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Long term condition monitoring of tapestries using image correlation

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ABSTRACT

Digital Image Correlation (DIC) is used to extract non-contact full-field three-dimensional displacement and in-plane strains from an historic tapestries. A DIC-based approach is devised that allows the effect of RH variations on a tapestry to be quantified. A historical tapestry has been monitored in a closely controlled environment and in the natural environment. The results revealed that very small variations in RH can have significant effects on strain. An automated long term monitoring approach has been devised to allow strain data to be extracted in real time from tapestries in remote locations. The results show that DIC provides better understanding of the effect of RH fluctuations on strain which will ultimately lead to more insight into the degradation process of historical tapestries. The paper demonstrates the potential for using DIC as a condition monitoring tool.

1. Introduction

Tapestries are hand-woven textiles that are often large, have intricate designs, were very time consuming to produce and expensive to commission. Tapestry conservation is a key issue in the heritage sector so specialists are employed to examine the condition of tapestries and recommend conservation strategies that do not alter their intrinsic characteristics and maintain their appearance and function. Tapestries are produced by weaving on a loom where closely spaced, highly twisted yarns, i.e. warp yarns, are stretched and fixed in one direction. Less dense yarns are woven transverse to the warp yarns to produce the pattern, i.e. weft yarns. On completion the tapestry is hung so that the weft yarns support the weight of the tapestry. It is known that tapestry degradation is related to the environment, however the precise mechanics of the failure of tapestries has not been physically characterised and currently condition assessment is based on the observation of an experienced conservator. In this paper a means of determining the rate of tapestry deterioration is established that related the relative humidity (RH) changes directly to the strains induced in the tapestry.

Inappropriate humidity can have severe effects on many artefacts e.g. paintings and wooden furniture [1]. To a lesser degree, tapestries are also affected by humidity. For this reason, museums galleries, and historical houses normally control humidity to tight ranges (typically 50%± 5%RH [1]) using air conditioning systems that can be very expensive to run. However, it has not been established if this range provides the 'ideal' conditions for preserving and displaying textiles, this is still a subject of debate within the conservation community [2]. Therefore, if it can be shown that widening the 50%±5%RH range has little or no significant effect on textiles, the budgets spent on expensive humidity control systems can be allocated to other conservation activities.

As the moisture content of the air surrounding the tapestry changes, the tapestry responds rapidly to this change by altering its own moisture content to stay in equilibrium with the surrounding air. In [2] a tapestry was displayed and the weight of the tapestry, RH, and temperature were recorded regularly over a period of nine days. Two important observations can be made: there is a strong positive correlation between the weight of the tapestry and fluctuation in RH. Secondly and more importantly, in only one week, the weight of the tapestry had dropped by approximately 700 g then increased back to its initial weight. Although this change in weight did not cause any noticeable damage at the time, it is a fair assumption that this will cause deformation in the tapestry. Therefore the continual cycling of RH will cause cyclic deformation to occur and may lead to failure. The work in the present paper proposes a DIC-based continual monitoring approach for quantifying the effect of RH fluctuation not on weight, but on strain in a tapestry (which is more directly linked to material performance and hence damage). This monitoring approach has been applied to study the effect of RH fluctuation on tapestries in both controlled and uncontrolled humidity environments. Since DIC is a non-contact full-field deformation measurement tool, there is a strong potential for using the continual monitoring approach developed in this work to study the effect of RH fluctuation on other museum objects.

2. The tapestry and test set-up

The tapestry used in this work is known as the verdure fragment and was woven over 300 years ago. It is 185 x 165 cm x 1 mm thick and has a mass of about 5.8 kg. The warp material is wool and the weft materials are a mixture of wool and silk. It has a linen backing attached by stitching to the four edges. It has 24 weave repeats per cm^2 (3 warp and 8 weft). The tapestry is mounted by means of a Velcro strip attached to its top edge to a specialist display device that enables the tapestry to stand away from the wall.

An essential part of DIC is that sufficient contrast is available in the image so that the image processing algorithm can detect features that enable the correlation. For engineering structures this 'correlation device' usually takes the form of a painted 'speckle pattern' applied to the surface of the material using an aerosol spray. This approach is unacceptable for tapestries as the paint would cause permanent disfigurement. In previous work [3] the suitability of the regular weave pattern along with the natural random contrast in the fibre, inherent in all textiles, was shown to be suitable as a correlation device. Therefore the DIC readings are all taken directly from the surface of the tapestry.

