3D, 3X, 3D, 3X, 3D, 3X, 3D, 3X, 3D, 3X, 3D
1800 PRINT "Average"
1810 PRINT USING 1780; Avg(I,2), Avg(I,3), Avg(I,4), Avg(I,5), Avg(I,6), Avg(I,7)
1820 PRINT
1830 PRINT "Standard Deviation"
1840 PRINT USING 1750; Dev(I,2), Dev(I,3), Dev(I,4), Dev(I,5), Dev(I,6), Dev(I,7)
1850 GOSUB Space
1860 NEXT I
1870 PRINT "PRESS Ctrl"
1880 PAUSE
1890 GOTO 100
1900 I
1910 !
1920 Results: !
1930 I
1940 GOSUB Data
1950 Q=16
1960 INPUT "PRINTER IS ?",I
1970 PRINTER IS Q
1980 GOSUB Space
1990 PRINT "INSTRUMENTED IMPACT FALLING WEIGHT"
2000 PRINT
RESULTS

MATERIAL : PROPATHEN GEM 101

PRINT Rb$(R,2); injection moulded disc ";Ra(R,1);"mm Diz, ";Ra
a(R,2);"mm Thick"

PRINT PROCESSING CONDITIONS

PRINT " Melt Temp Mould Temp Inj Speed" 

PRINT USING 1640;Ra(R,3),Ra(R,4),Rb$(R,3)

PRINT GRAD P/YF P/YD P/YE FD FE T

PRINT "N/mm N mm Nm mm Nm T"

FOR X=1 TO 5

T=-30+X*10

IF Data(X,1,1)=0 THEN 2250

PRINT USING 1780;Avg(X,2),Avg(X,3),Avg(X,4),Avg(X,5),Avg(X,6),Avg(X,7)

PRINT USING 1790;Dev(X,2),Dev(X,3),Dev(X,4),Dev(X,5),Dev(X,6),Dev(X,7)

PRINT "Press CONI" 

PAUSE 

PRINT "Do you want a plot?"

INPUT W$ 

IF W$="N" THEN Plot

GO TO 100

Plot: :!

GSCREEN

PRINT PAGE 

PRINT "WHICH PLOT?"

PRINT "Gradient (2)"

PRINT "Yield Force(3)"

PRINT "Yield Displ(4)"

PRINT "Yield Energy(5)"

PRINT "Break Displ(6)"

PRINT "Break Energy(7)"

PRINT "Ductile Energy(8)"

PRINT "None (1)"

