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Assessing the Feasibility of Monitoring the Condition of Historic Tapestries Using Engineering Techniques

J.M. Dulieu-Barton[a], M. Sahin[b], F. L. Lennard[c], D. D. Eastop[c], A. R. Chambers[a]

[a]School of Engineering Sciences,

University of Southampton, Highfield, Southampton, SO17 1BJ, UK

[b]Department of Aerospace Engineering,

Middle East Technical University, 06531, Ankara, Turkey

[c]The Textile Conservation Centre,

University of Southampton, Park Avenue, Winchester, SO23 8DL, UK

janice@soton.ac.uk, melin@ae.metu.edu.tr, fjl@soton.ac.uk, dde@soton.ac.uk, a.r.chambers@soton.ac.uk

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Abstract. The findings of a year-long programme carried out by a multidisciplinary engineering/conservation team are described. A mass-produced textile material that can be used to represent tapestries is identified and mechanical tests are detailed which demonstrate it behaves in a similar way to tapestry. The feasibility of using optical fibre sensors, full-field optical strain measurement techniques and thermography for monitoring tapestry degradation is assessed. The results of preliminary findings are presented and a rationale is developed for in-situ quantitative strain monitoring of tapestries.

Introduction

Tapestries form an integral part of many historic house interiors. These hand-woven textiles are often large with intricate patterns that were very time-consuming to produce. Tapestries were extremely expensive to commission and were often more highly valued than paintings. For example in 1528 Henry VIII bought a set of ten tapestries depicting the Story of David for £1500, while in 1538 Holbein, the King's painter, was paid £30 per annum. The conservation of tapestries is a key issue in the heritage sector. Specialists are employed to assess the condition of tapestries and recommend conservation strategies that do not detract from their appearance and function on display, nor alter their intrinsic characteristics. The local environment plays a role in the deformation process, and environmental monitoring and control, and condition assessment by visual inspection, are now routine. Textile conservators are experienced in visually assessing textiles for evidence of damage. However conservators have seldom quantified the strain imposed by the textile's own weight. In the case of a tapestry, this strain is presumed to be another significant factor in its deterioration. The effects of deformation under a constant load are well understood within engineering and procedures exist for monitoring deformation; a tapestry experiences similar deformations under the load resulting from its own weight.

The authors form an interdisciplinary research team at the University of Southampton, consisting of researchers from the Textile Conservation Centre and the School of Engineering Sciences. The team has completed a pilot study investigating a number of possible techniques for monitoring tapestries. The pilot study has been ground-breaking in bringing together conservators and engineers in an integrated research project, developing collaborative research between the sciences, arts and humanities. The pilot study was successful and the authors have received further substantial funding from the UK Arts and Humanities Research Council (AHRC) to continue this research. The current paper describes the findings of this pilot study. The mechanical behaviour of a representative textile, a tapestry-like fabric, is described. This shows that the textile behaves in a predictable fashion and can be monitored using engineering techniques. The damage mechanisms in the material are established, informing the relationship between the damage and applied load. The work examines both contact and non-contact monitoring techniques, including optical fibre strain gauges, electronic speckle pattern shearing interferometry (ESPSI), photogrammetry and thermography.

Damage mechanisms and representative material

Tapestries are produced by weaving on a loom where highly twisted yarns, known as warp yarns, are stretched and fixed in one direction. To create a fabric structure and simultaneously to create a pattern coloured weft yarns (which are usually less densely spun) are woven transverse to the warp. The weft yarns are tightly packed and completely cover the warps to create a weft-faced material. One feature of tapestry weaving is that the weft yarns are discontinuous. Creating a continuous planar surface is achieved in two ways: by interlocking weft yarns together during weaving; alternatively, slits can be left during the weaving, and be sewn up afterwards. On completion the tapestry is hung so that the weft yarns support the weight of the tapestry, causing the self-loading of the tapestry in the direction of its weakest individual components and across the discontinuities in the weft yarns. The process of deterioration is similar to the creep mechanism experienced by engineering structures.

To avoid using and destroying actual tapestries, tapestry-like textile samples were required for testing purposes that adequately represented tapestry behaviour. A plain-weave hand-woven wool fabric was identified as a suitable representative textile. The fabric has a thin compressed selvage edge that is of tighter construction than the rest of the fabric. The warp yarns are made up of strong and tightly-spun (twisted) threads as in most tapestries. The weft yarns are made from soft and bulky threads and are similar to the weft in tapestries, in that they are more loosely spun.

