

STRAIN DISTRIBUTION IN A BIAXIALLY LOADED CRUCIFORM COMPOSITE SPECIMEN

Carla Ramault¹, Andreas Makris¹, Danny Van Hemelrijck¹, Ebrahim Lamkanfi² and Wim Van Paepegem²

¹ Department of Mechanics of Materials and Constructions, Vrije Universiteit Brussel
Pleinlaan 2, 1050 Brussels, Belgium
cramault@vub.ac.be

² Department of Mechanical Construction and Production, Ghent University
Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium

ABSTRACT

At the Vrije Universiteit Brussel, a plane biaxial device has been developed for testing of cruciform specimens. One of the aims of doing biaxial experiments is the determination of the failure envelopes. Obtaining the present stresses is not easy, so strain measurements become more important. In this paper, full field measuring techniques like Digital Image Correlation (DIC) and Electronic Speckle Pattern Interferometry (ESPI) are evaluated. Due to the strain calculation methods, errors are made when cracks occur in the specimen. Thus, the techniques calculate higher strains than in reality around these cracks. To get a validation of the Finite Element Model (FEM), another technique has to be used. By strain gage measurements at various places of the biaxially loaded zone, the uniformity of this zone was proven.

1. INTRODUCTION

In general, composite laminates are developing multi-axial stress states [1]. To get an accurate representation of the behaviour of composite materials in a structure, tests under a uniaxial stress state do not satisfy. Therefore biaxial testing has to be considered. Despite the large demand for this experimental biaxial information there is little existing experimental capability to evaluate the multi-axial response of composite materials [2].

The commonly used method to apply biaxial loads to a composite specimen is the combined torsion and tension/compression or pressure and tension/compression of a thin-walled tubular specimen. In real constructions, components in fibre reinforced composite materials are often made in the form of flat or gently curved panels. Consequently the biaxial behaviour of the tubes is different from the real behaviour. The most appropriate method for biaxial testing consists of applying in-plane biaxial loads to cruciform specimens. Therefore, a plane biaxial test device and a suitable cruciform specimen geometry have been developed at the Vrije Universiteit Brussel [3].

One of the aims of doing biaxial experiments is defining the failure envelope of the considered material. Since stress determination is not straightforward due to the uncertainty of the loading area size, the importance of strain determination increases. In this paper the use of various measuring techniques on the biaxially loaded cruciform specimen will be evaluated. Other intentions are the investigation of the uniformity of the strains in the biaxially loaded zone and the validation of the strains in the Finite Element Model.

2. BIAXIAL TESTING

2.1 Test Bench

Many techniques to produce biaxial stress states in a specimen can be distinguished [4]. The most realistic method for biaxial testing consists of applying in-plane biaxial loads to a cruciform specimen. The plane biaxial test rig shown in Figure 1 was developed at the Vrije Universiteit Brussel. It consists of four independent servo-hydraulic actuators with a capacity of 100kN in each perpendicular direction. The use of hydraulic actuators represents a very versatile technique for the application of the loads. When only one actuator per loading direction is used [5], the centre of the specimen will move. This causes a side bending of the specimen, which results in undesirable non-symmetric strains. Systems -like the one used by the authors- with four actuators [6] and a close-loop servo control using the measured loads as feedback system, allow the centre of the specimen to stand still.

As no cylinders with hydrostatic bearing were used, failure or slip in one arm of the specimen will result in sudden radial forces which could seriously damage the servo-hydraulic cylinders and load cells. To prevent this, hinges were used to connect the specimen to the load cells and the servo-hydraulic cylinders to the test frame. Using four hinges in each loading direction results in an unstable situation in compression and consequently only tension loads can be applied.



Figure 1: Plane biaxial test device.

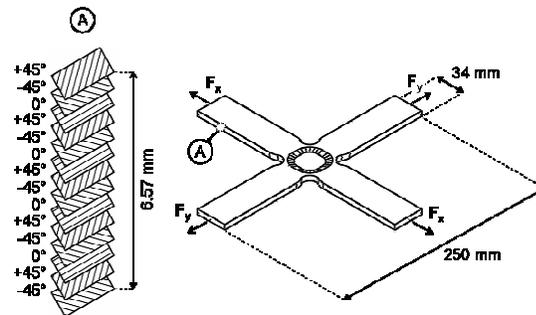


Figure 2: Cruciform specimen geometry.