The DIC system used in the current work is manufactured by LaVision, and comprises two 2-Megapixel CCD cameras. The images were processed using the standard features of DaVis 7.2 software (developed by LaVision) and the StrainMaster package to obtain full-field strain maps. The digital cameras were fitted Nikon 50 mm f/1.8D lenses.

The verdure fragment was monitored initially in a room where humidity was controlled to 50% ± 5% RH i.e. the same humidity level that tapestries are typically exposed to in the museum environment and then in the natural environment. The cameras were positioned approximately 0.6 m away from the tapestry. The angle between the cameras is approximately 40º and the distance between them is 0.5 m. Calibration was carried out using a LaVision Type 11 two-level calibration. A 120 × 90 mm region of interest was selected for monitoring within the central part of the tapestry. The DIC system was set to record one image every 5 minutes. An environmental sensor was positioned approximately 10 cm in front of the tapestry and was set to record RH and temperature at the same rate. Note that temperature was controlled to 22ºC in all the experiments that have been conducted in controlled environment. The DIC image acquisition and the RH/temperature data recording were started simultaneously. The room was closed and the monitoring process was checked remotely at regular intervals. Once recording is completed the images are processed using Davis 7.2 and global strain data are extracted from the region of interest using 128 x 128 interrogation cells that covered a region on the tapestry of about 0.5 cm^2.

3. Controlled humidity experiments

The tapestry was monitored for 48 hours and the humidity was controlled to 50% ± 5% RH. Figure 1 shows strain, temperature and RH plotted against time (temperature was controlled to 22ºC). Note that strain on the y axis has been magnified 105 times so that it can be plotted with RH on the same graph. For instance, the '20' mark on the y axis corresponds to 20% RH, 20ºC and 0.02% strain. The main observation from the results in Figure 1 is that longitudinal strain responded rapidly to fluctuation in RH, even though the test has been carried out in a controlled humidity environment. A variation of approximately 8% in RH has caused the longitudinal strain to fluctuate by more than 0.06%. Recalling the results of [2] as RH increases the mass of the tapestry increases. Likewise, in Figure 1 it can be seen that as RH increases the longitudinal strain increases.

It could therefore be concluded that the strain increase is directly related to the increase in mass (and therefore self-load) as a result of moisture uptake. Therefore, the increase in moisture content does not only affect the mass of the tapestry, but also the strain. In conducting this work it was not possible to measure the mass change as this would mean removing the tapestry from display and would affect the DIC readings. Furthermore, the mass change in the tapestry used in [2] was 700 g for a tapestry of mass 43 kg. The total mass of the verdure fragment is 5.8 kg so overall moisture uptake would be less and more difficult to measure accurately as it would be reasonable to assume fluctuations would be around 100 g.

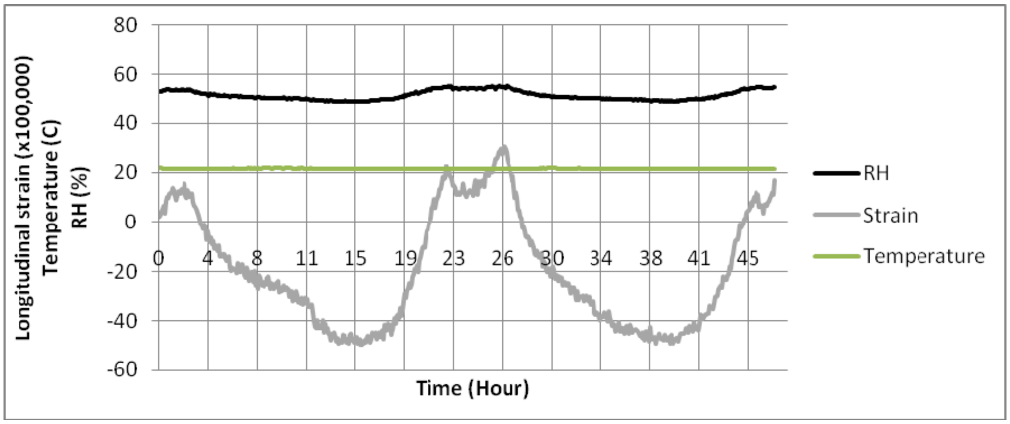

Figure 1: The effect of humidity fluctuation on longitudinal strain

Another experiment was conducted over a 130 hour period and this yielded similar results. The transverse strains were also calculated and these showed similar trends i.e. an increase in strain for increased humidity. The strong positive correlation between longitudinal strain and RH fluctuation can be seen more clearly in Figure 2 which plots strain in the longitudinal and transverse directions against RH in a scatter diagram for both the 48 hour and the 130 hour experiments. One of the main differences between the four plots is that they cross the x axis in different points. It is understandable that the two longitudinal strain plots cross the x axis at different points compared to the points at which the two transverse strain plots cross the x axis. However, since both experiments were carried out on exactly the same part of the tapestry, it would be expected that the two longitudinal strain plots would cross the x axis at the same point and the two transverse strain plots to cross the axis at the same point. It is clear from Figure 2 that this is not the case because the variations of RH in the two experiments do not have the same trends. While RH in the 48 hour experiment fluctuated within a range of [49% 55%], fluctuation in the 130 hour test was in the range of [45% 52%].

