BIAXIAL FATIGUE TESTING USING CRUCIFORM COMPOSITE SPECIMENS

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KEYWORDS: biaxial mechanical testing, biaxial fatigue loading, Digital Image Correlation technique.

ABSTRACT

Due to the complex anisotropic behaviour of composite materials more advanced experimental testing is needed. Multiaxial testing under complex loading conditions will improve the understanding of their mechanical behaviour and allow the validation of analytical and numerical predictions. For biaxial mechanical testing various techniques have been proposed [1]. At the Free University of Brussels (V.U.B), at the department of mechanics of materials and constructions a special test bench was designed and created in order to realize biaxial mechanical testing. Near to the design of a cruciform specimen for the determination of strength properties under static biaxial loading, a special cruciform specimen geometry and clamps were developed in order to actualise biaxial fatigue tests on the existing test bench (see Fig.1). In this study the mechanical behaviour of glass epoxy composite laminates under biaxial mechanical fatigue loading is investigated and compared with uniaxial test data. The latter data were obtained from exactly the same material during the European project 'Optimat blades'. Cruciform specimens were loaded just uniaxially in order to check whether results would match with those obtained from uniaxially loaded beam specimens (as an evaluation of the cruciform geometry). The material has the typical lay-up of wind turbine blades. During the whole test duration the Digital Image Correlation technique (DICT) was used in order to get full field displacement measurements.

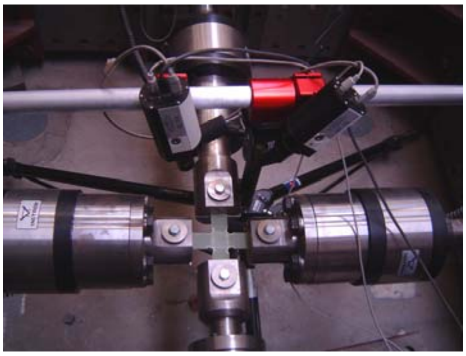

Figure 1: The test set up.

1. INTRODUCTION

Although the usage of composite materials in any industrial branch (e.g. aeronautic or automotive industries) is increasing rapidly, reliable rules for the prediction of laminate failure are not generally available or accepted for all types of composite materials. It is even more difficult to predict the life time of composite laminates when they are subjected to fatigue loading. Mainly three different approaches could be used to study these kind of materials under fatigue loading [2]: (i) the traditional usage of S-N or E-N curves, (ii) the residual strength/stiffness approach and (iii) progressive damage modelling, where the degradation of the mechanical properties of the laminate is investigated in more detail.

In literature, multiple papers related to biaxial fatigue experiments using tubular, bar and planar specimens can be found. These are (i) tension/torsion set-ups of composite tubes, (ii) internal pressure/tension of composite tubes, (iii) bending/torsion set-ups of composite bars and (iv) axial loading or bending moment on the edges of cruciform specimens or rectangular plates respectively. In 1995, Lin et al [3] subjected plain-woven glass fabric laminates to pulsating tension and pulsating torsion biaxial loading. They obtained S-N curves at different biaxial stress ratios. Lee et al [4], examined the failure of carbon/epoxy cross ply composite tubes under combined axial and torsional loading. Ellyin, F. and Martens, M. [5] presented the biaxial fatigue behaviour of a multidirectional filament-wound glass-fiber/epoxy pipe when it is subjected in internal pressure and axial loading and investigated their leakage characteristics. Ferry et al. [6,7] investigated the fatigue behavior of composite bars under bending and torsion loading. In that paper, the long-term characteristics of glass- epoxy bars loaded under bending and torsion were studied. A special mechanical device was designed in order to apply loadings with different stress ratios (force/torque). A visual acquisition system (CCD camera) was also developed to follow the evolution of the extent of damage in terms of the number of cycles.Chen and Matthews [8] clamped all edges of flat rectangular composite plates and applied fatigue load by a central indenter to obtain biaxial bending. A comprehensive overview of all multiaxial fatigue testing techniques was also presented by Quaresimin at the ICFC'4 conference [9]. In the present study the response of cruciform specimens under biaxial in-plane fatigue loading is investigated.

