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Methodology for tensile testing historic tapestries

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Abstract. Historic tapestries are very important and complex artworks. Their heterogeneous structure composed with different materials is weaved in warp and weft threads with the objective of render an image to be displayed. Often on open display these objects are exposed to forces caused by their own weight as well as by the strain experience due to moisture adsorption and desorption cycles when temperature and relative humidity of the surrounding environment fluctuate. Since physical damage is usually supported by conservation stitching techniques there is a need to understand how certain decisions would influence future mechanical behaviour of a tapestry. This requires the need of establishing a methodology that helps to understand how different sections of these heterogeneous objects respond when forces are applied to them.

Past research considered tensile testing of primarily new woven aged sections which are not representative of the historic tapestries [1]. Digital image correlation (DIC) was also successfully used in order to characterize the strain states of woven tapestries [2]. However, information on how wool and silk behaves as well as the influence of damage and stitching in some areas is still scarce and there is the lack of a methodology for a full strain analysis.

In this research, tensile mechanical behaviour is being studied in order to inform on how different fragments of historic tapestries behave when a certain tensile force is applied on them. For this, a new methodology of analysis is proposed. Force strain curves collected from tensile tests are analysed together with complementary DIC data to understand the strain states that were present in different stages of the mechanical tests. Results proved that a holistic methodology, using both techniques required for successful interpretation of data. Furthermore, this experimental work demonstrated that tapestry areas behave differently when a tensile force is applied.

1. Introduction

Historic tapestries are one of the finest artistic works that exists in European art. Their manufacture process in a loom usually required the work of several high skilled weavers that transposed into textile what was their own interpretation of a cartoon previously designed by an artist [3]. After mounting the warp threads in the loom, the weaver will then interweave the dyed weft threads against the undyed warp structure, beating down each one of the weft threads until the warp structure is completely hidden in the final result [4]. In the process of weaving a tapestry slits are formed when there is a break in colour

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on the line of one warp. When a tapestry was finished, the slits were usually stitched together so the tapestry could be displayed by hanging in its weft direction. This meticulous work not only required a big workload effort from all the people involved in the tapestry manufacture but most of the times it also required the use of expensive materials including silk, silver and gold.

Tapestry production which had its high peak of production from the 15th to the 18th centuries were a symbol of status meant to be hanged only on special occasions [5]. However with the change of trends in the end of the 18th century, tapestry manufacture fell on decay and some of the best sets of tapestries were being used in permanent display as wallpapers to hung paintings or even burned to extract its precious metal threads [6, 5].

Notwithstanding the story of neglect that many tapestries have experienced, during the last decades there was an increasing interest towards their conservation and preservation. Nowadays tapestries are regarded as precious historic objects, however to preserve them to future generations there is the need of understanding conservation techniques implemented as well as how displaying conditions affect their mechanical behavior and therefore their deterioration processes.

Tapestries are usually displayed in a long-term basis without a complete understanding on how environmental factors cause mechanical damage to their structure. When on display, in their weft direction, these objects are always supporting their own weight. However, cycles of moisture adsorption and desorption makes weight change through time making the research of tensile loads in tapestry structures an area with major interest.

Past research studied how DIC can be used to monitor strain in historic tapestries [2] as well as how tensile tests are useful to extract tensile properties from tapestry samples [7].

This work aims to test a methodology of using together tensile testing with digital image correlation in historic samples of tapestries. Since the purpose of a tapestry is to render an image with interweaving threads, every section in an historic tapestry has always a high level of heterogeneity in its structure. This heterogeneity in the weaving is even more enhanced when there are slits, damaged areas or stitching repairs that most of the times use different materials than those used in historic weaving. Therefore its mechanical behavior cannot be evaluated according to only tensile tests performed in some weaved samples since this can lead to incorrect interpretations of what is really being quantified.

Previous research on tensile testing of tapestries considered mainly new woven aged samples [1], or performed tests on single yarns [8] which are not representative of the complex structure of the historic tapestries. This study explores the results of a methodology obtained for testing historic tapestry samples selected from Historic Royal Palaces (HRP) collection of tapestry fragments made available for the purpose of this study. This paper discusses the development and testing of a proposed methodology as well as informs of some unique mechanical characteristics that can be found in historic tapestry structures.

