Determination of through thickness properties for Composite thick laminate

S.Vali-shariatpanahi*
*Stress Engineer/Durability group leader -Airbus
Address: Building 09J, Airbus UK,FILTON,BRISTOL BS 99 7AR
EMAIL:Sepideh_vali@hotmail.com

Abstract

This paper presents a study of through thickness failure mechanism and material properties for three particular types of composite laminates, through an experimental program. The study of the test results show different crack path occurs for different laminate lay-up, resulting to have different out of plane material properties.

Keywords: Composite material property, Composite through thickness properties, Composite through thickness failure.

Summary

This paper is a study of the through thickness characteristics of specific CFRP with three particular balanced lay-up of thick cured laminates. This study involves experimental program to determine the material properties. The material properties will be used for failure analysis of a new type of fastener joint in composite laminate, which has a potential use in Aerospace industries. Two sets of Twenty-one test samples were experimented using 3 different lay-ups. Some thickness tolerances, were caused by using different laminate lay- up, all other geometric parameters were kept similar for each set. This paper is looking at the through thickness failures with tow set of testing. Set-1 has been used to determine the material modulus and set-2 were used to measure the material strength in through thickness direction.

Introduction

General problem with composite is joint failure. Type of laminate failure at the joint is the key to understand, analyse and predict the joint failure. Major industrial companies are doing more and more analysis and testing to understand composite joint failure and design the best composite joint. The first step to analyse a joint is to have a correct and appropriate material characteristics. The Effect of fibre orientation and interaction between the fibre directions and the matrix in laminate are playing the key role in laminate characteristic, the type of laminate failure and so as the joint failure. To study and failure analysis of a composite laminate joint, several material properties are needed. Recently the use of thick laminate becomes more common in aerospace and other industries. Hence the material properties in third-direction through the thickness of laminate are more important and play significant role in joint failure. This paper presents and studies the through thickness property of 3 specific CFRP laminate and the driving type of failure for these particular lay-ups. In this paper the through thickness test procedures, study of results of through thickness test and material properties for 3 particular laminate lay-ups will be discussed. Performing through thickness test program for these 3 types of laminates-lay ups proves that, through thickness properties are depended on the laminate lay-up. Currently in industry it is assumed that the through

thickness laminate property is not much depended on the laminate lay-up and can be estimated by using tension test on UD-90^o thin laminate.
Experimental program and test results show that strength and the type of failure in thick laminate are also depended on the laminate lay-up.

Experimental Approach

The experimental program includes two sets of testing. Test program set-1 was designed and performed to determine the through thickness modulus. In this test simple block specimen under the tension force where strain gauges fitted on all the 4 sides of the block. Test program Set–2 is using similar concept of D 7291/D 7291M – 07 method Ref [1] but in different process, which determines the through thickness strength of material by using through thickness tension. Minimum of seven specimens were used for each UD-0^O, 0/90^o and QI laminate lay-ups. In this test the specimens were especially designed to fail in the centre section.
Using the above, test, specimen behaviour under the test and test results give a close look to the changes in through thickness property and laminate failure.

Test method

Two shapes of composite specimens were used for this test program. Straight-sided Square shape and reduced gage cubic section (waisted specimen).A schematic of the specimens used for this test shown in Fig1-a and Fig1-b
The composite specimen weather in the shape of straight-sided Square section or a reduced gage cubic section is adhesively bonded to rectangular metal ends.The bonded assembly is loaded under “flatwise” tension loading by a force applied normal to the plane of the composite laminate until failure of the laminate occurs (Fig. 2). The test is considered valid only when failure occurs entirely within the composite laminate. The test is considered invalid if failure of the bond-line or partial failure of the bond-line and the surface layer of the composite occurs. The failure mode of this test is not controlled; therefore, the actual failure may be intralaminar or interlaminar in nature.

