Lennard, F. , Costantini, R. and Harrison, P. (2021) Understanding the role of friction and adhesion in the display of tapestries on slanted supports. *Studies in Conservation*, 66(1), pp. 32-43.
(doi: [10.1080/00393630.2020.1761184](https://doi.org/10.1080/00393630.2020.1761184))

The material cannot be used for any other purpose without further permission of the publisher and is for private use only.

There may be differences between this version and the published version. You are advised to consult the publisher's version if you wish to cite from it.

<http://eprints.gla.ac.uk/214689/>

Deposited on 28 April 2020

Enlighten – Research publications by members of the University of
Glasgow
<http://eprints.gla.ac.uk>

Understanding the Role of Friction and Adhesion in the Display of Tapestries on Slanted Supports

Frances Lennard,^a Rosa Costantini,^a Philip Harrison^b

^a Centre for Textile Conservation and Technical Art History

^b School of Engineering

University of Glasgow

Glasgow G12 8QQ

Frances Lennard: <https://orcid.org/0000-0002-4289-4685>

Rosa Costantini: <https://orcid.org/0000-0002-1591-3940>

Philip Harrison: <https://orcid.org/0000-0002-5171-6506>

Abstract

This paper reports on an investigation into slanted support, an increasingly common method of displaying tapestries in mainland Europe. Two factors contribute to the efficacy of slanted supports for tapestry: the angle of display and the degree of friction between the tapestry and the support. Initial analysis demonstrated that a small degree of slope, of 5°, has only marginal impact on reducing the load experienced by the tapestry. Experiments were carried out to compare the friction between small tapestry fragments and a range of fabrics commonly used to cover slanted supports. Lined and unlined tapestry fragments were placed on a fabric-covered board and tilted from horizontal to vertical. In most cases it was found that the board could be tilted beyond vertical before the tapestry began to slip; this meant it was not possible to calculate a coefficient of friction. It was clear that the simple Coulomb model of friction does not apply in this situation and that adhesive forces are even more significant than friction. Loading the tapestry samples demonstrated that the coefficient is dependent on load, confirming this observation. The paper also reports on the use of digital image correlation (DIC) to calculate strain data. A tapestry fragment was suspended on a vertical board half covered in cotton molton fabric. The strain values were very low on the half of the tapestry against the molton; they were higher on the half against the uncovered board. It was also apparent that the tapestry with board-covering fabric was less subject to expansion and contraction caused by fluctuating relative humidity. The research concluded that the friction/adhesion forces are so effective that a tapestry is well supported on a vertical fabric-covered board; there is no additional benefit in providing a small degree of slant.

Keywords

Tapestry display, slanted support, sloping board, friction, adhesion, digital image correlation.

Introduction

Conservation science has focused predominantly on the chemical deterioration of objects and the establishment of environmental parameters to inhibit their degradation. More recently a body of work has also begun to consider the physical response of objects to their environment. A major project at the University of Southampton in 2006-10,¹ led by Lennard, investigated mechanical aspects of tapestry conservation in contrast to previous research which had been mainly concerned with their chemical changes. The research trialled techniques used by engineers to monitor structures, to investigate their value for assessing tapestry condition. It was believed that tapestries were a useful case study as they are large and heavy and it was assumed that their own weight is a factor in their degradation (Lennard et al., 2011; Lennard and Dulieu-Barton, 2014; <http://www.tapestry-strain.org.uk/>). The project indicated that three-dimensional digital image correlation (3D DIC) is a useful monitoring technique for tapestries and other artefacts. 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 images over time to measure displacement within the tapestry. Correlation software translates this into strain, defined as the amount of deformation in the direction of the applied force (in this case the tapestry's own weight), divided by the initial length of the material. The software produces highly visual strain maps which can be overlaid on an image of a tapestry and show areas of high and low strain. We thought it fair to assume that areas of high strain are areas where damage would happen first. Strain monitoring has since been used more widely in the heritage sector with further work eg at English Heritage (Vilde et al., 2017) and Historic Royal Palaces (Máximo Rocha et al., 2018).

More recently, a Leverhulme Trust funded project, *From the Golden Age to the Digital Age: Monitoring and Modelling Historic Tapestries*, built on the University of Southampton work, fulfilling a long-term aim to apply DIC as a means of assessing tapestry conservation methods. This project, a collaboration between researchers at the Centre for Textile Conservation and Technical Art History (CTCTAH) and the School of Engineering at the University of Glasgow, developed the DIC strain monitoring methodology and used it successfully to provide quantitative data and visual strain maps of tapestry display and conservation stitching techniques, in order to inform conservation practice. This paper focuses on display; it reports on an investigation into the use of slanted supports as this is an increasingly common method of displaying tapestries in mainland Europe. Research on conservation stitching techniques was also carried out as part of the research project and is published separately.

