Original research or treatment paper

Mechanical properties of wool and cotton yarns used in twenty-first century tapestry: Preparing for the future by understanding the present

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The conservation of historic tapestries is a complex and highly skilled task. Tapestries now being woven will need conservation in years to come. Can we, by understanding the properties of these contemporary works, assist the conservators of the future? The recreation of the *Hunt of the Unicorn* tapestries being undertaken by the West Dean Tapestry Studio offers a unique opportunity to access the materials being used and to create a body of data on their initial properties. This study uses tensile testing of the warp and weft materials to determine their maximum load at break, extension at maximum load, and specific stress (tenacity). Wool weft yarns from two different sources and of two thicknesses were examined. These wools were dyed 'in house' and the effect of the different dyes used was also assessed. These parameters all showed some significant ($P < 0.05$) differences. Cotton warp yarns of differing thickness and a gold thread were also tested. The comparison of how cotton and wool break demonstrates that when a tapestry is put under sufficient stress the cotton will snap but the wool may only stretch. However, this could often be beyond its recovery range resulting in a failure to return to shape.

Keywords: Contemporary tapestry, Material properties, Mechanical testing, Wool yarn, Cotton yarn, Tenacity, Conservation

Introduction

Historic tapestries are complex structures, woven from wool and silk yarns, and sometimes also including metal threads; the weave structure of tapestry is discontinuous, creating areas of weakness where different coloured yarns meet. The degradation caused by many decades or even centuries of open display increases the difficulty of understanding a tapestry's physical integrity. Recent work has begun to investigate methods of assessing the condition and degradation of historic tapestries. Khennouf *et al.* (2010) assessed the use of digital imaging correlation to monitor strain while Vanden Berghe (2012) used calibrated amino acid analysis to detect oxidative degradation of protein fibres. Odlyha *et al.* (2005) carried out a study on the chemical and physical conditions of historic tapestries and used model tapestries to quantify changes as part of the European Commission 5th Framework project 'Monitoring of Damage to Historic Tapestries' (MODHT).

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Such studies have often analysed samples of wool and silk weft yarns taken from the backs of tapestries under investigation. However, it is difficult to assess the present condition of tapestry materials when there is no known baseline, no knowledge of the original properties of the materials used. Model tapestries, modern surrogates, have also been used as a means of reproducing typical damage under accelerated ageing regimes, although it has so far proved impossible to recreate the extreme damage seen in historic tapestries (Duffus, 2013). Much research on the physical and chemical properties of yarns and fibres used in textile manufacture has been carried out (Dubro, 1987; Montazer *et al.*, 2011; Periolatto *et al.*, 2011), but processing, spinning, and dyeing would have affected the individual properties of yarns used in the past. The research reported here aimed to seize the valuable opportunity of a contemporary major tapestry weaving project, the creation of a set of tapestries for

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Stirling Castle, to capture information on the properties of the wool yarns used in the weaving. This was not intended to yield immediate information, but aimed to provide a baseline for future analysis of the yarns, in the expectation that in the long term this will add to our understanding of the degradation of materials used in tapestry weaving. In the same way, Young and Jardine (2012) recently produced a comprehensive study of artists' canvas identifying the properties and durability of a variety of materials commonly used today. This paper shows the value of prior knowledge of the properties of canvases for conservators in the future, and perhaps may guide artists in their choice of materials.

West Dean Tapestry Studio is coming to the end of the 'Stirling Tapestries Project' (2001–2013), a re-interpretation of the *Hunt of the Unicorn* tapestries, a £2 million project funded by Historic Scotland with a range of donors including $2.125 million from the Quinque Foundation, USA (Historic Scotland, n.d.). The original set of seven tapestries dates from 1495 to 1505 and was donated to the Metropolitan Museum of Art in New York, USA, by John D. Rockefeller Jr in 1937; they are displayed in the Cloisters Museum. These tapestries have been re-interpreted by the West Dean Tapestry Studio for the Queen's Presence Chamber in the palace at Stirling Castle. The palace is one of the finest and best-preserved Renaissance buildings in the UK and was recently restored to show how it may have looked on completion around 1545. The tapestries were woven at two locations, in a purpose built studio at Stirling Castle and at West Dean. Those woven at Stirling were made on a high warp loom and those at West Dean on a low warp loom. The tapestries were woven with cotton warp yarns and weft yarns of wool, cotton, and metallic threads. Although silk would have been used previously in the weft, it was replaced by cotton which has greater durability. The original tapestries have faded as a result of many environmental factors over the last half millennium. The newly woven tapestries appear bright and vibrant giving a sense of how the originals would have looked when new.

