Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 21 (2019) 198–205

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

1st International Workshop on Plasticity, Damage and Fracture of Engineering Materials

Interlaminar tensile strength of different angle-ply CFRP composites

Burak Ogun Yavuz[a], Levend Parnas[b], Demirkan Coker[a]*

aDepartment of Aerospace Engineering, Middle East Technical University,
Ankara 06800, Turkey
bDepartment of Mechanical Engineering, TED University,
Ankara 06420, Turkey

Abstract

Due to high specific strength and modulus requirements, demand for the use of polymer-based composites in structural applications has been increasing more than ever. On the other hand, their interlaminar properties are known to be relatively weak. Such structures are prone to interlaminar failures including delaminations under static or impact loads. Interlaminar tensile strength (ILTS) is one of the interlaminar properties which gives an indication of delamination onset in through the thickness loading for composite structures, while fracture toughness is another property which gives information about the propagation of delamination. Conventionally ILTS value which is experimentally obtained specifically for 0˚//0˚ interface according to ASTM International D 6415/D 6415 M (2013) is used in design and analysis even for interfaces with different ply orientation. In this paper, our objective is to investigate the effect of ply orientation on the ILTS for CFRP. For this purpose, curved beam strength (CBS) experiments are conducted on CFRP 0˚//0˚, and 45˚//-45˚ interfaces. It is found that for CFRP laminates 0˚//0˚ ILTS is significantly higher than the other orientation.

Keywords: ILTS, CBS, CFRP Composite

---

* Corresponding author. Tel.: +905396401254; fax: +903122104250.
E-mail address: coker@metu.edu.tr

10.1016/j.prostr.2019.12.102

1. Introduction

The use of composite structures has been increasing year by year. This attaches importance to failure mechanisms of their structures. Delamination, which is a separation of laminates in a composite structure, is one of the main failure mechanisms due to it being the weakest plane in the composite structure having 3% of strength in the fiber direction by Kedward et al. (1989). Being such, interlaminar interfaces are the weakest plane in the composite structure, and their failure can be the reason for a dramatic decrease in load-carrying capacity in curved beam structures.

Initiation and propagation of delamination are controlled by interlaminar strength and fracture toughness, respectively. Interlaminar tensile strength (ILTS) is a property that determines the initiation of delamination through the direction of the thickness. There are several methods to assess ILTS in the literature. The direct load method and 3-point bending method to measure ILTS are compared by Hara et al. (2012). They recommend a 3-point loading method because of easy production and simple calculation method in comparison to the direct load method, which has stress concentration, multi-axial stress creation, and volume effect problems. As a result, the volume effect on ILTS was clearly shown in this study. Moroni et al. (2018) measured ILTS of co-cured and co-bonded CFRP joints with the direct load method. Cui et al. (1996) compared methods using a direct load specimen, diametrical compression disk, a semi-circular/elliptical specimen, a ring/curved beam specimen, an L-beam specimen, pure moment on curved beam and a four-point curved beam specimen. They suggested a different type of curved beam strength (CBS) specimen, which is loaded with pure moment load as per the ASTM standard D6415/D6415M (2013). This Four-Point curved beam method has an advantage for both specimen production and test set-up. Additionally, the CBS specimen is an appropriate choice for a volumetric comparison. As it is mentioned, there are three primary test types, which are the direct load test, 3-point bending test, and the CBS test. Firstly, less material is needed to produce the CBS specimen. Secondly, they are close in thickness to real structures. Finally, there is no stress concentration and alignment problems compared to the direct load method. Therefore, the best method is the CBS test. Thus, many studies about ILTS used CBS specimens. Yet, the CBS experiment is not only for determining ILTS but also is related to the max load-carrying capacity of the L shaped composite under pure moment load. Some studies compared CBS values of different lay-up orientations however these do not show the ILTS values of the different interfaces.