2.TESTING CONFIGURATION

2.1 Test bench/clamps

The biaxial test rig developed at the VUB has a capacity of 100kN in each perpendicular direction As cylinders without hydrostatic bearings are 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. The specimen is clamped in special designed clamps using a pin, in order to reserve the possible rotation (see fig.2).

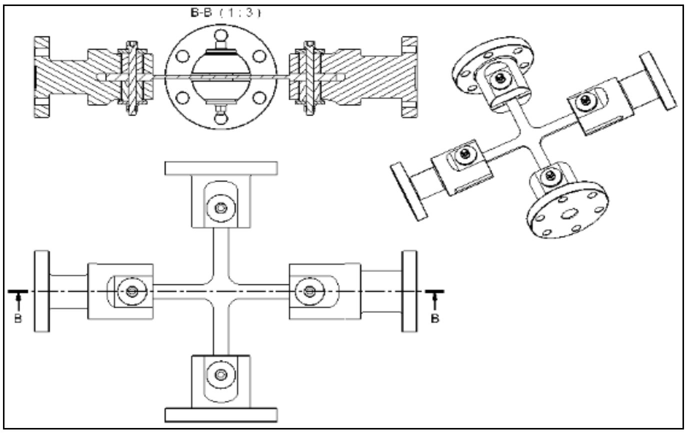

Figure 2: Setup for fatigue testing.

2.2 Specimen

A cruciform geometry was proposed by Smits et.al [4] in order to actualize quasi-static biaxial testing and obtain σ_x/σ_y or $\varepsilon_x/\varepsilon_y$ failure envelopes.This geometry was modified to actualize biaxial fatigue testing, see fig.3. Two major changes on the proposed geometry were done. First end tabs were glued on the arms of each specimen and a hole through each arm was drilled.The purpose of these modifications was to reinforce the arms, preventing unacceptable failures on them and avoid the slipping of the specimen in the clamps during cyclic loading.The specimen consists of four uniaxially loaded arms and a milled central zone which is biaxially loaded. The lay up of the specimen's arms is [(+45°,-45°,0°)$_4$(+45°,-45°)] and of the central zone [(+45°,-45°,0°)$_2$(+45°,-45°)].The [(+45°,-45°,0°)$_n$(+45°,-45°)] lay up is often used in wind turbine blades, in order to resist to shear and normal strains coming mainly from torsion and bending of the blade. The laminate is not symmetric but only balanced. The maximum twist coming from multiplying the load vector (maximum values) with the values of the coupling stiffness matrix [B] is K_{xy}=0.55e-3mm^{-1} which is much smaller than the appearing strain in the axial directions ($\varepsilon \cong$ 20e-3). Cruciform specimens were machined from plates produced by LM Glasfiber, Denmark, using RTM (resin transfer moulding) technology. When cured, the [±45°] plies have a thickness of 0.61 mm and the [0] ones of 0.88 mm. This gives a total thickness of 6.57 mm for the arms of the cruciform specimen and of 3.59 mm where one group of [±45°/0°] was milled away at each side of the specimen. The width of the arms is 25 mm; the total length of the specimen is 250 mm.

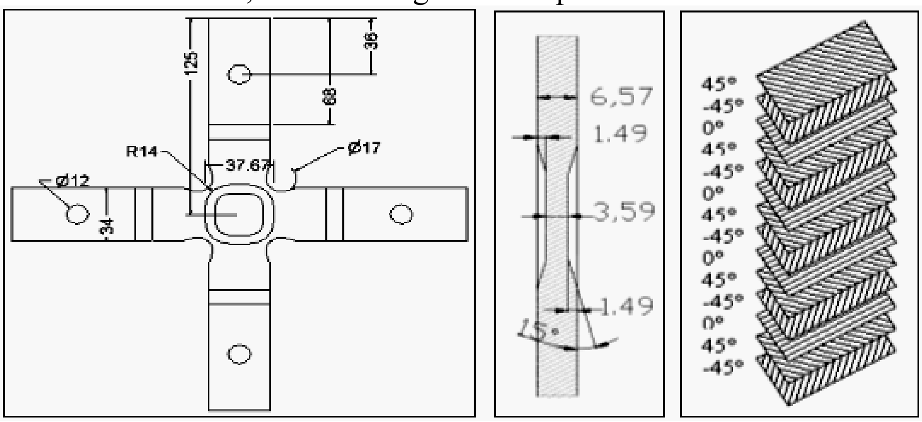

Figure 3: Specimen and lay up.

