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Condition monitoring of textiles using optical techniques

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Abstract. In the paper it is proposed to use fibre Bragg grating (FBG) sensors to monitor the deformation and strain in a woven textile. Non-contact digital image correlation (DIC) is used to validate the results. The principal objective of the work in this paper is to identify a suitable adhesive for attaching the FBG sensors to tapestries and textiles. To do this, the interfacial interactions of the optical fibre, the textile material and the necessary adhesive must be considered. The performance of two types of adhesive are studied: a PVA conservation adhesive and a two-part epoxy adhesive Araldite 2015. The effect of the application of the adhesives on the mechanical response of the textile is investigated. Full-field stain maps are obtained from the DIC and are used as the basis to characterise the behaviour of the FBG sensors/adhesive system. The strain transfer coefficients and a reinforcement factor are determined under quasi-static conditions. It is shown that the local reinforcement introduced is more significant in the specimen with the FBG bonded using the Araldite adhesive than those with conservation adhesives. Nevertheless, the Araldite adhesive has a better strain transfer coefficient than the conservation adhesive, although not as high as that expect with conventional engineering materials.

Introduction

Tapestries are hand-woven textiles that often large and heavy, so it is possible that the strain imposed by their own weight is the key factor in their deterioration [1,2]; the mechanism is analogous to creep in engineering structures. The conventional condition assessment methods used in the heritage sector are visual inspections carried out by experienced textile conservators. It is not possible to identify damage prior to the appearance of visible deterioration using this approach. Tapestries are culturally significant and valuable items. It is essential that they are appropriately repaired so that they can be enjoyed by future generations. A multidisciplinary project has been set-up that is examining the possibility of using engineering approaches to monitor deformation with the aim of providing insight into the precursors to visible damage. The outcome of the project will enable timely intervention and permit a new strategy in conservation.

On of the approaches suggested in [1] was the installation of FBG optical fibre sensors on tapestry. This was because the sensors are small and do not detract from the visual impact of the tapestry. Experimental work has been initiated that has attempted to measure strains in textile materials using FBGs [1, 2]. This demonstrated that the installation of fibre Bragg gratings (FBGs) on a textile was a promising approach for tapestry monitoring. It was recognised that the effect of the installation of the FBGs on the mechanical behaviour of the tapestry warranted further investigation. Since the mechanical properties of tapestries and textiles are significantly different from those of metals or composites, it is important to consider the reinforcing effects of attaching

FBG sensors to a tapestry. For this reason, the various encapsulations of FBGs developed for structural health monitoring of engineering structures are not suitable for application to tapestries. It has been shown that bonding FBGs with adhesive is preferable to attaching them by stitching or weaving [1], but the amount of reinforcement introduced by both the adhesive and the FBG sensor has not been investigated. Therefore the strain obtained from the FBG sensors may be smaller than the true strain in the tapestry, and to date the strain transfer coefficients between the tapestry, adhesive and the FGB sensor have not been established. As the deformation of the tapestry occurs over long period of time the performance of the sensor and its attachment over extended time periods also must be established; this will be the object of future work.

The purpose of the present paper is to define the considerations that are required for identifying an adhesive that is suitable for bonding FBG sensors to tapestries. As historic tapestries are valuable the experiments described in this paper are carried out on tapestry-like machine woven wool textile specimens. It has been confirmed in previous work [1] that this material provides a good model of tapestry stress-strain behaviour. The effects of application of different adhesives on the mechanical response of the textile are investigated using digital image correlation (DIC) [3-4]. The object is to assess the possible reinforcing effects of the adhesive/sensor on the textile. The DIC approach provides a non-contact full-field measure of strain. Strain transfer coefficients were obtained using simultaneous measurements from the FBG and DIC. The DIC provided readings local to the installation of the FBGs and also from the textile material remote from the FBGs. The performance of the FBG/adhesive installations are characterised in terms of strain transfer and reinforcement.

