

# MEASUREMENT NOTE

**NPL Report MN 09**

## **Towards a Planar Cruciform Specimen for Biaxial Characterisation of Polymer Matrix Composites (PMCs)**

The vast majority of composite components experience multi-axial loading during service life and in use, these materials are often combined in a multi-directional laminate. Existing composite material test standards for generating mechanical design data are predominantly uni-axial in scope, and although several laboratories are proposing standard methods for biaxial characterisation, there is currently no standard protocol in place. A world-wide exercise to compare different failure theories for multi-axially loaded polymer composites has already been undertaken [1-12] and it is particularly important that the experimental data used for these inter-comparisons are robust and can be achieved by all using best practice.

The work detailed in this Measurement Note has been undertaken in support of developing a test method for the biaxial response of a planar cruciform specimen manufactured from fibre-reinforced plastic laminates subject to tension-tension loading.

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## INTRODUCTION

The vast majority of composite components experience multi-axial loading during service life and in use, these materials are often combined in a multi-directional laminate. Existing composite material test standards for generating mechanical design data are predominantly uni-axial in scope, and although several laboratories are proposing standard methods for biaxial characterisation, there is currently no standard protocol in place. A world-wide exercise to compare different failure theories for multi-axially loaded polymer composites has already been undertaken [1-12] and it is particularly important that the experimental data used for these inter-comparisons are robust and can be achieved by all using best practice.

There are several methods suitable for creating multi-axial loading, including the use of axial forces and pressure (internal/external) using tube specimens, biaxial plate or cruciform type biaxial configurations and full rig systems applying combinations of axial, bending and/or twisting loads. Whilst considerable work has been conducted using tubular specimens, recent moves by industry towards both larger and lighter composite structures requires the planar performance of these materials to be better understood. Currently, the biaxially loaded cruciform specimen has been identified as of most interest. A standards working group was recently formed under the VAMAS umbrella, comprising of QinetiQ (Farnborough), NPL and Vrije Universiteit Brussel (VUB). The objective of this international working group is to propose acceptable methodologies that will lead to internationally accepted test methods for the evaluation of the multi-axial strength of fibre-reinforced composites. The group aims to produce guidance that will outline a methodology based on previously validated information and that lists the benefits and limitations of biaxial evaluation. It is an opportune time to undertake this work because a growing number of laboratories world-wide have (or are developing) capability this area.

The work detailed in this Measurement Note has been undertaken in support of developing a test method for the biaxial response of a

planar cruciform specimen manufactured from fibre-reinforced plastic laminates subject to tension-tension loading only.

## SPECIMEN REQUIREMENTS

In general, specimens that are suitable for biaxial characterisation must satisfy a number of requirements, namely:

- The shape of the test specimen shall be cruciform with a central gauge section, an example is shown in Figure 1.
- The shape and dimensions of the test specimen shall be such that when loaded in tension in the primary and secondary loading directions simultaneously, a uniform biaxial strain field is produced within a minimum centrally located gauge-section of 20 mm diameter,
- Final failure should occur within the gauge-section and is deemed to have occurred when the load carrying capacity of the specimen drops by 20%.

It is noted that the specimen loading rate can be of equal or unequal proportions in the two directions. The specimens and procedures detailed in this Measurement Note are suitable for use with thermoset and thermoplastic matrix laminates made from either unidirectional or woven pre-preg materials, where the lay-up is symmetrical and balanced about the specimen mid-plane. Fibre reinforcement should be present in both the loading directions.

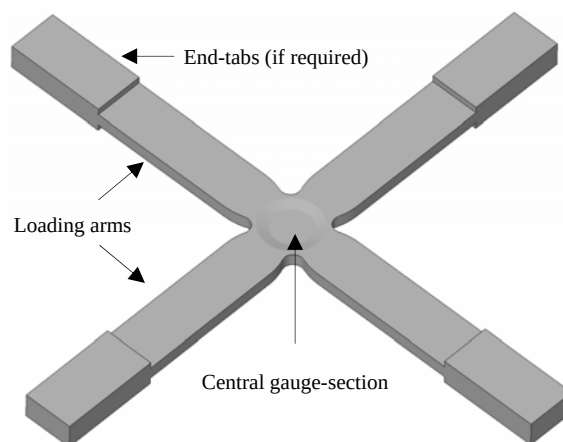


**Figure 1: Schematic of generic biaxial cruciform specimen geometry**

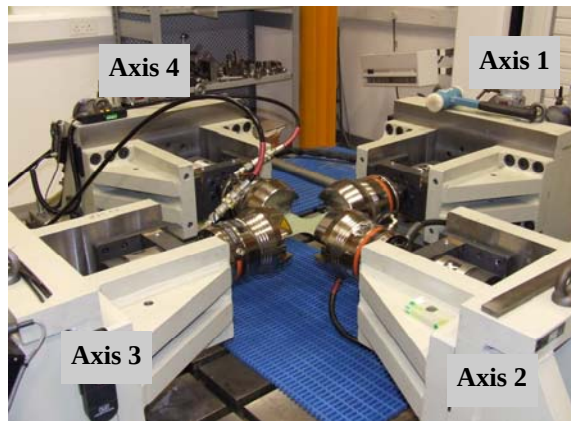


**Figure 2: The NPL multi-axial test facility**

### MULTI-AXIAL TEST FACILITY

The NPL multi-axial test facility consists of a tee-slotted cast iron strong floor, upon which can be mounted up to four hydraulic actuators (axes 1-4), each with a static rating of  $\pm 50$  kN. Each of the hydraulic rams has a stroke of  $\pm 50$  mm and can be positioned on the strong floor independently, providing, for example, the flexibility to configure the facility from four single-axis test rigs, to a biaxial loading arrangement for cruciform test components. Figure 2 shows the set-up as used for biaxial testing of a cruciform specimen geometry.

### MATERIAL AND LAY-UP DETAILS

The material system used in this study was SE84 LV unidirectional carbon fibre-reinforced epoxy pre-preg supplied by Gurit Holdings AG as an industrial co-funding contribution. The lay-up of the laminates from

which all specimens were machined was  $[+45^\circ/0^\circ/-45^\circ/90^\circ]_{2s}$ , equating to a thickness of  $\sim 4.7$  mm.

### SPECIMEN DESIGN

Specimen design was based on the generic form shown in Figure 1, with specimen arms all of the same length and a circular central gauge section. The size and geometry of the test specimens was limited by the maximum size of square panel (300 x 300 mm) that could be manufactured in the NPL autoclave facility. The size of the specimen gauge-section and arm width was limited by the load capacity of the multi-axial facility which is 50 kN.

Initially, a coupon with 50 mm wide arms and a circular gauge-section 40 mm in diameter was designed in order to give a large area of uniform strain in the centre of the specimen in which biaxial strain measurements could be made (Figure 3). The specimen width/length was 300 mm and the radius at the intersection of the arms was 25 mm. The thickness of the central gauge-section was reduced from 4.7 to 2.3 mm via a tapered zone 5 mm in length. The reason for ‘waisting’ the thickness was to promote failure in the gauge section. This type of coupon is referred to as the ‘50 mm’ design for the remainder of this report.

