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# Experimental study of thick composites stability under thermal loading using 3D ESPI set-up

J. Molimard<sup>a</sup>, A. E. Dolinko<sup>b</sup> and G. H. Kaufmann<sup>c</sup>

## Abstract

*Due to the impulsion of aircraft manufacturers, Carbon Fibre Reinforced Polymers have become thicker. But the manufacturing process still implies the development of important residual stresses, either due to moisture effects or thermal effects [1]. If the symmetry of the composite part is broken, the global part shape will be affected by any moisture/temperature variation. In this communication, a simple L thick composite shell is studied under moderate temperature changes. An error in the stacking sequence is voluntarily added to the sequence in order to simulate possible manufacturing error. Displacements are recorded on the shell front and on its side using a mixed in-plane and out-of-plane DSPI set-up [8]. The zone of interest is limited here to the central part of the L shape i.e. where the curvature is significant. Variations of the L-shape with temperature are recorded; typical flexure strain effects are outlined. Interesting global or local parameters can be deduced from this experiment: through thickness coefficient of thermal expansion, ply thickness and consequently local fibre volume fraction.*

*Keyword optical technique: DSPI, fringe projection, digital image correlation*

*Keyword application: airplane structural analysis*

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33 **Introduction**

34 Composite laminates for structural applications are commonly processed under high  
35 temperature compared to their working conditions (180 °C vs. 25 °C). Coefficients of thermal  
36 expansion mismatch combined with different stiffness from one component to the other imply  
37 the development of high internal stresses [1]. These stresses can even cause the structure's  
38 failure without any external loading (micro-cracking of transverse ply). Another consequence  
39 of these internal stresses is a lack of dimensional stability, especially in the case of non  
40 symmetric parts, but such effect can occur even if the stacking sequence is symmetric.  
41 Theoretically, such a situation is not predictable if the components volume fraction is  
42 nominal. In fact, the shape variation sources have to be found in the defaults induced by the  
43 manufacturing process, especially the variations in the components distribution.

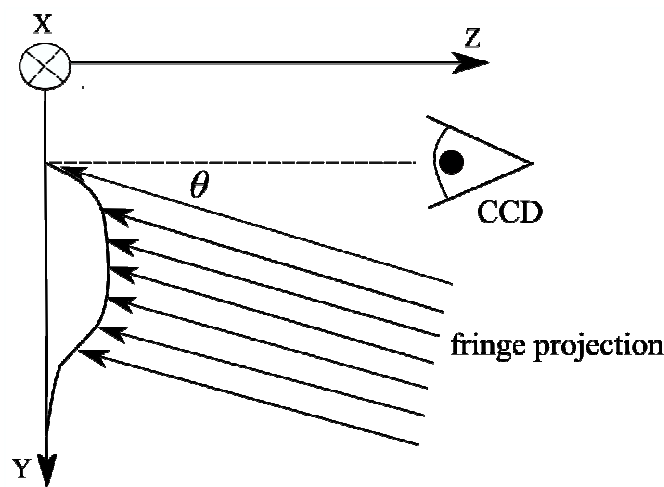
44 We propose here an experimental study on a typical L shape submitted to a temperature  
45 change; the stacking sequence is symmetric, but we simulate an error in the manufacturing  
46 process by adding an extra ply to the sequence. Chosen composite coupon is rather thick (9.5  
47 mm) to simulate realistic industrial application.

48 Strain fields have to be recorded first on the coupon side, second on its face. Due to the  
49 particular shape of the specimen, expected displacement fields are both in plane (x and y axis)  
50 and out of plane (z axis); the difficulty here is to define the appropriate plane in the analysis,  
51 the specimen being non-planar. Expected displacements are supposed to be small; finally, the  
52 chosen optical full-field technique is a 3D ESPI set-up for displacement measurements  
53 coupled with fringe projection set-up for shape measurement. This approach is simpler than  
54 the one proposed by Goudemand [2]. Here, the fringes are projected by a classical video-  
55 projector and not by the DSPI sources.

