Deformation and strain measurement techniques for the inspection of damage in works of art

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Abstract

The engineering techniques used for inspecting structural damage are not widely known in the conservation sector. Techniques are available based on deformation or strain measurement that have the ability to provide quantitative data. This paper reviews currently available techniques, covering point-strain measurements using resistance strain gauges and fibre-optic sensors, as well as full-field optical measurement approaches such as holography, electronic speckle pattern interferometry, photoelastic stress analysis and photogrammetry. The underlying technology of each of the techniques is described for the non-specialist. The relevance of each technique is established from a conservation perspective through accounts of usage. The application of the techniques to a wide range of artwork, including panel paintings, statues, murals and mosaics is described and the results critically reviewed. The paper also provides an insight into possible future applications of the techniques and identifies areas for further investigation.

Introduction

Pressures in the heritage sector to optimise the use of existing resources, coupled with a wider acceptance of variations in the condition of works of art on display and concern about inappropriate interventions, have led to a focus on preventive conservation. Decision-making as to appropriate interventions has historically been qualitative and based on experience. A greater understanding of ageing mechanisms is enabling a more quantitative approach in determining how and why such decisions are made, thereby permitting a more informed choice of intervention while minimising its degree and extent. Developing more cost-effective ways of monitoring structural damage would be a welcome outcome to many public and private custodians, by allowing limited resources to be used more productively. In addition, successful monitoring of the structural changes in artworks will support the development and evaluation of effective remedial and preventive techniques.

The aim of this paper is to identify a range of well-established deformation/strain measurement techniques that could be used to inspect and monitor works of art. Although not directly related to the scope of this paper, it is appropriate to cite here some examples of where other engineering approaches are being readily adopted. A good example is the mechanical testing of tapestry samples [1], where strength reduction is related to humidity variations. Further work by the same authors investigates the effect of linings on the overall strength of tapestries [2] using mechanical testing procedures. In 1993 a project on in-situ monitoring of a mock icon was briefly described [3] in relation to a project for which deformation, humidity and temperature data were collected with specially designed transducers and the results correlated during a gallery display. To date the results from this project have not appeared in the open literature, but this example demonstrates the increasing need to relate environmental changes to strain/deformation measurements.

The present review focuses only on techniques that enable a quantitative assessment of the degree of deformation that an object has undergone, as ultimately this can be related to the final failure of the artefact. Other inspection techniques such as ultrasound, X-ray inspections and thermography, which can reveal the extent of damage but cannot provide information on the deformation state, are in use in the heritage sector [4–6] but are beyond the scope of this review. A further technique based on non-contact laser Doppler vibrometry has enabled the evaluation of deformation states. The technique requires high-frequency loading; it is only suitable for rigid materials such as those found in statuary and ceramics [7, 8] and is not included in the review.

The techniques described here are divided into two categories: 'point strain measurement' and 'full-' or 'whole-field strain measurement'. In the former, strain measurement data are recorded using sensors that are mounted on the surface of an artefact at spatially defined points. The basis is that the strain in the artefact is transferred into the sensor, which responds to the strain in such a way that a measurement can be taken. In general, there are two types of sensors that are available for the measurement of point strain. The first method employs resistance strain gauges (RSG) [9, 10] and the second uses optical fibre sensors (OFS) [11, 12]. In contrast to the point measurement techniques, whole-field strain measurement techniques are based on optical measurements and do not require contact with the surface of the artefact. A digital image of the deformation is produced. In this paper, three types of full-field optical technique will be discussed: holography and its close relation speckle pattern interferometry [13], photoelastic stress analysis [14] and image correlation [15]. In the case of the first two techniques the measurement is based on the light path interference, while in the third technique the measurement is based on the intensity of the light. (A recent review [16] has described the developments since the 1970s of the application of holographic and speckle techniques to works of art. Some reference to this review will be made in the present paper.) For clarity a brief description of each technique is provided in non-specialist

