Optical techniques applied to the study of building materials and to the inspection of civil structures

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OPTICAL TECHNIQUES APPLIED
TO THE STUDY OF BUILDING MATERIALS AND
TO THE INSPECTION OF CIVIL STRUCTURES

by

Mauro Facchini

A Doctoral Thesis
submitted in partial fulfillment of
the requirements for the award of
Doctor of Philosophy
of
Loughborough University of Technology
U.K.

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To my family
This work has been carried out at the Laser and Applied Optics Laboratories, Diagnostics and Reliability Sector, Industry and Environment Unit, Institute for Systems Engineering and Informatics (ISEI), Joint Research Centre, European Commission, Ispra (VA) Italy under an EC grant cat.22.
Abstract

Where the evaluation of the mechanical properties and behaviour of building materials is concerned, there is still not a universally accepted solution for making such measurements.

Optical diagnostic techniques are particularly attractive for a non-destructive evaluation of a surface's state and the detection of incipient damage. Non-contact, high precision measurements and full-field of observation are features that can bring enormous advantages in experimental tests.

The aim of the author has been to investigate the applicability of optical techniques to the evaluation of building structures and to the characterization of building materials. The observation of fracture propagation, the full-field evaluation of deformations, the estimation of surface micro-changes, the early detection of defects and the retrieval of shape are here discussed and accompanied by tests and experimental results.

The innovation of this work is not simply derived from the field of application but also from some contribution to the development of optical architectures, techniques and procedures.

Attention has been paid, during these investigations, to the development of some digital routines for fringe pattern interpretation, to the design of new optical configurations and to the improvement of techniques of analysis.
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INTRODUCTION

Preamble

The experimental evaluation of characteristics of materials and reliability of structures has been for a long time a fundamental task. In the field of mechanical and structural engineering, structures require periodic inspection to verify their safety condition maintenance and to plan their repair.

The performance of materials has also to be characterized precisely in order to provide for the optimal and most functional planning solutions. Moreover, experimental methods are in some cases used to check theoretical calculations or to refine mathematical models, while in others can be the only way to solve a problem.

Concerning with the measurement of the mechanical properties and behaviour of building materials (units and mortars), there is still not a universally accepted solution for making such measurements.

The measurement of deformations under loading conditions is usually obtained in mechanical tests by means of strain gauges glued directly to the specimen, or by displacement transducers connected at points of interest. However, this approach presents some drawbacks: both methods provide values averaged over the evaluated area only and it is often not possible to assume with certainty that their presence do not affect the measurements. This influence is especially dramatic when small-size specimens are studied and for this reason NDT (non-destructive-testing) techniques are increasingly used for material characterization and structural evaluation.

NDT methods come from different branches of Physics: Acoustics (acoustic emission and ultrasounds), Thermology (thermal emission), Electro-Magnetism (Magnetic inspection, Eddy currents), Microwave physics (X-Rays, Tomography), Chemistry (Penetrant inspection) and Optics (interferometry). Among these techniques optical methods are considered particularly promising. In addition to their high sensitivity, they allow a full-field analysis of the inspected area without any need to be physically in contact with the surface or very close to it.
State of the art

Optical techniques have been the subject of many studies and, consequently, many advances have been made. Since 1950 new optical methods have been invented and developed and a few have emerged as practical tools in the broader field of experimental mechanics. After the advent of the laser, in the early sixties, many interferometric methods became available and increasingly found their way in many branches of research and technology, ranging from heavy industrial production to medicine applications. Holography, Moiré methods, Speckle techniques and Photoelasticity were among the most exploited and studied novelties to be applied in experimental mechanics. They were applied to many fields such as optical testing, shape measurement, displacement and strain inspection, vibration evaluation and flow analysis.

The fringe patterns obtained by optical techniques are graphically descriptive of the qualitative behaviour of the surface under evaluation. However, the advent of digital computers has allowed the creation of new tools providing for processing quantitative evaluation. Routines that at first were long time consuming and needed the input of a considerable amount of manual data, became more and more rapid with the improvement in computer power and with the exploitation of new automatic techniques for fringe interpretation.

Most of the experiments have been performed inside optical laboratories provided with special tools such as vibration-free tables, controlled heating and humidity and reduced ambient illumination. However, applications of these methods in-the-field has been recently envisaged: the portability of ESPI systems and the possible use of pulsed lasers allows the application of optical interferometric techniques on actual structures, directly in-situ.

In civil engineering the use of optical techniques has been attempted. Grating-based techniques and stereo-photogrammetry have been preferred for the study of large scale building structures, where a global view of the inspected surface can give interesting information about local displacements and failure processes. Other interferometric techniques, (Holography, Speckle techniques ,... ) have been preferred where the evaluation area is usually more restricted and the results are required with great precision. Due to their difficult implementation and their high sensitivity to ambient conditions, however, the application of these last techniques has not yet reached a wide acceptance and popularity among structural specialists.
Aims and Objectives

The aim of the author is to investigate the applicability of optical interferometric techniques to the evaluation of building structures and to the characterization of building materials. Structural engineers, at first sceptical about the utility of these methods to their working field, revealed an increasing interest as the research progressed and themselves began to propose new possibilities of application. This research continues where some other groups have stopped and includes the presentation of innovative applications and interesting results.

The determination of the behaviour of building materials has been the object of studies for a long time. Dealing with so many different masonry materials used as units, in the past and present times, and so many mortar compositions, the measurement and evaluation of strength and deformability of these requires standardization. Such parameters as codified dimensions, surface treatments, conditioning and rate of loading need to be reliably measured and accurately controlled in order to achieve consistent results. The CEN-TC125 Committee has since 1988, for example, been debating about compressive stress tests and a common solution is far away from being reached. The literature contains many inconsistent results obtained independently from different institutes by following different testing procedures and different standards.

Some NDT techniques have been applied in this field: acoustic emission, ultrasound analysis and computerized tomography are just some examples of adopted methods. The objective of this work is to demonstrate the effectiveness of some optical techniques in the analysis of building structures and in the characterization of building materials, in order to encourage their use as alternative solutions. An extensive investigation of some optical methods and improvements to their application in experiencing measurements has been conducted by the author.

Optical methods have, usually, good resolution: accurate quantitative data concerning the mechanical characteristics of some building materials can be retrieved, e.g. Young's Modulus and Poisson's Ratio can in this way be evaluated very precisely. These numbers can be useful in the field of civil engineering when creating new projects or when using FEM (Finite Element Modeling) tools. Moreover the knowledge of these results may be helpful in some cases for attempting a comparison between different materials. From the accuracy and sensitivity of the obtained results a catalogue of all the material units employed in construction could be attempted.
Optical methods allow a full-field observation of the surface under inspection: the strain distribution, crack formation and propagation in structures can be easily observed. The formation of cracks can be controlled in real-time: a precise estimation of the fissure's propagation, which is invisible to the naked eye, can be done. A real knowledge of the complete strain state of surfaces could be interesting for the evaluation of the safety of structures; it could be useful for predicting dramatic failures and avoiding, in this way, catastrophic consequences. For this reason, an application of these optical techniques in the seismic field could, probably, give new information about the behaviour of stressed buildings and some new ideas about optimal construction design.

The innovation of the thesis is not simply derived from the field of application but also from some contribution to the development of optical architectures, techniques and procedures. Some attention has been paid to the development of some digital routines for fringe pattern interpretation. The main contributions are especially in the field of automatic retrieval of displacement maps and in the evaluation of strain distributions directly from interferograms. Appropriate optical configurations have been created for the experiments: portable systems for ESPI experiments to be performed directly in the field, ESPI systems using optical fibres, systems having a geometry allowing a complete in-plane acquisition of interferograms, optical set-ups for surface survey using speckle techniques, optical solutions in the application of the moiré technique.

Structure of the thesis

In chapter 1 an overview of traditional tools applied to experimental measurements in the field of building materials and civil engineering is briefly presented. The reason for the increasing application of NDT in this field is highlighted. The advantages and the drawbacks of using optical techniques are presented and a short introduction to some of them is included. For every method the principles are basically presented; a comparison between their performances will be useful in order to understand the particular fields where the application of each one should be more suitable. As a conclusion ESPI, moiré and Speckle Correlation techniques are selected as tools to be used for the experiments.

Most common methods for fringe pattern interpretation are briefly presented. They range from semi-manual routines (based on fringe counting) to completely automated procedures (based on phase-shifting or Fourier Transform methods). Some consideration about image processing and digital filtering is treated as well.
In chapter 2, some preliminary applications of optical interferometric techniques are presented. The wide area of applications is demonstrated by some examples and the possibility of use in non-typical or less exploited areas is highlighted. This chapter has the purpose to provide familiarization with the experimental application of optical techniques in order to understand their enormous possibilities without forgetting their limitations.

Chapter 3 is devoted to the presentation of some new features introduced by the author. New optical techniques, new optical arrangements and some new fringe analysis tools are presented. Some of these find application in chapter 4, where some optical techniques are applied to the study of building materials and structures.

Two optical techniques have been improved and applied to some experiments: the optical speckle decorrelation and the real-time ESPI stationary vibration analysis.

Some new optical arrangements have been conceived: five portable systems for ESPI analysis, a system for complete ESPI in-plane analysis and some fibre-optics based systems.

Some software has been developed for the interpretation of interferometric patterns: an unwrapping program, a software for calculating derivatives of displacement directly from interferograms, a method of calculating derivatives directly from the bidimensional FFT of an image, a "virtual" strain gauge.

In chapter 4, the attention is focused on some applications of optical techniques to the field of building materials and structures.

A first section is devoted to the description and utilization of optical techniques used for surface shape retrieval in civil engineering and architecture: photogrammetry; profilometry based on the time of pulse-flight; stripe or grating projection.

Afterwards two interferometric techniques for deformation analysis are discussed: ESPI and moiré interferometry. ESPI is a powerful tool for efficient non-destructive testing involving the evaluation of micro-deformations and providing a full-field visualization of surface behaviour. In this work, it is applied in some experimental measurements where a high sensitivity to displacements (micrometers) is necessary. Specimens having surface area of several cm² are considered under compressive or flexural tests. The distribution of strain is observed and some quantitative mechanical properties (Young's Modulus or Poisson's Ratio) are measured with high accuracy. The drawbacks related with the use of traditional transducers are demonstrated and, as a consequence, their application is critically reviewed.
Mechanical properties of building materials are evaluated in the elastic zone of the compression test, when the deformations involved are small (some microstrains); different materials are tested and, in some cases, a comparison of performance is attempted. The formation of cracks and the propagation of fissures can be observed as well, also when they are invisible to the naked eye.

Some masonry joints have been studied for verifying that the formation and propagation of cracks depend not only on the mutual influence of the different deformability of materials, but also on the bond existing between bricks and mortar. Some solution to this problem has been attempted by analyzing interferometric patterns obtained by compressing small-scale walls.

Some applications of the moiré technique are presented. It has been used on real-scale objects such as a concrete column subjected to a periodic bending. The mechanical deformations, the location of cracks and their propagation are observed.

High-resolution moiré gratings (down to 240 lines/mm) have been used for inspecting specimens having surfaces of interest of some cm² and showing small deformations; results are compared with those obtained with the ESPI technique, with a discussion of limitations and drawbacks.

An optical technique based on the decorrelation analysis of the speckle pattern coming from a surface is discussed: it is shown how changes in the speckle pattern can be related to some modifications in the surface characteristics. This method of this technique has found application in the analysis of salt efflorescence of stone surfaces under the action of aging or watering.

Optical measurement techniques are not only applicable to constitutive units or assemblies of building structures, but also to the inspection of some ornamental parts. A section is devoted to applications of ESPI to the non-destructive inspection of decorations or frescoes. This application could be of particular interest in the field of restoration and conservation of works of art.

As a conclusion chapter 5 contains a discussion about the application of optical techniques in the field of civil engineering. A comparison with traditional techniques is here summarized and advantages or drawbacks are highlighted. Finally possible envisaged developments for the future are presented and new open areas of application are proposed.
Chapter I

Review of experimental measurements in civil engineering and introduction of optical methods

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1.1. The role of experimental techniques in material characterization and in performance evaluation of structures in civil engineering.

The role of experimental techniques in the design, construction, performance evaluation, repair and rehabilitation of civil structures is of primary importance [1]. In fact, due to great advances in material technology, new materials more reliable and having higher performances have been conceived. Their structural behaviour is sometimes essentially unknown and extensive experimental techniques should be envisaged for their characterization.

Research in this field may be broadly subdivided in two main categories:
- characterization of material behaviour
- evaluation of structural performance.

1.1.1. Characterization of the mechanical behaviour of units of building materials

Many factors contribute to the performance and durability of building materials: a list of the most influencing factors is presented in table 1.1.[2] When studying building materials, many characteristics can be investigated by experimental means: specific gravity, porosity, permeability, thermal properties (dilatation, conducibility), chemical and petrographic properties, mechanical properties. For the study of every single characteristic there are some standards to be respected for the shape of the specimens, the testing machines to be used, the experimental procedure to be followed, the method of interpretation and classification of results to be adopted [3,4,5].

The knowledge of deformation parameters has great importance for the designer because it allows an estimation of the response, in terms of deformation, that can be expected from the structure as function of change in the applied loading distribution.

The determination of resistance limits of materials makes possible a tentative evaluation of the margin of safety possessed by the structure.

Specimens may have many different shapes ranging from cylindrical to cubic, generally depending on the quantity that must be evaluated.

The bench tensile testing machine must fulfil certain requirements depending on the applied experimental procedure. For example, the speed of the cross-head and the increasing rate of the applied load are important parameters that may be different from one test to the other.

Most common experimental procedures for the evaluation of mechanical characteristics are: tests of compression, tensile stress, flexure and impact resistance.
<table>
<thead>
<tr>
<th>degradation factor</th>
<th>degradation process</th>
<th>type of damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>mechanical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wind</td>
<td>fatigue</td>
<td>deformation</td>
</tr>
<tr>
<td>long term loading</td>
<td>micro-cracking</td>
<td>deformation</td>
</tr>
<tr>
<td>settlements</td>
<td>imposed deformation</td>
<td>deformation</td>
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<td>erosion</td>
<td>loss of material</td>
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<tr>
<td>running water</td>
<td>deposition</td>
<td>soiling</td>
</tr>
<tr>
<td>aerosols</td>
<td>cavitiation</td>
<td>loss of material</td>
</tr>
<tr>
<td>wind with sand</td>
<td>deposition</td>
<td>soiling</td>
</tr>
<tr>
<td>servicing</td>
<td>erosion</td>
<td>loss of material</td>
</tr>
<tr>
<td>touching</td>
<td>wastage</td>
<td>loss of material</td>
</tr>
<tr>
<td>impact</td>
<td>cracking</td>
<td>failure</td>
</tr>
<tr>
<td>graffiti</td>
<td>cleaning</td>
<td>loss of appearance</td>
</tr>
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<td>scratching</td>
<td>wastage</td>
<td>loss of material</td>
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<tr>
<td>walking</td>
<td>wastage</td>
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<tr>
<td>physical</td>
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<td></td>
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<tr>
<td>frost/thaw</td>
<td>ice formation</td>
<td>scaling</td>
</tr>
<tr>
<td>temperature rise</td>
<td>expansion</td>
<td>deformation</td>
</tr>
<tr>
<td>temperature fall</td>
<td>shrinking</td>
<td>deformation</td>
</tr>
<tr>
<td>humidity rise</td>
<td>swelling</td>
<td>deformation</td>
</tr>
<tr>
<td>humidity fall</td>
<td>shrinking</td>
<td>deformation</td>
</tr>
<tr>
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<td>hydration</td>
<td>powdering, scaling</td>
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<td>crystallisation</td>
<td>efflorescence</td>
</tr>
<tr>
<td>chemical</td>
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<td></td>
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<td>sulphate</td>
<td>ettringite</td>
<td>cracking</td>
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<tr>
<td>smoke gas</td>
<td>thaumasite</td>
<td>cracking</td>
</tr>
<tr>
<td>acid rain</td>
<td>corrosion</td>
<td>sulphate</td>
</tr>
<tr>
<td>salt</td>
<td>leaching</td>
<td>disintegration</td>
</tr>
<tr>
<td>carbon dioxide</td>
<td>crystallisation</td>
<td>efflorescence</td>
</tr>
<tr>
<td>soft water</td>
<td>carbonation</td>
<td>scaling</td>
</tr>
<tr>
<td>biological</td>
<td></td>
<td></td>
</tr>
<tr>
<td>moss</td>
<td>growth</td>
<td>loss of appearance</td>
</tr>
<tr>
<td>alga</td>
<td>growth</td>
<td>loss of appearance</td>
</tr>
<tr>
<td>climbers</td>
<td>growing roots</td>
<td>disintegration</td>
</tr>
<tr>
<td>micro-organisms</td>
<td>acids/leaching</td>
<td>disintegration</td>
</tr>
</tbody>
</table>

**TABLE 1.1: Most common degradation processes in building materials**

In compression tests the specimen must be crushed between two plates that, in some cases, are connected to the cross-head through a coupling joint.
In tensile tests the specimen must be very well tightened between the grips but care must be taken into account in order to avoid unwanted breaking.

In flexural tests the specimen, usually being rectangular, is loaded by a knife shaped head and supported at its extremities by two cylinders. In these tests the deformation of the specimen can be controlled continuously by using some measuring tools that will be introduced later in this chapter.

In impact tests the specimen's resistance is evaluated by hitting it with steel bullets.

1.1.1.1. Traditional experimental tools

Mechanical analogue comparators, reaching displacement resolutions down to the micrometric range, were initially used by the experimentalists.

Nowadays they have been almost completely replaced with electronic instruments, and three main groups can be considered: strain gauges, variable resistance potentiometers and variable inductance displacement transducers [6]. A short description is included here, as they will be mentioned later in chapter 4.

a) Strain gauges

The electrical -resistance strain gauge [6] is the most common choice for the great majority of experimentalists: it is attached directly to the specimen surface at the area of interest and continuously gives information about the deformation. A good strain gauge is required to be independent from temperature and time, to show a linear response and to have a good sensitivity (down to $10^{-6}$). The three basic types of electrical-resistance strain gauges are constituted by metal-foils, semiconductors and liquid metals.

Because they have to be fixed to the surface area under inspection, they produce a reinforcement that, in some cases, can influence the strain in the local area around the gauge. A strain gauge pasted to a specimen's surface is shown in fig. 1.1.

b) Variable resistance potentiometers

Variable resistance potentiometers [6] usually contain a wire-wound component and the resolution is limited by the wire size used but this limitation can be overcome if resistance films are used.

They are displacement sensors: their working principle is based on the fact that any displacement of the object under inspection produces a change in the resistance value.

c) Variable-inductance displacement transducers

Linear displacements can be measured with linear variable differential transformers (LVDTs) [6].
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Fig. 1.1: Strain gauge pasted to a brick specimen

Fig. 1.2: LVDTs used for evaluating the displacement of brick specimens
This kind of displacement transducer consists of three wire coils wound on an insulated circular shell which contains a movable magnetic core: displacement of the core produces a linear output voltage over the linear range of motion of the transducer. Some LVDTs applied to compressed brick specimens are shown in fig. 1.2.

*d) Clamp in Place Displacement Transducers.*

The most accurate devices for local deformation measurements are, probably, the Clamp in Place Displacement Transducers (CPDT): they usually include electrical-resistance transducers and are coupled to points of interest through knife shaped connections. They have been successfully used in the measurement of masonry materials deformations, because they can be applied also on small specimens, with a very small reference point on the surface [7]. Unfortunately, despite the good results, they are not commonly employed due to their high cost. The use of CPDTs is shown in fig. 1.3a and in fig. 1.3b where they are combined with four LVDTs.

**1.1.1.2. Criticism of traditional experimental tools**

The use of traditional experimental tools shows some advantages such as reliability, simplicity, availability, relative low cost and sufficiently good precision. However some intrinsic drawbacks can not be avoided:

- they give only measurements averaged over the area of interest
- they are disturbed by electro-magnetic fields and influenced by electronic noise
- they greatly depend on ambient conditions (temperature, humidity, ...) and require frequent recalibration
- they are characterized by a maximum strain that can be applied
- for those attached directly to the surface, unwanted modifications of the specimen's behaviour may be introduced
- for those not attached to the surface, very stable mountings must be used.

**1.1.2. Characterization of the mechanical behaviour of building structures**

In the field of civil engineering a periodical inspection of structures can bring some benefits [8]:

- early warnings of severe damages
- reliability control
- necessity of reinforcement or restoration
- effectiveness of reinforcements or restorations completed so far

Building structures are in general characterized by the presence of elements with mechanical characteristics that often are not very well known.
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Fig. 1.3a: CPDTs applied to the evaluation of displacement

Fig. 1.3b: CPDTs and LVDTs together applied to the evaluation of displacement
These structures usually exhibit an heterogeneous composition such as in reinforced concrete or in masonry constructions. In this last case elements having good mechanical characteristics are alternated with mortar layers having poorer performances. This material heterogeneity makes the determination of mechanical characteristics difficult; for this reason it is often necessary to set-up techniques suited for the analysis of the specific structure under inspection.

The methodological approach initially requires a series of preliminary investigations providing details of the structure's geometric characteristics, of the crack distribution and of the construction phases. In a following step a more investigative series of tests must be carried out to determine and define the structural behaviour of the structure [9].

1.1.2.1. Traditional experimental tools

Although in some measurements mechanical transducers still find some application (e.g. flat-jack tests, see paragraph 1.1.2.3 below), their use has been almost completely replaced by electronic transducers. In table 1.2 [8] a list of the main quantities measured and most commonly used electronic sensors for structural evaluation are presented.

<table>
<thead>
<tr>
<th>Measurement of</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Thermocouple</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Corrosion sensor</td>
</tr>
<tr>
<td>Dynamic displacement</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>Deflection</td>
<td>Hose-balance</td>
</tr>
<tr>
<td>General deformation</td>
<td>LVDT</td>
</tr>
<tr>
<td>Natural frequencies</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>Forces</td>
<td>Force Transducer</td>
</tr>
<tr>
<td>Strain</td>
<td>Strain gauge</td>
</tr>
<tr>
<td>Crack width</td>
<td>LVDT</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pressure transducers</td>
</tr>
</tbody>
</table>

TABLE 1.2: Most common experimental techniques for structural evaluation

All these classical techniques of measurement combine the same group of tools:

- sensors and amplifiers
- connecting lines
- systems for data acquisition and evaluation

They are in general substantially similar to those described in paragraph 1.1.1.1 with the only difference that often the resolution required is less important. The drawbacks
related with the use of all these tools are very similar to those described in paragraph 1.1.1.2.

1.1.2.2. Traditional non-destructive tests

The study of the mechanical characteristics of building structures is often approached by using non-destructive testing (NDT) techniques. [10,11] The results obtained by these testing techniques are generally only qualitative and can give just a preliminary evaluation of the mechanical characteristics; however their use is very important as they can provide useful information about the homogeneity of the characteristics of the structures and on the prospective presence of areas of anomalous behaviour.

a) Sonic measurements

These are the non-destructive investigation methods most widely used [12,13]. The technique is based on the generation of sonic or ultrasonic impulses at a certain point of the structure and their collection by a receiver placed in different parts. Interpretation of the data consists of measuring the time that the impulse takes to cover the section of material between the generator and the receiver. Whilst ultrasonic waves are preferably used for the study of continuous structures, sonic impulses are usually adopted in the inhomogeneous cases. The following information can be obtained by sonic methods:

- the mechanical quality index (estimate of deformability modulus)
- the homogeneity of the building structure
- the effects of reinforcements
- the presence of cracks

By choosing an appropriate grid of positions for the generator and the receiver, it is possible to obtain a detailed map of the sonic velocity distribution on a section of the structure under investigation. This approach is sometimes called Sonic Tomography [14].

The primary advantage is related to the feature of penetrating solid objects and detecting flaws in the interior of the structure. The disadvantages are related mostly to the limited sensitivity caused by material and physical properties such as grain size and surface roughness.

b) Acoustic Emission

Acoustic Emission [15] is a method for checking the degradation progress in structures; the acoustic signals studied are composed of the elastic waves emitted by the
deformation of a solid body. The propagation of cracks, for example, is always accompanied by the emission of elastic waves transmitted in the structure and received on the surface. With this method it is possible to localize cracks and, within certain limits, to evaluate their extent. The main drawback is related to the difficulty of data interpretation: it is often very difficult to relate the obtained data to real occurrences and to separate important signal from the noise coming from the ambient.

c) **Radar investigations**

The radar testing technique [16] uses high-frequency electromagnetic waves (100MHz-1GHz) emitted through an antenna with impulses of microseconds. It allows location of the separation surfaces between materials having different dielectric constants, where there is reflection of the signal. The presence of damp areas, cavities, metal structures, piping and other anomalies or inhomogeneities can be located. The limit of the technique is that it can just detect the presence of materials or layers of different dielectric constants and the resolution is sometimes very poor.

d) **Radiographic inspection**

Is one of the oldest NDT techniques and its primary advantage is that it can detect the presence of flaws in the volume [17]. An x-ray source of finite size emits a radiation that is recorded permanently at the other side of the structure on a radiographic film [18]. An evolution of this method is used to perform computerized tomography, from which the operator may obtain a complete map of the interior of the structure. The drawback is mainly related with the cost of the x-ray source and the danger of the radiation.

e) **Thermographic analysis**

Thermographic analysis is based on the thermal conductivity of the material and can be passive or active. In the former case it analyses the radiation of the structure during the cycle of thermal stress due to natural phenomena (insulation and subsequent cooling). If the survey is active, forced heating is applied to the studied surface. The thermal radiation is collected by apparatus sensitive to infrared radiation and turned into images having different shades of colour. It is possible in this way to identify areas where some construction anomalies are present (such as the presence of cavities) [19]. It is particularly interesting in the study of frescoed walls for finding some defects or detachments [20].
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It must be pointed out that the penetration depth of this technique is very limited (few centimetres) and the spatial resolution is often poor.

f) Magnetometric analysis

Magnetometry [21] locates the presence of metallic elements within the structure. The test includes a magnetic probe which is placed on the surface: the presence of metallic materials can be identified by anomalies appearing on the instrument’s magnetic field. It can be interesting, for example, for locating the presence of chains or tension bars inside reinforced concrete.

1.1.2.3 Quasi-Destructive tests

The non-destructive testing techniques are often not sufficient to determine the parameters necessary for the evaluation of the condition of a structure. This further evaluation requires unfortunately special mechanical tests involving small destructive operations on the structure. Obviously, slightly-destructive tests are not to be used when studying structures having an important artistic value or in works of art.

a) Coring technique

The coring technique [22] is widely used in this field of analysis. To understand the structural properties of the different parts from which a building is composed, it is useful to core small diameter boreholes. This coring operation allows samples to be extracted from the material on which laboratory tests can be made. This is particularly important when identifying chemical-physical and mechanical characteristics of materials. The insertion of video-cameras inside the boreholes can, in some cases, bring some additional information about the structural state of the building.

b) Flat-jack tests

An interesting technique has been developed by ISMES laboratories in Italy for the evaluation of existing mechanical characteristics in structures. It is called flat jack test [23] because it involves the insertion of thin flat-jacks into the structure: the application is really effective in masonry structures where it can be introduced in the mortar layer, being, in this way only slightly destructive.

1.1.3 Reasons for applying optical techniques in this field

It may be stated that traditional experimental tools (paragraphs 1.1.1.1 and 1.1.2.1) have the advantages to be easy to handle and to be easily accessible.
Application of "conventional" NDT techniques (paragraph 1.1.2.2) becomes necessary when it is essential to avoid any contact that may influence the real behaviour of the inspected surface. Sometimes this instrumentation is very costly and requires the intervention of specialized operators. NDT inspection must be often accompanied by quasi-destructive tests (paragraph 1.1.2.3) especially when the knowledge of the interior characteristic of a solid is necessary.

With all these techniques a full-field information can be hardly obtained and results with poor resolution have been achieved; better results will be probably obtained when thermographic and tomographic techniques will reach higher performances.

Optical NDT are alternative measuring methods that can, sometimes, provide more or different information where other techniques fail or can not be applied. In the analysis of building materials the most important advantage is brought by the possibility of having information about the displacement distributed all over the surface, without any need to be physically in contact with it. In the analysis of complete structures the most important advantage is brought by the full-field observation, allowing an evaluation of the displacement distribution and the analysis of fracture propagation.

From a single interferometric pattern it is possible to obtain qualitative results giving information that can be immediately interpreted and understood. By performing some post-analysis, quantitative results can be obtained.

Which advantages can the application of interferometric techniques bring in this field? The answer can be derived by listing their main features:

- they are non-destructive
- they usually don't require direct contact
- they have in general high resolution
- they allow a full-field inspection
- they are not subjected to electromagnetic influence.

However some drawbacks have to be considered when dealing with all these techniques:

- the requirement of a know-how and a back-ground of opto-electronic devices, techniques and properties
- the possibility of getting information about surfaces and not about entire volumes
- the fact that high resolution is at the expense of unavoidable sensitivity to ambient conditions: vibrations and other ambient conditions could influence the precision of results.
- the cost of the optical tools and materials
- the fragility of the materials: optical elements must be handled with care and the presence of dust or spalls in tests on building materials can damage it.
1.2. Description of main optical techniques (to be applied in material characterization and performance evaluation of structures in civil engineering).

Optical techniques are increasingly becoming useful tools for precision measurements in research and for industrial applications. [24] The purpose of this section is to provide the reader with an insight into the way some optical techniques can be applied to the field of civil engineering. Over the last few years there has been a significant increase in both the scope and volume of applications. This has been due to a number of factors such as a greater familiarity with laser techniques, the availability of new commercial equipment and the increasing requirement tendency to apply these techniques to many different areas. The use of solid-state detector arrays (CCD cameras), image memory boards together with microprocessors and computers, new special-purpose software for image processing and interpretation, find important application in optical metrology. In this section a short review of the most commonly used optical techniques is presented. The presentation has been, for clarity purposes, subdivided in subsections concerning speckle techniques, interferometric methods, application of optical fibres and shape measurement. Some discussion about the evaluation of optical results is presented as well: the most commonly used algorithms for the extraction of data by automatic analysis of images are presented and discussed. Programs involving image filtering and processing, fringe analysis, correlation evaluation or pattern recognition are widely used and their application is related to the optical technique actually adopted.

1.2.1. Speckle Techniques

The advent of random speckle methods [25] has been of great importance for the development of some measurement techniques in mechanics and metrology. There are two distinct main aspects:

- First, a random collection of bright and dark dots (speckles) is used as a gauging device rather than a well-defined geometric element.
- Second, quantitative information is not obtained by following the movement of individual speckles but is retrieved from the correlation properties between two displaced clusters of speckles.

Two kinds of speckle patterns can be considered, depending on the illuminating source:

- Laser speckle
- White-light speckle.
1.2.1.1. Laser Speckle

When a rough surface is illuminated by a laser beam, the intensity of the light that is scattered back has a randomly spatial varying value, giving a granular appearance [26] (similar effects occur as well in coherent radar and ultrasonic imaging). By optically rough surface it is meant a surface having height variations of the order of, or greater than, the wavelength of the illuminating light. Each point re-emits the incoming light acting as a source of spherical waves: the complex amplitude of the scattered wavefront at any point in space is given by the vectoral sum of all waves coming from the surface. When the surface properties change, the speckle pattern changes as well.

Over the last two decades the applicability of this method to a number of mechanical problems has been extensively researched [27]. However a few drawbacks have to be considered. Since the method depends on the correlation between two laser speckle fields, any decorrelation caused by small out-of-plane tilts, excessive straining of the object or random modification of the surface, reduces the fringe visibility. However an evaluation of the decorrelation rate could be envisaged as an estimation of these phenomena. Actually the degree of decorrelation will be used further in this work for evaluating random changes of the inspected surface.

1.2.1.2. White light speckle

Another method using white-light illumination in conjunction with an artificial speckle pattern painted directly on the object has been developed [28,29] in an effort to overcome some of the above mentioned decorrelation problems associated with laser speckle methods. There are many ways of producing white light speckles: black paint sprayed on a white base, surface coated with retrorefractive liquid, laser speckle created on a stripping film and pasted to the surface, surface texture on concrete walls, surface texture of aluminium blocks, surface texture of wooden blocks, etc...

These random patterns are illuminated and recorded onto the image field of a recording tool (usually a camera). By double exposures of the photographic film, correlation fringes can be retrieved (analytical correlation) and post-processed for quantitative evaluation. By using computers a correlation between two speckle images corresponding to two different states of the surface under inspection (digital correlation) can be evaluated.
1.2.2. Interferometric techniques

1.2.2.1. Holography and holographic interferometry

The holographic technique [30,31] is composed of two separate operations: recording and reconstruction. During the recording process (fig. 1.4) the wavefront from the object interferes with the light of a reference beam on a photosensitive medium, giving rise to a distribution of intensity which contains all the information about amplitude and phase of the two waves.

In the reconstruction process (fig. 1.5), by re-illuminating the developed emulsion with the reference field, the object can be seen again in its three-dimensionality.

Double-exposure holographic interferometry [32] is well-known as an NDT tool, since its main characteristics are the accuracy of measurement (displacement of tenths of a micron can be detected) and the fact that it is intrinsically non-intrusive and contactless.

In double-exposure holographic interferometry, two holograms are recorded on the same holographic plate; each captures the object in a slightly different position. During the hologram's reconstruction process the three dimensional image of the object appears overlaid with a set of fringes. This is the result of the optical interference of the simultaneously reconstructed two images and it is due to the local change in the optical path of the second object field caused by the displacement of its surface. In appendix B some equations concerning the theory of holographic interferometry are reviewed.

The interferometric pattern has an intensity distribution that can be described by the general equation (equation B.6 of appendix B)

\[
I(x,y) = K(x,y)[1 + \cos(\Delta \phi(x,y))] 
\]

(1.1)

where \( K(x,y) \) is a modulation factor related to the surface intensity and \( \Delta \phi(x,y) \) is the phase change related to variations in the optical path produced by displacements of the object's surface. This equation has a fundamental importance in optical interferometric processes: interferometric patterns obtained by holographic interferometry, ESPI, moiré or photoelasticity can be always described by a similar equation. Taking into account the illumination and observation directions, surface deformation can be successfully evaluated.

1.2.2.2. Electronic speckle pattern interferometry (ESPI)

Electronic speckle pattern interferometry (ESPI) is an interesting alternative to conventional holographic interferometry [33]. It was at first investigated at Loughborough University [34] and used in many fields of application [33,35].
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Fig. 1.4: Holographic recording process

Fig. 1.5: Holographic reconstruction process

Fig. 1.6: Acquisition elements of an ESPI system
It has the added advantage that, since it uses a video-electronic system for inspection and processing, measurements can be made in real time and the detection of micrometric deformation evolution can be performed. However, this increased temporal resolution is at the expense of spatial resolution, which is lower than in ordinary holographic interferometry.