56 **Shape measurement using fringe projection technique**

57 The fringe projection method [1][3] has been selected as a reasonable tool for measuring the  
58 specimen shape. The physical principle of the fringe projection method is straightforward: A  
59 periodic pattern of white and black lines is projected on an object; the light is diffused by the  
60 object and captured by a CCD video-camera (Figure 1). The deformation of the fringes,  
61 recorded as phase maps, has a known dependency to the out-of-plane contour variations of the  
62 illuminated object.

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*Figure 1: Fringe projection basic principle.*

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68 The fringe projection technique exploits the light diffused by an object in order to measure its  
69 shape or shape variation. Moreover, in order to observe out-of-plane displacements, the angle  
70 between the projected fringes and the observed diffused light must not be null. Light  
71 intensities on an object illuminated by a set of fringes can be described by a periodic function  
72  $I_{ii}$ , with a perturbation  $\phi$  corresponding to the object shape:

$$73 \quad I_{ii}(x, y) = I_0(x, y) \left[ 1 + \gamma(x, y) \cos \left( \frac{2\pi}{p(x, y)} y + \phi^{FP}(x, y) \right) \right] \quad (1)$$

74 This equation involves an average intensity  $I_0$  and a contrast  $\gamma$ . These values should be  
75 constant over the whole map, but some low-frequency variations due to illumination  
76 inhomogeneities or diffusivity changes on top of the surface can occur. Consequently, both  
77 average intensity and contrast have to be considered as local quantities, typically calculated  
78 over few fringe periods, and can be denoted  $I_0(x, y)$  and  $\gamma(x, y)$ . The pitch  $p$  is the distance  
79 between two light peaks on a flat surface. Again, due to perspective effects in particular, this  
80 pitch can change over the map, but this variation can be known either using a model or a  
81 calibration procedure.

82 Lastly, the object is responsible for a phase shift  $\phi^{FP} = \phi^{FP}(x, y)$  at each point of the field.  
83 Consequently, eqn (1) is based on three unknown quantities ( $I_0(x, y)$ ,  $\gamma(x, y)$ ,  $\phi(x, y)$ ) which need  
84 at least three equations to be identified. The phase is extracted through the home-made code  
85 Photomecanix and the out-of-plane position  $Z(x, y)$  can be retrieved from to the following  
86 basic equation:

$$87 \quad \phi^{FP}(x, y) = \frac{2\pi \tan(\theta(x, y))}{p(x, y)} Z(x, y) \quad (2)$$

88 In this expression, the sensitivity characterized by the slope of the linear relationship between  
89  $\phi^{FP}(x, y)$  and  $Z(x, y)$ , can be adjusted by modifying the pitch  $p$  or the angle  $\theta$  between the CCD  
90 video-camera and the video-projector. It has to be noted that the sensitivity can vary locally.  
91 In particular, in the present experiment, the video projector and the CCD camera used  
92 divergent beams, leading to a more complex situation than the one described in Figure 1. A  
93 specific calibration procedure has been developed based on prescribing a known translation of  
94 a reference object. The phase variation  $\phi^{FP}$  is extracted using a temporal phase shifting  
95 algorithm proposed by Surrel [4]; the phase shifter is the video-projector itself, controlled by  
96 Photomecanix. Last, no camera distortion model has been applied here.

97 An estimation of the resolution based on a repeatability test on a given stable situation gives a  
98 value of 0.9 % of one fringe, i.e. the noise level is 20  $\mu\text{m}$ . Because of the use of the temporal  
99 phase shifting algorithm, spatial resolution is kept to 1 pixel i.e. from 18.6 to 29.3  $\mu\text{m}$   
100 depending on the experiment.