2.2 Cruciform specimen

Designing an appropriate specimen is probably the most difficult issue of biaxial testing. In order to achieve a successful biaxial test, the cruciform specimen has to fulfill some conditions: (i) specimen failure in biaxially loaded test zone, (ii) minimization of shear strains, (iii) minimization of strain concentrations, (iv) maximization of the region of uniform biaxial strain, (v) repeatable results [7]. Various specimen geometries have been compared by Smits et al [3] in order to obtain a proper cruciform specimen design. On the base of FE analysis, completed with experimental results, the geometry in Figure 2 was developed. The specimen has a total length of 250 mm, an arm-width of 34 mm and a corner fillet radius of 20 mm. In the centre, material is milled away in the thickness direction to ensure biaxial failure. Biaxial tests can be carried out on various materials, but we focus on composite materials. In this article, we use glassfibre reinforced epoxy with a $[(\pm 45^\circ 0^\circ)_4 (\pm 45^\circ)]$ lay-up, typical for wind turbine blades. The thickness of the arms and the central zone are respectively 6.57 mm and 3.59 mm.

3. FAILURE ENVELOPES

3.1 Stress space

One of the aims of biaxial testing is to determine the failure envelopes of various lay-ups and materials. Generally they are plotted in stress space. The determination of the present stresses in a uniaxially loaded beam specimen is straightforward. Unfortunately it is not that easy to determine the stresses in a biaxially loaded specimen, since the exact loading area is unknown. The authors use two techniques to define the stresses. The first method is based on the uniaxial strength data. The failure stress of a uniaxially loaded specimen, both beam and cruciform, is the same. Consequently we can determine the failure areas $A_{eq,x}$ and $A_{eq,y}$ of the uniaxially loaded cruciform specimen in both X and Y direction. The stresses in a biaxially loaded cruciform specimen can be calculated by dividing the applied forces by the equivalent areas. The second method is based on strain measurements. By multiplying the strain vector with the stiffness matrix, the stress vector can be found.

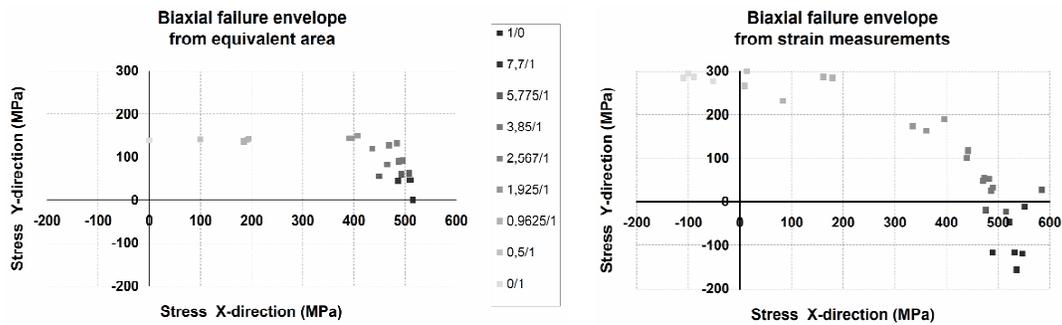


Figure 3: First quadrant of the failure envelope of glassfibre epoxy with specified lay-up, determined by the (Left) “Equivalent area” method and (Right) “Constitutive law” method.

Figure 3 represents the failure envelopes of the specified material and lay-up, found by using the two methods. With the first method, an error is introduced by the fact that the loading area in the biaxially loaded cruciform specimen will not be totally the same as in the uniaxially loaded cruciform specimen. The second method overestimates the applied stresses because we presume linear behaviour in X and Y direction. Thus we introduce an error when calculating the stresses perpendicular to the fibre direction.

3.2 Strain space

Since the calculation of the stress field in the cruciform specimen is not straightforward due to the uncertainty of the failure area size, it is easier and more accurate to work with strains. Strains can be calculated directly out of the displacements, which are rather easy to measure. To measure the strains present in the cruciform specimen we can use various techniques, which can be divided into local and full-field strain measuring methods. Examples are for the first category strain gages, and for the second the Digital Image Correlation Technique (DICT). The mayor disadvantage of using local techniques is that the obtained results are only an average of the strains along the gauge length. The uniformity of the biaxially loaded zone can thus not be investigated with this measuring method. Also, unexpected strain concentrations or asymmetry which can occur due to imperfections in the specimen or incorrect load introduction cannot be

traced. In order to get an idea of the surface strains of the whole specimen, we have to use a full field measuring technique. Appropriate optical techniques are DICT and Electronic Speckle Pattern Interferometry (ESPI).

