An investigation of the mechanical behaviour of carbon epoxy cross ply cruciform specimens under biaxial loading

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Abstract: **In the present study carbon epoxy cruciform type specimens with a cross ply lay up, were biaxially and uniaxially loaded in their plane using four independent servo-hydraulic actuators. Four different biaxial loading ratios were investigated while the applied load was quasi-static. A comparison between experimental observations for the strain evolution of the biaxially loaded central section of the specimen coming from digital image correlation measurements (DIC) and a three dimensional finite element damage model (FEDM) will be shown. Furthermore the failure loads coming from the load shells of the machine were straightforward compared with the output of the FEDM.**

Keywords: **Biaxially loaded, Digital Image Correlation (DIC), Finite Element Damage Model (FEDM)**

INTRODUCTION

The lack of reliable multiaxial or even biaxial experimental data to validate failure theories is the critical step in the evolution and a most efficient usage of composite materials [1]. Due to the complex anisotropic behaviour of composite materials more advanced experimental testing is needed. The current practice of using uniaxial test results to predict failure for multiaxial stress states seems inadequate. To study the mechanical behaviour of fibre reinforced polymeric matrix composite laminates under static and cyclic in-plane complex stress states a horizontal biaxial loading frame and a special cruciform type specimen have been developed. The reliability of the experimental failure data depends a lot on the proper design of the cruciform specimen and in the accuracy of the measurements [2]. The specimen should fulfil some requirements as failure must occur mainly in the biaxially loaded centre and the strain distribution should also be uniform. Smits et.al. [3] proposed a geometry to satisfy these requirements. In the present study the evolution of the strain of the biaxially loaded central section of the common used cruciform geometry [4,5] was experimentally and numerically investigated. Furthermore a progressive damage modelling (PDM) [6,7] technique was applied using the commercial finite element software 'Ansys' in order to simulate the biaxial mechanical test.

A) Experimental part

A1. Plane biaxial test bench for cruciform specimens

The biaxial test rig, see Fig.1, developed at VUB has a capacity of 100kN in each perpendicular direction, but only in tension, limiting the experimental results to the first quadrant of the two-dimensional stress space. This type of machine is often used in order to actualize mechanical biaxial tests of composite materials or metals [8-10]. 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. The stroke of the cylinders is 150mm. The loading may be static or dynamic up to a frequency of 20Hz. Each cylinder is independently controlled and any type of loading waveform, including spectral sequences of variable amplitude, can be efficiently introduced using the dedicated software and control system.

Fig.1. Plane biaxial test device for testing cruciform specimens.

A2. Cruciform specimen and mechanical properties of the UD material

The specimens tested were manufactured using carbon UD SE84 prepreg material. The lay up used for this study was $[(90/0)_2\ ,\ (0/90)_2]_{sym}$ and the thickness of each lamina was 0.28mm. This gives a total nominal thickness of 4.48 mm for the arms of the cruciform specimen and of 2.24 mm for the biaxially loaded zone where one group of [$(90/0)_2$] was milled away at each side of the specimen, see Figure 2a. A special speckle pattern was also applied on the surface of the specimen in order to actualize accurate measurements using the Digital Image Correlation Technique, see Figure 2b.


Fig 2a. Cruciform geometry.


Fig 2b. Applied special speckle pattern.

In order to obtain the elastic properties and strength of the UD material, mechanical tests were realized. For the uniaxial properties (E_1, E_2, ν_{12}...), rectangular coupons were tested under tension or compression while for the shear properties v-notched specimens were selected. In table 1 the elastic properties of the UD SE84 material can be found. These properties together with the strength of the lamina, see table 2, were used as basic input for the FEDM.

Table 1.
Elastic properties of the UD SE84 carbon lamina.

	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	G_{12} [GPa]	G_{23} [GPa]	G_{13} [GPa]	ν_{12} -	ν_{23} -	ν_{13} -
average	124.3	8.14	7.8	4.49	2.44	3.93	0.32	0.32	0.32

where ‘123’ is the fiber coordinate system, ‘1’ is the fiber direction, ‘2’ is the direction transverse to the fibers and ‘3 is the direction through thickness.

Table 2.
Strength of the UD SE84 carbon lamina.

	X_T [MPa]	X_C [MPa]	Y_T [MPa]	Y_C [MPa]	Z_T [MPa]	Z_C [MPa]	S_{12} [MPa]	S_{23} [MPa]	S_{13} [MPa]
average	2751	1180	25	165	42	165	106.9	35.21	97.87

where X_T, X_C are the tensile and compressive strength longitudinal to the fibers, Y_T, Y_C are the tensile and compressive strength transverse to the fibers normal to ‘13’ plane, Z_T, Z_C are the tensile and compressive strength transverse to the fibers normal to ‘12’ plane and Sij, i,j=1,2,3, is the shear strength of the lamina.