The starting point for the research was an understanding that two factors contribute to the efficacy of slanted supports for tapestry: the angle of display and the degree of friction between the tapestry and the support. There has been virtually no investigation of these mechanisms in the conservation field despite the increasing use of slanted support to display, for example, carpets and tapestries. We began by carrying out trial strain mapping of model fabrics on slanted supports to investigate the effects of different display angles

¹ *Towards in-situ monitoring of tapestry degradation using strain-based engineering techniques* (Funded by the Arts and Humanities Research Council, AH/D001404/1, 2006-10).

and their relationship to theoretical modelling (Costantini et al., forthcoming). This paper focuses on the considerable effect of the interface between the support and the tapestry; it was found that, in addition to friction, adhesion plays a major role in providing support. The implications of the findings for textile conservation practice are considered in the final section, including the effect of mounting on a tapestry's appearance. The paper aims to draw together project findings from a textile conservation perspective, and to focus discussion on what practising conservators would find useful.

Previous work

Tapestries have traditionally been hung from their top edges – tack holes attest to former nailing, while press-stud tapes and sleeves have also been used. Contact fastener strips such as Velcro® have been used by conservators to hang tapestries since the 1970s and this is still the most frequently used method in the UK. However in Germany, and other parts of mainland Europe including France and Switzerland, it has become common to display tapestries on slanted supports in recent decades, a practice believed to have been initiated by the conservator André Brutillot working in Bavaria. Tapestry supports are often inclined at 5° from the vertical. In 2006 Wild and Brutillot discussed displaying tapestries on slightly inclined boards covered with textured molton or domette fabric, “the combination of the angle and the force of friction reduce the weight and the tensions on the wefts, particularly in the upper part of the tapestry. Regular examinations show that the effect of elongation due to weight is reduced in this way.” (Wild and Brutillot, 2010: 182). It is intuitive that both angle and friction play a role in the increased support offered to a tapestry by a slanted support and it is common practice to use a napped or pile fabric, such as brushed cotton molton (molleton) or velvet, to cover the support board and increase friction between the board and the tapestry.

Using the simple Coloumb model of friction, friction is the force that resists the sliding of one solid object over another. We are concerned here with static friction, where two surfaces are at rest, rather than dynamic friction where two surfaces are moving in relation to each other. The coefficient of friction (denoted μ) can be calculated to quantify the amount of friction generated by two materials in contact with each other. The coefficient is a measure of how easily one object moves in relation to another; a lot of friction between materials gives a high coefficient of friction value. In fact we found that adhesion played an even larger role than friction at the interface between the tapestry and the board-covering fabric. Adhesive forces refer to the forces of attraction between two different substances and can include physical (mechanical) adhesion, where two materials physically interlock, and electrostatic forces, where two materials are attracted to each other by opposing electrical charges.

As previously demonstrated by Barker (2002), in the absence of friction or adhesion, it is a simple undertaking to calculate mathematically the reduction in load at the top of a tapestry caused by increasing the angle of support. She used trigonometry to explain this mechanism (her diagram is reproduced as Figure 1): “Obviously when the angle [a] is zero [ie vertical], the strain down the length is 100% and when it is 90°, ie horizontal, there is no strain at all. The surprising result is that for [a slant of] 25°, probably a greater angle than would be

considered for a large item, the strain is still 90%. Halfway down, 45°, it is just over 70% and to get a 50% reduction the tapestry must be at 60°." (Barker, 2002: 30). Our initial investigation (Costantini et al., forthcoming) also calculated the load and strain that would be experienced by a tapestry on a slanted support, assuming a simple stress-strain behaviour, and introducing a range of different friction values. The theory was illustrated by experiments where wool rep fabric samples were suspended against an MDF board at a range of inclinations; DIC was used to calculate strains and to produce strain maps, enabling us to compare the effect of different degrees of slant. The main point demonstrated by this analytical analysis was that, even when considering friction values traditionally thought of as being high, e.g. greater than 0.5, a slope of 5° has only marginal impact on reducing the load experienced by the tapestry. It is clear from this discussion that the material behaviour at the interface between tapestry and board-covering fabric is a critical factor.

Figure 1. The forces acting on a tapestry displayed on a fabric-covered board. Reproduced from Barker (2002: 30).