3.2.1 DICT

Digital Image Correlation (DIC) is an experimental technique which offers the possibility to determine displacement and deformation fields at the surface of objects under any kind of loading, based on a comparison between images of the applied speckle pattern taken at different load steps. The software processes and visualizes the data gathered in order to obtain an impression of the distribution of displacements and strains in the measured object.

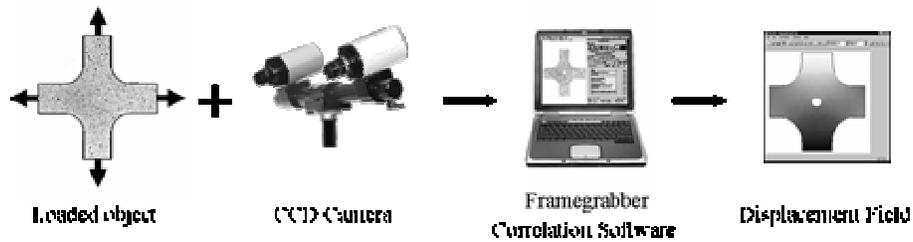


Figure 4: Cruciform specimen geometry.

Each picture taken with a CCD camera corresponds to a different load step. The cameras of the current set-up use a small rectangular piece of silicon, which has been segmented into 1392 by 1040 pixels. Each pixel stores a certain grey scale value ranging from 0 to 4095 (12 bit), in accordance with the intensity of the light reflected. Two images of the specimen at different states of loading are compared by using a pixel grey value in the undeformed image and searching for the pixel in the deformed image, in order to maximize a given similarity function. A grey-value is not a unique signature of a pixel, so neighbouring pixels are also used. Such a collection of pixels is called a subset. The displacement result, expressed in the centre of the subset, is an average of the displacements of the pixels inside the subset. The step size defines the number of pixels over which the subset is shifted in x- and y- direction to calculate the next result. For the actual tests the subset size is 19 pixels, the step size 5 pixels and the image resolution varies between 11 and 16 pixels/mm. The image correlation routine allows locating every subset of the initial image in the deformed image. Subsequently, the software determines the displacement values of the centres of the subsets, which yields an entire displacement field. Figure 4 depicts the sequence of taking a picture of an object before and after loading, storing the images onto a computer through a frame grabber, performing the correlation of both images and finally calculating the corresponding displacement of the centres of the subsets, which yields the desired displacement field. The strain field is then calculated by numerical differentiation of the smoothed displacement field.

3.2.2 Strain results obtained with DICT and FE-Analysis

Figure 5 represents the strain results of a biaxially loaded cruciform specimen at 80% of the failure load. A load ratio of 3,85/1 was applied. The strains in the biaxially loaded central zone are uniform, apart from what seems to be strain peaks in the e_{xx} field.

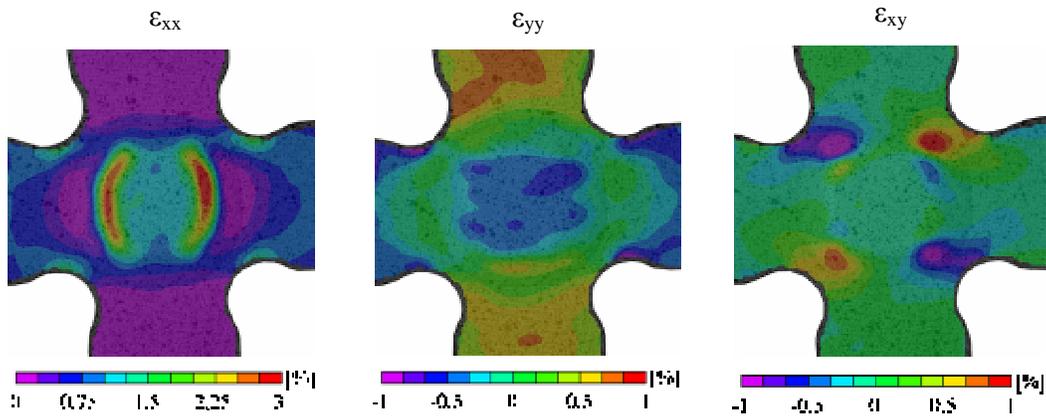


Figure 5: Strain fields (measured with DICT) of a biaxially loaded cruciform specimen with load ratio 3,85/1 at 80% of failure.

