Investigating Tapestry Conservation and Display with Digital Image Correlation

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Introduction

A long-term research project in the UK, initially based at the University of Southampton and then at the University of Glasgow, has investigated physical aspects of tapestry degradation and conservation. Initial investigation by the Textile Conservation Centre and the School of Engineering at Southampton considered the techniques used by engineers to monitor structures, to see if they could be useful for assessing the condition of tapestries (Dulieu-Barton *et al.* 2005). This pilot study indicated that three-dimensional digital image correlation (3D DIC) would be a useful technique, and this was trialled in a three-year project funded by the UK Arts and Humanities Research Council[1].

3D DIC is a non-contact monitoring method which takes simultaneous images with two cameras to provide information on out-of-plane deformation. It then compares successive pairs of images over time to measure displacement within the tapestry. The computer software translates this into strain, a measure of percentage deformation (the change in length compared with the original length). We thought it is fair to assume that, in a historic tapestry, damage is likely to happen first in areas of relatively high localised strain. The project demonstrated that DIC gives both quantitative and qualitative information – it also creates strain maps - though at that point we could only record data from a small area. Further information on the project methods and outcomes can be found at Lennard *et al*. (2011) and Lennard and Dulieu-Barton (2014), and on the project website at http://www.tapestry-strain.org.uk/

More recently the DIC technique has been employed as a tool to investigate the conservation treatment of tapestries in a new project funded by the Leverhulme Trust, a collaboration between the Centre for Textile Conservation and Technical Art History (CTCTAH) and the School of Engineering at the University of Glasgow[2]. This allowed us to use the strain monitoring methodology to examine conservation stitching techniques and display methods, particularly the use of slanted supports. This paper reports on the more recent work in Glasgow.

DIC Set Up

Before implementing the DIC as our monitoring technique, we needed to be sure that we could trust the results it gives us. The complex structure of tapestry presents a challenge when interpreting its behaviour: tapestries are heterogeneous, meaning they don’t have the same properties throughout. They are made of various materials, the weave structure is discontinuous, and the warp and weft yarns have different properties, with the warp yarns being more tightly twisted. Material degradation over centuries and previous treatments also contribute to the complexity of the structure.

DIC works by breaking the overall image down into small areas or subsets – a subset is a group of pixels. As the tapestry stretches and deforms, the DIC algorithm compares the position of each of these subsets from the first reference image to the subsequent images taken over time. To do this successfully each subset has to be unique and identifiable so that the camera can recognise it after it has moved. This is usually achieved by applying a random speckle pattern to the substrate to be monitored, helping the cameras to register and track displacement. We obviously cannot do this with a historic tapestry so the project's researchers, Dr Jafar Alsayednoor and Dr Kenneth Nwanoro, looked at whether the tapestry design itself can be used in lieu of a speckle pattern.

The researchers found that some features can cause problems, especially where the colour changes abruptly from light to dark, and in large areas of similar coloured yarn. A computational tool designed to assess the error in DIC strain measurements for a given tapestry image under arbitrary applied strain fields was developed by the researchers to better evaluate the use of DIC for a given tapestry (Alsayednoor *et al.* 2019).

Another challenge is determining the appropriate subset size for a tapestry. The DIC averages strain information across the subset – if it averages across too large an area, spikes in the data are smoothed out and information is lost. The average figure is more accurate with a smaller subset size, but if this is too small, there is a risk that the subsets all become too similar to each other and then the DIC has difficulty correlating the images. Finding a balance is critical in obtaining good strain information and this might be different for different tapestries (Alsayednoor *et al*. 2019).

The 3D DIC system combines images from two cameras but the project also investigated the use of 2D DIC with a single camera for strain monitoring. It is more straightforward to use one camera, which can be sited in a historic building more discreetly than a dual camera system and is much less expensive. A long-term trial using one camera to monitor a newly woven Unicorn tapestry at Stirling Castle (with Historic Environment Scotland) demonstrated that monitoring can be successful if the tapestry hangs flat against a wall and movement is minimal. But we have found that accurate strain data can only be obtained from one camera if the tapestry is flat. If the surface is undulating, as in many historic tapestries, it is necessary to use two cameras in a 3D system to register the out of plane deformation and calculate the strain (Alsayednoor *et al.* 2017).