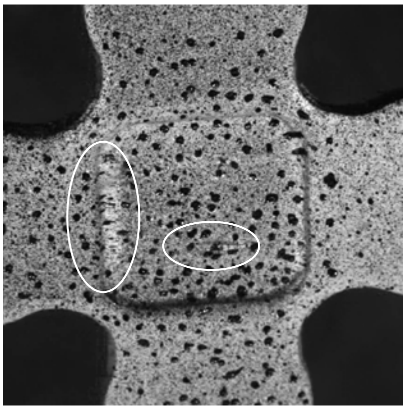
A3. Strain measurements using Digital Image Correlation technique

To be able to study the symmetry of the strains and the occurring shear strains experimentally, full field methods are necessary. Strain measurements using a strain gage or extensometer are not sufficient because both give an average value of the deformation along their gauge length and sometimes fail earlier than the specimen.

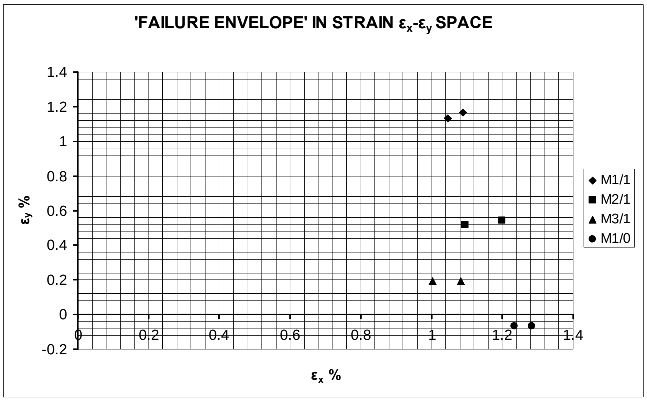
The strain field of glass epoxy specimens of the same geometry under uniaxial or biaxial loading conditions was in a previous study extensively investigated [2]. There due to the complexity of the specimen's geometry different measurement techniques (Strain gages, Digital Image Correlation (DIC) and Electronic Speckle pattern Interferometry (ESPI) techniques were used combined or separately) were applied to investigate strain concentrations and finally obtain the valid strain field of the zone of interest.

In the present study Digital Image Correlation Technique (DICT) was used to follow the strain evolution of the areas of interest. DICT is an experimental technique, which offers the possibility to determine in-plane and out of plane displacement and deformation fields of the surface of objects under any kind of loading, based on a comparison between images taken at different load steps. By deriving the displacement field the desirable strain field is obtained.

In the present study four different load ratios (Fx/Fy) were applied on cruciform specimens (three different biaxial cases 1/1, 2/1, 3/1 and a uniaxial case 1/0) and for each ratio average two specimens were tested in tension until total failure, see Figure 3a. Biaxial testing of cruciform specimens was performed using load control of the machine with a constant load speed of 5kN/min and uniaxial testing of them by displacement control with a displacement rate of 1mm/min. Below is also presented the failure envelope for the cross-ply cruciform laminate in strain space from measurements coming from the geometrical centre of the central section, see Figure 3b.



(a)



(b)

Figure 3. (a) A specimen under 80% of the total failure load (3/1 load case), marked are local damaged areas, (b) Failure envelope of the cross ply laminate.

B) Numerical Part

B.1 Progressive damage modelling

A three dimensional finite element model was developed using the commercial software 'Ansys' in order to compare with the experimental observations. The model is using a progressive damage scenario. Progressive damage modelling (PDM) technique has four basic steps, (i) stress analysis of the structure, (ii) failure analysis in an element basis, (iii) degradation of the properties of the failed elements and (iv) application of a total failure criterion. The procedure stops when the total failure occurs which means that the structure cannot take any additional load. Below is briefly described how each step of the method was used in order to simulate the testing of the cruciform specimen.

Stress analysis was done by using 'Ansys' solver

Failure analysis:

Six different failure modes are considered namely, matrix tensile and compressive cracking, fibre tensile and compressive cracking, and delamination in tension and compression. These failure modes represent basic failure modes of the composite materials. For the detection of the failure modes, a set of 3-D stress-based polynomial failure criteria is used. Specifically, Hashin-type failure criteria [11] are used for detecting the failure modes of the matrix, the fibre compressive mode and delamination, while for detecting the fibre tensile mode, the Maximum Stress was used. The specific set of failure criteria has been proposed in [12, 13], in which it has been successfully used for analysing failure of composite bolted joints subjected to tensile loading.