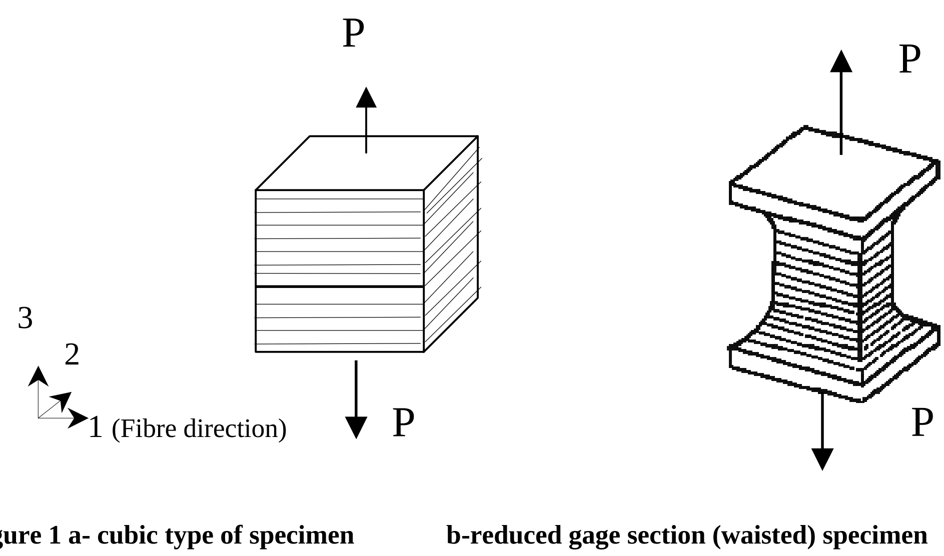


Figure 1 a- cubic type of specimen b-reduced gage section (waisted) specimen

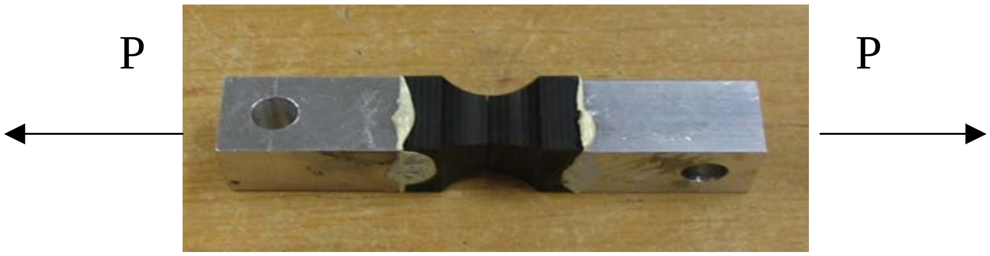


Figure 2 bonded assembly

Suitable testing machine capable of controlling constant-rate-of-crosshead movement were used. Load-indicating mechanism is set up for showing the total tensile load carried by the test specimen during the test. A supporting jig, shown in Fig3, is used to hold the specimens in line with direction of load in the test machine.

Figure 3 specimen in the jig in the tension machine

To find the through thickness modulus, strain gages were fitted in four sides of *block* specimens. Using recorded displacement data in all three directions from these strain gages and correlated applied load will determine the 3-3, 2-3 and 1-3 modulus based on applied tension load in direction of 3. See fig 1

Strength data is recorded from the waisted specimens' test, using the maximum load at the failure and corresponding cross section.

Material selection and coupon sizing

Panels were made by using prepreg hand lay-up at clean room and cured at autoclave. Ply Table and all related equipment for cutting and measuring including plies saw and grinding wheel were used for cutting laminate into specimens.

For each panel CFRP 977-2 HTS is used. The material is a UD tape. During the manufacture the laminate is de-bulked every 4 plies. The laminate is consolidated using

an autoclave and Airbus method for curing thick- laminate. Then is checked using NDT method (C-Scan). Each panel consist 100 plies with dimension of 280mm x 280mm in size.
The finished laminate will be a flat rectangular plate with the thickness of 25mm and 0.2m tolerance.