## 101 **Displacements measurement using DSPI set-up**

102 To measure the  $u(x, y)$ ,  $v(x, y)$  and  $w(x, y)$  components of the displacement field at the surface of  
103 an object, three speckle interferometers with in-plane and out-of-plane sensitivity are used.

104 The basic equation of DSPI that describes the optical phase difference  $\Delta\phi$  due to the  
105 displacement  $u$  of the object is given by

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$$\Delta\varphi^{DSPI}(x, y) = 2\frac{\pi}{\lambda}(\mathbf{e}_i - \mathbf{e}_o) \cdot \mathbf{u} \quad (3)$$

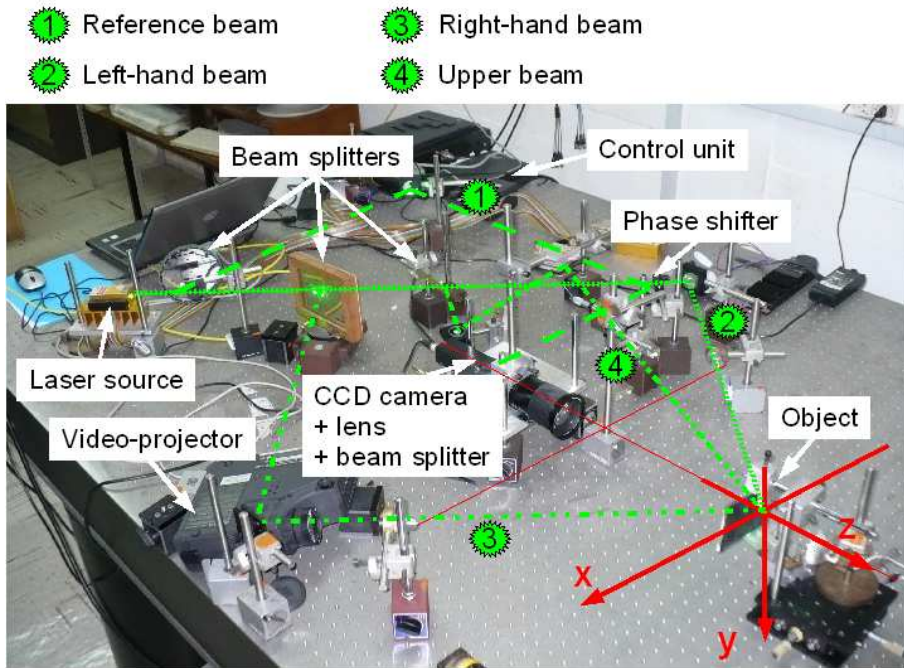
107 where  $\mathbf{e}_i$  and  $\mathbf{e}_o$  are the illumination and the observing unit vectors, respectively, and  $\lambda$  is the  
 108 wavelength of the laser light.

109 Here the specimen is observed along  $\mathbf{e}_o=(0,0,-1)$  and is illuminated with three different beams,  
 110 using the same reference beam as for a classical out-of-plane set-up. Two beams are in an  
 111 horizontal plane, i.e.  $\mathbf{e}_1=(\sin \gamma_1, 0, \cos \gamma_1)$  and  $\mathbf{e}_2=(\sin \gamma_2, 0, \cos \gamma_2)$ ,  $\gamma_2 \approx -\gamma_1$ , while the last one  
 112 is in a vertical plane, i.e.  $\mathbf{e}_3=(0, \sin \gamma_3, \cos \gamma_3)$ . The phase changes between both object beams  
 113 and the reference are given by:

$$\begin{cases} \Delta\varphi_1^{DSPI}(x, y) \\ \Delta\varphi_2^{DSPI}(x, y) \\ \Delta\varphi_3^{DSPI}(x, y) \end{cases} = \frac{2\pi}{\lambda} \begin{bmatrix} \sin\gamma_1 & 0 & (1 + \cos\gamma_1) \\ \sin\gamma_2 & 0 & (1 + \cos\gamma_2) \\ 0 & \sin\gamma_3 & (1 + \cos\gamma_3) \end{bmatrix} \begin{cases} u_1(x, y) \\ u_2(x, y) \\ u_3(x, y) \end{cases} \quad (4)$$

