SCIENTIFIC RESEARCH

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STRAIN MONITORING OF TAPESTRIES: RESULTS OF A THREE-YEAR RESEARCH PROJECT

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ABSTRACT

The outcomes of an interdisciplinary research project between conservators and engineers investigating the strain experienced by different areas of a tapestry are described. Two techniques were used: full-field monitoring using digital image correlation (DIC) and point measurements using optical fibre sensors. Results showed that it is possible to quantify the global strain across a discrete area of a tapestry using DIC; optical fibre and other sensors were used to validate the DIC. Strain maps created by the DIC depict areas of high and low strain and can be overlaid on images of the tapestry, creating a useful visual tool for conservators, custodians and the general public. DIC identifies areas of high strain not obvious to the naked eye. The equipment can be used in situ in a historic house. In addition, the work demonstrated the close relationship between relative humidity and strain.

RÉSUMÉ

Les résultats d'un projet de recherche interdisciplinaire entre restaurateurs et ingénieurs ayant étudié la contrainte subie par différentes zones d'une tapisserie sont décrits. Deux techniques ont été utilisées : une surveillance globale par corrélation d'images numériques (CIN), et des mesures ponctuelles avec des capteurs de fibre optique. Les résultats ont montré qu'il est possible de quantifier la contrainte globale sur une petite zone d'une tapisserie par corrélation d'images numériques ; de la fibre optique et autres capteurs ont été utilisés pour valider la CIN. Une carte des contraintes créée par la CIN décrit les zones de forte et faible contrainte et peut être superposée sur des images de la tapisserie, créant un outil visuel utile pour les restaura-

PROJECT AIMS AND OBJECTIVES

A three-year interdisciplinary research project between conservators and engineers at the University of Southampton aimed to investigate the strain experienced by different areas of a tapestry (2007–2010). The research was funded by the UK's Arts and Humanities Research Council.[1] It aimed to enhance the long-term preservation of tapestries by developing well-established engineering techniques to monitor the mechanical behaviour of tapestries in terms of the strain developed within them, simply and unobtrusively, in situ. Strain, a measure of the percentage deformation of a material, is assumed to lead to damage in the long term.

The research questioned if the strain imposed on different areas of a tapestry can be quantified, and whether it is possible to identify incipient damage before it is visible to the naked eye. It also asked if the data could be presented in a form that is accessible to conservators and curators to aid informed decision-making. The project objectives were to develop two techniques which an earlier pilot project had identified as the most promising for use on historic tapestries. These were firstly, a full-field, strain measurement technique based on a 3D photogrammetry technique, known as digital image correlation (DIC); and secondly, optical fibre sensors to obtain point measurements of strain. The final objective was to combine the two techniques into a hybrid system and use it to monitor tapestry samples in the laboratory, a newly woven tapestry and a historic tapestry in situ in a historic house. Lennard et al. (2008) gives further details of the context of the project, the pilot study and the techniques of optical fibre sensing and digital image correlation. More images and PDF files of interim publications can be found on the project's website: http://tapestry-strain.org.uk.

RESULTS

Digital image correlation

Series of tests were conducted on aluminium coupons using different strain monitoring sensors, including the optical fibre sensors (see below), to validate the results from the DIC. Further work on representative wool fabric samples demonstrated the viability of the DIC technique for strain measurement on tapestry-like materials.

teurs, les conservateurs et le grand public. La CIN identifie des zones de forte contrainte qui ne sont pas évidentes à l'œil nul. Le matériel peut être utilisé sur place dans une demeure historique. De plus, ce travail a démontré l'étroite relation entre l'humidité relative et la contrainte.

RESUMEN

Se describen los resultados de un proyecto de investigación interdisciplinario entre conservadores e ingenieros que investigan la tensión experimentada en diferentes zonas de una tapicería. Se utilizaron dos técnicas: un seguimiento de campo completo con correlación digital de imágenes (DIC, en sus siglas en inglés) y mediciones puntuales con sensores de fibra óptica. Los resultados mostraron que es posible cuantificar la tensión global en una pequeña zona de la tapicería por medio de la DIC. Para validar la DIC se utilizaron la fibra óptica y otros sensores. Los mapas de tensión creados por la DIC representan las zonas de tensión alta y baja y se pueden sobreponer sobre imágenes de la tapicería creando una herramienta visual útil para los conservadores, los custodios y el gran público. La DIC identifica zonas de tensión elevada que no son evidentes a simple vista. El equipo se puede utilizar in situ en una casa histórica. Además, el trabajo demostró la estrecha relación entre la humedad relativa y la tensión.