When the surface of the object is displaced, the speckle pattern changes in a way that the phase of all the scattered components changes by the same amount $\Delta \phi(r)$. The acquisition system must be able to resolve, at least partially, the speckled structure of the image: so the spatial response of the video-camera, that depends also on the aperture and the magnification of the focusing system, must be wide enough to accept the high frequencies of the speckles. In a common ESPI system the signal caught by the video-camera is transferred to a monitor and a computer (the acquisition elements of this system are shown in fig. 1.6). The first image (called reference image) is transferred from the video-camera to a computer-controlled board (via an analogue to digital converter), where it is saved in memory, and then displayed on a monitor. After the object under investigation has been deformed, a second intensity pattern is transferred to the board and subtracted from the previously stored one. The result is then displayed on the monitor: what will be seen is a pattern of dark and white fringes. In appendix C some equations concerning the theory of holographic interferometry are reviewed. The intensity distribution of the obtained interferometric pattern can be represented by the equation (equation C.7 of appendix C):

$$I(x, y) = A \sin \left( \frac{\phi + \Delta \phi}{2} \right) \sin \left( \frac{\Delta \phi}{2} \right)$$  \hspace{1cm} (1.2)\

where $A$ is the background component, $\phi(x, y)$ the random phase related to the speckle distribution and $\Delta \phi(x, y)$ is the phase change related to variations in the optical path produced by displacements of the object surface.

An interesting feature of this system is the possibility of grabbing continuously images from the object while a deformation is occurring and subtracting them in succession from the first reference one: in this manner it is possible to observe the real-time formation and the progressive changes of the fringe pattern related to the deformation of the investigated surface.

Many configurations are possible and, unlike holographic interferometry, information concerning in-plane deformations can be retrieved.
1.2.2.3. Moiré technique

The superposition of periodic and/or quasi periodic patterns in optics frequently results in striking spatial configurations commonly called moiré patterns [36]. These new patterns may contain some spatial frequencies that can be considerably lower than the original ones [37]; in this way fringes are produced. This effect can be experienced everyday, for example by looking at two overlapping nets, at the noise in a TV picture (when the pattern has a spatial period similar to the one of the monitor or of the camera), the railing of a bridge, etc.

The moiré effect has been widely used in the field of topographic contouring (i.e. shape of human bodies for medical purposes [38]) as well for strain [39] and vibration analysis[40].

Moiré patterns can be formed in at least three different ways: by addition, subtraction or multiplication (three of the four basic rules of arithmetic) and can be performed by optical or digital means.

The gratings can be projected, directly pasted, painted or created on the surface to be inspected [41,42]. The moiré pattern can be obtained in some different ways:

- by making the deforming grating beat with a reference one
- by acquiring a double exposure of the grating before and after deformation
- by digitally comparing the grating before and after deformation.

As an example, when making the absolute subtraction between the grating before and after displacement of the surface, the moiré pattern is described by the following equation (equation D.6 of appendix D):

\[ I(x,y) = B|\sin(2\pi vx)\sin\left(\frac{\Delta\phi(x,y)}{2}\right) | \]

where B is the modulation factor, \( v \) the carrier frequency of the grating in the x direction and \( \Delta\phi(x,y) \) the local change of phase directly related to the displacement.

Some further details about this technique are presented in Appendix D.

1.2.3. The use of optical fibres

The use of optical fibres [43] is becoming more and more important and it seems to be very promising in the field of civil engineering.

With the use of optical fibres, holographic or ESPI systems become very flexible [44]: the user acquires almost unlimited freedom in selecting object and reference angles; furthermore, the number of optical elements is reduced and the portability of the system is increased.
Light from monomode fibres is appropriate for object illumination and provides a very suitable reference beam too. Monomode are always preferred to other types of fibres because their output wavefront is more uniform and because they are less sensitive to distortion effects on the carried light caused by external stresses or temperature changes [45].

Attention has been particularly devoted to some particular applications:
- set-up for holographic interferometry or ESPI using optical fibres [44]
- set-up for portable ESPI using optical fibres [46]
- electronic servo-system for phase changes compensation [47]
- design of endoscopes [48,49]
- design of optical fibre extensimetres [50].

Some of these will be described in the following chapters and some applications will show their performance.

1.2.4. Optical techniques for contouring

The human eye has an extraordinary ability for detecting small details but is poor in estimating distances. Contouring means mapping the surface of an object in order to obtain a detailed description of its 3D profile. Optical sensing techniques for 3D shape measurements have been extensively studied because of their inherent non-contact nature [51] and are applied to many metrological problems including industrial inspection, robotic vision, solid modelling for computer graphics and so on [52]. Optical techniques described till now are especially used for displacement and strain analysis; however holography, ESPI and moiré can be used for contouring purposes as well. Other optical techniques have been expressly developed for optical 3D measurements ranging from old and classic methods (photogrammetry, triangulation, ...) to more new and sophisticated ones (coherence radar, tunnel microscopy, ...).

<table>
<thead>
<tr>
<th>Technique</th>
<th>$\Delta x$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of flight</td>
<td>1000</td>
</tr>
<tr>
<td>Triangulation</td>
<td>1% of range</td>
</tr>
<tr>
<td>Moiré</td>
<td>0.5</td>
</tr>
<tr>
<td>Interferometry (two wavelength)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Photogrammetry</td>
<td>100</td>
</tr>
<tr>
<td>Coherence radar</td>
<td>1-10</td>
</tr>
<tr>
<td>Speckle techniques</td>
<td>1</td>
</tr>
<tr>
<td>Tunnel microscope</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

TABLE 1.3: Most commonly used techniques of contouring
In table 1.3 the most commonly used techniques for contouring are listed and a comparison between their resolutions is presented [53]. These data can be obviously criticized as they change whenever technological improvements are available. In this section just those techniques actually used by the author, for his experiments, are presented.

1.2.4.1. Triangulation

Many active methods are based on the principle of triangulation. Many different configurations of structured light can be projected onto the inspected surface: a single stripe, a set of parallel lines, a pattern of dots [54,55]. An observer that is not placed along the direction of projection sees the grating structure modulated by the shape of the object. Depending on the illuminating and observing geometry it is possible to obtain a quantitative evaluation of the shape.

1.2.4.2. Photogrammetry

Photogrammetry [56], or more exactly stereophotogrammetry, relies on the overlapping of photographs for the extraction and analysis of three-dimensional information. The relative geometrical orientation of the overlapping photographs permits the reconstruction of a hypothetical three-dimensional stereomodel which is then used to measure the size, shape and location of the object scene. This technique generally needs a skilled operator and extensive interpretation time. This way of operation repeats exactly the behaviour of human eyes: the eyes are separated by a small horizontal distance that enables the viewer to see two slightly different aspects of close objects, which the brain interprets in terms of distance and depth. Initially, the main application of photogrammetry was in the field of topography for plotting maps of the earth's surface. However the application of photogrammetry to other disciplines such as engineering, biomedicine, architecture and art has given rise to wide acceptance of this technique. The processing of data is becoming more and more sophisticated: by using very expensive high-resolution scanners it is possible to digitize automatically the photographs and extract automatically the shape of the surface (digital photogrammetry).

1.2.4.3. Time of flight

This technique relies on the same operation principle of radars[57].

21
where $v$ is the speed of the signal propagation, $r$ is the distance from a reflecting object, and $\tau$ is the transit time of the signal travelling from the radar transmitter to the reflecting object and back to the radar receiver.

Lasers can be used for this purpose: a laser pulse is sent, the time needed to receive its reflection from the target is measured and from equation (1.4) the distance is calculated. This procedure can be repeated for many points on a certain object in order to obtain the complete profile.

This might seem a very simple task, but one should not forget that light travels three meters in only ten nanoseconds ($10 \times 10^{-9}$ sec). To reach an accuracy of one millimetre, the accuracy in measuring time must be in the range of tens of picoseconds ($10 \times 10^{-12}$ sec) which is far from being easy.

In the last few years lasers increased their performances: with semiconductor lasers costs are reduced and more compact devices are available. Laser pulses are coming shorter and shorter, increasing the precision of measurement of radar systems.

1.2.5. Techniques for the interpretation of interferometric patterns

As previously said, interferograms may contain information relative to the displacement or to the shape of the inspected area. Fringe analysis procedures [58,59] including fringe peak detection and fringe order determination were used at first, making the processing tedious and time-consuming. With the advent of fast computers and image processing boards, automatic fringe analysis and precision phase measuring techniques became available. Automatic quantitative evaluation of interferograms requires accurate phase measurement, independent from intensity variations superposed onto the interferograms. Nowadays, the phase-shifting (or phase-stepping) and the Fourier Transform techniques are mainly used for interferogram interpretation.

Some new advances are being made in the application of Artificial Neural Networks and parallel computing for the interpretation of interferograms.

1.2.5.1. Fringe peak detection and fringe counting

The fringe centres can be found manually by using a digitizing tablet as well as by using video and image processing techniques [32,59]. To estimate fringe peaks, the fringe density binarization technique is commonly used in many fringe analysis systems because of the simple algorithms used. The grey-level method, where the local variation of fringe density is considered, is sensitive to noise, but can detect peaks by processing only local areas smaller than those in the binary case. In order to extract fringe peaks in
the grey-level method, it is important to reduce the influence of noise, including speckle noise. Once the peaks have been detected the displacement information can be retrieved by simply counting the number of fringes or by more sophisticated automatic routines.

1.2.5.2. Phase-shifting

This method is widely used in interferometric measurements since it provides high resolution in phase evaluation and needs a relatively simple experimental set up. Phase-shifting [60] is based on the introduction of a known amount of lateral shift in the interferometric pattern and the resulting effect is a movement of the intensity peaks across the interference pattern. The theory related to this technique is diffusely described in appendix E. By the computational point of view, a variety of versions of the method exist, based on the acquisition of different numbers of shifted images. By simple arithmetic or trigonometric operations on the acquired images, the phase distribution, modulo $2\pi$, can be retrieved locally with high accuracy. For evaluating the effective displacement, related to the phase distribution, the phase unwrapping procedure is needed.

1.2.5.3 Fast Fourier Transform Technique

Unlike the previous method, Fourier analysis allows phase detection by the acquisition of a single image [61,62]; this is a great advantage since the phase shifting experimental equipment is no longer necessary. The critical point is the detection of sharp edges and great attention has to be paid to avoid elimination of the highest spatial frequencies. For applying this method to phase retrieval it is necessary to introduce, sometimes, a carrier frequency for eliminating all closed fringes [63]; in this case the useful information about phase modulation are contained in that part of the Fourier spectrum close to the frequency $f_0$ (carrier spatial frequency). The theory related to this technique is diffusely described in appendix F. Again the phase information is retrieved modulo $2\pi$ and the phase unwrapping procedure must be applied.

1.2.5.4. Phase unwrapping

Phase-shifting and Fourier methods evaluate phase modulo $2\pi$ and further processing is necessary to recover the absolute phase diagram. This problem, known as phase unwrapping, has been greatly considered and many efforts have been addressed to reach a completely automated solution that, probably, is still far from achievable [64].
Many difficulties arise from discontinuous phase changes, image noise and signal undersampling and solutions are often suggested on the basis of a priori knowledge of the physical phenomena involved. Normally, the image has to be scanned pixel by pixel to detect the positions of the jumps: a variety of paths can be followed along the image and jumps can be detected by comparing two or more adjacent pixel values. The simplest and still most common way to perform phase unwrapping is to add or subtract $2\pi$ to a phase value every time that a jump greater than $\pi$ occurs between two adjacent points in the wrapped phase diagram. The presence of noise or geometrical discontinuities makes the process complex and errors are sometimes difficult to avoid. Some of the problems can however be solved by using appropriate image processing tools [65]. A trade-off has to be made between precision, time, simplicity and degree of automatism. Some iterative algorithms (i.e. [66,67]) may require a lot of time before reaching the solution.

1.3. CONCLUSIONS

In this work two different worlds, with different competencies, meet together and find a common subject of operation: it is intended to be a "trait d'union" between two different scientific fields. This chapter has been included as an introductory part in order to give some highlights and to provide the reader with some knowledge about the subjects that will be treated further on.

People working in the optics field get acquainted with some problems of civil engineering they have to face with. Section 1.1 has been completely devoted to the presentation of some experimental techniques (classical tools and most common non-destructive methods) for material characterization and evaluation of performance of structures.

People working in the civil or building field can find in this review some notions about optical techniques for an understanding of their potential. Section 1.2 consists of the presentation of some methods from which promising results can be expected: techniques for strain analysis and shape measurement have been shortly described. A comparison with classical experimental techniques has been attempted: some advantages and drawbacks have been highlighted.

All subjects in this chapter have been presented briefly without going deep into details, as they are widely described in literature. Some references have been included in order to allow the consultation of specific tests where the subjects are discussed more diffusely. Appendices are included at the end of the thesis for providing interested people with a quick background of some notions presented in this chapter.
Chapter 2 will be devoted to the presentation of a series of experimental results obtained by applying some optical techniques. It has, actually, a double purpose:

- providing familiarization with optical techniques
- putting emphasis on their enormous possibilities and features.

After the acquisition of some confidence with these techniques, some improvements and upgradings will be introduced. To this purpose chapter 3 is devoted to the development of some optical techniques, the design of some optical systems and the development of algorithms for the interpretation and elaboration of images. This part is mostly performed in prevision of applications that will be carried on in the field of civil engineering.

Applications of optical Non-Destructive Testing in Civil Engineering (NDT-CE) is the main objective of this thesis and will be the subject of chapter 4.
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Chapter II

Familiarization with some existing optical techniques

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Introduction

Over the last few years there has been a significant increase in both the scope and volume of applications of optical techniques [1]. This has been due to a number of factors such as a greater familiarity with laser techniques, the availability of new commercial equipment and the increasing requirement to apply these techniques to many different areas. The purpose of this chapter is to present some experiments and results obtained by the author, performed for acquiring a better familiarization with optical techniques.

2.1. Investigation of deformations

A key feature of the described optical techniques is that they allow the observation of small surface changes. Many optical techniques are now considered as extremely powerful tools for experimental analysis of displacement and strain. Sometimes qualitative results are sufficient for the experimentalist: the overall appearance of the fringe pattern can be a qualitative guide for evaluating the distribution of displacement. If precise estimation of data is necessary, some methods of fringe analysis must be applied in order to extract quantitative results.

2.1.1. Holographic Interferometry

A lot of applications of holographic interferometry in different fields have been tested and results can be found in the literature[2,3]. When continuous wave lasers are used, the main drawback comes from the high sensitivity of the measurements to external factors such as mechanical vibrations. To avoid these effects the experimental set-up is often mounted on special optical benches loaded with high masses.

A common set-up for holographic interferometry experiments is presented in fig. 2.1a. The light from a He-Ne laser is split into two beams by using a semi-reflecting mirror: the first was used to illuminate the object and the second as a reference field. Both the wavefronts, reference and light scattered by the object, reached a high-resolution photographic emulsion. The hologram recording medium was mainly a thermoplastic film of a holocamera, but several interferograms were also recorded on holographic plates. This choice had definite advantages (positioning, neatness in film developing, work speed, etc.), but implied some compromise in the quality of the holograms. For having quantitative results the double reference (fig. 2.1b) configuration technique [4] could be used. For this purpose a Michelson interferometer was inserted in the reference path.
Chapter II: Familiarization with optical techniques

Fig. 2.1a: Optical set-up for Holographic Interferometry (distances are in cm)

Fig. 2.1b: Optical set-up for Holographic Interferometry with double reference (distances are in cm)
The beam entering the interferometer was divided into two parts, slightly inclined to each other, producing two reference paths. During the recording process the undeformed state was acquired with just one reference field and the deformed state with the other one. During the reconstruction process the holographic emulsion was illuminated with both reference fields, producing two overlapped holograms: their relative phase could be changed by simply displacing one of the two mirrors in the Michelson interferometer. By introducing precise phase steps between the reference fields the phase-shifting algorithm could be applied.

This set-up was used by the Author for inspecting the deformations arising in a circular plate displaced at its centre. The laser was a Spectra Physics 127 (wavelength $\lambda =$632nm, power $P=35$mW) and the recording medium was Newport thermoplastic film; the holographic images were transferred through a Sony CCD videocamera from the thermoplastic film to a Compaq 486sx personal computer, where they were digitally stored in an FG100 Image Technology Frame Grabber and further processed if desired. An interferogram obtained with this experiment is presented in fig. 2.2, the absolute phase map (obtained with the double-reference phase-shifting technique) related to the deformation in fig. 2.3 and the 3D representation of results in fig. 2.4.

Every single optical configuration of holographic interferometry is sensitive to just one component of displacement (the bisector between illumination and viewing directions). For complete information, at least three holograms with different sensitivity directions should be recorded [2]. Moreover it is not possible to obtain the evaluation of in-plane deformations from one single hologram.

2.1.2. Electronic Speckle Pattern Interferometry (ESPI)

ESPI is gaining more and more popularity in many fields of application, and it is often preferred to traditional holographic interferometry as it doesn't require developing processes, it is less sensitive to ambient light, it allows an easy real-time inspection and makes possible the analysis of in-plane deformations[5,6]. Due to the sensitivity to ambient mechanical vibrations, experimental arrangements are often mounted on special tables as for holographic interferometry.

In a common ESPI system the speckle pattern coming from a surface illuminated by a laser light is imaged by a video camera, transferred to a frame grabber in a computer where it is processed and then displayed on an RGB monitor (display based on the three fundamental colours Red Green and Blue). The real-time formation of fringes can subsequently be acquired and stored by a video-recorder. A schematic representation of the acquisition set-up is presented in fig. 2.5.
Chapter II: Familiarization with optical techniques

Fig. 2.2: Interferogram obtained for a centrally loaded circular plate

Fig. 2.3: Phase map obtained after the phase-shifting elaboration

Fig. 2.4: 3D representation of the deformation
In the Author's experiments the following components were used: an He-Ne laser Spectra Physics 127 ($\lambda=632\text{nm}, P=35\text{mW}$) or a Nd-YAG laser Coherent ($\lambda=532\text{nm}, P=200\text{mW}$), a Teli 3330 CCD camera, an FG100 Imaging Technology frame grabber, a 486sx Compaq computer and a Panasonic video-recorder.

After some preliminary tests, it was observed that for obtaining good quality ESPI images, with an optimum fringe contrast, some experimental conditions had to be possibly fulfilled:

- the incident light intensity should be as high as possible until the saturation value of the camera is almost reached.
- the mean values of the reference and the object fields should be as similar as possible.

Differently from what is still expected by some researchers, it is not necessary that the CCD camera resolves the speckle structure: many speckles per pixel can be accepted.

Hereinafter two experiments, designed by the Author, are presented: the first for out-of-plane displacements and the second for in-plane displacements.

### 2.1.2.1. Out-of-plane

In fig. 2.6 an example of an ESPI arrangement for static out-of-plane deformation analysis is presented. The light coming from the laser is split into two paths for illuminating the object and for providing a reference field that interferes at the sensitive area of a CCD camera. The object under investigation was a cantilever loaded on its upper side (fig. 2.7) and the displacement could be considered practically pure out-of-plane. The image of the object in a steady state without any external load was grabbed and recorded in the frame store; subsequent images were acquired and digitally subtracted continuously from the stored image.

While no load was applied to the cantilever, a completely black image was obtained but when a force was applied, the object was subjected to a deformation revealed by the appearance of fringes. The out-of-plane displacement $d$ is related to the phase information of the interferogram by the equation

$$\Delta \phi = \frac{2\pi}{\lambda} d(1 + \cos \theta)$$  \hspace{1cm} (2.1)

where $\theta$ is the angle between illumination and viewing directions shown in fig. 2.6.

The interferogram obtained with a load of 20 grams is presented in fig. 2.8. When the magnitude of the forcing load was increased, the number of fringes obviously increased.
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**Fig. 2.5:** Acquisition set-up for ESPI

**Fig. 2.6:** Experimental arrangement for ESPI out-of-plane investigation

**Fig. 2.7:** Loading scheme of the inspected cantilever
Fig. 2.8: Interferogram obtained for the loaded cantilever

Fig. 2.9: Phase map obtained after the phase-shifting elaboration

Fig. 2.10: 3D representation of the deformation
If phase-steps were introduced in the reference field, the mirror is displaced by a piezo-translator, by using the phase-shifting algorithm the absolute phase map related to the deformation (fig. 2.9) could be evaluated and represented with a 3D mesh (fig. 2.10). In this case the same result could be obtained from a single interferogram by using the FFT technique.

2.1.2.2. In-Plane

The set-up presented in Fig. 2.11 was used for the evaluation of in-plane displacements. The light from the laser was split into two paths for illuminating the inspected object from two directions both forming an angle $\theta$ with the normal to the surface. The object under investigation was an aluminium plate fixed at one extremity and statically loaded at the other end (fig. 2.12): the object was subjected to heating and as a consequence, its length increased. The in-plane displacement $d$ is related to the phase information of the interferogram by the equation

$$\Delta \phi = \frac{2\pi}{\lambda} d(2\sin \theta)$$  \hspace{1cm} (2.2)

where $\theta$ is the angle in fig. 2.11.

The interferogram is presented in fig. 2.13, the phase map obtained with the Fourier transform procedure from one single interferogram in fig. 2.14 and a vectoral representation of the distributed displacement in fig. 2.15.

2.1.3. Moiré Method

The moiré interferograms can be produced in many different ways by using a pair of gratings or a single one, with analogue or digital procedures[10].

When two gratings are used, the first is directly pasted, created, painted or projected onto the inspected surface (object grating) and the second (reference grating) can be put directly onto the previous, in front of the viewing camera or created digitally in a computer. The two gratings are continuously compared and the real-time formation and evolution of fringes can be observed.

It is possible to consider just the object grating: photographic double exposure of the deforming surface or digital subtraction (addition or multiplication) of two images acquired at different moments, give rise to interferometric patterns.

Quantitative evaluation can be obtained by applying lateral movement of the object or reference grating (depending on the technique adopted) in order to obtain phase-shifted interferograms or by using the Fourier transform technique.
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**Fig. 2.11:** Experimental arrangement for ESPI in-plane investigation

**Fig. 2.12:** Loading scheme of the inspected aluminium beam

**Fig. 2.13:** Interferogram obtained for the heated beam
Fig. 2.14: Phase map obtained after the Fourier transform elaboration.

Fig. 2.15: Vectoral representation of the deformation (maximum deformation about 6μm).

Fig. 2.16: Experimental arrangement for moiré interferometry investigation.
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Fig. 2.17:
Interferogram related to
the deformation of the
loaded box

Fig. 2.18:
The same interferogram
after low-pass filtering

Fig. 2.19:
3D representation
of the deformation
Many experiments have been conducted by the author in the field of the moiré technique and only an example application is presented here.

The schematic arrangement is presented in fig. 2.16: a slide-projector mounted on a translating board was used to illuminate the object from a certain angle, a Sony CCD camera for acquiring the scene, a Data Translation 2862 frame grabber in a Toshiba 3200 portable computer for processing the data and an RGB monitor for displaying the results. Ronchi grating slides were projected: a set of gratings with different spatial frequencies (ranging from 50 to 2500 lines/inch) was available, the choice depending on the desired precision, the resolution of the acquiring system and the dimension of the inspected area.

The deformation of a plastic box was observed: the surface was illuminated with a Ronchi grating and the image, crossed by 80 vertical lines, was acquired and stored in memory. After deformation the same grating was projected onto the surface and four new images were acquired with a lateral displacement of the projector between each. The step was set equal to a quarter of the grating pitch. The result of subtraction of the first acquired image with one of these final four is shown in fig. 2.17. For this application, low-pass filtering in the Fourier domain was very useful: the unwanted high frequency was very well known (the grating frequency) and it was thus easy to choose the cut-off limit. The image obtained after this filtering is shown in fig. 2.18.

Finally an image resulting from the phase retrieval process followed by the phase unwrapping procedure was obtained and the corresponding 3D plot is presented in fig. 2.19.

2.1.4. Use of Optical Fibres

The use of optical fibres makes holographic or ESPI arrangements very flexible[11], and allows the development of endoscopic systems [12,13].

2.1.4.1. Holographic interferometry with optical fibres

The set-up presented in fig. 2.20 has been used by the Author for experiments of holographic interferometry: the light coming from an He-Ne Spectra-Physics laser was launched in one arm of a Newport fibre optic beam splitter. The two arms at the output were used to provide the reference field and the illumination of the object. As a recording medium, Kodak holographic plates or Newport thermoplastic film were used. With this arrangement it was very simple to change the directions of the illumination and of the reference fields: a simple change in the geometrical position of the fibre extremities made the system sensitive to different components of deformation.
Fig. 2.20: Experimental set-up for holographic interferometry using optical fibres

Fig. 2.21: Experimental set-up for out-of-plane ESPI using optical fibres

Fig. 2.22: Experimental set-up for in-plane ESPI using optical fibres
2.1.4.2. ESPI with optical fibres

Optical fibres can be used for ESPI arrangements too. The use of optical fibres is very expedient because it allows a fast passage from a certain configuration to another. For example, in ESPI it is very easy, with only simple changes, to move from an out-of-plane (fig. 2.21) configuration to an in-plane configuration. (fig. 2.22). The same laser and fibre-optic beam-splitter applied in paragraph 2.1.4.1 were used and the holographic emulsion was replaced by a Sony CCD camera connected to a Data Translation 2862 Frame Grabber in a Toshiba 3200 portable personal computer. For this flexibility and for their relative small dimensions, these set-ups are especially suited for the construction of portable systems.

In all these systems, it was noted that some caution must be observed:
- the coherence length must be respected
- the fibres must not be influenced by ambient effects that may cause unwanted phase changes
- the extremity of the fibres must be carefully cleaved and polished in order to obtain fields of very good quality at the output.

2.2. Investigation of vibrations

In section 2.1 it was assumed that the original and displaced states of the surface under inspection were static or quasi-static. This meant that the variations of position were sufficiently slow for the resultant fringe motion to be resolved by the eye. However, the basic principles of holographic interferometry and ESPI can be extended to the measurement of vibrations and to this purpose, the technique known as time-average interferometry is used. Two main methods were applied by the author in this section:
- holographic interferometry for vibration analysis [14]
- ESPI for vibration analysis [15]

These two techniques are suitable for the measurement of small amplitude periodic displacements and can be carried out by the use of continuous wave lasers. In the case of considerably large amplitude periodic displacements, non-periodic motions or transients, dual pulsed holographic interferometry or dual pulsed ESPI should be used. The test specimen was a square steel plate having thickness of 1mm. The specimen was held fixed with four tightening screws, one on each corner, between two heavy steel block frames having a circular opening of 30cm. Thus the structure under consideration behaved as a circular plate of radius of 15cm, with support conditions approximating closely those of the clamped edges. Its position was vertical. The plate
was excited to vibration by sound waves of sinusoidal form, produced by a wave generator and emitted by a loud-speaker located at a distance about 50cm from the plate. These waves impinged at the non-illuminated side of the plate (fig. 2.23).

2.2.1. Holographic Interferometry

The time-average holographic interferometry technique was used: during the acquisition time the object vibrated continuously and the obtained interferogram showed fringes representing zones vibrating with the same amplitude. In appendix G the theory of time-average holographic interferometry is developed. The same experimental set-up described in paragraph 2.1.1 and depicted in fig 2.1a was used in this case. The plate was forced to vibration by sweeping through a range of excitation frequencies; the formation of the fringe patterns, which are indicative of the vibration mode and amplitude, was observed. The resonating frequencies of the plate were identified when a clear visualization of the corresponding nodal system was observed. Thus the natural frequencies were at first searched in the vicinity of their theoretically predicted values. When located, a fine frequency tuning of the wave generator was sought so that, for a constant intensity level, the maximum number of fringes was obtained. The image of the fringe pattern viewed on the thermoplastic film (or holographic plate) was next sent, via the video camera, to the computer for storage. Working in this manner, a number of natural frequencies of the plate was determined. In fig. 2.24 a,b two different stationary states of vibration are presented.

Fig. 2.23: Configuration adopted for vibration analysis by holographic interferometry
Fig. 2.24a,b: Stationary states of vibration by holographic interferometry
2.2.2. ESPI

Electronic speckle pattern interferometry can also provide a display of vibration modes of an object at resonance. It usually allows an easier real-time observation than with holographic interferometry and doesn't require complete darkness and photographic developing processes.

The experimental set-up described in paragraph 2.1.2 and depicted in fig 2.6 was adopted and applied to the same specimen. A number of natural frequencies of the plate was determined: in fig. 2.25a,b two different modes of vibration, corresponding to frequencies of 1816 Hz and 731 Hz, are presented.

Some calculations have been performed [16] in order to compare the resonance frequencies found by both optical interferometric methods with those expected by the theory: the difference between experimental data and expected values was lower than 10 Hz.

2.3. Strain measurement

When an object is subjected to external forces, it undergoes a certain deformation. An evaluation of its local value is, in some applications, sufficient. However the operator, in many cases, would like to determine strain, stress and bending moments that arise in the inspected object. The relationship existing between displacement, strain and stress is presented in appendix A: stress is closely related to partial derivatives of displacement.

2.3.1 Methods for derivative calculation of phase maps

In this section some techniques for calculating spatial derivatives are considered:
- indirect mathematical method in which strains are calculated from displacements by numerical differentiation [17].
- direct optical approach in which derivatives are evaluated by a direct observation of fringes [5,18].

2.3.1.1. Numerical Differentiation

The first and conceptually easiest way to calculate digitally a derivative is to use an incremental approximation. For a function \( f(t) \), the Taylor series is given by
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Fig. 2.25a: Stationary state of vibration by ESPI (1816 Hz)

Fig. 2.25b: Stationary state of vibration by ESPI (731 Hz)
Chapter II: Familiarization with optical techniques

\[ f(t) = f(t_0) + f'(t_0)(t - t_0) + f''(t_0)\frac{(t - t_0)^2}{2} + \ldots \]  

(2.3)

By taking into account just the initial two terms, the first derivative can be expressed by:

\[ f'(t_0) = \frac{f(t) - f(t_0)}{t - t_0} \]  

(2.4)

The derivative evaluation at \( t_0 \) can be carried out in some different ways:

by considering two consecutive points

\[ f'(t_0) = f(t_0 + 1) - f(t_0) \]  

(2.5)

by choosing an arbitrary interval \( h \) between

\[ f'(t_0) = \frac{f(t_0 + h) - f(t_0)}{h} \]  

(2.6)

or by considering the so-called centre difference approximation (a point before and a point after the position of interest)

\[ f'(t_0) = \frac{f(t_0 + 1) - f(t_0 - 1)}{2} \]  

(2.7)

This technique has been applied by the author to an ideal and to a real case by using a computer routine written for performing the numerical differentiation.

In the ideal case a bidimensional gaussian image was created: in fig. 2.26 and fig. 2.27 the grey-level image and the 3D plot are presented. The derivative was then evaluated in the \( x \) direction by choosing an increment \( h=5 \) in equation 2.6 above. In fig. 2.28 and fig. 2.29 the grey-level image and the 3D plot of the results are presented.

In the real case the out-of-plane deformation of a plate loaded in its centre, obtained in an ESPI experiment and followed by a phase-shifting process, was used as a starting point. Fig. 2.30 and fig. 2.31 show respectively the grey-level image and 3D plot of the deformation while fig. 2.32 and fig. 2.33 show the grey-level image and 3D plot of the derivative calculated in the \( x \) direction by choosing again the increment \( h=5 \) in equation 2.6.
Fig. 2.26: False colour level representation of an ideal gaussian

Fig. 2.27: 3D representation of Fig. 2.26

Fig. 2.28: False colour of the partial derivative in x direction with increment $h=5$

Fig. 2.29: 3D representation of Fig. 2.28
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Fig. 2.30: False colour representation of a real displacement: plate pushed at the center

Fig. 2.31: 3D representation of Fig. 2.30

Fig. 2.32: False colour of the partial derivative in x direction with increment $h=5$

Fig. 2.33: 3D representation of Fig. 2.32
The procedure of derivative calculation is influenced a lot by the presence of noise and unwanted ripples in the original image. Their effect is greatly increased by the derivation process.

2.3.1.2. Optical differentiation (Shearing interferometry)

ESPI shearing interferometry is one of many ways for performing optical differentiation [18].

An optical interferometric configuration sensitive to the first derivative of displacement is depicted in fig. 2.34. The light back-scattered from the observed object passes through a Michelson interferometer where one of the mirrors is perfectly perpendicular to the viewing direction while the other has a slight inclination \( \alpha \). On the sensitive area of the viewing camera two images of the object, not perfectly overlapped, interfere: this arrangement produces a shearing action. In fig. 2.35 the sheared area produced by this set-up is shown. The intensity at a point Q is given by the sum of the light coming from two different points of the original object having a distance \( S_2 \) from each other. The following equations yield [5]

\[
\Delta \phi = \frac{2\pi}{\lambda} \left( \frac{\partial d}{\partial x_2} \right) S_2 ; \quad \frac{\partial d}{\partial x_2} = \Delta \phi \frac{\lambda}{2\pi S_2}
\]  

(2.8)

\[\text{Fig. 2.34:}\]
\text{Optical configuration for shearing interferometry}

\[\text{Fig. 2.35:}\]
\text{Description of the sheared area}
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Fig. 2.36: Interferogram of a centrally loaded plate obtained by shearing interferometry

Fig. 2.37: Phase map obtained with the phase shifting method

Fig. 2.38: 3D plot of fig. 2.37
where $\Delta \phi$ is the change in the phase of the laser field related to the displacement $d$. The last equation demonstrates that the phase change is directly proportional to the derivative of the displacement. By simply changing the relative inclination of the two mirrors in the set-up it is possible to change the direction of differentiation and/or the measuring sensitivity.

The use of this interferometer for shearing interferometry leads in a very easy way to the analysis of strain components without any need of deformation analysis and further computational derivation. However the quality of interferograms obtained is usually poor and the decorrelation effect strongly limits the performance of the method.

In this case, the phase-shifting method (by moving one of the two mirrors of the interferometer) or the FFT method can be used to obtain quantitative results.

The out-of-plane deformation of the loaded circular plate described in paragraph 2.3.1 was observed with this optical arrangement and followed by a phase-shifting process. Fig. 2.36, fig. 2.37 and fig. 2.38 show respectively the obtained interferogram, the grey-level map and the 3D plot representation of the derivative.

2.3.2. Example of strain evaluation.

If a simple experimental geometry is considered, where the object surface is flat and only in-plane deformations are present, the strain tensor described in appendix A (equation A.1) takes the simplified form

$$ S = \begin{pmatrix} \frac{\partial u(x,y)}{\partial x} & 1 \left( \frac{\partial u(x,y)}{\partial y} + \frac{\partial v(x,y)}{\partial x} \right) \\ \frac{1}{2} \left( \frac{\partial u(x,y)}{\partial y} + \frac{\partial v(x,y)}{\partial x} \right) & \frac{\partial v(x,y)}{\partial y} \end{pmatrix} $$

(2.9)

where only 4 components are present instead of 9 [19]. By simply knowing the distribution of the horizontal and vertical components of displacement $u(x,y)$ and $v(x,y)$, all information about the strain can be retrieved.

The configuration of fig. 2.39 was used by the author for carrying out a complete in-plane deformation analysis: the inspected area was illuminated from four different directions positioned as the four lateral edges of a pyramid whose vertex was located in the centre of the object. Illumination in the horizontal and in the vertical planes made, respectively, the system sensitive to x and y directions of deformation. By stepping every time, the movement of one of the two mirrors, four images could be acquired and phase-shifting quantitative evaluation could be applied.
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Fig. 2.39: Optical arrangement for complete in-plane analysis

Fig. 2.40: Specimen used for experimental evaluation of strain
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The system included a He-Ne laser Spectra Physics 127 (λ=632nm, P= 35mW), a Teli 3330 CCD camera, an FG100 Imaging Technology frame grabber in a 486sx Compaq computer. The selection of the illuminating plane was performed by manually operated mechanical switches.

