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 terms, and this is followed by a summary of its advantages and limitations.