Slanted support: investigating the effect of friction

Methodology

i Friction tests: unweighted tapestry samples

Tests were carried out to compare the friction between small tapestry fragments and a range of fabrics commonly used to cover slanted supports; friction between the tapestry fragments and an uncovered support was also calculated. Four small tapestry samples from the Karen Finch Reference Collection at CTCTAH were tested. Two small fragments were unlined; of these one was of a slightly finer weave than the other. One was 'lined' on the reverse with linen fabric, and one with cotton downproof fabric; the lining fabrics were simply stitched around the edges of the fragments. Details of the fragments are provided in Table 1; the large tapestry fragment in the table was used in a later test described below.

	Max dimensions	Weave count per inch (25mm)	Image
Small tapestry fragment 1	210mm x 90mm	19 warps 78-84 wefts
Small tapestry fragment 2	150mm x 105mm	17 warps 66-68 wefts
Tapestry fragment with linen lining	300mm x 240mm	12 warps 38-44 wefts
Tapestry fragment with cotton lining	225mm x 200mm	17-18 warps 64-70 wefts
Large tapestry fragment	980mm x 950mm	13 warps 40-44 wefts

Table 1. Tapestry fragments used in the tests.

Four different board-covering fabrics were tested. Results from a questionnaire sent to tapestry conservators around Europe as part of a student dissertation project (Catic, 2019) showed that in Germany, where nearly all conservators (81% of 12 responses) reported displaying tapestries on slanted supports, cotton molton is commonly used to cover the support board. The UK equivalent is cotton domette fabric and this was also tested along with velvet, which has been used as a board-covering fabric for tapestry display, and polyester felt. Details of the fabrics are given in Table 2.

	Fibre and weave	Comments	Image
Board-covering fabric			
Molton	Organic cotton. 2:1 twill with brushed surface on both sides. 270gsm.	The molton fabric is thicker than the domette. The brushed surface is even and obscures the twill weave structure.
Domette	Cotton. 2:1 twill with brushed surface on both sides.	The twill weave structure is more visible than in the molton.
Velvet	Cotton. Velvet, cut warp pile.	The velvet pile is dense and even.
Polyester felt	Polyester. Non-woven, needle punched, 3mm. 120gsm.	This fabric is much loftier and less dense than the others.
Tapestry support/lining fabric			

Linen	Linen. Tabby (plain weave).	The image shows fabric after washing at 90°C.
Downproof cotton	Cotton. Tightly woven tabby (plain weave).	The yarns also appear tightly spun.

Table 2. Details of the board-covering fabrics and tapestry support/lining fabrics used in the tests. The images are of a 25mm square of fabric, photographed through a linen tester.

Friction tests were conducted using a simple inclined plane method. Although more elaborate friction testing techniques have been developed for textiles (Gul et al., 2009; Moorthy, 2015), this method was chosen both for its simplicity and because it closely replicates actual tapestry display conditions. A MDF board was covered with the fabric and the tapestry fragment placed on it (in the case of the velvet board-covering fabric, the velvet was placed with the pile direction facing towards the top of the board, to create the maximum friction between the tapestry and board). The board was slowly raised from horizontal until the tapestry began to slip. The inclination at which this happened was measured with a smart phone app in order to calculate the coefficient of friction. 15 tests were carried out for each covering fabric and the mean inclination at which slippage occurred was calculated. The test was also conducted with no board covering fabric to calculate the coefficient of friction between the tapestry and the MDF. Table 3 shows the values recorded.

ii Friction tests: weighted tapestry samples

An alternative friction testing method for textiles employs a weight to increase contact between the two surfaces (Mercier, 1930). Tests carried out by Trosbach (2002) as part of a dissertation research project utilised this technique to investigate board-covering fabrics for tapestry, with specimens wrapped around a metal plate. This technique was also trialled here with a tapestry fragment loaded with a glass weight (121.2g). In addition, in order to more closely replicate the display of an actual tapestry, a larger tapestry fragment, part of a seat cover, was tested with a board cover of molton fabric (the large tapestry fragment in Table 1, maximum dimensions 980mm x 950mm).

iii DIC monitoring of larger tapestry fragment on vertical board

A final test aimed to replicate more closely the display of tapestry and to compare the support provided by a covered support and an uncovered support. A larger piece of tapestry, a fragment from the Karen Finch Reference Collection measuring 1600mm high x 400mm wide² was suspended from its upper edge against a vertical board. It 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, as shown in Figure 2. The tapestry was in weak condition with several open slits and weak areas; while the left and right halves were not in identical condition, they showed similar types of damage before the test. Images of the tapestry were taken at one-hour intervals over the course of 14 days in order to obtain a strain map and quantitative DIC strain data (Figures 3 and 4). These allowed direct comparison of the support provided to the tapestry from the covered and uncovered sections of the vertical board.