115 where  $\Delta u_1$ ,  $\Delta u_2$  and  $\Delta u_3$  are respectively the in-plane and out-of-plane displacement  
 116 components. In fact, due to the specimen geometry and the lens divergence,  $\gamma_i$ ,  $i=1..3$  is not  
 117 constant over the covered field. Knowing the optical arrangement and the specimen geometry,  
 118 it is possible to determine pointwisely  $\gamma(x,y)$ . As a general form, each sensitivity vector ( $\mathbf{e}_i - \mathbf{e}_o$ )  
 119 is expressed according to the optical centres of the divergent beam and the camera, and the  
 120 local position of each surface point M. The frame of reference is shown in Figure 2 (red  
 121 arrows). For each couple illumination beam / reference beam, the phase is extracted through a  
 122 temporal phase shifting algorithm, and, if necessary, and unwrapping algorithm described in  
 123 [5].

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Figure 2: Optical arrangement

## 129 **Experiments**

### 130 *experimental set-up*

131 The DSPI system used to measure the displacement field is shown in Figure 2. The light from  
132 a doubled-YAG laser with a wavelength  $\lambda=532$  nm is divided by a tunable beam-splitter into  
133 a reference beam (denoted 1) and 3 beams illuminating the object (denoted 2~4). Each of  
134 these latter beams are separated using tunable beam splitters. Both beams are expanded by  
135 microscope objectives, illuminate the specimen and the diffused light interferes with the  
136 reference beam. The specklegram is imaged by a CCD camera (Pulnix TM-620) whose output  
137 is fed to a frame grabber (Matrox Pulsar) located inside of a personal computer which  
138 digitises images with a resolution of  $512 \times 512$  pixels  $\times$  8 bits. The video camera has a zoom  
139 lens which allows to image a small region of the specimen of about  $18 \text{ mm} \times 18 \text{ mm}$ . A  
140 piezoelectric transducer linked to one of the mirrors (M) is used to perform the phase shifting.  
141 This transducer is linearly displaced by the control unit. A video-projector ensures the fringe  
142 projection with an mean angle of incidence close to  $30^\circ$ .

### 143 *Uncertainty analysis*

144 In the following experiments, the camera centre is located at point  $\{0, 0, -450\}'$  mm, and the  
145 illumination beams foci respectively at  $\{-505, 0, -450\}'$  mm,  $\{0, -229, -450\}'$  mm,  $\{485, 0, -$   
146  $450\}'$  mm.