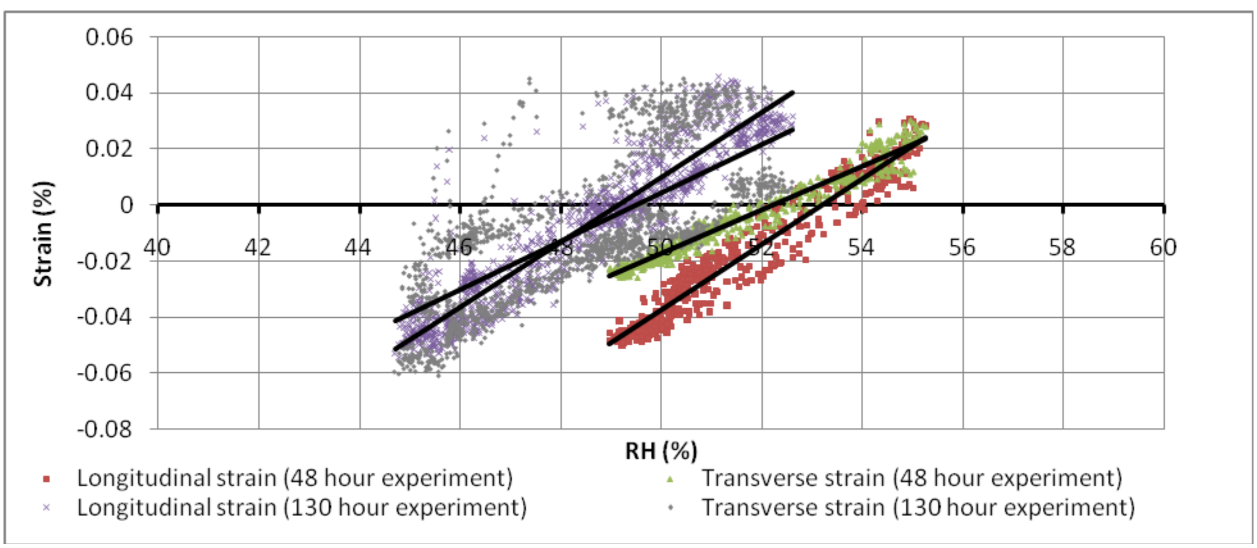

Figure 2: Comparison of the 48 hour and the 130 hour experiment results on the verdure fragment

Despite affecting the points at which the four plots cross the x axis, the difference in the ranges within which RH has fluctuated did not have any significant effect on the slopes of the trend lines. As illustrated in Table 1, in both experiments the longitudinal strain scatter plots had a slope of 0.011 and both of the transverse strain scatter plots had slopes that are approximately 0.008, clearly demonstrating the repeatability of such an approach.

Table 1: Slopes and coefficients of correlation from the 48 hour and 130 hour experiments

Experiment	**Slope**	***-x-* axis crossing**	**Coefficient of correlation (R^2)**
Longitudinal strain (48 hour experiment)	0.0117	53.20	0.9389
Transverse strain (48 hour experiment)	0.0078	49.90	0.9547
Longitudinal strain (130 hour experiment)	0.0114	47.20	0.9296
Transverse strain (130 hour experiment)	0.0087	47.60	0.5163

4. Continual in-situ monitoring in uncontrolled humidity

The experimental arrangement described above was used to monitor the verdure fragment for a period of 260 hours. The humidity was left uncontrolled in the room. RH over this period fluctuated between 48% and 34%, which is well below the 50% ± 5% RH range. The temperature during this period rose from 14ºC to 18ºC, which is most likely the reason for the reduction in of RH. Figure 3 depicts the effect that RH fluctuation had on the longitudinal strain. It is important to note that strain has been scaled by 104 times so that it can be plotted with RH (as opposed to 105 in the plots of the previous section). Therefore the 20 mark on Figure 3 refers to 20% RH and 0.2% strain. The main observation from the graph is that the longitudinal strain remained well below 0.1% until the 85th hour of the test where RH started to decline at a faster rate. The longitudinal strain immediately responded to this decrease reaching nearly -0.7% near the end of the experiment. This strain level is one order of magnitude higher than the strain observed in the controlled humidity experiments. Therefore, displaying or storing tapestries in uncontrolled humidity environment may have significant effects on the rate of tapestry degradation.