To determine the stress strain behaviour of the representative textile 50mm wide samples were cut and mounted in a standard Instron 5569 electromechanical test machine. Standard wedge grips or clamps caused the textile to fail prematurely at the grips. Therefore, self-tightening grips [1] were designed to maintain sufficient pressure to grip as the tensile load was increased. The grips consist of a clamping mechanism with a roller. The sample was wrapped around the rollers and as the tension was applied the rollers gripped it. The initial grip separation, which is the distance between the centre of the upper roller and that of the lower one, defined the gauge length of the sample. After some optimisation experiments a gauge length of 250mm was selected. Another reason for the choice of the gauge length was that in [2], it is recommended that longer length samples are used, because inherent weak points in single yarns are more likely to be included in a longer sample and provide a better representation of actual material behaviour.

To observe individual yarn breakage during failure, all quasi-static tests were carried out at relatively slow extension rate of 0.25mm/s to allow recording of more data. Tests were performed in the warp and weft directions to investigate tensile behaviour in both directions of the textile, and to assess the repeatability of the tests. In the case of the warp direction the average maximum stress from the four tests was 16.50 $\pm$2.5% MPa and in the weft direction 14.82 $\pm$3.2% MPa. The stress-strain behaviour in each direction was very different. When the load was applied in the warp direction, the textile showed a behaviour that could be characterised as virtually perfectly elastic-plastic.

When the load was applied in the weft direction (see Figure 1) the textile showed two regions of almost linear behaviour up to the maximum stress and then yarns started to break and failure occured in a progressive way. Every step change (i.e. a drop) in stress values corresponds to an individual yarn breakage. This clear difference in stress-strain behaviour in the two directions was attributed to the nature of the twist in the yarn. When on display, tapestries hang in the weft direction so the deformation under self-load is expected to follow the behaviour shown in Figure 1.

To compare the behaviour of the representative textile and that of a tapestry, tapestry samples (measuring 150mm by 50mm) were woven and tested in the weft direction. A comparison of the weft direction behaviour in the two materials is shown in Figure 2. It is clear that the textile weft