Curved beam test studies to measure ILTS are reviewed in this section. Hao et al. (2012) investigated thickness and curved beam radios/thickness effect on ILTS value, which decreases with an increase in thickness that is a volumetric effect. Even though different angle-ply lay-ups were used in the study, all delaminations were found to occur at 0/0 interfaces. According to the author, the reason is that the fracture toughness of the 0/0 interface is lower than the other interfaces. However, comparing the ILTS values with fracture toughness is not applicable. Moreover, some studies tried to produce stronger interface properties. The effect of carbon nanotubes was studied by Arca (2014). Interestingly ILTS is decreased by the addition of carbon nanotubes, while fracture toughness increased. Hence these results show that ILTS is not always related to fracture toughness. Stitching is another way of strengthening the interlaminar properties as shown by Ranz et al. (2017) whilst the thickness effect is demonstrated by three different thickness CBS specimens. Stitching, which is done in the center of CBS specimen where max interlaminar tensile strength is created, is very effective on ILTS values. Up to 40% increase is founded on thin specimens. In addition, ILTS values are profoundly affected by specimen production, which is mentioned by Seon et al. (2013). It can change with porosity, fiber resin ratio, geometric quality of the specimen, and types of resin-fiber.

Consequently, delamination failure is important in composite components such as curved beam, tapered beam and beam under impact loading where interlaminar tensile stresses play an important role in their failure by Murri et al. (1998), Gulasik and Coker (2014), Armanios and Parnas (1991), and Celik and Parnas (2017). Kedward et al. (1989) also give the example of interlaminar failures and emphasize that this must be solved in the design process to prevent future failures. Hence, it is crucial to use the correct values of these interface parameters in the design and analysis of these components. To the best of authors' knowledge, the interlaminar strength of composite laminates with different ply orientations has not been studied. In this paper, CBS experiments are conducted on CFRP 0/0, and 45/-45 interfaces in order to find the ILTS of these interfaces.

2. Experimental Procedure

2.1. Specimen Preparation

The main composite part for five specimens was produced in an autoclave with prepreg carbon and glass unidirectional composite layers using the hand lay-up technique. $[\pm\Theta]_{20}$ lay-up configuration was used for carbon specimens with Θ=0, and 45. During the lay-up process, layers were compacted after placement of every three layers. After the final vacuum process, the curing process took place in an autoclave. The autoclave worked with 6 bar pressure and 0.45 bar vacuum pressure. Specimens were cured at 120 ℃ in the autoclave for 2 hours in the chamfer. Then, the cured part was cut using a water jet cutter into 25mm wide pieces in order to prevent edge cracks, which occurs when a CNC machining process is applied. The carbon specimen is seen in Figure 1. The thickness of the specimen is 5 mm, and the length of the legs is more than 90 mm. The specimen has a 6.4 mm inner radius of curvature

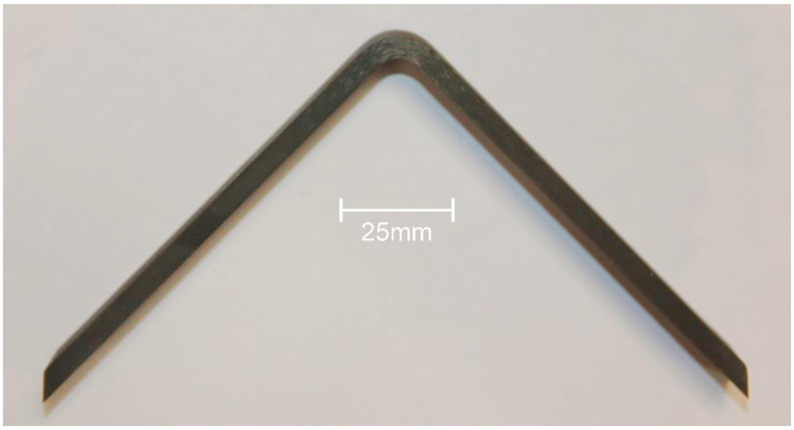

Fig. 1: CBS Specimen

Before the experiment, according to ASTM standard D6415/D6415M (2013), the specimen can be painted with a white color in order to see cracks and delaminations on the specimen. However, each lamina and matrix crack could not be examined with a microscope with the white color. For this reason, specimens in this study were sanded and polished for microscopic investigation. However, the process was not done for all specimens because it is a time-consuming process.