2. Materials and Methods

A tapestry by its nature, has a heterogeneous structure composed of warp and weft threads. Considering this heterogeneity, 5 different fragments were selected to be tested in this study. In each one of these fragments, 5 different zones measuring 76 mm per 80 mm were tested using the grab method for tensile testing. Since the average results of the tensile tests were used to characterize the tensile response of each fragment, sample zones were selected with the objective to be representative of the whole fragment. Test samples were chosen accordingly with characteristics that were most common across all the fragments. However, in some cases these 5 samples shared common areas between each other due to the reduced size in some fragments as well as the difficulty in the selection of 5 representative test zones. Notwithstanding, the selection process of samples was a crucial step in this study once that the 5 samples needed to be characteristic of the whole fragment, otherwise it would not be suitable to work with the average results from the 5 tensile load-strain curves.

Physical properties of thickness, fineness, percentage of silk and a ratio for slits were characterized for each of the selected sample zones.

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The methodology used in this study results from a combination of two common methods applied in textile testing. These two methods are the tensile testing using a Universal Tensile Machine (UTM) and Digital Image Correlation (DIC). Each method has been proved to be useful in the understanding of the mechanical behaviour of tapestry structures [7, 9]. However, what is now explored is the simultaneous use of these two methods in a more holistic way by characterizing the heterogeneous physical properties of historic samples by clarifying the understanding on how these complex tapestry structures behave. This methodology is summarized in Figure 1.

Samples used were selected and named according to their file number in the collection of tapestry fragments at HRP. For this selection, 2 homogeneous fragments were chosen, fragment 44 with weft threads woven entirely from wool and fragment 143 from silk. Fragment 131 is also entirely made from wool, yet it has a heterogeneous structure typical of historic tapestries. Fragment 154 was chosen since it has similar quantities of silk and wool in its weft direction. Finally fragment 68 had a large number of silts in its structure. Destructive sampling on these woven textiles was not considered by the fact that these fragments are historic. Instead, grab test method for tensile testing selected sample areas on each fragment was carried out.

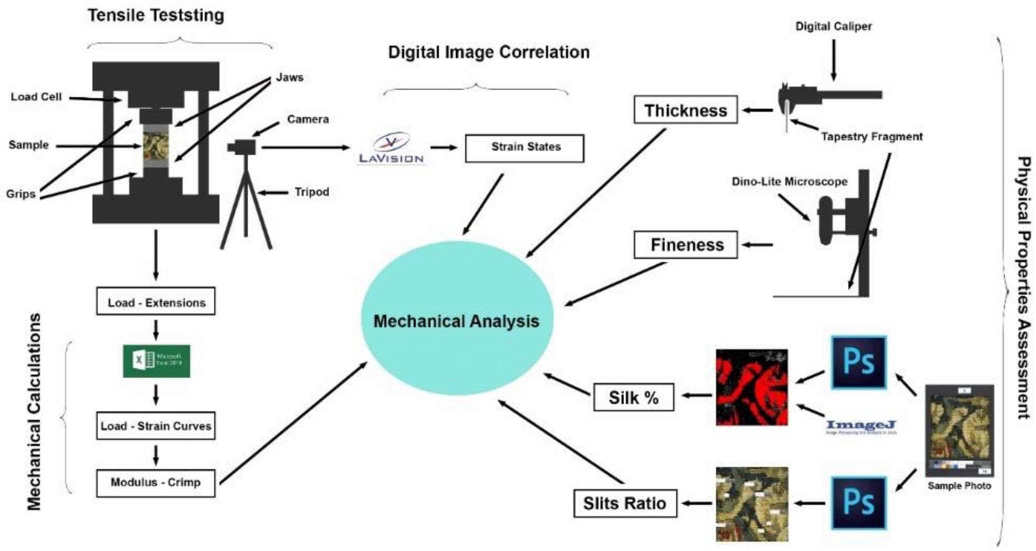

Figure 1. Methodology used to characterize and test the samples.

2.1. Physical Properties assessment

Tapestries are usually weaved with multiple materials being wool and silk the most common ones. To differentiate and quantify the different materials present on each sample, a material assessment was carried out. This assessment was done considering photographs taken on the perpendicular direction of the selected samples. After distinguishing silk from wool, silk weaved areas were manually highlighted using the software Adobe Photoshop CS6 and had latter their percentages measured under ImageJ. To characterize the number of slits that were present in each sample, photographs of the samples were used to measure the length of horizontal projection of each slit to create ratio. This ratio was calculated as $S = \frac{\sum_1^n(w)}{76}$ where S is the slit ratio, w the width of slits in mm, n the number of slits measured and 76 is the width of each sample in mm.