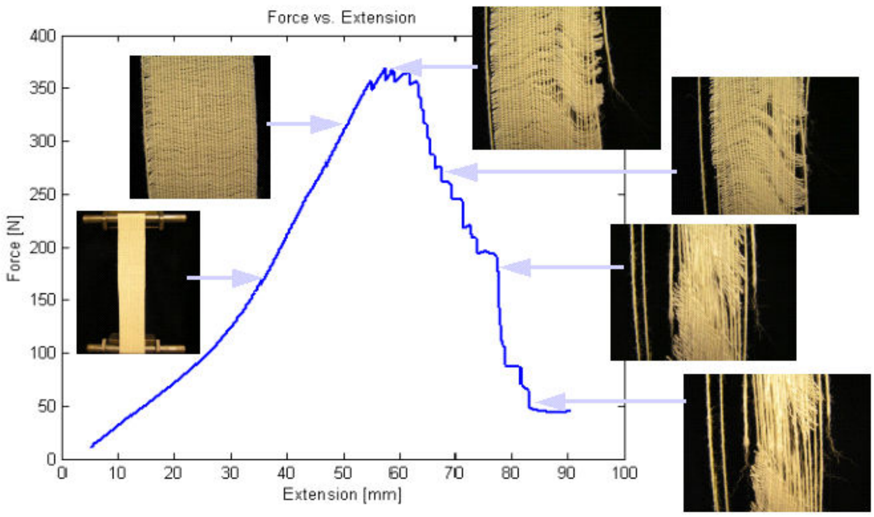

Figure 1 Failure of representative material

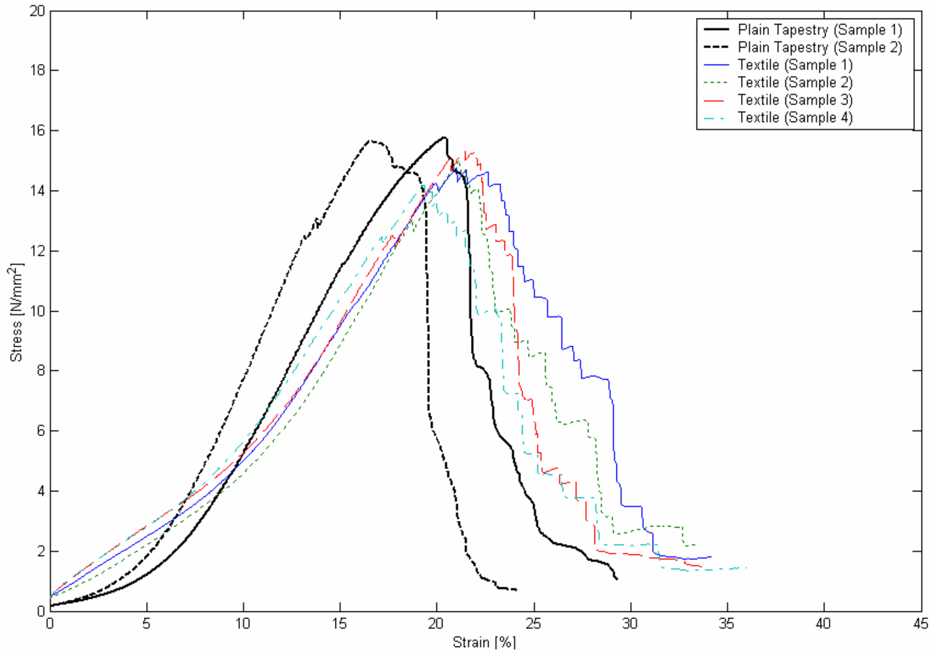

Figure 2 Stress strain behaviour of tapestry and representative material

direction behaviour is following that of the tapestry behaviour, although the tapestry material is slightly stiffer. The behaviour of all the weft direction samples indicates that a sudden breakage is to be expected rather than observable stretch. This means that monitoring will only be successful if the sudden breakage can be predicted by measurement of the strain in the region where there is no visible damage. Figure 1 shows that this is in the region of up to 10% strain.

Optical Fibre sensors

The application of optical fibre Bragg grating sensors to the representative material and the tapestry samples is described in [3]. When integrating the optical fibre with the tapestry it is crucial that no damage is caused to the tapestry. In the feasibility study three techniques were examined: (i) bonding using a conservation adhesive, (ii) stitching using a standard stitch employed by conservators, and (iii) weaving into actual tapestry (with and without crimping the Bragg grating). Figure 3 shows the response of these Bragg gratings to a quasi static strain applied to the materials. The ordinate of Figure 3 shows the strain as determined from the test machine cross head deflection; the abscissa shows the normalised change in wavelength of the gratings. The applied strain was kept low as Bragg gratings can only measure strain of the order of 2 to 3%, i.e. in the region where the damage initiates in the tapestry and is not apparent in visual inspections. The bonded sensor shows a linear response to the applied strain and therefore is the most suitable. Both of the woven-in sensors show two linear regions, probably as a result of the straightening of the crimp in the fibre. The stitching is clearly not providing any means of strain transfer. Current work is focussing on the long-term response of the bonded gauge to a creep loading representative of the actual loading.

