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

J. Molimard^a, A. E. Dolinko^b and G. H. Kaufmann^c

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

contact information

^a molimard@emse.fr

SMS/LTDS, UMR CNRS 5513, Ecole des Mines de Saint-Etienne,
158 cours Fauriel, 42023 Saint-Etienne cedex 02, France

^b dolinko@ifir-conicet.gov.ar

Instituto de Física Rosario (CONICET-UNR),
Bvd. 27 de Febrero 210 bis, S2000EZP Rosario, Argentina

^c kaufmann@ifir-conicet.gov.ar

Instituto de Física Rosario (CONICET-UNR),
Bvd. 27 de Febrero 210 bis, S2000EZP Rosario, Argentina

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.

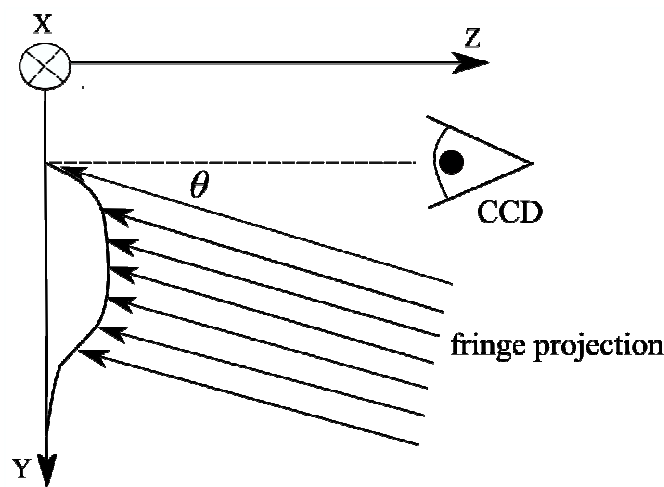
44 We propose here an experimental study on a typical L shape submitted to a temperature
45 change; the stacking sequence is symmetric, but we simulate an error in the manufacturing
46 process by adding an extra ply to the sequence. Chosen composite coupon is rather thick (9.5
47 mm) to simulate realistic 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 ϕ 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 γ . 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 θ 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 ϕ^{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 μm . 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 μm
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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$$\Delta\varphi^{DSPI}(x, y) = 2\frac{\pi}{\lambda}(\mathbf{e}_i - \mathbf{e}_o) \cdot \mathbf{u} \quad (3)$$

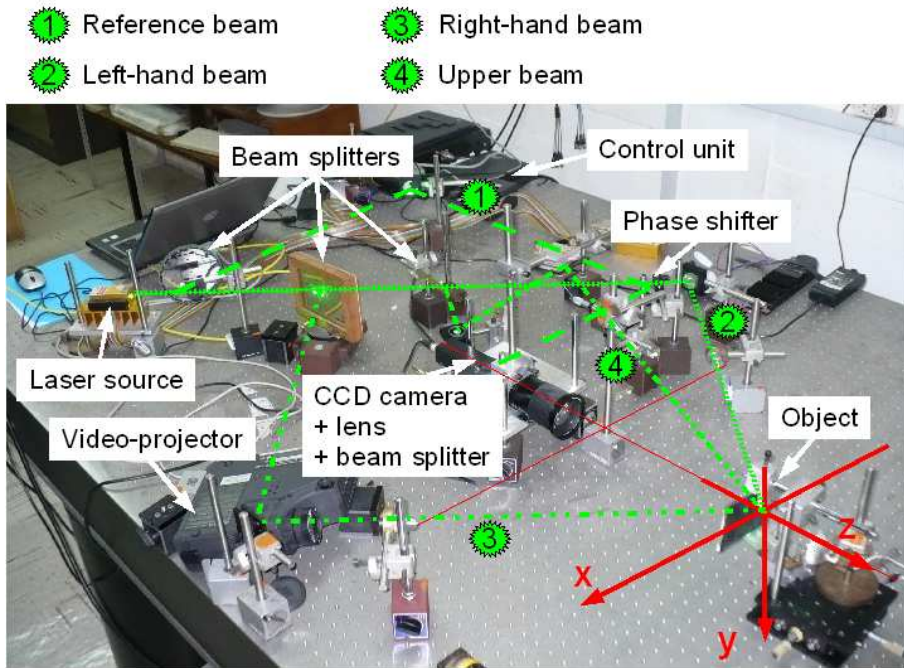
107 where \mathbf{e}_i and \mathbf{e}_o are the illumination and the observing unit vectors, respectively, and λ is the
 108 wavelength of the laser light.