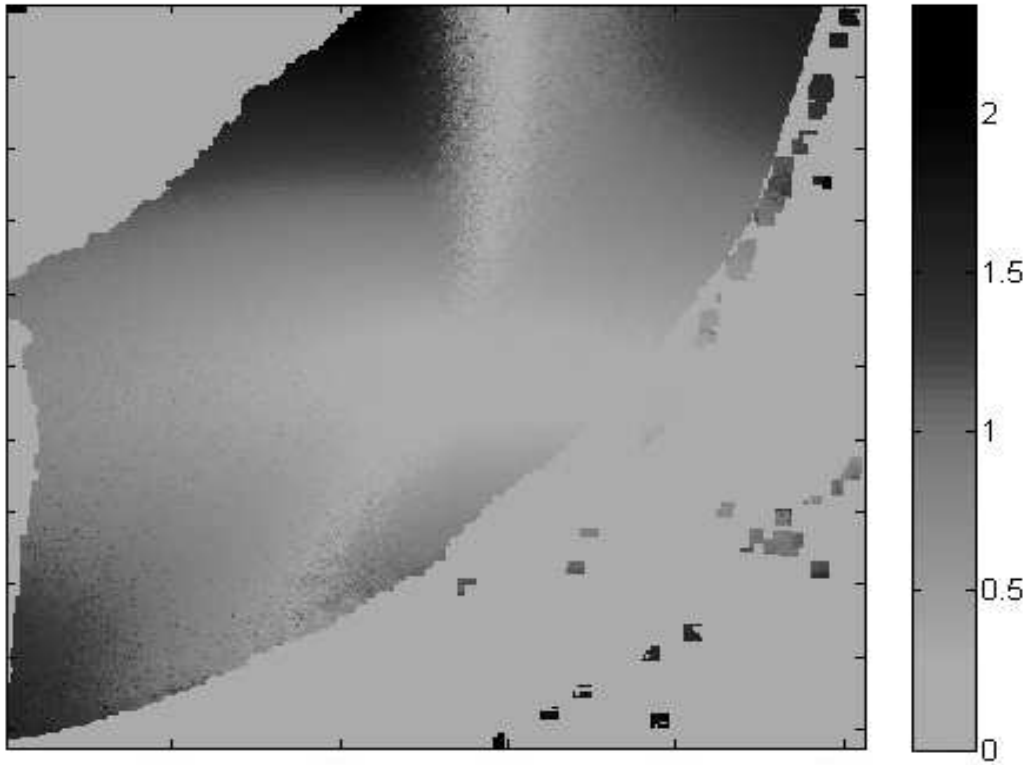
147 These values are one order of magnitude higher than the region of interest size ( $18 \times 18$   
148  $\text{mm}^2$ ). In fact, if the surface is flat, i.e. that each measuring point is in the plane  $M(x, y, 0) \forall$   
149  $x, y$ , the beam divergence has few influence on the result. Figure 3 shows typical error maps  
150 for a representative loading condition, in this case a temperature change of  $9^\circ\text{C}$ . Under these  
151 experimental conditions, the error without using the beam divergence is lower than 2 %.

152 Points with different positions should also lead to some uncertainties. In order to evaluate the  
153 error on these positions, a variation on the vertical illumination focus has been imposed ;  
154 because the position is measured using a rule with precision of 1 mm on its two ends, the  
155 variation has been set to +1.4 mm on each direction. Then, the maximum error encountered  
156 on the experimental map is 1 % (see figure 4).

157 Last, on flat surfaces, errors related to the surface position are mainly due to the vertical axis:  
158 the two others being symmetric, a simple reflective surface is sufficient to minimize any  
159 left/right misalignment. We can suppose that on a  $18 \times 18 \text{ mm}^2$  surface, a variation of  $\pm 1$  mm  
160 is reasonable on the vertical direction. The relative error related to this event gives a  
161 maximum value of 0.18 %.

