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Numerical and Experimental Analysis for Shape Improvement of a Cruciform Composite Laminates Specimen

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Abstract
The use of composite materials has spread to different applications among which, those using thin sheet plates subjected to biaxial loads are commonly used in the car and aerospace industries. Hence, there is need of a reliable specimen to test these materials under biaxial loads. This reliability depends on measurements that are accurate and repeatable. Thus these measurements depend on the proper design of specimens. This paper reviews the development of cruciform specimens of carbon fibre composite materials and how the geometric shape has evolved. Based on this review, a new geometric shape is proposed. This improvement is based on numerical analysis of the specimen and tests results of experimental measurements carried out using a four piston rig in an orthogonal arrangement. Deformation is measured in the centre of the specimen using strain gauges. By obtaining the principal stresses, it was found that maximum stresses occur in the centre of the specimen.

Key words: *polymer-matrix composites (PMCs), mechanical properties, finite element analysis (FEA), non-destructive testing, Biaxial testing, cruciform specimen.*

Introducction

The use of composite materials has increased exponentially in recent years thanks to its high resistance and light weight [1, 3]. However, mechanical testing composites reinforced with high perfoemance fibres presents some problems, due to the fibre distribution inhomogeneity, different fibre lengths and orientations [16, 18, 27]. Also selection of a representative sample cross section in order to get mechanical properties independent on material, sample size and its geometry, is difficult [27]. In most applications of thin composite plates, biaxial stress states are present [1, 2, 6], and even triaxial or multiaxial stress states are being studied [7, 18, 20]. The anisotropic character of these composites has made its analytically modelling difficult and thus there has not been a satisfactory result [19]. Therefore, so far, experimental methods have been the best approach to study the state of stress and strain in a thin plate under biaxial loads [16, 23, 24]. Hence, the important part of the biaxial tests is having a probe that maximises the area where one can find a) a uniform biaxial deformation, b) a minimum shear stress in this area, c) a minimum stress concentration outside the measurment area, d) the specimen failure and e) consistent results reproducibility [6, 21, 22]. In this paper an optimisation design of a cruciform specimen with thickness reduction in the central part is presented. Experimental measurements show this specimen fulfills the above mentioned conditions.

Composite materials specimens for biaxial testing

Cross-shaped specimens give the best results to determine biaxial stresses [10, 13, 23, 24]. It has been proven that cruciform specimens allow to obtain the greatest deformation in its middle part and minimisation of stress concentration in other areas of the specimen [17]. However, the arms of the specimen are affected by each other because of the intersecting loads, and hence if the specimen geometry and load applied are not correct, maximum stresses and failure will occur in the arms border [5]. Considering this situation, a proposal to reduce the central specimen section was presented by Ohtake [10] as shown as ***Figure 1***.

Using the previous idea, Welsh and Adams [21] developed a cruciform specimen with reduced thickness at the centre, thus avoiding failure occurring outside the measurement section (***Figure 2***, see page 90).

This thickness reduction at the specimen centre allowed obtaining better results. Smiths (2006) [6] proposed a cruciform test specimen with central area reduction, but also with the testing of various radii of curvature at the edges