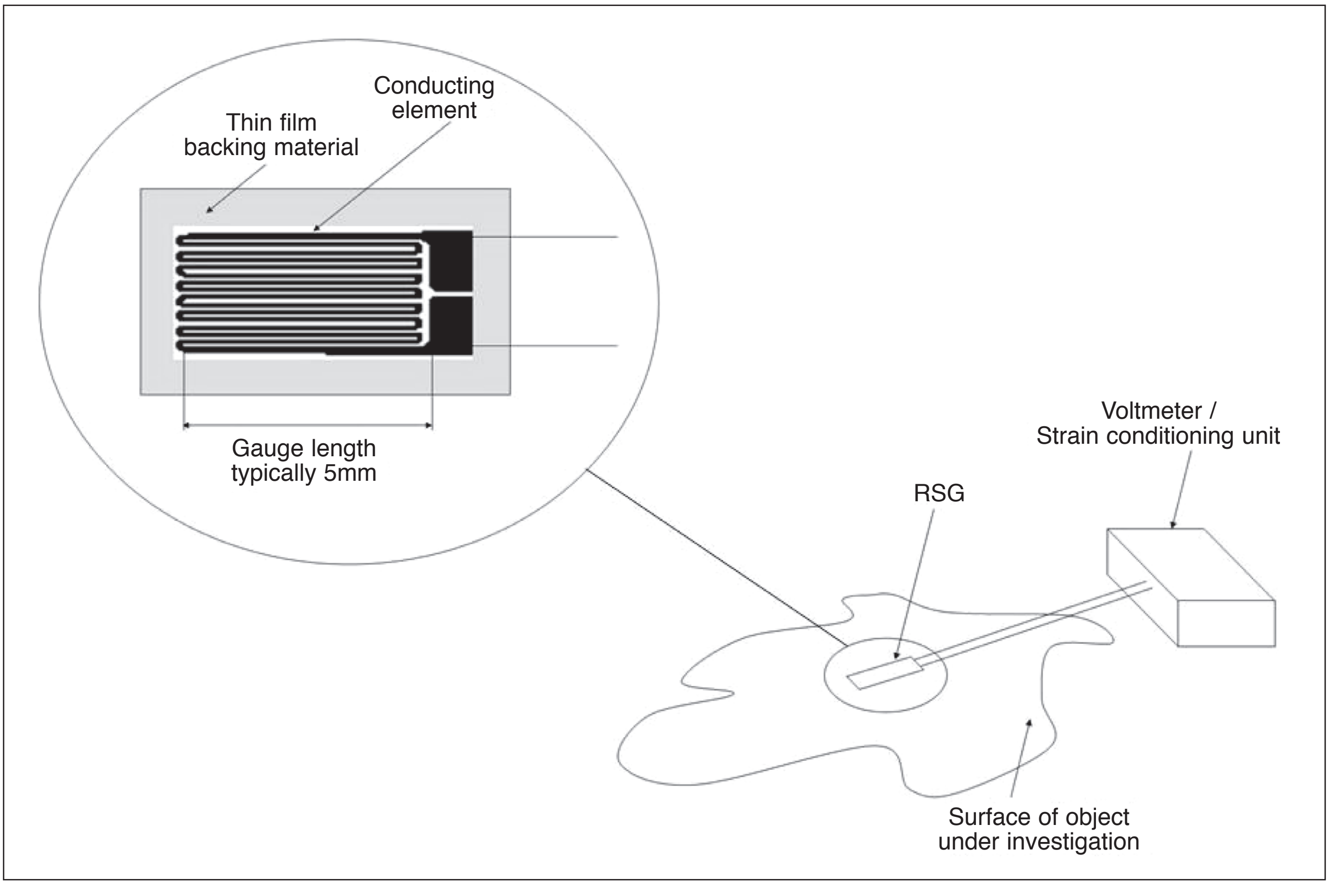

Fig. 1 Resistance strain gauge

terms. Then the current status of the use of these techniques in the cultural heritage sector is reviewed. The potential for expanding their application range is discussed in terms of mounting sensors on artefacts to monitor damage.

Resistance strain gauges

A RSG [9, 10] is shown in Figure 1 and comprises a thin film with a metallic conducting element etched on it. The gauge is attached to the structure in such a manner that any strain changes in the structure are transmitted fully into the gauge. Hence, the gauge copies the surface strain in the structure. The gauge is normally bonded to the structure using a cement or adhesive. Clearly, the quality of the measurement is dependent on the quality of the bond. A range of adhesives is available for use with strain gauges. These have been designed to optimise the strain transmission and to match the material properties of the object under investigation. The strain is measured by passing an electric current through the conducting element. As the structure, and hence the gauge, deforms the conducting element will deform and its resistance will change. The change in resistance results in a change in measured voltage across the gauge (indicated on the voltmeter in Figure 1) that can be directly related to the strain. Gauges are available as simple single sensors or as multiple sensors known as rosettes. A single gauge will provide the strain in the gauge direction, which may or may not be the maximum or principal strain. To obtain the principal strains (i.e., the maximum and the minimum) it is necessary to use a three-gauge rosette.

RSGs have long been employed to monitor strain in engineering components and structures. They are relatively cheap, but require wiring that significantly adds to the initial installation procedure and to the mass of the artefact and gauge assembly. Furthermore, local reinforcement of the structure by the gauge and, hence, the modification of the material response is a well-known limitation. The application of RSGs in conservation is not widespread, principally because of the need to adhere the gauge to the structure. However, the Opificio delle Pietre Dure has reported the use of 'strain gauges' on panel paintings [17]. The exact nature of the gauge was not described but it was reported that the gauge was bonded to the panel using a non-permanent means. Positive and negative deformations could be recorded, although the method was not repeatable. Moreover, readings could be taken only twice per day, i.e., one data point in the morning and one in the evening [18], so continuous data could not be provided by the application of this technique.

Optical fibre sensors

OFSs have been established over the past ten years as a method for strain measurement and damage detection in a wide range of engineering materials and structures [19–22]. OFSs are very small in comparison to RSGs and therefore can be applied to a structure with minimum modification of the behaviour of the structure. OFSs can be surface mounted as with RSGs, or it is possible to embed the fibre in layered-fibre reinforced plastic materials during the moulding process with minimum effect on structural integrity. In addition, it is possible to include multiple sensors in a single optical fibre [23].