Degradation:

The material properties degradation is performed in an element basis. That means that each time a specific failure mode is satisfied for an element then its material elastic properties are being degradated properly according to degradation rules. Details about the nature of these rules can be found in [12, 14, and 15]. The proposed degradation scenario was extended in this study, by means that the second time that the same failure criterion is satisfied in a specific element, the material properties of it are being degradated close to zero (and not to zero, to avoid numerical instabilities). Three different degradation factors are used for matrix failure, fiber failure and delamination failure.

Total failure:

The total failure criterion declares when the structure cannot take any additional load. It depends on the nature of the problem what can be considered as total failure. In this study total failure is achieved when the displacement of an edge node of an arm of the specimen exceeds a predefined value (ex. 20mm). It can be also shown as a sudden change of the slope of the Load –displacement graph. Below the Load-Displacement graph is plotted for the uniaxial case from the FEDM and from the experimental data see Figure 4.

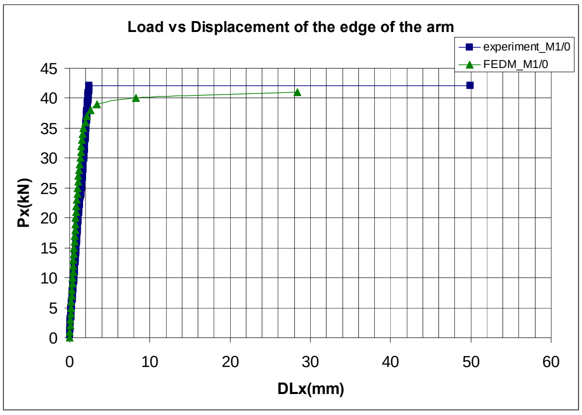


Figure 4. Load – displacement graph for the edge of the specimen

B.2 Flowchart of the model

A computer program has been created using ‘ANSYS’ FE code [16] in order to implement the progressive damage technique and simulate the mechanical testing of the cruciform specimen. The geometry of the specimen was parametrically built which allowed modifications of the dimensions easily to be done. An important feature of the program is that the steps of failure analysis and material property degradation have been programmed in a separate subroutine. This adjustment gives the ability to choose failure criteria and degradation rules according to the specific case studied. The program is explained by the flowchart shown in Fig. 5 and involves the following steps: (i) creation of the 3-D model by giving as input the material properties, the geometry of the examined configuration, the boundary conditions, the initial load and the load step, (ii) performing stress analysis using ‘Ansys’ solver to calculate the stresses, (iii) check for final failure (iv) performing failure analysis by applying the failure criteria, (v) check for failures; if no failure is predicted, the applied load is increased by a pre-defined increment and the program returns to stress analysis; if a mode of failure is predicted the program continues to the next step, (vi) degradation of material properties increase load and return to stress analysis.

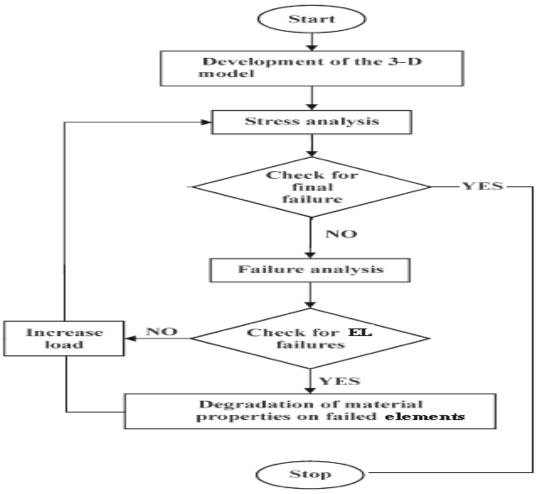


Figure 5. Flowchart of the Finite Element Damage Model

B.3 Cruciform modelling using solid elements

For the 3d modeling of the specimen ‘solid46’ element type [17] was selected. ‘Solid46’ is an 8-node layered solid element, designed to model layered thick shells or solids, with three degrees of freedom at each node: translations in the nodal x, y, and z directions. For the cruciform modeling through thickness one element corresponds to one layer, see fig. 6.