When comparing the strains obtained by DIC with these calculated by a Finite Element Model (FEM), it can be noticed that the strain fields are similar to each other. Taking a closer look at the ϵ_{xx} field of the FEM tells us there is also a rise of the strain values in the neighbourhood of the tapered zone, but just a slight one, much lower than when measured with DIC. The strains at the centre match perfectly. An important question we can ask ourselves is whether the FE-model is incorrect or the DIC measurements. To get a validation of the DIC results and/or the FE model, an additional study is needed. Therefore, we are going to compare the DIC results with another full field measuring technique, Electronic Speckle Pattern Interferometry (ESPI).

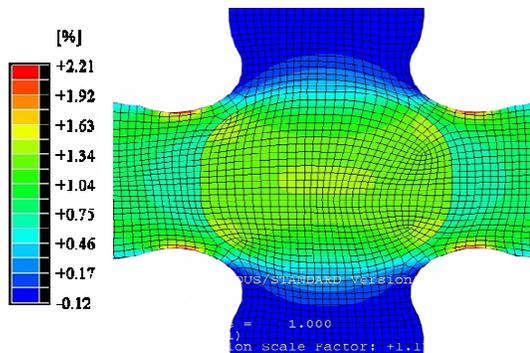


Figure 6: ϵ_{xx} at 80% of failure load (FEM).

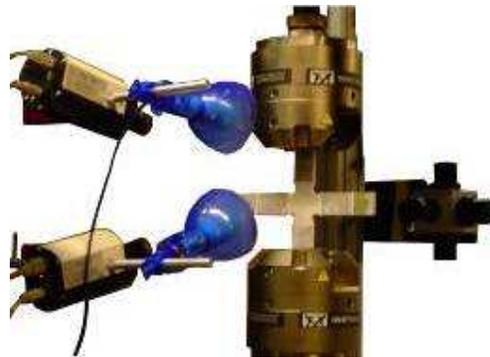


Figure 7: Test setup DICT and ESPI.

4. TEST SETUP AND RESULTS

4.1 Strain measurements with DICT and ESPI

4.1.1 Electronic Speckle Pattern Interferometry (ESPI)

ESPI is a technique which calculates the deformations at the surface of the specimen by way of a fringe pattern. The surface of the specimen is illuminated by two coherent light sources, in this case lasers. The interference of the two backscattered light waves leads to interference patterns or a speckle pattern. This speckle pattern changes when the specimen's surface deforms. By subtracting the reference and deformed speckle patterns, a fringe pattern is obtained. Evaluation software then analyses and counts the

correlation fringes and transforms them into a quantitative set of deformation and strain data.

Because of the sensitivity to vibrations, the ESPI system cannot be mounted on the biaxial test bench. Therefore, only the case of a uniaxially loaded cruciform specimen will be studied, both parallel and perpendicular to the fibre direction. Figure 7 shows the test setup. One side of the specimen will be observed by the ESPI system and one by the DIC system. The results will be compared with each other and with the FE model.