Test specimens

1-Test Panels

Test panels were prepared in accordance with EN 2565 method B Ref. [3] for carbon fibre reinforced laminates. The variation in the thickness measurements for any laminate, are within ± 2% of nominal thickness. The panels were subjected to NDT (C-scan) to find any delamination or imperfection.
Three different panel lay-ups were used for this experiment UD-0^0, $0^0/90^0$, and QI.
2-Test samples
Test panels were cut to test sample using defined dimension shown in Fig4 and in accordance with ENISO 2818 Ref. [3]. Using specific water jet cutting method gives adequate tolerance at the edges of samples and to ensure that no delamination is occurred during the machining and cutting the test specimens. Straight-sided Square shape Specimens were equipped with Strain Gages (Tee Rosette 062wt) in all 4 sides. Seven test specimens were tested for each test conditions and lay ups

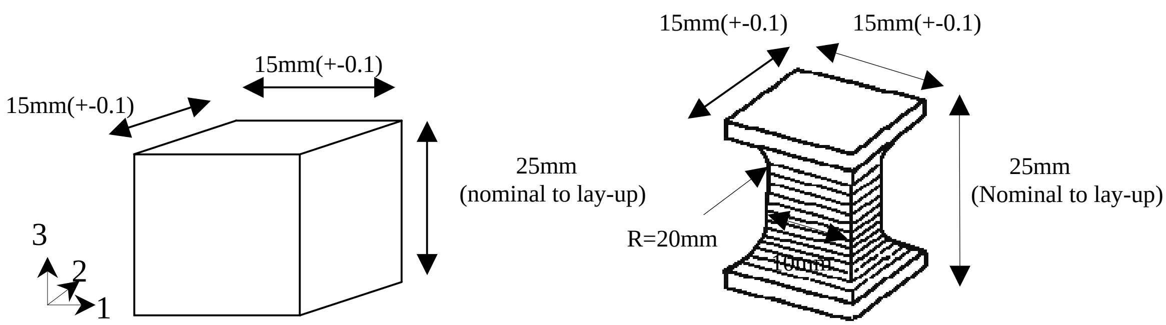


Figure 4 through Thickness Specimens and dimensions

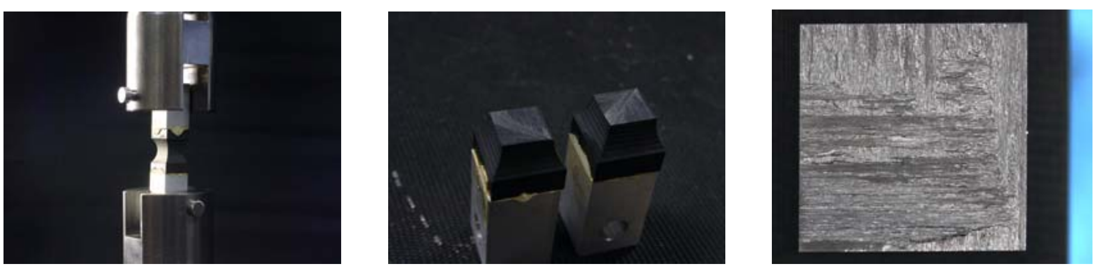
Test definition

Each specimen was measured to determine thickness and width using mean value obtained from three selected points. After measurements each specimen was bonded to the side blocks (Fig. 2) and mounted in the supporting jig (Fig 5). Then it was tighten to the loads plates and placed in the tension machine, recording of the load and cross head displacement was carried out during the test. Test speed was fixed at 1mm/min. All tests were done in RT and normal humidity conditions.

Figure 5 test setting

Modes of failure

Based on direction of the load, delamination is the expected failure mode for the laminate. Measurement of the strength of material in z direction and drawing the load displacement curve will give the material property in the laminate in z-z (or 3-3 thought the thickness direction)



a) b) c)

Figure 6 Typical specimens before and after testing a)Specimen in side jig and load sell before failure b) Specimen in side jig after failure c) looking at cross section 0/90lay-up failure

All specimen failed in delamination but with the different crack grows' path.
Although all specimens failed near to the centre line of the specimen in z direction, but the strength of UD-0 , $0^o/90^o$ and QI laminate lay-ups were different Fig 6-c shows the Microscopic picture of the failed area for specimen with $0^0/90^0$ lay up.

Data collections

Specimens' dimensions were measured and recorded (e i. Width, thickness,..)
Deflections were measured using stain gages and LVDT. Electronic load and corresponding deformation data in three directions were collected for each specimen. Finally the strength data read from the maximum loads at the failure point of the waisted block test.