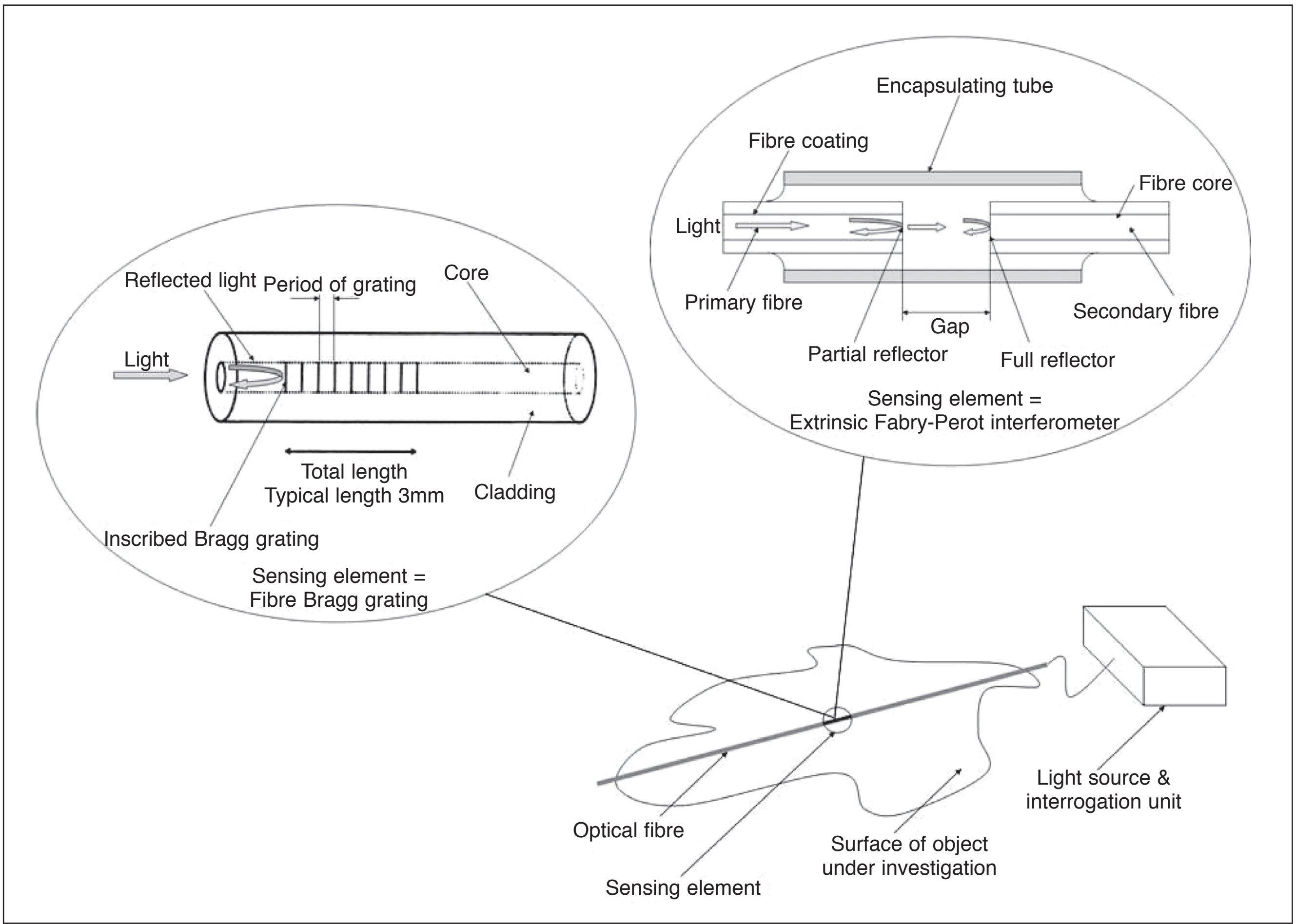

Fig. 2 Schematic of fibre Bragg grating (FBG) sensor and extrinsic Fabry-Perot interferometric (EFPI) sensor

Furthermore, OFSs are single-ended so only one connection needs to be made into the data acquisition system, as shown in Figure 2.

OFSs do not provide a conducting path through the structure and do not generate additional heat that could potentially damage the artefact. In addition, optical fibres are immune to corrosion and therefore do not deteriorate significantly with time [11]. However, they are sensitive to temperature change and a means of compensation is required. For this purpose, reference sensors can be used or mathematical techniques can be applied in order to separate the strain from the effects of temperature. OFSs operate using the strain transfer principle (as do RSGs) and therefore must be attached to the structure along the length of the sensor. The sensing element makes up only a small part of the overall fibre (see Figure 2). There are two main types of optical fibre sensors: fibre Bragg grating (FBG) sensors [11] and the extrinsic Fabry-Perot interferometer (EFPI) [24].

The most popular type of OFS makes use of FBGs in silica-based fibres. The sensing element (i.e., the grating) is inscribed into the fibre using ultraviolet light [11] and can be visualised as a series of lines on the fibre. The inset on the left in Figure 2 shows a schematic of a single Bragg grating inscribed on an optical fibre. Light is passed along the optical fibre through the grating. The cladding prevents light losses to the surroundings while the grating causes a change in the refractive properties of the fibre material, resulting in a shift in the operating wavelength. When light is passed through the grating it is reflected back to the data acquisition equipment, which determines the wavelength of the reflected optical signal. When the fibre is bonded to a structure and strained, the grating spacing and, hence, grating wavelength changes, a change that is directly related to the change in strain in the structure. FBGs are ideal for remote sensing over long distances as they are not affected by changes in optical power.

A different type of OFS is the extrinsic Fabry-Perot interferometer (EFPI), which consists of two optical polyamide-coated fibres (primary and secondary) and an encapsulating tube (shown in the inset on the right of Figure 2). The optical fibres are inserted and attached into each end of the encapsulating tube. At each end of the fibres within the tube there is a reflective element and the gap between the reflecting elements forms the sensor. Light is passed through the sensor, some light is reflected back from the primary fibre and the rest passes through and is reflected back from the secondary fibre. As the fibre is strained, the distance between the two fibre ends changes from its initial position. A change in the displacement induces phase differences between the reflected waves, which can be quantified as strain using interferometric techniques [25]. The EFPI sensor has the advantage that it is relatively insensitive to strains transverse to the longitudinal axis of the fibre and to temperature changes. The main disadvantages of this type of sensor are that they can be difficult to manufacture and calibrate, and only a single sensor can be produced in the optical fibre. In contrast to FBGs, long fibres result in optical losses that affect readings from the sensor.