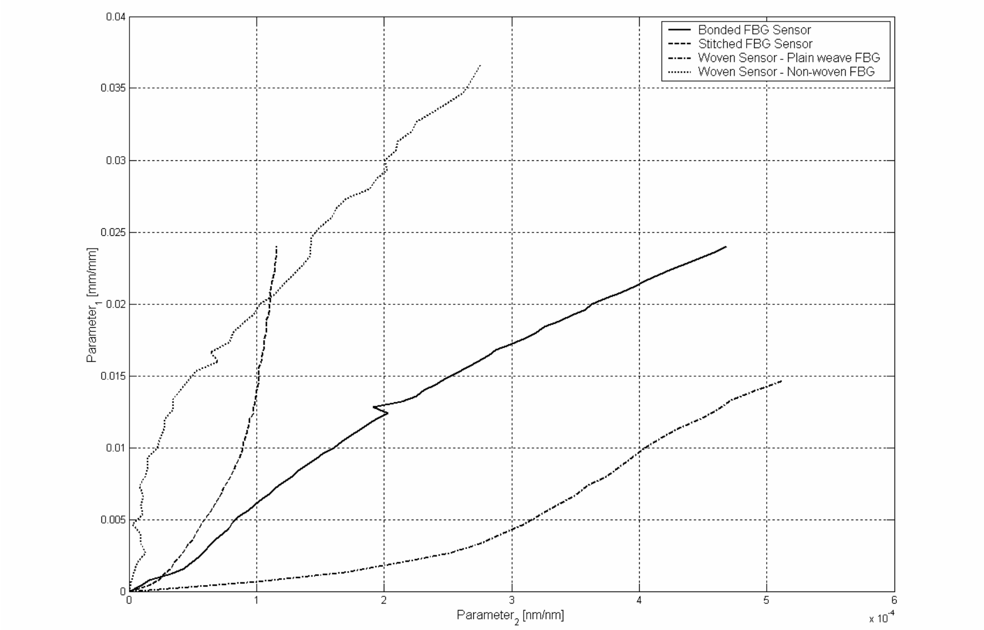

Figure 3 Response of Bragg grating and attachment method

Full-field strain measurement techniques

Full-field non-contact measurement techniques, such as electronic speckle pattern interferometry (ESPI) have been used in the cultural heritage sector to assess damage and deterioration, e.g. of panel paintings, mosaics and frescos. A comprehensive review of the application of these techniques in the heritage sector has been carried out [3]. Full-field techniques seem ideal for monitoring tapestries as they do not require attachment. However, some full-field interferometric techniques are susceptible to small vibrations and environmental changes. Furthermore, they require a change in the strain state and for tapestries this would occur naturally over a considerable period of time so accuracy in the positioning of the measurement system is an essential feature. To date condition monitoring in museums and historic houses [3] has been based on purely qualitative assessments; the overall purpose of this work is to develop a means of quantitative on-site assessment. A robust but as yet little used technique is 3-D photogrammetry. The literature review [3] revealed only one example of its use in textile conservation: to assess the optimum way to display the cowl of St Francis of Assisi. In this work pins were spaced in a grid pattern on the cowl and used as the basis for the measurement; the results were promising and it was decided that the application of photogrammetry to tapestries must be explored.

Two techniques have been assessed using representative textile samples with one warp fibre cut to simulate a point of weakness. It was concluded that the high sensitivity of electronic speckle pattern shearing interferometry (ESPSI) to very small out-of-plane deformations makes the technique unsuitable for tapestries. However a second technique using 3-D photogrammetry and digital image correlation produced excellent results showing the strain concentrations around the damage. Figure 4 shows a full field strain image superimposed on the loaded representative textile and a line plot through the data, highlighting the strain concentrations. In this work the ‘contrast’ required to aid the image correlation was facilitated by producing a ‘speckle’ pattern on the material using spray paint. Clearly this is undesirable on actual tapestry so work has been carried out that shows the contrast in a typical tapestry design is sufficient to carry out the image correlations.

Current work is focusing on combining the optical fibre data with 3D photogrammetry to establish a technique where the optical fibre can be used as an absolute strain reference to aid repositioning of the cameras used in the photogrammetry.

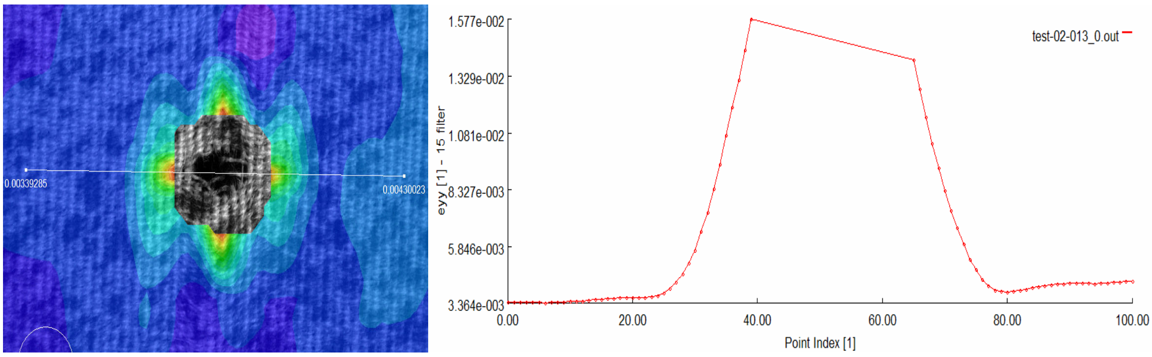

Figure 4 Strain field derived from 3-D photogrammetry

Thermography

In thermography a radiometrically calibrated infra-red detector is used to measure temperature changes in structures. It is a non-contact non-destructive technique and therefore is also an attractive proposition for monitoring tapestry degradation. Initial experiments were carried out by loading textile samples to failure and observing the specimens using a Flir infra-red camera system; these showed that close to failure significant temperature changes occurred yarn by yarn. A sample of this data is shown in Figure 5. It is clear from these images that the use of an infra-red detector in failure modelling would highlight the individual fibre fracture and aid visualistion. In Figure 6 a heat source was provided by a 40 watt lamp behind a damaged specimen. Here the thermography revealed only what could be seen by visual inspection and it was concluded that thermography is only as useful as photography in this application.