2.2. Experimental Protocol CBS

According to the ASTM D6415/D6415M standard (2013), a CBS specimen was loaded with the pure moment using a Shimadzu 10 kN test machine. The experimental set-up prepared according to the standard is seen in Figure 2. The standard suggests a fixture which has four rollers that are supported between bearings. These bearings help rollers to rotate during the deformation of CBS specimen. The fixture is aligned with a ±0.05 mm error of the roller's locations. Error in the fixture can lead to uneven stress distribution through the thickness and change the initial delamination location. There are two essential dimensions for rollers; one is l_t, which is a distance between the top roller, and the second is l_b, which is a distance between the bottom roller. The standard suggests l_t= 75 mm and l_b=100 mm. Loading was applied with 0.5mm/min stroke speed using a 10 kN Shimadzu electro-mechanic test machine. Load and displacement values were taken from the machine at 20 *Hz*. The experiment was continued until the load drop when the delamination, which had occurred, reached 50% of the max load. After the load drop, specimens were unloaded at the max speed of the machine.

Fig. 2: Experimental Set-up

2.3. Post-Processing of data CBS

The CBS experiments showed ILTS of the delaminated interfaces. Dimensions were used in the formulation as shown in Figure 3. l_t is the top roller's distance which is 75 mm in length. l_b is the bottom roller's distance which is 100 mm in length. ϕ is the angle of one leg with respect to the ground which was initially 45°. It is an important parameter that is calculated from the stroke of the machine (d_y). D is the diameter of the fixture, which was 8 mm for the fixture. P is the load, which was read from the machine load cell.

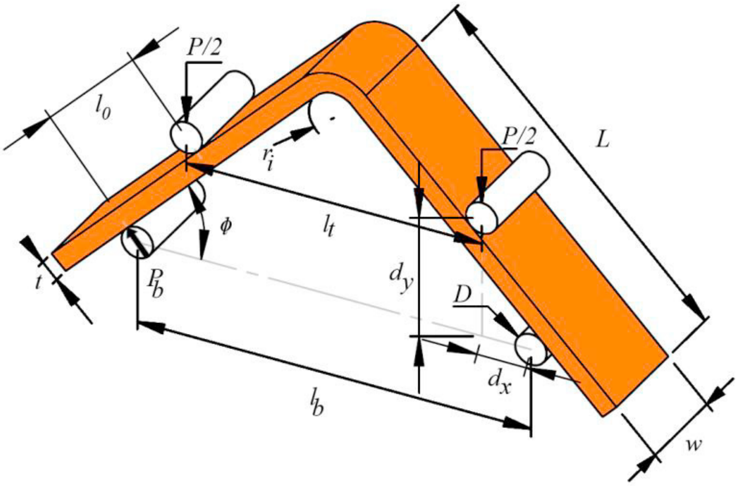

Fig. 3: Dimensions of the specimen and the fixture

When the first delamination occurs as a huge load drop in the load-displacement graph, the max load right before the delamination is taken as a P (load) in the formulation in 1 and 2. r_i is inner, and r_o is an outer radius of the CBS specimen and t is the thickness of the specimen. ILTS is calculated from the CBS of the specimen at first delamination.

$$CBS = \frac{M}{w} = \frac{P_b I_0}{w} = \left(\frac{P}{2w\cos\phi}\right)\left(\frac{d_x}{\cos\phi} + (D+t)\tan\phi\right) \tag{1}$$

$$ILTS = \sigma_r^{\max} = \frac{3CBS}{2t\sqrt{r_i r_o}} \tag{2}$$

3. Result

3.1. Results for [0]$_{40}$ lay-up

As it is mentioned in the method section, [0]$_{40}$ CFRP CBS specimens are loaded with a four-point bending fixture. A pure bending moment is applied to specimens. Load-displacement plots for three specimens tested are shown in Figure 4. Slopes of curves in the elastic region are seen to be almost the same. However, failure loads are observed to be changing from 3500 N to 4500 N. The failure, which is in the form of delaminations, shows itself with a load drop of about 3000 N for all specimens. These load drops correspond to more than 75% of max loads. Because of that, immediately afterwards, the test was stopped since the ASTM standard recommends the loading to continue until a 50% load drop is reached. ILTS is defined as the value which corresponds to the initiation of delamination and CBS is calculated based on the first load drop. ILTS is calculated by using CBS as given in the ASTM standard (2013). From the specimens used in this test program, ILTS was calculated, on average, to be 87.6 MPa.