The object considered in the experiments was the specimen sketched in fig. 2.40, very well fixed in its lower left corner and loaded in the x direction.

Four speckle patterns obtained by illuminating along the horizontal plane \((X_1X_2X_3X_4)\) and four obtained by illuminating along the vertical plane \((Y_1Y_2Y_3Y_4)\), with \(\pi/2\) phase shifts in between, were acquired and stored in computer memory. After deformation of the object, one speckle image for each plane of illumination, \((X')\) and \((Y')\), was acquired and stored. As a final step eight interferograms were obtained by performing the digital subtractions:

\[
\begin{align*}
|X'\!-\!X_1| & \quad |X'\!-\!X_2| & \quad |X'\!-\!X_3| & \quad |X'\!-\!X_4| \\
|Y'\!-\!Y_1| & \quad |Y'\!-\!Y_2| & \quad |Y'\!-\!Y_3| & \quad |Y'\!-\!Y_4| 
\end{align*}
\]  

(2.10)

In fig. 2.41 and fig. 2.42 interferograms related to the in-plane deformation in \(x\) and \(y\) directions are shown, and the related phase maps obtained with the phase shifting procedure are presented in fig. 2.43 and fig. 2.44.

In fig. 2.45 and fig. 2.46 the distribution of displacement components in the \(x\) and \(y\) directions is shown by using a vectoral representation; these two results are combined in fig. 2.47.

From the displacement maps the shear strain \(1/2(\partial u/\partial y + \partial v/\partial x)\) was calculated by using the finite difference approximation (equation 2.6 with \(h=3\)) and the result is displayed in the 3D plot of fig. 2.48.

2.4. Optical Contouring measurement

Contouring means examining the surface of an object in order to obtain a detailed description of its 3D profile. Optical methods offer attractive solutions alternative to traditional techniques with the advantage of being contactless and non-intrusive and providing full-field information.

Optical contouring techniques are based on a variety of principles including triangulation, moiré, interferometry, speckle, photogrammetry and pulse time of flight. Hereinafter applications of some of these techniques are presented in an attempt to explore the advantages and the limits of each one.
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Fig. 2.41: Interferogram related to horizontal displacement

Fig. 2.42: Interferogram related to vertical displacement

Fig. 2.43: Phase map related to horizontal displacement

Fig. 2.44: Phase map related to vertical displacement
Fig. 2.45:
Vectoral representation
of horizontal component
of displacement
(Max. displ. about 2 µm)

Fig. 2.46:
Vectoral representation
of vertical component
of displacement
(Max. displ. about 1.7 µm)

Fig. 2.47:
Vectoral representation
of global displacement
(Max. displ. about 2.5 µm)
Fig. 2.48a: False colour representation of shear strain

Fig. 2.48b: False colour representation of fig. 2.48a
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2.4.1 Triangulation by grating projection

A simple and common way to measure depth contours is to project onto the object's surface a set of equi-spaced, parallel lines and evaluate the modification of their shape produced by the surface profile. This grid can be obtained by using the slide projector considered in the moiré experiments. The method used in this section is based on optical interference and was carried out by using the arrangement depicted in fig. 2.49a,b where a Michelson interferometer, provided with two slightly inclined mirrors, was included.

Contour information is encoded in the phase modulation of the projected fringe pattern. As the sinusoidal fringes are parallel, a one dimensional analysis was carried out. The intensity $i(x)$ in the recording plane of the viewing system can be written as:

$$i(x) = b(x) + c(x) \cos(2\pi f_0 x + \phi(x))$$  \hspace{1cm} (2.11)

where $x$ is the horizontal co-ordinate, $f_0$ is the spatial frequency of the projected lines, $b(x)$ is the image background, $c(x)$ is related directly to the fringe contrast and $\phi(x)$ is the phase. By using special purpose image processing routines the phase can be decoded and the result converted to height [20,21]. As for deformation analysis, two approaches can be considered to solve the phase evaluation problem: the first referring to phase-shifting techniques (one of the mirrors in the Michelson interferometer can be mounted on a piezo-translator) and the second based on Fourier analysis of the image spectrum.

Great attention has to be paid to the quality of the interference fringes: in fact small deviations from the sinusoidal behaviour may introduce errors in the decoding process. Spherical aberration of the optical wavefronts can affect the shape of the fringes and care is needed in the choice of the lenses. If non-collimated wavefronts are projected, special software is needed to correct the curvature effects arising in the profile evaluation. The diameter of the collimating lens ($L_4$ in fig. 2.49) determines the limit of the maximum dimension of the inspected area.

The sensitivity to external factors is low even though the system is based on optical interference: the fringes are very stable because the arms of the Michelson interferometer are only few centimetres long.

An experiment has been carried out on a piece of wood 100x68 mm² showing three hollows roughly carved on its surface with different depth values as in fig. 2.50. The specimen was painted white to improve the quality of the projected fringe pattern in terms of uniformity and fringe contrast.
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Fig. 2.49a: Optical arrangement for interferometric fringe pattern generation.
M1, M2, M3, M4: mirrors; L1, L2, L3, L4: lenses; BS: beam splitter; PZM: piezo modulator

Fig. 2.49b: Michelson interferometer with slightly inclined mirrors.

Fig. 2.50: Specimen for testing the grating projection method (the measures in mm indicate the maximum depth of each hollow).
Fig. 2.51: One of the four phase shifted images of the projected grating

Fig. 2.52: Power spectrum related to the fringe pattern

Fig. 2.53: Contour map of the object

Fig. 2.54: 3D representation
In the phase shifting procedure, a set of four images, differing in phase by $\pi/2$, of the grating projected onto the inspected surface were acquired (fig. 2.51). Phase shifts were introduced by a computer controlled movement of one of the two mirrors mounted on a piezo transducer in the Michelson interferometer. After some image processing and evaluation a phase map was obtained; the subtraction of an inclined plane of reference from it was necessary to obtain the contour map of the object.

For the Fourier analysis just one image was sufficient. After the Fourier transform, the spectrum (fig. 2.52) was obtained, band-pass filtered (background and high-frequency components are cut out) and translated by an amount corresponding to the carrier frequency of the projected fringe pattern. The inverse Fourier transform allowed a reconstruction of the phase modulation in the fringe pattern regardless of the background and contrast components in the image; unwrapping was finally necessary to obtain the final contour map. The final phase map and the 3D representation obtained in both cases are presented respectively in fig. 2.53 and fig. 2.54.

If the surfaces under inspection have very irregular peaks, steep valleys, or holes then shadow effects may arise. Shadowing is the main shortcoming of this technique, especially when the projection angle is close to 90 degrees.

2.4.2 Triangulation by stripe projection

Another triangulation procedure can be performed by scanning the object surface with a light stripe that is modulated by the surface height changes. A number of commercial systems exist but the author decided to construct his own arrangement in order to create a completely open system, easing any desired modification.

The hardware used includes two "theodolites": the first is used to project a vertical light stripe and the second to acquire the scene under inspection; all images obtained with these two theodolites are then processed by special purpose software.

**Theodolite 1: Stripe projector**

This station can simply consist of a projector with a slide having a narrow vertical slit and positioned on a rotating or translating board: the width of the slit must be as narrow as possible, limited just by diffraction effects.

The system arranged by the author consists of a 10mW He-Ne Laser with low beam divergence, a cylindrical glass rod, a mirror and a rotating board (the sketch of the arrangement is depicted in fig. 2.55).

The laser beam is projected onto the cylindrical rod that behaves as a cylindrical lens of very high curvature (the diameter of the rod is of 2mm) giving rise to a stripe of light. A small mirror is used to direct the projection of the stripe.
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Fig. 2.55: Optical arrangement mounted on the projecting theodolite.

Fig. 2.56: Theodolite used for acquisition.

Fig. 2.57: Sketch of the complete system.
Since a perfectly straight line is needed, the alignment of all these components must be very precise: it is especially very important for the laser beam to intersect the rod perpendicularly to its axis. The rod must be perfectly clean in order to obtain a uniformly bright stripe.

This projection system is mounted on a rotating board (Microcontrole) whose rotation angles are driven very precisely by a Compaq 486sx personal computer: the movement can reach resolutions down to $1/100$ of a degree. The board is positioned on a conventional photographic tripod.

**Theodolite 2: CCD Camera for acquisition**

This theodolite, depicted in fig. 2.56, is simply constituted by a CCD camera mounted on another tripod. A high-resolution Sony CCD camera is used, equipped with a set of different objectives: the objective is chosen depending on the dimension and on the distance of the scene under inspection. This camera is connected to a frame grabber (Imaging Technology) controlled by the same Compaq computer. Software has been developed by the author to perform image processing calculations and real time operations. Some steps are necessary in the evaluation process:

- Calibration of the system on test specimens
- Acquisition (scanning of all the surface under inspection)
- Data processing
- Data presentation (2D grey-image presentation, 3D plot)

In fig. 2.57 a sketch of the complete system is presented. This system was applied to the evaluation of the surface profile of the front side of a violin. In the set-up the violin was at a distance of about 2 meters from the viewing theodolite in an horizontal position.

Contouring results are shown with the help of five images:

- 2D grey-level image (fig. 2.58)
- Profile of a section of the surface (fig. 2.59)
- Level-line image with an interline resolution of 1mm (fig. 2.60)
- Level-line of a zoomed area with an interline resolution of 0.2mm (fig. 2.61)
- 3D plot of the surface (fig. 2.62)

### 2.4.3. Moiré technique

The same set-up adopted for deformation analysis and presented in fig. 2.16 or the one described for interferometric fringe projection and presented in fig. 2.49 can be used.
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Fig. 2.58: False colour level image

Fig. 2.59: Profile of a section of the surface
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Level lines in a violin

All units are in cm

Fig. 2.60: Level plot with an interline of 1mm
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Fig. 2.61: Level plot of a detail with an interline of 0.2 mm

Fig. 2.62: 3D plot of the surface
The image of the object is acquired by a TV camera and transmitted to a monitor through an FG100 Imaging Technology image processing board controlled by a Compaq 486sx personal computer.

Four reference gratings shifted by a quarter of the pitch are created digitally by the computer: the frequency must be selected carefully in order to be as close as possible to the carrying frequency observed on the object's surface. Moiré interferograms are then obtained by digitally subtracting the object image from the reference patterns.

A loudspeaker was used as test object and its profile was studied by using the moiré technique. The object, illuminated with a Ronchi grating was displayed on the monitor, and the image was acquired and stored in memory. About 80 vertical lines on the surface could be observed from the monitor. Four sinusoidal images in the horizontal direction, with 80 peaks each and a shift of a quarter of pitch in between, were created digitally via the computer. In fig. 2.63 the result of subtraction of the acquired image with one of these four is shown. For this application, a low-pass filter in the Fourier domain improved the quality of the interferograms: in fact the unwanted high frequency was very well known and so it was easy to choose the cut-off limit. The spectrum of the original image and the result after filtering are shown in fig. 2.64 and fig. 2.65.

Finally the image resulting from the phase retrieval process followed by the phase unwrapping is presented in fig. 2.66 and the corresponding 3D profilometric plot in fig. 2.67.

2.4.4. Dual wavelength Holographic Interferometry

It is well known that holography (and ESPI) allow an interferometric reconstruction of two wavefronts recorded at different times[22]. If the difference of the path-length between these two wavefronts is made to depend on the surface geometry, a double exposure hologram shows level lines describing exactly the object contour. A first beam of wavelength \( \lambda_1 \) and a second of wavelength \( \lambda_2 \) are used for illuminating the object and creating two holograms on the same recording medium. If only \( \lambda_1 \) is used in reconstruction, the object is superimposed by contour lines with intensity maxima in correspondence of height differences of

\[
\Delta z = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}
\]

(2.12)

The method is contactless but the main drawback comes from the laser sources to be used: two wavelength holographic contouring has been tried [23] with combination of different sources (Argon + He-Ne, Argon + Ruby) or by tuning the same laser (Dye [24] or Semiconductor lasers [25]).
Fig. 2.63: Interferometric contouring pattern obtained with the moiré technique

Fig. 2.64: Power spectrum of the interferogram

Fig. 2.65: Interferometric contouring pattern obtained after low pass filtering
Fig. 2.66: Phase map related to profile of the loudspeaker

Fig. 2.67: 3D representation of the profile
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If an Argon (514 nm) and a He-Ne (633 nm) laser are used, the contouring resolution is about 3 microns.
Instead of changing the wavelength of the illuminating laser, contour fringes can be obtained by changing the refractive index of the medium in which the object is dipped [26].

Intensity maxima are located where the difference in phase between the two wavefronts is an integer multiple of $2\pi$. The depth difference between two consecutive fringes is

$$\Delta z = \frac{\lambda}{n_1 - n_2}$$

(2.13)

where $n_1$ and $n_2$ are the refraction indexes of the medium in the two acquisitions.

With both these methods, resolution tuning is possible. No shadowing effects limit the area of inspection as in the previous techniques based on fringe projection.

This holographic method has been tested by the author for evaluating the profile of a shell immersed in a solution of water and sugar [27] (a sketch of the experimental set up is presented in fig. 2.68). After a first exposure, the concentration of the solution was changed by adding some sugar and a second exposure was performed. The contour resolution could be controlled very well by simply changing the concentration of the solution (the relationship between sugar concentration and refraction index can be found tabulated in many texts [28]).

Contour fringes of the shell are depicted in fig. 2.69: they correspond to a change in concentration corresponding to a resolution of 1 mm. The experiments are a simple approach to the holographic technique and further application of two laser wavelengths can be eventually tried.

As for holography, dual-wavelength ESPI, usually in conjunction with tunable diode lasers, has been applied in the literature for the evaluation of surface contours [29].

2.4.5. Coherence radar

By using the system described in fig. 2.70 [30,31] it is possible to evaluate the profile of some surfaces with a resolution of around 0.1 microns, depending on the light source adopted.

At the beginning of the procedure, the reference mirror is positioned closer to the beamsplitter than the object surface. By moving the mirror step-by-step away from the beam splitter, the reference plane scans the object surface: every speckle on the surface modulates only when the difference of optical paths between the reference and the object surfaces is within the coherence length of the used light.
Fig. 2.68: Experimental set-up for contouring by double holographic interferometry. The object is dipped in a solution; the concentration is changed by adding sugar.

Fig. 2.69: Contour fringes obtained on a shell's surface
The CCD pixels are labelled by integer pairs \((i,j)\) and the corresponding 8 bit digitized intensity values at the N-th translation step are denoted by \(I_N(i,j)\). The absolute value of the difference \(I_N(i,j) - I_{N-1}(i,j)\) is calculated for each pixel and compared with a reference value \(I_s\). More precisely, for those pixels such that

\[
|I_N(i,j) - I_{N-1}(i,j)| > I_s
\]  \hspace{1cm} (2.14)

(undergoing a modulation) a value \(N\) was assigned. At the end of the translation process of the reference mirror, to every pixel corresponded a value related to the last step for which condition (2.14) was fulfilled. From this profile map the 3D surface of the object could be simulated. To obtain a good profile map the speckle contrast variations at each step must be greater than the CCD noise: a proper choice of the threshold value \(I_s\) can eliminate the CCD noise as well as small intensity fluctuations of the illuminating beam. In fig. 2.71 an example of 3D profile obtained by the above procedure is reported.

The vertical resolution attainable by the proposed method is related to the coherence length of the adopted light source. Lateral resolution can be related to the pixel dimensions of the CCD camera, speckle size and system's optical magnification: the inspected area is usually smaller than 20 cm\(^2\).
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Fig. 2.71a: False colour image of the profile of a coin obtained by the coherence radar technique

Fig. 2.71b: Three-dimensional plot of Fig. 2.71a
2.5. Conclusion

Optical techniques are very interesting and very well suited for non-destructive analysis and testing. Their success comes from some interesting features they intrinsically have: contactless measurements, full-field inspection and good resolution (if compared to other more traditional techniques).

They have been widely used in many fields of application to identify the deformation occurring on surfaces when they are subjected to external agents or to evaluate their shape. From this information it could be possible to study the complete strain status and by simply knowing the mechanical characteristic parameters of the material under inspection, to retrieve the stress distribution.

Vibration analysis can be performed in real-time: it allows the identification of resonance frequencies of some structures that could be eventually critical for their safety.

The work described in chapter 2 has given the author an insight into the application of some well-known optical techniques for surface state identification. Carrying out these experiments and the subsequent analysis of the results obtained has enabled him to acquire complete familiarization with all these methods.

Due to the continuous increase in the volume of applications and the evolution of hardware and software capabilities, this is a field in expansion and open to the exploitation of improvements or completely new solutions. Many features will need optimization: portability, physical size, insensitivity to external agents and flexibility of application.

In chapter 3 some novelties coming from the author’s research are presented: new techniques, new arrangements and new interpretation methods based on ideas generated during the above investigations are there described.

Many optical techniques described in chapter 2 and chapter 3 find, finally, original application in chapter 4.
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Development of new techniques, instrumentation and interpretation methods

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3.5. REFERENCES
Introduction

Chapter 3 begins with the presentation of the original and innovative work that has been accomplished by the author. New optical techniques, new optical arrangements and some new fringe analysis tools are here presented.

The contributions that are described here are almost completely new and are a direct consequence of the experience acquired by the author in the field. While in this chapter priority is given to the description of some new measuring techniques and systems in the field of optics, in chapter 4 the attention will focus on the applications.

The chapter has been subdivided in three subsections:
- new techniques
- new optical systems
- new methods of analysis.

Before starting, it is important to make clear what "new" conceptually means in this context: the author has not the presumptuousness of having invented anything from nothing, but just the consciousness of having brought some upgrading or innovative idea to the production of something that is actually new in the scientific panorama. Some of these solutions will find their application in chapter 4.

3.1. New techniques

In this section two techniques, in which some new features have been introduced, are presented: they deal with the application of speckle decorrelation analysis to the study of the modification of surfaces and with an innovative ESPI technique for the inspection of stationary vibrations in real-time.

3.1.1 Speckle decorrelation for inspection of surface modification

3.1.1.1. Introduction

Obviously, this technique can be used only for those surfaces where the formation of speckle is possible.

Optical correlation measurements have usually been performed by holographic and speckle techniques. Holographic correlation has been successfully applied to evaluate fatigue damage [1], quality control [2] and surface displacement [3]. Interesting results have been reported by Hinsch and co-workers [4], who successfully monitored the effects of humidity variations on stone surfaces. However, since the correlation signal refers to the whole illuminated area, no information is obtained on the local distribution of the surface alterations.
In speckle correlation measurements, results have been obtained mainly in surface roughness studies [5], and particle sizing [6]. Only recently, digital methods for image processing have unfolded new perspectives in the analysis of correlation phenomena. In particular the work by Chu et al. [7] is an interesting example, in deformation analysis, of local correlation between small areas of two speckle images. Local modifications of the surface microstructure can be adequately monitored by measuring the corresponding changes in the speckle image. Speckle modification could be actually related to a number of factors [8]: it would be interesting to relate these changes to the transformations of the surface. Actually, the aim of this section is to demonstrate the possibility of relating the digital difference of two speckle images coming from the same surface at different instants, with the decorrelation coefficient. This technique will be applied in chapter 4 for studying and characterizing the modifications of the surface of stones, due to salt efflorescence [9-11].

### 3.1.1.2. Principle and theory

When a rough surface is illuminated by coherent light, it appears to be covered with randomly distributed bright grains, called "speckles". In his review article [12] Goodman provides a comprehensive description of the statistical properties of laser speckle patterns. If \( m \) is the mean value of the light intensity \( I \), the probability distribution \( p(I) \) is described by

\[
p(I)dl = \frac{1}{m} \exp \left( -\frac{I}{m} \right) dl
\]

where the phase of the speckles is uniformly distributed in the range 0-2\( \pi \). This model is valid under the hypotheses of illumination with monochromatic light and perfectly polarized speckles.

In the present study, a point by point correlation between the intensities of two speckle patterns is carried out. Let \( I_1 \) and \( I_2 \) be the intensity values for the same point in the image plane at two different times \( t_1 \) and \( t_2 \). If the intensity mean value is \( m \), and the standard deviation is \( \sigma = m \), the correlation coefficient \( \rho \) is expressed by:

\[
\rho = \frac{\langle (I_1 - m)(I_2 - m) \rangle}{\sigma^2} = \frac{\langle I_1 I_2 \rangle - m^2}{m^2} = \frac{\langle I_1 I_2 \rangle}{m^2} - 1
\]

where the angular brackets indicate the averaging operation that should be evaluated over many images for each point. Alternatively, if correlation is assumed constant for a
small area of an image, a spatial average over a number of pixels in the close
neighbourhood of that point can be calculated.

If \( I_1 \) and \( I_2 \) are identical, then completely correlated, \( \langle I_1 I_2 \rangle = \langle I_1^2 \rangle \), and since the probability theory yields \( \langle I_1^2 \rangle = \sigma^2 + m^2 = 2m^2 \), a unity correlation coefficient \( \rho = 1 \) results.

On the contrary, when \( I_1 \) and \( I_2 \) are independent, and consequently uncorrelated, \( \langle I_1 I_2 \rangle = \langle I_1 \rangle \langle I_2 \rangle = m^2 \) and a null correlation coefficient \( \rho = 0 \) is obtained.

3.1.1.3 Relation between correlation coefficient and digital subtraction of speckles

The relation between \( \rho \) and \( \langle (I_1 - I_2)^2 \rangle \) is next derived. Starting from

\[
\langle (I_1 - I_2)^2 \rangle = \langle I_1^2 + I_2^2 - 2I_1I_2 \rangle = 4m^2 - 2\langle I_1I_2 \rangle
\]  

(3.3)

it is readily seen that:

\[
\langle I_1I_2 \rangle = 2m^2 - \frac{1}{2} \langle (I_1 - I_2)^2 \rangle
\]  

(3.4)

and finally, the correlation coefficient can be expressed as

\[
\rho = 1 - \frac{\langle (I_1 - I_2)^2 \rangle}{2m^2}.
\]  

(3.5)

This demonstrates that the correlation coefficient can be effectively deduced by squaring and averaging the arithmetic difference between the speckle images \( I_1 \) and \( I_2 \).

The intensity of a "grain" of the speckle pattern is made of contributions from an area \( A_0 \) in the object plane. According to the diffraction theory, the diameter of \( A_0 \) is \( D = 2.4\frac{\lambda z_0}{a} \). If, for example, the object is at a distance \( z_0 = 50 \) cm from the camera, the illuminating wavelength is \( \lambda = 633 \) nm, and the viewing aperture is \( a = 1.5 \) cm, the diameter of the area \( A_0 \) is \( D = 50 \) \( \mu \)m. Any surface alteration in \( A_0 \) accounts for a change of the speckle intensity.

In this way it is possible to relate the intensity difference to the rate of decorrelation of every single area \( A_0 \) of the surface. In chapter 4 this technique will be applied by the author to the evaluation of the real-time modification of a stone’s surface due to the salt efflorescence mechanism.
3.1.2 Vibration analysis with ESPI

Many different techniques have been developed for inspecting, in real-time, stationary vibrations occurring on surfaces. The most common method used for vibration analysis is the time-average method.

A common arrangement for out-of-plane ESPI analysis (fig. 2.6) can be adopted and general equations described in appendix C can be still applied to the description of the phenomenon[13,14]. While in common deformation analysis surface displacement can be considered quasi-static (i.e. slower than the acquisition rate of the CCD camera), in vibration studies the object is continuously moving. For this reason the local phase of the field diffused from the object must be expressed with a time dependent function:

$$\phi(x,y,t) = \frac{4\pi}{\lambda} z(x,y,t) + \phi_o(x,y)$$

(3.6)

where $z(x,y,t)$ is the displacement of a point denoted by $(x,y)$ at time $t$ and $\phi_o(x,y)$ is the phase of the same point in static conditions.

With this change equation C.3 becomes:

$$I(x,y) = o^2(x,y) + r^2(x,y) + 2o(x,y)r(x,y)\cos(\frac{4\pi}{\lambda} z(x,y,t) + \phi_o - \phi)$$

(3.7)

or, in a simpler form,

$$I = I_o + I_r + 2\sqrt{I_o I_r} \cos(\frac{4\pi}{\lambda} z(t) + \phi)$$

(3.8)

If the vibration frequency is considerably higher than the acquisition rate (usually 50 Hz for a CCIR standard CCD camera), the second term in equation 3.8 is acquired averaged in time

$$I(x,y) = A + B \frac{1}{\tau} \int_0^\tau \cos\left[\frac{4\pi}{\lambda} z(x,y,t) + \phi(x,y)\right] dt$$

(3.9)

where $\tau$ is the acquisition period of the single frame.

If the object is vibrating harmonically with an angular speed (radial frequency) $\omega$, the displacement of every single point is described by

$$z(x,y,t) = Z(x,y)\sin(\omega t)$$

(3.10)
and equation 3.9 becomes

$$I(x, y) = A + B \cos \frac{4\pi}{\lambda} Z(x, y)$$

(3.11)

This means that, apart from a certain background value, the intensity pattern is modulated by a Bessel function with some unavoidable speckle noise superimposed. If this distribution is compared to the one obtained with holographic interferometry [15], a difference is immediately obvious: in ESPI measurements the intensity is modulated by $J_0$ (equation 3.11) while in Holographic Interferometry by $J_0^2$ (equation G.6 in appendix G). Remembering that the Bessel function varies between 0 and 1, it is clear that the contrast is better in ESPI measurements.

The shape of the Bessel function is depicted in fig. 3.1 and the points of its zero values are presented in Table 3.1.

<table>
<thead>
<tr>
<th>n</th>
<th>$\xi_n$</th>
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<th>$\xi_n$</th>
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<td>12</td>
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<td>8.65</td>
<td>13</td>
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<td>15</td>
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</tr>
<tr>
<td>10</td>
<td>30.63</td>
<td>20</td>
<td>62.05</td>
</tr>
</tbody>
</table>

TABLE 3.1: Zero values of the Bessel function

It may be concluded that, in principle, with a CCD camera having very good resolution and very good dynamic range of acquisition, the results obtained with ESPI can be really good, but the drawback due to the presence of speckle noise is always present! ESPI fringe patterns can be generated without (analogue method in paragraph 3.1.2.1) and with (digital method in paragraph 3.1.2.2) the use of digital frame grabbers. In paragraph 3.1.2.3 an original digital method is proposed by the author: some experiments are performed and a comparison with other procedures is attempted.
Chapter III: Development of new tools

Fig. 3.1: The Bessel Function

Fig. 3.2: Optical arrangement for ESPI vibration analysis with reference active control
3.1.2.1. Analogue method

A simple ESPI technique, not requiring the use of frame grabbers, for obtaining interferograms of stationary vibrations directly on a monitor was adopted in initial experiments presented in the literature [13]. If the intensity described by equation 3.11 is directly displayed on a monitor, only variations in the contrast of the speckle pattern can be observed. However, if the electronic signal from the camera is first high-pass filtered and rectified, correlation fringes can be observed. The contrast of the interferogram is usually poor and few antinodes can be observed. Moreover, in many cases, the spatial frequency of \( J_0 \) is rather low and a low-pass filter for background elimination is practically difficult to design. The visibility of time-averaged vibration fringes is considerably improved if the laser beam is amplitude modulated at source (i.e. stroboscopic ESPI). An additional technique, which is an extension of stroboscopic ESPI, relies on the phase modulation of the reference beam at the same frequency of the object [14]: this technique can reach displacement amplitude resolutions down to the nanometric range. The main limitation of this technique is due to the necessary \textit{a priori} knowledge of the stationary frequency of vibration of the surface. The usual method is to produce actively, by using piezoelectric transducers, the surface vibration and to modulate the phase of the reference in the same way.

3.1.2.2. Digital method

By using a frame grabber for real-time subtraction, some other solutions can be adopted and the author focused his attention on these method. The first procedure consists of acquiring the speckle pattern of the steady state surface as a reference and to subtract from this the speckle pattern generated during vibration. If an absolute subtraction is performed between equation 3.11 and equation C.4, the following intensity distribution yields:

\[
I(x, y) = A + B \cos \phi J_0 \left[ \frac{4\pi}{\lambda} Z(x, y) \right]
\] (3.12)

In this way the background has been eliminated. The advantage comes from the possibility of inspecting all stationary vibrations without any electronic filtering of the camera signal. However the quality of the interferograms is still poor: improvements can be obtained if image processing is applied for speckle noise reduction and contrast enhancement.
Another solution consists of acquiring a first time-averaged pattern as the object is vibrating, the intensity being described by equation 3.11. Without changing the stationary frequency of the object, and introducing a phase variations $\alpha$ in the illumination or reference field, a second time-averaged pattern is acquired\[16].

$$I_2(x, y) = A + B\cos(\phi + \alpha) J_0\left[\frac{4\pi}{\lambda} Z(x, y)\right]$$ (3.13)

By performing an absolute subtraction, the following distribution yields

$$I(x, y) = |I_2 - I_1| = |2B| J_0\left[\frac{4\pi}{\lambda} Z(x, y)\right] \sin\left(\phi + \frac{\alpha}{2}\right) \sin\left(\frac{\alpha}{2}\right)$$ (3.14)

The intensity contrast reaches the maximum value $|2B|$ when

$$\sin\frac{\alpha}{2} = 1 \quad \frac{\alpha}{2} = (2m + 1)\frac{\pi}{2} \quad \alpha = (2m + 1)\pi$$

and the intensity distribution becomes

$$I(x, y) = |I_2 - I_1| = |2B| J_0\left[\frac{4\pi}{\lambda} Z(x, y)\right] \cos(\phi)$$ (3.15)

that is very similar to equation 3.11, with the difference that the background has been eliminated, and to equation 3.12, with the difference that the peak value has been doubled. It may be concluded that in this way, the contrast is actually higher.

3.1.2.3. Digital method with reference active control

Phase changes $\alpha$ can be introduced by ambient conditions, as thermal gradients or air flows: they are almost random and often not uniform all over the field of view. Another drawback comes from the need of upgrading the reference speckle every time that the vibration frequency changes.

The author designed the arrangement described in fig. 3.2 where it is possible to introduce actively phase changes of $\pi$ in the reference path in order to fulfill the optimum condition in equation 3.14 \[17\]. The phase was modulated in two different manners:

- by changing the path length
- by changing the refractive index.
Variation of geometric path length

The phase of the reference field can be modulated by simply changing the geometric length of the path. This was obtained, for example, by using the configuration depicted in fig. 3.3 where a mirror was mounted on a piezoelectric transducer and moved forward and backward by a simple change in the driving voltage. The dependence of the introduced phase $\alpha$ from displacement $d$ of the mirror is given by:

$$\alpha = \frac{4\pi}{\lambda} d$$

and if a phase shift of $\pi$ is needed, it is sufficient to displace the mirror by $\lambda/4$.

It was not difficult to find 2 voltage values producing this desired relative displacement of the mirror. The calibration had not necessarily to be perfect: it was experimentally observed that with deviations of $\alpha$ of $\pm20\%$ from $\pi$ good results were still obtained.

Variation of index of refraction

The phase of the reference can also be modulated by introducing a small change in the index of refraction of the reference path. This could be obtained, for example, by using the configuration depicted in fig. 3.4 where an LCD crystal was inserted.

It is well known that a change in the index of refraction $\Delta \varepsilon$ in a certain material produces an optical path change:

$$\Delta l = d \Delta \varepsilon$$

where $d$ is the distance travelled inside the material, introducing a shift in the phase

$$\alpha = \frac{2\pi}{\lambda} d \Delta \varepsilon$$

Liquid Crystal Cells are lattices in which the principal direction of the molecules can be changed by applying an external voltage producing, in this way, some physical changes such as a new refraction index or a new polarizing behaviour [18].

It was not difficult to find 2 voltage values producing a relative phase shift of $\pi$ without changing polarization. The use of a Liquid Crystal instead of a piezoelectric transducer brought some advantages: it was smaller and less delicate to handle, less expensive and required lower control voltages.
Chapter III: Development of new tools

Fig. 3.3: Reference modulation by mirror movement

Fig. 3.4: Reference modulation by index of refraction change (LCD Crystal)

Fig. 3.5: Interferogram showing a stationary vibration occurring on the surface of an impeller stimulated at a frequency of 647 Hz
This system allows a continuous monitoring of stationary vibrations. Continuous acquisition, real-time subtraction and modulation of the phase in the reference path by a square wave permit, in an easy way, the inspection of the evolution of vibration phenomena.

The process was driven by a routine acting as a continuous loop in which the phase of the reference path was step modulated (by using a square voltage signal) between $\pi$ and 0 at the frequency acquisition rate of the CCD camera. Every acquired frame was subtracted from the next one: this continuous upgrade of subtracted time-averaged speckle patterns allowed a perfect control of the surface behaviour as the excitation frequency changed.

Many interferograms were obtained with the application of this active control; an example is presented in fig. 3.5: it represents an impeller excited at a frequency of 647 Hz.

3.2. New optical arrangements

Some new optical systems have been developed to facilitate applications that will be described in chapter 4. The aim has been to conceive optical arrangements not easily available on the market: thus, systems for complete in-plane evaluation of deformations and portable systems for direct application in-situ have been designed.

The use of optical fibres can bring enormous advantages and can fulfil requirements of flexibility and portability when they are needed and so they have been incorporated in the designs where appropriate.

3.2.1 Portable systems

Some different portable systems, having different degrees of complexity, have been conceived at Ispra by the optical group where the author worked, with the external support of the University of L'Aquila for the use of optical fibres. Interferometric experiments, at first possible just if a vibration-free table was used, became feasible directly in-situ: measurements in laboratories of experimental mechanics, in museums, in churches, were in this way performed.

All these portable systems are composed of two different parts: an optical "head" for object illumination and pattern acquisition, and a computing station for interferogram analysis, information retrieval and data processing.
3.2.1.1 Computing station for interferogram analysis

The computing station has the purpose of acquiring the speckle patterns coming from the surface under inspection, performing the digital subtraction and showing the resulting intensity distribution on a monitor (fig. 3.6). In order to make this station easily transportable, light devices must be used.

A portable computer Toshiba T3200SXG (13 Mbyte RAM, 160 Mbyte hard disk) was used as host computer, including a frame grabber Data Translation DT-2862 for image digitization and processing. This graphic board has a memory of 1 Mbyte distributed into four pages of 512 x 512 pixels, with 8 bit resolution each. Special purpose software for image processing and phase retrieval has been included for the extraction of quantitative results.

All patterns, interferograms and processed images (phase maps, profiles, 3D plots) are displayed on a 9 inch colour monitor. With the use of a video recorder it is possible to store on a tape the real time evolution of fringes for a later examination of the experiment.

![Diagram of the computing station](image)

Fig. 3.6: Scheme of the instrumentation used in the computing station of portable systems
3.2.1.2 Optical heads for speckle pattern acquisition

In this section, the design and application of novel ESPI arrangements are described. Some basic optical configurations have been designed by simply using optical components arranged on a steel board. Improvements to this simple configuration have been conceived for increasing the portability and the flexibility of the system, especially with the introduction of laser diodes and the application of optical fibres.