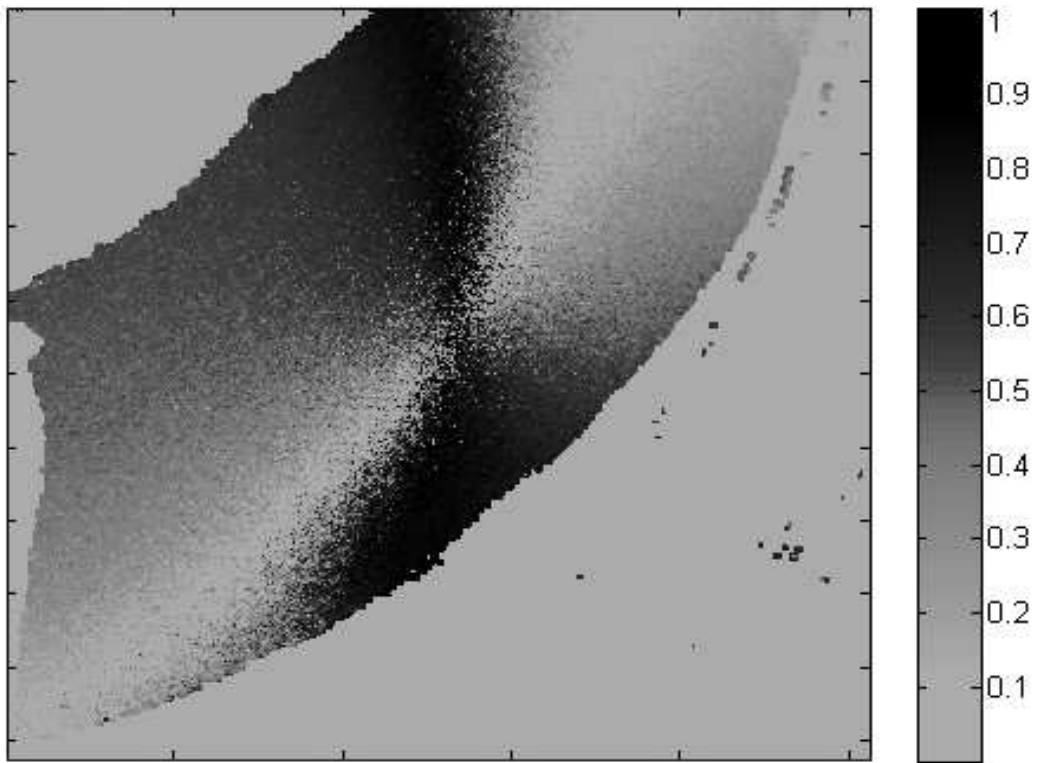
162 If extending these results using classical error propagation rules [6], the overall error on  
163 elements position is lower than 2 % (using the divergence beam formulation) or lower than  
164 2.7 % if the divergence effect is neglected. Finally, the variations on displacements induce  
165 few effects on strain maps. Induced errors are lower than  $2 \mu\text{m/m}$  ; this can be explained by  
166 the pixels size, and consequently the derivation kernel, and by the low-frequency shape of  
167 error functions.

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**Figure 3:** Relative error on the displacement norm if not considering the divergence (for a specimen submitted to a 9°C temperature change, viewed from its flat side)



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**Figure 4:** Relative error on the displacement norm due to uncertainties on illumination beam position (for a specimen subjected to a 9°C temperature change, viewed from its flat side)

178 *Temperature set-up*

179 Expected temperature changes are below 35 °C. These small changes were selected due to the  
180 very high sensitivity of DSPI, and because of the versatility of heating systems in such a  
181 range. Here, an halogen lamp has been placed beside the specimen. A screen avoids light to  
182 propagate in the direction of the camera in such a form that no noise is added to the signal.

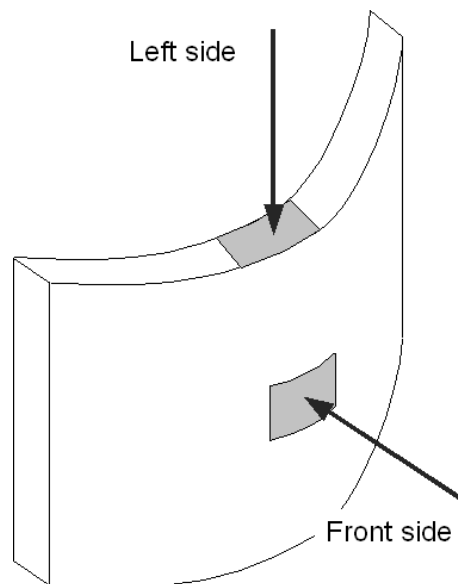
183 Experimental conditions have been optimized to generate an homogeneous temperature field  
184 over the area of interest. In fact, temperature variations over the field are lower than 1 °C, and  
185 from de back side to the front side of the specimen lower than 2°C. Lastly, a repeatability test  
186 shows that the temperature resolution is 1.5 °C.