Adhesives and specimen preparation

Textile specimens of 50 mm width were cut from a roll of 0.57 mm thick representative material. Fig.1 shows an image of a typical specimen with a FBG installed using adhesive bonding. In Fig.1 there is a schematic of the woven structure. The representative textile differs from a conventional tapestry as it is 'warp-faced' or warp covered. The wool yarns in horizontal direction are referred to as warp yarns and have a spacing of 0.8 mm, and the yarns in vertical direction are weft yarns with a spacing of 1.7 mm. The specimen is loaded in the weft direction as this is how tapestries are hung.

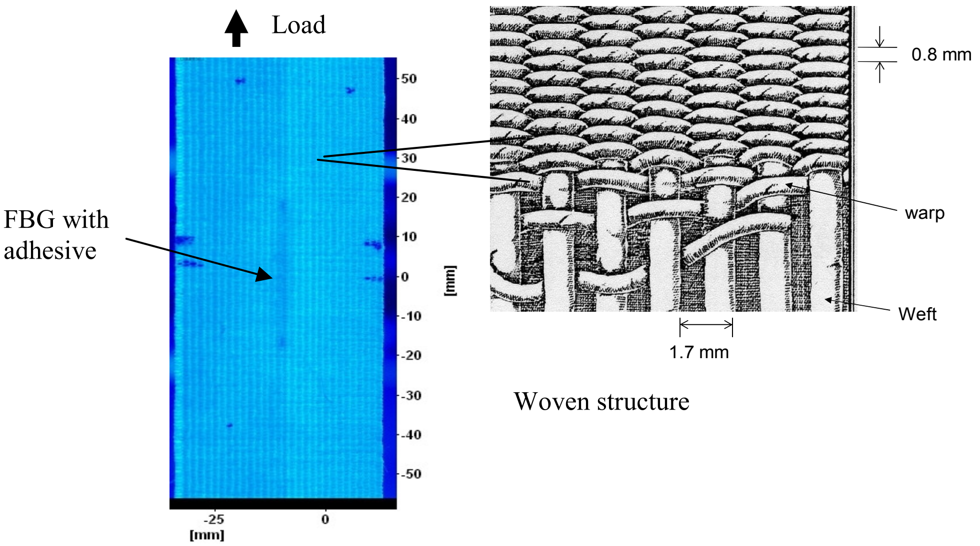


Fig.1. Image of representative textile specimen, with a FBG bonded to the rear side of the specimen.

PVA based conservation adhesives are widely used in repair procedures for historic textiles. They do not have any known long term damage effects on tapestries. Thus these adhesives were initially selected as bonding agents for the FBGs; Mowilith DMC2 and Vinamul 3252. In earlier work [1] it was found the strain transfer coefficient between the textile and a FBG sensor was very low when using this type of adhesive. Therefore it was decided to use a structural adhesive typical of that used to bond a FBG to an engineering component to benchmark the experiment. A two part epoxy (Araldite 2015) was used. Since Araldite 2015 has not been used in textile conservation, it was necessary to establish if the adhesive has any long term chemical effects on textile materials. To do this an 'Oddy test' [5, 6] was carried out. In the Oddy test adhesive samples are placed in a sealed glass container along with metal coupons and exposed to elevated humidity and temperature. If the metal coupons corrode it is an indicator of any off-gassing of volatile compounds from the adhesive. After 28 days of exposure at 60^{o}C there was no noticeable change in the metal specimens, so it was concluded that the application of Araldite 2015 would not be harmful and the adhesive could be used in conjunction with historic textiles.

It is unfortunately the case that FBG sensors are relatively expensive and this limits the number of experiments that can be done on different samples. Three representative textile test specimens were prepared, each with a FBG bonded centrally, using the three adhesive types, as shown in Fig.1. The FBGs had a nominal wavelength of 1540 nm and a gauge length of 6 mm. The FBGs were located in a 25 mm section of the optical fibre where the dual acrylate coating was removed for fabrication. The optical fibres were attached to the specimens over length of about 15 mm either side of the FBG. The extent of the cured adhesive patch was controlled by using a mask and was approximately 3 mm wide.