**Portable system 1: Board 60x30 cm**

The basic optical elements necessary for ESPI measurements have been placed on a steel bench (30x60cm): a He-Ne laser (Melles Griot $\lambda=632\text{nm}$, $P=10\text{mW}$), a beam-splitter cube, some mirrors, an expanding lens and a Sony CCD camera for image acquisition (fig. 3.7). All the components have been mounted on magnetic bearings and the optical configuration can be easily modified. It is possible to change the angles of illumination of the object, to move from the in-plane sensitive to the out-of-plane sensitive configuration, to change the distance of the inspected surface from the video camera and to modify the path of the beams. This system was used directly in the field by the Author, especially for testing surfaces of specimens subjected to the action of machines that could not be moved to optical labs [19-21]. In these measurements the steel board was strongly fixed to the testing machine in order to avoid, as far as possible, any relative motion between the optical arrangement and the surface of the specimen.

This system has been used for in-plane rather than for out-of-plane deformation evaluation. In fact, in-plane sensitive configurations are subjected to a lower relative motion between the two interfering wavefronts (coming from the same surface) as they follow similar paths. In fig. 3.8 a photograph of the system in its in-plane sensitive configuration is shown.

Although some good results were obtained with this system, it was decided to build up smaller and lighter arrangements for increasing the portability of the optical set-up.

**Portable system 2: Box 21x15cm (out-of-plane sensitive)**

An overall reduction of the system's dimension was obtained by using smaller optical components and by substituting the He-Ne laser with a diode laser. The small size of semiconductor lasers makes their use as light sources very attractive in the design of portable systems: as a result, diode laser systems have recently been applied to interferometry [22], holographic interferometry [23] and ESPI [24].
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Fig. 3.7: Optical arrangement of portable system 1 in its in-plane configuration

Fig. 3.8: Photograph of portable system 1 in its in-plane configuration.
The use of laser diodes, however, requires some additional control when applied to interferometric measurements. In order to maintain an acceptable frequency stability, a temperature control is necessary, commonly obtained by using a Peltier cell. In this way, coherence lengths of some metres can be obtained. The wavefront emitted from the laser diode is not spherical but usually shows an elliptical shape (almost a line) for it is emitted from a junction. In order to produce a spatially uniform intensity output, special purpose optical components are required. The solution adopted in this work was based on the use of optical fibres directly connected to the laser, giving a good quality spherical output.

A factory-built system (mod PM-550I-780-HL7851G by Seastar Optics Inc.) composed of an optically isolated pigtailed laser diode with polarization maintaining fibre and thermoelectric cooler was used (see fig. 3.9). The laser source (HITACHI HL7851G, $P=50$ mW, $\lambda=785$ nm), is coupled to a polarization preserving single mode fibre (YORK HB750) and to avoid amplitude instabilities or frequency drifts of the optical radiation caused by reflections, the coupling arrangement includes an optical isolator (35 dB) based on a Faraday crystal. The output light from the optical fibre has a spherical wavefront (no astigmatism), an excellent polarization figure (640:1), and a power of $P=6$ mW at an operating diode current $I_{op}=129$ mA. The laser diode junction is temperature stabilized by a thermoelectric controller (mod. TC5100) using a Peltier device driven by a feedback circuit and with this control a coherence length longer than 4 meters was effectively measured in the laboratory.

The size of the CCD camera was important for the final dimension of the system: smaller and smaller devices for video acquisition are offered by the market with high sensitivity, resolution and noise immunity. A TELI B/W CCD camera model CS3330L was used for image acquisition. The camera head is very compact and lightweight, since most of the electronic circuitry is contained in an external control unit. The sensor matrix has 756x581 pixels, each of which has a unit cell 11x11 µm resulting in a detection area of 8.8x6.6 mm. The signal to noise ratio, specified in the data sheets, is 50 dB.

The main drawback is related to the reduced possibility of changing the experimental configuration with respect to portable system 1.

An arrangement sensitive just to out-of-plane displacements has been designed and the optical set-up is schematically presented in fig. 3.10. The laser light emitted by the output end of the optical fibre directly illuminates the surface under investigation. Since the glass core of a monomode fibre has the diameter of just few microns, the output wavefront can be considered spherical and presents a smooth wavefront.
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Fig. 3.9: Scheme of the diode laser's packaging

Fig. 3.10: Optical arrangement of portable system 2 (out-of-plane)

Fig. 3.11: Photograph of the optical arrangement of portable system 2
A small part of the spherical wavefront is caught by a polarizing beam-splitter cube (BSC1, 0.5" side), and is used as a reference beam. Another beam-splitter cube (BSC2, 0.5" side) reflects the reference light onto the CCD sensor, where it interferes with the object image focused by the objective lens L1. A 3:1 ratio between the object and reference beams can be obtained by changing the aperture of the viewing lens and by adjusting the fibre output polarization until the reference beam intensity is minimized. The system is completely closed in an aluminium box in order to protect optical elements from dust and to reduce the ambient light intensity falling on the CCD sensor. A photograph of the system's internal arrangement is shown in fig. 3.11.

The optical "measuring head" is usually positioned over a conventional photographic tripod. All the electronic devices for laser diode operation (power supply, control unit and temperature stabilizer), or for CCD camera control (power supply and control unit) are mounted in a rack that can be easily moved and positioned next to the tripod.

**Portable system 3: Box 21x15 cm (in-plane sensitive)**

An optical head has been designed for the generation of interferograms descriptive of in-plane displacements. It has the same external dimensions of portable system 2, but the number and the arrangement of the optical elements are different. A design of this device is presented in fig. 3.12: a beam-splitter cube, two mirrors and the same CCD camera described before are the components used in this set-up. Their position is not fixed but can be changed by the operator, allowing a certain flexibility in selecting the system resolution (related to the illumination angle) and the dimension of the illuminated area.

The same pig-tailed laser diode described in portable system 2 can be used: the light at the output of the fiber is re-directed on the two mirrors by the beam-splitter cube and then pointed onto the inspected area. A photograph of the system's internal arrangement is shown in fig. 3.13. This optical head can again be put on a tripod, or directly connected to the portion of the object to be observed, in order to assure a better relative stability between measuring device and surface. As the two interfering fields are following almost the same optical path, the coherence length of the adopted laser is not as critical as for out-of-plane measurements. All the associated electronic devices are again included in a separate rack.

**Portable system 4: all optical fibre paths (in-plane sensitive)**

The design of this optical system has been conceived within a collaboration with the Energetics Department of the University of L'Aquila in Italy.

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Fig. 3.12: Optical arrangement of portable system 3 (in-plane sensitive)

Fig. 3.13: Photograph of the optical arrangement of portable system 3
Optical fibres were introduced into an ESPI layout to make the measuring system very flexible and suited for in-situ operation. The use of optical fibres offers the possibility to measure either in-plane or out-of-plane displacements by simple readjustments of the set-up [25].

The polarized light of a He-Ne laser (Melles Griot mod. 05-LHP-991), was launched into a single mode fibre. A coupling efficiency of 50% was readily obtained when the fibre end was correctly cut and cleaned. The fibre, approximately one meter long, was the input of a bi-directional coupler (Newport model F-506-A), which split the light with a 50%±5% ratio between two output single mode fibres. Small variations of temperature and polarization had negligible effects on the splitting ratio of the coupler. However the coupler introduced an additional power reduction of 9%, specified by the manufacturer as intrinsic power loss. Since the glass core of a monomode fibre at 632 nm has a diameter of only a few microns, the output wavefronts can be considered spherical, as happened for the pig-tailed lasers. If the object is symmetrically illuminated, (as depicted in fig. 3.14), sensitivity to horizontal in-plane displacements is obtained. A complete study of the in-plane deformation can be performed if the illuminating fibres are rotated by ninety degrees around the viewing axis to make the system sensitive to vertical in-plane displacements. The sensitivity of the measurements depends on the angle \( \theta \) (see equation 2.2); in practice, small values of \( \theta \) were used to give more compactness to the system and to avoid contrast losses due to speckle decorrelation effects. A CCD video camera (VIDEOSYS CCD 500 614 x 806 pixels), with a zoom lens (MITAKON wide MC 1:2.8 f=28 mm) was used to capture the speckle images.

**Portable system 5: all optical fibre paths (out-of-plane sensitive)**

To measure out-of-plane displacements, it was decided to use a smooth in-line reference beam configuration. In practice, the end of a single mode fibre at the fiber coupler output was used as a point source reference wave (see fig. 3.15). The fibre end was positioned at ninety degrees from the optical axis of the viewing lens and a beam splitter cube was finally used to align the reference and object beams. Unlike the previous set-up for in-plane displacements, the optical paths needed to be matched. The optical path difference between reference and object beams was effectively reduced by increasing the reference path with the addition of a single mode fibre, coupled to the reference fibre using gradient-index (GRIN) lenses [26].

Power losses were intentionally introduced by misalignment of two GRIN lenses (SLW 1.8-0.25p-0.63, Nippon Glass Sheet) in order to control the intensity value of the reference beam at the CCD plane.
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Fig. 3.14: Optical arrangement of portable system 4 using optical fibres (in-plane)

Fig. 3.15: Optical arrangement of portable system 5 using optical fibres (out-of-plane)
The ratio between the reference and object beam intensities was set at a typical value of 3:1 for each measurement. The object was illuminated with the other output fibre from the coupler. In both configurations, sensitive to in-plane or out-of-plane displacements, at a working distance of 40 cm from the camera lens, an object area of approximately 10x10 cm was inspected.

3.2.2 ESPI system for automatic complete in-plane inspection

The illumination arrangement

For a complete in-plane deformation analysis, the object under inspection must be illuminated from four directions, lying on two perpendicular planes, as can be seen in fig. 3.16. One plane of illumination makes the system sensitive to deformation in the vertical direction and the other in the horizontal direction.

A system having this purpose has been designed by the author [27,28]: four mirrors are positioned at the extremities of an imaginary Greek cross, with a CCD camera in the centre having a viewing direction perpendicular to the surface. This system is sketched in fig. 3.17a,b: the mirrors are mounted on steel railings where they can be moved in order to change the illumination directions with respect to the normal. Typical illumination angles are set at 30 degrees away from the surface normal. The system incorporates an opto-electronic LCD based switch allowing a fast automatic change between the two planes of illumination. As a light source, a cw Nd:YAG diode-pumped laser (COHERENT frequency-doubled, $\lambda$=532 nm, $P$=200 mW) is used. It is very useful because it is compact (50x15x10 cm) if compared with other lasers having the same output power, doesn't require any cooling apparatus and has a very high coherence length (more than 100 m). A photograph of the front view of the system is presented in fig. 3.18.

The opto-electronic switch

An opto-electronic switch was created by using a Liquid Crystal Display (LCD) and a polarizing beam-splitter cube. An LCD is normally made of birefringent material and can be used as a variable retarder: in fig. 3.19 a typical graphic of retardance as function of applied voltage for a nematic LCD is presented [29].

Retarders are used as optical components to change the polarization of incoming light: if linearly polarized light with wavelength $\lambda$ enters a retarder whose fast axis is 45° to the input polarization, the polarization at the output is related to the retardance $\delta$ (as shown in fig. 3.20)[30].
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-- -- -- Planes

--- --- Rays

--- --- Normal

Fig. 3.16: Illuminating geometry for complete in-plane deformation analysis

Fig. 3.17a,b: Sketch of the system for complete in-plane deformation analysis:

a) front view b) back view
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Fig. 3.18: Photograph of the front view of the system for complete in-plane deformation analysis

Fig. 3.19: Plot of retardance as function of applied voltage for a common nematic LCD
By carrying out preliminary benchmark tests on the LCD it is possible to evaluate the voltages corresponding to retardances of $\delta=\lambda/2$ and $\delta=0$: the first ($V_1$) rotates the input polarization by $90^\circ$ whereas the second ($V_2$) leaves it unchanged. 

When a linearly polarized light source is used, for each of these two selected voltages only one output direction is actually permitted by the beam-splitter polarizer cube positioned after the LCD (fig. 3.21). The desired propagation direction can be changed by simply switching the voltage applied to the LCD: path 1 or path 2 are respectively selected when voltages $V_1$ or $V_2$ are applied. The ratio between the intensity propagating in the selected and in the undesired directions (commonly called extinction ratio) has been experimentally evaluated at better than 20:1.

This is a completely electro-optical switch and unlike mechanical shutters or Pockel's cells no physical movement or high voltage control are required. Applied voltages used for this control are commonly lower than 10 Volts. Response times are not instantaneous because the molecules in the LCD need a certain time to reorient themselves ($\tau < 100$ msec).

The computing station

Experiments are completely controlled by a 586 Pentium Intel personal computer containing two electronic cards:
- an Imaging Technology frame grabber FG-100 connected to a Sony CCD camera for image acquisition and processing
- a National Instruments PCplus DAC (Digital to Analog Converter) for driving the opto-electronic switch.

Interferograms representing the deforming specimen can be observed sequentially in real time for both horizontal and vertical directions of displacement, depending on the driving voltage to the LCD; they are displayed on an RGB monitor and they can be stored in a tape by using a video recorder.

The computer allows fast image processing of the images and quantitative data can be obtained.

In fig. 3.22 a picture of the computer controlled set-up is presented.

3.2.3 Other new systems

In this section a brief description of two optical systems, both using optical fibres, has been included. Actually, they will not be used in chapter 4 but their application in some cases should be really interesting. The first presentation deals with the description of an endoscopic system used for ESPI purposes and the second with a phase compensating system for the correction of unwanted phase changes, due to ambient factors, in fibre optics systems.
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<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
</table>
| Retard. $\delta = \lambda /2$ | Retard. $\lambda /4 < \delta < \lambda /2$ | Retard. $\delta = \lambda /4$ | Retard. $0 < \delta < \lambda /4$ | Retard. $\delta = 0$

Fig. 3.20: Changes of polarization produced by different values of retardance

Fig. 3.21: Scheme of the opto-electronic switch

Fig. 3.22: Scheme of the computer controlled set-up
3.2.3.1 Endoscopic system

Interferometric techniques allow measurements of micro displacements of surfaces without any need to be physically in contact with them. This type of inspection can, through the employment of fibre optics technology, be applied to hidden zones [31]. An endoscope for holographic interferometry and ESPI experiments has been designed by the author [32-34]: the reduced dimension of the endoscopic probe makes possible the access to areas particularly difficult to reach by more classical configurations.

Two main problems had to be solved in the probe design:
- the illumination of the object
- the capture and transfer of the image in the endoscope.

Laser light to illuminate the object is carried in a monomode fibre (N.A. 0.1) provided with a Selfoc micro-lens [26] at the extremity in order to expand the area being illuminated. After some preliminary tests, it was decided to use a Selfoc NSG-SLH and to put the extremity of the fibre at a distance of 1-1.5 cm from it; in this way an area of 3 cm diameter at a distance of 5 cm from the probe could be illuminated.

For carrying the image, a coherent image bundle [35] was used: in a diameter of 2mm take place more than 17000 multimode fibres. The observed area had to be focused at one extremity of the bundle in order to be transferred to the other end: the focusing was obtained by using another Selfoc micro-lens (NSG-SLW).

In fig. 3.23a a principle scheme of the probe design is presented: the external dimensions of the probe are 30mm length and 6mm diameter. In fig 3.23b,c two photographs of the probe show respectively a front view and a section of the probe.

The optical arrangement is, in principle, very similar to the one presented in fig. 3.15 (for out-of-plane ESPI by using optical fibres) with the only difference that the object pattern is carried by the endoscope (fig. 3.24).

Light coming from an He-Ne laser (Spectra Physics 127 , λ=633nm, P=35mw) is launched in one arm of a fibre optics beam splitter where it was subdivided in two parts. The first output arm is coupled to a monomode fibre 50cm long whose second extremity is inside the probe. At its extremity light is expanded by a Selfoc micro-lens (NSG-SLH 1.8 mm of diameter) and the resulting spherical wave illuminates the area of interest. This illuminated zone is focused by the second Selfoc microlens (NSG-SLW 2 mm of diameter) on the edge of a coherent image bundle (2mm in diameter). The image is carried inside the bundle until it reaches the other extremity; here a lens is used to catch the image and focus it on the sensitive area of a video camera.
Fig. 3.23a: Principle scheme of the designed probe

Fig. 3.23b: Photograph of the front view of the probe

Fig. 3.23c: Photograph of a longitudinal section of the probe
Fig. 3.24: Scheme of the complete optical system including the endoscope.

Fig. 3.25: Example of application: the probe is inserted in a tube.
The second arm is used to provide the reference field; the insertion of a beam-splitter cube results in the superposition of both object and reference beams at the video camera head.

It is fundamental, for interference to occur, that the difference between reference and object optical paths is lower than the laser coherence length.

An application of the described device is presented in the photograph of fig. 3.25: the probe was inserted into a T-shaped tube to see what kind of deformation took place under the action of an external heat flow. In fig. 3.26 the resulting ESPI interferogram is shown: the probe was kept at a distance of 5 cm from the object and the circular inspected area had a diameter of 3 cm.

Two disadvantages associated with this optical solution were the small area detectable and the poor image quality due to the speckle effect and to the pattern sampling performed by the honeycomb structure inside the image bundle. As in all other arrangements using optical fibres, relative phase changes between reference and illuminating paths might influence the result. A self-controlled system for phase compensation has therefore been studied as a solution for overcoming this problem.

Fig. 3.26: ESPI interferogram related to the deformation of the inside surface of the tube
3.2.3.2 Phase compensation

The use of optical fibres in experimental arrangements clearly offers the advantage of portability and quick setting-up of holographic and ESPI experiments. While permitting this significant increase in geometric flexibility and ease of installation, the use of optical fibres introduces some errors in interferometric measurements. These arise from environmentally induced relative phase changes between the reference and illumination arms, during experiments.

These phase changes in the fibres can be reduced by active compensation with an electronic servo and a piezoelectric phase modulator [36-38]. The compensation is based on the fact that a small change in the fibre length introduces a change in the phase at the output. The set-up, presented in fig. 3.27a, was designed at Ispra by the group were the author worked and with the external collaboration of the University of Pavia.

The stabilization of relative phase can be implemented by using the Fresnel reflections at the ends of fibres 3 and 4; these reflected fields mix together in the coupler and the resulting interference is accessible from port 2 of the beam splitter. Any differential phase change between illumination and reference fibres appears as an intensity change at this port.

A schematic description of the loop-back optoelectronic system is presented in fig. 3.27b: the intensity from port 2 is acquired by a photodiode and transformed in a voltage signal by a transresistance amplifier; after comparison with a reference voltage, the error signal, appropriately amplified, is used to drive a piezoelectric transducer (PZT) cylinder around which one of the output fibre arms is wrapped. By selecting the number of wraps and the diameter of the cylinder, the gain factor of the feedback is chosen. The maximum frequency response is limited by the characteristics of the amplifiers used in the loop.

In order to obtain the best performance from the feedback, the reference voltage must be set to the central value of the interferometric signal obtained from port 2. In fig. 3.28 the possible changes of the measured voltages from the transresistance amplifier are plotted as function of phase and points of maximum stability are depicted with crosses (+) and circles (o). Two consecutive points of maximum stability lock are separated by a phase difference of $2\Delta\phi=\pi$; this corresponds to a phase difference of $\Delta\phi=\pi/2$ between the fields at the output of the fibres. It is possible to jump automatically from one point of stability to the following (the slope of the curve is opposite), by simply changing the sign of the error signal in the loop. This is obtained by inserting an inverter and a switch in the feedback.
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Fig. 3.27a,b:
(a) Set-up for phase compensation in interferometric systems using optical fibres
(b) Scheme of the feedback control

Fig. 3.28: Plot of voltage from the transresistance amplifier as function of phase: points of maximum stability are depicted with crosses (+) and circles (o).
The PZT can be driven automatically in order to introduce three phase steps of $\pi/2$, between the fields of ports 3 and 4, by simply switching three times the sign of the feedback signal: four phase-shifted images can, in this way, be obtained with good accuracy (errors lower than 3 degrees in the shifts were observed). This feedback system was applied to compensate all fibre optic systems described in previous sections. An application in the portable system 5 (paragraph 3.2.1.2), sensitive to out-of-plane displacements, is here presented. A cantilever was loaded in its upper side and the observed interferograms were automatically phase-shifted. The loading scheme, one interferogram, the phase map, the three-dimensional plot and a profile along a section are respectively presented in fig. 3.29-3.33.

3.3. New methods of analysis

Automatic analysis of interferograms is very important for retrieving quantitative data: specialists are aiming at real-time retrieval of information from interferometric patterns. Due to the increasing performance of computers, image processing and data extraction have in recent times reached a high degree of automation and reliability. Some novel contributions have been made by the author in this direction: techniques for phase retrieval, derivative evaluation and strain calculation have been exploited.

3.3.1 New conception unwrapping program

The design of phase unwrapping algorithms has been the object of many efforts, but a general solution for automated analysis has not been reached yet. Most important difficulties arise from discontinuous phase changes, image noise and signal undersampling [39]. Solutions are often suggested on the basis of a priori knowledge of the geometry and of the physical phenomena involved in the problem. Normally, the image has to be scanned pixel by pixel to detect the positions of the jumps: a variety of paths can be followed along the image and jumps can be detected comparing two or more adjacent pixel values. A trade-off has to be made between precision, time, simplicity and degree of automation. Some iterative algorithms [40] may require a lot of time before reaching the solution. The simplest and still most common way to perform phase unwrapping is to add or subtract $2\pi$ to a phase value every time that a jump greater than $\pi$ occurs between two adjacent points in the wrapped phase diagram. The solution here proposed is a sequence of five different steps:

- filtering of interferograms
- phase retrieval
- automatic detection of uncertain points
- interactive introduction of cuts
- phase unwrapping algorithm working on an edge-surrounding principle.
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Fig. 3.29: Experimental loading scheme

Fig. 3.30: ESPI interferogram obtained (one of four)

Fig. 3.31: Phase map obtained with the phase shifting algorithm
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Fig. 3.32: 3D representation of Fig. 3.32

Fig. 3.33: Profile of deformation along a selected section (microns)
The novelty of the procedure comes mainly from last step: after the wrapped phase and a map of critical points has been generated, an unwrapping program processes only the appropriate points.

**Filtering of phase shifted interferograms**

Good quality interferometric patterns are necessary if precision and reliability in the extracted quantitative information is required. The interferometric patterns can be filtered in the spatial or in the frequency domain. In the first case most common smoothing procedures are used: e.g. mean, median or blurring filters. In the second case the image pattern is Fourier transformed, low-pass filtered (usually by using rectangular, exponential, or Butterworth windows) and then reconducted to the spatial domain: the cut-off frequency must be adequately selected in order to eliminate high-frequency speckle noise without losing the fringe information. Contrast enhancement techniques are often useful and are applied in order to increase the quality of fringes.

**Phase retrieval**

A method based on consideration of phase-shifted images [41] or a technique requiring processing in the frequency domain [42] are the most popular methods for phase calculation. In the first case, some phase-shifted patterns (at least two [43]) are obtained and by using simple trigonometric equations the wrapped phase can be easily retrieved (Appendix E). The algorithm usually preferred in this work is based on the processing of four interferograms. In the second case just one interferogram is necessary (Appendix F) but some requirements about the fringe orientation must be fulfilled for calculating the wrapped phase. Once the phase has been retrieved, an unwrapping procedure must follow for obtaining the absolute information.

**Automatic detection of uncertain points**

The unwrapping process is often not trivial and complicated by the presence of uncertainty points or sudden jumps in the fringe geometry. Many methods and possible procedures have been proposed in the literature for overcoming these problems [44]: an algorithm involving most popular proposed solutions was designed by the author and applied to wrapped phase maps in order to locate points that can be a possible source of error for the unwrapping process. A Bad Points Mask (BPM) is in this way obtained.
Interactive introduction of cuts

Experience has taught that automatic techniques are in many cases not sufficient for eliminating all possible sources of error. The operator's intervention is sometimes required: an *a priori* knowledge of the surface shape and a quick look at the wrapped phase map is, in many cases, sufficient for the skilled user to manually select points that could be possible sources of uncertainty. This is especially the case when discontinuities in the shape of fringes are present or when the inspected surface has not a smooth and elementary profile. This manual intervention adds bad points to the BPM obtained with the automatic procedure.

Phase unwrapping algorithm working on an edge-surrounding principle.

Phase unwrapping consists of preliminary detection of the fringe order, and further reconstruction of the absolute phase function. Once the wrapped phase pattern and the BPM are available the algorithm must be able to consider all the pixels whilst avoiding calculation in masked out points. In the proposed solution (fig. 3.34) a starting pixel P is selected and compared with the neighbouring good points P_n (n=1 to 4) in the four directions (after control in the BPM). If the difference between the phases of P and P_n is greater (or smaller) than a defined threshold (normally taken as π) then it is assumed that the pixels lie in two distinct fringes. The absolute phase value is obtained by adding (or subtracting) 2π to the phase of P_n. Pixel P is then marked out as evaluated point. The four P_n pixels become in their turn starting points and are compared with good and still not evaluated neighbours. The procedure ends when all good points have been evaluated. In this way the unwrapping process is performed surrounding all obstacles contained in the BPM. If the unwrapping process fails (mistakes can be easily observed) the operator's intervention is required for adding new sources of error to the BPM.

A completely automatic procedure of phase unwrapping that is extremely robust and able to solve all problems still doesn't exist: good quality interferograms and the user's intervention are still necessary for obtaining reliable results.

3.3.2 New techniques for phase derivative retrieval

In some cases the phase derivatives are required for a full understanding of the physical properties being investigated [45]. In strain analysis the phase retrieved from the interferograms is proportional to displacement; however partial derivatives of displacement are necessary for the description of the strain tensor [46] as can be found in Appendix A.
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Fig. 3.34: Procedure of unwrapping: the order in which the first 20 pixels are elaborated (starting from number 1) is there presented.

Fig. 3.35: Loading scheme of the circular plate.

Fig. 3.36: Interferogram of the centrally loaded plate obtained by Holographic Interferometry.
Phase partial derivatives can be calculated by application of digital algorithms to the phase map [47] or by using speckle shearing interferometry [48] as described in chapter 2.

Two original methods for the calculation of the phase derivatives have been designed by the author: the first is based on the direct calculation of phase-shifted interferograms and the second operates in the frequency domain.

3.3.2.1 Phase derivative calculated directly from phase-shifted interferograms

In this section the author presents a new method for calculating the displacement derivatives by a direct manipulation of phase-shifted interferograms and the advantages deriving from this procedure are highlighted. [49]

Intensity patterns of the interferograms \( I_{\alpha_{i}}(x,y) \) can be described by the equation:

\[
I_{a_{i}}(x,y) = I_b(x,y)(1+\gamma(x,y)\cos[\phi(x,y)+\alpha_{i}])
\]

where \( \phi(x,y) \) is the interferometric phase, \( I_b(x,y) \) represents the background, \( \gamma(x,y) \) the contrast modulation and \( \alpha_i \) the introduced phase shift.

From the computational point of view, a variety of versions of the method exist, all of them sharing the ability to eliminate the background and contrast terms by simple arithmetic or trigonometric operations on the acquired images. When a number \( N \) of interferograms is considered, the interferometric phase can be expressed as

\[
\phi(x,y) = \arctan \left( \frac{\sum_{i=1}^{N} a_i I_{a_{i}}(x,y)}{\sum_{i=1}^{N} b_i I_{a_{i}}(x,y)} \right)
\]

where \( a_i \) and \( b_i \) are constants which depend on the phase-shift values. By taking the derivatives of equation 3.20 along the \( x \) sensitive direction, the following expression is obtained:

\[
\frac{\partial \phi(x,y)}{\partial x} = \frac{\sum a_{i} \frac{\partial I_{a_{i}}(x,y)}{\partial x} \sum b_{i} I_{a_{i}}(x,y) - \sum a_{i} I_{a_{i}}(x,y) \sum b_{i} \frac{\partial I_{a_{i}}(x,y)}{\partial x}}{(\sum a_{i} I_{a_{i}}(x,y))^{2} + (\sum b_{i} I_{a_{i}}(x,y))^{2}}
\]

The derivatives \( \partial I_{\alpha_{i}}(x,y)/\partial x \) of each interferogram can be replaced with their finite difference approximation.
\[
\frac{\partial I_{\omega}(x, y)}{\partial x} = \frac{I_{\omega}(x+h, y) - I_{\omega}(x, y)}{h}
\]  
(3.22)

where \( h \) indicates the distance between two adjacent points along \( x \), yielding

\[
\frac{\partial \phi(x, y)}{\partial x} = \frac{1}{h} \sum_{l} q_{l} I_{\omega}(x + h, y) \sum_{l} h_{l} I_{\omega}(x, y) - \sum_{l} q_{l} I_{\omega}(x, y) \sum_{l} h_{l} I_{\omega}(x + h, y)}{(\sum_{l} q_{l} I_{\omega}(x, y))^2 + (\sum_{l} h_{l} I_{\omega}(x, y))^2}
\]  
(3.23)

Each term of equation (3.23) can readily be calculated by digitizing the interferograms shifted in phase. Therefore, phase derivatives are obtained without evaluating the absolute phase distribution. It is clear that, in order to obtain fine derivative maps, it is better to apply the technique to interferograms having sufficient quality: for this reason a pre-filtering of interferometric patterns can be often useful.

When the maps of the partial derivatives along two orthogonal directions \( x \) and \( y \) are known, the interferometric phase term \( \phi(x, y) \) can readily be retrieved by a finite integration procedure. In fact, by letting \( \Phi \) be the phase at \( P = P(\bar{x}, \bar{y}) \), the phase of a point \( Q = Q(\bar{x} + h, \bar{y} + k) \) in the neighbourhood of \( P \) can be approximated by

\[
\phi(Q) = \frac{\partial \phi(P)}{\partial x} h + \frac{\partial \phi(P)}{\partial y} k + \phi(P)
\]  
(3.24)

where \( h \) and \( k \) represent the distance between the two points along \( x \) and \( y \) respectively.

The phase map is obtained by performing the calculation in equation (3.24) from point to point along a path which covers the whole interferogram. However, it should be noted that any error occurring between two points affects the phase values of the other points to be processed.

The method proposed has been applied to process holographic and speckle pattern phase-shifted interferograms, as described in [50]. As example, the static deformation of a circular steel plate with a diameter of 10 cm was studied by using holographic interferometry. Between the first and the second exposure the plate was loaded in its centre with a point-like pushing force. A sketch of the loading set-up is shown in fig. 3.35 and one of the obtained phase-shifted interferograms is presented in fig. 3.36.

In the case of four images \((N=4)\) shifted by \( \pi/2 \), equation (3.20) becomes

\[
\phi(x, y) = \arctan \frac{I_{3\pi/2}(x, y) - I_{\pi/2}(x, y)}{I_{\omega}(x, y) - I_{\pi}(x, y)}
\]  
(3.25)
and, according to equation (3.21), the expression for the phase derivatives along \( x \) becomes

\[
\frac{\partial \phi}{\partial x} = \frac{\left( \frac{\partial I_{\text{peak}}}{\partial x} - \frac{\partial I_{\pi/2}}{\partial x} \right)(I_0 - I_\pi) - (I_{3\pi/2} - I_{\pi/2}) \left( \frac{\partial I_0}{\partial x} - \frac{\partial I_\pi}{\partial x} \right)}{(I_{3\pi/2} - I_{\pi/2})^2 + (I_0 - I_\pi)^2}
\]

(3.26)

and by substituting the finite difference approximation of equation (3.23) the following final result is yielded

\[
\frac{\partial \phi}{\partial x} = \frac{1}{h} \left( I_{\text{peak}}(x+h,y) - I_{\text{peak}}(x,y) \right) - \left( I_{\pi/2}(x,y) - I_{\pi/2}(x+h,y) \right) \left( I_0(x,y) - I_0(x+h,y) \right)
\]

\[
\frac{1}{h} \left( I_{\pi/2}(x,y) - I_{\pi/2}(x+h,y) \right)^2 + (I_0(x,y) - I_0(x+h,y))^2
\]

(3.27)

A similar expression can be obtained for calculating the phase derivative along the \( y \) direction. The maps of the \( x \) and \( y \) phase derivatives are presented in fig. 3.37a,b and the corresponding 3D-plots are shown in fig. 3.38a,b. According to equation (3.25), the phase map, proportional to the static displacement of the circular plate has been retrieved. The phase and the corresponding 3D-plot are displayed in fig. 3.39 and fig. 3.40 respectively.

3.3.2.2 Phase derivative calculated from the Fourier transform of the interferogram

The derivative of a function can be evaluated by using some mathematical properties of the Fourier Transform [1].

The Fourier Transform of a function \( f(t) \) is given by

\[
f(t) \leftrightarrow F(\alpha)
\]

\[
F(f(t)) = F(\alpha) = \int f(t) \exp(-i2\pi\alpha t) dt
\]

(3.28)

By simple mathematical analysis it is easy to find the fundamental relation existing between the derivative and the Fourier transform of a function

\[
\frac{\partial f(t)}{\partial t} \leftrightarrow i2\pi \alpha F(\alpha)
\]

(3.29)
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Fig. 3.37a,b: Maps of partial derivatives: a) in x direction; b) in y direction

Fig. 3.38a,b: 3D plots of the derivatives: a) in x direction; b) in y direction

Fig. 3.39: Phase map of displacement retrieved from partial derivatives

Fig. 3.40: 3D representation of fig. 3.39
Fig. 3.41: False-colour map of partial derivative for the ideal case

Fig. 3.42: 3D representation of fig. 3.41

Fig. 3.43: False-colour map of partial derivative for the real case

Fig. 3.44: 3D representation of fig. 3.43

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The derivative of function $f(t)$ can be evaluated with the application of 3 steps:

1) Fourier Transformation of $f(t)$
   
   $f(t) \leftrightarrow F(\alpha)$

2) Multiplication of the Transform by $2\pi \alpha i$
   
   $i2\pi \alpha \cdot \text{LPF} \{F(\alpha)\}$

3) Inverse Transformation
   
   $i2\pi \alpha \cdot \text{LPF} \{F(\alpha)\} \leftrightarrow \frac{df(t)}{dt}$

The Fourier transform $F(\alpha)$ can be low-pass filtered for reducing high frequency noise (whose effect would be greatly increased by the derivation process). This theoretical analysis can be applied to the calculation of partial derivatives from a phase map. In this bi-dimensional case equation 3.29 becomes:

$$\frac{\partial f(x,y)}{\partial x} \leftrightarrow i2\pi \alpha \cdot F(\alpha, \beta)$$

$$\frac{\partial f(x,y)}{\partial y} \leftrightarrow i2\pi \beta \cdot F(\alpha, \beta)$$

(3.30)

where $\alpha$ and $\beta$ are the variables in the frequency domain. From these relations, by following a procedure similar to the uni-dimensional case, partial derivatives in $x$ and $y$ directions can be retrieved.

This technique was applied to the ideal and to the real cases described in the paragraph 2.3.1.1. The grey-level image and the 3D plot of the derivative are presented for the ideal case in fig. 3.41 and fig. 3.42, for the real case in fig. 3.43 and fig. 3.44.

3.3.3 Virtual strain-gauge

In experimental mechanics, the real-time evaluation of relative displacement between two points is usually performed by using strain gauges and is affected by all the drawbacks discussed in paragraph 1.1.1.2.