Trial Strain Monitoring of Historic Tapestry

Costantini tested the DIC monitoring technique on a fragment of historic tapestry measuring 1600mm high x 400mm wide (Costantini et al.2020). The fragment, from the Karen Finch Reference Collection at the CTCTAH, was in weak condition with several open slits. It was suspended from a vertical board to prevent out of plane movement and monitored for 200 hours with a single camera. Strain data were calculated to provide both the average strain across the whole fragment – the global strain – and the local strains in the area of the slits; both evolved over the course of the trial. The maximum global strain, in the longitudinal direction, was around 0.2%.

The slits gradually opened over the 200 hours and these areas showed as red areas of high strain on the strain map (Figure 1). It is important to note, however, that the software interpolates strain calculations across small holes in the tapestry (there is no material strain where there is no fabric) so these were denoted as areas of pseudo-strain. Nonetheless, the strain map gives a clear picture of areas of concern to a conservator.

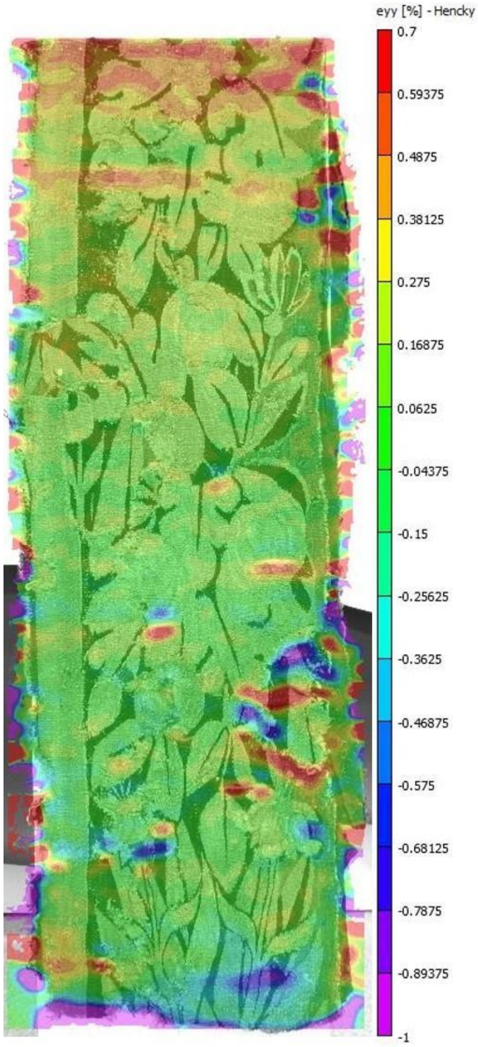


Figure 1. Strain map of the tapestry fragment after 200 hours of monitoring. The red areas show where slits and other weak areas opened up. The DIC cannot measure strain across holes, where there is no fabric, so these areas were interpreted as areas of 'pseudo-strain' © University of Glasgow

As it was not possible to carry out tests in a controlled environment, the relative humidity (RH) fluctuated over the course of the test. There was an extremely strong correlation between RH and strain data as had been demonstrated during the Southampton project. This is believed to be caused primarily by an increase in moisture absorption with rising RH, leading to an increase in weight of the tapestry. However, the mechanism is complex, and the swelling of fibres also plays a role; global strains (strain calculations averaged across the entire measurement area) in the horizontal direction were also correlated with RH but to a lesser extent. This correlation gave additional confidence in the results, showing us that we could trust the globally averaged DIC strain data.

This test confirmed University of Southampton results demonstrating that fatigue - repeated expansion and compression caused by fluctuating RH - is likely to be an influential mechanism causing damage to tapestries in the long term, a significant factor if the environment is not able to be controlled. However, creep, or permanent deformation, is also likely to occur, particularly in damaged areas, and in the weeks after the tapestry is first hung (Costantini *et al*. 2020). Having carried out these tests, we were confident that the 2D DIC was giving us accurate results, and on larger areas of a tapestry than previously achieved.