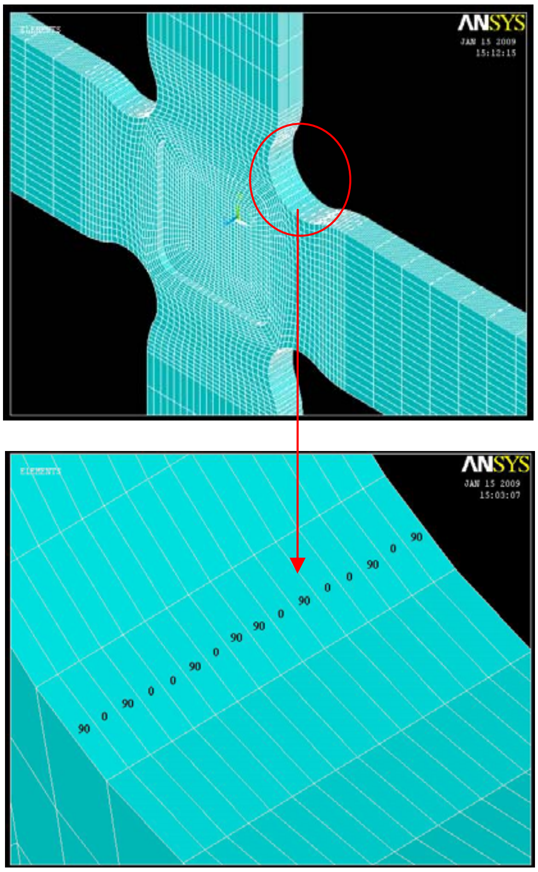


Figure 6. 16 layers meaning 16 elements through thickness or 1 element/layer

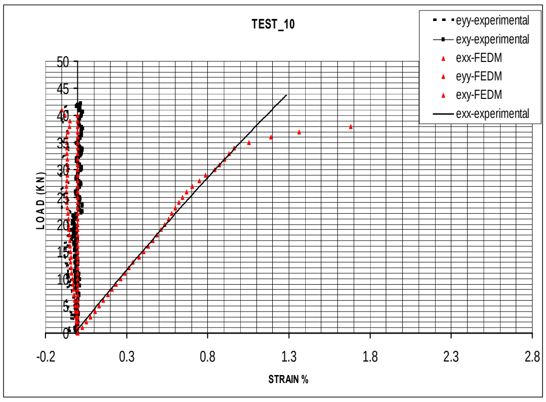
C) Comparison between FEDM and DIC observations

Below, table 3, are compared the failure loads as measured from the load shells of the biaxial machine with the output failure loads from the finite element program. The variation of the results was from 2% to 6%.

Table 3. Failure loads

BIAXIAL	EXPERIMENTS		FEDM		FEDM vs EXPERIMENTS
RATIO	Failure Fx (kN)	Failure Fy (kN)	Failure Fx (kN)	Failure Fy (kN)	variation %
M1/1	42.10	42.16	43.00	43.00	2.09
M1/1b	40.50	40.71	43.00	43.00	5.81
M2/1	44.41	22.21	42.00	21.00	5.75
M2/1b	42.35	21.17	42.00	21.00	0.82
M3/1	37.78	12.59	40.00	13.33	5.54
M3/1b	37.57	12.52	40.00	13.33	6.08
M1/0	42.14	0.00	41.00	0.00	2.77
M1/0b	42.40	0.00	41.00	0.00	3.41

Below, figure 7, are presented the load strain graphs from the four loading cases, for both FEDM and from the DICT measurements, from the centre of the specimen. Strain is plotted for both directions (e_{xx}, e_{yy}) and the in-plane shear strain e_{xy} as well. For all the loading cases the shear is negligible and there is a good correlation between measurements and the FEDM.



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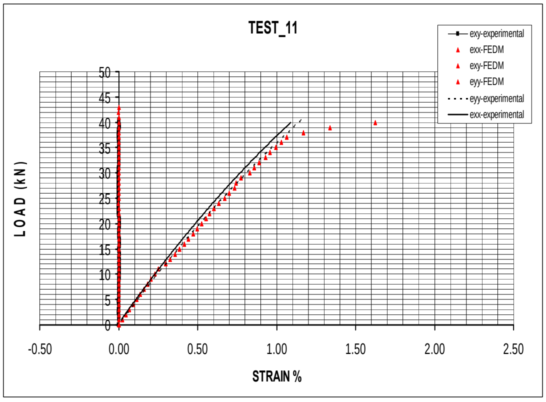