The DIC system used in the work employed two white light high-resolution (2-megapixel) cameras to obtain images from the objects under investigation. The software system brings the images from each camera together and allows 3D deformations to be established. The image correlation software tracks changes in the images and allows the change in strain to be determined image by image. The team worked with the manufacturer, LaVision, to refine the software processing methods and to improve the accuracy of results for this novel application of the technology to tapestries. To obtain the strain it is necessary to divide the images into interrogation cells; the choice of cell size is a compromise between spatial resolution and strain resolution. Replacing the 2-megapixel CCD cameras with 5-megapixel cameras improved the strain resolution. The new cameras also aided the development of an algorithm to allow the camera set-up to be changed between pairs of images; this is called the map function. This allows the equipment to be moved between images, and so to be used periodically, in situ. Further tests showed that the tapestry weave provided sufficient surface detail for the DIC to use in registering images taken at different times – no other marking technique was necessary. An advantage of the DIC technique is that the results are computed to provide strain maps clearly showing areas of high and low strain (Figure 1).

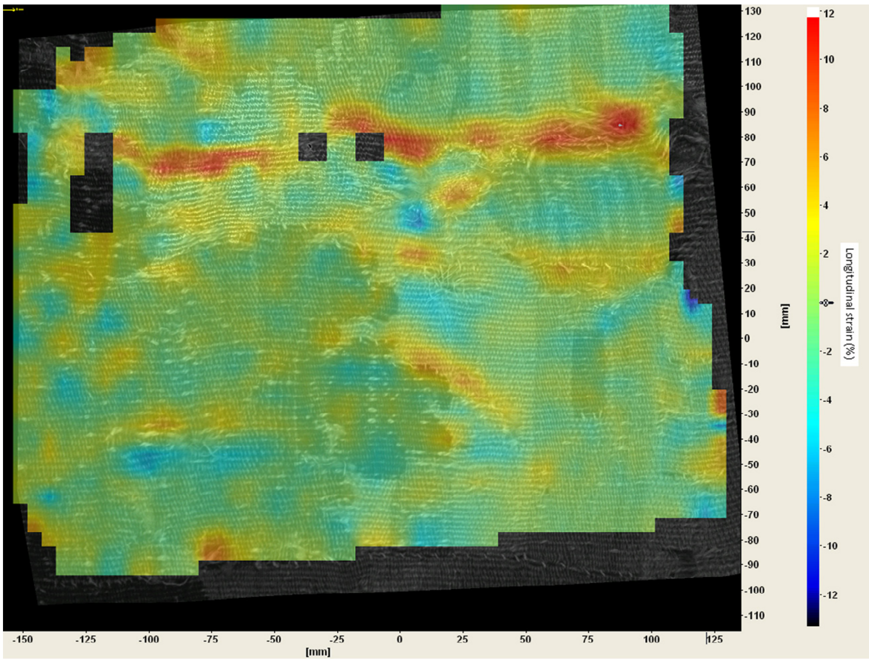


Figure 1

A strain map overlaid on an image of an area of a tapestry. The map clearly shows areas of high strain, in red, graduating to areas of low strain, shown in blue

Optical fibre sensors

Initial work also aimed to validate data from the optical fibre sensors. Different types of strain monitoring sensor, an extensometer and strain gauges, were tested alongside the Fibre Bragg Grating optical fibre sensors (FBGs), initially on aluminium coupons then on representative wool fabric. Although there was a 9-10% deviation between the FBG and the other techniques, it was demonstrated that the results from the FBGs could be successfully correlated against the other results. This confirmed that the optical fibre sensors had the potential to validate the non-invasive DIC technique, whereas it is not possible to attach strain gauges to a tapestry without reinforcing it and affecting the strain readings.