INPUT L

GO TO L GCOCO 100,2510,2550,2650,2730,2870,2940,2600
! Gradien
2520 Xmin=100
2530 Xmax=500
2540 Yint=50
2550 Y$="GRAD (K/mm)"
2560 Y1$="Gradient"
2570 GOTO 3020
2580 ! Yield Force
2590 Xmin=0
2600 Xmax=4500
2610 Yint=500
2620 Y$="F/YF (N)"
2630 Y1$="Yield Force"
2640 GOTO 3020
2650 ! Yield Displacement!
2660 Xmin=0
2670 Xmax=36
2680 Yint=4
2690 Y1$="Deform at Yield"
2700 MOVE 30,Ymax+Yint/2
2710 Y$="P/YE (mm)"
2720 GOTO 3020
2730 ! Yield Energy
2740 Xmin=0
2750 Xmax=45
2760 Yint=5
2770 Y$="P/YL (Nm)"
2780 Y1$="Yield Energy"
2790 GOTO 3020
2800 ! Ductile Energy
2810 Xmin=0
2820 Xmax=25
2830 Yint=5
2840 Y$="D E (Nm)"
2850 Y1$="Ductile Energy"
2860 GOTO 3020
2870 ! Fracture Displacement
2880 Xmin=0
2890 Xmax=36
2900 Yint=4
2910 Y$="FD (mm)"
2920 Y1$="Deform at Break"
2930 GOTO 3020
2940 ! Fracture Energy
2950 Xmin=0
2960 Xmax=45
2970 Yint=5
2980 Y$="FE (Nm)"
2990 Y1$="Fract Energy"
3000 GOTO 3020
3010 1 Plot sequence
3020 1 CSIZE 3.3, 9/15
3030 GCLEAR
3040 FRAME
3050 SCALE -40, 40, Ymin-Yint, Ymax+Yint
3060 AXES 10, Yint, -30, Ymin, 10, Yint
3070 MOVE -37, Ymax-Yint/2
3080 DEG
3090 LDIR 90
3100 LABEL Y$
3110$ MOVE 20, Ymin-Yint*3/4
3120 LDIR 0
3130 LORG 5
3140 LABEL "test Temp"
3150 MOVE 10, Ymax-Yint/2
3160 LABEL kat$
3170$ MOVE 10, Ymax-Yint
3180 Y2$=Y1$ &" vs. Temp"
3190 LABEL Y2$
3200$ MOVE 10, Ymax-Yint*3/2
3210 LABEL "LOT &RB$(R, 4)
3220 FOR I=1 TO 5
3230 T=-30+10*I
3240 MOVE T, Ymin-Yint/4
3250 LABEL T
3260 NEXT I
3270 LORG 4
3280 FOR I=1 TO 8
3290 Y=Ymin+Yint*(I-1)
3300 MOVE -33, Y
3310 NEXT I
3320 N$="*
3330 N$="-
3340 FOR J=1 TO 5
3350 T=-30+10*J
3360 LORG 5
3370 IF Z>6 THEN 3430
3380 AVG(J, Z)=AVG(J, 7)-AVG(J, 5)
3390 DEV(J, Z)=0
3400 MOVE T, AVG(J, Z)
3410 LABEL N$
3420$ MOVE T, AVG(J, Z)+DEV(J, Z)
3430 LABEL N$
3440$ MOVE T, AVG(J, Z)-DEV(J, Z)
3450 LORG 5
3460 LABEL N
3510 NEXT J
3520 BEEP
3530 PAUSL
3540 PRINT PAGE
3550 PRINT "Want a hard copy?"
3560 Z$="Y"
3570 INPUT Z$
3580 IF Z$<>"Y" THEN Plot
3590 DUMP GRAPHICS
3600 GCLLAF
3610 PRINTk IS 0
3620 PRINT
3630 PRINT Date$
3640 GOSUE Space
3650 PRINTk IS 16
3660 GoTo 2280
3670 Space: !
3680 PRINT
3690 PRINT
3700 PRINT ":"
3710 PRINT
3720 PRINT
3730 RETURN
3740 EnG: !
3750 PRINTk IS 16
3760 PRINT PAGE
3770 PRINT "Programme terminated"
3780 PAUSE
3790 END
APPENDIX 4

INSTRUMENTED IMPACT TEST RESULTS
TESTS ON PP GWM 101 (BATCH I)
**INSTRUMENTED IMPACT FALLING WEIGHT**

**MATERIAL:** PROPATHENE GWM 101

### LOT D RESULTS

<table>
<thead>
<tr>
<th>GRAD</th>
<th>P/YF N/mm</th>
<th>P/YD mm</th>
<th>P/YE Nm</th>
<th>FD mm</th>
<th>FE Nm</th>
<th>TEST TEMP</th>
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<tbody>
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<td>247</td>
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Note: Lot D = El B₁

### LOT E RESULTS

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<th>P/YD mm</th>
<th>P/YE Nm</th>
<th>FD mm</th>
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<th>TEST TEMP</th>
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Note: Lot E = El A₁
## INSTRUMENTED IMPACT FALLING WEIGHT

**MATERIAL:** PROPATHENE GWM 101

### LOT A

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<th>P/YD mm</th>
<th>P/YE Nm</th>
<th>FD mm</th>
<th>FE Nm</th>
<th>TEST TEMP</th>
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**Note:** Lot A ≡ El D₁

### LOT H

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**Note:** Lot H ≡ El C₁
INSTRUMENTED IMPACT FALLING WEIGHT