Figure 4 plots RH and longitudinal strain in a scatter diagram. The plot can be divided into two parts. In the part where RH was between 45% and 49%, the strain was below 0.1% and the slope was 0.0136. In the region of [34% 45%] RH on the other hand, the plot exhibits a different linear relationship between longitudinal strain and RH with a slope of 0.0514 RH. This linear part however contains two flat regions where strain remained constant at -0.3% and -0.6%, these correspond to the times when humidity was in the ranges of [41% 43%] and [36% 38%] respectively. These regions also correspond to the flat parts of the strain curve of Figure 3; the [125 170] and [220 250] hour ranges. Although the positive correlation between RH and strain can be explained using the moisture absorption properties of the yarns, no information has been found in the literature as to why the tapestries might behave differently in the [41% 43%] and [36% 38%] RH ranges. This requires further experiments to be carried out in where humidity can be controlled to these particular ranges.

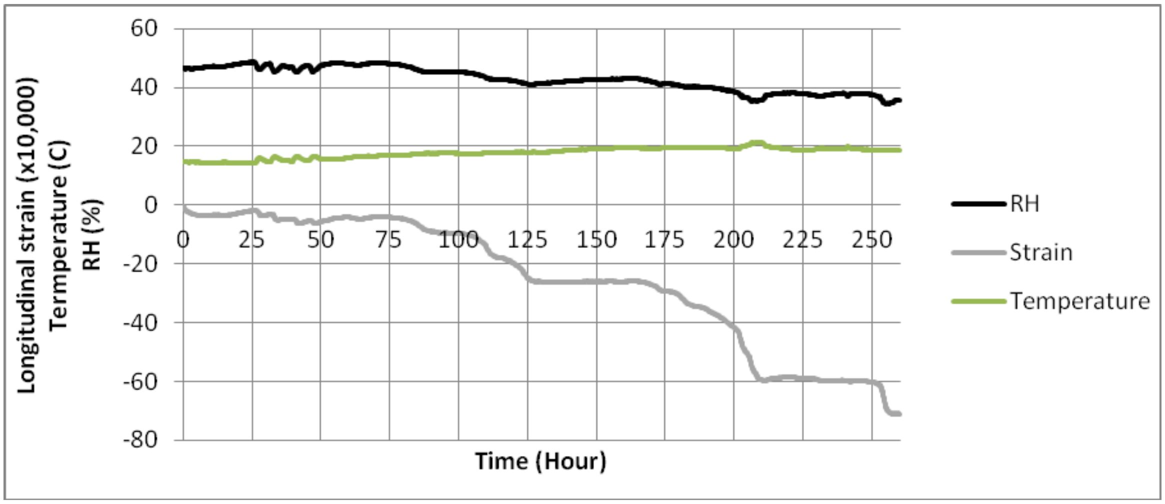

Figure 3: The effect of humidity fluctuation on longitudinal strain (verdure fragment 260 hour monitoring)

As humidity was within the 50%±5% RH range in the first 100 hours of the experiment, the slopes of the clusters of points in the controlled regions have been calculated. The slopes are 0.0136 and 0.0073 for the longitudinal and transverse strain scatter plots respectively, which agrees with the findings of the verdure fragment experiments conducted in controlled humidity conditions.