The mechanical testing of the materials used in contemporary tapestries has to our knowledge never been carried out and so access to materials used by the West Dean Tapestry Studio has allowed data on the mechanical properties of contemporary yarns to be collected. The Dovecot Studios, which also employs tapestry weavers who work with artists to produce hand-woven contemporary tapestries, also provided materials for testing. Can we, by understanding the properties of these contemporary works, assist the conservators of the future?

Material and methods

Materials

The wool and cotton yarns used in the *Unicorn* tapestries were supplied by a variety of companies. The wools were dyed 'in-house' at West Dean using acid-milled dyes which have a strong affinity to wool. A total of 250 colours of wool were created by the dyers and some 100–150 of these were used in each tapestry (Penney, 2012). In this work, two weights of wool weft were tested with counts 2/28 and 2/12 of which 2/28 is the finer. The first number of the fraction is the number of plies, where a ply is a single strand, and the second number of the fraction is the yarn thickness, meaning the number of times the yarn has been spun times its standard length. As this wool is worsted the standard length is 560 yards (521 m).

Two suppliers' wools were tested here, named after their place of origin: 'Wensleydale' wool was supplied in 1 m lengths and stored in skeins whereas the 'New Zealand' (NZ) wool was wound onto cones and stored as shown (Fig. 1A and B, respectively). The cotton weft yarn used in the tapestries is DMC 25 Mouliné Spécial. The 1/28 gold thread used was 2% gold with a cotton core. The cotton warp used was 9 ends per inch (epi) 9/12 (Penney, 2012) and was supplied by Fibrecrafts (Fibrecrafts, George Weil & Sons, Guildford, Surrey). In addition to the warp yarn used in the Stirling Tapestries, a selection of cotton warps used routinely in the construction of large tapestries was also tested. These were cotton warps, 6, 8, and 10 epi (epi is the number of warps per inch of tapestry) used at the Dovecot Studio. The 6 and 10 epi were supplied by Bockens (Bockems Garner, Holma-Helsinglands, Forsa, Sweden) and were described as Bockens Makramegan 12/24 and Bockens Bomullsmattvarp 12/6 (http://www.holma.se). The 8 epi was supplied by Bingley Textile Supplies (Bingley Textile Supplies, Bradford, West Yorkshire) and was a 3/6/12 which is described by the company as a 6/12 cotton twisted three times. Also the studio had 'old' cotton warp suspected to be 50–60 years old. Its origins were not known but it represented the effects of ageing on cotton warp and so was included in the testing.

Wool and cotton are very different materials and thus a tapestry when complete is a composite material. Wool is an animal fibre with a proteinaceous structure and is almost entirely composed of a family of proteins generally known as the α-keratins. These proteins (it is estimated that wool contains >170) are formed by the covalent bonding of the polypeptide chains (cross-links) and also non-covalent physical interactions between the molecules. Polypeptides are formed by the joining together of peptides that have the general formula (–NHCHRCO–), an amide group. However, the most important crosslinks are the sulphur-

Figure 1 (A) Wensleydale wool in skeins; (B) NZ wool in cones; (C) Weaver Jennifer Bennett working on 'The Mystic Taming of the Unicorn' (Stirling Tapestries Project); (D) the newly woven tapestry 'The Unicorn at Bay' (Historic Scotland image).

containing disulphide bonds which form during fibre growth by a process called 'keratinisation'. These make the keratin fibres insoluble in water and more stable to chemical and physical attacks than other types of proteins (CSIRO Materials Science and Engineering, 2012). Worsted yarn which has been used for the weaving of these tapestries is processed in a different way from woollen yarn, resulting in the fibres lying more parallel and more tightly twisted. This produces a thinner yarn with a smoother surface.