187 **Results and analysis**

188 *Specimen*

189 The specimen used for this experiment is a  $[0\ 90]_{60}$  laminate of Carbon Fibre Reinforced  
190 Polymer T300 from Hexcel Company. It should be noticed that the sample is slightly non-  
191 symmetric: an extra 0 (or 90) ply is added to simulate a possible error during the  
192 manufacturing process. It is cured in a rigid mould. Its final geometry is an L-shape. The L  
193 inner and outer curvature radii are respectively 9 mm and 21 mm. the total mean thickness is  
194 9.5 mm [7].

195 Results will be presented here for a temperature change of 12.4 K. A set of 3D displacement  
196 fields is recorded both from the front side and from the left side of the specimen, as described  
197 in figure 5. The total covered area is  $18 \times 18\text{ mm}^2$ . For clarity of the purpose, only results on  
198 the left side will be presented here.



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*Figure 5: Schematic view of the specimen and measuring areas*

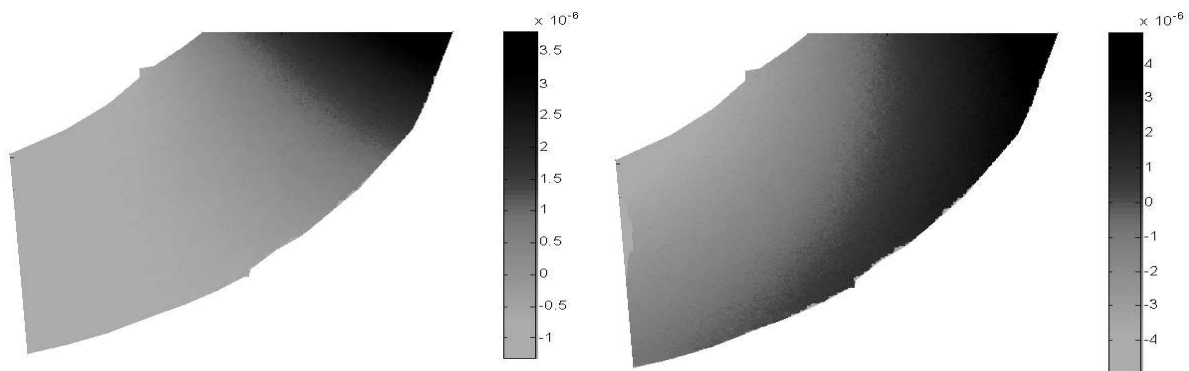
202 *Results*

203 Left side results should have been taken with two classical in-plane ESPI interferometers. In  
204 fact, we used here a 3D set-up, adding extra information (out-of-plane). Displacements found  
205 in x- and y- directions follow the specimen curvature (Figure 6). Because it is a quasi-plane