As thermography has been used in engineering to reveal hidden damage its potential role in revealing hidden damage in tapestries was investigated using layers of the representative material with seeded damage. Four layers of the representative material were used. The outer layers were intact and the two inner layers had shapes cut in them to represent gross damage; as shown in Figure 7. The upper image in Figure 7 is at room temperature and the lower is with the 40 watt lamp behind the sample. The damage is clearly revealed with the higher temperatures showing the damage sites. Although the heating of historic textiles with lamps may cause some degradation, limited exposure with low power bulbs could provide an excellent means of locating hidden damage.

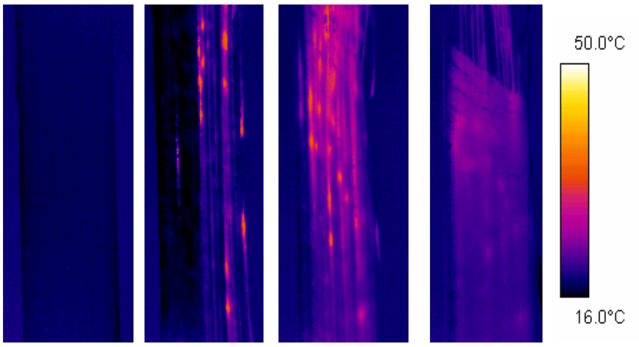

Figure 5 Heating of yarns at failure

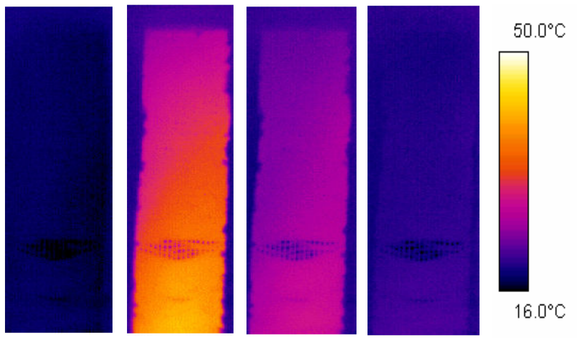

Figure 6 Heat source to reveal damage

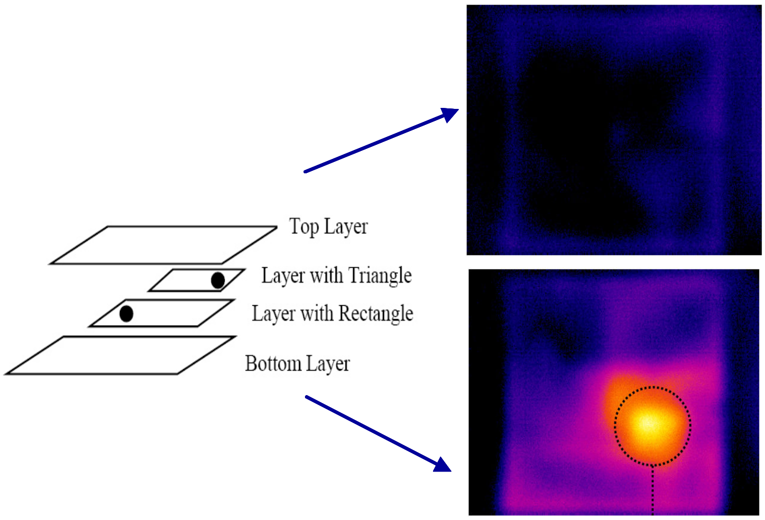

Figure 7 Seeded damage

Closure

The work described in this paper has allowed the authors to assess the feasibility of using engineering techniques for damage assessment of historic tapestries. The main conclusion from the feasibility study is that a hybrid approach is required that combines measurements from reference sensors (optical fibres) integrated with long-term full-field assessment using 3D photogrammetry and digital image correlation. The reference sensors will allow accurate repositioning of the photogrammetry cameras. A further facet to the work will be an assessment of textile failure behaviour and it is planned to use infra-red thermography to aid the failure assessment. The overall goal of the programme is to provide a means for non engineering specialists to visualise the damage in tapestries and to provide a means of predicting failure. The work formed the basis of a successful application to the UK Arts and Humanities Research Council for a research project that commenced on the 1st January 2007.

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