In order to reduce the load required to fail the biaxial specimens, a smaller gauge section specimen design was also investigated (Figure 4). This design has 25 mm wide arms and a

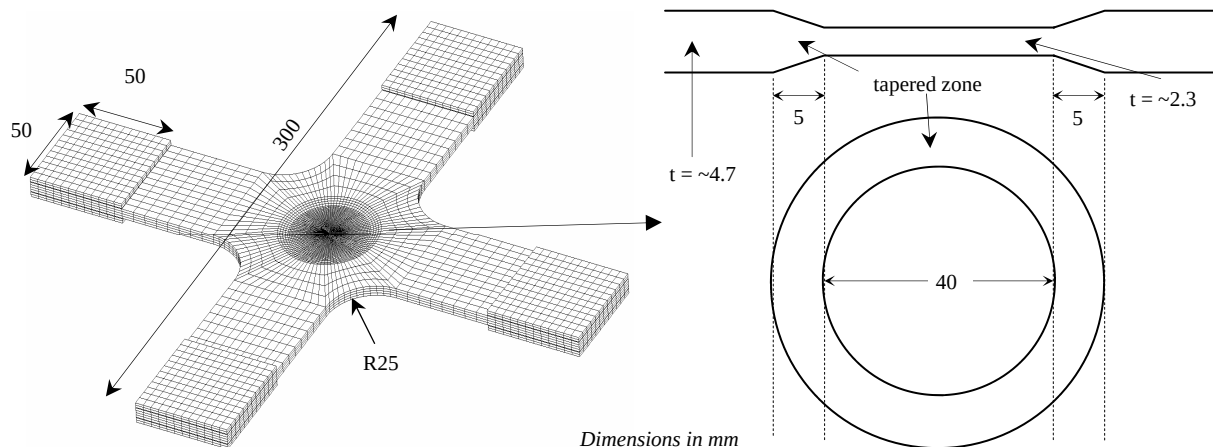


**Figure 3: Details of 50 mm biaxial coupon design - used for initial elastic testing**

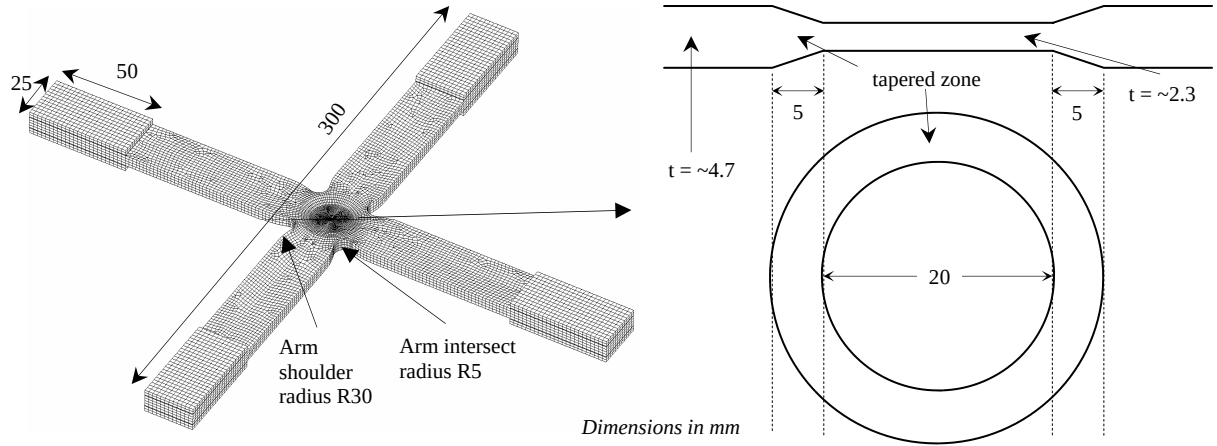


**Figure 4: Details of 25 mm biaxial coupon design**

circular gauge section 20 mm in diameter, which was the minimum size of gauge-section as specified in the specimen requirements agreed by the VAMAS working group. As for the 50 mm design, the specimen width/length was 300 mm. The design of the radius at the intersection of the arms was changed to an intruding radius of 5 mm with an arm shoulder radius of 30 mm. The protruding radius was chosen in an effort to reduce the stress transfer between specimen arms via the  $\pm 45^\circ$  plies and promote failure in the gauge section rather than at the radius of the arms. This approach had shown potential in work reported by Smits et al [13]. As for the 50 mm specimen design, the thickness of the central gauge section was reduced from 4.7 to 2.3 mm via a tapered zone 5 mm in length. This smaller type of coupon is referred to as the ‘25 mm’ design for the remainder of this report.

#### Finite element analysis (FEA)

A series of finite element analyses (FEA) were undertaken for the biaxial coupon designs using LUSAS Composite software. The analyses were 3D and elastic. Glass fibre-reinforced epoxy end-tabs and a 0.25 mm thick adhesive bond-line were also included in the model. Elastic (and strength) ply data for the SE84 LV material system (previously measured at NPL) were used as input into the FE models (Table 1). For all of the models, a 20 MPa clamping stress was applied to the end-tab regions to replicate the clamping pressure applied in the experimental tests via initially mechanical, and later, hydraulic grips.

The FEA analyses were used to predict strain distributions for comparison to values measured using strain gauges and digital image correlation (DIC).

**Table 1: Elastic Property Data for UD SE84 LV Material Used in FEA Analyses**

| Elastic Property        | Value             |
|-------------------------|-------------------|
| $E_{xx}^T$ (GPa)        | $124.3 \pm 4.4$   |
| $E_{yy}^T$ (GPa)        | $8.14 \pm 0.1$    |
| $E_{zz}^T$ (GPa)        | $7.8 \pm 0.12$    |
| $E_{xx}^C$ (GPa)        | $110.0 \pm 5.6$   |
| $E_{yy}^C$ (GPa)        | $8.5 \pm 0.4$     |
| $E_{zz}^C$ (GPa)        | $8.3 \pm 0.14$    |
| $G_{xy}$ (GPa)          | $4.49 \pm 0.07$   |
| $G_{xz}$ (GPa)          | $3.93 \pm 0.21$   |
| $G_{yz}$ (GPa)          | $2.44 \pm 0.10$   |
| $\nu_{xy}^T$            | $0.32 \pm 0.02$   |
| $\nu_{zx}^T$            | $0.017 \pm 0.004$ |
| $\nu_{zy}^T$            | $0.505 \pm 0.005$ |
| $\nu_{zx}^C$            | $0.020 \pm 0.009$ |
| $\nu_{zy}^C$            | $0.518 \pm 0.007$ |
| Strength Property (MPa) | Value             |
| $S_{xx}^T$              | $2751 \pm 32$     |
| $S_{yy}^T$              | $25 \pm 9$        |
| $S_{zz}^T$              | $42 \pm 2.5$      |
| $S_{xx}^C$              | $1180 \pm 53$     |
| $S_{yy}^C$              | $173 \pm 3.2$     |
| $S_{zz}^C$              | $165 \pm 2.5$     |
| $S_{xy}$                | $106.9 \pm 2.78$  |
| $S_{xz}$                | $97.87 \pm 5.20$  |
| $S_{yz}$                | $35.21 \pm 3.93$  |

## SPECIMEN PREPARATION

Test panels, 300 x 300 x ~4.7 mm, were manufactured at NPL according to the fabrication method given in ISO 1268 [14] and following material supplier's guidance. All panels were autoclave cured at 120°C for 1 hour (3°C/minute ramp at 6 bar).

For the 50 mm specimen design, the reduced thickness central gauge-section was created by dropping off the outer +45°, 0°, -45° and 90° plies from each surface of the base laminate (Figure 5a). The plies were dropped off over a 5 mm long tapered zone. The cruciform specimen was then produced by machining from the base laminate. It is noted that the ply drop-off method for creating a reduced thickness gauge section is a labour intensive process and can present difficulties in accurately locating the plies with respect to the centre position of the specimen. The surface of the ply drop-off region was smooth due to resin bleeding from the laminate during cure, forming a resin rich region on the surface.