Both silica and polymer optical fibres (POFs) were trialled. Dr David Webb at Aston University contributed expertise on the novel technology of polymer optical fibre sensing. Although polymer optical fibre sensors are not yet commercially available, POFs appear to have more long-term potential for use with tapestries as they are less stiff and more elastic, with a Young's Modulus in a similar range to wool. Oddy tests and light and thermal ageing tests demonstrated that all silica and polymer fibres tested are safe to use with tapestries.

Tests on the best method of attachment to the tapestry focused on bonding, as this proved the most promising in terms of strain transfer, although optical fibres were also woven into a new tapestry (see below). Tests on a range of adhesives ultimately concentrated on two types: an epoxy resin, Araldite 2015, and a poly(vinyl acetate) adhesive used in textile conservation, Mowilith DMC2. The POFs showed a good strain transfer coefficient whether bonded with Araldite (0.93) or with PVA (0.90) (Ye et al. 2009). The conservation adhesive was more sensitive to changes in temperature and relative humidity (RH). Silica optical fibres were bonded to the new tapestry as part of the testing process. Although there would be obvious reluctance to bond optical fibres to a historic tapestry, the small amount of resulting damage would need to be weighed against the information gained.

One conclusion from the work is that optical fibre sensors are an easy-to-install strain measurement technique requiring very little equipment. It could be possible to use them routinely for continuous strain measurement of tapestries and other artefacts.

Hybrid methodology

The previous experiments exposed the representative textile material to increasing load over a short period of time. Longer tests were then conducted, over 48 hours. If a constant stress is applied to a material at certain temperature and humidity conditions over a long period of time, it may experience creep strain. This type of deformation is considered to be common in tapestries because of their relatively large size and heavy weight, and the determination of creep properties in tapestries was one of the key challenges of this study. All tests incorporated monitoring of temperature and RH. They aimed to correlate strain with temperature and RH fluctuations, in order to separate out the possible underlying movement caused by creep strain.

Subsequently, the techniques were trialled on wool tapestry woven strips commissioned from West Dean Tapestry Studio, using a purpose-built test rig. The DIC highlighted areas of strain surrounding slits in the tapestry (Figure 2). It also showed high strain in spots which appeared to correlate with discontinuities in the weft yarns only visible on the reverse of the tapestry (Williams et al. 2010), demonstrating the ability of DIC to show strains not evident to the naked eye.

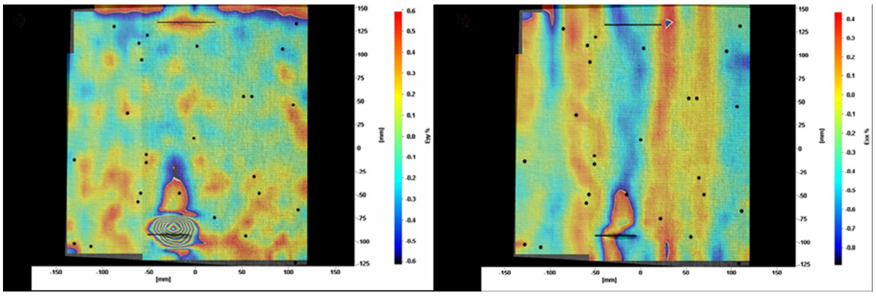
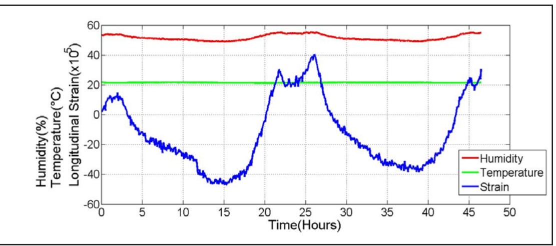


Figure 2
The strain map on the left shows the longitudinal strain surrounding a stitched slit at the top, and the greater strain surrounding an unstitched slit at the bottom of the tapestry panel. The strain map on the right shows transverse strain, i.e., from side to side



