Parametric Analysis of Interlaminar Toughness of Unidirectional Carbon Fiber and Woven Carbon Fabric Composites

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Abstract—*The present study focusses on the parametrical investigation of unidirectional and woven carbon fiber double cantilever beams subjected to mode I, in order to study its effects on their strength and failure. Different crack lengths as well as width and thickness of the specimens have been analyzed extensively. The maximum normal and shear stresses are found to decrease as the crack length increases for both types of composites. The crack length directly affects the strength of the specimens. A numerical model was developed using the Comsol Multiphysics to predict the failure of double cantilever beams. The crack initiation and progression in the specimens was predicted using the cohesive zone method (CZM) and the delamination at the interface.*

Keywords—fracture toughness, uni-directional, woven fabric, crack propagation, double cantilever beam.

I. INTRODUCTION

The literature review shows that carbon fiber reinforced composites have been widely used in a variety of structural applications in the aerospace, automotive and civil industry [1-19]. High specific modulus (stiffness to weight ratio) and intralaminar tensile fracture toughness [20] are possible the main reasons in the widespread use of these composites. Moreover, the intralaminar tensile fracture toughness is relevant not only to material qualification for the design of composite aerostructures, but also to the definition of the softening laws used in the computational models for predicting the behavior of composite structures [20]. Laminated composite materials made of brittle matrices are susceptible to interlaminar cracks (interlaminar mode of fracture -delamination) and to propagation of that cracks also. Especially low-velocity impact damage and micro-cracks formed during manufacturing, service, or maintenance cause to delamination in laminated composite materials. It is interesting to note that**,** the performance evaluation of the advanced reinforcing fibers such as carbon [21,22], and epoxy resins [23–26], in final composite is necessary for their safe application, especially for the manufacturing of large light weight structures[3, 5-7].

For the composites of interest, the delamination process is typically brittle. Cracks in the form of delaminations and disbonds are the most common failure modes observed in composite structures [27].One approach to solve this problem involves the use of three-dimensional woven and braided reinforcements [28-32]. Fiber stitching [33] or architected adhesives [34] are also alternative methods for solving such problems. It should be mentioned that interlaminar fracture resistance [35, 36] remains a weakness of polymer composites. Such property indicates the amount of stress required to propagate a pre-existing thin crack. On the other hand, damage tolerance is the desired basic property for various structures depending upon the end application [37]. A more systematic and theoretical analysis is required for fracture toughness characterization of composites which is still on the way of growth as compared to metals.

Several theories have been proposed to composites, some focusing on the fracture toughness associated with fibre-dominated tensile failure [38-42], others on the fracture characteristics of composite laminates and developed a fracture criterion which showed that the critical stress intensity factor for fibre failure is a material constant [43], as well as the tensile intralaminar fracture toughness of woven composite laminates [44]. Woven fiber reinforcement is typically used in applications where multidirectional laminates are required (ship hull). It should be mentioned that woven fabric composites exhibit relatively unstable crack growth compared to unidirectional laminates [45, 46]. Unstable crack growth in woven fabric composites can be observed as the crack jumps between transverse tows. Woven fabrics tend to have heavier tows (e.g., higher filament count) than unidirectional reinforcement. Another parameter that affects the fracture toughness is the width of the specimen which does not affect the fracture toughness of unidirectional composites [47]. Moreover, for the case of woven composites, further investigation is needed to determine size effects of woven fabric composites on fracture toughness.

Unidirectional composites and woven fabric composites are physically different in that the individual fibers are bonded in unidirectional composites, whereas fiber bundles or tows are bonded in woven fabric composites. Fora heavy woven fabric composite, the number of tows per specimen width will depend on where the specimen is cut from a panel, which can result in an increase in variability. Several existing studies in the broader literature have examined the variability of fracture toughness in woven fabric composites [48, 49]. Toughening mechanisms in heavy woven fabric composites vary from the mechanisms exhibited in unidirectional laminates. Unidirectional laminates undergo significant fiber bridging when subjected to mode I fracture; [50] however, the weave in woven fabric composites limits the amount of fiber bridging which can occur [45]. Other toughening mechanisms include the presence of inclusions and resin-rich areas. Energy can be stored behind a transverse tow as it acts like an inclusion within the laminate, causing the crack to deviate from the mid-plane of the fracture specimen. The amount of energy capable of being stored behind each tow is highly variable due to thickness variations in the woven fabric. Additionally, it is possible for resin-rich areas to form in a regular pattern as a result of the weave structure. The result is unstable crack propagation for woven fabric composites made with heavy woven fabrics. Research has shown that both the thickness and location of the end of the film used to create the initial crack within the laminate can affect the observed fracture toughness at onset [51, 52].