For production of the 25 mm specimen design a different approach was adopted. Specimens were extracted from cured panels using water jet profiling undertaken by GFM (UK) Ltd.

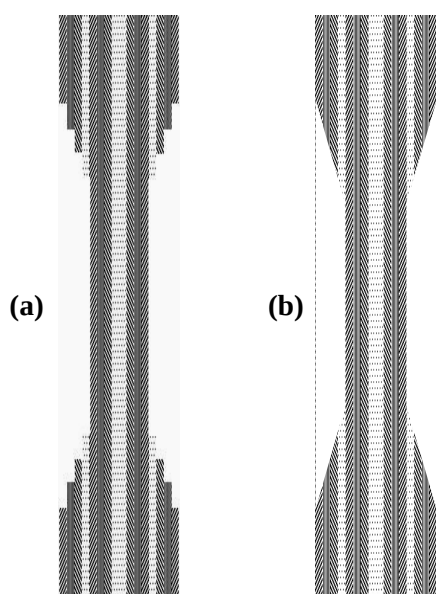


**Figure 5: Reduction of gauge-section thickness by; (a) ply drop-off and (b) machining**

This was a much quicker and cheaper machining method compared to milling, and it was easier to machine a more complicated profile. The waisted thickness gauge section was created by milling away material in 0.1 mm increments from both sides of the specimen until the correct depth profile had been achieved.

Specimens were end-tapped using 2 mm thick Tufnol 10G/40® woven glass fibre-reinforced epoxy material cut at 45° to the 0° fibre direction. End-tabs were bonded to the CFRP material using Scotchweld 9323 adhesive. It is noted that end-tabs are not essential providing failure does not occur at or within the arms. However, for the work detailed in this Measurement Note, all specimens were end-tapped.

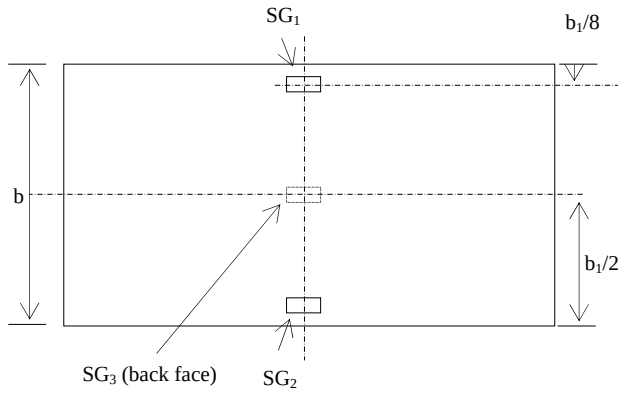
Advice on parameters for machining is specified in ISO 2818 [15]. Further guidance on machining of composite specimens is given in [16].

## MEASUREMENT OF STRAIN

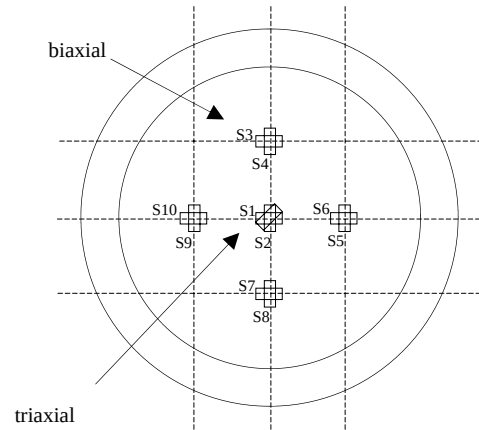
A combination of DIC and metal foil electrical-resistance gauges were used for strain measurements. In the central-gauge section, one side of the specimen was used for DIC measurements whilst strain gauges were bonded on the opposing faces.

### Digital Image Correlation (DIC)

DIC is a non-contact full-field strain measurement technique. The basic concept of DIC is to compare images of a component before and after deformation. Displacements and strains are determined by correlating the position of pixel subsets or blocks in the original and deformed images, normally based upon contrast i.e. grey intensity levels. The size of the pixel block can be varied, thus allowing many random patterns to be correlated. In order to identify if there is any movement between the two blocks there must be sufficient detail for it to be considered unique. It may be the case that the specimen or component already has a suitable level of surface features which can be imaged directly, but if not, some form of spray paint or coating or scratches on the surface can be used. Specimens analysed with DIC were sprayed



(a)



(b)

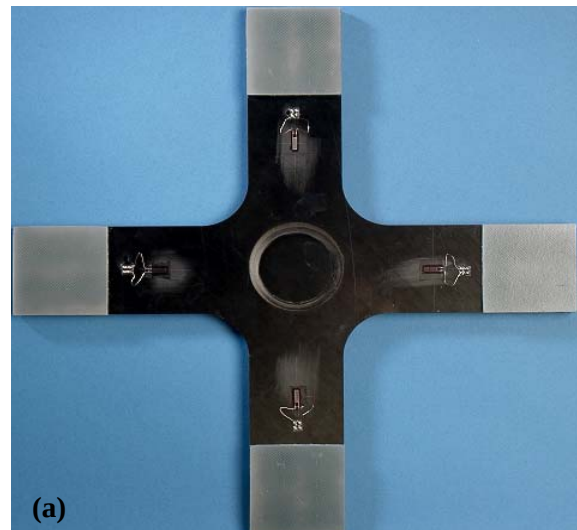
**Figure 6: Strain gauge positions for; (a) 25 and 50 mm specimen arms and (b) central gauge-section of 50 mm specimen**

with white, grey and black paint to achieve a unique surface finish with a variety of grey levels. A LaVision® DIC system was used with 14 and 39 megapixel digital SLR cameras and a 5 megapixel video camera to map 2D strain distributions. Images were recorded throughout the tests and all strain results were calculated relative to the first image recorded at zero load.

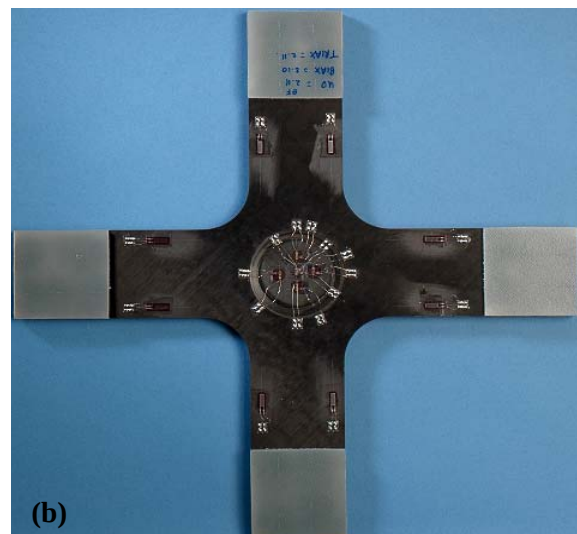
DIC was used to measure the strain in and around the central gauge section of 25 and 50 mm specimens.

### Strain Gauges

For the 50 mm specimen, 5 mm long TML FLA-5-11 strain gauges were bonded to all 4 arms according to the configuration shown in Figure 6a and at a position mid-way between the end of the end-tab and the start of the radius. A strain gauged specimen is shown in Figure 7. These gauges were used to monitor the degree of in-plane and through-thickness bending. The configuration of the gauges, bending analysis and limits for an acceptable level bending have been taken from ISO 527-5 [17] which provides best practice for uni-axial tensile testing. It is noted here that the combined (in-plane and through-thickness) limit level of bending of <3% is considered too strict for a test where load is applied in orthogonal directions. However, the analysis is of value in that it provides a means for assessing the alignment of the test set-up and specimen.