Cotton is a plant fibre made up of around 95% cellulose and is based on a repeating monomeric unit (D-glucose). The presence of linear chains of thousands of glucose units linked together allows a great deal of hydrogen bonding between OH groups on adjacent chains, causing them to pack closely into cellulose fibres. As a result, cellulose exhibits little interaction with water or any other solvent. Cotton and wood, for example, are completely insoluble in water and have considerable mechanical strength (Lancashire, 2011).

Experimental procedures

The testing was carried out on an Instron 5544 mechanical tester using Bluehill version 1.4 software. The load cells used were a 100 N cell for the wools and cotton yarns and a 1 kN cell for the cotton warp yarns. Testing was carried out at ambient temperature and humidity of the laboratory where the instrument is based, and all samples were conditioned in this environment prior to testing. Five replicates of 100 mm lengths from each type of yarn were pulled at a rate of 10 mm/minute. The method chosen was based on previous work on similar materials (Garside & Brooks, 2005; Garside & Wyeth, 2005) and also to reach a compromise between testing regimes which would be recommended for wool and cotton given their different physical properties. The wools were tested 'as is', in that they were not separated into single strands. The cotton, which was six stranded, was tested as a single yarn and the gold thread was tested as supplied. In addition, a typical combination of wools used in the weaving was also tested comprising two 2/28 and one 2/12 wools, described as compound wools here. The multi-stranded warp yarns were tested 'as is'.

Statistical analysis

The properties of the wools were compared using the General Linear Model for a factorial design in the statistical software Minitab Version 15. Because of the large differences in count, 2/12 and 2/28 wools were then analysed separately. The comparison of the wools dyed a different colour was carried out using a 5% Tukey's honestly significant difference (HSD) test.

To determine the probability of a result being significant, $P < 0.05$, 0.01, and 0.001 are used, meaning significant, very significant, and highly significant, respectively, or put another way <1 in 20 chance of being wrong, 1 in 100 chance of being wrong, and 1 in a 1000 chance of being wrong.

Results and discussion

Strength and flexibility testing of the wools and cottons

The extension, force at breaking point, and specific stress (tenacity) are all reported here. The extension shows the amount of stretch of a specimen when a force is applied to it. The force at breaking point gives a value for the force that is required for that specimen to fail (break) and is an absolute measure of strength. However, in order to compare yarns with differing densities and thicknesses it is necessary to calculate specific stress (tenacity).

Fig. 2 shows a typical force vs. elongation (usually labelled extension) diagram. It exhibits the three characteristic regions: elastic stretching, yield point, and non-elastic stretching. The elastic region (sometimes termed Hookean) is up to the yield point. If the force is released the specimen will return to its original length. However, after the yield point, the material is no longer elastic but inelastic and lengthening in this region will not be fully recoverable (illustrated in Fig. 3B). However, wool is unusual in that it does exhibit some elastic recovery after the yield point, and when describing wool the non-elastic region is often termed the 'yield region' (Hearle, 2000).

Stress is the term used when the applied force is expressed relative to the cross-sectional area of the specimen being tested:

$$\text{Stress} = \frac{\text{Force}}{\text{Cross-sectional area}}$$

It is difficult to determine the cross-sectional area of yarn specimens as they are often irregular in shape; therefore, stress is usually expressed as 'specific stress' (commonly referred to as tenacity), which is the load relative to linear density. Linear density is a measure of the mass of yarn in grams per 1000 m length, and is given the unit of tex.

$$\text{Specific stress (tenacity)} = \frac{\text{Force}}{\text{Mass/Length}} = \frac{\text{Force}}{\text{Linear density}}$$

Wool wefts

Two of the wools from different sources were tested. Source is used to describe the origin and storage of the wools, i.e. Wensleydale (skein Fig. 1A) or NZ (cone Fig. 1B). Count is used here to describe the wool weight, i.e. 2/28 and 2/12.

Extension at maximum load

The values ranged from 7.5 to 15.5 mm for the 2/28 NZ wool; from 17.6 to 32.3 mm for 2/12 NZ wool; 9–17.5 mm for 2/28 Wensleydale wool and 13.7–19.8 mm for 2/12 Wensleydale wool for a 100 mm length test sample (Fig. 4). Hacke & Carr, (2005) reported % elongation for unaged natural dyed and undyed wools with a tex of 153 tested at a constant speed of 250 mm/minute. These ranged from 10 to 40% elongation while those tested here fell in the range 10–25% elongation for a tex of 147.6.