In each fragment, the thickness was characterized using a digital calliper HITEC 101-45 having 0.01mm precision. Initially with the jaws joint together in the closed position the calliper was set to zero. After, the jaws were open and then closed sequentially on each measurement point dispersed around the fragment. A total of 10 measurement points were considered in each fragment being 5 in the weft and 5 in the warp direction. A period of time of 30±5 seconds was given after closing the jaws and before reading each measurement in accordance with the current standard [10]. Each one of these points were measured 3 times and the results were then averaged.

2.2. Tensile Testing

Since tapestries are displayed by hanged in the weft direction, supporting their own weight, tensile tests only considered this orientation.

To characterize the tensile properties of the selected samples a universal testing machine (UTM) Instron 3365 connected to a pressurised pump was used. To ensure the homogeneity of every experiment, every specification used during the tests was the same on every sample. Tensile tests used serrated jaws in the holding grips with the purpose to avoid slippage of samples during testing. However, to prevent the damage that can be caused by weakening of the samples in the holding areas of the serrated jaws, an adhesive tape was used on each jaw. Each sample was mounted in its relaxation state with the weft threads perpendicular to the edges of the Jaws. Just before closing the grip's jaws, the sample was carefully adjusted to ensure that sample areas of each fragment placed on the UTM matched the previously recorded areas. After sample adjustment, the pressurised air pump was activated to hold samples at a pressure of 3.5 bar.

In these tests, the rate of extension was 2 mm/min and a load cell of 5KN was used. The accuracy of the measurements was 0.25N for the force and 0.12mm for the extensions.

These tensile tests were done under controlled environmental conditions of 25,0±2,0 °C for temperature and 45,0±4,0% for relative humidity. All samples were conditioned in this environment during 24h before testing.

The stopping criteria was defined as the break of any thread except for samples 44-1 and 143-1 that were tested to a level where there was a defined linear zone.

Results are presented in load-strain curves to be more comparable with other values on literature, however since stress is defined by $\sigma = \frac{F}{A}$ where F is the force applied and A the area, it means that stress is dependent on the thickness of material and some considerations regarding interpretation of results were taken.

To measure stiffness in each curve, Young modulus was considered as the slope of the linear zone in a stress-strain curve [11]. However due to the fact that textiles are mechanically different from other materials [7], in this study the slope of the linear region was called the apparent linear modulus and was calculated by the slope of the linear zone in the load-strain curve as suggested in the literature [1]. Units of KN/m were used to compare results with others available in literature [1,7]. To confirm the linearity of the linear zone in each curve a linear regression line was calculated on excel in steps of 1% strain, starting from 0% until the end of the curve. When the coefficient of determination R^2 of the regression line was higher than 0.9985 the slope was considered linear and the value of the apparent modulus was recorded. Strain where this linearity started was taken as a measure of the end of the crimp zone.

2.2.1. DIC

A DSLR camera Canon EOS 700D with an ISO 100 was used to capture a sequence of photographs along the test. Just before the test started, two photographs were taken in order to inform about the noise values that were taking place under DIC.

Each photograph was captured manually using the remote control of EOS Utility software. This was made using a levelled tripod which hold the camera lenses without vibrations in a parallel direction of the tensile tested sample. For light conditions, flash was not considered, however good and constant illumination of the samples was satisfied. To ensure the best possible quality, these photographs were shot using RAW format, which was later converted into a .tiff format and grey level image using both dcraw [12] and Adobe Photoshop CS6 software respectively.

All photographs were processed with the software Davis 8 from La Vision using 2D DIC. The strain states on each one of the samples were measured by comparing the distorted images with the reference photographs of the samples before the test. Strain distribution on both vertical and horizontal directions was calculated and extracted using the "sum of differential" as correlation mode in Davis software.