The first recorded use of OFSs in conjunction with artwork was not for strain measurements but for pigment identification using reflectance spectroscopy [26]. More recently, Falciai et al. [17] used FBG sensors to continuously monitor the deformations in painted wooden panels. Simulated art works were used that consisted of a wooden panel coated with a mixture of chalk and rabbit-skin glue to represent the traditional materials. On a real work of art it would not be possible to mount FBG sensors directly on the painted surface. Therefore, a method of protecting the simulated painted surface was devised that comprised a sandwich of materials made from a sheet of Japanese paper bonded to the surface with acrylic resin and a Melinex polyethylene terephthalate (PET) sheet bonded to the paper using BEVA 371 thermoplastic adhesive. It was shown that this could be removed without the artefact sustaining damage. Seven FBG sensors were incorporated into a single fibre. Five of the sensors were used to measure strain, two on the front, two on the back and one on a supporting cross member. These were attached to the panel only at either end of the gratings. Two further gratings were left free for temperature compensation purposes. The panel was monitored for 19 days in an uncontrolled environment and the response to changes in relative humidity (RH) was recorded. The cross member was removed from the panel and more readings were taken. Following this, the unsupported panel was monitored for a further seven days. During the first period results from the front, back and supporting member were consistent and showed only small variation front to back, indicating only small amounts of bending. On removal of the cross bar the readings revealed that significant bending was taking place. In the final period the different readings front to back were also interpreted as evidence of bending.

Clearly, this is a very important demonstration of the value of optical fibre sensors in monitoring works of art. The work indicates that strain sensors can be attached with minimum intrusion. However, it should be noted that by attaching the gauges at either end, only tensile strain can be recorded initially. After initial stretching the compressive range of the gauge is limited by the amount the gauge has been stretched. This means that any compressive strain developed in bending after the removal of the cross member may not have been accurately measured and could account for some of the differences in the results recorded in the second and third periods.

Conventional silica-based optical fibres have a high stiffness and may cause local stiffening when they are attached to artefacts that are more flexible. Some examples of where this might be expected to occur are textiles and painted canvases. The local stiffening effect of the fibre will produce inaccurate readings and also may cause damage to the artefact. However, OFSs are very versatile and have great potential for monitoring in the cultural heritage sector. Alternatives to the conventional glass-silica fibres would extend their application range. A possible alternative is polymer optical fibres (POF). POFs generally have a larger diameter than a silica-based fibre. However, they are mechanically flexible and therefore would be easier to install on canvas, for example. Furthermore, POF sensors are less costly than the conventional silica-based FBGs. They are durable and because they can be manufactured from a variety of materials [27] such as poly-methylmethacrylate and polycarbonate there may be an opportunity to match the mechanical properties of the gauge with that of the artefact.

The application of POFs has been demonstrated in a range of materials including textiles. Recently [28] a study was carried out to evaluate a range of optical-fibre materials and manufacturing methods applied to the following areas: illumination and wave-guides, biochemical sensing, audio systems, automotive applications and multimedia and telecom applications. It was demonstrated that the POFs could be integrated with textiles for 'intelligent' clothing with potential in both military and commercial applications.

POFs have been used in fabrics as illumination elements for decorative purposes. POFs have been woven into the textile at the manufacturing stage and it was demonstrated that this process did not impair the integrity of the fibre [29]. It was shown that the POFs could be used up to 100 m away from the light source, indicating that a similar distance could be used in measurement applications. The results are very promising and demonstrate that the utilisation of POFs for monitoring cultural heritage artefacts, such as tapestries, costume and banners, is feasible.

Holographic and electronic speckle pattern interferometry

Holograms were first conceptualised in the 1940s but were only realised fully when high power coherent light (at a single or restricted range of wavelengths) could be generated by a laser. Developments in holography commenced in the 1960s [16]. A hologram differs from a photograph in that it can provide a three-dimensional (3-D) representation of an object as it not only records the amplitude or intensity of the light, but also the phase of the light. This is achieved by splitting a laser light into a reference and illumination beam and recording the interference of the two beams on photographic plate. The 3-D image of the object is reconstructed by illuminating the photographic plate with a light source of the same wavelength as that used for recording the image. A detailed description of holography is provided by Ambrosini and Paoletti [16]. Holographic interferometry makes use of the interference of two images: one in the deformed and the other in the undeformed state. An interference pattern is generated and forms a series of light and dark bands known as fringes that can be related to the deformation of the structure. (See [16] for a full description of the techniques used in holographic interferometry.)

When a surface is illuminated by laser light, interference occurs between the source and the reflected light, causing a speckle pattern [13]. The size of the speckles results from the nature of the light and the aperture it passes through. In speckle pattern interferometry, a video or TV camera records two light patterns: one from the

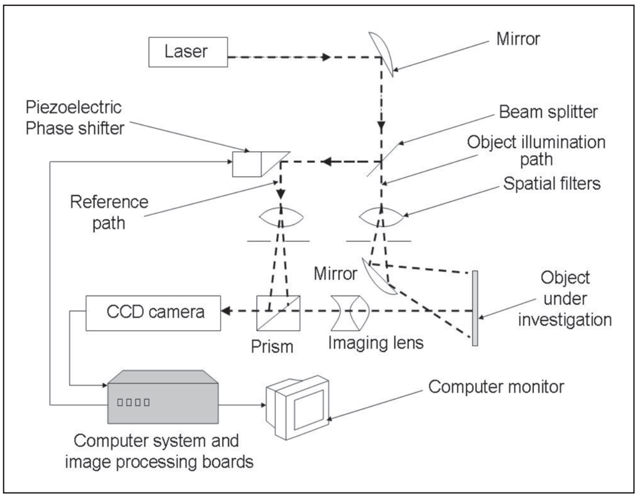

Fig. 3 Schematic of an electronic speckle pattern interferometry set-up

undeformed condition and the second from the deformed condition. The light patterns are compared and the changes in the speckle pattern provide readings that can be processed into strain. Modern systems utilise data collection via a CCD (charged coupled device) camera into a computer system. The technique is known as digital speckle pattern interferometry. The terminology 'electronic speckle pattern inteferometry' (ESPI) was first coined to describe analogue techniques used in conjunction with data collected by TV methods but is now commonly used to describe digital approaches and will be used throughout the remainder of this paper in this context.