It is well known, that the critical strain energy release rate (SERR) occurs immediately before crack growth and is commonly defined as G_c. Fracture toughness of laminated composite materials under static loading has been shown to be dependent on the relative amounts of G_I and G_{II} [53]. Mixity is typically used to describe what portion of the total SERR comes from G_I and G_{II} and is defined as the ratio of G_{II} to G_T. The G_c value at which the delamination essentially starts to spread differs largely depending on the mode of loading [**16**]. As the material is being tested and the crack begins to propagate, the stiffness and force on the material begin to decrease. The decrease in the load means that the strain energy stored in the material is also reducing or being released.

Finite element method has become the most popular numerical method for delamination modelling. Virtual Crack Closure Technique (VCCT) and Cohesive Zone Method (CZM) are mainly used to predict delamination growth. These techniques have potential to solve contemporary problems in components of the strain energy release rate.In comparison with other techniques; VCCT has the advantage of analyzing crack propagations in laminated composite materials with brittle matrix. The literature review shows that VCCT can be used to characterize of mode I delamination growth [54, 55]. Some authors [56] have also suggested that VCCT can be used to simulate mode I delamination growth even though the technique exhibits significantly overestimated critical strain energy release rate. Moreover, Bonhomme et al. [57] investigated mode I interlaminar fracture toughness of carbon/epoxy composite by using a two-step numerical method similar to the VCCT.

The use of cohesive zone method was introduced by Barenblatt [58] and Dugdale [59]. A difference between these methods can be attributable to the nature of materials (brittle and ductile). Barenblatt method removes stress singularity at the crack tip (in atomic scale), while Dugdale introduce the concept that stresses in the material are confined by the yield stress. That means, a plastic zone is generated in front of the crack tip.This method as well as VCCT can be used in 2D and 3D problems [60, 61]. The most difficult part for this method is the size of the FE mesh, which increases the time and the cost of the analysis. Furthermore, it suffers from convergence problems. In order to reduce the cost, is to use beam finite element elements instead of plane solids to model the bulk material of the specimens in 2D analysis of delamination [62, 63], but it will suffer from convergence problems and spurious oscillations. A cohesive zone model is frequently used in various types of materials and applications [64, 65, 66], but the traction-separation law must be defined (shape, cohesive strength, and fracture toughness).

A large number of existing studies in the broader literature have examined models such as traction-separation based on an exponential form, a trapezoidal form and the bilinear form [65]. The most difficult part is the direct measurement of these parameters by the experimental procedure. This is the reason that numerical analysis was based on an idealized cohesive zone model [64, 67, 68]. For instance, Turon [68] used bilinear cohesive zone model to estimate these parameters, while the effects of the cohesive law on ductile crack propagation was investigated by Yuan and Li [69].

The aim of this research is to investigate parametrically the effects of crack length on the double cantilever beam while the width and thickness of the sub laminates varies.

II. MATERIALS AND METHODS

2.1 Joint Configuration and Materials

The "testing" configuration was based on the ASTM standards D5528-13 for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites. It is well known double cantilever beam is the most widely used test configuration for the study of crack propagation and arrest for composite materials and adhesives. In this context, in order to investigate the influence of crack length on the DCB specimen, four different crack lengths (a_o) were used: 10, 20, 30 and 40mm. The lever length was kept constant at 44.5mm for all the configurations while the specimen's width (W) was varied from 20mm to 25mm. Similarly, the thickness (t) of the two sub-laminates also varied from 1.5mm to 1.75mm, respectively (figure 1). Moreover, two different types of composites were adopted in the present parametrical procedure. Firstly, the unidirectional carbon epoxy composite and secondly the woven carbon epoxy composite, where the mechanical properties are shown in table 1.