2.3 Strain measurements using digital image correlation technique (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 taken at different load steps. The software processes and visualizes the data gathered in order to obtain an impression of the distribution of strains. A measurement session consists of taking several pictures of the region of interest with a Charge Coupled Device (CCD) camera. In this case, see fig.4, two cameras were used to be able to measure both in-plane and out of plane displacements on specimens not entirely flat as is the case for the specimens with a milled surface in the centre. Each picture corresponds to a different loading step. The camera uses a small rectangular piece of silicon, which has been segmented into an array of 1392 by 1040 individual light-sensitive cells (pixels). Every pixel stores a certain grey scale value ranging from 0 to 4095, in agreement with the intensity of the light reflected by the surface of the tested specimen. Full field experimental techniques that enable the assessment of the overall strain distribution in the cruciform specimen are absolutely 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. To be able to study the symmetry of the strains and the occurring shear strains experimentally, a full field strain method is necessary.

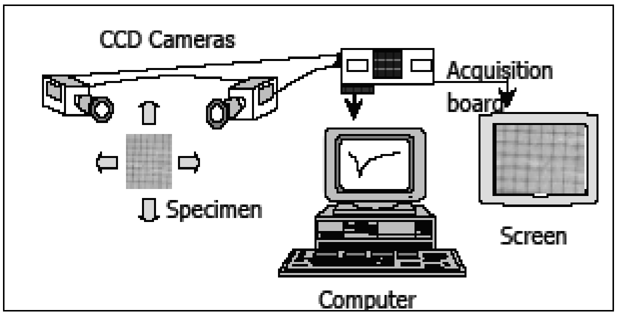

Figure 4:Digital image correlation system.

3.BEHAVIOUR OF GLASS EPOXY LAMINATES UNDER UNIAXIAL AND BIAXIAL FATIGUE LOADING

For the same material and lay up uniaxial tests on beam and cruciform specimens, as well biaxial tests on cruciform specimens, were performed in order to compare the different loading cases and at the same time validate the capability of the cruciform geometry in producing reliable data. The geometry of the beamlike specimens tested was the standard geometry obtained during the 'Optimat blades' project for MD glass epoxy laminates fatigue testing.

3.1 Uniaxial testing of beam specimens

Beam specimens were loaded uniaxially by a load ratio R=-1, for a range of load values and a frequency from 2 to 5 Hz. An extensometer and strain gages were used during the whole test in order to follow the strain evolution, see fig.5a. Using the obtained data, stress-strain curves for every cycle can be plotted. From the slope of stress strain curves the stiffness was calculated and plotted as a function of the increase of the number of cycles, see fig.5b.

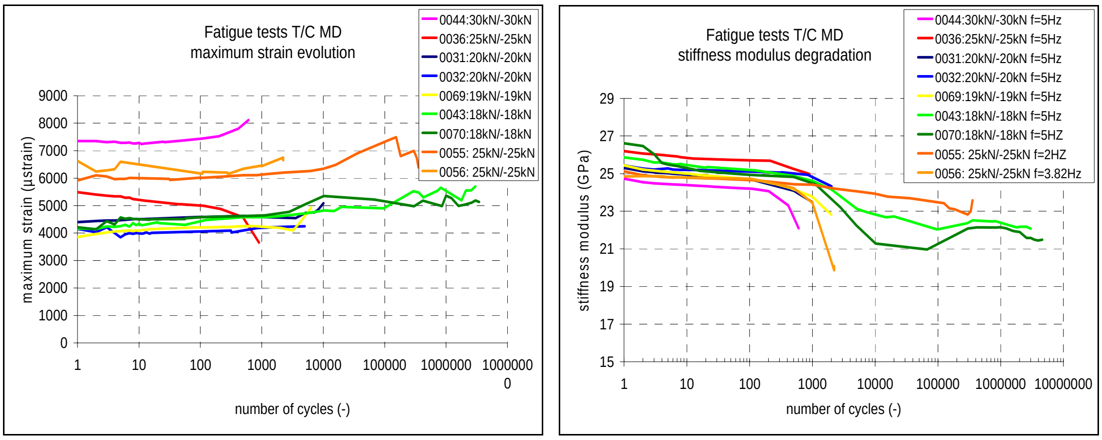

Figure 5: a) Maximum strain evolution of beam specimens uniaxially loaded
b) Stiffness degradation of beam specimens uniaxially loaded (tension part).