² This tapestry fragment was used for the initial strain monitoring tests reported in Costantini et al. (forthcoming).

Figure 2. The DIC test set-up. The tapestry fragment is suspended from a vertical board; the left half is in direct contact with the board; the right half has a layer of cotton molton between the tapestry and the board. The camera took one image of the tapestry per hour for 300 hours using an automatic shutter; these images were used to obtain a strain map and numerical strain data.

Results of friction tests

i Friction tests: unweighted tapestry samples

Table 3 shows the mean inclination at which the unweighted tapestry fragments started to slip when the board was tilted. There was no correlation between the weave count and the degree of tilt recorded. With the uncovered MDF board, the tapestry slipped when the board was raised to around 49° from the horizontal. Adding a board-covering fabric had a very large effect. Surprisingly, it was found that in almost all cases, 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. It is not possible to calculate a coefficient of friction if the board tilts beyond 90° from the horizontal - it would result in a negative number. It is clear that the simple Coulomb model of friction does not apply and that additional, adhesive forces are having an effect. Hosseinali and Thomasson, in an investigation of the friction properties of cotton fibres, confirm that, “the fraction of the energy transferred between sliding surfaces is influenced by the extent of intermolecular attractive forces (adhesion force) and existence of a lubricant film layer” (2018: 5). Both tapestry and the board-covering fabrics have a textured surface, which increases the points of contact between them. It is likely that mechanical interlocking between the fibres of the tapestry and the fabric covering on the board generates mechanical adhesion between the fabric surfaces; electrostatic forces may also play a role. A range of factors contributes to the roughness or smoothness of a fabric surface, particularly in the case of natural fibres. These include fibre morphology (eg convolutions in cotton fibres and scales on wool fibres), fibre processing, yarn spinning, the weave (eg pile weave) and finishing processes (eg napped surface). Although this was not investigated, it is likely that environmental factors also play a role. If electrostatic forces are a component of the adhesion, the degree of attraction may be affected by relative humidity (RH).

	Unweighted tapestry				
Board-covering fabric	Small tapestry fragment 1	Small tapestry fragment 2	Tapestry fragment with linen lining	Tapestry fragment with cotton lining	Large tapestry fragment

Uncovered MDF board	48.79° (± 4.04°) μ 1.15	49.83° (± 2.98°) μ 1.92			
Cotton molton	107.24° (± 4.62) μ *	101.09° (± 6.41) μ *	100.19° (± 3.43) μ *	100.65° (± 5.24) μ *	95.16 (±5.94) μ *
Cotton domette	100.63° (± 4.67) μ *	107.19° (± 3.28) μ *	100.21° (± 6.29) μ *	96.34° (± 2.93) μ *	
Polyester felt	99.07° (± 4.60) μ *	102.81° (± 6.63) μ *	79.39° (± 3.17) μ 5.34	70.05° (± 2.48) μ 2.75	
Cotton velvet	78.58° (± 3.29) μ 4.95	75.59° (± 5.20) μ 3.89	97.50° (± 3.54) μ *	87.19° (± 1.53) μ 20.37	

Table 3. The inclination at which the unweighted tapestry fragments began to slip on the board (mean of 15 samples, in ° from horizontal); and the calculated coefficient of friction between the tapestry and the board-covering fabric (μ). The coefficient of friction could not be calculated if the inclination was greater than 90° (denoted *).

In the few cases where the fabric slipped at an inclination of less than 90° it was possible to calculate a value which we have interpreted as the coefficient of friction, although it is clear that it is in fact a mixture of friction and adhesion. The figures were extremely high, as shown in Table 3. To put them in context, for example, the coefficient of friction of rubber against rubber is 1.15 and the value of wood against wood is 0.25 - 0.5. Nonetheless the calculated figures did give an indication of the relative effect of the different covering fabrics, with slight differences apparent in the mean values recorded (Table 3). The inclination at which the tapestry started to slip was highest with the molton, domette and polyfelt fabrics, above 100° from horizontal in each case. The tapestry slipped at a slightly lower inclination with the velvet board covering, around 76-78° from horizontal, indicating that there was slightly less friction/adhesion between the tapestry and the velvet. The coefficient of friction recorded for tapestry against velvet was calculated as around 4-5.