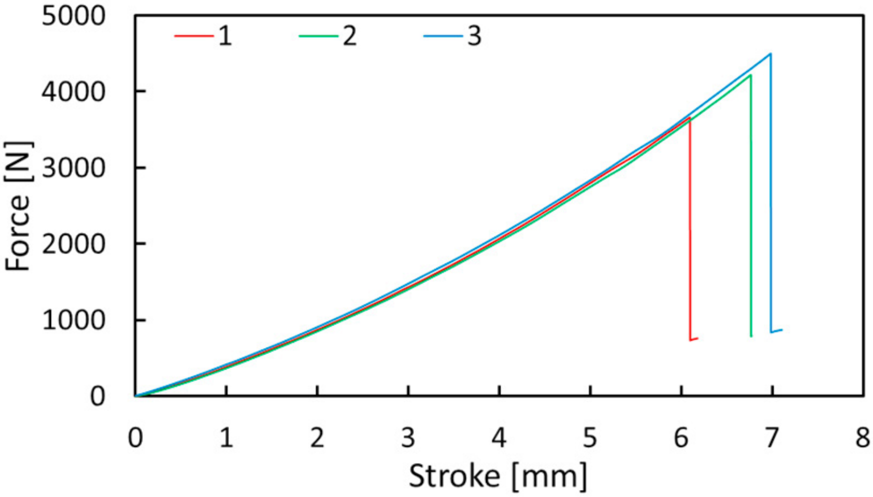

Fig. 4: Load-displacement graph for [0]$_{40}$ CFRP CBS specimens

One of the reasons for the variation in the maximum load values is suggested to be due to the manufacturing defects in CBS specimens. ILTS is a property that is known to be dependent on production parameters. There is a certain nonlinearity before failure, which comes out as a function of angle Φ. There is a difference between the load

P_b which is forming the bending moment and load P, which is measured by the machine. It is represented by the following formula;

$$P = 2P_b \cos\phi \tag{3}$$

In the majority of three tests, multiple delaminations were observed which occurred during the first load drop. They can be clearly seen in Figure 5 along with a picture of their microscopic views. In microscopic pictures, however, ply interfaces that are supposed to be resin rich cannot be clearly identified. This is not unusual for 0-degree laminates with similar volumetric fiber ratios.

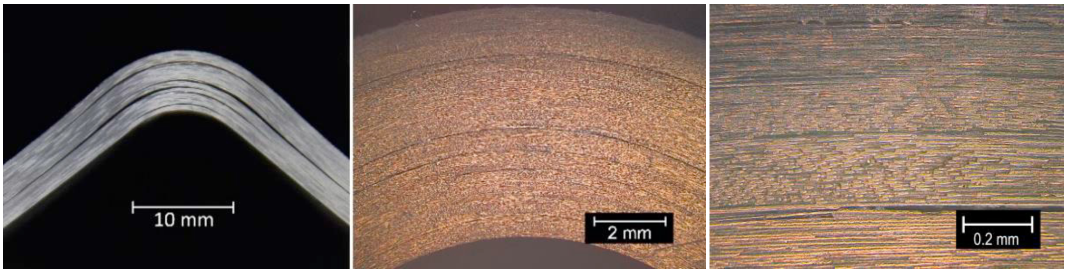

Fig. 5: Delamination onset picture and microscopic views of a $[0]_{40}$ CFRP specimen

3.2. Results for $[\pm 45]_{20}$ lay-up

These specimens are similarly loaded with the four-point bending fixture where geometric parameters l_t and l_b are the same as in Figure 3. For this set of specimens, the load-displacement curves show very similar patterns in terms of maximum load, slopes, and load drops as given in Figure 6. The load drops are from about 3000 N and to about 750 N for all specimens. After the first load drops, the loading is stopped as dictated by the standard (Ref 3) since a 75% load drop is reached.