Experimental work

Loading and measurement systems. The system used to obtain the wavelength shift from the FBGs was a Swept Laser Interrogator (FBG-SLI) by Micron Optics. The swept laser illuminates the FBGs through fibre couplers and each FBG reflects its corresponding wavelength. The detected spectral signals are processed and displayed using LabVIEW software. The resolution of measured wavelength is 1 pm, corresponding approximately to 1 με, i.e. 0.0001%.

The StrainMaster 3D DIC system, from LaVision GmbH [3, 4, 7], was used to obtain the DIC data. The system is shown schematically in Fig.2. It comprises two 2 MPixel digital cameras that collect synchronised images of the specimen under load. A series of images are acquired during a

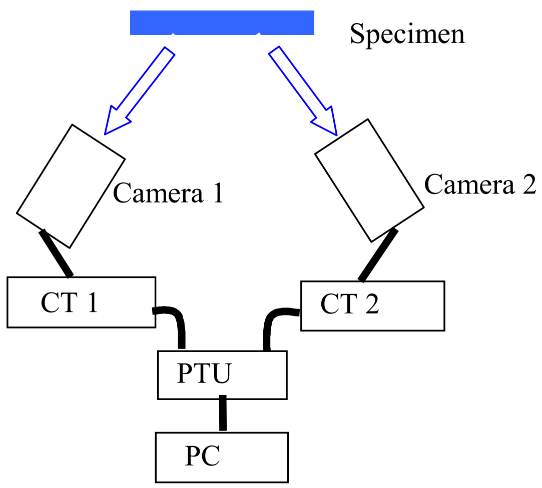


Fig.2. Schematic of StrainMaster 3D DIC system.
PTU: Programmable Timing Unit; CT: camera controller

test, with the first image pair being the case of zero applied load. The images are processed and correlated with the zero load images using the DaVis Version 7.2 software. The result is a series of full-field strain maps of the specimen at each load increment that provide an independent non-contact measure of the strains in the samples. It is important to note that instead of the standard spray painted speckle, the textile natural weave pattern was used as the device for correlation. In DIC the strains are calculated by correlation of features in a reference image and in a deformed image. To do this the field of view is divided into cells or 'interrogation windows'. In the LaVision system these must be made up of at least 4 pixels and increase in size in powers of two. The minimum size of interrogation window to obtain an acceptable image correlation was found to be 32 x 32 pixels, corresponding to ~2.8 x 2.8 mm on the textile surface and hence approximately about 3 weave repeats per cell. The quoted strain resolution for 32 x32 interrogation cells is given in the range of 0.06% to 2.5% strain [7]. The higher value is the order of the maximum strain recorded during the experiments. A better strain resolution could be obtained with larger interrogation cells. However as the area covered by the adhesive was 3 mm wide it was considered that the 2.8 x 2.8 mm interrogation cell was the maximum size that could be tolerated to give the spatial resolution across the area covered with adhesive. In previous work [2], 64 x 64 pixel interrogation cells were used and the scatter in this data was large as the cells overlapped areas that were partially covered by the adhesive. Away from the FBG installation, an average strain can be obtained over a larger area enabling a much better level of precision.

Each specimen was mounted in an Instron 5569 test machine in wedge grips, with a distance between the grips of 250 mm and loaded under a constant displacement of 15 mm/minute until the applied load reached 30 N. The DIC data was collected simultaneously with that from the FBG sensors.

Quasi-static tests. A typical longitudinal DIC strain map of the specimen with the Araldite adhesive is shown in Fig.3. In the area where the FBG is bonded the strain is much smaller than that elsewhere in the specimen, clearly shows the reinforcing effect of bonding the FBG.