When the linen and cotton fabrics were used to line the tapestry fragments, this resulted in significantly lower values with the velvet and, particularly, the polyester felt fabrics. In comparison 'lining' the tapestry fragments did not seem to cause a marked effect when used with the molton and domette fabrics. The coefficient of friction recorded for the tapestry lined with linen on the polyester felt was 5.34, while the value for the tapestry lined with downproof cotton on the polyester felt was 2.75. This indicates that there was less friction between the cotton and the polyester felt than between the linen and the polyester felt (as would be expected, as the cotton fabric has a smoother surface than the

linen). These results are obviously related to the fabric properties (as detailed in Moorthy, 2015): molton and domette are similar fabrics, they have loosely spun yarns and are coarsely woven with a raised nap and highly textured surface. Polyester felt and velvet are also textured fabrics but the nap or pile is more dense and even, producing a smoother surface. Polyester felt was the only synthetic material used in the tests; unlike the natural fibres, its fibres are uniformly smooth and often have a round cross-section.

ii Friction tests: weighted tapestry samples

It was notable that the larger, heavier tapestry fragment, tested with the molton fabric, slipped at a lower inclination than the smaller tapestry fragments – at 95° compared with over 100° (see Table 3). The small, unlined and lined, tapestry fragments all slipped at a lower inclination (less than 90°) when they were loaded with a glass weight (Table 4), making it possible to calculate a coefficient of friction value. Values for the weighted fragments were similar to those recorded by Trosbach, using a similar method, but these values were lower than for the equivalent unweighted tapestry fragments. This confirms that the coefficient of friction for these textiles is influenced by the load and that they are not experiencing Coulomb type friction - where the coefficient is independent of the load - but that more complex behaviour is at play. Indeed Hosseinali and Thomasson note that, “At low loads, the friction force is mostly adhesion-controlled” (2018: 6), whereas at higher loads, the load becomes dominant. They show that both deformation and adhesion play a role in this mechanism, with a range of factors contributing to their relative importance, including surface roughness, polymer viscoelasticity, temperature and moisture content. This makes sense in the context of the tapestry on a fabric-covered board where a higher load would flatten the fibres of tapestry and board-covering fabric, making them less able to interlock physically. In a display context there could be a long-term flattening of the board-covering fabric over time, perhaps particularly in the case of the fluffy domette and molton fabrics, which could potentially reduce adhesion between the two surfaces.

	Tapestry loaded with glass weight (121.2g)			
Board-covering fabric	Small tapestry fragment 1	Small tapestry fragment 2	Tapestry fragment with linen lining	Tapestry fragment with cotton lining
Cotton molton	72.87° (±2.53) μ 3.24	58.34° (± 1.02) μ 1.62	56.98° (± 3.25) μ 1.54	62.25° (± 3.58) μ 1.90

Table 4. The inclination at which the weighted tapestry fragments began to slip on the board (mean of 15 samples, in ° from horizontal); and the coefficient of friction between the tapestry and the board-covering fabric (μ).

iii DIC monitoring of larger tapestry fragment on vertical board

The experiments detailed above revealed that adhesion, not Coulomb type friction, was the main interaction between the tapestry and board-covering fabric. The adhesive component of the interaction meant that substantial reductions in load could be achieved, even when displaying the tapestry at only a 5° inclination from vertical. Indeed the effect of friction/adhesion appeared so great that we hypothesised that it would be effective on a vertical surface, with no slant. The DIC monitoring of the larger tapestry fragment was carried out to replicate a more realistic display situation and in order to test this hypothesis. Images of the fragment taken over 300 hours were used to produce both a visual strain map (Figure 3) and numerical strain data (Figure 4). Figure 3 shows the strain map of the tapestry after 300 hours of monitoring; here the DIC software has compared images of the tapestry from the beginning and end of the period to measure the amount of displacement caused by hanging, and from that to calculate the strain. Areas of high strain are shown in red, neutral areas in green and areas of compressive strain (where the applied forces cause contraction rather than extension) are shown in purple. The red areas shown on the strain map indicate areas of high strain around unsupported holes and slits. It is important to note that the software cannot actually calculate strain in areas of opening slits where there is no fabric; we denoted these as areas of 'pseudo-strain'. Nonetheless, the strain map gives a clear picture of areas of concern to a conservator.

In addition to the graphic strain map, numeric strain data were calculated (shown in Figure 4). When calculating the strain data for the tapestry, only the upper part of the tapestry (enclosed by the dotted line in Figure 3) was selected, to exclude an area of comparatively extreme movement at the bottom left apparently caused by the opening of a slit. Here an area of high strain shown in red indicates the opened slit, with what appears to be a resulting area of compressive strain beneath it, although these values may also be errors caused by out-of-plane movements in this area. Edge effects were also avoided. The experiments were carried out in an uncontrolled environment subject to fluctuating RH; the strain data show areas of positive and negative strain, reflecting the resulting expansion and contraction of the tapestry. 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. While the tapestry on the uncovered board was also supported to some degree, Figure 4 shows that 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. It should be noted that small strains like these are subject to a higher error than larger strains, but the strong correlation between RH and strain gave confidence in the strain results. Although only one test was carried out and there is no statistical certainty, these results indicated that the domette board covering was conferring additional support to the tapestry without using a slanted support.