Figure 6 represents the evolution of the stress-strain curves by the increase of the total number of cycles for a uniaxially loaded beam specimen. The load was tension/compression ± 25 kN.

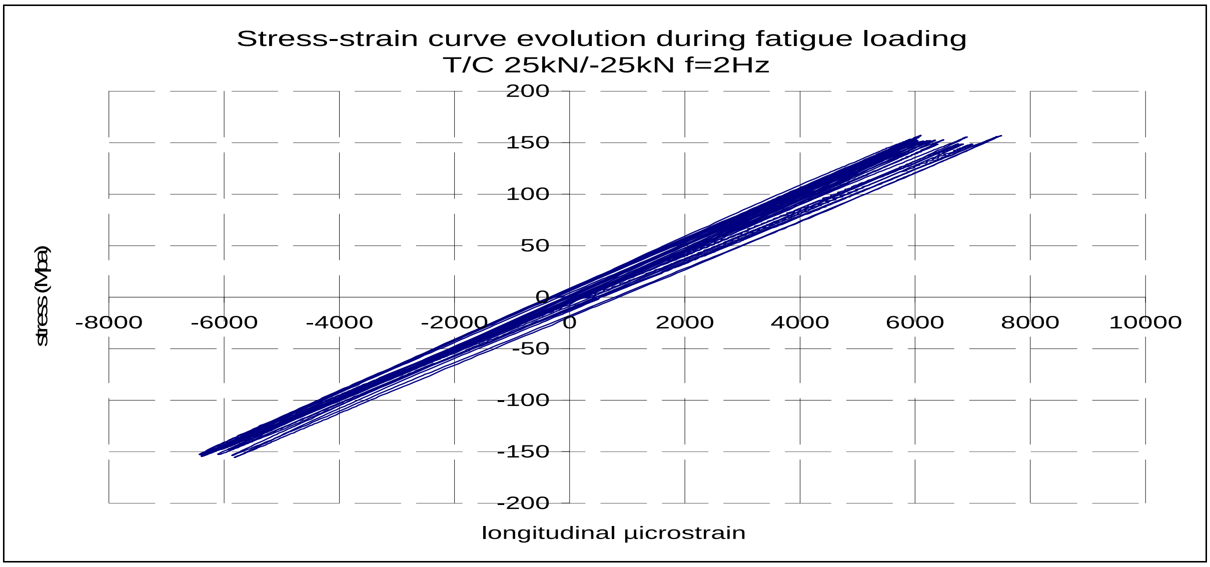

Figure 6: Evolution of the stress- strain curves by the increase of the number of cycles.

The enclosed surface of the dynamic tension-compression loops in stress-strain space represents the amount of energy that is transformed to heat, plastic deformation, damage or sound. Figure 7 shows this enclosed surface for four different numbers of cycles. The surface is significantly larger for cycle 6161 than for the first cycle, but has not a big difference for cycle 298520.