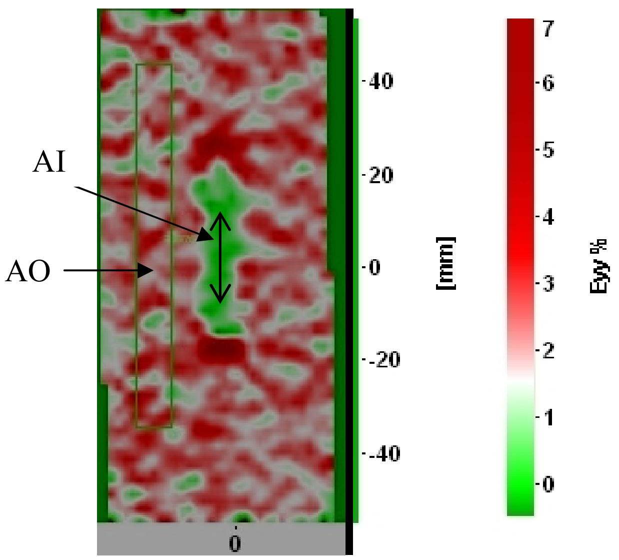


Fig.3. Longitudinal strain map for specimen with FBG bonded with Araldite2015. Applied load was 30 N

Figs. 4 and 5 show the stress (calculated simply from load/area) versus strain from the bonded FBGs and the DIC. For all of the three specimens, the stress-strain curves from the FBGs are linear.

In all cases, the DIC data was collected over two areas: AO is the area marked by the rectangle in Fig.3, i.e. the area away from the grating; AI is coincident with the FBG. The strain obtained from AO is the averaged local strain [7] from each of the interrogation cells within AO (approximately 100). Whilst the AI strain is a 'virtual extensometer' measurement [7] taken by correlating the interrogation cells at either end of the 20 mm line shown in Fig.3. It can be seen in Figs. 4 and 5a and b that the DIC AO readings are significantly greater than the DIC AI readings. The recorded stress-strain behaviour for the textile material (AO) in all three tests is practically the same, but is nonlinear. There is significant uncertainty in AI strain readings for the FBG bonded with Araldite. This is because the strain is less than 0.3%, and is on the limit of the quoted resolution of 0.18% (see section 3.3 below). It is noteworthy that for the larger AI strains obtained from the PVA adhesives shown in Fig.5 the scatter diminishes. In addition, the spatial resolution of the measurement obtained from DIC is approximately 2.8 mm, which is close to the width of the AI area (~3 mm). Therefore, the non-uniform strain distribution across the AI area is not well resolved. This will also account for the scatter in the DIC AI measurement compared with the DIC AO measurement. The scatter in the DIC AO readings is smaller since they are averaged over a larger area.