There was a highly significant ($P < 0.001$) effect of count; the extension of 2/12 was greater than that of 2/28. This was as expected as the spinning has already drawn out the wool fibres to a greater extent in the 2/28 and thus there is less potential for further

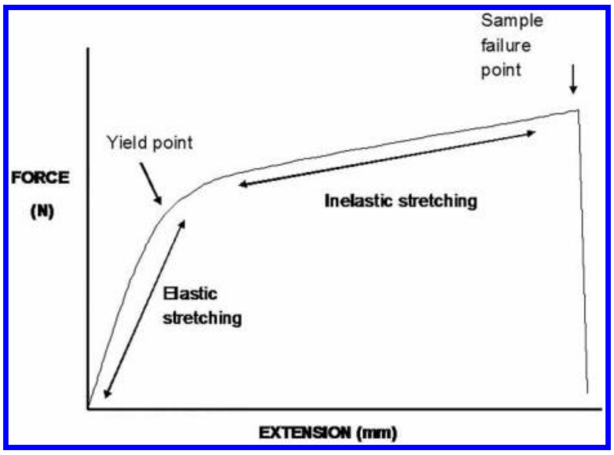

Figure 2 Force vs. elongation curve for wool.

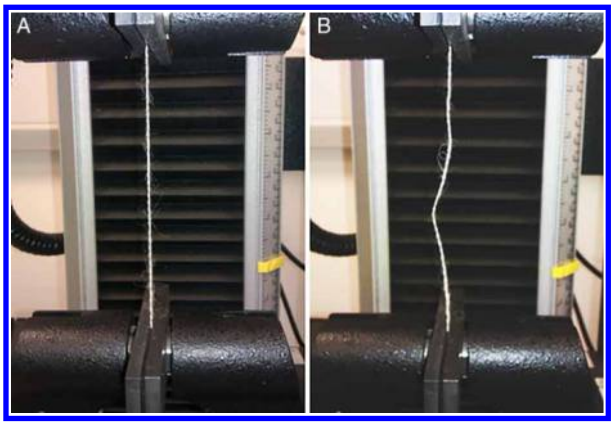

Figure 3 (A) Wool strand before application of force; (B) force released after stretching wool beyond elastic point.

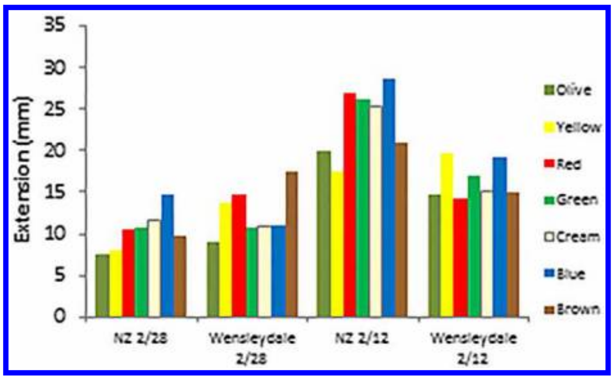

Figure 4 Maximum extension of the wools at break point.

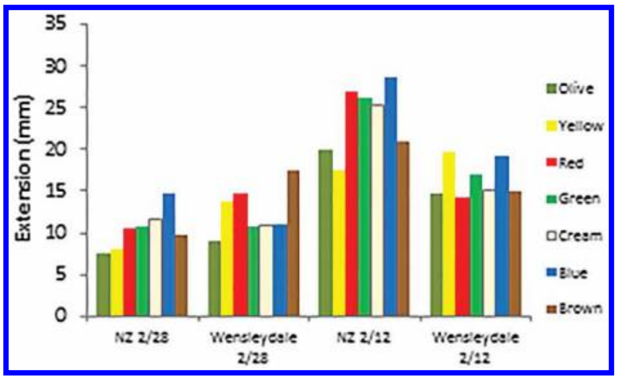

Figure 5 Maximum forces at sample breaking point of the wools.

slippage before break. For the 2/28 wool, extension was very significantly ($P < 0.01$) greater for the Wensleydale wool than for the NZ wool. However, for the 2/12 wool, the extension of the NZ wool was highly significantly greater than for the Wensleydale wool. These differences may be due to processing methods such as spinning or dyeing. For 2/28, there were also very significant effects of the different dyes used (which will be referred to as colour for ease of reading).The significant differences between colours are shown in Table 1 with the extension of brown, blue, and red being significantly greater than olive wool. However, in the 2/12 wools there were no significant effects of colour (Table 1).