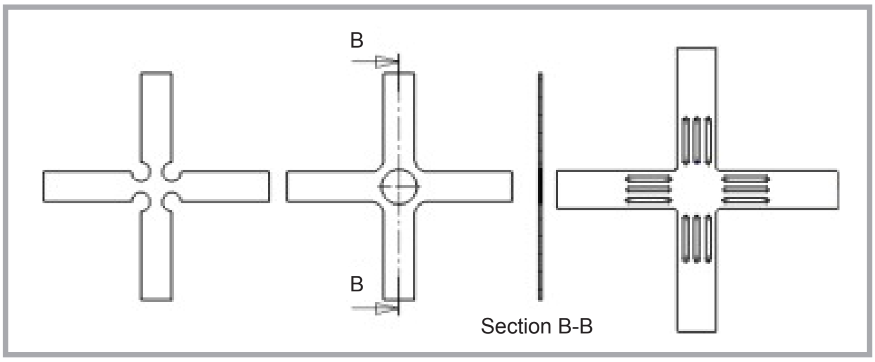


Figure 1. *Proposal for biaxial specimen central area reduction [10].*

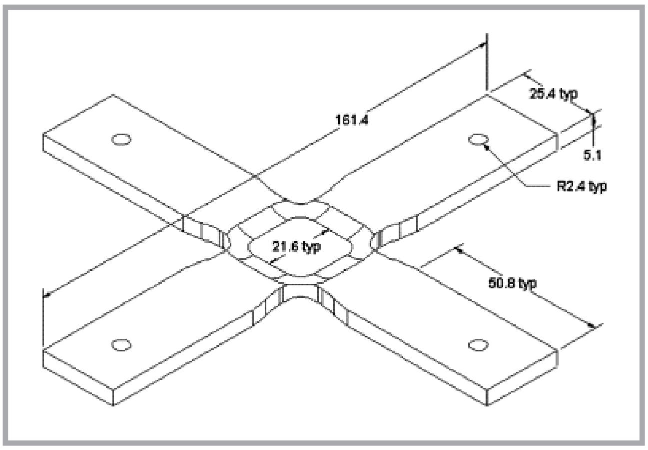


Figure 2. *Specimen proposal with a reduced thickness in its central section [21].*

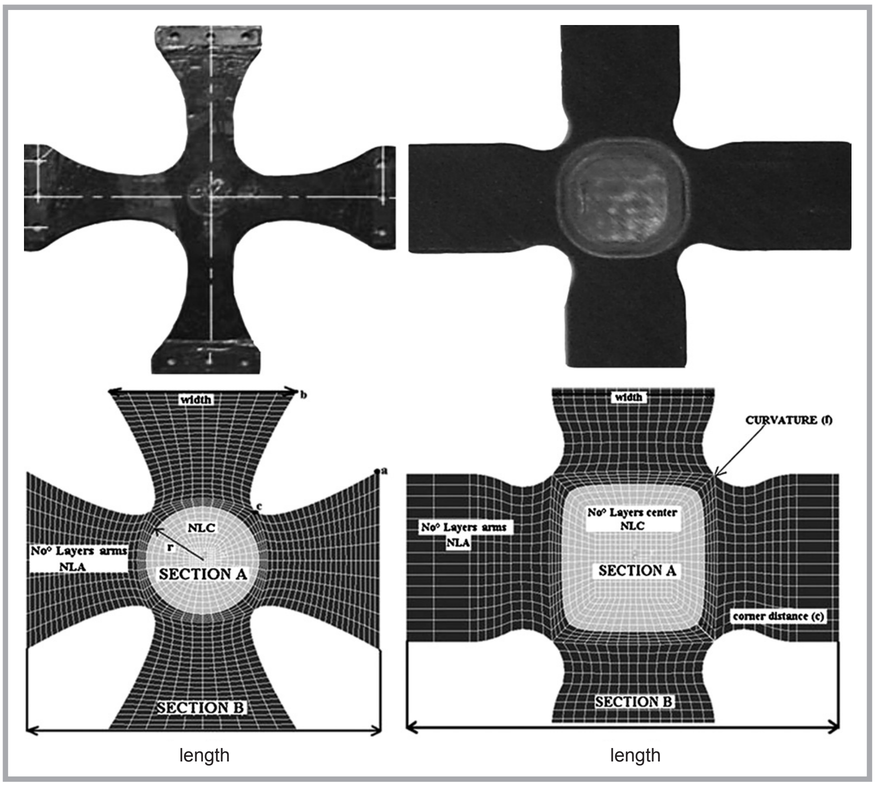


Figure 3. *Cruciform specimens with A) variable width of arm, B) fillets in corners; (up) actual specimen, (down) simulated specimen (Markis and Mayes, 2008).*

of the specimen. In this way it was possible to state that failure occurred in the thinner region, instead of on the arms