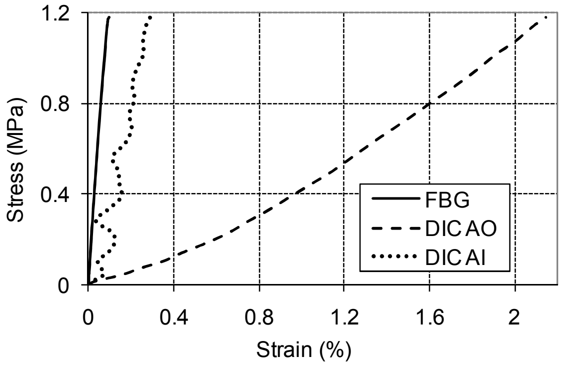
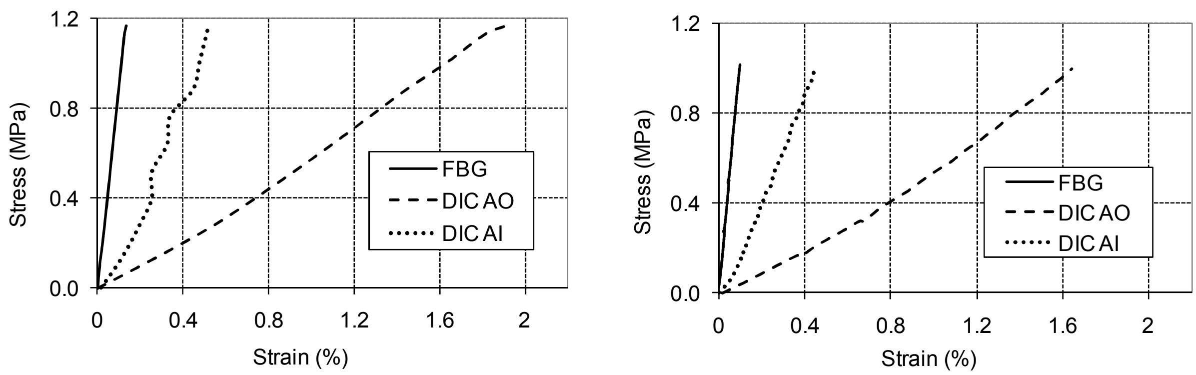


Fig.4. Stress-strain behaviour of specimen with FBG attached with Araldite 2015 adhesive



(a) (b)

Fig.5. Stress-strain behaviour of specimen with FBG attached with Vinamul 3252 adhesive (a), and with DMC2 adhesive (b).

Strain transfer coefficient and reinforcement. To summarise the findings of the previous section the strain transfer coefficient $\varepsilon_{FBG}/\varepsilon_{AI}$ and strain ratio $\varepsilon_{AI}/\varepsilon_{AO}$ for three specimens are given in Table 1. $\varepsilon_{AI}/\varepsilon_{AO}$ can be considered as a measure of the reinforcing effect of bonding the optical fibre to the textile. The data in Table 1 uses the maximum strain measured at the 30 N load. The DIC AO value is an average of the strain given by the cells in the AO area and is provided in Table 1 with corresponding standard deviations. The uncertainty in AI global strain determined from the length of the line (the gauge length) and the displacement error, which is 0.2 pixel in the worst case [7]; e.g. if the gauge length is 20 mm and equivalent to 229 pixels, the error in the strain is ~ 0.18% (i.e. 0.2 x 2/229). The accuracy of FBG strain is of an order of a few $\mu\varepsilon$, which is negligible here. The error in the $\varepsilon_{FBG}/\varepsilon_{AI}$ and the $\varepsilon_{AI}/\varepsilon_{AO}$ was calculated from the sum of the relative errors in each quantity.

Table 1 Measured strain transfer coefficients and ratio $\varepsilon_{AI}/\ \varepsilon_{AO}$ for different specimens

Adhesive used to bond fibre sensor on textile specimen	Stress (MPa)	ε_{AI} (%)	ε_{AO} (%)	ε_{FBG} (%)	$\varepsilon_{AI}/\varepsilon_{AO}$	Strain transfer coefficient $\varepsilon_{FBG}/\varepsilon_{AI}$
DMC2	1.00	0.44±0.18	1.64±0.06	0.100	0.27±0.12	0.23±0.09
Vinamul 3252	1.17	0.52±0.2	1.91±0.06	0.137	0.27±0.11	0.26±0.10
Araldite 2015	1.18	0.27±0.18	2.14±0.06	0.096	0.13±0.09	0.36±0.24

The difference in reinforcement ratio $\varepsilon_{AI}/\varepsilon_{AO}$ for different specimens given in Table 1 can be explained in terms of the overall product of Young's modulus and cross section area for the part of specimen bonded with silica fibre. The overall product of $E{\cdot}A$ is the sum of the products of the cured adhesive, silica fibre and the textile covered with adhesive, and can be written as follows:

$$E \cdot A = E_{ad}(w \cdot t - \pi \cdot r_f^2) + E_f \cdot \pi \cdot r_f^2 + E_t \cdot w \cdot t_t \quad (1)$$

where E_{ad}, E_f and E_t are Young's moduli for the adhesive, silica fibre and textile, respectively, r_f the radius of the silica fibre, w and t the width and length of cured adhesive, and t_t the thickness of the textile.

