Evaluation of in-plane shear failure in composite laminate with high **percentage of 90^o plies**

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Introduction The first step in analysis composite joint is to have a correct and appropriate definition of properties of material used. The effect of fibre orientation and the interaction between them in the laminated composite play a key role in determining the laminate characteristics, the laminate mode of failure as well as the overall mode of joint failure. In order to study the failure of a new generation of composite laminate joints, sets of material properties are needed in three directions. This paper present the study of the in-plane (interlamina) shear properties and the behaviour of a specific Carbon Fibre Reinforced Plastic (CFRP) laminate with a particular balanced lay-up under compression load. This paper presents the continuation of a previous study by the author to study shear in a specific CFRP Ref [1]

Methodology This study involved detailed experimental program to determine the material property of a specific composite laminate. These material properties were needed when analysing the failure of a new type of fastener joint for composite laminates. Twenty shear tests were carried out using a minimum of 6 specimens for every lay-up. Although some thickness tolerances issues were caused by using different laminate lay-ups, all other geometric parameters were kept at nominal values. Ply failures were observed for $45^o/90^o$, 45^o, 90^0 specimens. A simple Finite Element (FE) model was also developed for each particular lay-up and results were compared against the test data. The FE method was used to explain why each coupon failed in a particular way. The FE model used 2D unsymmetrical material properties with shell elements representing the thickness. In terms of boundary conditions the model was constrained at one end with a compressive load applied at the other end as shown in Figure 1.

Fig 1- FEM mesh with BC and direction of applied load

The double notch shear test followed ASTM D 3846 method [2] for this experimental programme. The results of this study and the previous work [1] show that, the laminate with high percentage of 90^o fibre orientation (with no supporting fibre in 0^o direction) will fail in compression during shear test.

Experimental Approach In-plane shear strength is measured by applying a compressive load to a notched specimen of uniform width. The specimen is loaded edgewise in a supporting jig shown in Fig1and Fig2. Failure of the specimen was expected to be shear between two centrally located notches. Notches were machined halfway through the specimen's thickness and spaced at fixed distance on two opposite faces Ref [2].

Test specimens Test panels were prepared in accordance with EN 2565 method B, [3] each panel was made using 12 plies of pre-preg Cytec material (CFRP 977-2 HTS). All panels were hand layed and cured. The variation in thickness between all laminate, were within 2% of nominal thickness. The panels were subjected to NDT (C-scan) to find any preliminary damage, delamination or imperfection [4]. Three different panel lay-ups were used for this experiment $45^0/90^0$, 90^0 and 45^0. All panels were cut into specimens as shown in Fig2. A testing machine, as shown in Fig 4, capable of controlling constant-rate-displacement was used for these tests.

Fig2- specimen

Fig 3-Jig Fig4- test machine test setting

The load-indicating mechanism was set up to show the total compressive load carried by the test specimen during the test. A supporting jig, as shown in Fig2, was used to hold the specimens in line with the direction of load within the test machine. This jig secured the specimen from buckling by using a small suitable tightening torque. To find the in-plane shear or interlamina strength, the maximum shear load carried by the specimen during the test, was divided by the width of the specimen and the length of the failed area.

Test definition The nuts used in the jig were tightened to a torque of 0.113 + 0.000, − 0.028 N·m before placing the coupons in the compression machine. The speed compression rate was set at 1.3+/- 0.3mm/min. All tests were performed at Room Temperature (RT) and normal humidity conditions. The average RT is 23^{o}C and relative humidity of around 15%. Based on the direction of the load, the deflections were measured using cross head displacement via an inbuilt Linear Varying Displacement Transducers (LVDT) [1,2]. A typical sample shear failure is shown in Figs 5(a-c)

a) Specimen b) Failed specimen c)Interlaminate shear

Fig5- typical specimens before and after testing

During the testing of the $45^{o}/90^{o}$ laminate lay-up the specimens failed in compression modes Fig 5. This is an unexpected mode of failure. In order to discover the reason for this un-expected failure a further set of specimens with Unidirectional (UD)-$45^{o}$and UD-90^{o} laminates were made and tested to distruction and results can be seen in Fig 6(a-b)

a) b)

Fig6- the unexpected failure of the $45^{o}/90^{o}$ laminate

FE Modelling A 2-D finite element model was built using Patran and solved using MSc Nastran for each particular lay-up.

The FE model used the nominal geometry of the test
Shell elements were used with orthotropic material properties and with corresponding ply lay-ups. Each ply is represented by a row of shell elements. Shell elements are oriented on xz plane where x is parallel to load direction and z is lying through thickness of the laminate. This assumption is made considering the infinite direction of the shell represents the in-plane direction of the specimen.The model is constrained in two directions at one end and loaded at the other end similar to the test configuration Fig 1. The FE model was built on PATRAN and solved by NASTRAN using linear static analysis Ref [5]. Maximum and minimum shear stresses and displacement were read for each ply by using the corresponding row of shell elements.