By using interferometric techniques it is possible to store on a videotape the evolution of fringes related to the distributed displacement of the inspected surface. The operator would like to obtain in real-time a quantitative evaluation of displacement for all the points of the interferogram; however this is still not possible and the main limitation is due to the processing speed of computers. Such whole-field inspection will become possible in the future when the use of neural networks or parallel computing will reach a higher level of popularity and reliability.

A study aimed at the development of software for real-time measurement of displacement between two selected points of an interferogram has been started by the
author. This technique can bring some advantages over the use of classical strain gauges:

- absence of contact with the surface
- possibility to calculate during the same videotape observation, or in different ones, the relative displacement between many pairs of points.

For these features this procedure is considered as a "virtual strain gauge" and it can be implemented in two different ways:

- by evaluating the difference between the number of fringes passing over the two selected points
- by tracing a line connecting them and counting the number of fringes.

As the calculation is performed just on a limited number of points, the necessary computing time is low and can be completed in real-time. It can be shown that as the relative displacement is related to the number of fringes between the points, mean strain is related to their frequency.

If a sinusoidal pattern with a constant period is considered (fig. 3.45), the intensity profile between two points can be expressed by:

\[ I = A \sin(\Delta \phi) = A \sin(2\pi \nu x) \]  \hspace{1cm} (3.31)

where the displacement is related to the phase \( \Delta \phi \) and its partial derivative in the \( x \) direction is related to \( \partial \phi / \partial x = 2\pi \nu \) (directly proportional to the frequency of the sinusoid) and can be rapidly calculated in the frequency domain (in fig. 3.46 the Fourier transform is presented). However, in most common cases fringes do not have a periodic distribution and the spectrum is distributed over a certain number of frequencies: a weight averaging can be applied to the significant frequency components and a mean frequency value can be extracted. The main problem associated with this calculation deals with the choice of the significative part of the spectrum not due to electronic noise, speckle noise or background.

Some preliminary results of this technique will be presented in chapter 4 where the technique will be applied to interferograms obtained with the Moiré technique.

3.4. Conclusions

While chapters 1 and 2 dealt with the explanation of aspects involved in this thesis and familiarization with most popular optical techniques for non-destructive inspection, chapter 3 was conceived for the presentation of innovative contributions. These contributions were the result of two lines of exploration:

- an improvement of tools already available
- the development of some new facilities
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Fig. 3.45: Interferometric pattern and profile between two points (units are the pixels' grey level)

Fig. 3.46: Frequency spectrum of the line of fig. 3.45
For this innovative process, the research moved in two different directions:

- in some cases it was decided to start from a technique or an optical system with the purpose of introducing some upgrades for better functionality, independently from any field of utilization.
- in others the development has been accomplished in order to fulfil some necessary requirements arising in particular applications.

By following these main lines of research, new techniques have been explored, new measuring systems have been designed and new procedures of processing have been conceived.

New techniques have been developed which were aimed at the investigation of changes in structural characteristics of surfaces (Speckle decorrelation, section 3.1.1) or the real-time inspection of stationary vibrations (subtraction ESPI with reference active control, section 3.1.2).

New systems have been designed for permitting measurements to be accomplished outside the optical laboratory, fulfilling requirements of portability and flexibility (portable systems, section 3.2.1), or for allowing a more complete automatic inspection of surfaces of interest (system for complete analysis of in-plane displacements, section 3.2.2). The potential of using optical fibres has been widely explored and the possibility of creating endoscopic systems and automatic compensation devices has been considered (section 3.2.3).

New software procedures for processing the optical information, usually contained in interferometric patterns, have been developed, which were aimed at faster and more automatic retrieval of quantitative data having an acceptable degree of reliability and precision. Techniques for displacement analysis (new conception unwrapping method, section 3.3.1), for strain evaluation (techniques for phase derivative extraction, section 3.3.2) and alternative to classical tools (virtual strain gauge, section 3.3.3) have been studied.

The work completed in this chapter is obviously not exhaustive: this field of research is wide and still requires a lot of effort from all the scientific staff involved in it. However the author has the conviction that some contribution has been added by his research and that some of these novel concepts will be useful to other researchers.
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Chapter IV
Applications of optical techniques to the characterization of building materials and structures

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Introduction

Chapter 4 contains experimental results related to the application of optical techniques in the field of civil and structural engineering. While some of these methods are well accepted and are becoming almost routine, others are completely original. The purpose of this chapter, and of the whole work, is not to give answers to all problems arising in civil engineering through the application of optical techniques, but to open a door between the mechanical and the optical fields by describing some examples and possible applications.

Not all optical methods presented in previous chapters are here used, even though for each of them it would be possible to find an application domain. Here the reader can find applications involving optical systems for shape evaluation, ESPI and moiré methods for deformation analysis and speckle techniques for the inspection of surface changes. A last section is devoted to the description of some results obtained in the field of preservation of works of art.

The research is included in the European program for Measuring and Testing; applications have been performed in collaboration with some industries, universities or institutions and often involved the contribution of the research and technical staff of the laboratories of the Joint Research Centre at Ispra where the author carried out his work.

4.1. Optical techniques for shape analysis

Shape measurements can be important and useful in the context of civil engineering because they allow the three-dimensional digital reconstruction of objects and structures. This information can be useful for many purposes: evaluating the surface state, representing the object by digital animation tools, performing computer simulations. Optical non-destructive methods can be considered very promising tools in the field of contouring measurement.

Several optical techniques for shape evaluation are actually commercially available and the extent of their application in the field of civil engineering is becoming more and more important. While some methods have been extensively used for some decades and are becoming almost a standard (e.g. photogrammetry), others have only recently come into use. In this section techniques based on the use of digital photogrammetry, laser range finders and triangulation by stripe or grating projection are presented. In the concluding remarks some discussion about their features and limitations can be found.
4.1.1. Digital photogrammetry

It would be of no use to speak extensively about the properties of photogrammetry, as several books about this subject exist and many applications have already been accomplished [1]. However its digital use is probably less well known and examples of application can clarify some of the advantages coming from this method.

Digital photogrammetry consists of the automatic reconstruction of a structure in a numeric format (through the use of a computer) starting from some photographic pictures. As a first step the exact position of some points on the inspected surface (control points) must be measured with high accuracy, generally by using a laser range finder. Then pictures of the inspected surface are acquired from different angles by using a high precision camera (metric or semi-metric). These photographs, at least two, are digitized by using a high resolution scanner and the resulting numerical data are transferred to special purpose software. At this stage a digital correlation between the images is performed point by point and with the complete knowledge about the position of control points, a quantitative evaluation of the shape of the inspected surface can be obtained. The data can be transferred to other software for CAD, FEA and structural simulation.

Within a project of collaboration with the Sicily Region, aimed at the preservation of the cultural heritage, the technique has been applied to the digital reconstruction of an historical building located in Palermo (Palazzo Geraci). Measures have been accomplished under the supervision of Leica's research group (from Aarau in Switzerland). Some photographs have been acquired by using the metric camera CRC-2 (by Geodetic Services)[2] and some control points have been evaluated with a theodolite DIOR (laser range finder produced by Leica). In fig. 4.1 a picture of the front facade of the building is shown and in fig. 4.2 the geometry adopted for picture acquisition is presented.

Acquired images are then processed by using the Helava system produced by Leica: digitization is obtained with the DSW (Digital Scanning Workstation) connected to a high resolution scanner; data are then processed in the DPW (Digital Photogrammetry Workstation).

In fig. 4.3 the digital reconstruction of the facade is presented and in fig. 4.4 a simulation of strain response to loading of the structure is presented.

The main advantages related with the use of digital over classical photogrammetry come especially from the lower processing time required and from the complete automation of the process: no particularly trained operator is required anymore but just a normal software user is sufficient. However the system is still under development: improvements are still necessary for reaching complete reliability.
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Fig. 4.1: Picture of the front facade of Palazzo Geraci

Fig. 4.2: Geometry adopted for picture acquisition
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Fig. 4.3: Digital reconstruction of the building facade

Fig. 4.4: Simulation of the response of the structure to an external loading
An important improvement will be obtained when high resolution CCD cameras will become available on the market at low cost: the scanner digitization process will be bypassed and processing times will be dramatically reduced. As for triangulation techniques, photogrammetry suffers from shading problems: there are areas of the surface that are observable just from one direction of acquisition and can't be evaluated. With this technique large surfaces can be observed and the resolution is actually limited by the scene's dimension, the acquisition system (camera accuracy), the angle between acquired photos and the digitizer resolution. For surfaces of tens of m² depth resolutions down to the millimeter can be reached.

4.1.2. Time of flight

Another optical technique for surface profiling is based on the use of laser range finders [3]: these instruments are capable of evaluating with a precision better than 1mm, the position in space of a target point. The coordinates are evaluated in a spherical reference system relative to the position of the range finder: the point is located by the measured distance ($r$), the elevation ($\gamma$) and the lateral angle ($\theta$) of the instrument as can be seen in the fig. 4.5. For representation purposes a conversion from spherical to Cartesian coordinates may often be opportune.

With the collaboration of Leica Industries, it was decided to apply this technique to the surface shape measurement of a balcony of a tower in a castle situated in the neighbourhood of Bellinzona in Switzerland. This feature covered an area of 2 metres square and was situated at height of at least 10 metres from the ground. The laser range finder was connected to a computer having the double purpose of piloting the instrument's movement and acquiring the estimated data. A measuring matrix was defined before the experiment: starting from a decided position angular steps (elevation and lateral displacement) were selected in order to cover the area of interest with a certain grid of points. Every point was determined, at the end of the experiment, by a longitude, a latitude and a distance and the surface mesh could be easily plotted by most common software products such as MATLAB or MATHEMATICA. The three-dimensional plot of the evaluated surface is presented as a mesh (fig. 4.6) and as a shaded surface(fig. 4.7): the measured grid consisted of 40x40 points.

Main disadvantages are the poor lateral resolution and the relatively long time of acquisition (if compared to some other techniques): it is clear that the system precision is related to the range finder resolution and to the number of points considered in the area of interest. The measuring time increases with the number of points.
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Fig. 4.5: Schematic representation of the measurement performed by the laser range finder: the position of every point is determined by two angles and a distance.

Fig. 4.6: Three-dimensional plot of the balcony observed on the tower. (Mesh)

Fig. 4.7: Three-dimensional plot of the balcony observed on the tower. (False colours)
The single acquisition is fast but the mechanical displacement for moving from one point to the next may require some seconds. The main advantage is based on the fact that shading problems are avoided and once the measuring matrix has been defined the measurement is completely automatic.

4.1.3. Triangulation

Many different types of structured light can be projected on the inspected surface and observed from a different angle where they appear modulated by the height variations. An interpretation of the acquired images provides quantitative data.

4.1.3.1 Grating projection

A common way to measure depth contours is based on the projection of a structured grid onto the observed surface as was widely described in paragraph 2.4.1. In this section the laser system presented in fig. 2.49 was used to create the set of equispaced parallel lines. The arrangement is based on the use of a Michelson interferometer provided with two mirrors slightly inclined in the two arms (the pitch of the interferometric fringes depends on the relative angle of the mirrors). Great attention has to be paid to the quality of the interference fringes: a non perfect pattern introduces some errors in the surface shape retrieval. If collimated wavefronts are not projected, special software is needed to correct the effects arising in the profile evaluation.

For phase-shifting analysis of the fringe pattern further equipment is necessary. Phase-shifts are introduced by a computer controlled movement of one of the two mirrors mounted on a piezo-transducer in the Michelson interferometer. If the Fourier technique is used, just one image is sufficient for the surface evaluation.

The method was applied to the evaluation of a simple piece of marble (square surface of 5cm side) coming from the Duomo of Milan, in order to evaluate the surface distributed corrosion due to ageing. The specimen was painted white to improve the quality of the projected fringe pattern in terms of uniformity and fringe contrast. The inspected surface crossed by projected fringes is presented in fig. 4.8. The contour map of the test object was obtained following the two methods previously considered, i.e. phase-shifting and Fourier analysis.
Fig. 4.8: Vertical interferometric fringes projected on a marble surface.

Fig. 4.9: 3D plot of the marble surface obtained after elaboration of picture 4.8: undulations in the profile are due to corrosion.
After phase retrieval and phase unwrapping procedures, an absolute surface map was
obtained and the three-dimensional plot of fig. 4.9 was derived: the surface doesn’t show a
flat profile but some undulations due to corrosion are present.
This method can be easily used when small surfaces having a smooth profile are inspected:
this is often the case when corrosion effects due to pollution on building materials are
considered [4].

4.1.3.2 Stripe projection

The arrangement designed in the laboratories at Ispra and described in paragraph
2.4.2 was used to evaluate the surface profile of areas larger than in paragraph 4.1.3.
This system was applied to many different objects: here the results obtained on a
mannequin simulating the head of a statue are presented. The object was positioned at a
distance of about 2 meters from the viewing theodolite and the objective of the camera was
set for having the inspected area occupying all the screen (in this way the pixel resolution
was the best possible).
Contouring results are presented with the help of some images:
  - false colour image(fig. 4.10)
  - 3D plot of the surface(fig. 4.11)

4.1.4. Conclusion

Some optical techniques have been used in order to perform a quantitative evaluation
of the surface profile. They are contactless methods and for this reason their application can
be very useful especially in the field of works of art or historical buildings.
Measurements are usually performed in an automatic way: special purpose software can be
created for extracting quantitative data from the images that have been acquired.
Processing routines, sometimes long and still requiring the intervention of the operator, are
getting more and more sophisticated and reliable thanks to the increasing performance of
computers.
Resolutions that can be reached with optical techniques actually depend on the applied
method.
When choosing the technique suitable for an experiment, some factors have to be taken
into account: the surface dimension, the required spatial resolution, the acquisition time and
processing time. In Table 4.1 [5] these parameters are compared for the techniques that
have been applied in this chapter. The same critic to table 1.3 is valid here.
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*Fig. 4.10:* False colour contouring image of the scene inspected by stripe projection

*Fig. 4.11:* Three-dimensional representation of fig. 4.10
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### TABLE 4.1: COMPARISON OF APPLIED CONTOURING TECHNIQUES

<table>
<thead>
<tr>
<th>Technique</th>
<th>Surface Dimension</th>
<th>Depth Resolution $\Delta z$ (µm)</th>
<th>Operating Range</th>
<th>Acquisiti on time</th>
<th>Processing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Photogrammetry</td>
<td>Large (some m$^2$)</td>
<td>100</td>
<td>&lt;100m</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td>Pulse time of flight</td>
<td>Large (some m$^2$)</td>
<td>1000</td>
<td>&lt;100m</td>
<td>Long</td>
<td>Medium</td>
</tr>
<tr>
<td>Triangulation by grating projection</td>
<td>Medium/small (some cm$^2$)</td>
<td>1% of range</td>
<td>10-200cm</td>
<td>Short</td>
<td>Medium</td>
</tr>
<tr>
<td>Triangulation by stripe projection</td>
<td>Medium (some tens of cm$^2$)</td>
<td>1% of range</td>
<td>0.5-5m</td>
<td>Long</td>
<td>Short</td>
</tr>
</tbody>
</table>

The depth resolution of photogrammetry and triangulation techniques is actually higher and can be improved by increasing the angles involved in the geometric set-up of acquisition. The main limitation is due to shadowing problems (clearly visible in fig. 4.10 where some points have not been processed). The method based on pulse time of flight is less sensitive to shadowing problems but shows an inferior depth resolution. Moreover the number of points measured with this technique is limited and interpolation algorithms must be applied.

4.2. Deformation analysis by ESPI methods

Many different optical interferometric techniques are studied and applied at the moment: Holographic Interferometry, moiré Interferometry, Speckle Photography, and Electronic Speckle Pattern Interferometry. All these are powerful tools for efficient non-destructive testing involving the evaluation of micro-deformations and unlike more traditional techniques using transducers, they require no direct contact with the test specimen and provide for a full-field visualization of surface behaviour. Electronic Speckle Pattern Interferometry (ESPI) has been often preferred in this work since it allows a real-time inspection of the specimen and is less sensitive to ambient conditions. In this section it is shown how the use of ESPI in the study of stone specimens can contribute to the evaluation of some mechanical characteristics of these materials. Many different experimental configurations are possible for ESPI experiments [6] depending on which information the operator requires.
4.2.1. Preliminary tests

Whilst optical interferometric techniques have been widely applied in many fields of experimental mechanics[7], especially with the purpose of studying some particular materials (i.e. metallic compounds, composite materials, plastic elements), not much has yet been achieved in the study of building materials or stones in general [8-10]. For this reason it was thought opportune to carry out some preliminary experiments in order to verify the applicability of the technique to these materials. It was important to evaluate the stone’s surface response to laser illumination and the effect of decorrelation on the quality of interferograms. Some different configurations were applied for evaluating out-of-plane or in-plane displacements, followed by processing producing quantitative data. Effects due to rigid body motion on the formation of fringes were evaluated as well.

4.2.1.1. Surface requirements

It was observed that when experiments are carried out on metallic elements the quality of interferograms is usually better than when building materials or stones in general are considered. This fact is mainly due to three reasons:
- different reflectivity
- different physical structure and consistency
- better maintenance of polarization
Surfaces of stones usually reflect a lower quantity of light; for this reason laser sources with a higher power or intensified CCD cameras have to be used in order to acquire a speckle pattern with sufficient brightness and contrast.
Stones often show a crystalline structure allowing the laser light to penetrate to a certain depth inside, resulting in a set of multiple reflections from a portion of volume. This characteristic produces a fast decorrelation of the speckle field when the object undergoes deformation, causing a rapid reduction of the interferogram quality. Moreover powder and spall are present on the surface and also cause rapid decorrelation.
In order to overcome all these problems, it was decided to paint the inspected surfaces with white spray that, without influencing the normal behaviour of the object, brought the following advantages:
- better reflectivity
- light reflected only by the surface
- reduction of effects due to presence of powder and spalls.
4.2.1.2 Inspection of out-of-plane deformation

The first application of the ESPI technique concerned the observation of the real-time out-of-plane displacement of a sandstone cylinder (10cm height, 5cm diameter) when subjected to a compressive force in an hydraulic machine. The optical arrangement sensitive to out-of-plane deformation described in paragraph 2.1.2.1 was used. In the reference path one mirror was mounted on a piezo-transducer, appropriately calibrated, for acquiring four phase-shifted images when desired. Both the optical set-up and the test machine were positioned on the same vibration-free table.

In fig. 4.12 an interferogram of the loaded specimen is presented: the shape of the fringes shows that an anomalous deformation took place in the lower area, probably due to a non uniform contact with the compressing plate. With the phase-shifting technique the phase map (fig. 4.13) and the three-dimensional representation of the deformation (fig. 4.14) were obtained. By using the technique described in paragraph 3.3.2.1 for the evaluation of derivatives directly from the interferograms [11,12], the gradients of the deformation were evaluated in the vertical and horizontal directions. From these maps it was possible to have an idea about the zones where a maximum concentration of strain was present (the derivative calculated in the vertical direction is presented in fig. 4.15).

In fig. 4.16 an interferogram of the specimen just before rupture is presented. The distribution of fringes indicates the presence of a fracture in the left side, even though it was not visible to the naked eye. Actually the specimen failed in the way foreseen from the interferogram and in fig. 4.17 the broken specimen is shown.

4.2.1.3 Inspection of in-plane deformation

This section shows an example demonstrating the effectiveness of using ESPI arrangements sensitive to in-plane deformation to the inspection of stone surfaces [13-15]. In this case the system for complete in-plane analysis, described in paragraph 3.2.2, was used.

The specimen was a marble cube having a side of 5cm and a central hole of 1 cm diameter, subjected to external compression in an hydraulic machine (fig. 4.18). A sample with such a simple geometry was chosen in order to easily simulate the same deformation with FEA (Finite Element Analysis) software and thus make a comparison with the experimental results.
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Fig. 4.12: Interferogram related to the out-of-plane deformation of the compressed sandstone cylinder

Fig. 4.13: Phase map of the deformation

Fig. 4.14: Three-dimensional representation of the deformation (Maximum relative displacement about 1.8 μm)
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Fig. 4.15: Vertical partial derivative of the evaluated phase

Fig. 4.16: Interferogram of the compressed sandstone cylinder just before rupture

Fig. 4.17: Photograph of the cylinder after failure
The interferogram related to the vertical deformation and the simulation obtained with the FEA software are displayed in fig. 4.19 and fig. 4.20 respectively. A good agreement between experimental and expected results is observed (the slight slope of the fringes is due to rigid body rotation and will be discussed later).

By using the Fourier Transform technique it was possible to retrieve the phase map (fig. 4.21) and a schematic vectoral representation of the distributed vertical displacement (fig. 4.22).

![Compression scheme of the marble cube with central hole](image)

*Fig. 4.18: Compression scheme of the marble cube with central hole*

![Interferogram related to in-plane vertical deformation of the marble cube](image)

*Fig. 4.19: Interferogram related to in-plane vertical deformation of the marble cube*
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**Fig. 4.20:**
FEM simulation of vertical deformation

**Fig. 4.21:**
Wrapped Phase map obtained after quantitative evaluation of the interferogram in 4.19

**Fig. 4.22:**
Vectoral representation of distributed displacement
4.2.1.4 Experimental evaluation of rigid body motion on in-plane displacement measurements

In some cases the shape of fringes is sufficient for having qualitative information; in other cases a quantitative calculation will be required in order to obtain comparative data. The evaluation of the information contained in interferograms must be as precise as possible and for this reason some further discussion is necessary about the process of fringe formation. In this section some effects due to rigid body movements on the formation of fringes are described: rigid body movements can, actually, influence the formation of fringes.

By considering the common configuration for ESPI in-plane measurements presented in fig. 2.11, the effect of rigid body rotations or translations has been evaluated. Tests were carried out on a surface of a cube where rigid movements (three directions of translation and three axes of rotation) were possible (fig. 4.23). The illumination angles were set at 30° and consequently; the relative displacement between two points on two consecutive fringes was 0.63 microns.

Fig. 4.23: Six possible rigid body movements: three translations and three rotations
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Effect of rigid body translation

If pure rigid translation in the $x_1$ or $x_2$ directions were considered, no formation of fringes was observed: the points of the surface modulated all in phase and an overall change between black and white was observed. If the surface was displaced by 30 microns, about 48 consecutive changes of pattern intensity were counted. By applying theoretical equations the value $30/0.63 = 47.61$ was expected which is in very good agreement with the experimental result. When rigid translation was applied in the $x_3$ direction, formation of fringes was, in the contrary, observed. The sensitivity of fringe formation to this displacement was experimentally evaluate. When the object was moved by 100 microns, the formation of about 6 fringes was observed (a sensitivity of 25 microns between two consecutive fringes).

It may be concluded that the optical arrangement used is about 40 times less sensitive to the rigid displacement along $x_3$ than to the in-plane deformation.

For these reasons it may concluded that in experiments of in-plane displacement evaluation, the effects due to rigid body motion can be neglected without introducing significant errors in the results.

Effect of rigid body rotation

Three different rotations, around lines parallel to the coordinate axis were considered. A theoretical evaluation of the displacements introduced can be carried out by considering fig. 4.24: the cube is rotated around its lower left corner by an angle $\theta$. If $h$ and $v$ are the original dimensions of the edges, the following equations yield

$$
\begin{align*}
v_1 &= v \cdot \cos(\theta) \\
h_2 &= h \cdot \cos(\theta) \\
v_3 &= v_1 + h \cdot \sin(\theta) = v \cdot \cos(\theta) + h \cdot \sin(\theta) \\
h_3 &= h_2 - v \cdot \sin(\theta) = h \cdot \cos(\theta) - v \cdot \sin(\theta)
\end{align*}
$$

corresponding to the deformations:

\begin{align*}
\Delta v_1 &= v \cdot (1 - \cos(\theta)) \\
\Delta h_2 &= h \cdot (1 - \cos(\theta)) \\
\Delta v_3 &= v \cdot (1 - \cos(\theta)) - h \cdot \sin(\theta) \\
\Delta h_3 &= h \cdot (1 - \cos(\theta)) + v \cdot \sin(\theta)
\end{align*}
It is easy to understand that only vertical deformation $\Delta v_1$ is observed for rigid rotation around $x_1$, only horizontal deformation $\Delta h_2$ is observed for rigid rotation around $x_2$, both horizontal $\Delta h_3$ and vertical deformations $\Delta v_3$ are observed for rigid rotation around $x_3$.

If $h=v=1$ and $\theta=1^\circ$ the following values can be calculated:

$$\Delta v_1=1.52 \cdot 10^{-4} \quad \Delta h_2=1.52 \cdot 10^{-4} \quad \Delta v_3=-1.73 \cdot 10^{-2} \quad \Delta h_3=1.74 \cdot 10^{-2}$$

where units of measurement have not been written as the results are general and can be applied to any size.

From these results it may be concluded that the rotation effect around the $x_3$ axis is the most important: for these reasons rotations around $x_1$ and $x_2$ will be neglected in the experiments.

An experiment was performed in order to evaluate quantitatively the effect of rotation around $x_3$: by using the optical arrangement of paragraph 3.2.2, interferograms related to horizontal and to vertical displacement were obtained (in fig. 4.25 and 4.26 two interferograms related to these situations are presented). The two patterns show respectively just horizontal or vertical fringes. By using the FEA software the in-plane horizontal and vertical displacement related to this rotation was calculated (fig. 4.27 and 4.28). A good agreement is observed here between the obtained displacement distribution and the shape of the fringes.

Displacement of point $P$ of fig. 4.24 was produced by using a micropositioner; from the interferograms it was easy to evaluate this displacement by simply counting the number of fringes and multiplying it by 0.63 (it was the same in the vertical and in the horizontal sensitive configurations). In the plot of fig. 4.29 a comparison between the piezo-transducer applied displacement and the evaluation obtained by the fringes is presented: an almost perfect agreement is observed.

4.2.1.5 Preliminary tests for in-situ application

Many experiments were carried out in optical labs where the ambient noise level was very low and vibration-free tables were available. However the purpose of this work was to perform measurements directly in-situ or in laboratories of experimental mechanics under standard operating conditions.

Previous to any test, a feasibility inspection was necessary, as the ESPI technique is very sensitive to external factors, such as vibrations.
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Fig. 4.24: Effect of rotation around a pivot corner

Fig. 4.25: Interferogram of horizontal displacement due to rigid body rotation around $x_3$
Slight deformation is observed due to friction of the pivot corner

Fig. 4.26: Interferogram of vertical displacement due to rigid body rotation around $x_3$
Slight deformation is observed due to friction of the pivot corner
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**Fig. 4.27:**
FEM simulation of horizontal displacement due to rigid body rotation around $x_3$

**Fig. 4.28:**
FEM simulation of vertical displacement due to rigid body rotation around $x_3$

**Fig. 4.29:**
Plot showing the comparison between the displacement applied with a piezo transducer at point $P$ of Fig. 4.27 and the experimental interferometric result
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To this purpose a Michelson interferometer was used to evaluate the extent of disturbances introduced by the ambient conditions of the laboratory and by the experimental machine itself. This kind of inspection was carried out for testing machines in the laboratories of civil engineering of the Polytechnic of Milan and the Polytechnic of Turin. In both cases this inspection showed that unavoidable vibrations were present but their extent was acceptable for the purposes of the tests. Actually, successful interferograms were then obtained, as will be shown in the following sections.

4.2.2. Evaluation of mechanical properties of building materials by compression test

4.2.2.1. Introduction

The experimental determination of the mechanical properties of masonry materials (units and mortars) has been the object of an endless debate. This fact can be explained because there are so many different materials and geometries for the units, and so many mortar compositions have been used in past and present times. Therefore, in order to obtain reliable and comparable values of the properties, the dimensions, conditioning, surface treatments and rate of loading have to be codified. CEN-Committee TC125 is debating about compressive strength test for units since 1988: in more than 6 years a final agreement has not yet been found. Not only national interests promote this situation, but also a real difficulty in the definition of a single and commonly acknowledged testing method for the determination of values of comparison useful for product specification and structural calculation. When dealing with the measurement of deformation parameters, such as Young's Modulus or Poisson's Ratio, the difficulties increase to an even higher level. The measurement of deformations under increasing or decreasing loading conditions is usually obtained by means of strain gauges, directly glued to the specimen, by linear variable displacement transducers (LVDT) fixed between the loading plates or directly to the specimen and by clamp in place displacement transducers (CPDT) between the points of interest. These procedures, however, show some problems:

(i) the glue used to stick strain gauges can affect the specimen deformation;
(ii) LVDTs between the plates are highly sensitive to machine-specimen surface interaction, especially when small-size specimens are tested;
(iii) LVDTs and CPDTs, in any case, can provide only averaged values.

For this reason non-destructive testing techniques allowing local detection are more and more proposed for material characterization and structural assessment. Among these
techniques optical interferometric methods are considered very promising and are being applied to several materials [16].

4.2.2.2. Platens-specimen interaction

During a compression test, as the specimen surfaces are in contact with the plates of the loading device, two undesired effects arise. The first one is due to the eventual lack of planarity and smoothness of specimen surfaces causing a non uniform distribution of stresses in the first steps of loading. The second effect is due to the confinement against lateral expansion caused by the friction between specimen and platens surfaces. As a consequence, a quite complex state of stress develops near the loading plates, far from the expected uniaxial one.

In order to overcome this problem, two different solutions have been proposed:
- to increase the aspect ratio height/base dimension to almost 3:1 and observe just the central area, far away from the platens; specimens with different shapes have been proposed: prismatic units or the superposition of three cubes cut out from the same brick have been considered as best solutions[17];
- to reduce the friction exerted by the plates by interposing a low-friction material (e.g. a Teflon sheet) or by using special steel brushes to transfer the load to the specimen [18].

4.2.2.3. Experimental arrangement

As a first application of the ESPI inspection technique, a series of solid brick specimens were subjected to a simple compression load by a standard bench testing machine (Hounsfeld H50KM) providing a maximum load capacity of 50 kN.

For a complete in-plane analysis, the optical arrangement described in paragraph 3.2.2 was used.

The experiments were fully controlled by a personal computer, linked to the testing machine, by an RS232 connection, and to the optical equipment. The computer was able to acquire all the interferograms of the specimen as it was compressed and, at the same time, all the data coming from the loading machine. Images were acquired every 3-4 seconds, which was the minimum time necessary for the computer to perform all its procedures (i.e. speckle acquisition, digital subtraction, optical switch control, communication with the machine, etc.). The reference image could be updated by the operator every time the number of fringes was too high and the quality of the image was unacceptable. Strain rate,
maximum load, desired direction of sensitivity to deformation could be directly selected by the operator. All the software for machine control and image acquisition was written in the C language. In fig. 4.30 a sketch of the complete equipment and in fig. 4.31 a photograph of the experimental arrangement are presented [15].

Interferograms representing the specimen under deformation can be observed in real time for both horizontal and vertical directions of displacement.

During the test, a monitor displayed continuously at the same time (fig. 4.32):

(i) the name and date of the test
(ii) the interferogram related to the horizontal displacement
(iii) the interferogram related to the vertical displacement
(iv) the loading of the jack head
(v) the displacement of the jack head
(vi) the time elapsed from the beginning of the experiment.

If the evaluation of just one component of displacement was sufficient, the more transportable ESPI system, described in paragraph 3.2.1, could be used. This was a solution allowing measurements to be easily performed directly in laboratories of experimental mechanics. An photograph of the system applied in the experimental laboratories at the Polytechnic of Milan is presented in fig. 4.33 and 4.34 for the inspection of vertical and horizontal deformations respectively.

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**Fig. 4.30: Sketch of the complete equipment**
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Fig. 4.31: Photograph of the experimental arrangement

Fig. 4.32: Image observed on the monitor during the experiment

Def_x
bri_p04 8/2/1995
load = -18450
ext = -1260
time = 748

Def_y
Fig. 4.33: Photograph of the system applied in the experimental laboratories at the Polytechnic of Milan: inspection of horizontal displacements

Fig. 4.34: Photograph of the system applied in the experimental laboratories at the Polytechnic of Milan: inspection of vertical displacements
4.2.2.4. Confinement due to the compression plates

Optical interferometric techniques are very useful because they allow a full-field observation of the inspected surface. So far it is possible to visualize how displacements are distributed over the whole surface. In this way the effect of the confinement exerted by the machine platens to the upper and lower part of the specimen was observed [19]; furthermore the non-uniform distribution of the surface vertical displacements due to eventual defects could also be detected.

Compression tests were carried out on cubic brick specimens (40 mm side) under interferometric observation. Interferograms, obtained at a load level approximately equal to 35% of the failure level, showed clearly that the plates had exerted a constraint on the specimen, strongly reducing the horizontal deformations in the upper and lower areas. It is, in fact, observable from the interferogram (after low-pass filtering) of fig. 4.35, related to horizontal deformation, that the number of fringes in the central part is higher than at the top or at the bottom. Moreover, some defects present at the upper and lower faces of the specimen produced non-uniform vertical deformation at an early load level (fig. 4.36).

In order to reproduce a uniformly distributed state of stress some compression tests were performed by using three cubes one over the other. It was expected that the interferogram fringes could be undisturbed. The filtered interferograms of fig. 4.37a,b, obtained at a load level corresponding to 20% of the failure load, show that some non-uniform vertical displacements and horizontal constraints are still present at the contact surfaces between the central specimen and the upper and lower cubes.

Finally the use of steel brushes between the platens and the specimen was adopted in order to reduce the friction: fig 4.38a,b show the principle scheme and a photograph of the test respectively. This turned out to be the best way of testing when lateral displacements have to be allowed. An interferogram showing a very regular pattern of horizontal displacements is represented in fig. 4.39.

4.2.2.5. Comparison of classical and optical measuring techniques

One of the main targets of this study was to evaluate and eventually criticize the effectiveness of classical measuring techniques (strain gauges, LVDTs, CPDTs) in the mechanical characterization of soft materials.

In a first experiment a brick specimen (40x40x120 mm dimension), subjected to compression was investigated by ESPI controlling the area where a strain gauge was attached [11].
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Fig. 4.35: Interferogram related to horizontal deformation of the compressed specimen (after some image processing): the constraining action of the plates can be observed.

Fig. 4.36: Interferogram related to vertical deformation of the compressed specimen (after some image processing): the effect due to contact defects between specimen and plates is observable.

Fig. 4.37a: Interferogram related to horizontal deformation of the compressed specimen in the three-cubes configuration (after image processing)

Fig. 4.37b: Interferogram related to vertical deformation of the compressed specimen in the three-cubes configuration (after image processing)
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**Fig. 4.38a:** Sketch showing the use of brushes for compression purposes

**Fig. 4.38b:** Photograph showing the use of brushes for compression purposes

**Fig. 4.39:** Interferogram of horizontal displacement of the compressed specimen obtained by using the brushes
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A qualitative evaluation of the interferogram in fig. 4.40, related to the vertical deformation, gave evidence that the fringe pattern was disturbed by the presence of the strain gauge. By using a simple FEA (Finite Element Analysis) program, the deformation occurring on a surface having different mechanical characteristics (i.e. higher Young’s Modulus) in its central area was studied. As shown in fig. 4.41, the contour lines of the computed vertical displacement exhibited a very good qualitative agreement with the interferometric result (the white frame represents the pasted gauge’s area).