Table 2 *E·A* values for different specimens

Specimens	E_{ad} (GPA)	W (mm)	t (mm)	E·A (GPa ·mm^2)
FBG-Araldite	1.5	3.2	0.4	2.92
FBG-DMC2	0.006	3.1	0.3	1.02
FBG-Vinamul	0.002	3.2	0.3	1.02
Textile only				0.11

For standard silica fibres, E_f = 72 GPa [8] and r_f = 0.063 mm. The measured Young's modulus and thickness of the textile are E_t = 60 MPa and t_t=0.57 mm. The measured E_{ad} values and the *E·A* values for the three specimens are given in Table 2. The *E·A* value for the specimen with Araldite is approximately 3 times greater than those with conservation adhesives, which is consistent with the difference in ratio $\varepsilon_{AI}/\varepsilon_{AO}$. This provides an adequate explanation for the reinforcement. However the question remains that with this level of reinforcement can the FBG installations provide a useful measure in monitoring. Although the strain readings from an optical FBG sensor are smaller than the true strain values in the actual tapestries, the readings from such a gauge could be used as a reference measurement for the DIC during a long term test if the FBG readings can reflect the structural changes relatively.

A much more important consideration is the very low strain transfer coefficients reported in Table 1. The strain transfer coefficient for the specimen with Araldite is greater than those given by the conservation adhesives, but much less that would be expected when bonding the optical fibre to an engineering material. In initial validations reported in [2] it was shown that the strain transfer coefficient was very close to unity when attaching an identical FBG to an aluminium specimen. Notwithstanding the scatter in the measured strain transfer coefficient measurement, these results show that the strain is not being transferred adequately through either adhesive into the optical fibre. It should also be noted that these results account for the local reinforcement of the adhesive. In [8] a method is proposed for calculating the average strain transfer coefficient ($\bar{\alpha}$) based on the bonded length of the fibre ($2L$) as follows:

$$\bar{\alpha} = 1 - \frac{sinh(kL)}{kL\,cosh(kL)} \quad (2)$$

where $k = \sqrt{\frac{1}{(1+\nu_{ad})(E_f / E_{ad})r_f^2\, ln(t/r_f)}}$ and ν_{ad} is the Poisson's ratio of the adhesive and is taken to be 0.4 for all the adhesives.

Putting the values for the component parts of each installation into equation (2) gives $\bar{\alpha}$ = 0.95 for the Araldite and 0.39 for the DMC. Clearly this is not reflected in the measured data given in Table 1. Equation (2) was developed using an idealised form where the optical fibre is embedded in a cylinder of adhesive which is then embedded into a cylinder of linear elastic material. So the configuration of the installation in this paper departs from this idealised form. Therefore the values obtained from equation (2) should be considered only to provide a reasonable guide to the behaviour. It should also be considered that the equation developed in [8] is based on the substrate being a homogeneous material. Clearly the textile is not. Perhaps more importantly it is assumed that the bond between the optical fibre and the substrate is perfect. It may be the case that the voids in the textile cause localised 'debonds' and hence cause the reduction in the strain transfer coefficient. Perhaps a better encapsulation of the optical fibre in the textile material would produce an improved strain transfer coefficient. A possibility would be to embed the optical fibre in the textile material by threading through the woven structure and hence providing a more positive connection.

The Araldite adhesive clearly reinforced the tapestry material to a great extent so it would be desirable to obtain a much better compatibility between the stiffness of the optical fibre, the adhesive and the textile. If plastic optical fibres (POFs) are used the $\bar{\alpha}$ value given by equation (2) changes to 0.87 when the PVA adhesive is used (using E_f = 2.8 GPa and r = 0.063 mm [9]). This clearly warrants further exploration and will be the object of future work.