Figure 3. DIC strain map of the tapestry after 300 hours of hanging. The areas shown in red indicate areas of high strain around unsupported holes and slits. A large area of strain is seen at the bottom left of the tapestry where a slit was opening up. The purple area beneath it is an area of negative strain where the tapestry is compressed, perhaps as a result. The black dotted line shows the region of interest, reported in Figure 4.

Figure 4. Strain (mean ϵ_{yy}) in the half of the tapestry suspended against the uncovered board reached almost 0.05% at the maximum RH of 58, but only 0.01% in the areas against the board covered with molton. There is a close relationship between RH and strain, though strain recorded in the tapestry on the uncovered board follows RH fluctuations more closely than in the covered part of the board.

Discussion: implications for textile conservation practice

Displaying tapestries on a slant

The research gave very useful information about the effects on tapestry and tapestry-like fabric of display on a slanted support and helped us to better understand the complex material behaviour involved. While a theoretical analysis of this method of display is extremely simple in engineering terms, to date there has been virtually no testing of the effects of such display on tapestries or other artefacts in the heritage sector, despite slanted support being an increasingly common method of display for tapestries. Initial tests using DIC to monitor wool rep fabric samples suspended on a board at different inclinations confirmed that strain is reduced incrementally as the angle of slant increases, although they demonstrated that a small display angle, of 5° from the vertical, has a negligible supportive effect in itself, whereas a display angle of 45° from the vertical confers considerably greater support (Costantini et al., forthcoming). Textile conservators have used fabric-covered

boards slanted at 45° or more in the display of, for example, fragile archaeological textiles, and this has clearly been an effective approach.

However, if adhesion is introduced at the interface between display board and tapestry, then the story dramatically changes (Hosseinali and Thomasson, 2018). The experiments reported here clearly showed that friction and, particularly, adhesion between the board-covering material and the tapestry play a major role in the support provided by a slanted board. In fact, it is now apparent that, at small inclinations, these are very much more significant than the inclination itself. Where they could be measured, the coefficient of friction values between the tapestry and the covering fabric were extremely high, with values of 4-5 calculated, for example, for the tapestry on velvet. In most cases friction/adhesion was even greater and the board could be tilted beyond vertical to around 100° from horizontal, so that it was not possible to calculate a value for the coefficient of friction. This clearly demonstrated that the simple Coulomb model of friction does not apply to the relationship between the two textiles - the tapestry and the board-covering fabric - and that physical and/or electrostatic adhesion between the two surfaces is the dominant mechanism. The board-covering fabrics tested had similar physical properties in that all had napped, textured surfaces, and all proved effective in greatly increasing adhesion between the tapestry and its support, but further testing will be necessary to determine which type of fabric has the most effective properties in the long term.

While the friction tests were carried out using a simple (though standard) methodology, these findings confirm conservators' intuitive understanding of the support provided by a fabric-covered board at a slant. However, as a result of this investigation, it appears that a fabric-covered board provides even greater support than anticipated, to the extent that the tapestry is supported by the fabric even when the support board is vertical. This important finding means that a tapestry can be displayed vertically, without any optical distortion caused by slanted display, and still benefit from increased support from the board-covering fabric. (The tapestry is, of course, also supported at the top edge by Velcro or some other means.)

However it is also clear that the relationship between the tapestry, any support or lining fabrics and the board-covering fabric should be considered. It is interesting that in Germany, where slanted board display is common, it is more usual to attach patches of support fabric to a tapestry, rather than to completely cover the reverse with a support fabric.³ This leaves more of the reverse of the tapestry in direct contact with the board-covering fabric, increasing the friction and adhesion between them. In the UK, it is more common to give a tapestry a full stitched support of linen fabric; here some excess fabric, or 'bag' is often introduced into the support to ensure that it does not become too tight when intensive stitching is carried out – this would obviously affect the degree of contact between the linen-covered tapestry and the board-covering fabric. Cotton molton and domette were the

³ Catic (2019) records that 50% of 12 German conservators who responded to a questionnaire reported using patch support without a lining on tapestries. Of 38 UK conservators who responded, none reported using this method.

most effective of the board-covering fabrics tested. However the long term effects of such display have not been investigated. It is possible that the weight of a tapestry would flatten cotton molton or domette during long-term display, reducing its lofty properties; velvet and polyester felt might be more resilient over a long period. Environmental factors may also play a part; with moisture potentially influencing electrostatic forces, it is possible that friction/adhesion could be reduced at high RH. The response to RH of different fibres could also play a role; if the board-covering fabric expands and contracts at a different rate from the tapestry in response to fluctuating RH, there will be increased movement between them. This is likely to be more of a factor with the polyester felt; the other natural fibre board-covering fabrics would respond to RH changes in a more similar manner to the tapestry itself.