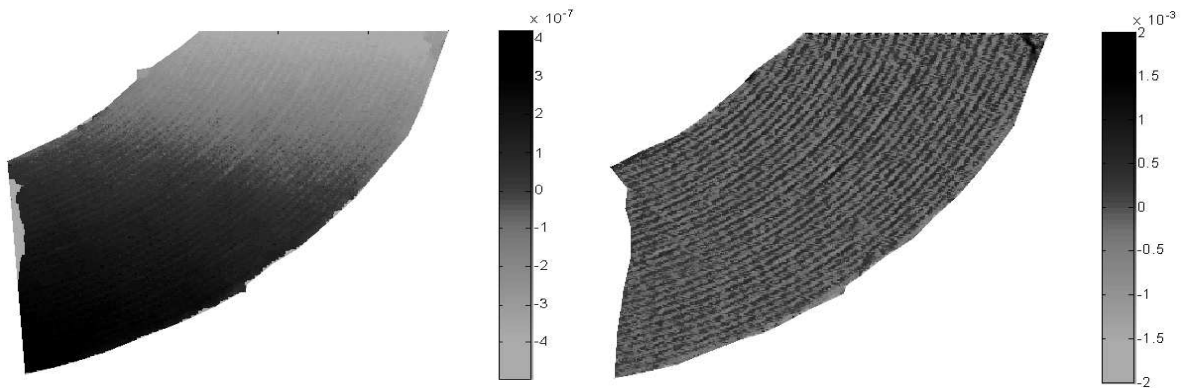
206 situation, the strain has been calculated in this case. In spite of the natural curvature, the  
 207 average orientation of the specimen is  $45^\circ$  off the horizontal axis. The specimen mainly  
 208 expands throughout its thickness. This result is commonly found for composite materials,  
 209 where the fibres have a lower dilatation coefficient than the resin. If the strain are projected in  
 210 a specimen frame of reference,  $\epsilon_{xx}$  and  $\epsilon_{yy}$  are constant, with respective mean values of  $136 \cdot 10^{-6}$   
 211  $^6$  and  $529 \cdot 10^{-6}$ . Consequently, it is possible to estimate the coefficient of thermal expansion of  
 212  $11.3 \cdot 10^{-6}$  m/m/K, and a throw thickness coefficient of  $58.0 \cdot 10^{-6}$  m/m/K. Even if the order of  
 213 magnitude is in agreement with common knowledge, a fine comparison is difficult, mainly  
 214 because the fibre volume fraction varies within the curvature area. The specimen is subjected  
 215 to an almost constant shear and a progressive rotation in the Earth frame of reference. Again,  
 216 using the specimen coordinate system, shear is different, and it varies linearly with the actual  
 217 position along the sample. Therefore, using a beam approximation, this implies that the  
 218 bending moment varies quadratically with the position.

219



**Figure 6:** Left side –  $x$ - and  $y$ -displacements for a temperature change of 12 K (in m).

220



**Figure 7:** Left side –  $z$ -displacement field, and displacement gradient. The plies of the part are clearly outlined.

221

222 Finally, the out-of plane displacement field has been also recorded and analysed. Of course,  
 223 the order of magnitude of the displacement is much smaller than the two others. It is believed  
 224 that the main source of out-of-plane displacement is related to the boundary effects, and  
 225 clamping variations with temperature because no low-frequency gradient is visible. Now, high  
 226 frequency information, corresponding to the plies stacking sequence, is visible (Figure 7).  
 227 These plies behave in a different way from one to the other because of their different

228 dilatation coefficient in this direction, due to fibres orientation. Analysing the signature leads  
229 to a mean ply thickness of 183.5  $\mu\text{m}$ . The nominal ply thickness is 152  $\mu\text{m}$ , so that, it is  
230 possible to estimate the effective fibre volume fraction: 49% instead of 59%.

231 The local effect also shows the very good spatial resolution achieved with this DSPI set-up:  
232 each ply has a mean measured thickness of 9.9 pixels, and the spatial resolution using the  
233 autocorrelation function on noise gave a value of 1 pixel.

## 234 **Conclusion**

235 The geometrical variations of a thick L-shape composite coupon subject to a temperature  
236 change have been recorded by a 3D DSPI set-up. The system takes into account the local  
237 variations of the three sensitivity vectors related to the beam divergence and to the specimen  
238 shape variations. Errors uncertainties due to the calibration procedure are supposed to be  
239 lower than 2 % for the displacements and  $2\mu\text{m}/\text{m}$  for the strains, strains being calculated  
240 performing a low-pass filtering and derivation over 11 pixels.

241 First results on the composite sample show that: 1<sup>st</sup>, the composite shape changes as if the part  
242 where subjected to a quadratic bending moment. 2<sup>nd</sup>, thermal expansion coefficients could be  
243 identified in-situ, with realistic values. 3<sup>rd</sup>, the ply thickness, and consequently the fibre  
244 volume fractions were found to be lower than the nominal value (49% instead of 59%).

245 Further work will concern the projection of strains in the local co-ordinate system, and the  
246 analysis of the front side results.

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