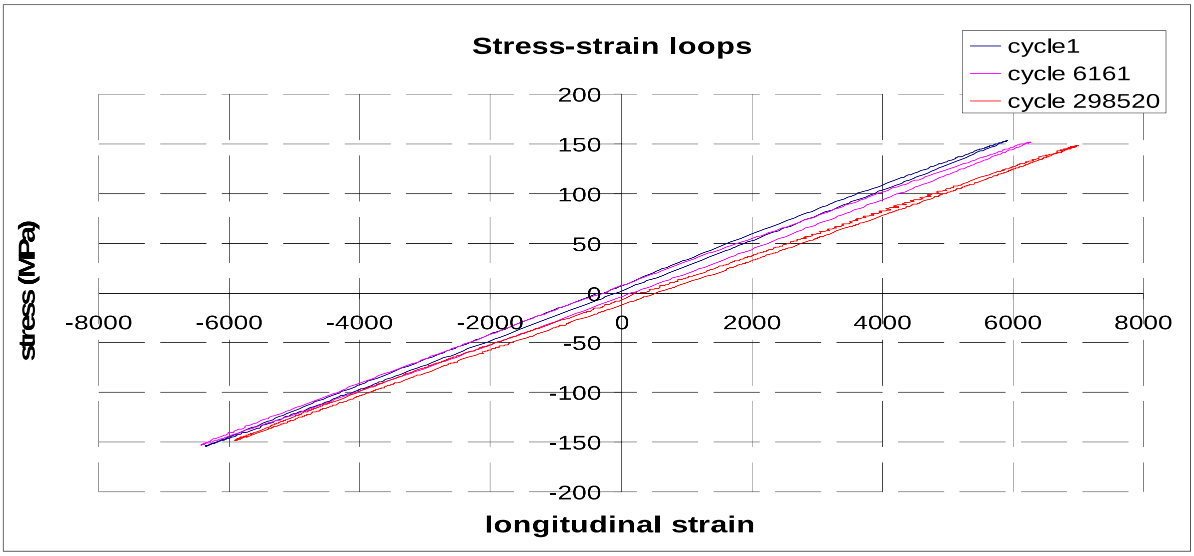

Figure 7: The strain energy dissipation by the increase of the number of cycles.

3.2 Uniaxial testing of cruciform specimens in biaxial testing device

Uniaxially loaded cruciform specimens were tested in order to investigate the capability of this geometry in producing reliable results, see table 1. Maximum strain from the first cycle was measured. Data were compared with those obtained from beam specimen testing. The loading ratio was tension/tension, 3/30 kN, with a constant amplitude and a frequency of 2Hz. The maximal applied force (30 kN) is 60% of the uniaxial failure load of the cruciform specimen. Presented is the e/n curve plotted from uniaxial tests on beam specimens, on it are added the data from cruciform specimen testing.

cycles to total failure (N)	11079	9027	13729
Maximum strain (exx) ,%	0.97	0.94	0.91

Table 1: Data from cruciform specimens uniaxial tested.

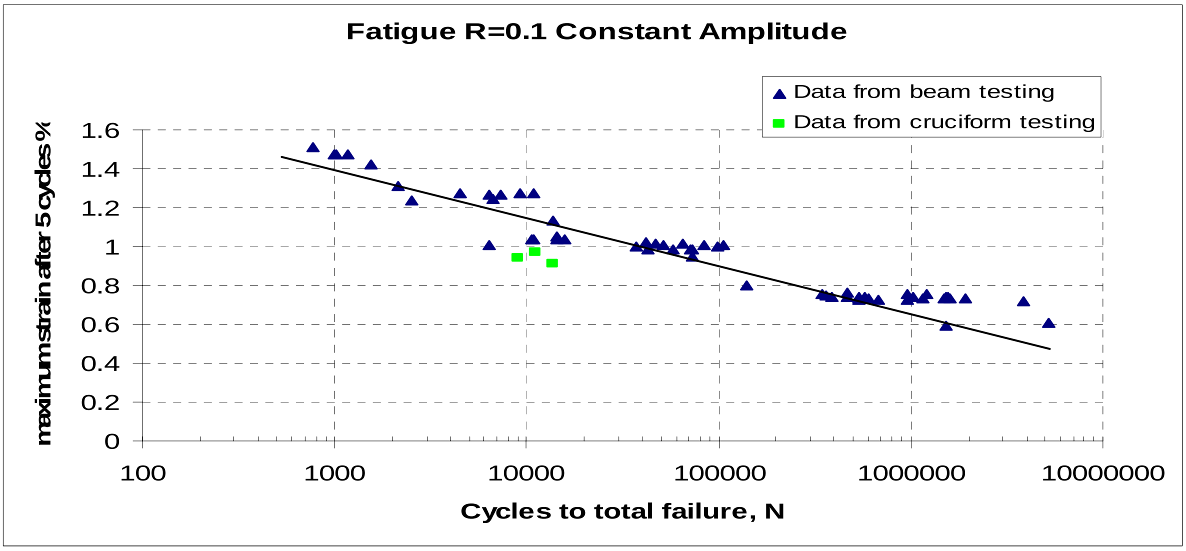

Figure 8: Cruciform and beam uniaxial test data, E/N curve.