3. Results and Discussion

Measured physical properties and calculated apparent linear modulus and end of crimp strain are displayed in Table 1. Load-strain curves of the averaged 5 tensile tests on 5 historic fragments are presented on Figure 2. Figure 2 also shows the tangent at the last stage of each load-strain curve. As a first observation on these curves it can be noticed that they follow the standard tensile behaviour that characterizes other textile woven samples that are found on the literature [7]. This behaviour is composed of three different stages. Initially there is a zone where the samples are adjusting to the pulling grips and that is commonly known as "slack" [7]. In tested samples of Figure 2, this is a very subtle change that happens before 1 % strain. After this primary stage, the weft threads are aligned with the pulling grip and they start to lose their crimp by becoming more and more stretched as the strain increases. This region is characterised of being mainly curvilinear and corresponds to the transition from a relaxed into a stretched state. This curvilinear region is placed in the load-strain curves between the end of the slack region until a stage where the behaviour is linear. This linear stage is named in the literature as the linear region [7]. In the linear zone, the woven textile, having its weft threads under tension and without crimp, behaves as an elastic material until its weft thread structure starts to fail. Tangents on Figure 1 show that for most of historic fragments tested, except for 44, there is not a clearly defined transition from crimp to the elastic region. Since fragment 44 is very homogeneous, this suggests that in historic tapestries the progression from crimp region to the elastic phase doesn't seem to have a clearly defined transition point.

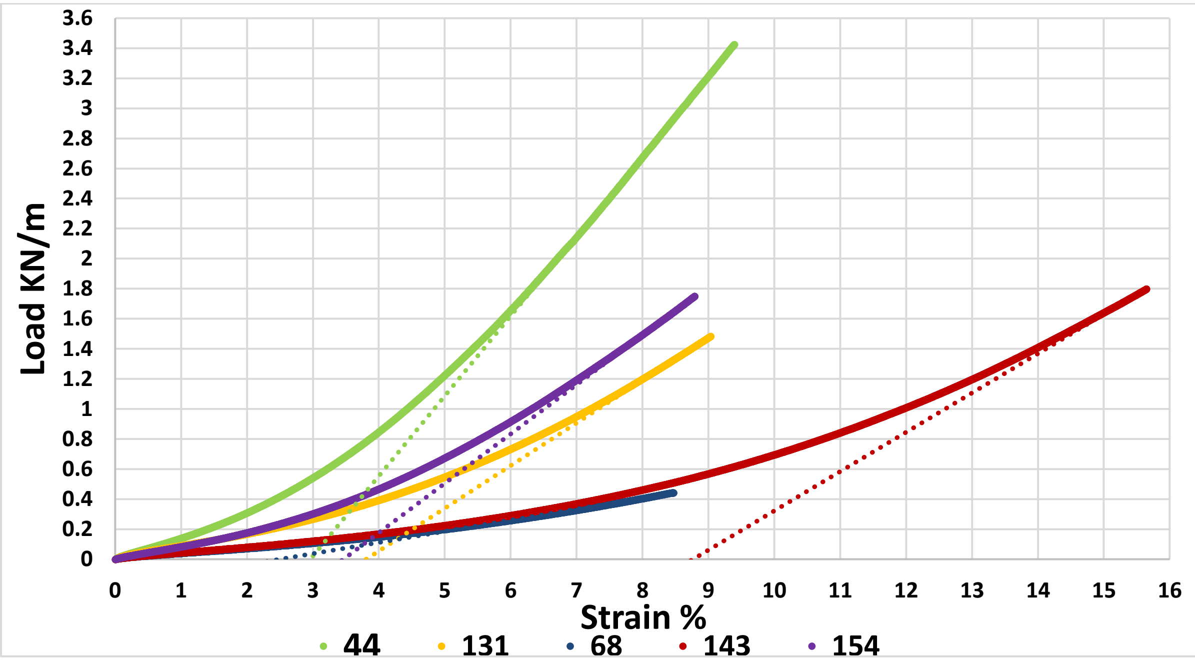

Figure 2. Averaged force-strain curves for 5 samples tested in each fragment.

Despite having some minor damaged zones, sample 44 and sample 143 are both very homogeneous. However, by observing Table 1 it can be noticed that while sample 44 has its weft structure composed entirely of wool, sample 143 is composed of silk. It can be observed that the sample made from wool is stiffer and has its elastic zone starting at around 6% strain, while on the one made from silk the elastic area only starts at around 14% strain. With this, it seems that samples made from wool are stiffer and had less crimp in the weft threads when compared to those made from silk. However, when looking at the other samples this could not to explain why wool sample 68 is behaving as the silk sample 143 and 154 and 131 although with different material compositions have stiffness between values of wool sample 44 and silk sample 143.