Maximum force

The maximum force at breaking point in Fig. 5 shows that the effect of count is highly significant and is greater for 2/12 than for 2/28. Again, this result is expected as the thicker yarn, 2/12, is expected to be stronger.

For the 2/28 wools, the source had no effect. There were, however, very significant effects of colour but this was due to a single difference between brown and green, where brown has the higher tolerance to load. Within the 2/12 wools, there was a highly significant effect of source with NZ wool tolerating a greater force than Wensleydale. There was a very significant effect of colour with cream having a higher tolerance to load than olive, brown, and yellow (Table 1).

Tenacity

The tenacity (specific stress) was calculated using the tex values of 62.3 for the 2/28 wools and 147.6 for the 2/12 wools as shown in Fig. 6. The statistical analysis of tenacity showed that there was still a significant difference at the breaking point between the 2/28 and 2/12 wools showing that the difference in strength was not due only to thickness and density, i.e. the 2/12 was more resistant to breaking than the 2/28 and had therefore a greater strength. The tenacity values (centiNewtons per tex, cN/tex) found for the wools ranged for 2/28 NZ from 4.7 to 10.2, 2/28 Wensleydale 4.5–9.6, 2/12 NZ from 6.7 to 11.2, and for the 2/12 Wensleydale 6.0–10.3. Fig. 7 shows the range for each of the seven colours and the five replicates tested (35 yarns in all).

Cook (1993) reported the normal range of tenacity for wool as 8.8–15.0 cN/tex when dry. Garside and Brooks (2005) measured a value 10.3 (+3.1) cN/tex. The wools tested here, using the same methodology as Garside and Brooks (2005), show similar values but are at the lower end of the range. The strengths differ for many reasons, from the sheep from which the fleece is taken to the techniques of production. However, industry standards required the wools used

Table 1 Significant differences between sources with the same count

	Extension		Max load	
Colour	2/28	2/12	2/28	2/12
Blue	a	a	ab	ab
Brown	a	a	a	b
Cream	ab	a	ab	a
Green	ab	a	b	ab
Olive	b	a	ab	b
Red	a	a	ab	ab
Yellow	ab	a	ab	b

Coloured wools with the same subscript letter are not significantly different: Tukey's HSD, $P < 0.05$.

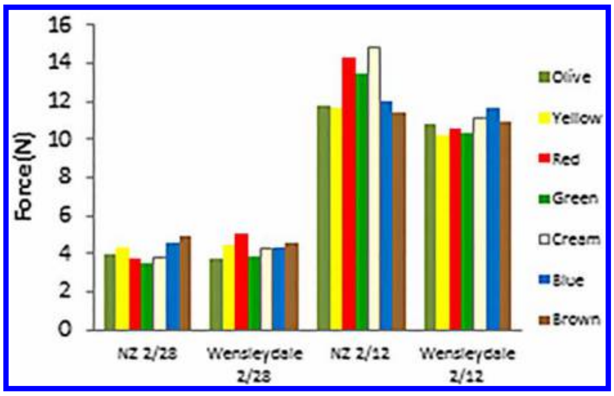

Figure 6 Maximum tenacity at sample failure point of the wools.

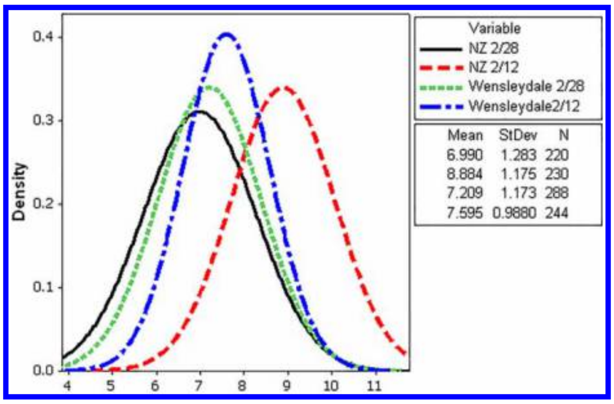

Figure 7 Tenacity of all four wools as normal distributions.