4.1.2 Results

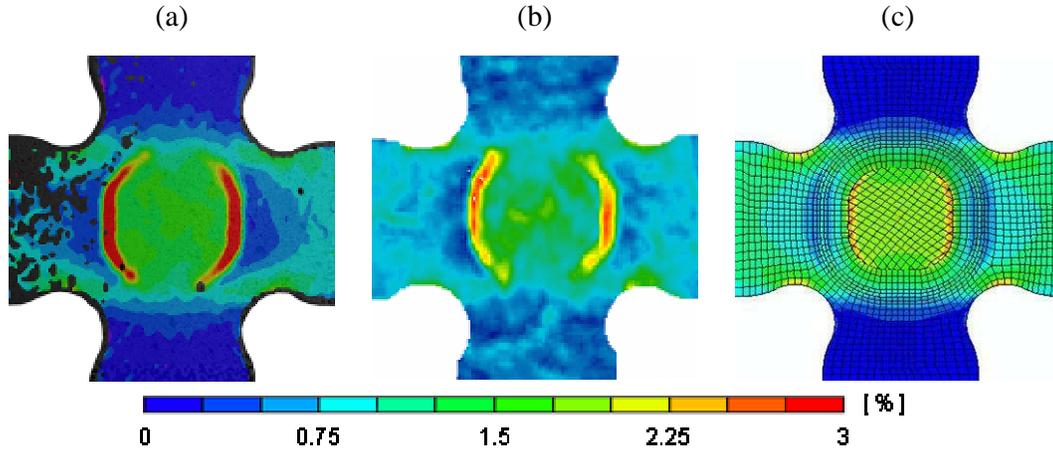


Figure 8: ε_{xx} of uniaxially loaded specimen at 80% of failure load in fibre direction (44 kN) : (a) DICT measurements, (b) ESPI measurements and (c) FE calculations.

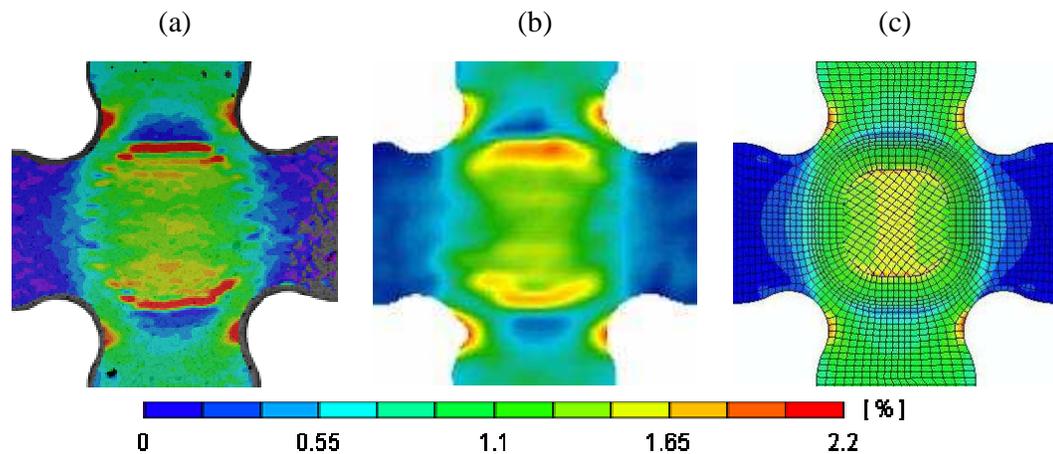


Figure 9: ε_{yy} of uniaxially loaded specimen at 80% of failure load perpendicular to fibre direction (17,5 kN) : (a) DICT measurements, (b) ESPI measurements and (c) FE calculations.

Figures 8 and 9 show the strain field in the load direction of a cruciform specimen loaded in respectively the fibre direction and perpendicular to the fibre direction. It can be seen that the strain fields obtained by DIC and ESPI are similar. Also with the ESPI technique, strain peaks can be observed on the edges, which are much higher compared to the ones in the FEM. If we take a closer look at the position of the strain peaks, we

see a difference between the two load cases. When loaded perpendicular to the fibre direction, the strain peak front shifts away from the central zone.

An explanation of these strain peaks can be found in the used strain calculation methods. Apparently, cracks in the specimen occur in an early stage of loading [8]. The DIC and ESPI software take this crack as a displacement, so locally higher strains are measured around the crack. It is possible to reduce the effect of the crack in the DIC measurements, by adapting the parameters like subset and step size. The study of these parameters will be discussed in a following paper.

Figure 10 shows the position of the crack when loaded in the two cases. When loaded in the fibre direction, a crack will appear just beneath the tapering, so DIC will consider strain peaks at this place. When loaded perpendicular to the fibre direction, the crack will occur in the centre of the tapered zone. This explains the shift of the strain peak front in the measured strain fields.