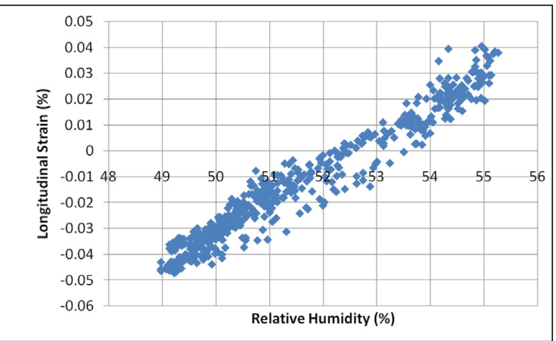


Figure 3
This plot shows that even small variations in RH had a strong effect on the strain readings during a 48 hour test on the Verdure tapestry – the day and night cycle is very apparent

Figure 4
This plot shows the information in Figure 3 in a different format – the data points show individual images captured over time by the cameras. The strain is positive above 52% RH, whereas the tapestry experiences negative strain as the RH falls below 52% RH

Testing then moved onto 48-hour tests on actual tapestries, including a fragment of Verdure tapestry from the reference collection of the Textile Conservation Centre (TCC), in the climate-controlled TCC building (Khennouf et al. 2010). DIC was used to monitor strain in a 120 mm × 90 mm area at the centre of the tapestry. A digital temperature and humidity logger was used to monitor changes in temperature and RH during the experiment. As well as showing relative areas of high and low strain, the DIC was also capable of providing quantitative measurements of the global strains across the area – this proved to be in the region of 0.1%. Local strains are likely to be higher, but these data were more difficult to interpret as they contained more noise, i.e., a wider scatter of data points.

Relationship between strain and relative humidity

The strain and environmental data were plotted against time (Figure 3) and it was very clear that even the small changes in humidity recorded had a strong effect on the strain – as RH increased, the tapestry deformed and the strain increased. This is presumably caused by a gain in weight, and also perhaps by slippage within the fibres and yarns as the moisture content of the tapestry increases. As the RH decreased, the tapestry contracted, showing a negative strain reading. Plotting longitudinal strain against RH, using the same data, demonstrates that the relationship is practically linear (Figure 4). The cycling demonstrated in Figure 3 represents repeated expansion and contraction of the textile and may lead to the type of fatigue damage familiar to engineers from other contexts. Textile conservators would not be surprised to find that repeated RH fluctuations may be more damaging to tapestries than the sheer load imposed by their own weight. In order to try to replicate the effect of repeated RH fluctuations, accelerated strain cycling tests were carried out. The representative wool textile was subjected to cycles of increasing and decreasing strain at high frequency. The mechanical properties of the fabric were measured before and after loading, using quasi-static tests with the DIC to create stress-strain plots. It was found that the repeated loading of the textile samples, through 36,000 cycles, affected the stress-strain curve of the material – it became more brittle (Figure 5). This is believed to be a result of the fibres lining up in the direction of the load and increasing crystallinity within the fibres. While this is not the same deterioration mechanism that would be caused by fluctuations in RH over a longer period, it is interesting that the textile properties were demonstrably affected by these mechanical stresses. Although these tests were necessarily brief, the results merit further investigation.

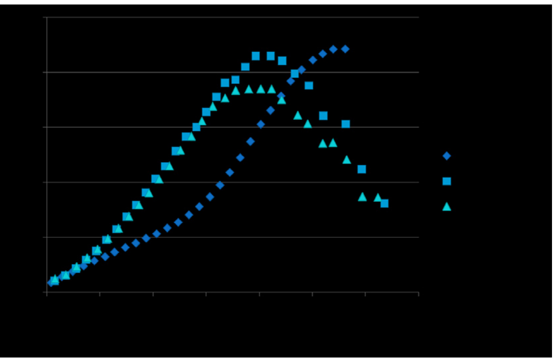


Figure 5
The stress-strain curve of the wool fabric has changed after repeated loading – it has become a more brittle material

Data were compiled from five DIC tests on three different tapestries: a 16th-century armorial tapestry,[2] the Verdure fragment and a new, specially commissioned tapestry (see below). The majority showed strain cycling from positive to negative in response to RH fluctuations. Two tests showed solely negative strain; the cause of this is unknown, but it is suspected that storage prior to hanging the tapestry may have had an effect. Further tests showed that the strain was higher for 48 hours if the tapestry had been unrolled and hung immediately before testing, i.e., its own weight caused initial deformation. This effect was absent if the tapestry had been hanging for a period before monitoring began.