3D DIC was also trialled by the project team to monitor a complete tapestry, before and after conservation treatment, in collaboration with the textile conservators at the Burrell Collection, Glasgow Museums. However it was apparent that direct comparisons could not be made between the strain maps from before and after treatment; these were effectively two different tests, and any changes in strain shown could have been attributed to different hanging conditions, rather than to changes in condition relating to conservation.

Display of Tapestry on a Slanted Support

The display of tapestry on a slanted support has become more common in recent decades, particularly in mainland Europe, following the practice of the textile conservator, André Brutillot (Wild and Brutillot 2006). Tapestries are often displayed at an angle of 5° from the vertical, with a textured fabric covering the board to increase friction between the board and the tapestry. Our research set out to investigate the contribution of these two factors: the angle and the board covering.

As previously demonstrated by Barker (2002), it is simple to calculate the reduction in strain caused by increasing the angle of support and lessening the effect of gravity, though her article did not include the influence of friction between the tapestry and the supporting board. Costantini *et al*. (2020) extended the analysis to include the influence of friction. If there is little friction between the support and the tapestry, as on an uncovered board, it can be demonstrated that there is a negligible decrease in load when the angle of the support is reduced from vertical to 5° from the vertical. As the angle increases to 45°, the reduction in load is more significant, around 30%. But increasing friction between the support and the tapestry has a considerable impact; with a high coefficient of friction of 1.5, there is a reduction in load of around 15% with a display angle of 5°. Next trials were conducted using new wool rep fabric[3], suspended at different angles against a solid board. 2D DIC was used to record the reduction in strain caused by increasing the angle of support.

Further tests were carried out to compare the friction between small tapestry fragments and a range of fabrics commonly used to cover slanted supports: cotton domette, cotton molton (or molleton, a domette-style fabric used in mainland Europe), polyester felt and cotton velvet (reported in Lennard *et al*. 2020).

Friction tests were conducted using a simple inclined plane method. A board was covered with the fabric and the tapestry fragment placed on it, then the board was slowly raised from horizontal until the tapestry began to slip, measuring the inclination with a smartphone app, Multi Clinometer. It was found that, with all fabrics, the friction was so great that the board could be raised from horizontal to vertical, and then tilted beyond vertical, so that the tapestry fragment was beginning to face the floor (around 100° from horizontal) before the tapestry began to slip. This made it impossible to calculate a value for the coefficient of friction, and it was apparent that the simple Coulomb model of friction does not apply in these cases. It is clear that additional forces are having an effect; it appears that mechanical interlocking between the fibres of the tapestry and the fabric covering generates an effective 'mechanical adhesion' between the fabric surfaces.

Electrostatic adhesion may also play a role. Weighting the tapestry samples confirmed this observation; when weighted, the tapestry samples slipped before the board passed vertical, so it was possible to calculate the coefficient of friction. This confirmed that the coefficient of friction for these textiles was influenced by the normal load and that they were not experiencing Coulomb type friction, where the coefficient is independent of the normal load.

The effect of friction/adhesion appeared so great that we hypothesised that it would be effective on a vertical surface, with no slant (with the tapestry suspended from the top edge). DIC monitoring of the CTCTAH tapestry fragment mentioned above was carried out to replicate a more realistic display situation and to test this hypothesis. The fragment was suspended with one half in direct contact with the board; a layer of molton fabric was used to cover the board beneath the other half (Figure 2).

Figure 2 (left). The tapestry fragment was suspended from a vertical board. The left half was in direct contact with the board. The board was covered with cotton molton beneath the right half of the tapestry © University of Glasgow

The tapestry was monitored for 340 hours. At the highest recorded RH of 58%, the strain value was very low (a maximum of around 0.01%) in the area with molton, compared with a maximum of almost 0.05% in the area without the molton board covering (Figure 3).