(a)



(b)

**Figure 7: Strain gauges on; (a) top and (b) bottom faces of a 50 mm specimen**

The equations for in-plane, through-thickness and combined bending, respectively are detailed below.

$$\text{In-plane bending: } B_b = \frac{4|e_2 - e_1|}{3e_{av}} \times 100$$

$$\text{Through-thickness bending: } B_h = \frac{|e_{av} - e_3|}{e_{av}} \times 100$$

$$\text{Average strain: } e_{av} = \left( \frac{e_1}{4} + \frac{e_2}{4} + \frac{e_3}{2} \right)$$

$$\text{Total bending: } B_b + B_h \leq 3.0\%$$

Where  $e_1$ ,  $e_2$  and  $e_3$  are the strains recorded using strain gauges  $SG_1$ ,  $SG_2$  and  $SG_3$  (shown in Figure 6a).

In addition to the arm gauges, a single triaxial and 4 biaxial rosettes (TML FRA-2-11 and TML FCA-2-11, respectively) were used for strain measurements in the central gauge section (Figure 6b).

For the 25 mm specimens, 2 mm long TML FLA-2-11 strain gauges were bonded to all 4 arms as per Figure 6a. As for the 50 mm specimen, these gauges were used to assess the degree of bending. As the central gauge section for the 25 mm specimens was only 20

mm in diameter, only a single triaxial gauge was used for measuring strain in this region of the specimen.

## EXPERIMENTAL SET-UP

Using an overhead crane, the four hydraulic actuators were positioned on the T-slotted strong-floor to form a biaxial loading configuration as shown in Figure 2. Accurate alignment of the two pairs of actuators was not a trivial task owing to the large size and weight (each 820 kg) of the side-loading protection brackets on which the actuators were mounted.

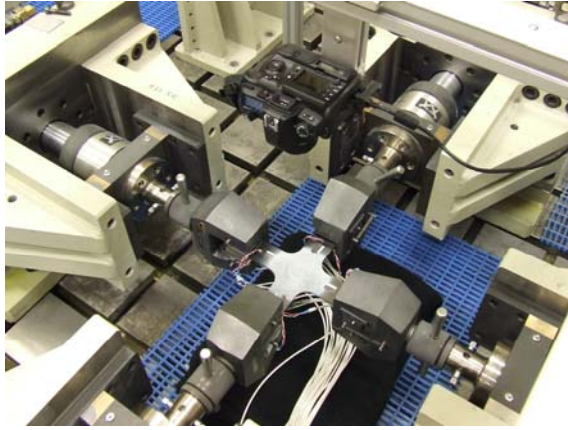
In order to obtain optimum alignment, female clevis pin fittings were bolted to the faces of opposing load cells, with location rings fitted between load cell and clevis fitting. With one actuator then bolted to the strong-floor via six M24 bolts, a large diameter steel rod, with male clevis pin ends, was connected to the female fitting on the fixed actuator. The other end of the rod was then offered up to the female fitting on the free actuator, and the actuator position adjusted gradually using two side bolts via a steel mount fixed to the strong-floor base until the male clevis fitting could slide into the female. The free actuator was then bolted to the strong-floor. The process was repeated for the other two, orthogonal actuators with squareness between the two pairs set using a large square.

With actuators correctly positioned, grips were fitted and each load cell was position tuned. Initially, mechanical wedge action grips (Figure 9a) were used for the 50 mm specimen tests, but it was found that once a specimen had been loaded and unloaded several times, the grips could come loose, resulting in loss of load control and potential damage to the specimen. Also, the use of mechanical wedge-action grips made it difficult to ensure that the same gripping pressure was applied to each end-tab region. Consequently, it was decided to use hydraulic wedge-action grips (Figure 9b) for the 25 mm specimen tests, so that a consistent and constant gripping pressure (200 bar) could be applied and maintained throughout the test.

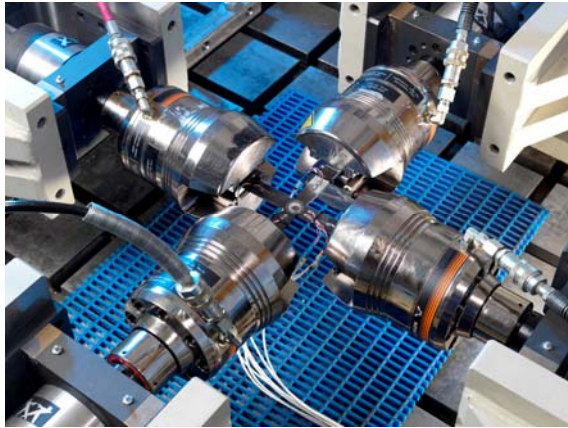
Opposing actuators were coupled together using the Instron control software to form a



**Figure 8: Arm and gauge-section strain gauges on a 25 mm specimen**



(a)



(b)

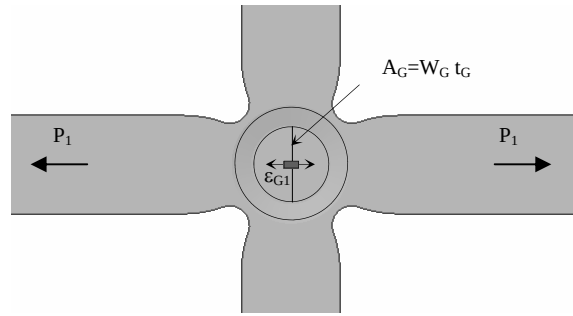
**Figure 9: Biaxial test set-up; (a) mechanical wedge-action and (b) hydraulic grips**

‘virtual’ axis. In each virtual axis, one actuator controls the translation displacement or load whilst the other controls the deformation displacement or load, depending on control mode. A trial test specimen was then gripped in the biaxial load configuration and the virtual axes load tuned.

### METHOD FOR BIAXIAL STRESS CALCULATION

It has been detailed in previous work [18] that determination of the actual stresses within the thickness-waisted gauge-section of biaxial cruciform specimens is slightly more complicated than for a uni-axial test specimen. This is due to the fact that a cruciform specimen contains loading arms that are common to two independent loading axes. This situation can result in a proportion of the load in each direction bypassing the gauge-section and being reacted by the material surrounding the gauge section.

To quantify the amount of stress bypassing the gauge-section, the approach used in this work is the same as that described in [18]. For a given cruciform design, a ‘pseudo’ uniaxial test is undertaken where the specimen is loaded in one direction only i.e. load is introduced via one pair of loading arms (Figure 10). The actual stress experienced in the gauge section,  $\sigma_{G1-ACT}$ , is determined by multiplying the measured strain ( $\epsilon_{G1}$ ) in the gauge section by the Young’s modulus of the laminate ( $E$ ). This stress is then divided by  $\sigma_{G1-ARM}$ , which is the stress in the gauge section calculated from the average load in the specimen arms ( $P_1$ ) by the gauge-section cross sectional area ( $A_G$ ). The ratio of stresses is termed the Area Correction Factor (ACF) and is an indication of the amount of stress that bypasses the central gauge-section. The ACF is used to calculate the biaxial stresses from



Where:

- $P_1$  = average load in 1-direction,
- $W_G$  = width/diameter of gauge-section,
- $t_G$  = thickness of gauge section,
- $A_G$  = cross sectional area of gauge-section,
- $\epsilon_{G1}$  = measured strain in 1-direction in the gauge-section
- $E$  = Young’s modulus of laminate

$$\text{Area Correction Factor, } ACF = \frac{\sigma_{G1-ACT}}{\sigma_{G1-ARM}}$$

Where:

$$\sigma_{G1-ACT} = \epsilon_{G1} E \quad \text{- actual stress in gauge-section}$$

$$\sigma_{G1-ARM} = \frac{P_1}{W_G t_G} \quad \text{- stress in gauge-section calculated from load in arms}$$

**Figure 10: Calculation of area correction factor for derivation of biaxial stresses**

the measured loads in the specimen arms and knowledge of the gauge section cross-sectional area.