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 Δu_1 , Δu_2 and Δu_3 are respectively the in-plane and out-of-plane displacement
 116 components. In fact, due to the specimen geometry and the lens divergence, γ_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 512×512 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° .

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.

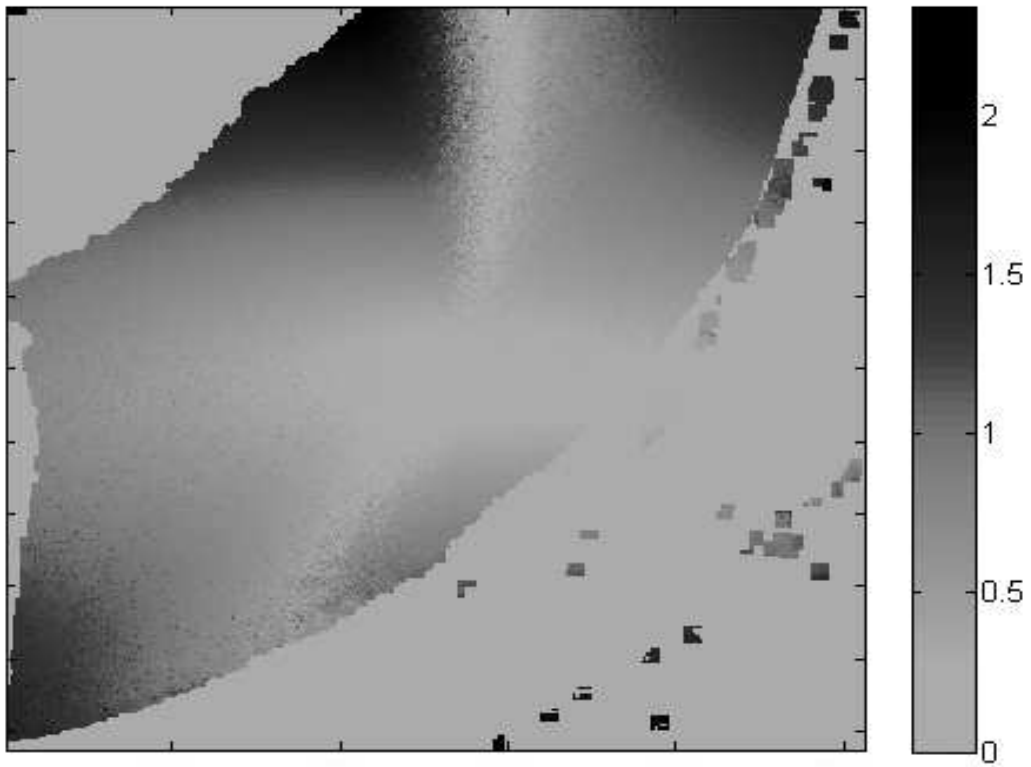
147 These values are one order of magnitude higher than the region of interest size (18×18
148 mm^2). In fact, if the surface is flat, i.e. that each measuring point is in the plane $M(x, y, 0) \forall$
149 x, y , the beam divergence has few influence on the result. Figure 3 shows typical error maps
150 for a representative loading condition, in this case a temperature change of 9°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 ± 1 mm
160 is reasonable on the vertical direction. The relative error related to this event gives a
161 maximum value of 0.18 %.