Each tapestry produced a signature slope when strain was plotted in the longitudinal direction against RH in the transverse direction, indicating a unique response to changes in the environment in terms of its material structure (Figure 6). The different results may be caused by variable factors, such as the fineness of the weave and the proportions of wool and silk. Repeated monitoring of the Verdure tapestry resulted in different slopes; the

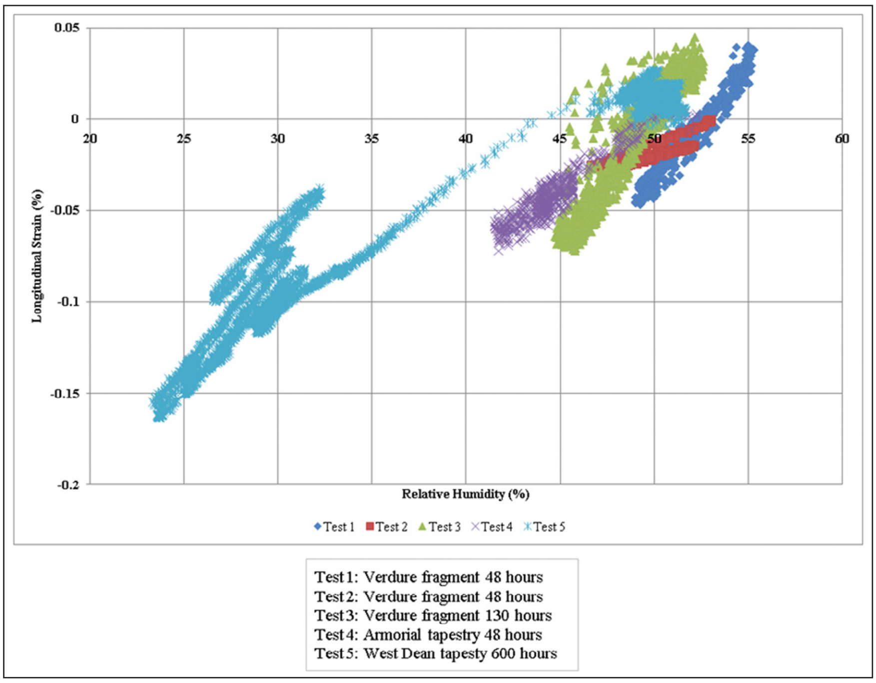


Figure 6
Longitudinal strain plotted against relative humidity results in a different slope for each tapestry. The three tests on the Verdure tapestry (tests 1, 2 and 3) also gave different slopes

strain behaviour is dependent on changes in RH and, as mentioned above, perhaps also on the way the tapestry had been stored before monitoring. The new tapestry showed a much greater increase in strain than the others. It is presumed that it gains more weight with increasing RH as its mass per m^2 is much greater, so it can hold more moisture. New wool also absorbs more moisture than aged wool fibres.

New tapestry

Figure 7
The new tapestry on display at Intech Interactive Science Centre

Figure 8
DIC equipment in the Green Velvet Bedroom at Hardwick House

The one metre-square tapestry was woven at West Dean Tapestry Studio for the penultimate stage of the project. It was designed by Rosalie Woods and Charlotte Agius, students from the University of Southampton's Winchester School of Art, and was inspired by the colours of medieval tapestries. It was constructed using traditional materials, wool and silk, and traditional techniques as far as possible. The design incorporates the formula for stress and the words 'diffuses' and 'reflects', in reference to the optical techniques used for the monitoring.

A silica optical fibre containing two FBG sensors was woven into the tapestry. Two arrays of five FBGs each were bonded to the back of the tapestry, one using Araldite, one using the PVA adhesive. The tapestry was monitored for three weeks from its first hanging, in climate controlled conditions at the TCC, using both DIC and optical fibres. The tapestry was displayed at Intech Science Centre near Winchester for 14 months from May 2009, funded by the Institute of Physics Public Engagement Grant Scheme. Monitoring was carried out in situ during the initial period. Information about the project was displayed next to it and the 'technological tapestry' proved a popular exhibit (Figure 7).