As an example of this procedure, the ACF for a 25 mm biaxial coupon was calculated from the loads and strain measured from a uniaxial

**Table 2: Values Used for Calculating the ACF for the 25 mm Specimen Design**

| Quantity                          | Value       |
|-----------------------------------|-------------|
| $P_1$ (kN)                        | 5.680       |
| $A_G$ (mm <sup>2</sup> )          | 44.2        |
| $\epsilon_{G1}$ ( $\mu\epsilon$ ) | 1801        |
| $E$ (GPa)                         | 45          |
| $\sigma_{G1-ACT}$ (MPa)           | 81.05       |
| $\sigma_{G1-ARM}$ (MPa)           | 128.51      |
| <b>ACF</b>                        | <b>0.63</b> |

test via arms A1 and A3. The specimen was loaded to ~5 kN and the strain in the gauge-section was measured in the direction of the applied load.

## BIAXIAL TESTING AND RESULTS

### Initial trials using the 50 mm specimen

Initial experimental work was undertaken using the 50 mm specimen and all tests were elastic i.e. the specimen was not taken to failure. The objective of the tests was to check the alignment of the biaxial set-up, compare

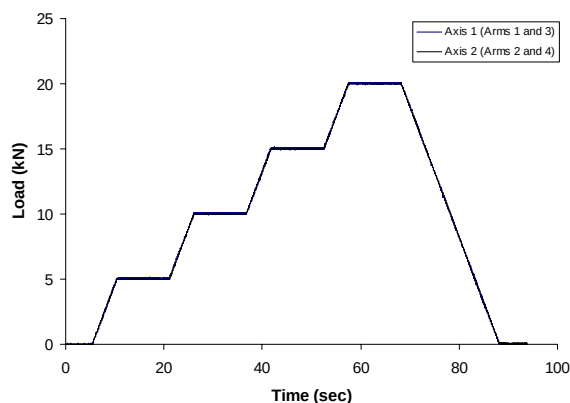


**Figure 11: Load profile for 50 mm specimen**

the strains measured using DIC and strain gauges with the strain field predicted using FEA, and also assess the uniformity of the strain field in the central gauge-section. Testing was performed using mechanical wedge-action grips and the load ratio in the two directions was 1:1 i.e. the same load level was simultaneously applied in both axes 1 and 2.

The load profiles, which were identical for both axes, are shown in Figure 11. Initially, the load was ramped at 1 kN/sec to 5 kN and then held for 10 seconds. The load was then ramped to 10 kN and held for 10 seconds. This loading pattern was repeated up to 20 kN at which point the specimen was unloaded. The reason for holding the load at 5, 10, 15 and 20 kN was to enable time for an image of the specimen to be recorded for DIC analyses using 14 and 39 megapixel (termed low and high resolution, respectively) digital SLR cameras. An image of the specimen prior to loading (at 0 kN) was also recorded and all DIC strain maps were calculated relative to this image.

Strain measurements on the specimen arms and in the central gauge-section were recorded continuously throughout the test using a National Instruments data logger. The strain gauge positions were as shown in Figure 6. Strain gauge data were analysed at 5, 10, 15 and 20 kN to assess the levels of in-plane and through-thickness bending in the specimen arms. The results of the bending analysis are shown in Table 3. It is noted that arms A1 and A3 are aligned on axis 1 and arms A2 and A4 are aligned on axis 2. The level of through-thickness bending in all arms and load levels was low (<3%). However, the level of in-plane bending in arms A1 and A2 (N.B. not on same axis) was high, up to 31% in arm A2 at 20 kN. Subsequent trials were undertaken to try to reduce the level of in-plane bending, but this did not result in any significant improvement. The degree of bending was thought to be due to the use of mechanical wedge action grips and the associated difficulties in ensuring that the same gripping pressure was applied to each arm.

A comparison of the strains measured in the central gauge-section, using strain gauges and DIC (low and high resolution), with values

**Table 3: Assessment of Bending in 50 mm Specimen**

| Arm | % bending under load |                |       |                |                |       |                |                |       |                |                |       |
|-----|----------------------|----------------|-------|----------------|----------------|-------|----------------|----------------|-------|----------------|----------------|-------|
|     | 5 kN                 |                |       | 10 kN          |                |       | 15 kN          |                |       | 20 kN          |                |       |
|     | B <sub>b</sub>       | B <sub>h</sub> | Total | B <sub>b</sub> | B <sub>h</sub> | Total | B <sub>b</sub> | B <sub>h</sub> | Total | B <sub>b</sub> | B <sub>h</sub> | Total |
| A1  | 15                   | 1              | 16    | 17             | 1              | 18    | 16             | 1              | 17    | 14             | 1              | 15    |
| A2  | 10                   | 1              | 11    | 21             | 2              | 23    | 27             | 2              | 29    | 31             | 1              | 32    |
| A3  | 5                    | 1              | 6     | 8              | 1              | 9     | 6              | 2              | 8     | 4              | 3              | 7     |
| A4  | 2                    | 1              | 3     | 7              | 1              | 8     | 13             | 1              | 14    | 11             | 2              | 13    |

**Table 4: Comparison of Strains in Central Gauge Section for 50 mm Specimen**

| Strain by:          |    | Gauge section strain readings* (microstrain) |      |      |      |      |      |      |      |      |      | Mean (SD, CoV)  |
|---------------------|----|----------------------------------------------|------|------|------|------|------|------|------|------|------|-----------------|
|                     |    | S1                                           | S2   | S3   | S4   | S5   | S6   | S7   | S8   | S9   | S10  |                 |
| DIC—low resolution  |    |                                              |      |      |      |      |      |      |      |      |      |                 |
| Load (kN)           | 5  | 180                                          | 149  | 121  | 126  | 115  | 140  | 133  | 140  | 144  | 109  | 136 (20, 15%)   |
|                     | 10 | 482                                          | 486  | 516  | 476  | 419  | 475  | 468  | 491  | 496  | 481  | 479 (25, 5%)    |
|                     | 15 | 801                                          | 850  | 801  | 884  | 722  | 808  | 731  | 852  | 848  | 834  | 813 (53, 6%)    |
|                     | 20 | 1150                                         | 1203 | 1175 | 1280 | 1109 | 1218 | 1129 | 1183 | 1204 | 1194 | 1185 (48, 4%)   |
| DIC—high resolution |    |                                              |      |      |      |      |      |      |      |      |      |                 |
| Load (kN)           | 5  | 228                                          | 508  | 326  | 321  | 373  | 204  | 242  | 441  | 472  | 515  | 363 (117, 32%)  |
|                     | 10 | 543                                          | 623  | 788  | 807  | 853  | 748  | 588  | 691  | 637  | 702  | 698 (101, 14%)  |
|                     | 15 | 861                                          | 1035 | 998  | 1049 | 977  | 952  | 928  | 1341 | 976  | 1131 | 1025 (133, 13%) |
|                     | 20 | 1322                                         | 1414 | 1410 | 1372 | 1433 | 1550 | 1247 | 1642 | 1453 | 1517 | 1436 (114, 8%)  |
| Strain gauges       |    |                                              |      |      |      |      |      |      |      |      |      |                 |
| Load (kN)           | 5  | 307                                          | 299  | 311  | 317  | 288  | 297  | 308  | 314  | 305  | 320  | 307 (10, 3%)    |
|                     | 10 | 620                                          | 609  | 640  | 631  | 582  | 591  | 614  | 634  | 614  | 654  | 619 (22, 4%)    |
|                     | 15 | 933                                          | 922  | 969  | 949  | 879  | 900  | 920  | 963  | 922  | 983  | 934 (32, 3%)    |
|                     | 20 | 1235                                         | 1244 | 1295 | 1269 | 1182 | 1208 | 1217 | 1289 | 1231 | 1321 | 1249 (44, 3%)   |
| FEA (elastic)       |    |                                              |      |      |      |      |      |      |      |      |      |                 |
| Load (kN)           | 5  | 327                                          | 324  | 308  | 339  | 309  | 342  | 308  | 339  | 309  | 342  | 325 (15, 5%)    |
|                     | 10 | 648                                          | 653  | 633  | 668  | 639  | 663  | 633  | 668  | 639  | 663  | 651 (14, 2%)    |
|                     | 15 | 972                                          | 980  | 956  | 997  | 963  | 983  | 956  | 997  | 963  | 983  | 975 (15, 2%)    |
|                     | 20 | 1296                                         | 1307 | 1252 | 1333 | 1285 | 1315 | 1252 | 1333 | 1285 | 1315 | 1297 (29, 2%)   |