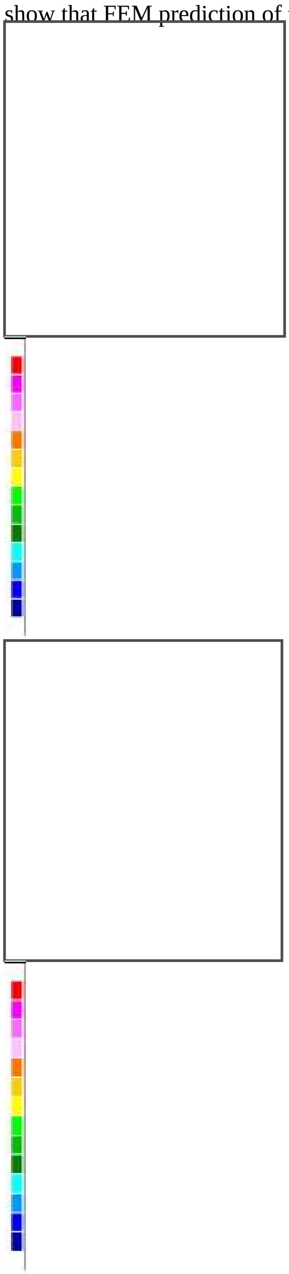
Results and discussion Specimens with a $45^o/90^o$ lay-up unexpectedly failed in a compression mode, as shown in Fig-5. FEM results showed the stress concentration around the notches for $45^o/90^o$ laminates (Fig 7).

Fig7-the shear stress plot for 45/90 compression failure

This result has been discussed in a previous paper by the Author [1] which covers the in-plane shear failure and ply stress plots for expected shear failure. Fig-7 also shows the shear stress plot for multi-directional $45^O/90^O$ laminate. In this plot each row of shell elements represents one ply. The colour contours in each ply shows shear stress variation in each and every ply. Here the crack was initiated at the corner of the notch; the notch being located at the high stress concentration area. It was also expected that the high stress paths grow through the weakest link, which is the region laying between the two notches. The stress distributions are shown in Fig-7. The high stress area does not stay between the notches in the same way as the other laminates [1]. In this case, the crack has jumped to the different plies in order to find the lowest energy path. The failure mode therefore is no longer an in-plane shear failure. This type of failure is observed during the in-plane shear test of $45^O/90^O$specimens and quoted as unexpected failure [1]. Further tests for UD-90^o and UD-45^o were carried out to analyze and better understand this mode of failure. Fig 8 show shear stress plots for UD 45^o with each row representing one ply. Specimens of this type (UD-45^O) fail due to interlaminate (in-plane) shear failure mode. In contrast the specimens with UD 90^o laminate did not fail in a shear mode (Fig 9). From the stress results, for UD 90^o laminate, it appears that the cracks initiated in the region of stress concentrations around the notches. The lower energy path dictates the path of advancing crack and therefore the unexpected failure mode. In this case the lower energy path does not lay on the link line between the notches. Having 90^o fibres against the direction of the force does not resist crack growth.
Therefore the crack will find the minimum energy path, which appears to be in the next ply and the resin between plies so it jumps into that area and cause micro failure and fibre breakage. Then, it continues to jump ply by ply damaging the fibres and growing to the edge of the laminate. In the case of the UD-45 the lower energy path is the weakest link between the two notches, this leads to the failure due to in-plane shear failure as shown in Figs 5c and 8.

Fig 8- shear stress for UD-45^O Fig 9- stress results for UD-90^O

In this case, fibres resist against the crack growth through the plies. Therefore the crack can only grow in the resin between plies lying and between the two notches. It is similar to the in-plane shear behaviour of all other laminates lay-ups with no 90^o ply or having a percentage of 0^{o}plies aside to 90^o plies [1]. The non 90^{o}plies provide the resistance and redirect the crack growth path through the resin area between the plies. Fig-10 a&b is the comparison between typical displacement plot happening at the in-plane shear failure mode (UD-45^{o}specimen) and the displacement caused by the compression failure (UD-90^o specimen). The results show that FEM prediction of the high stress paths is similar to the failure paths resulting from in plane shear test.



a) UD–45^o Failure in shear b) 90^o failure in compression

Fig 10-Normalised Displacement

It can be concluded that the compression type failure during the in-plane shear test is due to the indention of 90^o plies. The interaction between the 45^O plies and 90^O plies configurations or any configuration of laminate with 90^o (where there is no 0^o fibre) leads the shear test to exhibit compression failure.The material property determined from these three lay-up configurations are listed in Table 1.

Laminate lay-up	UD-90	UD-45	Lay-up 45/90
Normalised Modulus*	0.149	0.183	0.171
Failure mode	Compression	In planes hear	Compression

Table 1- modulus for specimens under compression (*not to be considered as conventional shear modulus)

Reference:

1- S.Vali-shariatpanahi "Evaluation of in-plane shear failure in composite laminates", AIAA conference Illinois, 7-10 April 2008, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference
2- ASTM D3846 –02 American Standard test method for In-Plane shear strength of Reinforced Plastics 2001.
3- AECMA Standard prEN 2565 edition 2 May 1993, Aerospace series preparation of carbon fibre reinforced resin panels for test purposes.
4- BS EN ISO 2818 British standard 1997, plastics preparation of test specimens by machining
5- Patran/ Msc Nastran (the McNeal –Schwendle cooperation) 2005

Notch depth is ½ specimen thickness, tolerance 0.2mm

P

P

P

BC

Max shear stress path jumping through thickness- ply by ply