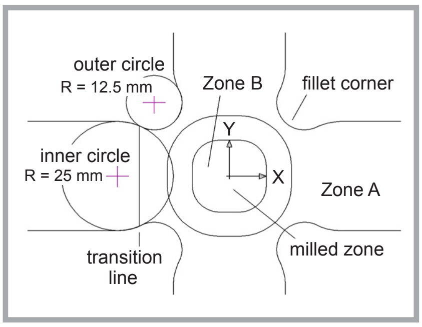


Figure 4. *Stress concentration reduction at the specimen's edges by varying their curvature radius [14, 15].*

of the specimen. The use of inspection techniques to verify the strain distribution results is reported in [8, 9, 14]. The techniques used were image correlation, interferometry (ESPI) and acoustic emission. Also reported was the use of the digital image correlation (DIC) [2, 6, 9], which allowed to determine the displacement and deformation fields on surfaces based on the comparison of images taken at different times. The latter technique offers advantages over the use of strain gauges in the visualisation of deformation zones rather than just detect these deformation values at a single point. Welsh and Mayes [19] used a carbon fibre based specimen. The arrangement of fibre at the centre of the specimen was (0/45/-45/90)whileinthearmsitwas(0/90) 4 (0/45/-45/90) [2]. Using CNC high speed machining, the thickness of the central part of the probe was decreased. In parallel, a numerical simulation using the multi continuous theory (MCT) was carried out. Symmetry between the numerical and experimental results were reported. Markis & Ramault (2008) [11] proposed a cruciform specimen when using the digital image correlation (DICT) to show specimen deformation evolution. Complementing this proposal, another specimen geometric design for testing biaxial loads and stress concentration at the centre, was presented by Markis (2010) [13]. The results obtained with that specimen were compared with numerical models based on sequential quadratic programming (SQP) and with finite element models (FEM). Their results are shown in ***Figure 3***.

Lankanfi et al. (2010) [14] and [15] presented another geometry obtained by a finite element model. For a given geometry, different radii edges in the transition zone between the arms and central part of the specimen were tested for minimum stress concentration. Also the specimen's central part thickness was reduced as shown in ***Figure 4***. Other specimens have been studied and optimised for metallic materials [26] and, thermoplastic compounds [12], especially for the aviation industry.

FEA specimen design and simulation results

Based on the literature review, two cruciform specimen geometries are proposed. In the first model the radius (R) of the corners between the arms is varied (***Table 1 & Figure 5.a***). In the second model the radius (R1) and distance from the axis to the centre of the radius (H) is also varied (***Table 1 & Figure 5.b***).

The objective of this design was to obtain in a consistent way the maximum stresses under biaxial loading occurring in the specimen's central part. Using the geo-

Table 1. *Cruciform specimen dimension for specimen A and B.*

Specimen A	R, mm	Specimen B	R1, mm	H, mm
1	20	4	15	26
2	15	6	10	21
3	10	7	5	15

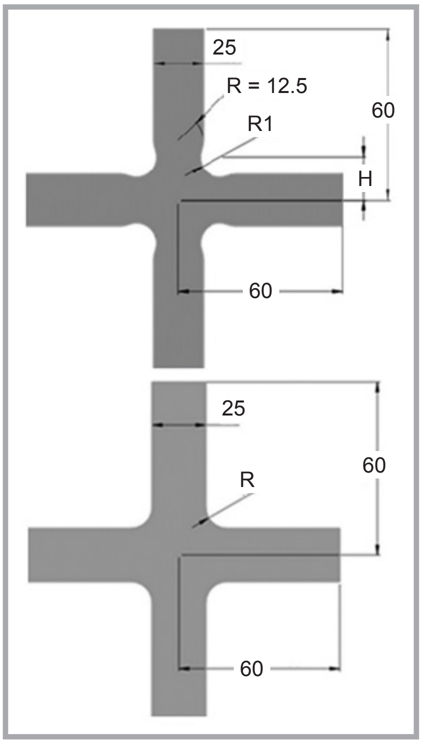


Figure 5. Biaxial specimen with: A) different edge radius, B) different H distances and fillet corner.