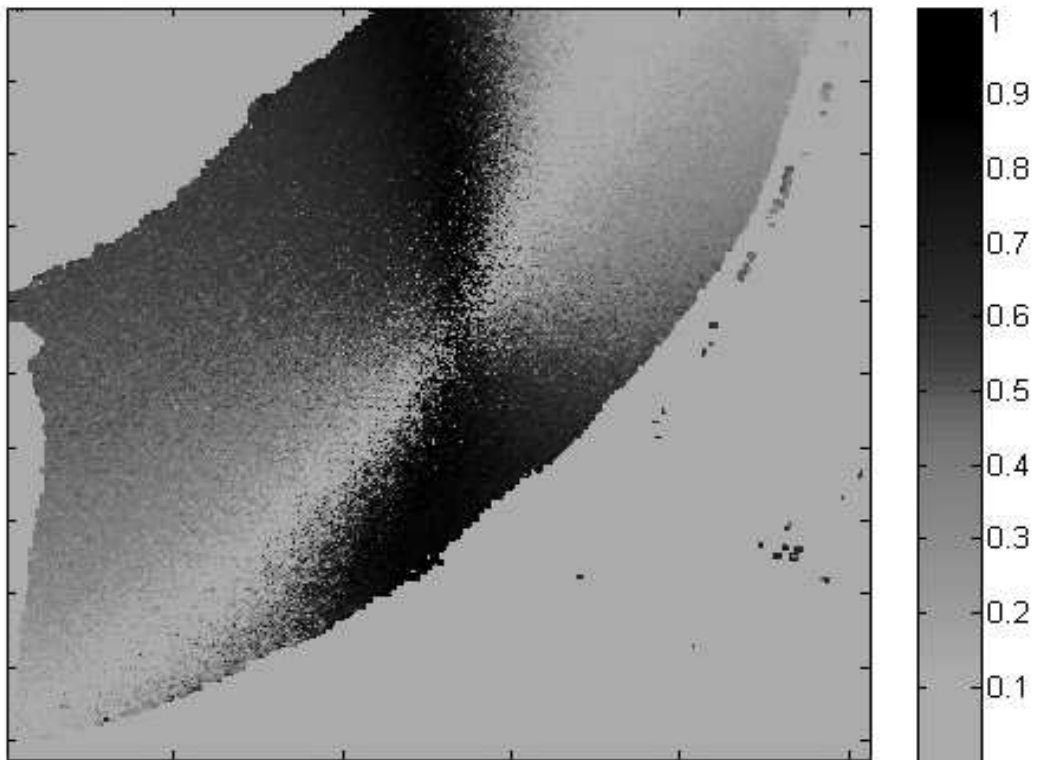
162 If extending these results using classical error propagation rules [6], the overall error on
163 elements position is lower than 2 % (using the divergence beam formulation) or lower than
164 2.7 % if the divergence effect is neglected. Finally, the variations on displacements induce
165 few effects on strain maps. Induced errors are lower than $2 \mu\text{m}/\text{m}$; 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.

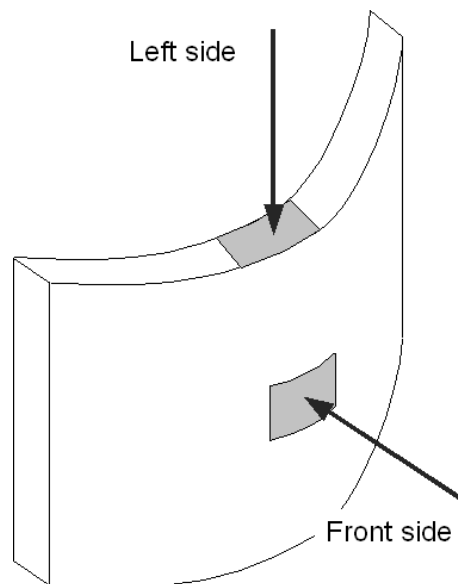
183 Experimental conditions have been optimized to generate an homogeneous temperature field
184 over the area of interest. In fact, temperature variations over the field are lower than 1 °C, and
185 from de back side to the front side of the specimen lower than 2°C. Lastly, a repeatability test
186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

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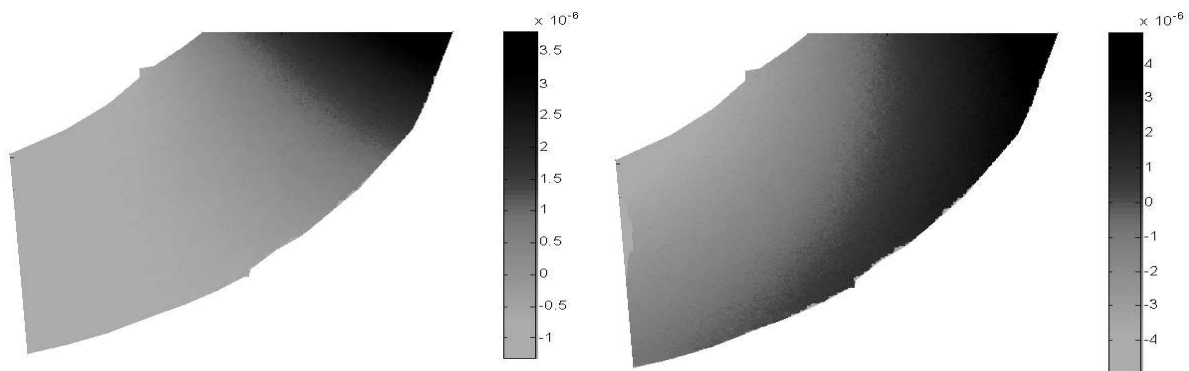


Figure 6: Left side – x - and y -displacements for a temperature change of 12 K (in m).