Results and discussion

Typical graphs for tensile stress versus strain are shown in following figures for UD-0, 0/90, QI lay-ups

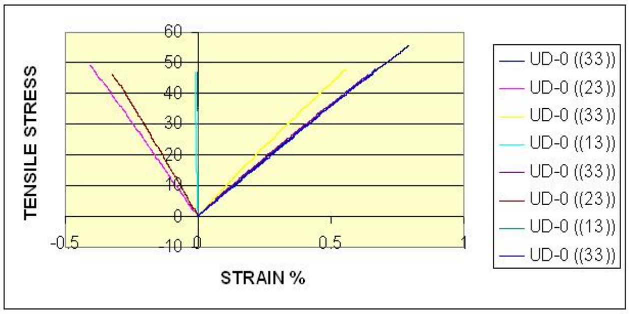


Figure 7 **UD-0 typical curve, data shown as % of stress versus %strain based on mean value of 7 tests (all data are normalized)- yellow and blue line indicating the upper and lower limit for data in 3 direction similarly every two line for 2 other directions**

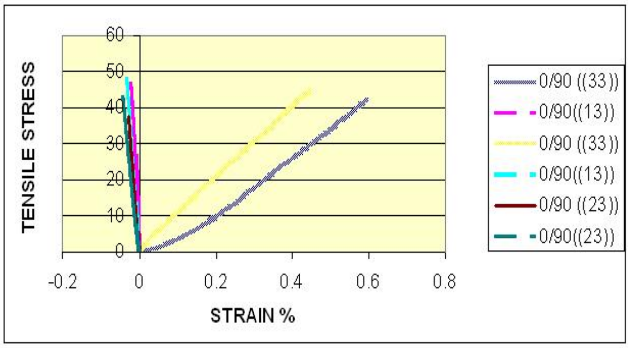


Figure 8 **0/90 typical curve, data shown as % of stress versus %strain based on mean value of 7 tests (all data are normalized)**

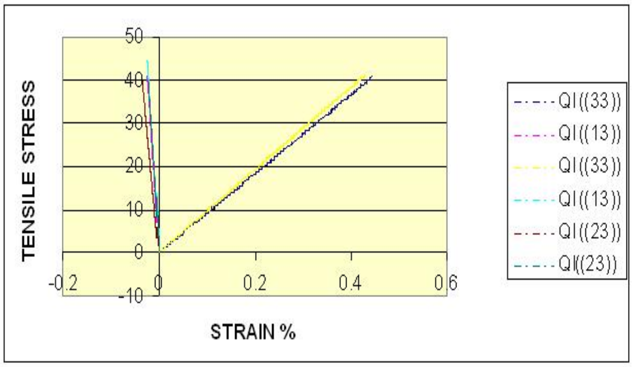


Figure 9 **QI typical curve, data shown as % of stress versus % of strain based on mean value of 7 tests (all data are normalized)**

The through thickness modulus (direction 3-3) is shown in first quarters of each graph and two modulus (1 and 2 direction) shown in left side of the graph.

Fig-7 to fig-9 shown having different lay-up, not only will determine different values in through thickness but also has a great effect on two other modulus in 1 and 2 direction. Bare in mind that always load applied in direction of 3 (see fig 10) and stain read on 4 sides of the block in direction 1 which is the fibre direction, 2 perpendicular to the fibre direction or 3 through the thickness direction.

From 3 above graphs, changes in Poisson's ratio are obvious. Poisson's ratio in different direction (block sample faces) is changing as the lay-up changes from UD to 0/90 and then QI. Curves on the left side of the graphs (fig-7 to fig-9) show big angle between the two set of curves. As the lay up become multidirectional (0/90) the angel between those curves become smaller and in QI lay up all 4 curves on the left side merge together showing one single Poisson's ratio on 4 side of the block. This is expected as the changes in the lay up moving from UD to toward QI resulting to have more homogenous behaviour of material.

Study of the result also indicate that Changing the lay-up from UD-0 to 0/90 increases the through the thickness modulus (direction 3-3). it reaches the highest value for QI lay-up. This is also true for modulus in direction of 2.

Table-1 summarises all modulus and through the thickness modulus determined by this test program.