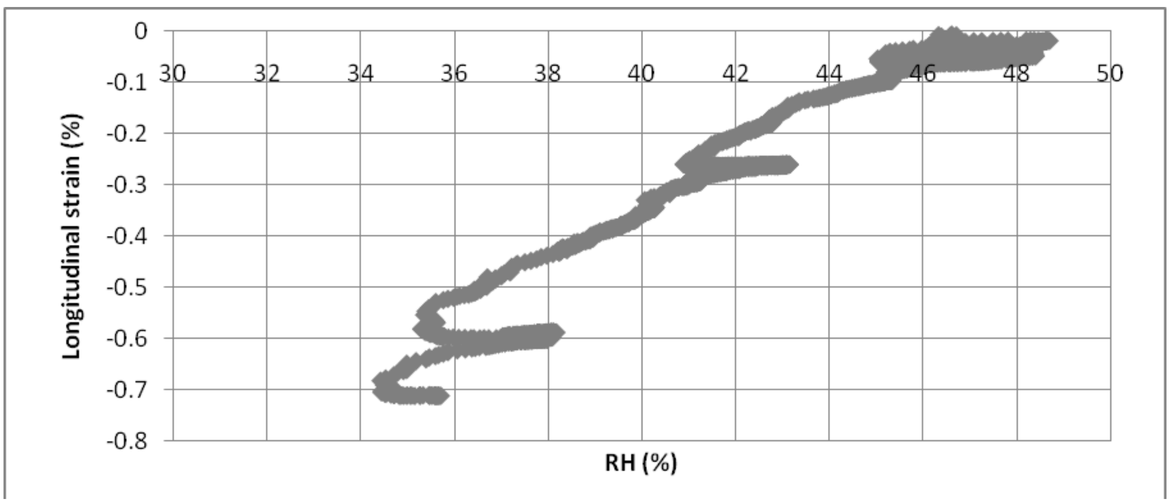

Figure 4: Scatter plot for RH against longitudinal strain

5. Definition of empirical models

From the monitoring experiments presented in this chapter, it would seem that although tapestries are complex mechanical structures, it is possible to approximate their strain response to RH changes using a linear mathematical model. To construct an empirical model for the three tapestries studied in this work for instance, a simple equation could be used of the form:

$$\varepsilon_{x,y} = k_{x,y} RH \qquad (1)$$

where *k* is a constant that can be determined experimentally and RH is relative humidity.

Table 2 shows values of *k* obtained from the experiments described in this paper and on other tapestries in other conditions. By examining the top four rows it can be seen that the verdure fragment, displayed in the standard way in controlled humidity conditions has a k_x value of approximately 0.01265 ± 0.0013 and a k_y of 0.0078 ± 0.0006. Note how these constants varied considerably when the storage and display conditions have been changed. Also note how the values of *k* differ from one tapestry to another. By applying the monitoring approach described in this paper on a larger number of tapestries, a complete, detailed, and comprehensible database could be developed that will provide conservators with a great deal of information on the mechanical effects of RH on tapestries.

Table 11: Comparison of the slope values of the scatter diagrams from various tapestries

Experiment	**Slope (longitudinal strain)**	**Slope (transverse strain)**
Verdure fragment in controlled RH(48 h)	0.0117	0.0078
Verdure fragment in controlled RH(130 h)	0.0114	0.0087
Verdure fragment (260 h) - controlled RH region	0.0136	0.0073
Verdure fragment unrolled tapestry (48 h) - controlled RH	0.0139	0.0076
Verdure fragment rolled tapestry (48 h) - controlled RH	0.0191	0.0063
West Dean tapestry (480 h) – controlled RH region	0.0015	0.0101
Armorial tapestry in controlled RH (48 h)	0.0087	0.0103
Verdure fragment constrained from four edges (48 h)	0.0044	0.0025
Verdure fragment (260 h) - uncontrolled RH region	0.0514	0.0317
West Dean tapestry (480 h) – uncontrolled RH region	0.0092	0.0119

After quantifying the effect of RH variation on museum objects, the data can be used to construct empirical mathematical models for predicting the behaviour of tapestries in various humidity conditions. Table 2 shows that different tapestries have different responses to RH fluctuation. To determine the response, experimental data must be gathered for each tapestry to make the model; DIC is the tool to do this. One this has been established, historical data on humidity can be used to ascertain how many strain cycles have been experienced in the past. To establish the condition it is necessary to inform the model using accelerated ageing data from representative samples tested to failure. This could be achieved by using the model to design tests that accelerate the effects of RH on samples in the lab. Furthermore, the mathematical models can be used to determine the 'ideal' RH condition for the museum environment. This way the long term effect of the strain changes resulting from humidity fluctuations can be estimated and the most convenient humidity levels for museum objects can be determined.

6. Conclusions

A DIC-based continual monitoring approach has been demonstrated that allows the effect of RH on strain in tapestries to be quantified. An experimental programme has been conducted that demonstrates the approach. The main outcomes are:

- The relationship between strain and RH in tapestries can be approximated by a linear model in controlled humidity conditions.
- If a tapestry is moved to a region of uncontrolled humidity strain can be increased considerably. This confirms that controlling humidity in the museum environment is an effective preventive conservation technique.
- The continual monitoring approach can be used to compare the response of different tapestries to RH fluctuations. Comparison can be carried out based on curves of RH and strain variation against time and slopes of scatter plots of strain against RH.

Acknowledgements

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