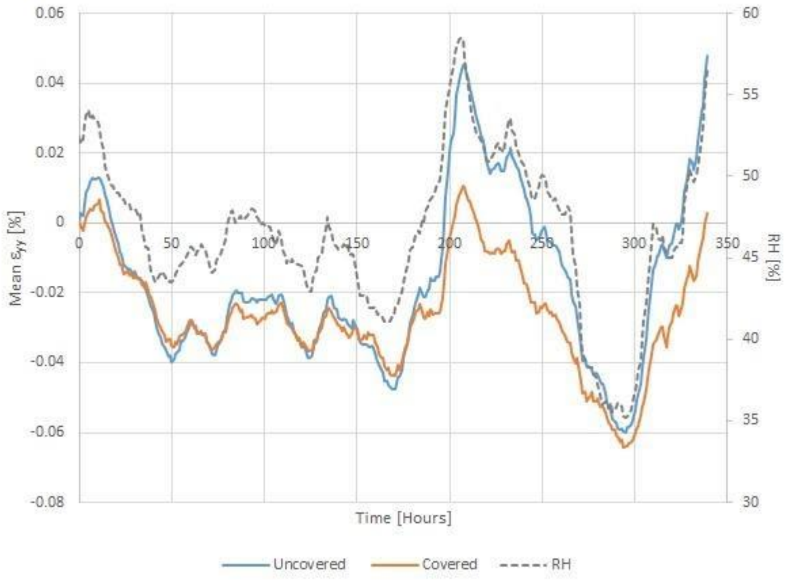


Figure 3 (right). The left side of the tapestry, in direct contact with the board, recorded a higher strain (0.05%) than the right side of the tapestry, against the molton fabric, (0.01%) at the maximum RH of 58%. The board covering conferred greater support to the tapestry and reduced expansion and contraction caused by RH fluctuations © University of Glasgow

While the tapestry on the uncovered board was also supported to some degree, the part of the tapestry on the covered section of the board was less affected by fluctuations in RH than the tapestry on the uncovered board, indicating that the molton board cover had a stabilising effect, reducing expansion and contraction of the tapestry. Although only one test was carried out and there is no statistical certainty, these results indicated that the molton board covering conferred additional support to the tapestry without using a slanted support. Further details of the tests and the results are given in Lennard et al (2020).

Stitched Support

In the UK it is more common to support tapestries by stitching them onto linen fabric so that they can continue to hang on display. A technique developed in the 1960s uses stitching to give structural support and to restore the tapestry image simultaneously (Bosworth and Clark 2006). Little has been published to date on the effectiveness of stitching techniques for tapestry, though a valuable exception is the trial at Historic Royal Palaces in the UK reported by Asai *et al.* (2008).

Our research team was keen to employ the DIC monitoring technique to investigate the effectiveness of different stitching methods used to attach the tapestry to the linen fabric - support lines of running stitches, brick couching and laid couching - and we compared the effectiveness of full and patched supports. It was proposed that a successful stitched support would allow the tapestry to expand and contract with fluctuations in RH, but would prevent weak and damaged areas from opening up under the tapestry's weight. The resource-intensive nature of a full stitched support system was also recognised; the research team repeated the questions asked by Asai *et al.*: "Was this the most efficient use of treatment time? … was there enough support stitching, or too much?” (Asai *et al*. 2008: 968). Full details of this investigation will be published; an outline is given here.

The main tests were carried out using the new wool rep fabric to model the tapestry; previous work had shown that the warp and weft have similar properties to tapestry weft and warp yarns respectively (Khennouf et al. 2010). It was not possible to use historic tapestry samples for comparative tests, as their weave structure and condition would have been too variable, while resources did not allow the weaving of new tapestry samples. The samples were artificially damaged to simulate an area of weft loss in a tapestry; rows of brick couching and/or laid couching were worked across the bare warps. In some cases a grid of running stitch support lines was added. The stitching was worked through washed linen scrim fabric with two threads from a stranded cotton yarn for the couching, and Gutermann M403 polyester yarn for the grid lines. The samples were suspended vertically from the upper edge, with the ‘warp’ yarns running horizontally, for 168 hours and monitored with 2D DIC. Strain graphs and strain maps were prepared following the tests and gave information on the deformation and the strain (percentage deformation) experienced globally, by the sample overall, and locally, across the area of damage.