The glue probably exerts a constraining action that influences the free behaviour of the specimen, affecting the measurement precision; the stiffening effect of the glue is clearly shown by the failure mechanism (formation of cracks around the gauge area) of the specimen in fig. 4.42.

In a second experiment [19], in order to outline the differences with more ‘classical’ measurement tools, three procedures were used on the same specimen for vertical displacement detection: strain gauges, LVDTs between the plates and the interferometric technique (fig. 4.43). The different results are collected in the plot of fig. 4.44. The plot of the ESPI data calculated in the central area of the specimen shows perfect coincidence with that of the strain gauge. The curve of ESPI data read at the left and right edges (free from the constraining action of the glue) gives higher strains. This plot is clearly parallel to the one obtained from the average values given by the LVDTs positioned between the plates, except that for the initial part where the last one shows the typical locking behaviour.

In a third experiment [19] CPDT transducers were applied in coincidence with the interferometric technique for measuring vertical displacements in order to confirm the reliability of the two measuring procedures. In fig. 4.45 a view of the experimental set-up is presented. The data obtained with the CPDT and with the interferometric technique on the two vertical sides are reported in fig. 4.46: it may be observed that the agreement is very good.

4.2.2.6. Mechanical evaluation of masonry materials

In order to verify the possibility of using the ESPI technique for quantitative evaluation of the mechanical properties of brittle soft materials, prismatic brick specimens (40x40x120 mm) were prepared and studied in compression tests. When just the central part of the specimen was observed, influences due to the compression plates were almost completely eliminated and more significant results could be obtained. Tests started with a pre-load of 1 kN and a maximum load was fixed at 25 kN with a cross-head speed of 0.5 mm/min.
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Fig. 4.40: Interferogram of vertical displacement of the compressed specimen having a pasted strain gauge in the centre: the effect due to the strain gauge is clearly visible.

Fig. 4.41: FEM simulation of vertical deformation of the compressed specimen with the pasted strain gauge.

Fig. 4.42: Photograph of the specimen with pasted strain gauge.
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Fig. 4.43: Sketch of the compression experiment controlled by:
- a strain gauge,
- two LVDTs, ESP!

Fig. 4.44: Plot collecting all measurements obtained by strain gauges, LVDTs and ESP
1) strain gauge
2) ESP at the center of the specimen
3) ESP at the borders of the specimen
4) LVDTs' measurement
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Upper compression plate

Specimen

Lower compression plate

Fig. 4.45: Sketch of the compression experiment controlled by:
- two CPDTs, ESPI

Fig. 4.46: Plot collecting measurements obtained by CPDTs and ESPI
Quantitative data were obtained by simply counting the number of fringes in the interferograms [13-15,19].

If pure compression and no rigid movement (rotation) were present:
- in the configuration sensitive to horizontal displacements just vertical fringes could be observed
- in the configuration sensitive to vertical displacements just horizontal fringes could be observed

If rigid body rotation occurred, the specimen displacement generated fringes in the other direction (as described in section 4.2.1.4.):
- in the configuration sensitive to horizontal displacements just horizontal fringes could be observed
- in the configuration sensitive to vertical displacements just vertical fringes could be observed

When both effects contributed to the formation of fringes:
- the real horizontal deformation occurring between two selected points was obtained by connecting them with an imaginary line and counting the number of vertical fringes crossed.
- the real vertical deformation occurring between two selected points was obtained by connecting them with an imaginary line and counting the number of horizontal fringes crossed.

The sensitivity factor of the system to in-plane deformation (relative displacement between two fringes) was related to the optical geometry: with an angle of 26 degrees the sensitivity factor is about 0.61 μm/fringe.

By applying this very simple fringe evaluation strain/stress plots were obtained for four different specimens, for the horizontal and vertical deformations (fig. 4.47 a,b,c,d). In fig. 4.48 the Young’s Modulus is plotted against the corresponding stress, calculated at each loading increment. The ratio between horizontal and vertical deformation (Poisson’s Ratio), calculated in the same way, is plotted in fig. 4.49. It may be seen that while the Young’s Modulus remains approximately constant in a wide range of stress, the Poisson’s Ratio increases with the stress value indicating a dilation effect even far from the failure.

4.2.2.7. Comparison of two different materials (marble and gneiss)

As pointed out in previous sections, data obtained from a compression test can be helpful to characterize the material under inspection: the deforming behaviour can be observed and the evaluation of some mechanical parameters can be attempted.
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Fig. 4.47a: Strain/stress plot obtained for prismatic brick specimen number 1

Fig. 4.47b: Strain/stress plot obtained for prismatic brick specimen number 2

Fig. 4.47c: Strain/stress plot obtained for prismatic brick specimen number 3

Fig. 4.47d: Strain/stress plot obtained for prismatic brick specimen number 4
Fig. 4.48: Young's Modulus/stress plot for the four prismatic brick specimens

Fig. 4.49: Poisson's Ratio/stress plot for the four prismatic brick specimens
These data can be important for many purposes:

(i) to catalogue characteristic data of materials
(ii) to compare different materials
(iii) to retrieve mechanical coefficients to be used as parameters in FEA analysis
(iv) to evaluate the changes in the behaviour of the same material under different conditions (temperature, humidity, ageing).

In this section experiments carried out for two different building materials, marble and gneiss, are presented. They show a different behaviour when subjected to a compressive test, mainly due to their different crystalline structure.

**Gneiss.** This stone is created from the deposit of products coming from the mechanical disgregation, produced by atmospheric phenomena, of pre-existent rocks (action of water, wind, sun, ice, etc.). Monodirectional pressures acted for very long times, producing the stratification of the material along planes perpendicular to the pushing action. For these reasons, preferential planes of fracture exist and this stone shows different behaviour, depending on the direction of compression.

**Marble.** This stone is produced from the chemical alteration of pre-existent materials. It comes from rock layers subjected to very high temperature giving rise to high mobility of molecules and ions, that try to recombine in a more compact structure, usually under the action of water or ice. This process gives materials without preferential layers and showing a more isotropic structure.

As a conclusion it must be pointed out that while the behaviour of gneiss depends on the loading direction, marble shows a more uniform response.

Three different tests were carried out on cubic specimens (4cm side):

(a) compression on a marble specimen
(b) compression on a gneiss specimen perpendicular to the direction of layers
(c) compression of gneiss specimen parallel to the direction of layers.

Video pictures obtained for these three different cases are presented in the fig. 4.50 a,b,c.

For every experiment plots of deformation (fig. 4.51 a,b,c), Poisson's coefficient (fig. 4.52 a,b,c) and Young's Modulus (fig. 4.53 a,b,c) were generated.

It is clearly observable from case (b) that the specimen did not show an important horizontal expansion: all the compressive action was absorbed by the material that didn't allow the formation of cracks, even at high loading rates. In case (c) the horizontal deformation was higher and fractures could be observed even at low loading rates.
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Fig. 4.50a: Video picture obtained for the compressed specimen of marble

Fig. 4.50b: Video picture obtained for the specimen of gneiss compressed perpendicularly to layers
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Fig. 4.50c: Video picture obtained for the specimen of gneiss compressed parallel to layers

Fig. 4.51a,b,c: Strain/stress plots:
- a) for the compressed specimen of marble
- b) for the specimen of gneiss compressed perpendicularly to layers
- c) for the specimen of gneiss compressed parallel to layers

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**Fig. 4.52a:**
Young's Modulus/stress plot obtained for the compressed specimen of marble

**Fig. 4.52b:**
Young's Modulus/stress plot obtained for the specimen of gneiss compressed perpendicularly to layers

**Fig. 4.52c:**
Young's Modulus/stress plot obtained for the specimen of gneiss compressed parallel to layers
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Fig. 4.53a:
Poisson’s Ratio/stress plot obtained for the compressed specimen of marble.

Fig. 4.53b:
Poisson’s Ratio/stress plot obtained for the specimen of gneiss compressed perpendicularly to layers.

Fig. 4.53c:
Poisson’s Ratio/stress plot obtained for the specimen of gneiss compressed parallel to layers.
4.2.2.8. **Splitting test (for tensile strength evaluation)**

One of the most difficult parameters to be calculated for bricks and weak mortars is certainly the tensile strength; indirect rather than direct tests are preferred due to the infrequent success in carrying out experimentally the second ones. Flexural tests are more frequent; nevertheless splitting tests give values which are nearer to the direct tensile strength values [20].

The control of the theoretical strain distribution in a cylinder under splitting test is certainly very interesting since compressive stresses are concentrated near the point where the load is applied and tensile stresses are supposed horizontal and uniformly distributed in the central part of the specimen.

Some splitting tests on brick cylinders of 50 mm diameter and 100 mm height were carried out under interferometric observation. The specimen was compressed in the hydraulic machine not along the axis direction but along a diameter (fig. 4.54a,b). The interferogram related to the vertical deformation and the simulation obtained with the FEA software are respectively displayed in fig. 4.55 and fig. 4.56: the agreement is actually very good.

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Fig. 4.54a: *Scheme of compressed brick cylinder in a splitting test*
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Fig. 4.54b: Photograph showing the compressed brick cylinder in a splitting test

Fig. 4.55: Interferogram related to vertical deformation of the brick cylinder during the splitting test

Fig. 4.56: FEM simulation of the vertical deformation of the brick cylinder during the splitting test
4.2.3. Evaluation of mechanical properties of building materials by flexural test

4.2.3.1 Introduction

The fracture energy of a material is another mechanical parameter interesting for the building industry. It is usually obtained as ratio between the total energy spent in flexural tests to divide into two parts the initially notched specimen (area between the load–displacement curve and the horizontal axis) and the area of the initial ligament, i.e. the area \((h-a)_s\) in fig. 4.57. Actually, the value obtained in that way represents a mean value of this parameter and depends on the scale of the specimen [21]. For determining more precisely its actual value it is possible, for example, to determine the fracture energy on notched specimens having different initial notch length [22], but it can be very costly. Optical techniques can optimize the determination, because they can give a complete map of the strain field during crack propagation and, in this way, facilitate the computation of the energy necessary to increase the fracture process of a unity area. Crack propagation and the position of the crack tip, usually not visible to the naked eye, can be observed with accuracy. In this work the portable system 1, sensitive to the horizontal in-plane component of displacement, described in section 3.2.2.2 was used.

Within a collaboration with the Structural Engineering Department of Polytechnic of Turin an attempt to apply interferometric techniques to crack observation and fracture energy evaluation has been done[23,24].

4.2.3.2 Specimens and experimental arrangement

The geometrical data of the specimens, obtained by sawing parts of clay blocks taken from ordinary industrial production, were characterized by a length of 240 mm (span length \(l=230\) mm), a depth \(h=40\) mm and a thickness \(s=7\) mm as indicated in fig. 4.57.

The tests were carried out in notch mouth opening controlled conditions, according to the three point bending scheme illustrated in the same figure [25].

The increasing rate of notch mouth opening at midspan was kept constant at \(8\cdot10^{-5}\) mm/s up to peak load and during the first part of the softening stage, characterized by a sharp loading decrease. Subsequently, it was progressively increased up to ten times the initial value.
Deflection at midspan and the settlements at the supports of the specimen were measured by means of three couples of LVDTs with 0.5 mm measuring range; their arrangement is shown in fig. 4.58, that also provides an overall view of the mechanical testing equipment normally used for fracture energy determination on clay specimens, including the optical equipment used for ESPI.

The servo-controlled machine was programmed in order to be able to perform the tests automatically and at the same time make manual adjustments possible, whenever necessary. Readings of the measuring instruments were taken at constant time intervals. The data were stored in files and printed out on paper at each reading step, including the elapsed time from the beginning of the test. The optical interferograms and load values were also acquired as a function of time. All the data could be in this way synchronized and compared.

As the damaged zone produced by crack propagation is restricted to a small part surrounding the midspan of the specimen, by adjusting the focus of the camera, an area of only 40x50 mm in that zone was observed. The geometrical angle involved by the testing set-up adopted was $\theta = 20^\circ$. A sensitivity factor to in-plane displacement of $0.92 \, \mu m/\text{fringe}$ between two neighbouring fringes was then obtained. The relative displacement between any pair of points could be obtained by simply counting the number of fringes in between and multiplying it by this sensitivity factor.

By using the interferograms obtained with the ESPI technique, some further information can be obtained:

- it is possible to observe the crack tip position as a function of the load level. In this way it is possible to obtain information on the amount of energy spent for producing the crack propagation.
- it is possible to obtain a strain map showing the damaged zone surrounding the crack and allowing the determination of the actual process zone extension, i.e. the zone where the material shows a non-linear behaviour.

The high sensitivity of the applied interferometric method in determining the displacements of one point (of the order of magnitude of one micron), allows the retrieval of results with an accuracy not obtainable by using most other traditional techniques or interferometric techniques.
A combination between classical measuring tools and optical techniques can be observed.
4.2.3.3 Experimental results

Results obtained with ESPI technique are presented for two specimens having a notch of 20 mm and 12 mm respectively.

Experiment 1: Specimen with a notch of 20 mm

Fig. 4.59 shows the load-deflection curve recorded by traditional mechanical transducers at midspan (after deduction of the settlement of the supports) for the specimen being considered [23]. The peak load was observed at 79.3 N while the maximum deflection, at the end of the softening branch (zero load), resulted of 168 μm.

Two different interferograms obtained by the ESPI technique at different load levels are here shown. The first interferogram (fig. 4.60a) relates to an instant when the fracture has not started, while the second (fig. 4.60b) shows an instant when the fracture is propagating. The evaluations were performed in terms of displacement and mean strains, in correspondence with five pairs of points along horizontal lines spaced 10 mm apart, as illustrated in fig. 4.61. In the same figure, the relative displacement and the load values are plotted versus time. The fracture tip propagation was evaluated as well as function of time (fig. 4.62).

It is possible to observe that in correspondence with the section A–A' the relative displacement is negative (compression) nearly up to complete separation of the specimen in two parts. The maximum relative displacement between these two points is 5.1 μm and, as a consequence, the mean strain at the compression edge is 0.25·10⁻³ (250 microstrains) observed at a load of 66.8 N, in the descending branch of the loading process.

In correspondence with section B–B' a change in sign of the relative displacement is revealed when the crack tip reaches that section at a load level of 55.2 N, always in the softening part of the load-displacement diagram.

In fig. 4.63 the mean strains between the pairs of points above mentioned, are plotted at the five load levels indicated in fig. 4.59. It is necessary to point out that the mean strain in correspondence with the sections D-D' and E-E' is purely virtual because of the notch in between.

It is possible to observe the mean strain proportionality at the first two load levels with a constant position of the neutral axis of deformations, corresponding to the ascending part of the load process. During the crack propagation (softening branch of the load process) a
more than proportional increase of deformations is observed along with progressive rising of the zero mean strain level, towards the compression edge.

**Fig. 4.59:** Load–deflection curve recorded by traditional mechanical transducers at midspan in Experiment 1

\[ P_{max} = 79.3 \text{ N} \]
\[ \delta_{max} = 168 \mu \text{m} \]

**Fig. 4.60a:** Interferogram related to an instant when the fracture has not started

**Fig. 4.60b:** Interferogram related to an instant when the fracture is propagating.
Fig. 4.61: Relative displacement and load values are reported versus time for the five couples of points selected.
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Fig. 4.62: Plot of fracture tip propagation evaluated as function of time

Fig. 4.63: Plot of mean strains between the couple of points at the five load levels indicated in Fig. 4.59
In this way it is possible to obtain the strain evolution in the notch tip zone when the fracture process starts and develops. In particular, at the onset of crack propagation the mean strain at C–C’ level was found to be $0.24 \cdot 10^{-3}$ (240 μstrain).

The actual strain along the section C–C’ at the onset of cracking and during crack propagation (as well as along any section in the upper part of the specimen) has, on the other hand, a varying value which could be obtained by processing of fringe images at shorter sections along the mentioned section.

**Experiment 2: Specimen with a notch of 12 mm**

Fig. 4.64 shows the load-deflection curve recorded by traditional mechanical transducers at midspan (after deduction of the settlement of the supports) for the specimen being considered and the crack tip propagation [24]. The peak load was observed at 86.2 N while the maximum deflection, at the end of the softening branch (zero load), was found to be 560 μm.

On the load-midspan deflection curve of fig. 4.64 the numbers 1 to 3 refer to three different load levels: to the onset of crack propagation, to a load level of 20 N in the descending branch and to the onset of the specimen’s failure (zero load). In fig. 4.65a,b,c interferograms obtained by the ESPI and related to these three instants are presented.

![Fig. 4.64: Load-deflection curve recorded by traditional mechanical transducers at midspan in Experiment 2](image-url)
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Fig. 4.65a: Interferogram related to instant 1 of plot in Fig. 4.64

Fig. 4.65b: Interferogram related to instant 2 of plot in Fig. 4.64

Fig. 4.65c: Interferogram related to instant 3 of plot in Fig. 4.64
The evaluations were performed in terms of displacement and mean strains, corresponding to seven levels spaced 5 mm apart (levels B, C, D, E, F, G, H as illustrated in fig. 4.66). At each level, four evaluations were performed, referred to pairs of points spaced 40, 20, 10 and 5 mm apart respectively, astride midspan (lengths 1, 2, 3, 4).

Fig. 4.67 summarizes the measured data: the load versus time curve is plotted together with the four strain versus time curves, referring to the four lengths C1=40 mm, C2=20 mm, C3=10 mm, C4=5 mm, at level C (approximately at the notch tip level). From this figure, it appears that the mean strain considerably changes for each considered length and that the maximum value (15·10^3 microstrains) is obtained for the minimum length. This fact suggests that strain concentration occurs close to the crack. A second very important consideration comes from the observation of the slope of the previously mentioned curves C1-C4: these curves show an evident knee (particularly visible for C3 and C4) located approximately on the vertical of the peak load. Actually, these knees seem to anticipate the peak load, revealing the coalescence of microcracks into major cracks at the onset of the fissure propagation in the notch tip region and a consequent decrease in the tensile stiffness.

In fig. 4.68 the load versus time curve is plotted together with the seven strain versus time curves referring to the length of 5 mm astride midspan at levels from B to H (B4, C4, D4, E4, F4, G4, H4). In this plot the presence of a knee is observed for the curve C4 in correspondence to the peak load, while the other curves (D4, E4, F4, G4, H4) show a knee when the crack tip crosses the corresponding level. On the other hand, when the crack approaches the upper edge, a marked proportionality between the mean strains at various levels is observed. In fact these strains are purely virtual because of the crack in between: the specimen, at these load levels, behaves approximately as constituted by two parts that rigidly rotate around a pivot point at the upper midspan hinge.

As for Experiment 1, it is possible to observe the change in sign occurring in the curves representing the mean strains at the levels above the notch tip (D4, E4, F4, G4, H4) when the crack tip, approaching the upper edge, crosses them (due to the scale of the plot this fact is evident for levels H4, G4 and F4 only). The maximum compression strain at level H4, corresponding to the peak load, is 0.224·10^3 (224 microstrains).

It is important to point out that the descending branch of the load versus time curves in fig. 4.67 and fig. 4.68 and the load midspan deflection curve in fig. 4.64 have a different shape: this is not only due to the different parameters reported in abscissa but also to the fact that during the tests the notch mouth opening rate was increased.

For the interferograms related to load levels indicated as 1 and 2 in fig. 4.64 the phase shifting procedure was applied; phase maps and vectoral representations of horizontal
distributed displacement obtained after elaboration are presented in fig 4.69a,b and fig. 4.70a,b.

Fig. 4.66:
Position of the couples of points considered for the quantitative evaluation

Fig. 4.67:
Load/time plot for the experiment and strain/time plot calculated for four couples of points on level C.

Fig. 4.68:
Load/time plot for the experiment and strain/time plot calculated for one couple of points at every one of the seven levels
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Fig. 4.69a: Phase map obtained after quantitative phase-shifting evaluation of the interferogram presented in Fig. 4.65a

Fig. 4.69b: Phase map obtained after quantitative phase-shifting evaluation of the interferogram presented in Fig. 4.65b

Fig. 4.70a: Vectoral representation of distributed horizontal displacement obtained from the interferogram presented in Fig. 4.65a

Fig. 4.70b: Vectoral representation of distributed horizontal displacement obtained from the interferogram presented in Fig. 4.65b
4.2.4. Study of interaction between bricks and mortar joints

4.2.4.1 Introduction

After having studied some properties of single units, assemblies of different materials have been inspected. The influence of mortar strength and deformability on the brick-masonry behaviour under compressive loads has long been a subject of study. Nevertheless, further clarification is needed. It is known that the crack formation and propagation in bricks and/or in mortar joints is dependent not only on the mutual influence of the material deformability but also on the bond between brick and mortar. Several theories have been proposed to explain the influence of the deformability of mortar on the compressive strength of masonry [26,27]. Nevertheless the mechanism of failure of masonry structures under compression is still not completely clear. Other hypotheses have been recently proposed based on fracture mechanics [28]. On the other hand, the direct measurement of horizontal and vertical displacements in the mortar joint by classical tools during loading and unloading is very difficult due to the joint dimension: furthermore some lime mortars can be weak and easily damaged even by the application of a strain gauge or a CPDT (Clamp on Point Displacement Transducer).

Optical interferometric techniques are very useful because they allow, without direct contact to the surface of the material, a full-field observation of the inspected surface. ESPI has been used by the Author in order to detect the strain distribution in a masonry specimen under compressive or shear stresses and to follow the crack formation and propagation in a small-scale masonry specimen under compressive loading. Specimens built with two bricks connected with a mortar joint have been subjected to a compressive test and the area around the joint inspected. The same operation has been repeated on a cylindrical specimen subjected to the splitting test. ESPI has subsequently been applied to shear bond tests carried out on triplets made with bricks and mortar and to cylinders subjected to splitting tests on inclined joints. Small scale specimens containing horizontal and vertical joints have been subjected to compressive tests in order to observe the formation of cracks at a very early stage. The results obtained seem to give promising hopes for future developments [29].
4.2.4.2 Experimental arrangements

Some experiments were performed on vibration-free tables by using the full in-plane inspection system described in paragraph 4.3.2.2 and used previously in this chapter for the evaluation of mechanical characteristics (paragraph 4.4.2.2): data from the test machine and the acquisition of interferometric patterns was completely controlled by a computer. Some other experiments were performed directly in the laboratories of experimental mechanics of the Polytechnic of Milan: the experimental portable arrangement used for these experiments is exactly the same as that used in paragraph 4.2.3 for flexural tests and for some applications in paragraph 4.2.2. This portable system was used to inspect horizontal or vertical components of displacement depending on the experimental requirements.

4.2.4.3. Compression test (vertical displacement)

Two types of specimens were used for the compression test [29], the first one made of two portions of a brick with mortar joint in the middle (dimension 100x100x110 mm) (fig. 4.71), the second one made of three portions with two mortar joints (dimension 115x100x180 mm) (fig. 4.72). The behaviour of the first specimen was studied and one of the most interesting interferograms, corresponding to a compression of 0.2 N/mm², was selected (fig. 4.73). The influence of the mortar joint deformability is clearly detectable: in fact, at this stage of the loading process a uniform vertical deformation would be present in the case of a homogeneous material and only horizontal fringes should appear. A deviation of these fringes from the horizontal direction means the presence either of a rigid body rotation or of a shear deformation. Since the fringes assume a symmetrical configuration with respect to the vertical axis, this deviation can be explained only by a state of shear. If the higher deformability of the mortar is taken into account, symmetrical shear stresses are generated along the contact surface mortar-brick. The number of fringes along a vertical line in the center of the specimen is lower than that counted on the two sides of the face, showing that a higher deformation is taking place there. Figs. 4.74a,b,c concern the specimen of three-brick height: the interferograms being taken at compressions of 0.3, 1.7 and 3.4 N/mm² respectively. In this case the inclined fringes corresponding to vertical displacements show clearly that the specimen is subject to a rigid body rotation under compression. The discontinuity in the fringe slope at the joint shows the presence of a material with a different stiffness (fig. 4.74a). The lower slope of the joint fringes means a higher component of the vertical displacement, therefore a lower stiffness
of the mortar. When the load is increased, the fringe pattern changes and the formation of a first vertical crack in the upper brick (fig. 4.74b) and the second in the lower one (fig. 4.74c) is revealed by discontinuities in the fringes.

Fig. 4.71: Two bricks with one mortar layer

Fig. 4.72: Three bricks with two mortar layers

Fig. 4.73: Interferogram of the specimen of fig. 4.71 at a compression load of 0.2 N/mm²
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Fig. 4.74a:
Interferogram of the specimen of fig. 4.72 at a compression load of 0.3 N/mm²

Fig. 4.74b:
Interferogram of the specimen of fig. 4.72 at a compression load of 1.7 N/mm²

Fig. 4.74c:
Interferogram of the specimen of fig. 4.72 at a compression load of 3.4 N/mm²
A mixed-method technique has been applied for retrieving quantitative information: the brick deformation was evaluated by the ESPI technique and the mortar deformation by the application of a CPDT. Fig. 4.75 presents the graph of stress/strain for the central brick (ESPI data) and the mortar joint (CPDT left and right measurements) and confirms the above considerations.

4.2.4.4. Splitting test (vertical displacement)

Splitting test were carried out on two cylindrical specimens (diameter 100 mm, length 120 mm) with a mortar joint [29]. In the first specimen the mortar layer was horizontal (fig. 4.76a,b), in the second it was inclined 45° (fig. 4.77a,b). Interferograms obtained in the first case corresponding to concentrated loads of 4.9, 8.9, 17.31 and 17.37 kN are shown in figs 4.78a-d respectively. This type of test is used by some researchers to define the masonry strength under compression [30]. Fig. 4.78a shows a behaviour similar to that of a homogeneous material [31]. In fig. 4.78b the influence of the joint deformability on the shape of the fringes is clearly visible: in fig. 4.78c the formation of the vertical crack in the center of the specimen is highlighted by the discontinuity in the fringes; fig. 4.78d represents a frame showing the mechanism of failure of the specimen.

Similar observations were made for the second specimen. Figs. 4.79a,b,c corresponding to concentrated loads of 6.9, 15.15 and 15.51 kN describe respectively the sequence of continuity, crack formation and failure.

4.2.4.5. Shear bond test (Horizontal displacement)

A shear bond test was carried on as shown in fig. 4.80a,b [26]. During the test, interferometric observation of the area marked in the figure was performed continuously up to failure.

Fig. 4.81a,b,c present the most interesting interferograms corresponding to the horizontal displacement. In fig. 4.81a the differential displacement between the two bricks causes a shear deformation of the mortar joint, but the fringes are still continuous. In fig. 4.81b and 4.81c the fringes in the mortar are no longer readable; the discontinuity in fringe number (fig. 4.81b) and orientation (fig. 4.81c) indicates a shear failure occurred. This behaviour was confirmed by numerical Finite Element Modeling.
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Fig. 4.75:
Stress/strain plot for the central brick (ESPI data) and the mortar joint (CPDT left and right measurements)

Fig. 4.76a,b: Cylindrical specimen with an horizontal mortar joint: a)Scheme b) Photo

Fig. 4.77a,b: Cylindrical specimen with an horizontal mortar joint: a)Scheme b) Photo
Fig. 4.78a: Interferogram of vertical displacement of the cylindrical specimen of fig. 4.76 at a load of 4.9 kN

Fig. 4.78b: Interferogram of vertical displacement of the cylindrical specimen of fig. 4.76 at a load of 8.9 kN

Fig. 4.78c: Interferogram of vertical displacement of the cylindrical specimen of fig. 4.76 at a load of 17.31 kN

Fig. 4.78d: Frame showing the mechanism of failure of the cylindrical specimen of fig. 4.76 at a load of 17.37 kN
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Fig. 4.79a:
Interferogram of vertical displacement of the cylindrical specimen of fig. 4.77 at a load of 6.9 kN

Fig. 4.79b:
Interferogram of vertical displacement of the cylindrical specimen of fig. 4.77 at a load of 15.15 kN

Fig. 4.79c:
Frame showing the mechanism of failure of the cylindrical specimen of fig. 4.77 at a load of 15.51 kN
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Fig. 4.80a: Specimen for shear bond test: the inspected area is in grey

Fig. 4.80b: Photograph of shear bond test: the illuminated area can be observed
Fig. 4.81a,b,c: Interferograms corresponding to the horizontal displacement in the shear bond test
4.2.4.6. Compressive test on a small scale assembly

A compressive test was carried on a 1/4 scale wall with few horizontal and vertical joints; the aim was to understand the influence of the joint on the behaviour of masonry [15,28]. ESPI was applied on an area of 70x50 cm, containing one horizontal and two vertical joints. The evolution of fringes due to the action of an external load was observed and stored on a videotape. Defects of bonding and the formation of cracks were easily observed, well before they became visible to the naked eye. Two obtained frames particularly descriptive of the phenomena involved have been selected and presented hereinafter.

From fig. 4.82a (uniformly distributed stress of 2.0 N/mm²), representing fringes of vertical displacement, different phenomena can be observed; e.g. discontinuity between the upper vertical joint and the bricks, caused by a poor bond, formation and propagation of a crack in the upper brick. fig. 4.82b (uniform stress of 6.0 N/mm²) represents a further situation, with propagation of the crack into the horizontal joint, loss of bonding in the lower vertical joint and formation of a new crack in the upper brick.

4.2.5. Loading test on a inhomogeneous specimen (the Pavia's tower case)

In 1988 the tower of the cathedral of Pavia, in northern Italy, one day suddenly collapsed causing the death of some citizens. This breakdown was completely unexpected: there was no warning about the possibility of failure, and this was mainly due to the difficulty in evaluating the behaviour of such a structure. The tower had been built with a regular masonry structure along the external surface and with a disordered mixture of mortar and stones in the inside: the behaviour of this last compound was very difficult to evaluate. For this reason the Polytechnic of Milan started some studies and the author participated to the program by performing interferometric experiments.

Some prismatic specimens (10x10x30 cm) (fig. 4.83) coming from the inside of the tower were prepared and a pair of them were subjected to the ESPI analysis under loading actions. An ESPI system sensitive to in-plane deformation along the axis of compression was used: the illumination and the viewing objective were arranged in order to observe the specimen taken as a whole.
Fig. 4.82a: Interferogram of vertical displacement of the small-scale wall at a compression load of 2.0 N/mm²

Fig. 4.82b: Interferogram of vertical displacement of the small-scale wall at a compression load of 6.0 N/mm²
During a phase of compression and a phase of the decompression the real time formation of fringes (related to vertical deformation) was recorded with a videotape and the data of the machine load and cross-head displacement were recorded in a file.

**Loading phase**

The specimen was subjected to a constant speed of compression of 0.1mm/min and the formation of fringes was observed and recorded in real time; the cross-head displacement and the machine load were recorded every 4 seconds. In fig. 4.84a the graph of load is presented as function of time: no strange behaviour or sudden jump can be observed. The formation of fringes was also very regular and progressive. The overall phase of compression lasted about 30 minutes.

**Unloading phase**

The specimen was subjected to an unloading phase having a speed of 1mm/min (ten times faster than compression): the overall phase lasted about 5 minutes. The graph of load as function of time is presented in fig. 4.84b and fig. 4.84c(zoomed). During the real-time recording of the interferograms, sudden failures with consequent formation of numerous fringes could be observed (fig. 4.85). It was observed that sudden fringe formation corresponded to jumps in the load/time plot. This means that the formation of sudden fringes (related to the occurrence of cracks) corresponded to an attenuation in the resistance of the material and to a reduction in the amount of load needed for deforming the specimen. It must be pointed out that the cracks, clearly located from the interferometric pattern, were not visible to the naked eye on the specimen.

*Fig. 4.83: Picture of the inspected specimen*
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Fig. 4.84a: Load/time plot in the loading stage

Fig. 4.84b: Load/time plot in the unloading stage

Fig. 4.84c: Zoom of the interesting part of the load/time plot in the unloading stage

Fig. 4.85: Interferogram showing the sudden formation of fringes
4.3. Deformation analysis by moiré methods

By using the moiré effect it is possible to inspect in-plane and out-of-plane displacements. As with the analysis performed in the previous section, attention is mainly focused on the inspection of deformation components in the plane of the surface. For this purpose a grating is pasted on the area of interest where it is distorted as the surface is subjected to a stress. By making the "object" grating interfere with a steady "reference" one (paragraph 4.3.1) or by comparing two different situations of the deforming grating (paragraph 4.3.2), fringes related to the surface strain can be obtained. While the first method is more suitable for small areas where the resolution needed is higher, the second is preferred for the inspection of large surfaces.

The application of the moiré technique shows some advantages over ESPI, mainly related with:

- the possibility of inspecting larger areas
- a lower disturbance from ambient conditions
- no need to use a laser source
- no need to use computers, but fringes directly observable with the naked eye.

However some intrinsic drawbacks can be pointed out:

- a lower resolution is attainable (due to diffraction limits of the grating)
- the behaviour of the surface can be sometimes influenced by the pasted grating
- the presence of fringes at the beginning of the experiment is unavoidable (for the two-grating procedure)

4.3.1 Interference of two gratings

4.3.1.1. Preliminary tests (diffraction limits)

In these experiments a first "object" sheet was directly glued on the inspected surface and the second "reference" was placed over the other: the two gratings were kept together with a thin film of oil in between (fig. 4.86). The reference grating should remain absolutely still as the object moved due to load. The area of interest was then illuminated with a white light lamp and observed with a CCD camera directly connected to a TV monitor where the real-time formation of fringes could be observed. For a complete absence of fringes at the beginning of the experiment, the object and the reference grating should be carefully...
positioned. However, perfect relative positioning is not trivial, especially when the frequency of fringes is very high. For this reason it is almost impossible to avoid the presence of fringes on the object at the beginning of the experiment but the operator is actually interested just in the change of the shape of fringes. The common way to perform a quantitative evaluation consists of processing the phase distribution at the initial state and thence use it as reference to be subtracted from phase maps obtained after displacement. Some considerations about the gratings to be used are important. Gratings can be scribed, etched, ruled, printed, stamped, photographed or cemented onto specimens and pitches can vary from some millimetres to some microns. Most commercial gratings have a line width of approximately 50% of the pitch: two gratings with 50% line width are optimum to achieve maximum fringe contrast. If very high density gratings are required, laser interferometry is necessary: the grating can be produced by exposing a photographic plate to two laser beams from the same source, the pitch being determined by the angle between the beams. The grating can be copied by applying a contact or photographic procedure. Gratings used in this section were obtained by this interferometric technique and transferred to transparent plastic sheets. The master grating was bought from companies specialized in holographic methods and the transfer was directly performed at Ispra by some specialists of photography. Two different gratings were used by the author: 120 lines/mm and 240 lines/mm. While with the first the formation of fringes was clearly observed, interferograms obtained with the second had a very poor visibility. Some preliminary test were carried out on stone specimens in order to evaluate the applicability of the moiré technique to the evaluation of stone characteristics.