Table 1. Physical and mechanical properties of tested samples.

Tapestry Fragment	Direction	Fineness (Threads/cm)	Thickness (mm)	Testing Zones (Samples)	Silk %	Slits Ratio	Apparent Linear Modulus (KN/m)	End of Crimp (Strain %)
44	Weft	10.1±6.2	1.7±0.1	1	0	0.00	0.55	4
				2	0	0.00	0.55	6
	Warp	6.2±0.5		3	0	0.00	0.41	5
				4	0	0.00	0.60	5
				5	0	0.00	0.47	6
68	Weft	9.3±3.9	2.5±0.2	1	0	1.26	0.10	8
				2	0	1.45	0.07	5
	Warp	3.9±0.3		3	0	1.17	0.11	8
				4	0	1.47	0.12	8
				5	0	0.91	0.13	8
131	Weft	6.9±4.4	2.9±0.2	1	0	0.00	0.24	7
				2	0	0.00	0.27	8
	Warp	4.4±0.4		3	0	0.00	0.31	7
				4	0	0.00	0.29	7
				5	0	0.00	0.3	8
143	Weft	10.8±7.6	1.3±0.1	1	100	0.00	0.25	15
				2	100	0.00	0.28	12
	Warp	7.6±0.4		3	100	0.00	0.22	14
				4	100	0.00	0.27	14
				5	100	0.00	0.37	14
154	Weft	15.0±5.0	2.1±0.2	1	59	0.00	0.21	4
				2	56	0.36	0.30	7
	Warp	5.0±0.4		3	61	0.00	0.30	7
				4	58	0.00	0.25	5
				5	63	0.00	0.39	6

Images of the DIC results for strain both on vertical and horizontal directions are presented on Figure 3. Here one single sample was selected to be representative of the 5 tested samples. This sample is identified by its fragment number followed by its sample number.

With results taken from DIC, interpretation of the tensile behaviour in each sample starts to emerge. First of all it is noticeable that homogenous samples 44 and 143 have fairly homogeneous strain distribution across its surface when a tensile force is applied on them. Moreover only with the exception of the vertical direction in sample 143 that is very homogeneous, damaged and creased areas became visible under DIC both on horizontal and vertical directions.

Sample 154 has 59% of silk, however its load-strain curve in terms of stiffness is more similar with the sample 44 made from wool. An observation of strain distribution on DIC results suggests that this behaviour happens since it's mainly the brown wool threads in sample 154 that are absorbing most of the tensile load applied in the vertical direction. On the horizontal direction, these areas are also the ones that have more compression which agrees with the Poisson ratio effect of shrinkage in the horizontal direction when the vertical is being stretched.

Regarding wool sample 131, although is thicker than the rest of the samples, it seems to have a very similar behaviour to sample 154. It is interesting however that this happens and this can mean two things. Once that in sample 154 it is the wool areas that seems to be absorbing most of the load applied, this could mean that both samples are in the range of the usual behaviour of heterogeneous wool samples or it can be that due to the small damage of sample 131, shown by the white warp threads in Figure 3, this wool sample has more crimp that what is usual in wool samples. However, to clarify this point and completely characterize the behaviour of wool samples more tests with different samples should be done. By observing the load-strain curves in Figure 2, a curious tensile behaviour of a wool sample is the one of sample 68 which its curve is very identical to silk sample 143. Yet an observation to the properties and strain states of this sample suggests the reason why this happens. Properties on Table 1 show that sample 68 is the only that has a considerable amount of slits in its structure. Moreover, a closer look at this sample on Figure 3 shows that this slits have some stiches closing them. This means that the crimp experienced by this sample is higher than the other ones since slits enable this sample to have an increased freedom of movement. Furthermore, DIC results show that areas with stiches are those that have more strain justifying the level of crimp present on this sample. Stiffness can also find an explanation by these observations since stiches are made with yarns of a different material than the one used to weave wool and silk areas.

As a general observation on DIC results it is noticeable that horizontal strain showed more compression in areas of damage and slits like in samples 44 and 68 and on areas of interrupted threads in samples 131 and 154.

It is also noticeable that the average load-strain curves showed correlation in values of strain with the individual DIC results, being consistent with them.