It should be noted that the findings discussed here are based on very small numbers of samples (due to the time taken to carry out the conservation stitching) and do not have statistical validity. Nevertheless we considered them of interest. The main conclusions were that all forms of stitching greatly reduced the strain across damaged areas, in comparison with the damaged, untreated samples which were used as controls – that is, there was less extension in the damaged areas after they had been supported. A grid of stitching alone conferred noticeable support, particularly when the support lines passed directly through areas of damage, in comparison with a grid fitted around areas of damage. Adding more intensive couching to damaged areas reduced the local pseudo-strain further.

In general, as would be expected, the greater the density of stitching across damaged areas, the lower the local pseudo-strain, that is the stitching reduces the opening up of damaged areas. However, it was observed that the most dense stitching (rows of laid or brick couching 8mm and 4mm apart) reduced the local pseudo-strain to a lower level than the overall global strain across the whole sample. In contrast, brick or laid couching at16mm spacing resulted in a stitched support where the global and local strains were very similar.

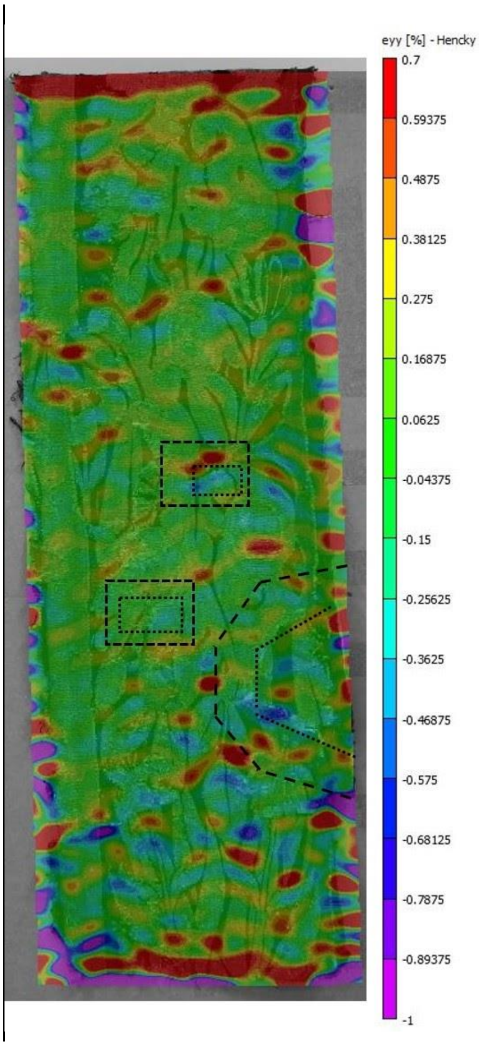
This was interpreted to mean that with 16mm spacing, the properties of the rep in the damaged area were similar to those in the rest of the fabric, and therefore that this level of stitching was optimal in this situation (though of course these results would need to be re-interpreted in the context of a historic tapestry). Interestingly laid couching appeared to reduce extension to a slightly greater degree than brick couching when they were directly compared – it was more restrictive of movement. Although again there were few samples to compare, this result was found in each test which investigated the two stitching techniques. This could mean that brick couching is better able to accommodate the tapestry’s expansion and contraction with RH fluctuations.

When patched and full supports were compared, it was concluded that a patch gives good support if the 'tapestry' is damaged in a discrete area but is basically sound in the surrounding area. If the tapestry is damaged overall, a full support provides better support for weak areas. Strain was noticeably lower in a damaged region if it was encompassed within an overall support structure, even if it was not itself stitched to the support fabric. This is intuitively understood and probably reflects current practice by conservators.

Figure 4. Support patches on the reverse of the tapestry fragment, showing the location and spacing of brick couching. The spacing did not appear to affect the strain data © University of Glasgow

A final stage of the testing used the same CTCTAH tapestry fragment to investigate whether the findings from the model rep samples were replicated on tapestry weave; this was found to be the case. The fragment was treated by stitching in two stages: firstly by applying three patches of linen fabric to the back, securing damaged areas with brick couching (Figure 4), and secondly by giving this area an overall support of linen using a grid of running stitch support lines.