4.3.1.2. Compression test

A sandstone specimen was observed as it was compressed in the Hounsfield H50KM machine used previously for some ESPI experiments. The specimen had a lower base not perfectly flat, but showing a groove in the middle (fig. 4.87): due to the geometry the formation of a vertical crack was expected. Two transparent plastic sheets with gratings of 120 lines/mm were used: the first one was pasted onto the zone where the occurrence of failure was more likely and the second was placed over the other with a thin film of transparent oil in between. Oil showed the advantage of keeping the gratings together whilst allowing a free relative displacement. The specimen was painted with a white spray in order to obtain interferograms with a sufficiently good visibility.
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**Fig. 4.86:** Schematic arrangement used for moiré experiments

**Fig. 4.87:** Picture of the specimen used for first compression test: the superposed gratings are clearly visible

**Fig. 4.88:** Interferogram showing the presence of a crack
The specimen was illuminated with an halogen lamp and an area of 3x2 cm was observed with a CCD camera: the imaged was directly displayed on a TV monitor connected to a video recorder for storing the experimental data.

Due to the non-perfect relative positioning of the two gratings, fringes were observable on the inspected area at the beginning of the experiment. As the loading increased, the shape of these fringes changed and discontinuities in their geometry appeared when the crack formation started. In fig. 4.88 the interferogram obtained at a load of 10kN is presented. By simply counting the difference in the number of fringes in the left and in the right side of the fracture, it is possible to obtain a quantitative idea of the opening rate. As the pitch of the grating was 1/120 mm, the relative displacement between two fringes was 8.3μm: in fig. 4.88 the crack opening gave rise to a difference of about three fringes (i.e. 25μm).

In order to increase the sensitivity to displacement, gratings with 240 lines/mm were used but the quality of the resulting interferograms was very poor.

4.3.1.3. Three-point bending test

Within the experimental program carried out by the Author, at the Structural Engineering Department of the Polytechnic of Turin, for obtaining comparative values of fracture energy of different clay products, the possibility of using the moiré technique was investigated [23,24].

The geometry of specimens and the experimental procedure was exactly the same as that used in paragraph 4.2.3.2. The increasing rate of notch mouth opening at midspan was kept constant at 8·10⁻⁵ mm/s up to peak load and during the first part of the softening stage and subsequently it was progressively increased up to ten times the initial value.

The servo-controlled machine was again programmed in order to be able to perform the tests automatically; readings of the measuring instruments were taken at constant time intervals, stored in files and printed out on paper as function of flowing time. The optical interferograms and load values were also acquired as a function of time: all the data could be in this way synchronized and compared.

As the damaged zone produced by crack propagation is restricted to a small part surrounding the midspan of the specimen, only an area of 40x50 mm in that zone was observed. A first grating was directly pasted to the area of interest and the second was placed over it with a thin oil film in between. The illumination and viewing configurations can be observed in fig. 4.89: the surface was illuminated by an halogen lamp and observed with a CCD camera directly connected to a monitor where the fringe evolution could be observed in real time. Gratings having 120 lines/mm, printed on transparent plastic sheets,
were used and the inspected area was previously painted white in order to increase the contrast of the interferograms. Due to the non-perfect relative positioning of the two gratings, the presence of fringes could be observable on the surface also for the unloaded state. Anyway the deformation of the specimen and the crack tip propagation could be perceived from the change in the shape of fringes. Two interferograms obtained at the beginning of the experiment and close to the complete failure of the specimen are presented in figs. 4.90a,b respectively.

However, the application of this technique showed a significant limitation. As the fracture propagated and the resistance of the specimen decreased, the effect due to the intrinsic resistance of the pasted grating influenced dramatically the measurement. Actually, what the experiment measured at the end was the deformation of the grating’s plastic support, rather than the specimen’s deformation. For this reason, even though the application of the moiré technique was quite simple and gave information about qualitative behaviour, it was decided not to rely on this method and to prefer instead the application of ESPI techniques.

4.3.2 Double exposure of a single grating

Moiré techniques in their various forms have proved to be a versatile way of measuring in-plane displacements on a variety of real-scale engineering structures under different conditions. As demonstrated in previous sections, in engineering applications, of moiré usually one pattern is attached to the structure and a second master is used to interrogate it. As the structure is deformed, fringes are generated revealing the local displacements. The use of CCD cameras and frame stores can improve the speed of acquisition and processing of data (real-time inspection is straightforward). However, their spatial resolution is low and if a very high displacement sensitivity is needed, it is better to use a photographic camera and fine-grain films to record the patterned structures. Another technique, often referred as moiré photography [32,33], is based on making double-exposure acquisitions, where moiré fringe patterns of good quality and resolution are thus obtained.

4.3.2.1 Experimental arrangement

The author participated to some experiments using the moiré photography technique in the laboratories of the Institute for Safety Technologies (IST) at JRC-Ispra [34]. The distribution of in-plane displacements and strains in a reinforced concrete column was studied.
Fig. 4.89: Photograph of the experimental arrangement for flexural tests with moiré method

Fig. 4.90a,b: Interferograms selected from the sequence observed
a) At the beginning of the experiment
b) After 30 minutes
This experiment was carried out in order to simulate the behaviour of concrete columns subjected to the action of an earthquake. The structure was fixed at the base and then studied when a cyclic load (fig. 4.91) was applied to its upper free end by an hydraulic actuator under computer control. The schematic loading arrangement and a photograph of the column at the end of the experiment are presented in figs. 4.92a and 4.92b respectively. The column was covered with a printed paper pattern having an array of 6 dots/mm. A modified 35 mm camera \cite{32,33} was employed with a special slotted mask inside the lens, which both "tunes" the lens response and increases its depth-of-field. The camera was positioned at a distance of 3m from the column, which is the "tuned" distance for this pattern.

The camera was used to record changes in the pattern by making single and double-exposure records on holographic film. In the first case the interferogram was obtained by superposition of two photos, while in the second fringes could be readily observed on the film.

As the grating was a crossed line pattern (horizontal and vertical lines) the interferogram contained information about deformations in the x and y directions. After development, the negatives were analyzed in a spatial filtering system (fig. 4.93) \cite{32} and moiré fringe displacement maps representing in detail the separate x and y movements were generated. The displacement is related to the phase information by the equation:

$$\Delta x \text{ (or } \Delta y) = \frac{\Delta \phi}{2\pi} \cdot 166 \mu m$$

(4.1)

For every load cycle applied to the column the speed of the movement was made constant and the maximum displacement was fixed. Every cycle was repeated twice and then the displacement was increased.

4.3.2.2. Experimental results

Photographs were recorded at different displacement positions of the column and from the resulting fringe patterns some interesting information about this reinforced concrete structure has been obtained \cite{34}.

Interferograms relating to three different situations are here presented and discussed:

- displacement of the column top from -3 to 3mm
- displacement of the column top from -12 to 12mm
- displacement of the column top from -36 to 36mm.
Evolution of displacement

Fig. 4.91: Plot of the cyclic load applied to the upper extremity of the concrete column

Fig. 4.92a: Sketch of the loaded concrete column
Fig. 4.92b: Photograph of the damaged concrete column

Fig. 4.93: Optical arrangement for the retrieval of interferometric patterns descriptive of vertical and horizontal displacement from the developed negatives
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It was possible to find out some interesting results by a simply qualitative observation of the interferograms.

-3 mm (fig. 4.94a,b)
a) The horizontal component of displacement doesn’t offer much information about crack formation. The fringes are larger in the lower area; in fact the upper zone is the more strained.
b) From the vertical component it is possible to observe that cracks are beginning to appear.

-12 mm (fig. 4.95a,b)
a) Again the horizontal component of displacement doesn’t offer much information about crack formation. The fringes are again larger in the lower area. The number of fringes is obviously higher than in the previous case.
b) From the vertical component the presence of cracks is very clear.

-36 mm (fig. 4.96a,b)
a) At this stage the column is completely damaged and the cracks can be observed clearly also in the horizontal component of displacement. In the upper area the number of fringes is very high (it is not possible to resolve them with the printer). It is interesting to observe that the base of the column is not at rest but it is still deforming: the loading action is transmitted by the steel that is present inside the concrete.
b) The same conclusions come also from the vertical component of deformation.

From the single and double exposure fringe patterns, some quantitative data can be obtained by applying phase-shifting or Fast Fourier Transform techniques.

As an example, the FFT method was applied to the double-exposure pattern representing the vertical component of displacement caused by a movement at the top of -12 mm to 12 mm (fig. 4.95b). A phase map (fig. 4.97a) was obtained and from this a vectorial map (fig. 4.97b) and a profile (fig. 4.97c) of vertical displacement. As it can be seen, resolution of displacements down to few μm are attained.

With this technique it was possible to resolve displacements down to at least 1/10th of a fringe (16 μm). This experiment was just one of many possible applications shows how the moiré technique can be a powerful tool for the analysis of small deformations in large objects.

The interferograms obtained with this experiment have been used for some preliminary tests using the “virtual strain gauge” described in paragraph 3.3.3. The line presented in fig. 4.98 has been considered; intensity profiles and corresponding frequency spectrums were evaluated along this section for interferograms 4.94a and 4.95a and the plots are presented in figs. 4.99a-d respectively.
Fig. 4.94a,b: Interferograms related to horizontal and vertical deformation for a displacement from -3 to 3 mm, respect to the position at rest, of the top of the column
Fig. 4.95a,b: Interferograms related to horizontal and vertical deformation for a displacement from -12 to 12 mm, respect to the position at rest, of the top of the column.
Fig. 4.96a,b: Interferograms related to horizontal and vertical deformation for a displacement from -36 to 36 mm, respect to the position at rest, of the top of the column.
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Fig. 4.97a: Phase map related to the interferogram of Fig. 4.95b

Fig. 4.97b: Vectoral representation of vertical displacement related to the interferogram of Fig. 4.95b

Fig. 4.97c: Distribution of vertical displacement along a line
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Fig. 4.98: Section studied with the "virtual strain gauge" method.

Fig. 4.99a: Intensity profile along the desired section in fig. 4.94a.

Fig. 4.99b: Power spectrum of the plot in fig. 4.99a.
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Fig. 4.99c: Intensity profile along the desired section in fig. 4.95a

Fig. 4.99d: Power spectrum of the plot in fig. 4.99c.
It can be observed that the spectrum moves to higher frequencies when the surface is more strained. An evaluation of the centre of gravity of the spectrum could be directly related to the strain.

4.4. Surface modification analysis by the speckle technique

As described in paragraph 3.1.1 the local speckle correlation method seems to be very suitable for the study of phenomena involving micro-structural changes of a rough surface. This effect was employed to monitor the micro structural modifications during ageing of a stone specimen by salt crystallization cycles [35-38]. A measure of local correlation was derived from the digital difference of speckle patterns. The proposed method based on local correlation was used to estimate the speed distribution of the salt efflorescence mechanisms. However, a quantification of the surface change is not trivial because it requires a full knowledge of the surface and volume scattering properties of the stone micro structure. Anyway, the 2D map of speckle correlation revealed interesting aspects of the efflorescence mechanism and the interpretation of the experimental results can greatly contribute to a better understanding of some decay mechanisms. However, the comparison of much more data and the investigation of a large number of specimens are necessary. This final work is now carried out in collaboration with groups of monument conservation scientists.

As the method is much less sensitive to external vibrations or temperature gradients than other interferometric techniques, the proposed experimental approach could be easily applied for in-situ measurements.

4.4.1. Experimental set-up

Speckles can be observed when a rough surface is illuminated by laser light: a linearly polarized laser (35 mW HeNe, $\lambda = 633$ nm) and a polarizing filter for the observation of the speckle pattern were used. The laser beam was collimated and spatially filtered to produce a uniform illumination of the surface under examination (fig. 4.100).

A CCD video camera was used to acquire the speckle image of the surface. The objective lens was a 28 mm focal length. The video signal was sent to a frame grabber (Image Technology Inc. IT FG100 4 memory pages on-board, 512x512 pixels 8 bit resolution), installed in a Compaq 486 Personal Computer.
4.4.2. Results

Local correlation is applied here to monitor the efflorescence formation during salt crystallization cycles. Ageing by salt crystallization is employed by scientists to investigate the decay of stone materials. Stone damage can be reproduced, in this way, very rapidly and in some cases only few crystallization cycles are sufficient to fracture a stone specimen [38].

Every cycle consisted of the following two steps:

a) Capillary absorption on filter paper soaked with a water solution of decahydrate natrium sulphate (5%) for two hours or less depending on the dimensions of the specimen (fig. 4.101a)

b) Evaporation in the air for 48 hours (fig. 4.101b)

Two different stones were inspected with this technique: the Angera Stone and the Biocalcarenite of Noto.

After the end of the absorption process the evaporation stage was started and correlation images were recorded every hour. Such images were obtained by squaring and spatial averaging the difference of two speckle patterns acquired at times $t_1$ and $t_2$, twenty seconds apart. The absolute value of the difference could be displayed on a video monitor and the time evolution of the difference signal was thus observed. According to the theory discussed in paragraph 3.1.1.3, the correlation coefficient $\rho$ could be evaluated for every obtained image (equation 3.5). It seems clear that the correlation coefficient was proportional to the speed at which the water solution evaporated and the salt efflorescence appeared at the surface. Thus a local correlation image can be effectively used as a map which allows some comparisons between different regions in terms of the evaporation rate. For readability purposes, the activity rate of the surface is not represented by $\rho$ but by $1-\rho$: in this way if correlation is complete the activity is null.

Angera Stone

The first experiments were performed on prismatic specimens (5x5x2 cm) of the Angera Stone (coming from the neighbourhood of Ispra), which is a sedimentary dolomitic rock mostly composed of carbonates.

A qualitative evaluation of the phenomenon can be obtained by analyzing subtraction patterns obtained in the experiment. In the first six hours of observation the correlation pattern was not uniform, indicating that the efflorescence was appearing in patches (fig. 4.102): this was probably due to a non-homogeneous structure of the surface resulting in preferential areas of water evaporation.
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Fig. 4.100: Simple laser system for illuminating the area under inspection

Absorption

a)

Evaporation

b)

Fig. 4.101a,b: a) Preliminary phase of absorption b) Phase of evaporation

Fig. 4.102: Correlation pattern showing the efflorescence in the Angera stone occurring in patches
Later on this random pattern gave way to a more uniform image of correlation. However, in a few hours the speckle change gradually decreased and slowed down to a point where no change was detectable; after 24 hours the efflorescence phenomenon ended.

To obtain a more quantitative evaluation about the surface activity the correlation coefficient was calculated for every image. In fig. 4.103 the parameter \((I-p)\) is expressed as function of the drying time.

**Biocalcarenite of Noto**

Samples of the *Biocalcarenite of Noto* (coming from northern Sicily), a sedimentary carbonatic rock, were subsequently investigated.

The typical cause of decay for this stone is "alveolation", whose most dramatic effect is the formation of cavities. Previous investigations [38] have attributed the formation of alveoli to the presence of cylindrical sedimentary structures, called 'tubuli' (0.5-2 cm in diameter). Scientists found that the alveolation process has its origin at the edge of the *tubuli*, where a layer (0.1-0.4 mm thick) of microfossil shells and calcite crystals separates the *tubuli* from the bulk stone. In fact, the correlation images confirm that the presence of the *tubuli* influences the crystallization mechanism.

A prismatic sample (5x5x2 cm) with a tubular structure in its interior was examined. After absorption, a face including an elliptical section of the 'tubulo' was monitored with the local correlation method. During the first hours of observation, surface changes predominantly occurred along the external perimeter of the sample. In a day's time, the activity switched to the central part, which contained the 'tubulo' (fig. 4.104). An elliptical line of maximum correlation was detected around it, indicating that at the edge of the 'tubulo' the response to salt absorption was anomalous. Twelve hours later, a line of minimum correlation was visible only around the 'tubulo'. After 24 hours from the beginning of the experiment the efflorescence phenomenon ended.

To obtain a more quantitative evaluation about the surface activity the correlation coefficient was calculated for every image. In fig. 4.105 the parameter \((I-p)\) is expressed as function of the drying time. High activity values observed in the first hour are due to the evaporation of water present in the surface layers.
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Fig. 4.103:
The parameter \((1-p)\) is expressed as function of the drying time.

Fig. 4.104:
Correlation pattern showing the efflorescence in the Biocalcarenite of Noto showing the effect due to the presence of the "tubulo".

Fig. 4.105:
The parameter \((1-p)\) is expressed as function of the drying time.
4.4.3 Conclusion

The formation of salt crystals on the surface of porous stone materials has been observed with the proposed technique based on speckle decorrelation. At least four advantages can be highlighted:

(i) it is a completely non-intrusive technique and does not modify the free behaviour of the inspected surface

(ii) information about the mean activity process can be obtained from the correlation factor but local behaviour can be retrieved directly from an attentive analysis of the subtraction images

(iii) when the surface is completely covered with salt, it is still possible to identify the active areas: where the efflorescence phenomenon is still taking place, the crystalline crust alters the surface profile producing a change of the correlation coefficient.

(iv) for each point of the surface the correlation changes are observed a couple of hours before the macroscopic appearance of salt efflorescence.

It is expected that in natural efflorescence phenomena, where processes are considerably slower, surface alterations can be detected much earlier than any visible effect.

4.5. Application of optical interferometric techniques to the field of works of art

The application of interferometric techniques to artwork diagnostics has been the subject of several scientific publications for many years [39-44]. Two main advantages are brought by these methods in this field of application:

(i) incipient and invisible flaws can be detected at very early stages without any need to touch directly the inspected surface

(ii) the effectiveness of the repair work can be also evaluated a posteriori by comparison of the interferometric fringes obtained before and after restoration [43].

Artwork restorers, in spite of these obvious advantages, have been reluctant to use interferometric techniques as a tool for non destructive testing. This can be attributed to a variety of factors, from the skeptical attitude on the use of new technologies to economical aspects.

Application of holographic interferometry has been attempted in this field but some procedures (i.e. optical alignment, the development and reconstruction of holograms) are time consuming and require skilled operators. Furthermore, the mechanical stability
Chapter IV: Application of optical techniques in Civil Engineering

necessary for holographic measurements is not readily compatible with in-field conditions unless pulsed lasers are used [44]. However these lasers are not very flexible and easy to handle.

What conservators actually required was a measuring instrument visualizing microdeformations, providing real-time analysis, and performing in-field measurements with a minimum of adjustments. These requirements can be fulfilled with systems based on electronic speckle pattern interferometry, as Gülker et al [45] recently demonstrated by using ESPI to monitor deformation and deterioration processes in historical buildings and monuments.

Some of the portable systems described in paragraph 3.2.1 were used by the authors' group for testing wooden panels and frescoes. A painting on wood or on a wall can be regarded as a layered structure with a support. The wooden or mural support is coated with some priming layers or plaster, which serve as a base for the painting. These layers, normally made of mixtures of gesso and glue, are less thick and more fragile than the support. Expansion and contraction of the support due to daily fluctuations of ambient parameters can produce large strains and eventually cracks in the priming layers, as they become less flexible with age.

Furthermore, abrupt changes of humidity and temperature, traffic induced vibrations and heat exposure may also cause unpredictable stress distributions in the heterogeneous materials of the support, with consequent damage for the painting. All these mechanisms may lead to the formation of detachments and cracks which are very common in mural and wooden paintings. For conservation purposes it is very important to know the deformation of the artifact caused by ambient drifts and how the presence of support cracks or discontinuities alter the movements of the painted surface. The usual way for revealing the presence of detachments in paintings entails knocking all over the surface in order to reveal some strange sounds: this procedure, however, may cause sudden cracks or dramatic failures of the work of art. For this reason a non-contact test must be proposed as the most suitable technique.

Some in-situ applications have been performed by using the portable systems described in paragraph 3.2.1. Here three examples showing the advantages introduced by the application of ESPI systems are presented.

The first two examples highlight the fact that the system can be used for predicting the presence of defects, even though they are not visible to the naked eye.

Portable ESPI system 5 described in paragraph 3.2.2.2. was tested on a mural fresco (15th century), located inside the church S. Maria in Collemaggio (13th century) at L'Aquila, Italy (fig. 4.106).
Fig. 4.106: Photograph showing the application of the ESPI portable system inside the church of S. Maria in Collemaggio (L'Aquila)

Fig. 4.107: Interferogram obtained on an inspected area: the presence of cracks is observable
ESPI fringes were produced by thermal deformation of the plaster. A flow of moderately hot air was used to vary the temperature of the surface of few degrees (typically $\Delta T = 4^\circ$C). Microcracks and detachments of the plaster were the most common defects observed during ESPI measurements on the fresco surface. In fig. 4.107 an interferogram related to the illuminated area observable in fig. 4.106 is presented: the presence of the cracks can readily be deduced by the location of fringe discontinuities.

Fringe discontinuities were detected in areas apparently faultless, indicating that the damage was present to a larger extent than indicated by visual inspection. Portable ESPI system 2 described in section 3.2.2.2. was used to make measurements on a terra-cotta angel located inside the Portinari Chapel (15th century) in the Church of S. Eustorgio (Milan, Italy). The angel, situated at the height of approximately 13 meters from the ground, was just a detail of a big decoration occupying a vast area of the interior wall of the chapel.

The equipment was taken to the sixth floor of the scaffolding for the examination of the angel (fig. 4.108). One foot of the tripod was placed on the scaffolding, whilst the others rested on a small platform by the chapel wall. The personal computer and a monitor were positioned at the ground floor in order to control the acquisition of the interferograms from a point external to the scaffolding. A 22 metres cable was used to connect the optical head to the acquisition unit. Vibrations were actually unavoidable; anyway interferometric patterns showing the presence of defects (fig. 4.109) were obtained.

The third example shows that the system can be used for evaluating the effectiveness of restoration interventions. A wooden panel (42 x 125 cm) (15th century), from the Home Museum in Florence was investigated. The measurements were performed before and after repair work on an area of the painting containing detachments. The panel was placed on a wooden support clamped to the wall. The first example relates to a region with one detachment (fig. 4.110). The defect was clearly revealed by heating the surface for two seconds with an infrared lamp (fig. 4.111): the closed fringe pattern, typical of detachments, can be observed. The same test was performed after one day from the consolidation of the damaged area (fig. 4.112): the fringe pattern showed no anomalies.
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Fig. 4.108: Photograph showing the application of the ESPI portable system inside the church of S. Eustorgio (Milan)

Fig. 4.109: Interferogram obtained on an inspected area: the presence of defects is observable
Fig. 4.110: Painting submitted to restoration: the inspected area is inside the white frame.

Fig. 4.111: Interferogram obtained before restoration

Fig. 4.112: Interferogram obtained after restoration
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4.6. Conclusion

The first three chapters introduced theoretical and experimental basis that found application in chapter 4. This chapter actually demonstrated that optical techniques employing laser light or structured white light, with the help of advanced methods of digital acquisition, processing and storing of images, constitute a powerful set of tools for Non Destructive Testing in Civil Engineering (NDT-CE).

They have been here applied to the evaluation of single units of building materials, to the behaviour of construction joints and to the study of structures.

Optical techniques have been used for shape evaluation, deformation analysis and surface state inspection.

Actually chapter 4 is a collection of a series of applications that have been conducted by the author in the LAO (Laser and Applied Optics) laboratories of the Joint Research Centre at Ispra or in collaboration with other Institutions (universities and industries).

Section 1 was devoted to the description of some contouring methods used in the field of Civil Engineering.

Digital photogrammetry possesses the same features of classical photogrammetry with the added advantage of being faster and easier. The working station, designed and produced by Leica industries (Aarau- CH), has been applied to photographs of some historical monuments in order to measure the profile. Obtained results encouraging but, in the author’s opinion, some work has still to be carried out in order to make the digital system more reliable.

The technique based on the use of laser range finders (calculation of pulse time of flight) has been tested on an historical building. The system was again produced by Leica: the measuring procedure was very simple but the resolution obtainable was poor compared with other methods.

Digital photogrammetry and pulse time of flight are still the most suited methods for the inspection of large size surfaces (tens of m²).

Triangulation methods based on the projection of single stripes or gratings of parallel lines have been applied: while the first was more suited for medium size areas (some m²), the second was preferably applied to quite small areas (some cm²). The tools and the software for performing triangulation measurement were completely developed by the author and applied to the measurement of profiles of statues or to the evaluation of stone corrosion.
All the techniques presented in section 1 showed the advantage of complete non-intrusion and the capability of full-field surface evaluation. However their application is sometimes not trivial and requires in most cases the intervention of skilled operators.

Optical interferometric techniques have been applied to the inspection of surface deformations. They inherently possess some advantages: they are non-intrusive, they give full-field information and they offer results having good precision. However their use is often not trivial and the influence of ambient conditions sometimes is a great limit to their application. As the aim of the author was to propose solutions that could be used directly in-situ, holographic interferometry has not been applied. The moiré method and especially ESPI have been selected as the most suitable tools for interferometric inspection as they can be used not only inside optical laboratories but also in some normal ambient conditions.

In section 2 the ESPI systems developed by the author and presented in chapter 3, were applied to evaluate some units of building materials, to test some joints and to inspect small scale structures. Actually the inspected area was limited, in the experiments, to some tenths or hundreds of cm², especially for the limited power of the used lasers. The technique was at first used to evaluate the properties of single units. A series of measurements has been conducted in collaboration with the Department of Structural Engineering of the Polytechnic of Milan. The experimental research carried out gave useful indications for the measurement procedures of mechanical parameters of masonry materials under compression tests. ESPI was used for the detection of strain distributions during testing, for the control of traditional measurement techniques in the cases when their application can be unreliable and for the determination of quantitative values when other techniques can fail. As a result it was found that:

i) strain gauges may influence the free behaviour of the specimen, 
ii) compression plates can exert a constraining action on the specimen and the use of steel brushes can avoid it, 
iii) rigid body movements of the specimen occur during the experiments.

Moreover ESPI was used, with satisfying results, to measure the lateral displacement parameter, i.e. Poisson's Ratio, even in the cases when other devices can fail and to evaluate the Young's Modulus.

In collaboration with the Department of Structural Engineering of the Polytechnic of Turin ESPI was applied to the determination of the crack tip position and the strain field surrounding the crack propagating in clay specimens in flexural tests.
The interferometric technique allowed the determination of a complete map of
displacements as a function both of time and of crack propagation. As a consequence,
information on the distribution of mean strains around the crack, crack process zone
extension and crack tip position during cracking process, can be obtained.
The behaviour of building joints has been studied in collaboration with the Polytechnic of
Milan. Some information about the interaction of brick and mortar in masonry structures
under different state of stress has been retrieved. The full-field continuous observation
obtained with ESPI, offered the opportunity of understanding some phenomena involved
in a complicated composite such as masonry.

ESPI measurements can evaluate displacements in the micrometric range, with very high
accuracy. Unfortunately large structures can not, at the moment, be inspected and some
progress is still needed in this direction. Moreover the influence of ambient conditions
such as vibrations or air turbulence may disturb the experiments.

In section 3 applications of the moiré method were presented. This tool has the advantage
that it can be applied to large areas and its resolution actually depends on the adopted
gratings and on the acquisition system. In this section two techniques have been applied:
the grating to grating method and the high resolution speckle photography.
The first one (a grating is pasted to the surface and a second is laid on top of it with an oil
interface) was used to study the same units of building materials, under compression and
flexural tests, described above. With gratings down to 120 lines/mm fringes could be
clearly observed, but higher frequencies gave interferograms with very poor resolution. It
was observed that, in some cases, the pasted grating actually influences the free behaviour
of the inspected surface by creating a constraining action. For this reason the ESPI
solution was preferred.
High resolution moiré photography has been used at JRC-Ispra in collaboration with the
Institute for Safety Technologies, for studying the distribution of displacements and
strains in a reinforced concrete column, actively displaced at the top. The location of
cracks was performed with high accuracy (apertures of some tens of microns could be
observed). Actually it seems that this method is the most suited for the accurate evaluation
of deformations occurring in large structures. The use of this technique can be foreseen in
the field of disaster prevention caused by earthquakes.

Section 4 was devoted to the application of the speckle decorrelation method for surface
modification analysis.
The method has been applied in collaboration with the "Centro Gino Bozza" of the Polytechnic of Milan to the ageing of stone by cyclic crystallization. Surface monitoring has been performed during the evaporation stage of the cycle. The efflorescence behavior depended on the kind of stone and the observation time. The influence of material defects, such as the "tubuli", on the efflorescence formation has been successfully detected. The interpretation of these results could greatly contribute to a better understanding of some decay mechanisms. However, the comparison of much more data and the investigation of a large number of specimens are necessary.

Finally, an original application of interferometric techniques in the field of civil engineering was presented in section 5. ESPI portable instruments presented in chapter 3 have been applied to study the integrity of paintings on mural support (frescoes or bas-relief). Defects can be predicted at a very early stage and the intervention of the restorer can be suggested. Moreover the quality of the restoration can be evaluated.
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Introduction

When we plan to erect a building or wish to maintain it in a good state of repair, many methods of inspection can be used. A primary goal of an architect must be the safety of all aspects of a building's construction. To meet this objective, a complete knowledge of material properties and the inspection of complex structural behaviour are of primary importance. Testing methods have to be developed to enable quality monitoring and to avoid manufacturing damage. Due to the fear of unpleasant results, many engineers often avoid many measurements forgetting that the sooner a problem or defect is detected, the better are the chances for repair and the lower is the resulting cost.

Many methods for building inspection actually exist: they all contribute to a better understanding of problems that arise and can bring interesting solutions. An interchange of experience and results obtained by different disciplines is necessary and to be encouraged.

Aims

The determination of the behaviour of building materials has long been the object of studies and results have been obtained independently at different institutes by following different testing procedures and standards. At first only classical measuring tools (mechanical or electrical transducers) were widely accepted. Then some non-destructive techniques were used in order to perform inspection without interfering with the object's behaviour.

The subject of the present work has been the investigation of the applicability of various optical techniques as non-destructive testing tools in civil engineering. The objective was to demonstrate the effectiveness of selected optical techniques in the analysis of building structures and in the characterization of building materials, in order to encourage their use as alternative solutions.

In order to reach this goal the author has followed a step by step approach. Starting from a short description of measuring methods in civil engineering and considering common optical techniques, he has moved to the introduction of novel tools and finally, to the presentation of the experiments he carried out by applying optics to the evaluation of building materials.
Experimental methods in civil engineering

Chapter 1 has been included as an introductory part in order to give some highlights and to provide the reader with some knowledge about the subjects involved in the work.

The use of traditional experimental tools has been criticized in paragraph 1.1.1. Although they show some advantages such as reliability, simplicity, availability, relative low cost and sufficiently good precision, nevertheless they can just give measurements averaged over an area of interest and often they influence the behaviour of the inspected object, affecting in this way the precision of results.

The application of NDT techniques in civil engineering can be useful when non-intrusive tests are necessary. A presentation of most common NDT methods is included in paragraph 1.1.2.2. However this instrumentation is often very costly and requires the intervention of specialized operators. NDT inspection must be often accompanied by quasi-destructive tests (paragraph 1.1.2.3) especially when the knowledge of the interior characteristic of a solid is necessary. Moreover all these techniques usually can not give full-field information and results have often a poor resolution. Better results are expected for the future with the development of high-resolution tomographic methods.

Optical NDT techniques have been introduced as alternative measuring methods that can provide more or different information where other techniques are not adequate (section 1.2).

They actually show some inherent advantages:
- they are non-destructive
- they usually don't require direct contact
- they have in general high resolution
- they allow a full-field inspection
- they are not subjected to electromagnetic influence.

However some drawbacks have to be considered when dealing with these techniques:
- the requirement of a know-how and a background in opto-electronic devices, techniques and properties
- the possibility of getting information about surfaces and not about entire volumes
- the fact that high resolution is at the expense of unavoidable sensitivity to ambient conditions: vibrations and other ambient conditions could influence, especially in interferometric methods, the precision of results.
- the cost of the optical tools and materials
- the fragility of the materials: optical elements must be handled with care

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Optical techniques

An extensive investigation of several optical methods and improvements to their application in experimental measurements has been conducted by the author. Techniques based on the correlation properties of speckles (laser or white light) have been first presented in paragraph 1.2.1.

The most common interferometric methods have then been introduced in paragraph 1.2.2: holographic interferometry, moiré and ESPI have been briefly described and some comparisons have been drawn. In prevision of in-situ application purposes holographic interferometry has been rejected for its problems related with ambient conditions. ESPI has been considered as the best solution for the measurement of small surfaces where high resolution (of the order of the visible light wavelength) is required. The moiré method has been preferred for the inspection of large surfaces where a lower resolution can be acceptable.

Interferometric patterns are already geometrically descriptive of the inspected surface's behaviour. By performing some post-analysis, quantitative results can be obtained and the most common computing methods have been presented in paragraph 1.2.3. As the performance of computers rapidly increases and their cost falls, application of neural-networks and parallel computing can be foreseen in the near future.

It was demonstrated that the use of optical fibres (paragraph 1.2.4) can introduce some flexibility in the design of optical systems and increase their portability.

Optical techniques are not only suited for evaluating deformations or structural changes of surfaces; they can also be alternative tools for the shape measurement of surfaces. Many such methods are presently available and a short description of some of them is given in paragraph 1.2.5. A comparison of their performance has been made and it was concluded that they can be suitable for large surfaces (photogrammetry, pulse time of flight), medium sized surfaces (triangulation), and small sized surfaces (double-wavelength, coherence radar). They all offer full field inspection and a high degree of automation.

All subjects, methods and tools in chapter 1 have been briefly presented and accompanied by literature references where more information may be found. However some practical experimentation was necessary and chapter 2 was devoted to the presentation of a series of experimental results obtained by the author by applying selected optical techniques. With this chapter a double objective has been achieved

- providing familiarization with optical techniques
- putting emphasis on their enormous possibilities
Chapter V: Conclusions

The work described in chapter 2 has given the author an insight into the application of some well-known optical techniques for surface state identification. People at first sceptical about such applicability of optical techniques can find examples here that may convince them about the positive features connected with their application. Experiments on the investigation of deformations (section 2.1), the study of vibrations (section 2.2), the evaluation of strains (section 2.3), and the measurement of shape (section 2.4) have been included.

Original contribution by the author

While chapters 1 and 2 provided for a general explanation of aspects involved in this work and familiarization with most popular optical techniques for non-destructive inspection, chapter 3 was concerned with the presentation of innovative contributions designed by the author. These novel contributions included, in some cases, the improvement of tools already available and, in others, the development of completely new facilities.

In some cases the author's attention was focused on a technique or an optical system with the purpose of introducing some upgrades for better functionality, independently from any field of utilization. In others the need to fulfil some requirements arising in particular applications was the reason for proposing new solutions.

By following these main lines of research, new techniques have been explored, new measuring systems have been designed and new processing procedures have been conceived.

A novel technique based on Speckle decorrelation properties has been developed and presented in paragraph 3.1.1: the method seems to be very suitable for the study of phenomena involving micro-structural changes of rough surfaces. Due to its low sensitivity to external vibrations, the application for in-situ measurements can be easily carried out. If the surface change is too abrupt however, decorrelation of speckle patterns is immediate and retrieval of useful information can be difficult.

An original subtraction ESPI method, with reference active control, for the real-time inspection of stationary vibrations has been described in paragraph 3.1.2. Vibration interferometric patterns can be observed in real time and their visibility is comparable with the one obtained with time average holographic interferometry with the advantage of being almost insensitive to ambient conditions.
Chapter V: Conclusions

A lot of attention has been devoted in paragraph 3.2.1 to the development of portable systems for permitting interferometric measurements to be accomplished outside the optical laboratory. These instruments, based on the ESPI principles, must fulfil requirements of portability and flexibility: by using optical fibres and diode lasers the overall dimensions of the measuring stations have been reduced. Applications in laboratories of experimental mechanics, in industrial ambient conditions, or directly on surfaces of buildings of interest can be accomplished successfully.