In Figure 3 a schematic of a simple ESPI set-up for measuring out-of-plane deformation is shown. Essentially there are two components in the system [13]. A laser is used to illuminate the material under investigation and provide the speckle on the surface of the object. The laser also provides a reference beam to the CCD camera via the beam splitter. The other component is the interferometer, which is shown in Figure 3 as a prism and lenses. Data from the deformed and undeformed condition are combined arithmetically by subtracting two speckle patterns. This results in a series of closely spaced lines appearing in the image that is displayed on the monitor, which are known as fringes. This representation is sufficient for a qualitative representation of the deformations. In order to process the data into quantitative information, multiple data sets are required for the deformed condition; these are obtained using the phase-shifting device (see Figure 3) that changes the optical characteristics of the ESPI system. A sequence of a minimum of three positions of the phase-shifting device allows the data to be processed into digitised data maps of the out-of-plane displacement field in terms of the phase of the light. These can be analysed directly or processed further to provide strain. To obtain in-plane deformation data it is necessary to illuminate the object from at least two directions (to provide deformation data in one direction). Commercial systems are available that allow both in-plane and out-of-plane deformations to be measured; these usually contain four laser illumination systems. A similar technique to ESPI is electronic speckle pattern shearing interferometry (ESPSI) [30]. Here a further optical device is included in the system that allows data directly related to strain to be collected.

To the authors' knowledge, the first recorded use of holographic interferometry in the cultural heritage sector was carried out by a group at the Universita dell'Aquilla in Italy in 1973 [31]. Their work investigated the condition of the paint film and ground on wooden statues and demonstrated that holographic interferometry could be used as a means to identify (non-destructively) sub-surface cracks. Further work [32] using holographic techniques demonstrated that areas of detachment in between the wooden support and the priming layer in panel paintings could be visualised. A technique for rapid evaluation making use of a modified exposure procedure known as 'sandwich-speckle hologram interferometry' has been developed [16, 33]. This was applied to a fourteenth-century wooden statue that was undergoing restoration [34]. The technique provided real-time holographic images and allowed areas of suspected damage to be revealed by observation of discontinuities in the fringe pattern. Other applications of the technique by this group include frescos [35] and panel paintings [36]. In a later study of erosion in Roman marble statues, the dell'Aquilla group modified their approach by introducing a CCD video camera into the system to record data from holographic plates [37]. Once again discontinuities in the fringe pattern were equated to damage and, moreover, the damage could be clearly seen with the unaided eye. However, the purpose of the paper was to demonstrate the applicability of the technique on works of art. Some excellent examples of holographic fringe data from artefacts are provided in [16] and the authors recommend that the reader consult Ambrosini and Paoletti in conjunction with the present review.

In 1993 the dell'Aquilla group further modified their approach by integrating an interferometer into their equipment, making use of digital speckle [38]. This was, to the authors' knowledge, the first recorded use of digital ESPI to measure out-of-plane deformations in artefacts. This enabled the instrumentation to be taken out of the laboratory to study mural paintings on site. Here a change in strain in the mural was introduced by heating and the data clearly shows areas where the mural had cracked and areas where the mural had totally detached from the wall. It should also be added that fibre optical devices were used to guide the laser to localised areas and reduce the number of optical components in the system, making it more suitable for on-site use [38]. The effect of microclimate variations on wooden panel paintings was studied using ESPI in the gallery where the paintings were on display [39]. Unlike holographic data, an ESPI image contains no visible details of the object and therefore locating a defect in the painting that is identified in the image is not straightforward. Defects were successfully identified using an edge detection technique to produce a map of the edges of the object, which was superimposed on the ESPI data [39]. It was shown that changes in RH of no more than 3% and temperature changes of around 5°C were causing sufficient displacement to allow defects to be identified with ESPI.

Since 1998 the dell'Aquilla group have used portable ESPI systems to evaluate the condition of ancient mosaics [40, 41]. Mosaics make a challenging application for ESPI because of their large dimensions and because the layered structure comprises different materials. Over time, subject to environmental changes, the mosaic will inevitably be damaged by thermal stresses developed from differential expansion of the individual layers. The deformations eventually cause cracking and delaminations either on the surface or subsurface. In order to assess and evaluate the ESPI technique, experiments were carried out on models and actual ancient mosaics in the laboratory and in situ [40, 41]. Out-of-plane displacements caused by changes in ambient temperature and humidity were not sufficient to achieve a good definition in the ESPI data. Therefore, thermal stresses were induced in the mosaics by heating with two 150 W infrared lamps at a distance of approximately 1 m. In the laboratory this approach was demonstrated by inserting simulated defects into a mosaic piece between the plaster and the mural support, which were clearly detected by the ESPI system. In addition, the heating technique was used in situ on a mosaic in Trajan's bath in Rome and the ESPI detected a detached region. The conclusion was qualitative once again. High spatial density or islands of fringes and discontinuities in some fringes indicated the presence of cracks.