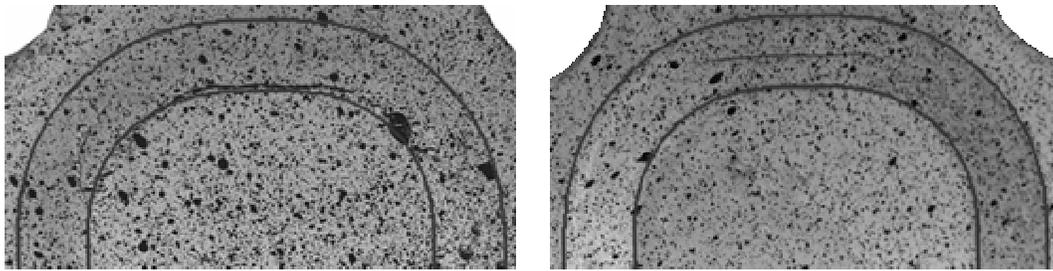


Figure 10: Crack when loaded (Left) parallel and (Right) perpendicular to the fibre direction.

4.2 DICT vs Str Gages

4.2.1 Test setup

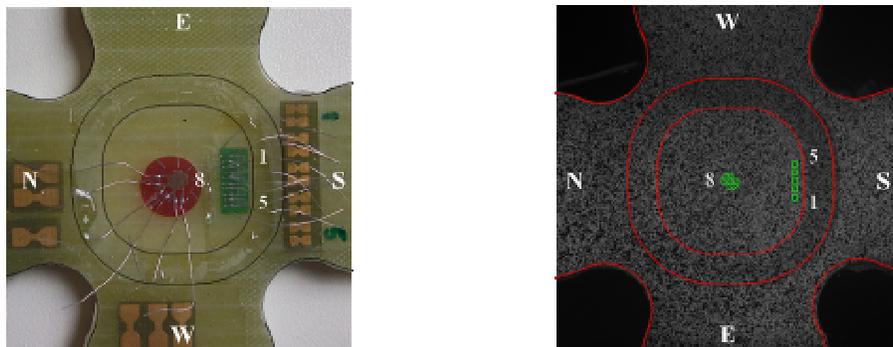


Figure 11: (Left) Strain gages glued in centre and on the edge of the central zone and (Right) Indication of strain gage positions on the other side of the specimen, where DIC is performed [biaxially loaded specimen with load ratio X/Y or $N/E = 3,85/1$].

Because the previous investigation could not give us enough information for the total validation of the FEM, an additional study was done. A uniaxial 5-element strain gage with elements of 1mm was glued near the edges of the milling. As an additional comparison, an extra strain gage rosette of 3mm was glued in the middle. On the other

side of the specimen DIC-measurements were performed. Figure 11 depicts the position of the strain gages and the considered strains in the DIC calculations. Two load cases are considered: one specimen will be loaded uniaxially in the fibre direction and another specimen will be biaxial loaded with a ratio of 3,85/1.

4.2.2 Test results

Figure 12 shows the evolution of the strain gage measurements with increasing force, both in the case of a uniaxially and biaxially loaded cruciform specimen. The strain gages debonded before the failure of the specimen, but still some things can be noticed. We can distinguish a minor difference between the strain in the centre of the milled zone (nr.8) and the strains near the edge of the milled zone (nr.1-5). As we can see, the strains near the tapered zones are higher than in the centre. Nevertheless this difference is much less than the strain peaks we can see on the DIC and ESPI measurements. The strain gage measurements are comparable to the calculations in the FE-model.

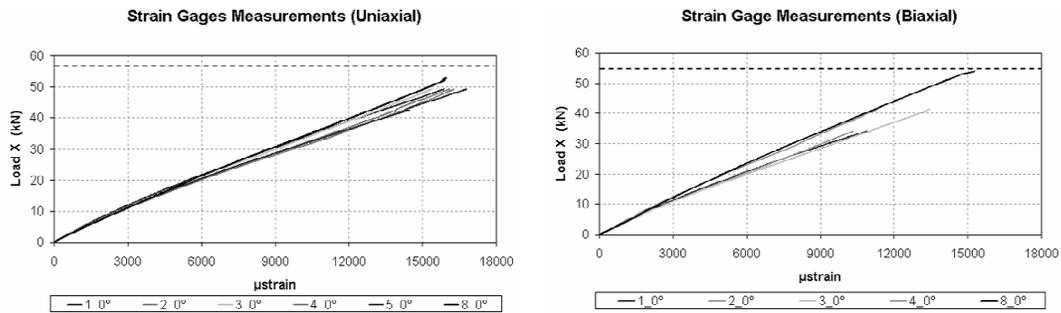


Figure 12: Strain gage measurements of a (Left) uniaxially [in X direction] and (Right) biaxially [load ratio X/Y = 3,85/1] loaded specimen

As can be seen in Table 1, the comparison of the strain results obtained by strain gages and by DIC is quite good. In contrast to the earlier mentioned DIC results, these strains were obtained by adapting the parameters in the DIC software so that the gage lengths matched. When smaller subsets are used and less averaging is done, the error due to the crack on the strain measurements can be reduced to a small area nearby the actual crack.