Conclusions and future work

FBG sensors have been attached to textile fabrics for strain sensing, and their sensing performance and characteristics of bonding with different adhesives have been investigated through the comparisons between strain readings from FBGs and those from the DIC system. It has been shown that whilst the strains can be detected using silica optical fibres they cannot be accurately measured because a suitable strain transfer coefficient cannot be achieved with the adhesive/optical fibre material combinations. Future work will concentrate on assessing optical fibres of differing material.

References

[1] Dulieu-Barton J.M., Sahin M., Lennard F.J., Eastop D.E. and Chambers A.R.: Key Engineering Materials, Vol. 347(2007), p.187
[2] Dulieu-Barton, J.M., Ye, C.C., Chambers, A.R., Lennard, F.J. and Eastop, D.E.:, Optical fibre sensors for monitoring damage in historic tapestries, SEM XI International Congress on Experimental and Applied Mechanics, 2008, Orlando, Florida
[3] Chu T.C., Rason W.F., Sutton M.A. and Peters W.H.: Experimental Mechanics, Vol. 25(1985), p.232
[4] Yan J.H., Sutton M.A., Deng X., Cheng C.S.: International Journal of Fracture, Vol.144 (2007), p.297
[5] Oddy W.A.: Museums Journal, Vol. 73(1973), p.27

[6] Green L.R., Thickett D.: Studies in Conservation, Vol. 40(1995), p.145
[7] DaVis Version 7.2 User Manual, StrainMaster 3D - Getting Started, and http://www.lavision.de
[8] Li D., Li H., Ren L., Song G.: Optical Engineering, Vol.45(2006), 024402-1-8
[9] Silva-Lopez M., Fender A., MacPherson W. N., Barton J. S., Jones J. D. C., Zhao, D., Dobb H., Webb D. J., Zhang L., Bennion, I .: Optics Letters, Vol.30 (2005) , p.3129

Damage Assessment of Structures VIII
doi:10.4028/www.scientific.net/KEM.413-414

Condition Monitoring of Textiles Using Optical Techniques
doi:10.4028/www.scientific.net/KEM.413-414.447

References

[1] Dulieu-Barton J.M., Sahin M., Lennard F.J., Eastop D.E. and Chambers A.R.: Key Engineering Materials, Vol. 347(2007), p.187
doi:10.4028/www.scientific.net/KEM.347.187

[2] Dulieu-Barton, J.M., Ye, C.C., Chambers, A.R., Lennard, F.J. and Eastop, D.E.:, Optical fibre sensors for monitoring damage in historic tapestries, SEM XI International Congress on Experimental and Applied Mechanics, 2008, Orlando, Florida

[3] Chu T.C., Rason W.F., Sutton M.A. and Peters W.H.: Experimental Mechanics, Vol. 25(1985), p.232
doi:10.1007/BF02325092

[4] Yan J.H., Sutton M.A., Deng X., Cheng C.S.: International Journal of Fracture, Vol.144 (2007), p.297
doi:10.1007/s10704-007-9101-6

[5] Oddy W.A.: Museums Journal, Vol. 73(1973), p.27

[6] Green L.R., Thickett D.: Studies in Conservation, Vol. 40(1995), p.145
doi:10.2307/1506472

[7] DaVis Version 7.2 User Manual, StrainMaster 3D - Getting Started, and http://www.lavision.de

[8] Li D., Li H., Ren L., Song G.: Optical Engineering, Vol.45(2006), 024402-1-8

[9] Silva-Lopez M., Fender A., MacPherson W. N., Barton J. S., Jones J. D. C., Zhao, D., Dobb H., Webb D. J., Zhang L., Bennion, I .: Optics Letters, Vol.30 (2005), p.3129
doi:10.1364/OL.30.003129
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