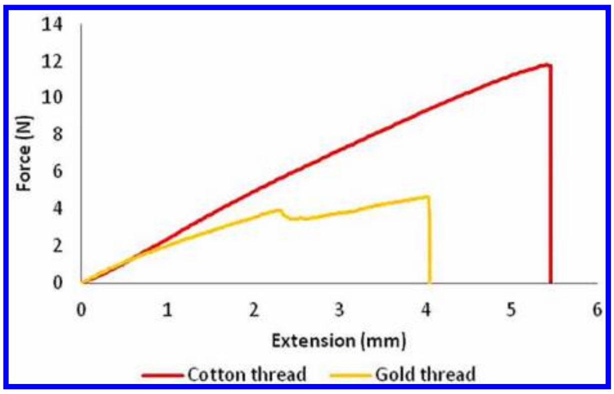

Figure 9 Graph showing force vs. extension for cotton and gold-coated threads.

here to have conformed to quality testing by the manufacturer prior to sale. The effects of dyeing 'in house' may have had some effect on them but as the undyed wool was not available for testing this cannot be ascertained.

Compound wool wefts

When a typical combination of wools used in the weaving, comprising two 2/28 and one 2/12, was tested, the three wools failed independently (Fig. 7) with the two 2/28 wools failing first (the difference between the tex values is within the variation of tex for the 2/28 wools) followed by the 2/12 wool. This is consistent with Fig. 3, which shows that the 2/12 wools exhibited significantly greater extension than the 2/28 wools at maximum load. This test shows that compound wool is only as strong as the weakest wool yarn – when the weakest fails the tapestry is weakened and is visibly damaged (Fig. 8).

Cotton and gold weft

The gold thread appears to show two break points corresponding to the thin outer gold coating failing followed by the inner cotton core. The cotton yarn's yield point is closely associated with its break. It has a very short or no inelastic stretching region appearing to go from elastic stretching directly to breaking. The tex values used in the tenacity calculations were for the cotton yarn 53.9 cN/tex and for the gold thread 24 cN/tex.

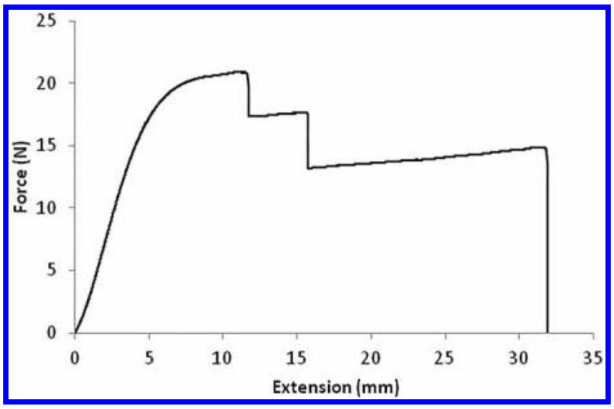

Figure 8 Graph of force vs. extension, of the compound yarns, two 2/28 and one 2/12.

Cotton warps

Today, most tapestries are woven with cotton warps. These have largely replaced wool due to their superior strength and durability.