metric conditions previously shown, the best combination of central thickness and radius edge was identified. FEA models were developed and then, values to calculate stresses using the criteria of Von Mises (***Equation 1***) and maximum principal stress (***Equation 2***) were evaluated. These values were later experimentally checked.

$$\sigma_{VM} = \sqrt{\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 3\tau_{xy}^2} \quad (1)$$

$$\sigma_{1,2} = \quad (2)$$
$$= (\sigma_x + \sigma_y/2) \pm \sqrt{(\sigma_x + \sigma_y/2)^2 + \tau_{xy}^2}$$

In all cases shown in ***Figure 5***, a FEA mesh smoothing high was employed with a 1000 Kg. load applied. From the analysis it was identified that specimen 2 in ***Figure 6*** has the highest stress concentration in the centre in relation, to the maximum stress at the edges of the arms. Hence this geometry was chosen for further improvement varying the specimen's shape of the central zone as indicated in ***Figure 7***.

The optimization process consisted in varying parameters of the specimen shown in ***Figure 5***, following the pattern of ***Figure 6***, according to what is shown in ***Figure 7*** and ***Table 2*** (distance between the centres (B), radius (R), and radius at the edges (r)).

For the five specimens considered, the following parameters were set:
- Specimen thickness 2.2 mm.
- Central area thickness 1.4 mm (thickness reduction 0.4 mm on both sides).

The results of these simulations are shown in ***Table 3***. which shows that specimen 2E has the optimum stress rate between the central and edges stress values. For this specimen, the stress values are shown in ***Figure 8***.

From these results, a (***Figure 8***), a new geometry with a rhomboid shape of different dimensions was proposed. The specimen's central area thickness was set to 0.4 mm on both sides. Hence, the centre area thickness was set to 0.6 mm thick.

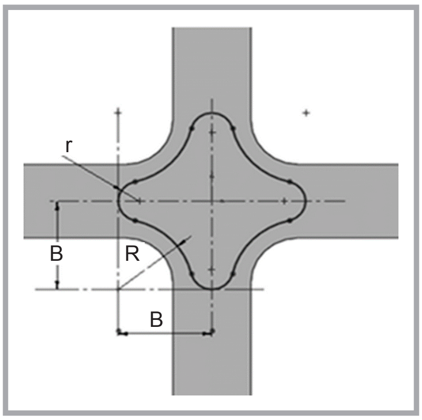


Figure 7. Test parameters values for specimen 2.

Table 2. Cruciform specimen parameters for Fig\ure 7.

Specimen	B, mm	R, mm	r, mm
2A	35	29	6.6
2B	30	25	6.7
2C	33	27	6.6
2D	30	21	10.9
2E	30	24	6.7

Table 3. Ratio between central and edges stress values.

Specimen	Max stress, MPa	Centre stress, MPa	Ratio, %
2A	32.17	20.18	62.7
2B	29.75	19.45	65.4
2C	31.07	19.86	63.9
2D	33.39	20.66	61.8
2E	**28.70**	**19.36**	**67.4**

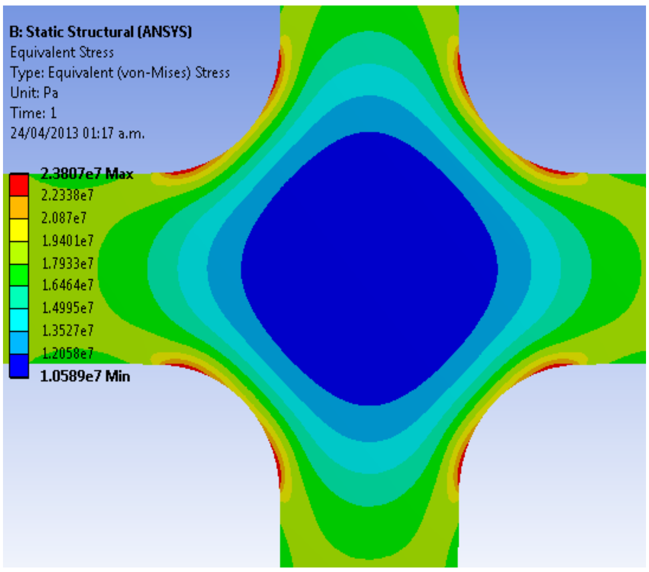


Figure 6. Base geometry selected for the specimen optimisation process.