In some experiments just in-plane displacements are involved or are interesting for the operator. A system for complete analysis of in-plane displacements has been designed and presented in paragraph 3.2.2. It allows a complete automatic inspection of surfaces of interest. The surface is illuminated from four directions on two perpendicular planes. The change between one direction of sensitivity to the other is performed by using an opto-electronic switch, designed by the author, that uses a liquid crystal display and a polarizing beam splitter cube. The optical system can be directly controlled by a computer and interferograms can be acquired automatically. This system is, for the moment, just a prototype and is used only inside the optical laboratory. However it has already been submitted as a patent and some improvements for reducing its dimension and increasing its portability are under consideration.

The potential of using optical fibres has been widely explored and the possibility of creating endoscopic systems has been considered (paragraph 3.2.3). These solutions can bring enormous advantages for increasing the flexibility of optical measuring systems and for allowing the inspection of hidden or difficult to reach areas. The possibility of adopting compensating systems for phase stabilization has been considered: their use could be fundamental for in-situ applications where ambient conditions can greatly influence the propagation of light inside the fibres.

New procedures for information retrieval from interferometric patterns have been developed by the author in section 3.3. Some contribution to displacement analysis has been presented in paragraph 3.3.1: a procedure for phase calculation and location of error sources followed by a new concept unwrapping algorithm has been described. The technique showed good applicability and, in most cases, it was demonstrated to be sufficiently robust. However, sometimes failure could not be avoided without the active intervention of the operator.

Two new techniques for phase derivative extraction have been proposed in paragraph 3.3.2. The first allows the calculation of derivatives directly from phase shifted interferograms without any need for previous evaluation of displacements. Unwrapping procedures are, in this way, avoided and gradients can be found easily and
Chapter V: Conclusions

rapidly. This procedure requires interferograms of good quality in order to obtain acceptable results. The second tries to evaluate derivatives by using well known properties of the Fourier transform: starting from one single interferogram the calculation is performed in the frequency domain. Some preliminary results have been presented for ideal and real cases but further work has to be carried out to make the method more reliable and robust.

Some preliminary considerations about a method called "virtual strain gauge" have been presented in paragraph 3.3.3. It is based on the fast measurement of the mean strain between any pair of points of an interferogram: it has been demonstrated that this quantity is directly related to the centre of gravity of the pattern spectrum.

Application of optical techniques in civil engineering

Optical methods allow a full-field observation of the surface under inspection: the profile, the strain distribution and crack propagation can be easily observed.

In chapter 4 the author demonstrated that optical techniques employing laser light or structured white light, with the help of advanced methods of digital acquisition constitute a powerful set of tools for Non-Destructive Testing in Civil Engineering (NDT-CE).

Section 4.1 has been devoted to the description of some contouring methods used in the field of Civil Engineering.

Measurements based on digital photogrammetry and laser range finders have been applied in collaboration with Leica industries to the three-dimensional measurement of surfaces. These two techniques are probably the most suited for the inspection of large size surfaces (tens of m$^2$). Results obtained with digital photogrammetry are good and encouraging but still some work has to be carried out in order to make the system more reliable and convenient. Laser range finders are, to the contrary, very easy to use but the inspection time increases dramatically with the number of measured points.

The author developed some tools for triangulation measurements based on the projection of single stripes or gratings of parallel lines: while the first was more suited for medium sized areas (some m$^2$), the second worked better when applied to small areas (some cm$^2$). Triangulation showed the advantage of being more precise than preceding methods but smaller areas could actually be inspected.

Optical interferometric techniques have been applied to the inspection of surface deformations. They inherently possess some advantages: they are non-intrusive, they give full-field information and they offer results with good precision.
In section 4.2 ESPI systems developed by the author have been applied to evaluate some units of building materials, to test some joints, and to inspect small scale structures. Some preliminary tests were accomplished for verifying the applicability of ESPI to stone surfaces. It was observed that decorrelation problems are often more important than with other materials (steel, wood, ceramic materials, etc...). For this reason inspected surfaces should be, when possible, painted with white spray. Results obtained with ESPI and with more traditional tools (strain gauges, LVDTs, CPDTs) were compared and good agreement was observed. Moreover the application of strain gauges was criticized: it was observed from the interferometric patterns that the pasting glue produces a constraining influence on the inspected area. The influence of testing plates in compression measurements has been observed and the use of brushes has been suggested.

Accurate quantitative data concerning the mechanical characteristics of some building materials have been retrieved, e.g. Young's Modulus and Poisson's Ratio can in this way be evaluated very precisely. These numbers are in many cases still unknown and their knowledge can be useful in the field of civil engineering when creating new projects or when using FEM (Finite Element Modelling) tools. Moreover the knowledge of these results may be helpful in some cases when attempting a comparison between different materials.

ESPI was applied to the determination of crack tip position and the strain field surrounding the crack propagating in clay specimens used in flexural tests. The propagation of the crack could be observed in real time (even though it was not visible to the naked eye) and information on the distribution of mean strains around it could be obtained.

The study of behaviour of building joints has been studied and some information about brick-mortar interaction and other phenomena involved in complicated composites, such as masonry, was obtained.

ESPI has been applied here to the inspection of small areas (some tens of cm²). It would be interesting to apply this technique to large structures but problems related with the limited resolution of CCD cameras, the requirement of high power lasers and the influence of ambient conditions such as vibrations or air flows have to be solved. The use of pulsed lasers and intensified CCD cameras could probably bring some advantages in this direction.

In section 4.3 applications of the moiré method were presented. It is more suited for large areas and its resolution depends on the adopted gratings and on the acquisition system.
A grating to grating technique (surface grating and reference with a thin oil film in between) was used to study units of building materials under compression and flexural tests. The visibility of interferometric patterns was very poor when gratings having more than 200 lines/mm were used. Moreover, it was observed that, in some cases, the pasted grating actually influences the free behaviour of the inspected surface by creating a constraining action. For this reason the ESPI solution was preferred. High resolution moiré photography has been used for the accurate evaluation of deformations occurring in real-scale structures (such as reinforced concrete columns). The use of this technique can be foreseen in the field of earthquake disaster prevention.

The application of the speckle decorrelation method for surface modification analysis was presented in section 4.4. This technique is very simple and can give interesting information about surface state modification. The salt efflorescence mechanism in some stones has been observed. Effects due to humidity changes, temperature gratings or bacteriologic actions could probably be monitored with this technique.

ESPI portable instruments have been applied to study the integrity of paintings on mural support (frescoes or bas-relief) and the results have been reported in section 4.5. Defects can be predicted at a very early stage and the intervention of the restorer can be suggested. Moreover the quality of the restoration can be evaluated.

Concluding remarks

After having moved from the introduction of some basic concepts concerning measuring methods in civil engineering to the presentation of some optical techniques and their applications in this field, the author hopes to have convinced the reader that the objectives of the work have been successfully attained. It has been demonstrated that optical methods have enormous possibilities and the volume of their applications is related to the inventive capabilities of researchers in this field. With these tools the opportunity of obtaining results impossible or hard to reach with other techniques has been demonstrated. The observation of fracture propagation, the full-field evaluation of deformations, the estimation of surface micro-changes and the early detection of defects, make the use of optical techniques almost unrivalled for some applications in the field of civil engineering and material inspection. With this statement the author has not the intention to say that these methods should completely replace other measuring tools,
preparation of articles for scientific journals and to the participation in conferences where obtained results were presented. It was especially at these meetings that the author had the impression that his studies had stimulated the curiosity of other researchers. While specialists in the optics field demonstrated interest for some of the innovative solutions (techniques, instruments and measuring methods), civil engineers and architects were more impressed by the possible applications and by the obtained results.

Especially the latter group of researchers stimulated, with some requirements, the author's inventiveness towards finding new solutions to their problems. New methods have been applied to the measurement of mechanical characteristics and the evaluation of structural assessment and the results are in some cases very promising (evaluation of Poisson's Ratio and Young's Modulus, early detection of failures, inspection of the behaviour of complex structures). A real knowledge of the complete strain state of surfaces could be interesting for the evaluation of the safety of structures: it could be useful for predicting dramatic failures and avoiding, in this way, catastrophic consequences.

The work completed so far is obviously not exhaustive: this field of research is wide and still requires a lot of effort from all the scientific staff involved in it. However the author has the conviction that some contribution has been added by his research and that some of these novel concepts will be useful to other researchers.

The application of optical techniques to the evaluation of building materials and to the inspection of civil structures is just at an initial stage. Due to the continuous increase in the volume of applications and the evolution of hardware and software capabilities, this is a field in expansion and open to the exploitation of improvements or completely new solutions.

Many features described in this work could be optimized and new directions of research can be foreseen. Interferometric methods for vibration inspection could be used to study the behaviour of building structures under the action of earthquakes. ESPI systems should be used to inspect large surfaces (some tens of m²) and to perform monitoring measurements directly in the field for many hours (for example the influence of changes in sun radiation throughout the day could be evaluated). The application of pulsed lasers in ESPI could allow the measurement of transient phenomena (e.g. propagation of shock waves in structures). Endoscopes could be applied to the inspection of areas difficult to reach with common measuring arrangements. Optical arrangements can be optimized for their portability, physical size and insensitivity to external agents and flexibility.
Application of optical techniques in the seismic field could give new information about the behaviour of stressed buildings and some new ideas about optimal construction design.

The author hopes that the use of optical techniques as non-destructive measuring tools in civil engineering will rapidly increase, and that his work can have a positive contribution to this.
APPENDIX A

Displacements, strains, stresses.

Under the influence of external forces bodies are deformed (i.e. they change their surface and shape). Strain is due to variations of the displacement through the body: it is a mechanical quantity related to the derivatives of displacement. Moreover strain and stress are quantities related to each other (proportional in elastic cases).

Displacement

In a fixed Cartesian reference system \((x,y,z)\) the components of displacement \(L\) of the points of a solid object calculated in the coordinate directions are indicated with \(u, v\) and \(w\).

Strain

Strain is a tensor quantity requiring nine components for its complete specification:

\[
S = \begin{pmatrix}
\frac{\partial u}{\partial x} & \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) & \frac{1}{2} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\
\frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} \right) & \frac{\partial v}{\partial y} & \frac{1}{2} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial y} \right) \\
\frac{1}{2} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial z} \right) & \frac{1}{2} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial z} \right) & \frac{\partial w}{\partial z}
\end{pmatrix}
\]  

(A.1)

Of these nine components, six are independent: three independent components of normal strain and three independent components of shear strain.

Components of normal strain

Physically the normal strain describes the change in length per unit length of a small element of the material in each coordinate direction.

\[
\varepsilon_x = \frac{\partial u}{\partial x}, \quad \varepsilon_y = \frac{\partial v}{\partial y}, \quad \varepsilon_z = \frac{\partial w}{\partial z}
\]  

(A.2)
Components of shear strain

The shear strain describes the decrease in angle between two line segments of material points which were initially parallel to the coordinate directions.

\[ \gamma_{xy} = \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \quad \gamma_{yx} = \frac{1}{2} \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \quad \gamma_{zx} = \frac{1}{2} \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \] (A.3)

As a conclusion, in order to calculate all the strain components, 9 different derivatives must be calculated:

\[ \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}, \frac{\partial v}{\partial z}, \frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}, \frac{\partial w}{\partial z} \] (A.4)

Stress

The mechanical state at a point of a strained object is characterized by the stress tensor

\[
\begin{pmatrix}
\sigma_x & \tau_{xy} & \tau_{xz} \\
\tau_{yx} & \sigma_y & \tau_{yz} \\
\tau_{zx} & \tau_{zy} & \sigma_z
\end{pmatrix}
\] (A.5)

The tensor is made up of normal (\(\sigma\)) and tangential (\(\tau\)) components acting on the faces of a volume element including the point in question, which are normal to the \(x, y\) and \(z\) axes.

If the material is elastic some simple relationships exist between stress and strain:

\[ \varepsilon_x = \frac{1}{E} (\sigma_x - \nu (\sigma_y + \sigma_z)) \] (A.6)

\[ \tau_{xx} = G \varepsilon_{xx} \] (A.7)

where \(E\) is the modulus of elasticity (Young's Modulus) and \(G\) is the shear modulus of elasticity.

\(G\) is related to \(E\) through the equation:
where \( \nu \) is known as the Poisson’s Ratio. It is a material property which is the constant ratio between lateral strain and longitudinal strain

\[
\varepsilon_x = -\nu \varepsilon_z
\]  

(A.9)

in a simple specimen subjected to a tensile or compressive load in the \( x \) direction perpendicular to \( z \).
Holographic Interferometry

Holographic interferometry is based on holography's property of completely reconstructing the image of an object. The amplitude and phase information contained in a coherent light wavefront can in fact be re-obtained by suitably illuminating a hologram. The holographic image reproduced appears indistinguishable from that of the original object, showing full three-dimensionality and all the parallax relationships of reality.

Holography

The holographic technique is composed of two separate operations: recording and reconstruction. During the recording process the wavefront from the object interferes with the light of a reference beam, giving rise to a distribution of intensity which contains all the information about amplitude and phase of the two waves. The complex amplitude of the object and of the reference wavefronts on a plane $xy$ are respectively:

$$O(x,y) = o(x,y) \exp(-j\phi(x,y))$$
$$R(x,y) = r(x,y) \exp(-j\psi(x,y))$$  \hspace{1cm} (B.1)

where $o(x,y)$ and $r(x,y)$ are the amplitudes, $\phi(x,y)$ and $\psi(x,y)$ are the phases. By summing and squaring the two preceding expressions, the interference pattern of intensity on plane $xy$ is:

$$I(x,y) = |O(x,y)|^2 + |R(x,y)|^2 + 2o(x,y)r(x,y)\cos(\phi(x,y) - \psi(x,y)) = 00^* + RR^* + R^*O + RO^*$$  \hspace{1cm} (B.2)

where the first two terms depend on the amplitude only, while the third and fourth depend on the relative phase too (the asterisk indicating the complex conjugate).

The interference between the light of the object and a reference beam makes possible the recording of phase information by media which are only sensitive to light intensity. A photographic plate in an $xy$ plane, correctly impressed and developed, is a hologram. By re-illumination of the hologram with a reconstruction wave $R'(x,y)$, a wavefront $U(x,y)$ composed of four distinct terms is obtained:
where $\beta$ is a constant factor related to the developing process of the emulsion. If $R' = R$ the third term becomes $\beta/RR':O$: it contains complete information about amplitude and phase of the wavefront from the object. For this reason the object can be seen in its three-dimensionality.

When continuous wave lasers are used, the main drawback is the high sensitivity of the measures to external factors such as mechanical vibrations. To get rid of these effects the experimental set-up is mounted on special optical benches loaded with high masses.

**Holographic Interferometry**

Double-exposure holographic interferometry is well-known as an NDT (Non-destructive Testing) tool, since its main characteristics are the accuracy of measurement (displacement of tenths of a micron is detected) and the intrinsic absence of contact.

In this technique, two holograms are superimposed on the same holographic plate; each captures the object in a different state. During the reconstruction of the hologram, the three-dimensional image of the object appears overlaid with a set of fringes. This is the result of the optical interference of the simultaneously reconstructed two images, and it is due to the change in the optical path of the second object beam caused by the object's deformation or movement.

Holography is a linear process, and two or more wavefronts can in fact be recorded sequentially and then reconstructed at the same time. Let $O_1(x,y)$ and $O_2(x,y)$ be the complex fields of the object wavefront at times $t_1$ and $t_2$ and $R(x,y)$ the reference used for both recordings. In the retrieval process the overall amplitude of the reconstructed wave is proportional to $O_1(x,y)+O_2(x,y)$. The intensity in the $xy$ plane is thus:

$$I(x,y)=\beta|O_1(x,y)+O_2(x,y)|^2$$

In interferometric applications, because of the small deformations of the object surface, the displacement between $O_1(x,y)$ and $O_2(x,y)$ is contained in the phase term. The expressions for the complex fields can be put in the form:

$$O_1(x,y)=o(x,y)\exp(-j\phi(x,y))$$
$$O_2(x,y)=o(x,y)\exp(-j\phi(x,y)+\Delta\phi(x,y))$$
by applying equation B.4, the intensity distribution of the reconstructed wave is:

\[ I(x, y) = \beta |O_1(x, y) + O_2(x, y)|^2 = 2\beta o^2(x, y)[1 + \cos(\Delta\phi(x, y))] \]  

(B.6)

The object intensity \(o^2(x, y)\) is modulated by the factor \([1 + \cos(\Delta\phi(x, y))]\). There are thus dark fringes for values of \(\Delta\phi(x, y)\) which are odd multiples of \(\pi\) and white fringes for the even multiples. The distribution of \(\Delta\phi(x, y)\) corresponds to variations in the optical path produced by displacements of the object surface. Taking into account the illumination and observation directions, surface deformation can be successfully evaluated.

Once \(\Delta\phi\) has been obtained, it is possible to retrieve the real deformation in the direction of the bisector of the angle formed by the illumination and observation directions, by using the well known equation:

\[ \Delta z = \frac{\Delta\phi \lambda}{2\pi 2} \]  

(B.7)

A complete knowledge of \(\Delta\phi\) is necessary.

Two techniques are considered in order to obtain quantitative results: phase-shifting and FFT techniques

**Double reference technique**

Phase-shifting is performed in combination with a double-reference technique. In this one, during the registration process, two different wavefronts, \(R_1(x, y)\) and \(R_2(x, y)\), are used as reference before and after deformation. In reconstruction the hologram is re-illuminated with both reference beams; in this manner the following wavefront is obtained:

\[ U(x, y) = \beta[(R_1 + R_2)[(R_1 R_1^* + O_1 O_1^* + R_1^* O_1 + R_1 O_1^*) + \\
+ (R_2 R_2^* + O_2 O_2^* + R_2^* O_2 + R_2 O_2^*)]] \]  

(B.8)

The contributions important in eqn. B.8 for the interferogram are given by \(\beta/R_1^2 O_1\) and \(\beta/R_2^2 O_2\). The result of all this process is that two independent holograms are recorded on the same emulsion (with different reference wavefronts), each one representing the object in two different moments. In this way, due to the overlapping of this two fields, the object is seen crossed by fringes. If during the reconstruction process the relative phase between
$R_1$ and $R_2$ is changed, the fringes move. By selecting appropriate relative changes, the phase-shifting technique can be applied.
APPENDIX C

Electronic Speckle Pattern Interferometry

When a surface is illuminated by a laser beam, the intensity of the light that is scattered back has a randomly varying spatial value, giving a granular appearance. This effect, known as speckle effect, occurs only when the surface is optically rough, i.e. its height variation is of the order of, or greater than, the wavelength of the laser illuminating light. Each point re-emits the incoming light acting as a source of spherical waves. The complex amplitude of the scattered wavefront at any point in space is given by the vectoral sum of all waves coming from the surface. Without going deep into the study of speckle formation, it can be said that the mean speckle size can be approximately expressed by:

\[
d_{sp} = \frac{2.4\lambda \nu}{a}
\]  
(C.1)

where \(a\) is the aperture of the viewing lens, \(\nu\) is the distance from the lens to the image plane and \(\lambda\) is the wavelength of the laser light.

If ESPI interferometric arrangements the field coming from the object is superimposed onto a constant reference field. Letting \(O\) be the object field complex amplitude at starting steady conditions and \(R\) the reference field complex amplitude

\[
O(x,y) = o(x,y)\exp[i\phi_o(x,y)] \quad R(x,y) = r(x,y)\exp[i\phi_r(x,y)]
\]  
(C.2)

where \(o(x,y)\) and \(r(x,y)\) are the amplitudes, \(\phi_o(x,y)\) and \(\phi_r(x,y)\) are the phases; \(o\) and \(\phi_o\) vary randomly across the object. The resulting intensity is:

\[
I(x,y) = o^2(x,y) + r^2(x,y) + 2o(x,y)r(x,y)\cos(\phi_o - \phi_r)
\]  
(C.3)

that can also be written in the form

\[
I_1 = I_o + I_r + 2\sqrt{I_o I_r} \cos \phi
\]  
(C.4)

where \(I_o = OO'\), \(I_r = RR'\) and \(\phi = \phi_o - \phi_r\).
When the surface of the object is displaced, the speckle pattern changes in a way that all the components scattered change by the same amount $\Delta \phi(r)$ and the new field coming from the object is

$$O(x,y) = o(x,y) \exp\{i(\phi_o(x,y) + \Delta \phi(x,y))\}$$  \hspace{1cm} (C.5)

with a new total intensity reaching the camera head

$$I_2 = I_o + I_r + 2\sqrt{I_oI_r} \cos(\phi + \Delta \phi)$$ \hspace{1cm} (C.6)

If an absolute difference is performed between the two intensity patterns, before and after deformation has taken place, an interferometric pattern is obtained described by the equation

$$I = |I_1 - I_2| = 2\sqrt{I_oI_r} [\cos \phi - \cos(\phi + \Delta \phi)] = 4\sqrt{I_oI_r} / \sin(\phi + \Delta \phi) / \sin(\Delta \phi)$$ \hspace{1cm} (C.7)

Since the phase change $\Delta \phi(x,y)$ is a function of the displacement, $I$ gives information about the different parts of the object that undergo the same relative displacement. Where $\Delta \phi = 2\pi n$ there is a null intensity, whereas other areas where $\Delta \phi = (2n + 1)\pi$, show a maximum mean intensity (where $n$ is an integer).

In an ESPI system, the object image is directly focused on the sensor plate of a video camera and then displayed directly on a colour screen or on a computer monitor. The power of the video system to solve small details of an image is clearly limited: the acquisition system must be able to resolve, at least partially, the speckled structure of the image. The spatial response of the video-camera, that depends also on the aperture and the magnification of the focusing system, must be wide enough to accept the high frequencies of the speckles.
APPENDIX D

Moiré Method

It is well known that the superposition of periodic and/or quasi periodic patterns in optics frequently results in striking spatial configurations commonly called moiré patterns. These new patterns may contain some spatial frequencies that can be considerably lower than the original ones. These composite patterns can be formed in at least three different ways: by addition, subtraction or multiplication (three of the four basic rules of arithmetic) and can be performed by optical or digital means.

Superposition of gratings

The following two patterns can be considered at first:

\[
I_1 = a + b \cos(2\pi v_1 x) \\
I_2 = c + d \cos(2\pi v_2 x)
\]

and three types of superposition can be considered.

a) ADDITION

The following equation is obtained:

\[
I_1 + I_2 = a + c + b \cos(2\pi v_1 x) + d \cos(2\pi v_2 x) = \\
a + c + b \cos(2\pi (v_1 + \frac{v_2}{2}, - \frac{v_2}{2}) x) + d \cos(2\pi (v_2 + \frac{v_1}{2}, - \frac{v_1}{2}) x) = \\
a + c + b \left[\cos[\pi (v_1 + v_2) x] \cos[\pi (v_1 - v_2) x] - \sin[\pi (v_1 + v_2) x] \sin[\pi (v_1 - v_2) x]\right] + \\
b + d \left[\cos[\pi (v_1 + v_2) x] \cos[\pi (v_1 - v_2) x] - \sin[\pi (v_1 + v_2) x] \sin[\pi (v_2 - v_1) x]\right] = \\
a + c + (b + d) \left[\cos[\pi (v_1 + v_2) x] \cos[\pi (v_1 - v_2) x]\right] - (b - d) \left[\sin[\pi (v_1 + v_2) x] \sin[\pi (v_1 - v_2) x]\right]
\]

where last term can be considered less important than the third because in general

\[(b-d)<<(b+d)\]
b) **SUBTRACTION**

The following equation is obtained:

\[
I_1 - I_2 = a - c + b \cos(2\pi v_1 x) - d \cos(2\pi v_2 x) =
= a - c + (b - d)\left\{\cos[\pi (v_1 + v_2) x] \cos[\pi (v_1 - v_2) x]\right\} - (b + d)\left\{\sin[\pi (v_1 + v_2) x] \sin[\pi (v_1 - v_2) x]\right\}
\]

(D.3)

where the third term can be neglected for the same reasons of the addition case.

c) **MULTIPLICATION**

The following equation is obtained:

\[
I_1 I_2 = ac + ad \cos(2\pi v_1 x) + bc \cos(2\pi v_1 x) + bd \cos(2\pi v_2 x) =
= ac + ad \cos(2\pi v_1 x) + bc \cos(2\pi v_1 x) + \frac{bd}{2} \cos(2\pi (v_1 + v_2) x) + \frac{bd}{2} \cos(2\pi (v_1 - v_2) x)
\]

(D.4)

In both additive and subtractive types of superposition a sinusoidal pattern of the average frequency, \((v_1 + v_2)/2\), is modulated by another sinusoid of half the difference frequency \((v_1 - v_2)/2\). In the multiplicative type of superposition, however, sinusoidal patterns of the original frequencies, of their sum and of their difference, are all summed together. In all three cases a d.c. term (background) is present.

It may be said that in all these patterns \(v_1\), \(v_2\) and \((v_1 + v_2)/2\) generate the "micro structure" of the composite pattern, while \((v_1 - v_2)/2\) and the background term generate its "macro structure".

The eye, that behaves as a low-pass spatial filter, will, of course, emphasise the low-frequency component.

**Interferograms of displacement**

In interferometric analysis of displacement it is clear that: \(v \equiv v_0\), \(a = c\) and \(b = d\)

\[
\begin{align*}
I_1 &= a + b \cos(2\pi v_1 x) \\
I_2 &= a + b \cos(2\pi v_1 x + \phi(x))
\end{align*}
\]

(D.5)

where the term of phase \(\phi(x)\) is related to the displacement
a) **ADDITION**

From equation D.2:

\[
\text{Lpf}(I_1 + I_2) = 2a(x) + 2b(x) \cos\left(\frac{\phi(x)}{2}\right)
\]

(D.6)

where there is a modulation superposed to a background.

b) **SUBTRACTION**

From equation D.3

\[
\text{Lpf}(I_1 - I_2) = 2b(x) \sin\left(\frac{\phi(x)}{2}\right)
\]

(D.7)

The pattern is similar to the one obtained in the addition case but without a background.

Sometimes the absolute value is preferred.

c) **MULTIPLICATION**

From equation D.4

\[
\text{Lpf}(I_1 \cdot I_2) = a^2(x) + \frac{b^2(x)}{2} \cos(\phi(x))
\]

(D.8)
APPENDIX E

Phase shifting method

In optical interferometry the relation between the intensity \( I \) and the spatial coordinates \( x,y \) of an interferogram can be written as:

\[
I(x,y) = a(x,y) + b(x,y)e^{i\phi(x,y)}
\]  \hspace{1cm} (E.1)

where \( \phi(x,y) \) is the interferometric phase, whilst \( a(x,y) \) and \( b(x,y) \) represent the contrast and the background modulation. Equation (E.1) can actually be used to describe interferograms obtained with holographic interferometry, moiré or ESPI.

The phase-shifting method is widely used in interferometric measurements for the quantitative retrieval of the phase map. Its success comes from its high resolution in phase evaluation together with a relatively simple experimental set up.

Phase-shifting is based on the introduction of a known amount of phase in the path of one of the interfering beams. These shifts can be introduced in many ways: with a micrometric movement of a piezoelectric driven mirror, a tilt of a glass plate, a small change in the laser wavelength, a change of refraction index. The resulting effect is a shift of the intensity peaks across the interference pattern.

By the computational point of view, a variety of versions of the method exist, all of them sharing the property to eliminate the background \( a(x,y) \) and contrast \( b(x,y) \) by simple arithmetic or trigonometric operations on the acquired images.

In this work the four-images method has been always adopted: four different fringe patterns are acquired with a phase shift of \( \pi/2 \) between.

Starting from a first image \( I_1 \), taken as reference, the four images, shifted by \( \pi/2 \) can be expressed by:

\[
\begin{align*}
I_1(x,y) &= a(x,y) + b(x,y)\cos[\phi(x,y)] \\
I_2(x,y) &= a(x,y) + b(x,y)\sin[\phi(x,y)] \\
I_3(x,y) &= a(x,y) - b(x,y)\cos[\phi(x,y)] \\
I_4(x,y) &= a(x,y) - b(x,y)\sin[\phi(x,y)]
\end{align*}
\]  \hspace{1cm} (E.2)

By subtraction and division \( a(x,y) \) and \( b(x,y) \) are eliminated, yielding the following:
\[ \tan(\phi(x,y)) = \frac{l_2 - l_4}{l_1 - l_3} \] 

(E.3)

and finally:

\[ \phi(x,y) = \arctan\left( \frac{l_2 - l_4}{l_1 - l_3} \right) \] 

(E.4)

Precision better than 1/100 of radians in the phase evaluation can be expected and main sources of error come from the non precise introduction of phase shifts.
APPENDIX F

Technique based on FFT analysis

Unlike the previous method, Fourier analysis allows phase detection by the acquisition of a single image; this is a great advantage since the phase shifting experimental equipment is no more necessary. This technique, almost prohibitive some years ago for the large amount of data involved, is becoming very popular thanks to the increasing performance of computers and software.

Great attention has to be paid to avoid elimination of the highest spatial frequencies. For this reason the technique is best suited to phase evaluations of fairly smooth interferograms.

For explaining this method the intensity distribution is preferably described by applying the Euler formula

\[ I(\mathbf{x},\mathbf{y}) = a(\mathbf{x},\mathbf{y}) + \frac{1}{2} b(\mathbf{x},\mathbf{y}) \exp\{-j\phi(\mathbf{x},\mathbf{y})\} + \frac{1}{2} b(\mathbf{x},\mathbf{y}) \exp\{j\phi(\mathbf{x},\mathbf{y})\} \]

or more simply

\[ I(\mathbf{x},\mathbf{y}) = a(\mathbf{x},\mathbf{y}) + c(\mathbf{x},\mathbf{y}) + c^*(\mathbf{x},\mathbf{y}) \]

with \( c(\mathbf{x},\mathbf{y}) = (1/2) b(\mathbf{x},\mathbf{y}) \exp[j\phi(\mathbf{x},\mathbf{y})] \). The phase \( \phi(\mathbf{x},\mathbf{y}) \) can be evaluated from the real and imaginary parts of the complex function \( c(\mathbf{x},\mathbf{y}) \). If the uppercase letters indicate the Fourier transformed functions, then

\[ I(f_x,f_y) = A(f_x,f_y) + C(f_x,f_y) + C^*(-f_x,-f_y) \]

In most cases \( a(\mathbf{x},\mathbf{y}) \) is a slowly varying function whose frequency components are grouped around the zero frequency. The mutually point symmetric terms \( C(f_x,f_y) \) and \( C^*(-f_x,-f_y) \) contain higher frequency components that are related to the spatial variation of \( \phi(\mathbf{x},\mathbf{y}) \). So the Fourier spectrum is composed by three different separated zones. If \( A(f_x,f_y) \) is cut out and just one of the other two areas is selected, by applying the inverse Fourier transform \( c(\mathbf{x},\mathbf{y}) \) or \( c^*(\mathbf{x},\mathbf{y}) \) can be retrieved and consequently the phase can be obtained:
The method actually suffers from two main drawbacks:

- sign ambiguity
- impossibility to solve closed fringes.

Some solutions have been proposed in this direction involving filtering of the spectrum in many directions or the introduction of carrier frequencies.
APPENDIX G

Time-average holographic interferometry

Time average holographic interferometry is the term assigned to the technique of producing an interferogram by exposing a hologram for a period of time during which the object executes a motion. The hologram essentially records the time-average complex amplitude of light scattered by the object to the hologram plane. For the special case of an object vibrating sinusoidally, a simple qualitative interpretation of the generation of fringes can be given. In fact, since the object spends most of its time near its two positions of maximum displacement, where its velocity is zero, time-average holographic interferogram will be like a double-exposure displaying contours of the object displacement between these two extreme positions. Quantitative interpretation requires a more precise analysis and the introduction of the temporal variable in the basic equations of holographic interferometry.

In the case of sinusoidal vibration, the movement of every point of the surface can be described by:

\[
z(x, y, t) = Z(x, y) \sin(\omega t)
\]  

\((G.1)\)

where \(Z(x, y)\) is the amplitude of the mechanical vibration at location \((x, y)\), and \(\omega\) is the circular frequency of vibration. Let \(O(x, y)\) represent the complex amplitude of light in the hologram plane which is scattered by the observed surface when it is stationary in its equilibrium position:

\[
O(x, y) = o(x, y)\exp[-j\phi(x, y)]
\]  

\((G.2)\)

On the assumption of a large object-to-hologram distance, light that travels a distance \(l_o\) from the source to a point on the static object and back to the hologram, will travel a distance \(l_o - 2Z(x)\sin\omega t\) while the object is vibrating. The corresponding optical phase change will be \(\Delta \phi(x, y, t) = (2\pi/\lambda)2Z(x)\sin \omega t\). Hence at any instant of time the complex amplitude of light in the hologram plane will be

\[
O(x, y, t) = o(x, y)\exp\left\{-j\left[\phi(x, y) + \frac{4\pi}{\lambda}Z(x, y)\sin(\omega t)\right]\right\}
\]  

\((G.3)\)
A time-average hologram is recorded by simultaneously exposing a film plate to $O(x,y,t)$ and to an off-axis reference wave for a period of time $T$. When this hologram is developed and illuminated by the reference wave, the reconstructed wave will have a complex amplitude that is proportional to the time average of $O(x,y,t)$ over the exposure time $T$:

$$O_{\text{aver}} = \frac{1}{T} \int_0^T O(x,y,t) dt = O(x,y) \frac{1}{T} \int_0^T \exp \left[ -j \frac{4\pi}{\lambda} Z(x,y) \sin(\omega t) \right] dt \quad (G.4)$$

The time-average integral of the last equation is called the characteristic function for sinusoidal vibration and is denoted by $M_T$. It can be easily evaluated if the exposure time is long compared to the vibrational period, $T >> 2\pi/\omega$:

$$M_T = \lim_{t \to T} \frac{1}{T} \int_0^T \exp \left[ -j \frac{4\pi}{\lambda} Z(x,y) \sin(\omega t) \right] dt = J_0 \left[ \frac{4\pi}{\lambda} Z(x,y) \right] \quad (G.5)$$

where $J_0$ is the Bessel function of the first kind of order zero. Using equations (G.4) and (G.5), the corresponding irradiance will then be proportional to

$$I(x,y) = |O|^2 |M_T|^2 = \sigma^2(x,y) J_0^2 \left[ \frac{4\pi}{\lambda} Z(x,y) \right] \quad (G.6)$$

Equation (G.6) indicates that for sinusoidal motions the virtual image is modulated by a system of fringes described by the square of the zero-order Bessel function. Dark fringes will be centred at each point on the object surface where the amplitude of vibration $Z(x)$ is such that the Bessel function in equations (G.5)-(G.6) is zero (these values are tabulated). They differ from the cosine type fringes, characteristic of the double exposure holography, in that their brightness and, to some extent, their spacing decrease with increasing order. The nodal, or zero-order, fringe is easily identified because it is much brighter than the others.
Scientific Publications (20 October, 1995)

International Journals:


A.C. Lucia, P.M. Zanetta, M. Facchini “Electronic Speckle Pattern Interferometry Applied to the study and conservation of Paintings” to be published in Optics and Lasers in Engineering


Conference papers:


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