The first stage of treatment showed that extension and strain were effectively reduced in the damaged areas that were supported. However further areas of damage between the patches were not supported and showed high strain values (Figure 5). When the additional full support was applied, strain was much lower in the damaged areas that were encompassed by the support fabric; even when they were not stitched to the support fabric directly, the linen gave noticeable support and prevented extension (Figure 6).



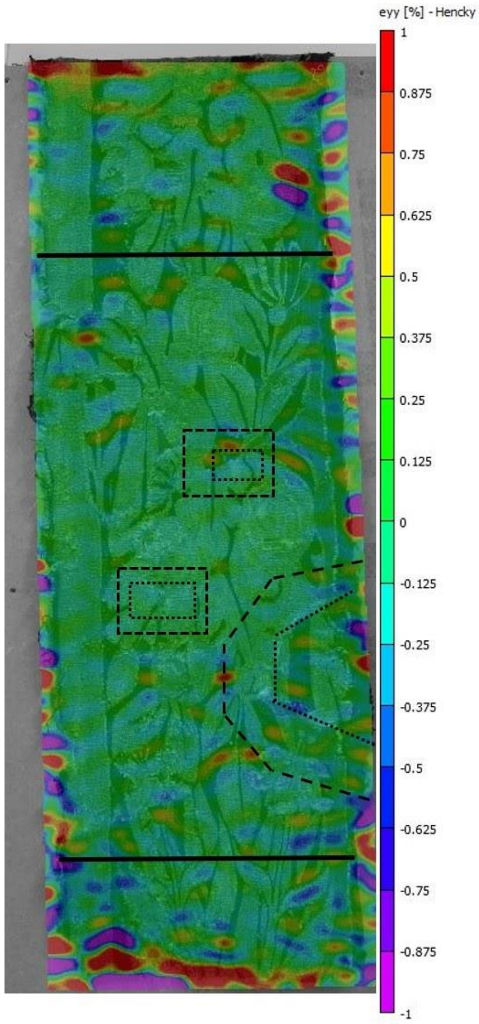


Figure 5 (left). Strain map of the tapestry fragment, showing the location of the three support patches and, within them, the areas of stitching. Strain was reduced in the supported areas but not in the damaged areas between them © University of Glasgow

Figure 6 (right) Strain map of the tapestry fragment after further monitoring with the additional full support. Strain was reduced in the areas of damage encompassed by the support, even if they were not directly stitched to it © University of Glasgow

Conclusions

It is apparent that DIC is a useful technique for assessing changes to tapestries, and other artefacts, over time. It can provide both accurate quantitative data in the form of globally averaged strain measurements, and qualitative, visual information in the form of local strain maps. It has been useful in providing information to help assess the impact of different conservation display and stitching techniques. Further investigation is needed, but the trials on the Glasgow Museums tapestry showed that the DIC technique appears better suited to long-term monitoring than to comparative modelling of two different treatment phases.

The DIC monitoring and friction tests gave useful information on tapestry display and conservation stitching techniques. Importantly the measurements are in agreement with theoretical predictions in suggesting that the role of friction/adhesion in providing support for tapestries on display is significant even when a display board is vertically positioned. Slanting the board to a small degree adds no further value, but a board covering on a vertical structure provides significant support due to the adhesive nature of the contact between tapestry and board (though we do not know whether this is reduced in the long term).

The stitching trials indicated that all support stitching confers benefit by limiting the extension in damaged areas of a tapestry, even when a damaged area is not itself stitched to the support. It appears that intensive stitching may not be necessary to confer significant support (though of course stitching is also used partly to restore the tapestry image) but it is clear that the placing of stitching is important.

The results overall bore out the intuitive understanding of tapestry conservators. Two common practices are: firstly, in mainland Europe, to apply patch supports in damaged areas, using laid couching stitching, before displaying a tapestry on a covered board; and secondly, in the UK, to provide a full stitched support onto a linen fabric using a combination of grid support lines and local brick couching, for hanging display. These practices appear to combine techniques in an appropriate manner to give good support to a tapestry on display.

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Notes

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[2] Leverhulme Trust Research Project: From the Golden Age to the Digital Age: Monitoring and Modelling Historic Tapestries: RPG-2015-179.
[3] From Context Weavers

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