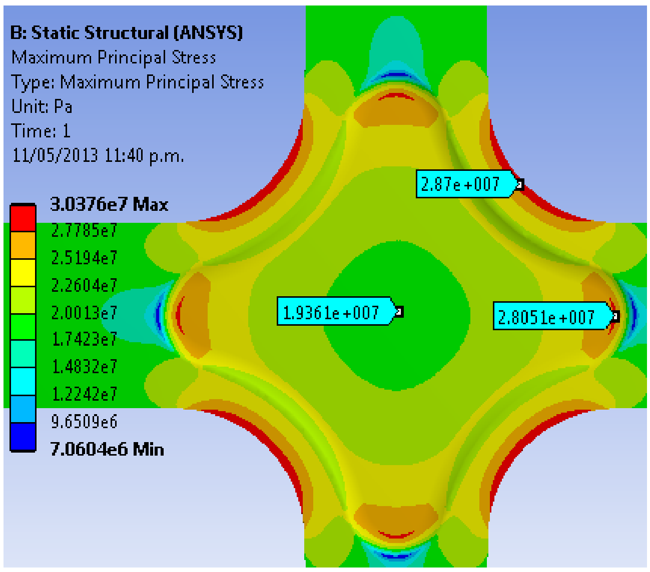


Figure 8. Stress state for specimen 2E.

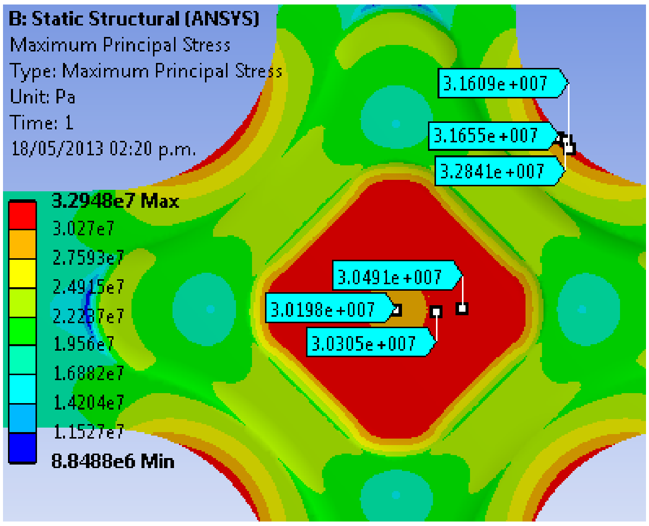


Figure 9. *Stresses on specimen 2E1.*

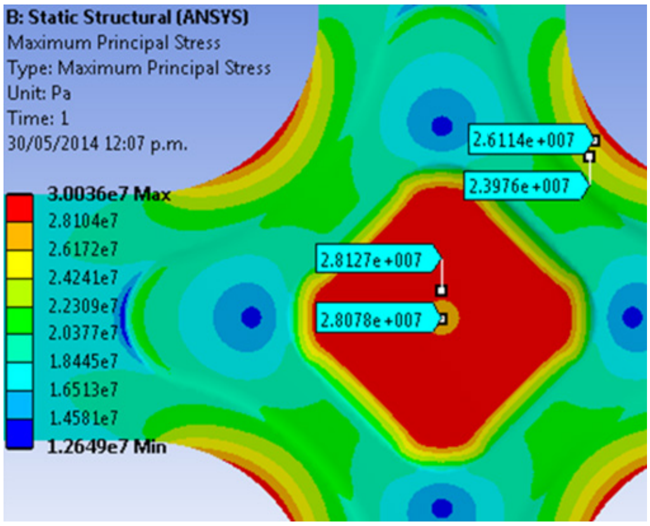


Figure 13. *FEM model stresses in the specimen's central area and edges compared with those calculated for a 1500 N load.*

Table 4. *Ratio of the specimen's central area to edge stresses.*

Specimen	Max stress, MPa	Centre stress, MPa	Ratio, %
2E1	**31.6**	**30.4**	**96.2**
2E2	34.7	30.0	86.4
2E3	34.1	30.1	88.2
2E4	34.7	30.5	87.8

Different romboid size simulations were carried out and the stress ratio was evaluated. Results are shown in ***Table 4***. showing that the geometry of test specimen 2E1 has the highest, stress to maximum stress ratio in the central part which is shown in ***Figure 9***.