These differences in value from lay-up to lay-up can be resultant of different crack grow path due to the type of the laminate lay up. Changing the fibre direction through the thickness of laminate can help to delay the crack or can speed up the crack grows, depend on the fibre interaction from ply to ply and its interaction with the matrix.

Up to now in industry the through thickness properties were assumed to be similar as the property resultant from thin laminate of UD 90 lay-up under the tension test. Most of the major industries use this type of value for design and manufacturing of its components and joints without considering the real lay-up of the thick laminate and the effect ply direction to the through thickness property of the laminate.

Table 1-modulus in three direction based on mean value of 7 tests for each lay-up (all data are normalized)

modulus	1-3	2-3	3-3
Lay-up 0^o	1.00	0.1787	0.0168
Lay-up $0^o/90^o$	0.300	0.2484	0.0211
Lay-up QI	0.2663	0.266	0.0214

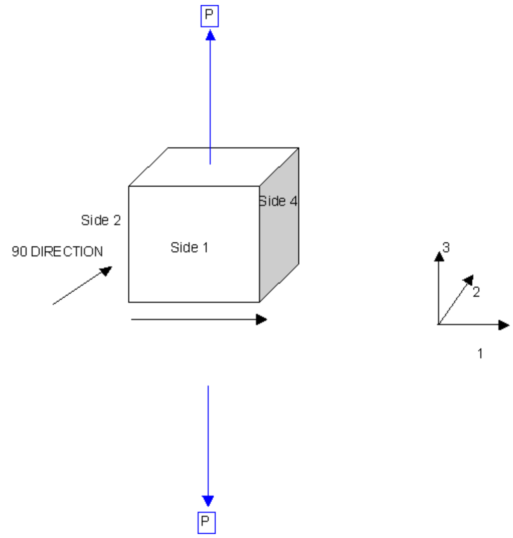


Figure 10 The three directions for reading The strain data and the applied load direction

Above results also shows as far as the laminate lay up getting closer to homogenous material the two other moduli in direction of 1 and 2 are getting closer to one value. Modulus of laminate with QI Lay-up in direction of 2 and 1 are almost identical as theoretically expected.

Table-2 and Fig-11 are representing the strengths data resultant from set-2 tests with the waisted specimens (see also fig-7). Table-2 shows that otherwise the modulus the UD-0 lay-up has the highest strength. As the laminate lay-up goes from UD to multi-directional lay-up the through thickness strength becomes lower where the QI lay-up shows the lowest of all.

Table 2-out of plane strength based on mean value of 7 tests for each lay-up(all data are normalized)

Laminate lay-up	Lay-up 0^o	Lay-up $0^o/90^o$	Lay-up QI
Strength(average of seven tests)	1	0.837	0.681

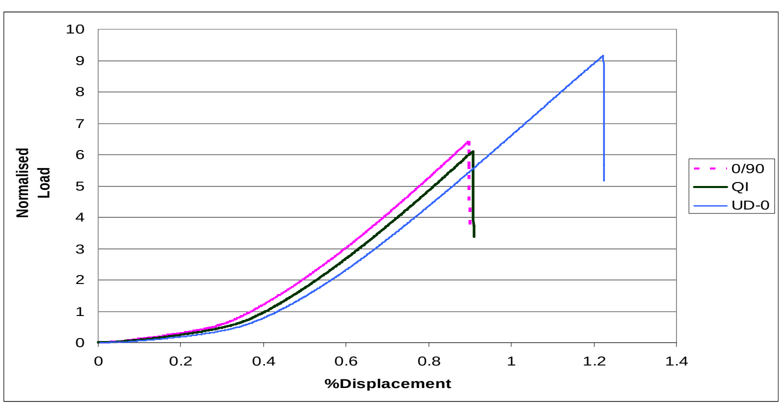


Figure 11 load-extension curve from waisted specimen test (mean value of 7 tests for each lay-up), all data are normalized