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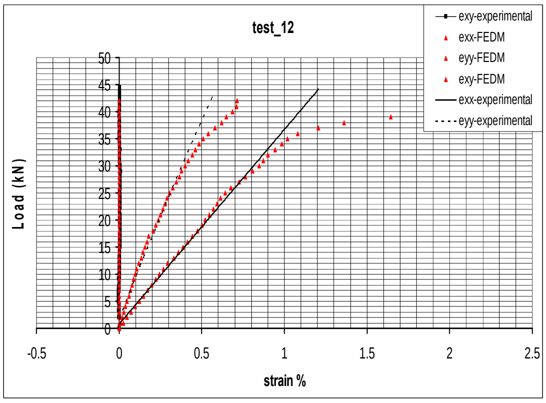
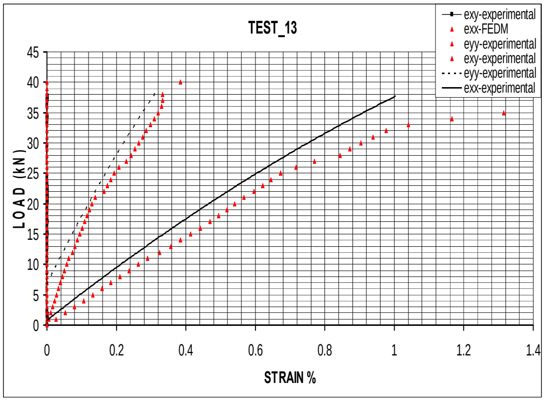


(c)



(d)

Figure 7. A comparison between DIC measurements and the FEDM for the load-strain graphs for the four loading cases.

A quantitative as well qualitative comparison between the first principal strain distribution coming from the DIC measurements and the finite element program is shown in Figure 8. The data are plotted for 50% of the total failure of each loading case.

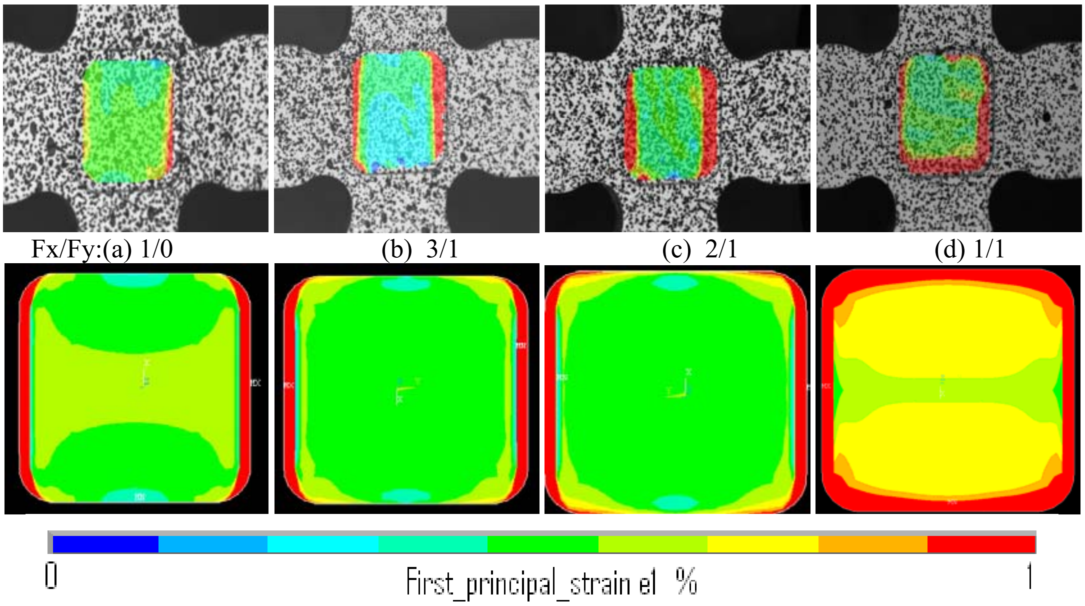


Figure 8. First principal strain for the four load cases i) measured using DICT (above) ii) calculated and presented for the central biaxially loaded section from the FEDM (below).

Conclusion/Future

The finite element model with the progressive damage scenario implemented showed good correlation with the experimental observations coming from the DIC measurements and the data from the load shells of the machine. The variation for the failure loads coming from the FEDM and the experiments is kept between 2-6 %. Moreover there is a good match, quantitative and qualitative, concerning the strain field of the central biaxially loaded section.

An optimization of the cruciform specimen using a shell finite element model and a gradient optimization technique has been done. There as optimization objective is used the uniformity of the central strain field and the concentration of the damage in the central biaxially loaded section. The 3d model which is presented here and proved to produce reliable results will be used as a simulation tool of the experiment in order to 'fast' evaluate the outputs of the optimization method before manufacturing and testing real specimens.

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