Another group based in Italy [42] investigated the use of ESPI to monitor panel paintings. Three wooden panels were examined and displacements induced by heating the surface of paintings for two seconds using an infrared lamp. Surface displacements of a few tenths of a micron caused by detachments and cracks were measured. In addition, damage caused by the curved metal supports that are fixed in the panels for hanging was revealed. ESPI was also used to assess the quality of an earlier repair to damage caused by a nail.

In the mid 1990s a group from the Carl von Ossietzky University (Oldenburg) began work on monitoring deformations in historical monuments using ESPI and ESPSI [43]. In the context of conservation this group is mainly interested in frescos and murals and the role of various environmental elements in their deterioration. They have used both ESPI and ESPSI to study a variety of wall decorations such as medieval murals in Lower Saxony and baroque murals on the walls and ceilings of Schloss Augustusburg near Cologne. An examination was made of the growth of a small crystallising salt as it grew within a mural. ESPI readings were taken at regular intervals, showing changes that could be correlated with the growth of the salt over a period of 76 hours. The result demonstrates that the technique can be used for quantitative studies. The effect of the movement of people and heating systems on the measurements has been identified as a bar to making long-term stable measurements. However, in some situations the movement of people has been used to advantage. In a room where a ceiling mural was loaded from the floor above, a correlation was made between the load and the fringe pattern from the ceiling. In summary, this work demonstrates that both ESPI and ESPSI can be used on site to quantitatively measure environmental deterioration and identify areas of cracking and debonding that are not visible to the naked eye. Recently the group has focused on the surface condition of natural stone artefacts [43] and has measured decay mechanisms with ESPI. In 2001 the technique was refined to include a microscope so that the condition of the paint layers on the famous ancient Chinese terracotta warriors could be evaluated, resulting in small-scale ≈ 25μm measurements [44].

Boone and Markov [45] have also used ESPI to examine the reaction of a nineteenth-century panel painting to environmental changes. Applying localised heating (resulting in a temperature change of a few degrees) for a few minutes with an infrared lamp, a large enough strain was induced to identify a zone of stress concentration, seen as sharp bends in a regular fringe structure, which indicate a discontinuity in the painted surface. They also used ESPI with localised heating to examine a seventeenth-century enamelled terracotta vase. Discontinuities in the fringe pattern indicated local delamination of the enamel that was subsequently confirmed by microscopic examination.

Young has investigated the feasibility of obtaining quantitative strain measurements using ESPI from flexible canvas paintings loaded in biaxial tension [46]. The work differs from that discussed above in that in-plane deformations were identified as a means to monitor deterioration. This is because panels, frescos and mosaics will warp as a consequence of deterioration causing an out-of-plane deformation. By contrast, canvas and fabrics will deform in-plane as a consequence of tearing and splitting. Therefore a system was built that could measure in-plane deformations in a single direction. Uniaxial tests were carried out and the strains derived from the ESPI fringes were compared with RSG readings. The accuracy of the ESPI data was considered to be within acceptable levels but local stiffening of the canvas by the RSG was identified as an error source. Both the ESPI and the RSG gave readings that were less than those calculated from simple crosshead displacement. This was attributed to distortion of the sample, resulting in a non-uniform strain distribution. It was also shown that the failure of a tear repair could be monitored in a qualitative sense using ESPI [46]. Young demonstrates that in-plane measurements on canvas paintings using ESPI were possible. However more detailed work on the constituent materials of paintings on canvas is required to obtain a quantitative interpretation from the data. To this end, in later work Young used a commercially available ESPI system that enabled in-plane measurements to be made in both directions to derive Poisson's ratio (the ratio of the deformation in each in-plane direction) values relevant to canvas painting [47]. Values were obtained for raw linen, linen with rabbit-skin glue, linen, glue and oil and also for nineteenth-century primed loose lining. The conclusion was that the addition of paint significantly changes the Poisson's ratio of the materials. More importantly comments were made on the accuracy of the measurements and how slight fluctuations in the loading that cause periodic rises and falls in strain can affect the processed data and, hence, the strain values derived from the ESPI readings. Therefore, Young concludes that the phase-shifting approach used in the commercial set-up for deriving the strain might be better replaced with a more direct approach to extracting phase gradients Fourier transforms [48].

Tornari et al. [49] have used holographic interferometry very recently as a part of a detailed study of an icon

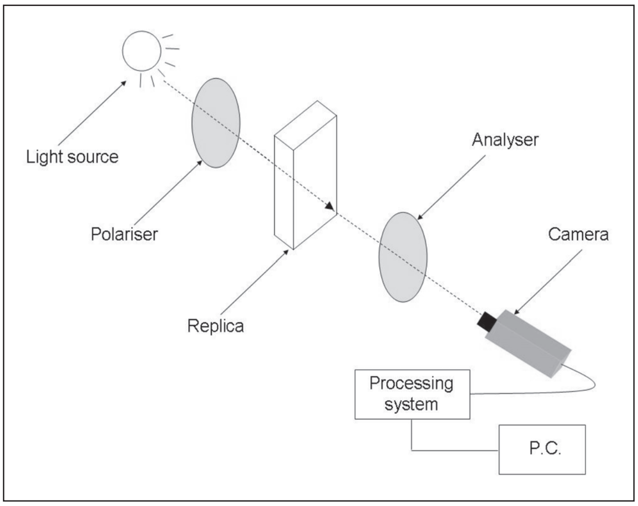

Fig. 4 Schematic of a conventional polariscope set-up

during restoration in order to reveal hidden defects and regions of localised stress. The reference image was taken before cleaning and another image was taken after treatment. Small cracks underneath the surface were identified as localised direction changes in the overall continuity of the fringe system. In addition, the authors used the holographic information to confirm the uniform removal of a stained layer of organic origin – fingerprints, grease, soot and dust. This work shows that holography remains a relevant technique and demonstrates it usefulness in conservation studies.