N.B. Low and high resolution DIC images recorded with 14 and 39 mega pixel cameras, respectively.

\* - see Figure 6 for details of strain gauge positions

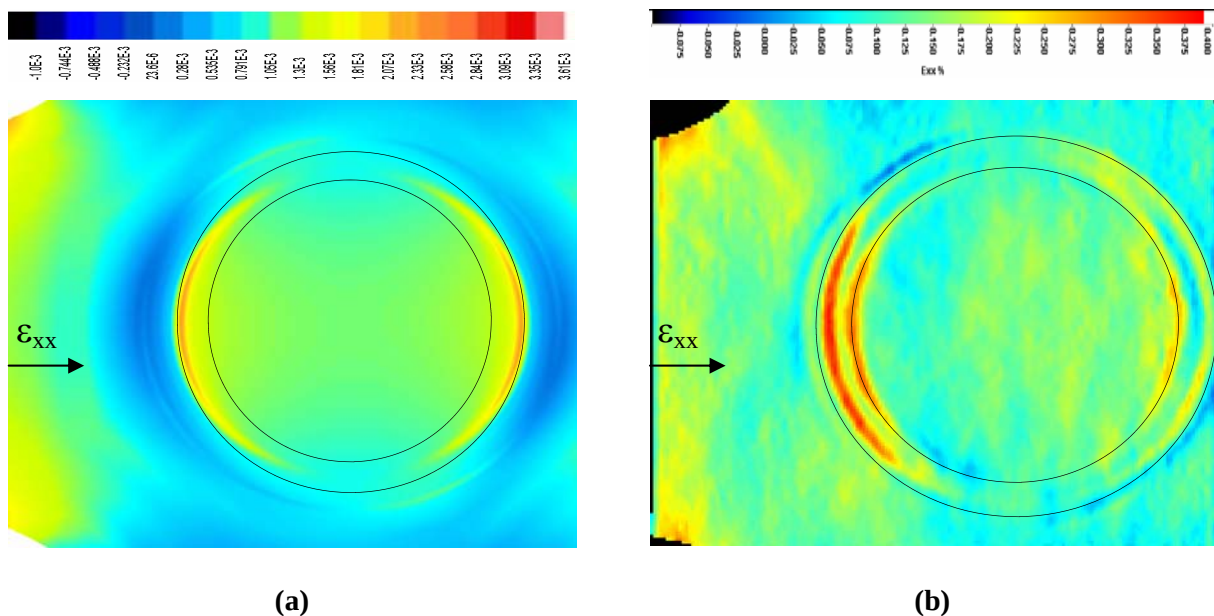
predicted using FEA is shown in Table 4. The first observation to make is that the agreement between strain gauge data and FEA predictions was generally very good at all load levels. This was despite the level of in-plane bending seen in the arms, which suggests that the criteria of <3% total bending is too harsh for a biaxial specimen and load case. The levels of scatter observed in the strain gauge data and predicted with FEA are also low (<4%), which is evidence of a uniform strain field in the gauge-section. The low resolution DIC data did not agree particularly well with the strain gauge data and FEA results, particularly at the 5 kN load level. This was reasoned to be due to the insensitivity of the low-resolution DIC technique for tracking relatively low levels of displacement at low loads. The high-resolution DIC data, however, was in better agreement although the values measured at 20 kN were generally slightly higher than the strain gauge and FE values.

The full-field strain maps, for strains in the x- and y- directions, measured using high-resolution DIC and predicted using FEA are shown in Figures 12 and 13, respectively. It was not possible to use the same contour levels for the DIC and FEA strain maps and therefore regions of equivalent strain level do not exactly correspond in terms of colour. In general, the DIC strain maps were in good

agreement with the FE predictions. As measured using strain gauges the strain in the gauge section is fairly uniform. The FEA results showed that there were regions of high strain concentration on the circumference of the circular gauge section corresponding to the tapered thickness zone (Figures 12a and 13a). These regions of strain concentration were also clearly evident in the DIC results (Figures 12b and 13b).

### Tests using the 25 mm specimen

Following initial trials with the 50 mm specimen, further tests were then undertaken on the 25 mm specimens. For this work, hydraulic grips were requisitioned and fitted to the biaxial set-up in order to improve the alignment of the system and uniformity of gripping. As for the 50 mm specimen, strain gauges were bonded to the specimen arms to monitor the degree of bending. DIC was used to measure the full-field strain map in the central gauge section of the specimen on one face, whilst a triaxial gauge was used to measure the strain at the centre of the specimen on the opposing face. A 5 megapixel video camera was used for the DIC measurements instead of the digital SLR cameras used for the 50 mm specimen. Images for DIC analysis were recorded throughout the loading at a frequency of 2 Hz.