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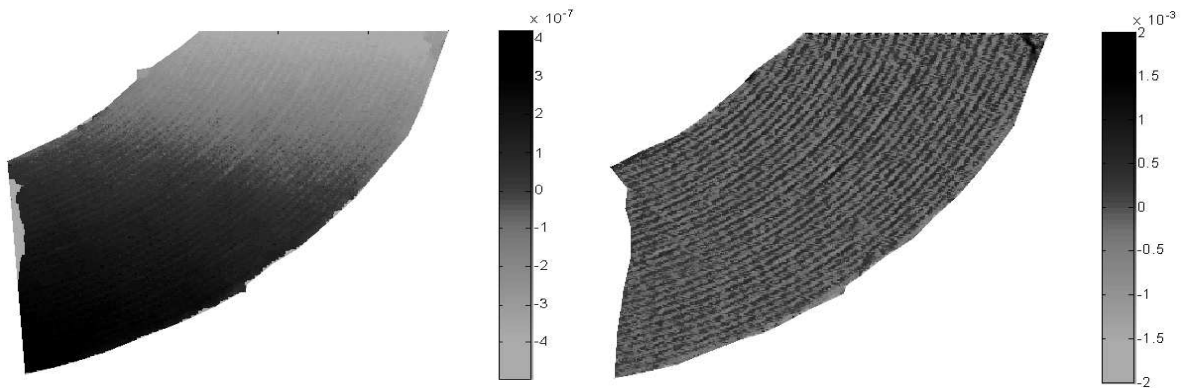


Figure 7: Left side – z -displacement field, and displacement gradient. The plies of the part are clearly outlined.

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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 μm . The nominal ply thickness is 152 μm , 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: 1st, the composite shape changes as if the part
242 where subjected to a quadratic bending moment. 2nd, thermal expansion coefficients could be
243 identified in-situ, with realistic values. 3rd, 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.

247 **References**

- 248 [1] GIGLIOTTI, M., JACQUEMIN, F., MOLIMARD, J., VAUTRIN, A., Transient and cyclical
249 hygrothermoelastic stress in laminated composite plates: Modelling and experimental assessment,
250 *Mechanics of Materials*, 39 (8): 729-745, 2007.
- 251 [2] N. GOUEMAND, 3D-3C Speckle interferometry: optical device for measuring complex
252 structures, PhD dissertation, Swiss Federal Institute of Technology, Zurich, 2005, 193p.
- 253 [3] BREQUE, C., DUPRE, J.C., BREMAND, F., Calibration of a System of Projection-Moiré for
254 Relief Measuring: Biomechanical Applications, *Optics and Lasers in Engineering*, 41: 241-260, 2004.
- 255 [4] SURREL, Y., Phase Stepping: a New Self-Calibrating Algorithm, *Applied Optics*, 32: 3598-3600,
256 1993.
- 257 [5] VIOTTI, M.R., KAUFMANN, G.H., Measurement of elastic moduli using spherical indentation
258 and digital speckle pattern interferometry with automated data processing, *Optics and Lasers in*
259 *Engineering*, 44: 495-508, 2006.
- 260 [6] Guide to the expression of uncertainty in measurement, Geneva: International Organisation for
261 Standardization, 1993.
- 262 [7] KLINKOVA, O., DRAPIER, S., BERGHEAU, J.M., Simulation des contraintes résiduelles dans
263 les structures composites: déformée après caisson et usinage, August 2009, Proceedings of the 19th
264 French Congress of Mechanics, Marseille (France) O. DEBORDES, C. REY eds. Marseille:
265 Electronic proceedings, 6 p. (in French).
- 266 [8] VIOTTI, M. R., KAUFMANN, G. H., Accuracy and sensitivity of a hole drilling and digital
267 speckle pattern interferometry combined technique to measure residual stresses, *Optics and Lasers in*
268 *Engineering*, 41: 297-305, 2004.