No unacceptable failure occurred, from the bolted joint, around the holes of the arms where the specimens were clamped and furthermore uniaxial data from beam and cruciform specimens showed significant correlation .Cruciform specimens failed slightly earlier than beams (see Fig.8) and this is probably due to stress concentrations that appear on the corners and on the milled zone of this kind of specimens.

3.3 Biaxial testing of cruciform specimens

In order to investigate the behaviour of the material under biaxial fatigue loading, four different biaxial ratios were selected.Longitudinal to the 0° fibers the load for all cases was varying sinusoidally from 3 to 30 kN and transverse to the fibers was 0.5-5 ,1-10 and 1.5-15 respectively. For all cases the load ratio $R=F_{max}/F_{min}=0.1$ and the frequency of 2Hz was kept constant. A special case was also investigated where in the 0° direction the load was varying sinusoidally from 3 to 30 kN and in the transverse direction the load was static and equal to 8,25kN, this case was selected in order to check if there would be a sensible difference with the simple uniaxial load case. For each case two or three specimens were tested. A summary graph is presented below ,see fig.9 where the average number of cycles to total failure by the biaxial ratio Fy^{max} / Fx^{max} is plotted. When the biaxial ratio is 0/1, 1/6, 1/3 and 3-30/8,25 failure occurs mainly by fiber breakage in the 0° direction but when the ratio is 1/2 the failure mode changes and failure mainly occurs by matrix cracking transverse to the 0° fibers, this is the main reason why for this biaxial ratio the number of cycles to total failure is smaller.

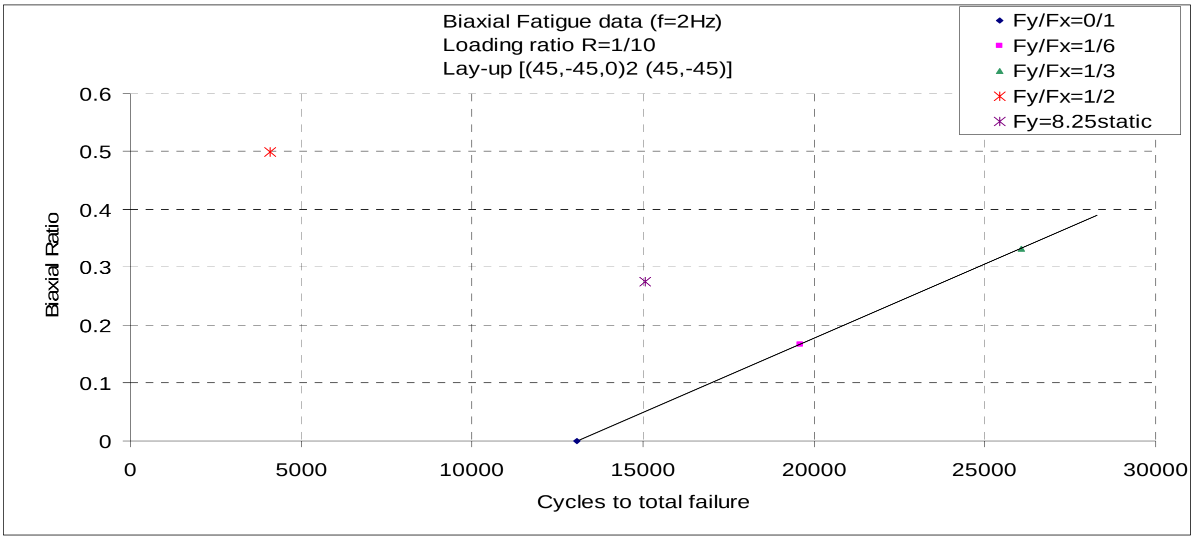

Figure 9: Cruciform biaxial test data.

By increasing the biaxial ratio (that means that the maximum load transverse to the 0° is increased) there is an increase also to the total number of cycles that the material can take. The physical explanation of this is the fact that by increasing the load in the transverse direction at the same time you constrain the perpendicular direction.This is also known as the poisson's effect and it is more intense for ± 45 laminates, where the value of the poisson's ratio is substantially larger. Between the cases where the load in the transverse direction is static and the simple uniaxial load case there is not a sensible difference in the number of cycles to total failure.