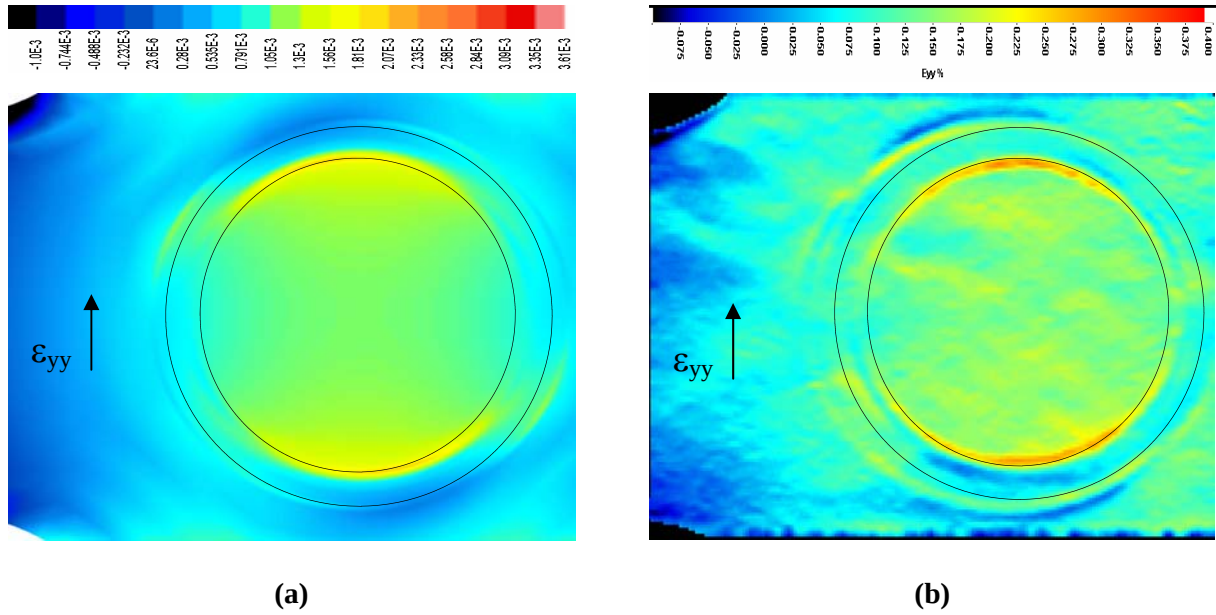


**Figure 13:  $\epsilon_{yy}$  strain at 20 kN for 50 mm specimen by;  
(a) FEA and (b) high-resolution DIC (39 megapixel)**

Initially the load and therefore strain ratio in the two directions was set to be 1:1. The load profile (identical for both axes) was a straight ramp up to 10 kN. The tests were undertaken in position control using a displacement rate on each axis of 1 mm/min until a 10 kN load had been reached. The specimen was then held under load for 10 seconds before unloading.

Elastic trials showed a difference in the measured strains in the central gauge section in the two orthogonal directions. This was an unexpected result as the strains should be the same in both directions.

On closer inspection of the specimen it was observed that the top surface of the thickness tapered gauge-section was not that of a  $+45^\circ$  ply (as it should have been), but of a  $90^\circ$  ply instead. It became apparent that the machining

of the waisted gauge-section had not been undertaken correctly and hence the difference in strains in orthogonal directions. Additional machining was undertaken to remove the remainder of the  $90^\circ$  ply (on both sides of the specimen) and to reveal the  $+45^\circ$  ply surface. Subsequent loading trials of the re-machined specimen resulted in strain measurements in much better agreement in both directions indicating that the specimen machining was improved compared to the initial state.

With the specimen gauge section corrected, a 1:1 loading ratio test was undertaken and the degree of bending was checked. The bending results at the maximum load of 10 kN (in both axes) are shown in Table 5. The degree of bending was considerably better than for the 50 mm specimen, with total bending in all arms less than 10%.

**Table 5: Assessment of Bending in 25 mm Specimen**

| Bending                      | Arm   |      |      |      |
|------------------------------|-------|------|------|------|
|                              | A1    | A2   | A3   | A4   |
| In-plane, $B_b$ (%)          | 2.75  | 3.94 | 5.81 | 9.12 |
| Through-thickness, $B_h$ (%) | -0.46 | 0.95 | 3.02 | 0.45 |
| Total, $B_b + B_h$ (%)       | 2.28  | 4.89 | 8.84 | 9.56 |

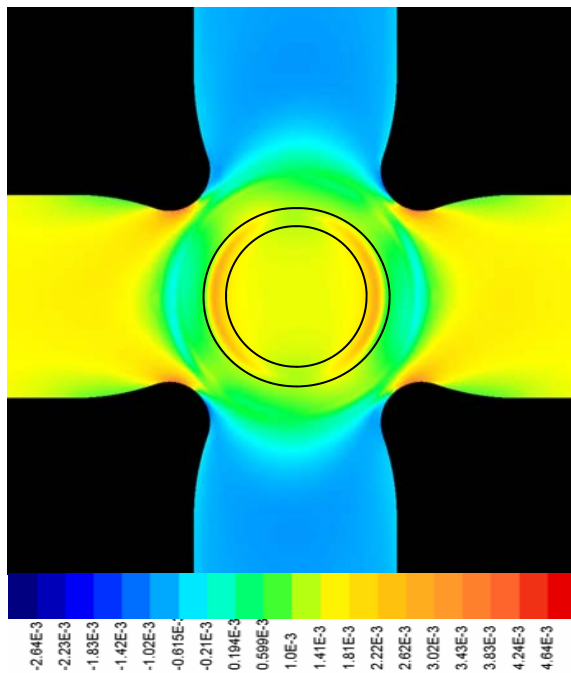
With the degree of bending deemed to be as good as could be achieved with the experimental set-up used, the strains in the central gauge section were measured using strain gauges and DIC on the same specimen. These strain measurements were then compared to the FEA model for the 25 mm specimen. The comparisons of measured and predicted strains were performed at 2.5, 5, 7.5 and 10 kN. The results are shown in Table 6. In general, the strains are in good agreement. The FEA predicts that the strains in the x- and y- directions should be the same, however there were differences in the strains in the two directions as measured by gauges and DIC,

with the strain in the x- direction lower than that in the y- direction. This was reasoned to be due to difficulties in accurately machining the gauge section to the exact depth across the gauge-section area.

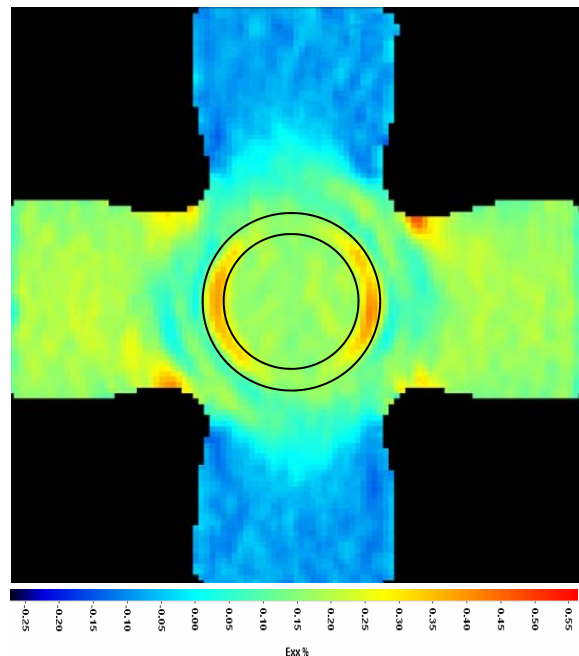
Figures 14 and 15 show comparisons of the FEA predicted, and DIC measured, strain maps in the x- and y- direction at 10 kN, respectively. As for the 50 mm specimen, it was not possible to use the same contour levels for the DIC and FEA strain maps and therefore regions of equivalent strain level do not exactly correspond in terms of colour. The predicted and measured strain maps were in

**Table 6: Comparison of Strains in Central Gauge Section for 25 mm Specimen**

| Load (kN) | Strain (microstrain) |      |      |                 |      |      |
|-----------|----------------------|------|------|-----------------|------|------|
|           | $\epsilon_{xx}$      |      |      | $\epsilon_{yy}$ |      |      |
|           | Gauge                | DIC  | FEA  | Gauge           | DIC  | FEA  |
| 2.5       | 403                  | 447  | 426  | 442             | 484  | 427  |
| 5.0       | 804                  | 872  | 850  | 886             | 943  | 854  |
| 7.5       | 1206                 | 1298 | 1280 | 1330            | 1402 | 1280 |
| 10.0      | 1608                 | 1723 | 1703 | 1774            | 1860 | 1709 |



(a)



(b)