Specimen manufacture

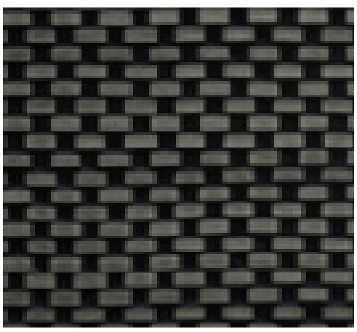
Based on the findings from the FEM, test specimens were manufactured using the Hand Lay-up technique [28]. Ten layers of carbon fibre material oriented at 0 ° and 90 ° with respect to the orientation of the arms of the specimen were placed. This arrangement gave a 2.4 millimeters specimen thickness. Characteristics of the resin used are shown in ***Table 5.a*** and those of carbon fibre material in ***Table 5.b***.

Thickness reduction of the specimen test area was obtained by milling. It is noted that although the specimen is external layers are cut, the centre ones remain unchanged. And precisely on these central layers all the measurements are carried out.

Table 5.a*. Resin characteristics used for specimen manufacture.*

	Resin RE – 7000-1	Catalyst HD-307
Appearance	Lump-free liquid	No suspension particles liquid
Colour gardner, max	2	< 9
Viscosity at 25 °C, cPa s	5000 - 9000	50 - 90
Specific weight, 25° C, g/cm^3	1.15 – 1.17	0.98 – 1.02

Table 5.b. *Carbon fibre characteristics used for specimen manufacture. *As describe in [29]. **Nomenclature used in NASA-INDUSTRY [30].*

	Description	3K-70-P**
	Weave	Plain*
	Warp	3K
	Weft	3K
	Construction (ends × picks), cm	30.48 x 30.48
	Linear density, tex	198
	Mass, g/m^2	193

Experimental test results

Test equipment

Based on Smith's [2] and [6], Kumazawa's [5] and Boheler's [17], a biaxial test equipment was constructed (***Figure 10***). This equipment has a load capacity of 50 kN in each direction. A ynamic load can be applied to a frequency of up to 5 Hz [4]. The control system is based on an analogue to digital converter (National Instruments card 779 994) and Lab View software.

The specimen was clamped using flat jaws with pyramid-shaped teeth and reinforcing the contact area with abrasive paper, thus increasing frictions levels at the clamp area. The equipment allowed to load the specimen both in tension and compression. Since the main objective of this paper was to show that the maximum stress occurs at the centre of the test specimen, a relatively low biaxial load was used. Thus it can be observed that the maximum stresses occur at the centre of the specimen as shown by the FEA model simulation.

Procedure

The specimens were subjected to loads of 1110 N to 1990 N. Three-axis strain gauges rosettes 031WW C2A-brand-350 Vishay were used to evaluate the specimen's central area deformation. Four specimens were analysed in order to get a reliable average deformation for the force applied.

Figure 11 shows the strain gauges location. This strain gauges position was defined based on the FEA model of specimen 2E1.

The fibre and resin were considered as a single material. Signals of the strain gauges gave ε_x and ε_y from experimental measurements values (***Figure 12*** and ***Table 6***). These values were used in ***Equation 3***.

Hence the principal stress (σ_1 and σ_2) and the load (***Table 7***) can be obtained from ***Equation 4.***

From the tensile test, the following values were considered: α = 45 °, ν_{12} = 0.3, E_{11} = 8351 MPa and E_{22} = 8240 MPa. Principal stresses obtained using the strain experimental values are shown in ***Table 7***, see page 92.