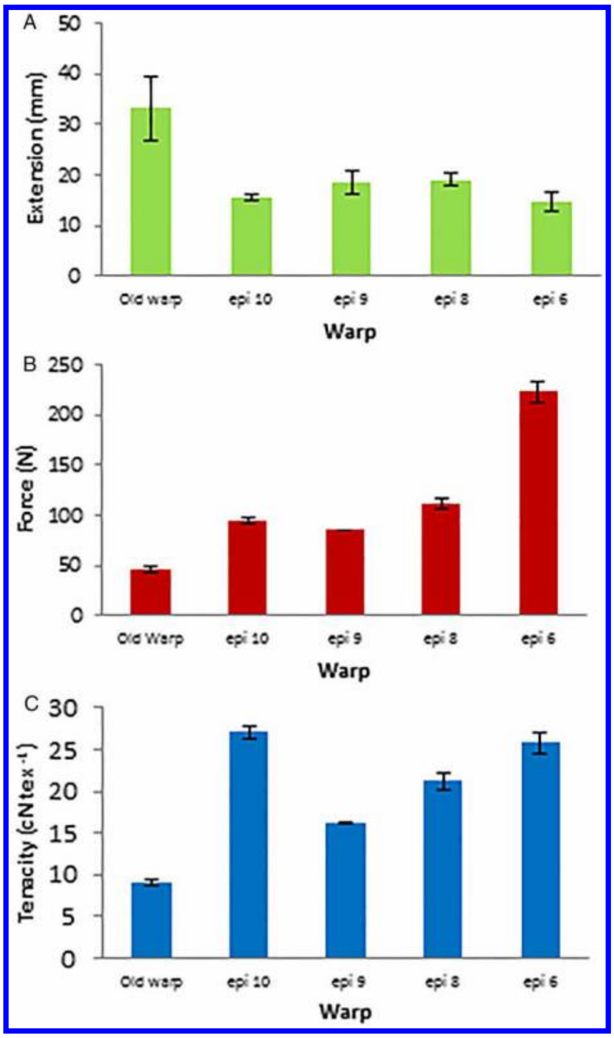

Figure 10 (A) Maximum extension at break; (B) maximum force at break; (C) maximum tenacity at break.

Extension at maximum load

The warps of epi 10, 9, 8, and 6 showed no significant difference in their maximum extension but the 'old' warp was significantly different from all the rest. There was a greater variation in the maximum extension at break and also the extension of the 'old' warp was much greater than for the other warps, an indication of the heterogeneous nature of its degradation (Fig. 9A).

Maximum force

The force required to break each warp was significantly different, although this was not a direct reflection of epi number, being in the order 'old warp' < epi 9 < epi 10 < epi 8 < epi 6, but can probably be more easily explained by the differing manufacturers/suppliers. The 'old' warp was the weakest as ageing had degraded it. Its actual epi is not known but it was judged by comparison to known warps to have an epi around 9–10. Fig. 10 shows graphically the differences in force and elongation between the tested warps.

Tenacity

As for the force, the tenacity of the cotton warps varied by manufacturer/supplier, the order being 'old warp' < epi 9 < epi 8 < epi 6 and epi 10. The inclusion of tex in the calculation changed the order slightly but the 'old warp' and 9 epi were still at the lower end. Fig. 11 shows these results graphically.

The experimental regime employed has generated results relative to these testing conditions and therefore is comparable to results which have undergone the same or very similar regimes.

In the weaving of a tapestry, materials with very different physical and chemical properties are being combined, and detailed studies of these properties have been reported previously in relation to tapestries and historic textiles (Garside & Wyeth, 2003; France, 2005; Hacke & Carr, 2005). The differing properties of cotton warps and wefts and wool can be explained by their differing structures, wool having a proteinaceous structure based on amino acids and cotton having a cellulose structure. Comprehensive discussion and research on these structures can be found in Cook (1993) and Hacke (2006). The comparison of the behaviour of the range of materials tested (excluding the warp yarns which are shown on Fig. 11) is shown by the force vs. extension curves (Fig. 12).

The results from testing the 'old' cotton warp clearly demonstrate the effects of degradation over time on materials. It is obvious that in the future the properties of materials tested here will change and that their responses to external factors such as temperature, relative humidity, and polluting species will differ. In addition, their degradation at differing rates will be caused by various reactions to moisture, air light, heat, and microorganisms (hydrolysis, oxidation, photolysis, thermolysis, biolysis) none of which will be completely mutually exclusive. Publications on these processes can be found (Park *et al.*, 2004; Odlyha *et al.,* 2005; 2007; Batcheller *et al.*, 2006; Vanden Berghe, 2012).

Conclusions

These results give us a greater understanding of the physical behaviour of different yarns within the tapestry structure. The comparison of how cotton and wool break demonstrates that when tapestry is put under sufficient stress the cotton will snap but the wool may only stretch and then recover. However, this extension could be beyond the wool's elastic region and so would be visible as 'bagging' on the tapestry. When wool is stretched beyond its yield point and moves to the yield region there will be some recovery, almost completely up to 30% extension, but after this point there is not complete recovery. In addition, this recovery is through a different curve (Hearle, 2000).