Monitoring demonstrated how strain fluctuated in response to the major fluctuations of temperature and humidity in the uncontrolled environment of the centre. There was little underlying movement caused by creep during this time period, although there was some initial deformation when the tapestry was first hung. Only one of the sensors on the optical fibre that had been woven into the tapestry still worked – this sensor was not able to transfer the strain as accurately as the sensors bonded to the tapestry.

Monitoring in a historic house

The final stage of monitoring took place in summer 2009 at Hardwick Hall, a National Trust property. The 2-megapixel cameras were used here as the data processing and transfer from the 5-megapixel cameras was computationally expensive, and bandwidth for data transfer at Hardwick Hall was limited. As it was therefore not possible to use the algorithms that enable the cameras to be moved, the DIC equipment was installed temporarily in front of a 16th-century Flemish tapestry (Figure 8). This provided an opportunity to disseminate information about the project to the public.

The major challenge was to gather the data generated by the DIC from Hardwick, a property without a broadband signal. To cope with the large quantity of data generated, a continuous monitoring system was developed whereby each image was processed, then sent to a computer at the university where surface height and strain map were calculated, before being processed by Matlab software to plot strain, RH and temperature against time. The images were transmitted from Hardwick to the university via a temporary modem and the challenges of gathering the data remotely were successfully overcome.

Strain data were recovered for the tapestry. The results were affected by the variability of the light source. A brighter light, used for the first 14 days, gave more precise results. Conservation protocols dictated that a lower intensity light was used for the remaining time; this produced results with more noise. The natural light also fluctuated – it would be useful to correlate the data with light readings, as well as with temperature and RH readings in future work. The DIC technique requires image contrast to work; lighting is essential to enhance the natural contrast in the tapestries. The high intensity lighting used here would not be necessary for periodic in situ monitoring where the map function would be employed. This trial demonstrated that the DIC system could be used successfully on site, in a novel use of this technology which routinely uses fixed equipment.

CONCLUSIONS

The project successfully achieved its overall aims and objectives and enabled the research questions to be answered. It proved possible to quantify the global strain in at least an individual area of a tapestry, although it is not yet possible to map a tapestry in its entirety. DIC has been validated by measurements from the optical fibre sensors and other strain sensing techniques. It generates colourful strain maps, clearly identifying areas of high and low strain. These can be superimposed on images of the tapestry, providing an extremely useful tool for conservators and custodians in demonstrating the changes experienced by tapestries. In addition, DIC has been shown to pick up areas of strain that are not visible to the naked eye, indicating that monitoring a tapestry in this way would identify areas at risk of imminent damage not apparent during visual assessment. Challenges were successfully overcome to be able to use the equipment in situ in a historic house. The project has successfully developed the technique of DIC for this new application and has created a good working relationship with the equipment manufacturer.

The work clearly demonstrated that there is a direct relationship between strain and humidity. The experiments showed that even small variations in RH can lead to considerable positive to negative strain cycling. It is clear that strain increases as RH rises, perhaps because the tapestry gains weight as it absorbs more moisture. Different results were obtained from monitoring the new tapestry and historic tapestries, perhaps caused by the difference in mass, and the different material properties of new and aged wool. Tapestries have proved to be a good case study for this investigation as they deform markedly with changes in RH.

In practical terms, the research appears to underline the importance of maintaining a steady RH for organic materials and shows that there may be issues of adding extra weight to textiles, in linings for example. It will be possible to compare the effects of different tapestry conservation techniques using these techniques, and also to monitor artefacts made from other materials.

The research began with a question – are tapestries being pulled apart by their own weight? It is clear that there is a complex relationship between creep, the permanent deformation to a tapestry caused by hanging, and the damage caused by fatigue, or the constant expansion and contraction of fibres and yarns caused by fluctuations in RH. This research has demonstrated that it is possible to quantify the strain and to gain a better understanding of the mechanisms causing damage. The information can be used to produce constitutive laws for tapestry behaviour; these, in turn, could be used to provide a model by which it would be possible to predict strain from RH data.

NOTES

[1] AHRC Research Grant award AH/D001404/1.

[2] The tapestry belongs to the Burrell Collection, Glasgow Museums, and was treated at the TCC prior to being displayed at Kenilworth Castle for English Heritage.

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