From the results above it was found that a maximum biaxial stress at the centre of the specimen can be achieved. ***Figure 13*** shows the results for an axial load of 1500 N. In this figure it can be seen that the stresses at the centre of the specimen are higher than those acting on the specimen's edges.

$$\varepsilon_{1,2} = [(\varepsilon_x + \varepsilon_y)/2 + (\varepsilon_x - \varepsilon_y)/2]\cos 2\alpha + (\gamma_{xy}/2) sin2\alpha \quad (3)$$

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_6\end{Bmatrix} = \frac{1}{1-(E_{22}/E_{11})\nu_{12}^2}\begin{bmatrix}E_{11} & \nu_{12}E_{22} & 0\\ \nu_{12}E_{22} & E_{22} & 0\\ 0 & 0 & G_{12}(1-(E_{22}/E_{11})\nu_{12}^2)\end{bmatrix}\begin{Bmatrix}\epsilon_1\\ \epsilon_2\\ \gamma_6\end{Bmatrix} \quad (4)$$

Equations 3 and 4.

Table 6. *Experimental strain obtained from gauge 1, (central area) and 2 (edge).*

Strength, N	Strain, %					
	Gauge 1			Gauge 2		
	ε_x[0°]	ε_y[90°]	γ_{xy}[45°]	ε_x[0°]	ε_y[90°]	γ_{xy}[45°]
856	1.01	1.07	0.86	0.13	0.18	-0.44
999	1.26	1.33	1.14	0.19	0.21	-0.58
1142	1.56	1.59	1.39	0.25	0.28	-0.74
1285	1.72	1.78	1.60	0.31	0.32	-0.91
1428	1.93	2.00	1.81	0.34	0.36	-1.04
1571	2.21	2.27	2.07	0.39	0.40	-1.20
1713	2.51	2.50	2.27	0.43	0.45	-1.34
1856	2.74	2.78	2.50	0.49	0.50	-1.50
1999	2.94	3.03	2.75	0.54	0.54	-1.65

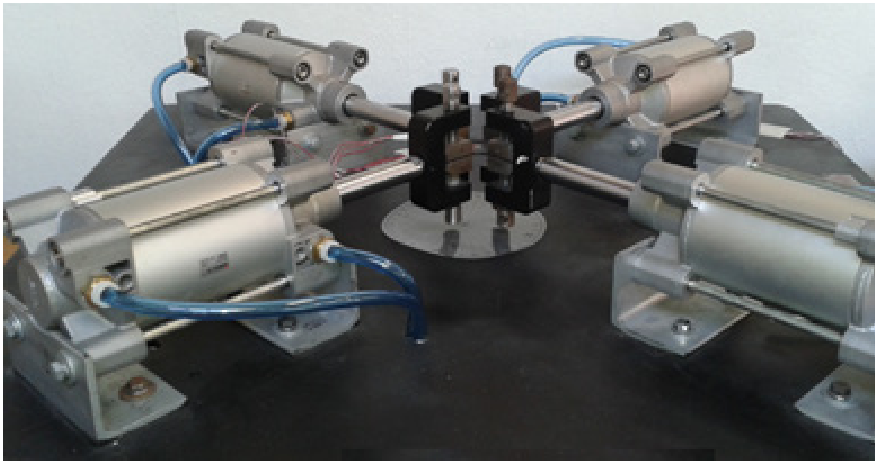


Figure 10. *Biaxial test equipment developed at the CICATA-IPN.*

Conclusions

Using Finite Element Analysis and experimental measurements, a cruciform specimen geometry was determined for obtaining the maximum stress value at its centre. This makes it suitable for the study of the behavior of composite thin films under biaxial loads. Hence using the design specimen presented, it is possible to obtain the maximum deformation at the centre of this specimen.