MATERIAL: PROPATHENE GWM 101

LOT B
RESULTS

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Note: Lot B = E3 D₁

LOT C
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Note: Lot C = E3 C₁
INSTRUMENTED IMPACT FALLING WEIGHT

MATERIAL: PROPATHENE GWM 101

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Note: Log G ≡ E3 B₁

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Note: Lot F ≡ E3 A₁
TESTS ON PP GWM 101 (BATCH II)
### Instrumed Impact Falling Weight

**Results**

**Material:** Propathene GM 161

Edge Gated injection moulded disc 115 mm Dia, 1.97 mm Thick

**Processing Conditions**

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*(Methanol)*

Edge Gated injection moulded disc 115 mm Dia, 2.92 mm Thick

**Processing Conditions**

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(Dry)

Edge Gated injection moulded disc 115 mm Dia, 2.97 mm Thick

**Processing Conditions**

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# Instrumented Impact Falling Weight

## RESULTS

**MATERIAL: PROPYLENE GMR. 101**

CentreGated injection moulded disc 101 mm Dia, 1.62 mm Thick

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CentreGated injection moulded disc 101 mm Dia, 1.63 mm Thick

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INSTRUMENTED IMPACT FALLING WEIGHT

RESULTS

MATERIAL: PROPATHANE GW 161

Double-Gated injection moulded disc 89 mm Dia, 3.2 mm Thick

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Double-Gated injection moulded disc 89 mm Dia, 3.13 mm Thick

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### Centre-Gated Injection Moulded Disc 101 mm Dia, 3.1 mm Thick

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#### Centre-Gated Injection Moulded Disc 101 mm Dia, 3.05 mm Thick

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#### Results

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Dry: (Dry) 48 hours: (48 hours) Methanol: (methanol) 295 days: (295 days)
A - to fit FRM load cell
1/2" UNF

B - to fit loading nose
1/2" UNF

A.S.D. POUZADA
PhD project
10-11-1981

INSTITUTE OF POLYMER TECHNOLOGY

CRATE TESTER
LOAD.G NOSE EXT.N.
INSTRON BASE

DRAWING 3.1

CRATE TESTER
GENERAL VIEW

1- FRM LOAD CELL
2- LOADING NOSE EXT.n
3- LOADING NOSE
4- 4"x2" TUBULAR BASE
5- SUPPORT PLATE
6- CRATE (rat cage)
SUPPORT BASE

INSTITUTE OF POLYMER TECH.  DEC. 80

DRAWING 2.2  A.S.D. POUZADA
115 mm RING

102 mm RING

A.S.D. POUZADA
PhD PROJECT
12.12.80

DIMS IN MILLIMETRES (mm)
MATERIAL: Mild Steel
TREATMENT: None
FINISH: Natural

SUPPORT RINGS

INSTITUTE OF POLYMER TECHNOLOGY

DRAWING No. 23
LOADING NOSE CENTERING RING

DIMENSIONS IN MILLIMETERS (mm)

A.S.D. POUZADA
PH.D PROJECT
15.12.80

DRAWING NO. 2.4

MATERIAL : MILD STEEL
TREATMENT : None
FINISH : Natural

INSTITUTE OF POLYMER TECHNOLOGY 1:1
6 Threaded holes equispaced
SUPPORT WITH T-SLOT.
(1 OFF)
BOTTOM SUPPORT BASE
(2 OFF)

LINE SUPPORT
(3 OFF)

MATERIAL - Mild Steel
SPECIFY - None
FINISH - Natural

INSTRON ATTACHMENT
FOR 3-LINE TESTING

A. S. D. POUZADA
Ph.D PROJECT
June 80

DRAWING NO. 1.2.

INSTITUTE OF POLYMER TECHNOLOGY
- EXTENSION BAR -

UNF 1/2"

2.5 deep groove

UNF 1/2"

- ADAPTOR TO EXT.n BAR
and LOAD BAR SUPPORT -

HALF SECTION A+A

MATERIAL - Mod Steel
SPECIF -
TREATMENT - None
FINISH - Natural
INSTRON ATTACHMENT FOR 3-LINE TESTING

INSTITUTE OF POLYMER TECHNOLOGY