Photoelastic stress analysis

One of the oldest and most useful forms of interferometric measurement for engineering purposes is photoelasticity, which involves the observation of fringe patterns caused by stress-induced birefringence [14]. The instrument that is used for photoelasticity is called a polariscope. A schematic of a conventional plane polariscope is shown in Figure 4. A replica of an artefact, which is produced in a transparent plastic material, is loaded in the polariscope as shown. Polarised light passes through the replica and is observed through a further polarising plate known as an analyser. The refractive index of the material is stress dependent and causes retardation in the light passage, which produces fringes in the replica that can be directly related to stress. Digital photoelasticity [14] has enabled rapid fringe analysis.

To produce an accurate replica, measurements can be taken from the artefact using 3-D scanning [50] and used in conjunction with computer-aided manufacturing to produce a mould. The replica could then be cast from a suitable birefringent material. However, this would be costly and time consuming. Stereolithography [51], a 3-D printing process, has recently allowed the rapid prototyping of parts from birefringent resins and could replace the casting process. However, on a practical level it would be costly to produce replicas and, therefore, an alternative to conventional transmission photoelasticity is required. A simple modification of the set-up shown in Figure 4 results in an approach known as reflection photoelasticity [14], which requires a plastic coating with a reflective backing to be applied to the surface of a material. This could find use in assessing stone, ceramic and metallic artefacts as well as possibly mosaics and murals. For paintings the properties of the paint or protective coating may be birefringent and allow readings to be taken without applying a further coating. To date, the authors have not been able to identify any use of the photoelastic technique in the analysis of cultural heritage. However, the justification for including this description is to make the reader aware of the technique and indicate its potential future use.

Photogrammetry techniques

Laser scanning and photogrammetry [52] have been used extensively to 'record' cultural heritage artefacts (e.g., [53–55]) for archival purposes. The techniques utilise a range-finding system that enables the mapping of the artefact into a 'cloud' of 3-D coordinate points. These coordinates are then digitised so that an exact replica of the artefact is reproduced as a computer image. The ideas behind photogrammetry can be used to monitor the condition of an artefact, simply by correlating one image with another taken later, hence the terminology 'image correlation'. In general, this idea has been used to monitor large displacements in buildings and underground sites [56, 57].

In order to monitor displacement and strain accurately at a small scale it is necessary to employ two digital cameras as shown in Figure 5. Here the angle between the two cameras is known and a point on the object is independently defined in the image recorded by each camera. When the object is displaced the position of the point is once again recorded and the relative displacement calculated from the data sets of the two images. It is important that the position of the point is defined in the image, which is achieved by mounting a 'grid' on the surface of the artefact. The grid can be a random pattern or something more uniform. The important factor is that there is contrast in the image. In order to facilitate the contrast, the surface of the artefact is illuminated by white light. The system can be simplified to a single camera, although this only provides displacements in the plane of the object. The stereo-photogrammetry system enables both in-plane and out-of-plane measurements and it is possible to calculate the strains from the displacement measurements using techniques identical to those employed in ESPI.

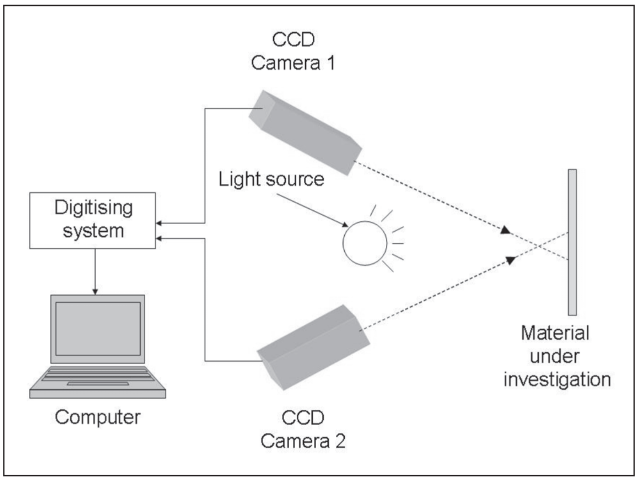

Fig. 5 Schematic of the three-dimensional image correlation set-up

Image correlation based on stereophotogrammetry has been used to assess the effects of displaying the cowl of St Francis of Assisi [58]. The grid was produced simply by putting pins into the material and then the effects of displaying vertically and inclined at an angle, as opposed to horizontally, were assessed. Clearly, laying the cowl horizontally would not lead to stress but it could not be easily seen in a gallery. Therefore, for display purposes it was concluded that minimum deformation would occurr when the cowl was mounted at a 30° angle. Spagnolo et al. [59] have used a fringe-projection technique to produce a 'grid' on stone artefacts and then assessed the effects of surface deterioration caused by erosion with an image correlation technique. A single camera system [60] has been used to assess the deformation of the *Adoration of the Magi*, a painting on panel by Leonardo da Vinci. It was possible to assess the shape of the surface and define the departure from a flat surface; further assessments would provide a means of monitoring the state of deformation. Assessing the effect of laser cleaning on ancient manuscripts has been another application, where a photogrammetry technique was used to monitor the cleaning process [61].