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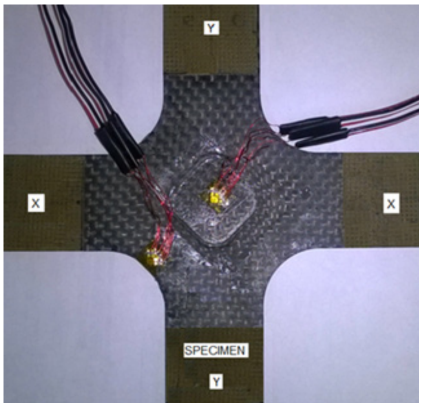

Figure 11. *Strain gauge position of specimen 2E1.*

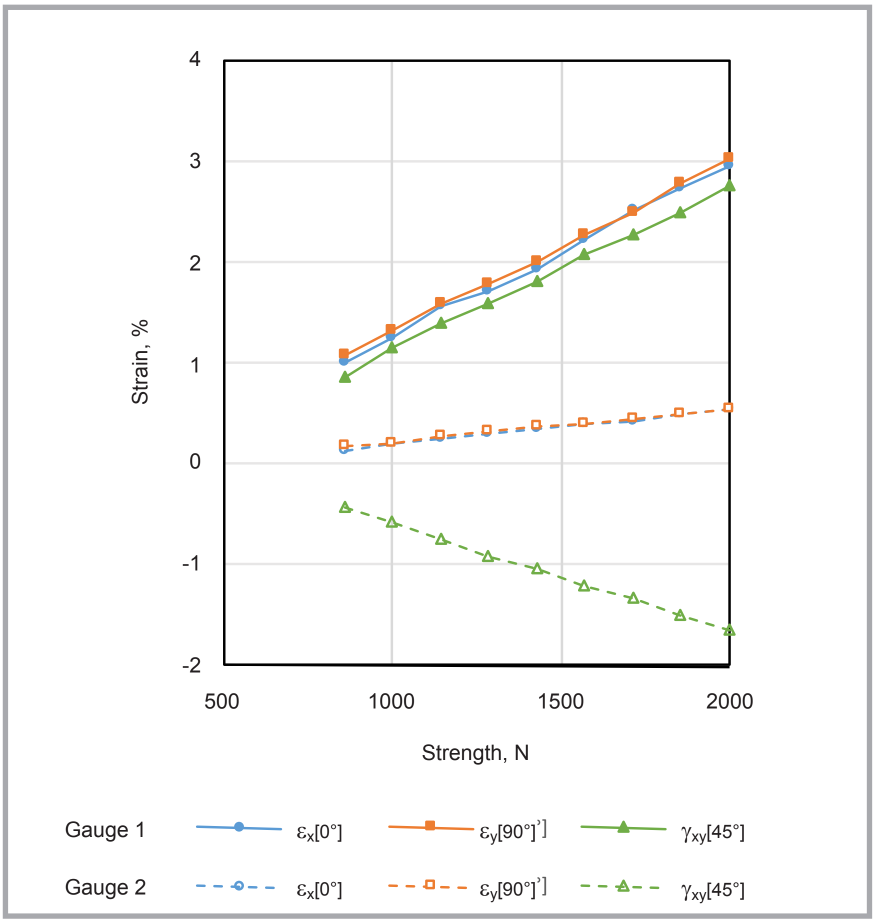

Figure 12. *Experimental strain obtained from gauge 1 and 2.*

Table 7. *Principal stresses obtained using experimental values of the strain.*

Strength, N	**Stress, MPa**					
	Gauge 1			**Gauge 2**		
	σ_1	σ_2	τ_6	σ_1	σ_2	τ_6
856	12.04	12.44	-0.12	1.64	1.97	-0.40
999	15.02	15.47	-0.11	2.27	2.41	-0.52
1142	18.47	18.63	-0.13	3.01	3.18	-0.68
1285	20.44	20.86	-0.10	3.66	3.78	-0.83
1428	22.92	23.36	-0.10	4.07	4.20	-0.95
1571	26.15	26.58	-0.12	4.66	4.73	-1.09
1713	29.53	29.49	-0.16	5.11	5.24	-1.21
1856	32.41	32.64	-0.17	5.81	5.86	-1.36
1999	34.90	35.50	-0.16	6.39	6.14	-1.49

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