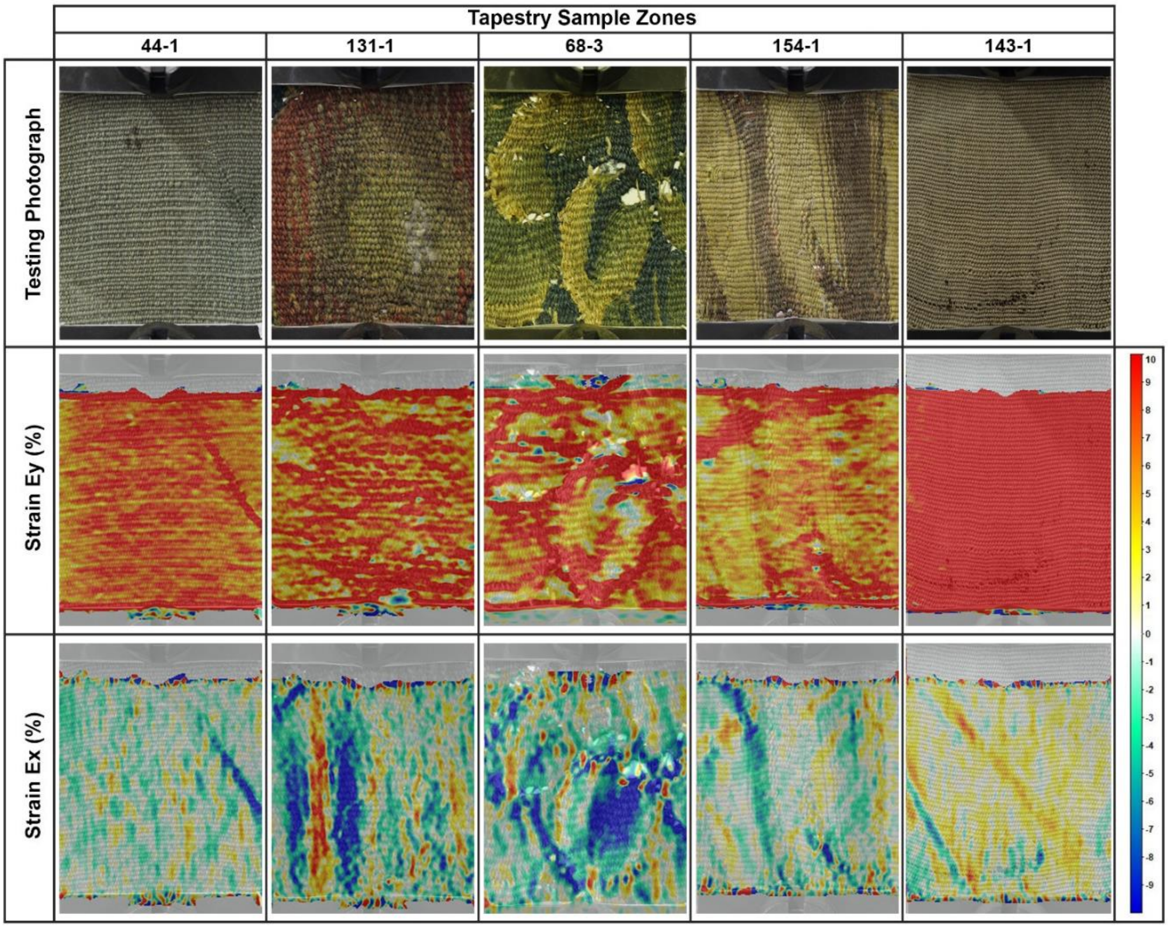

Figure 3. DIC results for vertical and horizontal strain distribution in 5 tested samples.

4. Conclusions

Performed tests seems to suggest that under hanging, different areas of an historic tapestry will behave differently according to number of factors. These areas will experience different levels of strain distribution and load concentration making some zones more susceptible to breaking when exposed to hanging loads. It is also suggested that the areas with more strain applied correspond to threads that have originally less crimp applied on them. Notwithstanding, to have solid conclusions about the behaviour of historic tapestries its required to test more examples of historic fabric.

Digital image correlation enabled not only to increase the understanding of the strain states that are present on a sample section but also the establishment of a relationship with the load-strain curves obtained on the tensile tests.

This methodology, implies that both techniques are being used at the same time. Furthermore, it has been showed that there is a consistency between results from tensile testing and from DIC. This testing procedure proved to be beneficial for interpreting the results of different heterogeneous historic tapestry samples with good repeatability.

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