Nr.	Strain gage [%]	DIC [%]	Nr.	Strain gage [%]	DIC [%]
1	1.481	1.524	1	1.058	1.047
2	1.543	1.554	2	1.009	0.913
3	1.445	1.550	3	1.073	1.184
4	1.512	2.147	4	0.904	0.780
5	1.568	1.834	5	-	0.958
8	1.413	1.423	8	0.885	0.956

Table 1: Strain measurements in a (Left) uniaxially loaded cruciform specimen at 80% of failure load (46 kN) and (Right) biaxially loaded cruciform specimen at 60% of failure load [33,4 kN / 8,7 kN]

These results validate the results obtained by the FEM. There still remains the question about the origin of the higher strains near the milled zone. This is the subject of another

paper, which will show the higher strains are a result of shear stresses between the $\pm 45^\circ$ and 0° layers in the tapered zone.

5. CONCLUSIONS

As the calculation of the stresses in a biaxially loaded cruciform specimen is not straightforward, the correct determination of the apparent strains is very important. The most appropriate techniques to use are the full field methods like Digital Image Correlation (DIC) and Electronic Speckle Pattern Interferometry (ESPI). Inherent to the strain calculation methods used in these techniques are the problems facing cracks. The considered techniques take these cracks as large deformations and thus find large strain peaks near these cracks. Consequently, other strain measuring techniques have to be used for the validation of some parts of the Finite Element Model (FEM). The results obtained by strain gage measurements in the biaxially loaded zone, both in the centre and near the tapering, showed good agreement with the strains obtained with the FEM. The uniformity of the strains in the biaxially loaded zone can be confirmed. DIC is still an excellent tool for strain determination in the cruciform specimen, but when considering the strains near the tapered zone the influence of the crack on the calculations has to be taken into account.

REFERENCES

- 1- Lin W.P. and Hu H.T., "Parametric study of failure stresses in fibre reinforced composite laminates subjected to biaxial tensile load", *Journal of Composite Materials*, 2002:36(12):1481-1504.
- 2- Soden P.D., Hinton M.J. and Kaddour A.S., "Biaxial test results for strength and deformation of a range of E-glass and carbon fibre reinforced composite laminates : failure exercise benchmark data", *Composites Science and Technology*, 2002:62(12):1489-1514.
- 3- Smits A., Van Hemelrijck D., Philippidis T.P. and Cardon A., "Design of a cruciform specimen for biaxial testing of fibre reinforced composite laminates", *Composites Science & Technology*, 2006:66(7-8):964-975.
- 4- Makris A., Ramault C., Smits A., Van Hemelrijck D., Clarke A., Williamson C., Gower M., Shaw R., Mera R., Lamkanfi E., Van Paepegem W., "A review of biaxial test methods for composites", *Proceedings of the 13th International Conference on Experimental Mechanics (Alexandroupolis, Greece)*, 1-6 July 2007.
- 5- Chaudonneret M., Gilles P., Labourdette R. and Policella H., "Machine d'essais de traction biaxiale pour essais statiques et dynamiques", *La Recherche Aérospatiale*, 1977:5:299-305.
- 6- Makinde A., Thibodeau L. and Neale K.W., "Development of an apparatus for biaxial testing using cruciform specimens", *Experimental Mechanics*, 1992:32(2):138-44.
- 7- Boehler J.P., Demmerle S., Koss S., "A new direct biaxial testing machine for anisotropic materials", *Experimental Mechanics*, 1994:34(1):1-9.
- 8- Lamkanfi E., Ramault C., Makris A., Van Paepegem W., Degrieck J., Van Hemelrijck D. and Sol H., "Experimental and theoretical study of the damage onset in biaxial cruciform specimens under static and hysteresis loading", *Proceedings of the 13th International Conference on Experimental Mechanics (Alexandroupolis, Greece)*, 1-6 July 2007.