Value of digital image correlation

Strain monitoring is proving to be a useful tool to give us, literally, a picture of what is happening to our tapestries as we display them. It is valuable both for long-term monitoring and, as in this research, to help visualise and compare the results of different interventions. This research project developed DIC as a tool for monitoring artefacts, and specifically textiles, within the cultural heritage sector and has reinforced the value of DIC in providing quantitative data on strain (Costantini et al., forthcoming). It should be noted that DIC interpolates strain data across holes and open slits so that these show as areas of high strain even though there is no fabric to measure. Nonetheless, these areas of high 'pseudo-strain' highlight areas of concern to a conservator, itself a useful feature. The research confirmed that DIC is a valuable technique for continuous strain monitoring for both long and short time periods, and showed that it is possible to monitor large areas of a tapestry, even a complete tapestry. Also, as hoped, strain mapping was shown to be an extremely useful tool for providing a visual analysis of tests on changing display conditions – here the effect of increasing inclination of display.

These tests trialled the use of a single camera and, importantly, demonstrated that 2D DIC, using one camera, provides accurate strain data and gives good results, as long as the object to be monitored is flat, as here (Alsayednoor et al., 2017). This makes the technique more practical as a long-term monitoring tool as a single camera can be discreetly mounted within a historic or museum interior and is less expensive to purchase than a 3D DIC system. However 3D DIC can provide strain data on objects which have an undulating surface, as do many historic tapestries, or where air currents cause movement. Two cameras in a 3D system register the out of plane deformation while calculating the strain whereas 2D DIC reports out of plane displacements as errors (Alsayednoor et al., 2017). Alsayednoor, a researcher with the project, also demonstrated that variables such as the woven design of the tapestry can have an effect on the quality of the data recorded, while consideration of DIC methodology, such as the appropriate subset size, is also necessary (Alsayednoor et al., 2019).

Conclusion

Simple friction tests have confirmed that slanted supports can be valuable in reducing strain on displayed tapestries, but that at only a small degree of slant, the overriding mechanism providing support is adhesion between the tapestry and the board-covering fabric. A slight slant, 5° from the vertical, confers no additional advantage. This research is not intended to be prescriptive or to suggest that one method of display is preferable to another, but it aims to provide information to help tapestry conservators and curators make decisions about display styles and methods. A vertical support with a textured fabric covering has been demonstrated to provide effective support for a tapestry, though it is clearly important to consider the relationship between the tapestry itself, any support and lining fabrics and the fabric used to cover the support board. It should be noted that this paper does not seek to compare this method of supporting a tapestry with the method commonly used in the UK, which provides a full stitched support onto a new fabric. In a separate investigation DIC has been used to interrogate conservation stitching techniques and this element of the research is being published separately. The final choice of support technique will depend on the tapestry condition. Finally – and this is an important caveat – it must be noted that this research is limited to the physical effects of tapestry support and does not consider the visual impact of this method of display. A tapestry displayed flat against a vertical board will not look the same as one that is free-hanging as the drape will be affected; in addition historic tapestries are often no longer flat and distorted areas may not lie smoothly against a support. However the effect of this method of display could perhaps return a tapestry which has been physically distorted by age and damage to an appearance closer to that originally intended. Visual aspects of display remain a vital part of any decision making process.

Acknowledgements

This work was supported by the Leverhulme Trust under Grant number RPG-2015-179. The authors are extremely grateful for support from a range of colleagues particularly: Susanne Bouret, independent textile conservator in France, for her major contribution to the development of this research; the textile conservators at Glasgow Museums who played a significant role in the project, Maggie Dobbie, Helen Hughes, Harriet Woolmore, Rosie Nuttall; Dr Margaret Smith, Lecturer in Conservation Science, University of Glasgow; Stephen McCann and Sam Dyer from the University of Glasgow Photo Unit. We are also grateful to members of the project's advisory panel for their invaluable support and advice.

Suppliers

Domette: obtained from <https://www.whaleys-bradford.ltd.uk>. Note the quality of domette used in the testing is no longer available from this supplier.