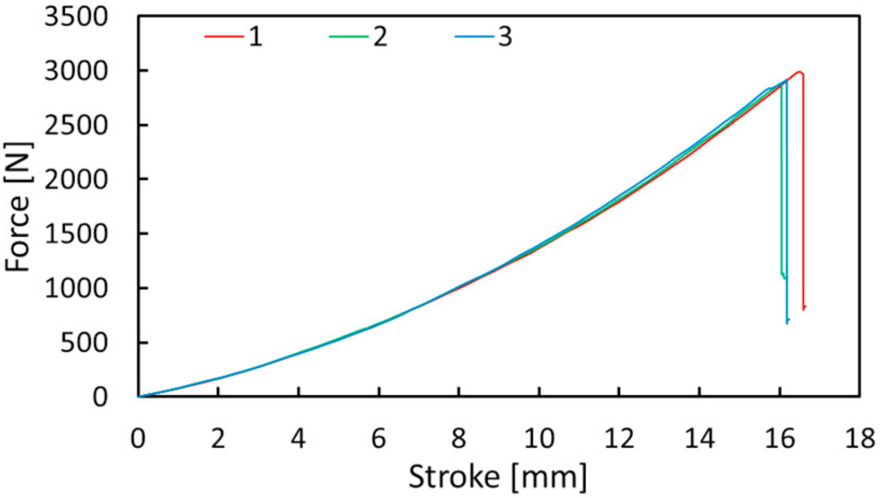

Fig. 6: Load-displacement graph for $[\pm 45]_{20}$ CFRP CBS specimens

Delaminations occur at higher displacement values compared with $[0]_{40}$ specimens. There is also a similar non-linearity in stiffness before failure. However, it is more significant since deformations to failure are higher in this case which corresponds to lower Φ angles.

Multiple delaminations occurring during the load drop are believed to be the main reason behind the huge stress waves after the delamination. Similarly, CBS values of specimens are calculated based on the maximum load value at the first load-drop. ILTS for these specimens is calculated to be 41.5 MPa on average. The delamination onset and microscopic view are shown in Figure 7. Opposite to the previous case, resin-rich regions at the interfaces can be clearly seen for this specimen.

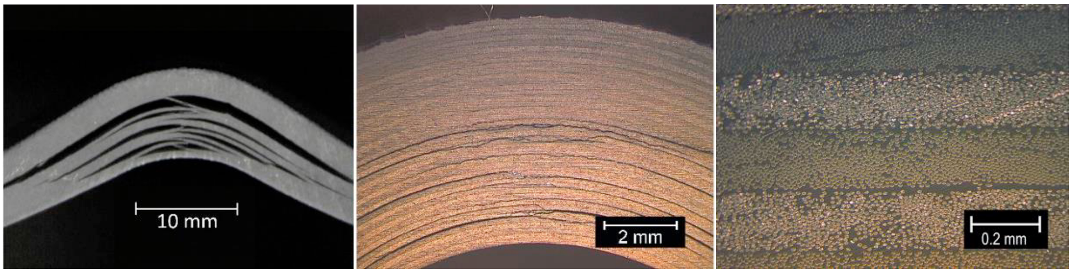

Fig. 7: Delamination on-set picture and microscopic view of [±45]20 CFRP specimen.

According to the ASTM D6415/D6415M standard [Ref 3], the ILTS value has to be calculated at the first large load drop. ILTS and CBS values obtained in this test program for CFRP are presented in Figure 8 for all specimens.

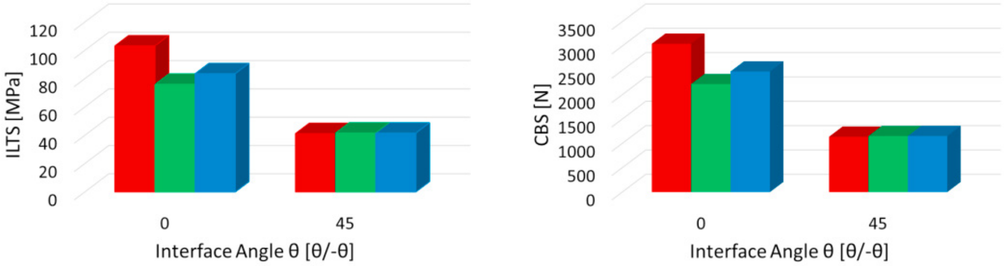

Fig. 8: ILTS and CBS results for CFRP laminates.