4.STRAIN EVOLUTION MONITORING USING DIGITAL IMAGE CORRELATION TECHNIQUE

Digital image correlation technique was used in order to study the strain evolution by varying the biaxial ratio. DICT, as a non contact full field measuring system, provides the full displacement field of the region of interest of the specimen, from the displacements the strains can be calculated.By the usage of an optical method can also be checked the homogenity of the strain field on the biaxially loaded zone. In the graph below, fig.10 the maximum strain by the increase of loading cycles is plotted ,for five different biaxial ratios, the average values are presented for each biaxial ratio.

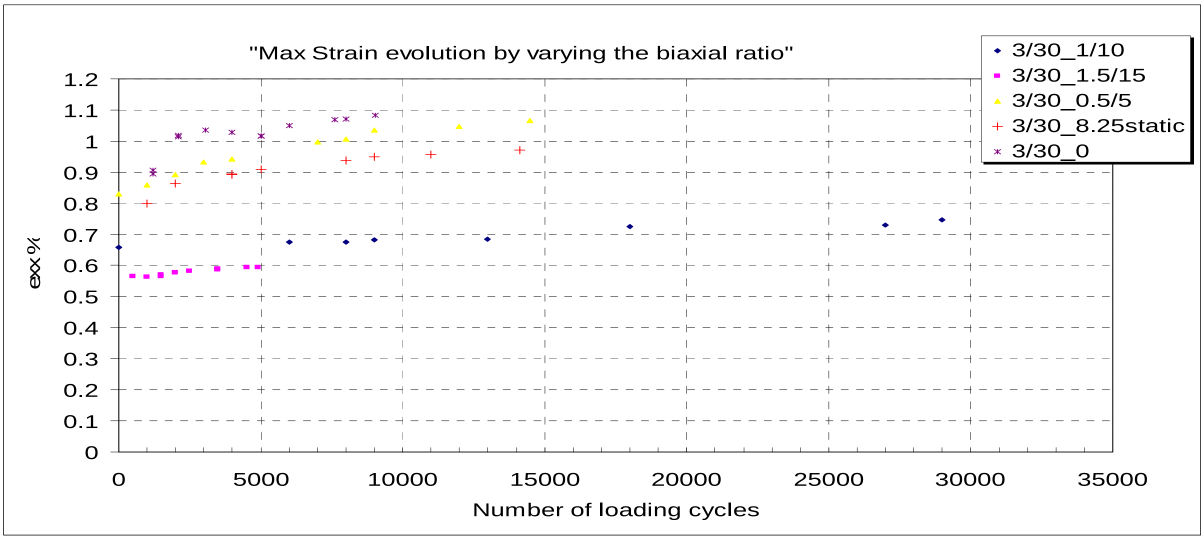

Figure 10: Maximum strain evolution by the increase of the total number of cycles.

The percentage increase of the maximum strain for the five different biaxial ratios is presented below, see table.2.

Biaxial ratio	0/1	1/6	1/3.6	1/3	1/2
% increase	17.36	21.98	18.34	11.78	4.70

Table 2: Percentage increase of maximum strain by varying the biaxial ratio.

5. CONCLUSIONS

The mechanical behaviour of glass epoxy composite systems under fatigue loading was investigated. A cruciform specimen and special clamps were proposed in order to actualize biaxial fatigue testing. Digital image correlation technique was also presented as a tool to obtain the full displacement field of the biaxially loaded zone to compute the strain field and to check the homogeneity of it. The cruciform geometry produced reliable results and unacceptable failure modes, coming from the clamping holes or edges of the specimen were avoided.

Material showed an increase in life time when it was subjected to biaxial loading instead of uniaxial loading but only under the condition that the failure mode is the same. The number of cycles that the material can take increases when the biaxial ratio Fy_{max}/Fx_{max} is increased. This has to be validated from more tests as for each biaxial ratio only two or three tests were carried out.

Further research on the topic could be done by especially investigating ± 45 or quasi-isotropic laminates under biaxial fatigue loading. The mechanical behaviour of these lay-ups under biaxial static or dynamic loading differs a lot from the simple uniaxial load case.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support for this research by the Fund for Scientific Research - Flanders (FWO) and express their gratitude to Hans Tommerup Knudsen from LM Glassfiber in Denmark for his effort in producing the cruciform specimens.

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