Downproof cotton: Optic white, <https://www.whaleys-bradford.ltd.uk>

Linen: Unprimed linen OV10, <https://www.claessenscanvas.com>

Molton: Bio-Molton 160, <https://www.naturstoff.de>

Polyester felt, 3mm, 120gsm, <https://www.preservationequipment.com>

Cotton velvet: supplier: Naples NESP, obtained from <https://www.mandors.co.uk>

References

Alsayednoor, J., Lennard, F., Yu, W.R. and Harrison, P. 2017. "Influence of specimen pre-shear and wrinkling on the accuracy of uniaxial bias extension test results." *Composites Part A* 101: 81-97. doi:[10.1016/j.compositesa.2017.06.006](https://doi.org/10.1016/j.compositesa.2017.06.006)

Alsayednoor, J., Harrison, P., Dobbie, M., Costantini, R. and Lennard, F. 2019. "Evaluating the use of digital image correlation for strain measurement in historic tapestries using representative deformation fields." *Strain* 55 (2). doi:[10.1111/str.12308](https://doi.org/10.1111/str.12308)

Barker, K. 2002. "Reducing the Strain: is it worth displaying a large fragile textile at a slight angle?" *Conservation News* September: 30.

Catic, E.M. 2019. *A research Project to Measure the Effectiveness of Stitching Methods when Stabilising Weak Areas in Tapestries*. Unpublished MPhil dissertation, University of Glasgow.

Costantini, R. et al. "Understanding mechanical damage mechanisms of tapestries displayed at different angles using 2D DIC." Forthcoming.

Gul, M., Koc, I.M., Gursoy, N.C. 2009. "A new instrumental method for measuring the surface friction of textile fabrics." *International Conference on Advances in Textiles, Machinery, Nonwovens and Technical Textiles (ATNT), 2009*.
https://www.researchgate.net/publication/313903146_A_New_Instrumental_Method_for_Measuring_the_Surface_Friction_of_Textile_Fabrics/citation/download

Hosseinali, F. and Thomasson, J.A. 2018. "Multiscale frictional properties of cotton fibers: a review." *Fibers* 6: 49. doi:10.3390/fib6030049.

Lennard, F., Eastop, D., Dulieu-Barton, J., Chambers, A., Khenouf, D., Ye, C.C and Williams, H. 2011. "Strain monitoring of tapestries: results of a three-year research project." In *Preprints ICOM Committee for Conservation 16th Triennial Meeting, Lisbon 2011*, edited by J. Bridgland. Paris: International Council of Museums. <https://www.icom-cc-publications-online.org/PublicationDetail.aspx?cid=a240e0f0-9013-43d1-8002-eea483edff17>

Lennard, F. and Dulieu-Barton, J. 2014. "Quantifying and visualising change: strain monitoring of tapestries with digital image correlation." *Studies in Conservation* 59 (4): 241-255. doi.org/10.1179/2047058413Y.0000000097.

Máximo Rocha, P., D'Ayala, D. and Vlachou-Mogire, C. 2018. "Methodology for tensile testing historic tapestries." *Institute of Physics Conference Series: Materials Science and Engineering* 364: 012003. doi:10.1088/1757-899X/364/1/012003.

Mercier, A.A.1930. "Coefficient of friction of fabrics." *Bureau of Standards Journal of Research* 5: 243-246. https://nvlpubs.nist.gov/nistpubs/jres/5/jresv5n2p243_A2b.pdf

Moorthy, R.R. and Kandhavadi, P. 2015. "Surface friction characteristics of woven fabrics with nonconventional fibers and their blends." *Journal of Textile and Apparel Technology and Management* 9 (3).

Trosbach, G. 2002. *Physikalische Untersuchungen an historischen Tapisserien*. Unpublished thesis, Fakultät für Architektur, Technische Universität München.

University of Southampton. *Towards In Situ Monitoring of Tapestry Degradation Using Strain-based Engineering Techniques. Tapestry Monitoring Research Project.* <http://www.tapestry-strain.org.uk/>. Accessed 11 December 2019.

Vilde, V., Thickett, D., Hollis, D., Grau-Bové, J. and Richardson, E. 2017. "Digital image correlation for condition monitoring of lined painting." In *Preprints ICOM Committee for Conservation 18th Triennial Meeting, Copenhagen*, edited by J. Bridgland. Paris: International Council of Museums. <https://www.icom-cc-publications-online.org/PublicationDetail.aspx?cid=220f7c3a-a3c6-4f0f-bde1-6f5abf1e9f98>

Wild, C. and Brutillot, A. 2006. "The conservation of tapestries in Bavaria." In *Tapestry Conservation: Principles and Practice* Edited by F. Lennard and M. Hayward. Oxford: Butterworth-Heinemann.