4. Conclusion

The interlaminar tensile strength of CFRP for different ply orientations is investigated experimentally. It is found that the 0/0 interface doubles the ILTS of the 45/-45 interface. This difference is attributed to the resin-rich region in the 45/-45 interfaces that is not obtained in the 0/0 interface.

Acknowledgements

This work is supported by the Turkish Aerospace Industries, Inc. by a special grant from The Under secretariat for Defense Industries (SSM) under grant number DKTM 2015/05. The authors would like to thank RUZGEM – METU Center for Wind Energy for the use of their facilities.

References

Arca, M. A., & Coker, D. 2014. Experimental investigation of CNT effect on curved beam strength and interlaminar fracture toughness of CFRP laminates. Journal of Physics: Conference Series,524, 012038. DOI:10.1088/1742-6596/524/1/012038

Armanios, E. A., & Parnas, L. 1991. Delamination Analysis of Tapered Laminated Composites Under Tensile Loading. *Composite Materials: Fatigue and Fracture (Third Volume),3*, 340-358. doi:10.1520/stp17726s

ASTM International, D 6415/D 6415 M, 2013. Standard test method for measuring the curved beam strength of a fiber-reinforced polymer-matrix composite.

Celik, O., & Parnas, L. 2017. Maximization of Ultimate Strength of Unidirectional Tapered Composite Structures Considering Different Failure Modes. *58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. DOI:10.2514/6.2017-0893

Cui, W., Liu, T., Len, J., & Ruo, R. 1996. Interlaminar tensile strength (ILTS) measurement of woven glass/polyester laminates using four-point curved beam specimen. *Composites Part A: Applied Science and Manufacturing,27*(11), 1097-1105. doi:10.1016/1359-835x(96)00071-1

Gulasik, H., & Coker, D. 2014. Delamination-Debond Behaviour of Composite T- Joints in Wind Turbine Blades. *Journal of Physics: Conference Series,524*, 012043. DOI:10.1088/1742-6596/524/1/012043

Hao, W., Ge, D., Ma, Y., Yao, X., & Shi, Y. 2012. Experimental investigation on deformation and strength of carbon/epoxy laminated curved beams. *Polymer Testing,31*(4), 520-526. doi:10.1016/j.polymertesting.2012.02.003

Hara, E., Yokozeki, T., Hatta, H., Iwahori, Y., Ogasawara, T., & Ishikawa, T. 2012. Comparison of out-of-plane tensile strengths of aligned CFRP obtained by 3-point bending and direct loading tests. *Composites Part A: Applied Science and Manufacturing,43*(11), 1828-1836. doi:10.1016/j.compositesa.2012.06.016

Kedward, K. T., Wilson, R. S., & Mclean, S. K. 1989. The flexure of simply curved composite shapes. *Composites, 20*(6), 527-536. doi:10.1016/0010-4361(89)90911-7

Moroni, F., Pirondi, A., Pernechele, C., Gaita, A., & Vescovi, L. 2018. Comparison of tensile strength and fracture toughness under mode I and II loading of co-cured and co-bonded CFRP joints. *Frattura Ed Integrità Strutturale,13*(47), 294-302. doi:10.3221/igf-esis.47.22

Murri G. B., O'Brien T. K., and Rousseau C. Q. 1998, Fatigue life methodology for tapered composite flexbeam laminates, *J. Am. Helicopter Soc.* 43, 146–155.

Ranz, D., Cuartero, J., Miravete, A., & Miralbes, R. 2017. Experimental research into interlaminar tensile strength of carbon/epoxy laminated curved beams. *Composite Structures,164*, 189-197. doi:10.1016/j.compstruct.2016.12.010

Seon, G., Makeev, A., Nikishkov, Y., & Lee, E. 2013. Effects of defects on interlaminar tensile fatigue behavior of carbon/epoxy composites. *Composites Science and Technology, 89*, 194-201. doi:10.1016/j.compscitech.2013.10.006