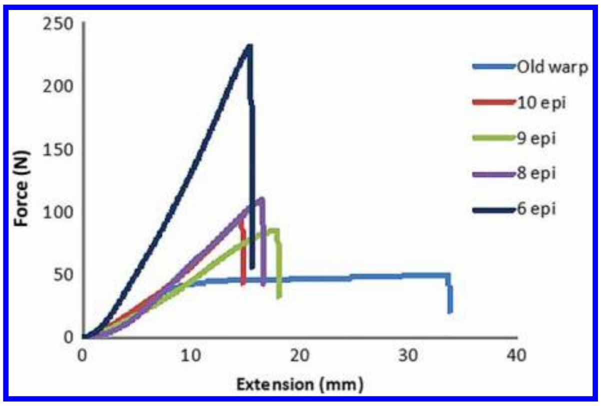

Figure 11 Force vs. elongation of the warp yarns.

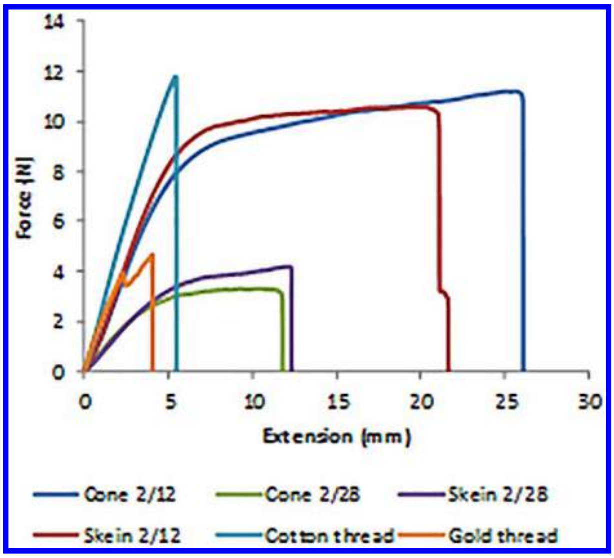

Figure 12 Force vs. elongation of cotton and wool yarns.

In this post-yield range, bonding within the wool structure has been altered, and sometimes broken, and the wool weakened (Liu & Yu, 2007). This part of the tensile testing process is analogous to breaking wool by hand as opposed to cutting it with scissors. It is therefore advised that weavers always cut using scissors to avoid including damaged wool in a tapestry. Although this work, in common with other studies (Garside & Brooks, 2005; Hacke & Carr, 2005), has focused on the break point, in terms of the wool weft further work on detailed study of the point between the yield and post-yield would be more useful as this would give an indication of the point where irreversible damage to wool yarn begins.

The differences in properties of the NZ and Wensleydale wools could be a result of a variety of reasons such as the sheep breed and environments (Cook, 1993). However, as our results demonstrate, differing processing methods have demonstrable effects. The effects of the dyeing of the wools show that the processes used have had an impact on the properties of, and from the findings here it would appear that specific dyes cause changes in strength. However, without detailed microchemical analysis it is impossible to say why these variations have occurred. The cotton warps showed variations in tenacity that indicated that the epi is not always an indication of strength; again, this is related to manufacturing processes and will therefore vary from supplier to supplier.

As wool and cotton yarns degrade, their strength decreases due to damage to their molecular structures. Therefore, comparison of future mechanical testing values with the results presented here will give numerical values of the changes over time, leading to a better understanding of the long-term degradation patterns observed in tapestries. While the overall strength of a tapestry is many orders greater than the force measurements recorded for yarns here, understanding the properties of the components of the composite helps in the overall interpretation of where weakness can be introduced even before the ravages of time and environmental factors come into play.

Tapestries now being woven in the twenty-first century will require conservation in years to come. The degradation of tapestries is a complex process involving many factors in addition to the mechanical properties of the yarns tested in this work. While the work reported here does not include the effects of modes of hanging, degradation processes, or physical damage, it does create a baseline dataset of mechanical strengths of the materials used. It is hoped that the tapestries newly displayed at Stirling Castle will provide a valuable resource for ongoing testing as the decades pass, informing our understanding of tapestry wool degradation in real time.

Donors and suppliers

www.westdean.org.uk/tapestry/tapestryhomepage.aspx.
www.dovecotstudios.com/tapestry-studios/.
www.bingleytextilesupplies.co.uk.
www.holma.se.
www.georgeweil.com.

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