To assess the effects of changes in humidity on cradled panel paintings, Moiré fringe analysis has been used [62]. Moiré analysis requires that the 'grid' is regular and in this case the grid was projected onto paintings. The measurements rely on the interference of the grid from readings taken in a reference and a deformed state. The technique provides both the in-plane and out-of-plane displacements of the paintings and from them it was possible to identify areas of strain concentration and, hence, damage. The paintings were subjected to humidity cycling in a specially designed system that changed the environment behind the panel and allowed Moiré readings to be taken from the front. In contrast to most of the other photogrammetry studies discussed here the authors were able to obtain quantitative values of strain and relate these to the different moisture-absorbing characteristics of each part of the panel assembly. Furthermore, they were able to make recommendations on improving the mounting of the painting such as using sliding battens and moisture barriers in the mounting material.

It is also possible to use speckle produced by laser light for image correlations. In two separate studies, the reference beam in an ESPI system was masked and the speckle decorrelation between the strained and unstrained data was used to characterise the physical condition of artefacts [63, 64]. An excellent description of this approach and its application to artefacts is provided in [16], the main finding being that the equipment can reveal defects sometimes masked by the fringes that are produced in ESPI.

Potential of strain/deformation measurement techniques for condition monitoring

It is clear that the major limitation of the application of point-strain measurements in the cultural heritage sector is the need to bond the sensor to the artefact. Falciai et al. [17, 18] devised a technique whereby the RSG could be removed, obviating the need for permanent installation and without adverse affects for the artefact or its presentation. They also applied a similar technique with OFSs, which were bonded at the ends only. It must be emphasised here that for true strain monitoring, the gauge (electrical or optical) must be attached to the artefact in such a way that it experiences the strain experienced by the artefact, i.e., the entire sensing element must be attached to the artefact. The nature of the adhesive must be such that it is thin so there is not a stress gradient through the thickness of the adhesive. It must also be strong enough to transfer load from the artefact to the gauge without detachment and it must behave in the same manner mechanically as the artefact.

In the case of metallic, ceramic or stone artefacts it may be possible to identify a suitable adhesive that can be removed using a solvent that does not affect the artefact. For flexible artefacts, such as canvases and textiles, bonding a sensor directly to the artefact is unlikely to be appropriate. Here an alternative means of attachment needs to be identified such as that described in [17]. It may also be possible to weave optical fibres into new textiles or develop a patch that can be sewn onto existing canvas or textile artefacts. Stitching optical fibres directly onto existing textiles has yet to be explored but clearly warrants investigation. It should be noted that the effect of long-term mounting of an OFS could result in the deterioration and degradation of the artefact under inspection. Therefore, a full chemical characterisation of the OFS should take place prior to any long-term installation. Furthermore, issues such as the presentation of the artefact must be considered prior to the permanent installation of any monitoring device.

In the preceding sections the techniques used in engineering to optically assess strain/deformation in objects have been described and their applications to conservation have been summarised. The overriding advantage of these techniques is that they do not require contact with the surface of the object. However, they measure deformation so that two images are collected of deformation in two states. This means that the object under investigation must undergo deformation during the measurement period. In many of the studies, heating or applying load has achieved the deformation. In a monitoring context it would be far more applicable to use environmental changes and natural deterioration as the cause of strain in the structure. Hence, the period between the two measurements may be considerable and issues such as alignment and stability must be addressed.

From this review it is clear that the ESPI-type techniques have found the widest application. Out-of-plane deformations measured by ESPI have been particularly useful in identifying damage in panel paintings, mosaics and frescos. In-plane ESPI measurements have been used to determine Poisson's ratio values for canvas paintings and to identify failure mechanisms in repair mends. However, the phase-stepping technique used to determine strain from the ESPI fringe patterns requires multiple data collection from objects in identical strain states and is sensitive to vibrations and fluctuations in the strain state. It, therefore, may not prove to be the optimal technique for processing data from artefacts monitored in a gallery environment. Photogrammetry applications designed for 3-D strain measurement are less sensitive to environmental fluctuations and, therefore, these may prove a more appropriate means of monitoring works of art in the future. Photoelasticity has not been used. However this technique does not rely on the strain difference and with advances in coatings may prove to be appropriate for some applications in the future.

Conclusions

This detailed review covers work that has been undertaken over the last three decades with a focus on quantitative measurements based on displacement or strain. The main findings of the study are as follows:

- Monitoring of artefacts for structural damage is in its infancy even though initial work commenced around thirty years ago.
- Point-measurement systems using strain gauges and optical-fibre sensors are underutilised because of the need to attach the gauges to the artefact. Development of techniques to remove the gauges without damaging the artefact would allow more widespread use.
- Optical-based non-contact techniques are ideal for monitoring works of art.
- Holographic interferometry and ESPI have been used extensively in assessments of artefacts. Some quantitative work has been conducted but the majority of the work is based on defect identification. A major step forward would be ESPI techniques to provide quantitative strain measurements from defect and damage sites.
- Considerable effort has been focused on making ESPI a portable technique that can be taken to the gallery or used on site. Furthermore, the processing and handling of the data from such systems has been simplified significantly in the past 10 years with use of powerful computers. Both of these have made ESPI more attractive as a tool for practitioners who are not familiar with the physical principles behind the technique.
- There are only a few reports of quantitative use of ESPI and Moiré interferometry on canvas and panel paintings. These demonstrate that accurate data can be obtained and related to the condition of the artefacts.
- Photogrammetry has been used in the conservation sector for recording archival material. However, it shows promise as a technique for condition monitoring as it is not as sensitive to environmental variations as ESPI.
- Photoelasticity is yet to be used in the conservation sector but with the development of new materials for coatings, this technique could provide a means for monitoring.

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