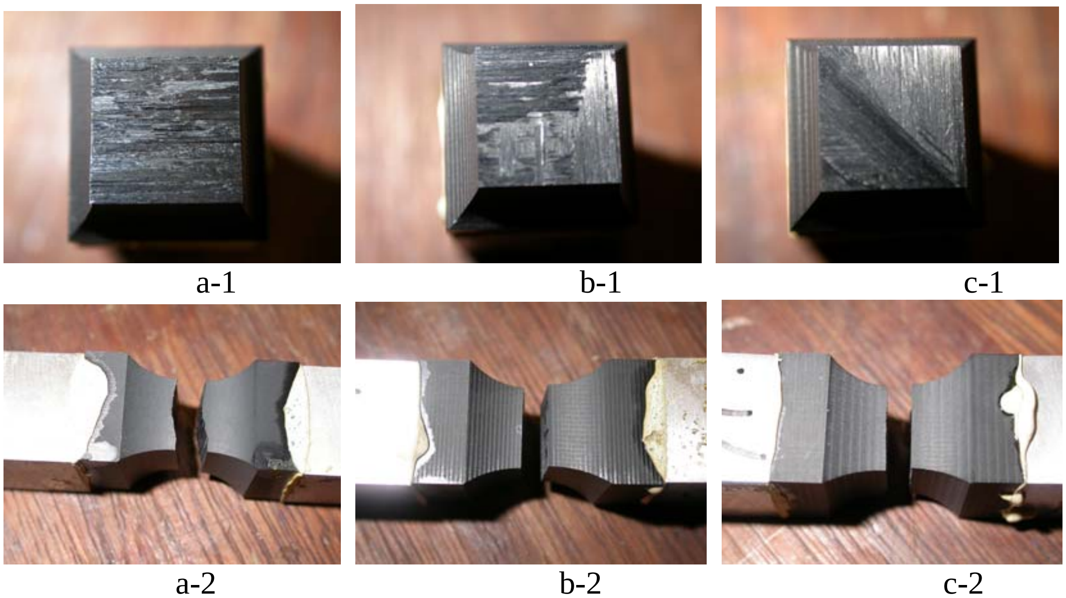


Figure 12 picture of fracture surface at the failed section a) lay-up 0^{O} b)lay-up 0/90 and c) Lay-up QI

Fig-12 shows the facture surface of 3 deferent laminates. The UD-0 laminate the through thickness strength is only to do with matrix strength and fibre resistance. This will help the material to reach high strength in 3-3 direction the failure surface shows the crack travels through the matrix freely around the fibre then matrix failure occurs through the thickness of material. Fig-12 (a-1 and a-2).

The multi directional laminate 0/90 fibre fractures in both 0 and 90 direction as well as matrix failure. This means the crack grows not only through the matrix but it propagates between plies and goes to fibres which cause fracture in fibre as well as matrix delaminations. In this case crack grows path redirected from plies to fibre and again to matrix find the lowest energy path it jumps by ply backward and forward which will results delamination and then total failure having lower through thickness strength compare to the UD laminate. Fig-12(b-1 and b-2)

This rapid jump of crack and delaminations even more advance in QI laminate lay-up. It find even the lower energy path to grow as there are more fibres every 45^{o} in angle differences in directions of 90^{0}, +/-45^{o} and 0^{o}. This results the even lowest strength through the thickness of material. The rotational fracture and crack grow path shown in Fig -12 (c-1 and c-2).

Failed section in 0/90 laminate and QI laminate have very clean section showing that the crack could find the lower energy path fairly easy throughout the thickness with few jumps over couple of plies (see fig-12 b-2 and c-2). Whereas in UD laminate crack travels several plies up and down to cause the matrix fracture and total failure. Fig-12 a-2 shows very rough surface at the failed section compare to very clean section failure for 0/90 and QI specimens. (see Fig-12 a-2, b-2 and c-2)

Conclusion

From the dissections in the previous section the type failure during the tensile test very much depend on the interaction between fibre directions and matrix. This can highly affect the through thickness material property of the laminate.

The UD laminate shows the highest strength but the lowest through thickness modulus. The QI lay up has the highest through thickness modulus and the lowest strength.

The main reason of this study was to determine the material properties and analyze the failure behavior for different type of laminate. This study and the material properties out come of this test program will be used for failure analysis of a new type of fastener joint.

The material properties for these three laminate lay-ups are listed in Table 1 and table 2 of this paper.

Acknowledgements

The study was funded by AIRBUS.

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