**Figure 14:  $\epsilon_{xx}$  strain at 10 kN for 25 mm specimen by; (a) FEA and (b) DIC**

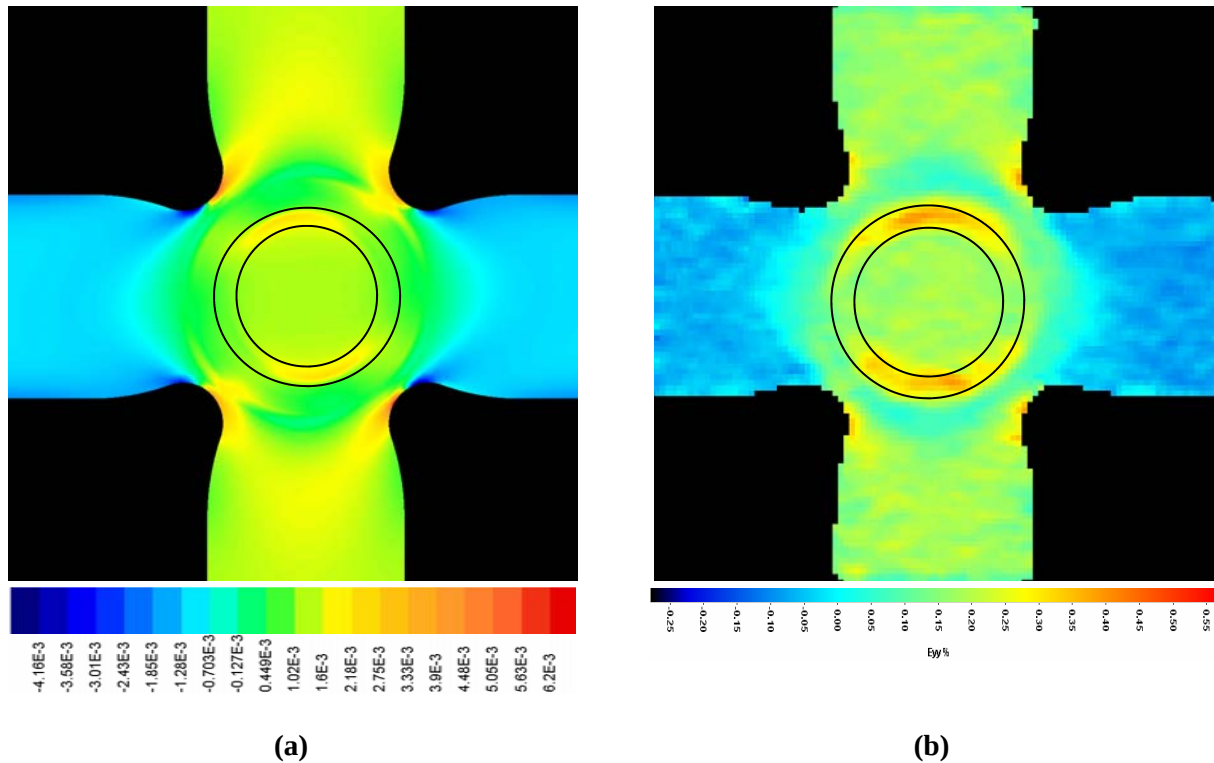


**Figure 15:  $\epsilon_{yy}$  strain at 10 kN for 25 mm specimen by; (a) FEA and (b) DIC**

very good agreement and show clearly a fairly uniform strain field in the gauge section. Also, shown clearly are regions of high strain corresponding to the tapered section and at the radius of the specimen arms.

Having completed the elastic measurements a specimen was loaded to failure using a loading ratio of 1:1 under position control. A displacement rate of 1 mm/min was used in both axes. The specimen failed at a load of 28.9 kN and in the manner shown in Figure 16. Interlaminar failure initiated at the tapered thickness section causing delamination failure to propagate into the specimen arm as shown. Also, failure was observed at the radius of one of the arms. The failure locations are in good agreement with the strain concentrations predicted using FEA and measured using DIC. The specimen did not fail in the specimen gauge-section, and thus the mode of failure is not considered to be representative of a true biaxial failure. Therefore, the stresses for this failure have not been computed using the method described earlier. Within the VAMAS working group activity, it had been planned to undertake a series of further tests to failure in which the strain ratio (between the two

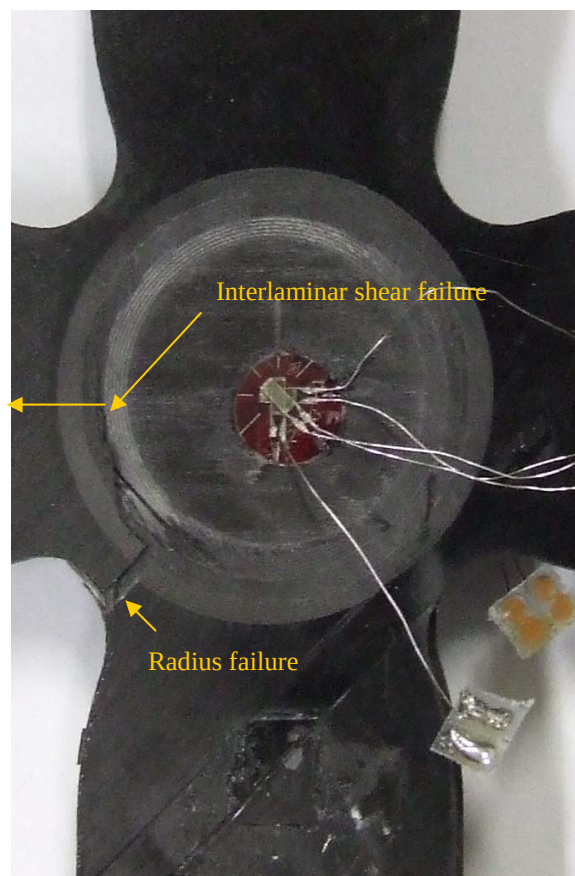


**Figure 16: Failure in a 25 mm specimen**

directions) at the gauge section of the specimen was varied from 1:1 to 1:0.5 and to 1:0.25. Having not achieved a satisfactory failure mode it was decided to postpone these tests until further work could be devoted to ensuring a true biaxial failure.

## DISCUSSION AND CONCLUSIONS

The work detailed in this report has highlighted the difficulties encountered in designing a planar cruciform specimen for the biaxial characterisation of composite materials. The goal of achieving true biaxial failure in a cruciform specimen without the need for the inclusion of a stress raiser, such as a hole, in the central gauge section, is a subject attracting much research globally and is by no means a trivial task. It is clear from this study that more work is required in this area before a standard method can be recommended.

The salient findings from this work are:

- The use of a thickness waisted cruciform specimen for biaxial strength measurements did not result in a satisfactory failure mode, although the strain distribution was uniform in the central gauge-section.
- The presence of high interlaminar strains (and stresses) around the tapered thickness zone result in interlaminar failure and delamination of the laminate propagating into the specimen arms. It is noted that this type of failure has also been observed in specimens of similar geometry by Makris and Ramault et al [19-20]. In an attempt to overcome this failure mode, Ramault [20] has recently attempted to use a specimen, which does not feature thickness reduction at the gauge section. Instead the specimen is clad with an adhesively bonded end-tabbing material everywhere except the gauge section. However, it has been shown that specimen failure now occurs in the adhesive bond-line between the tabbing material and the base laminate and again, biaxial failure does not result.
- The use of a thickness waisted gauge section presents a number of difficulties. The ply drop-off technique has the advantage that the surface of the gauge section is guaranteed to

be of the correct ply orientation. However, this production technique is laborious and it is difficult to accurately position plies around the centre location of the specimen. The method of milling material from the cured laminate is not only laborious and expensive but it is also extremely difficult to machine the gauge-section to the correct ply level.

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