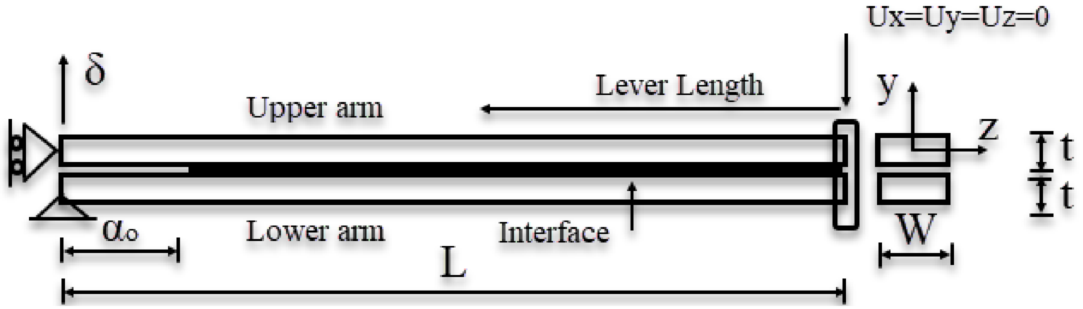


FIGURE 1: A test specimen configuration.

TABLE 1
MATERIALS PROPERTIES FOR (A) UNIDIRECTIONAL CARBON FIBER, (B) WOVEN CARBON FIBER COMPOSITES.

Property	Unidirectional CF/Epoxy	Woven CF/Epoxy
{ρ, kg/m^3}	{1570}	{1570}
{E_1, E_2, E_3, GPa}	{122.7, 10.1, 10.1}	{59.5, 7.46, 7.46}
{v_{12}, v_{23}, v_{13}}	{0.25, 0.45, 0.25}	{0.035, 0.31, 0.035}
{G_1, G_2, G_3, GPa}	{5.5, 3.7, 5.5}	{5.18, 5.18, 5.18}
{G_I, G_{II}, kJ/m2}	{0.969, 1.719}	{0.252, 0.665}
{Benzeggagh-Kenane}	{2.84}	{2.89}

III. FINITE ELEMENT METHOD

3.1 Model Parameters and Loading

The numerical analyses were performed in the Comsol Multiphysics software based on the boundary finite element. To reflect the real behavior of DCB samples during numerical tests on lines (3D) corresponding to the piano hinge locations, the boundary conditions were assumed. In our case, the boundary conditions are shown in figure 1. The displacement was constant at 0.006m, which held constant for all cases. The size of the element was 1/10, in order to reduce the computation time as well as the oscillations [70]. The minimum increment time step allowing to achieve satisfactory results has been set at 0.001 which is a value about ten times higher than the value assumed in [71].

The interfacial failure in the specimens was simulated by using the cohesive zone method, where the behavior is described in terms of a traction-separation equation (figure 2). According to figure 2, the cohesive zone method is based upon the assumption that cohesive bonding exists between two separated surfaces and progressive events of failure (along 0A-AC) are governed by a reduction of stiffness of interface between the two surfaces [72, 73]. The complete fracture obtains at point C (D_i=1).

Furthermore, it is assumed that the penalty stiffness (K_{nn}, K_{ss} and K_{tt}) was kept constant for all modes (10^6 N/mm^3) [70]. By keeping the penalty stiffness equal to 10^6 N/mm^3, the overall stiffness of the specimen is not affected by the applied displacement. A linear degradation was used for the damage evolution in which the Benzeggagh-Kenane (BK) fracture criterion [73, 74] was employed to define the mix mode softening of the cohesive surface, while a quadratic stress criterion was considered (t_n, t_s and t_t are the interface strength). It should be noted that t_n must be positive (intension) to initiate the delamination at the interface. The normal strength and the shear strength for unidirectional and woven carbon/epoxy composites are {80MPa, 30MPa}and {100MPa, 60MPa}, respectively.

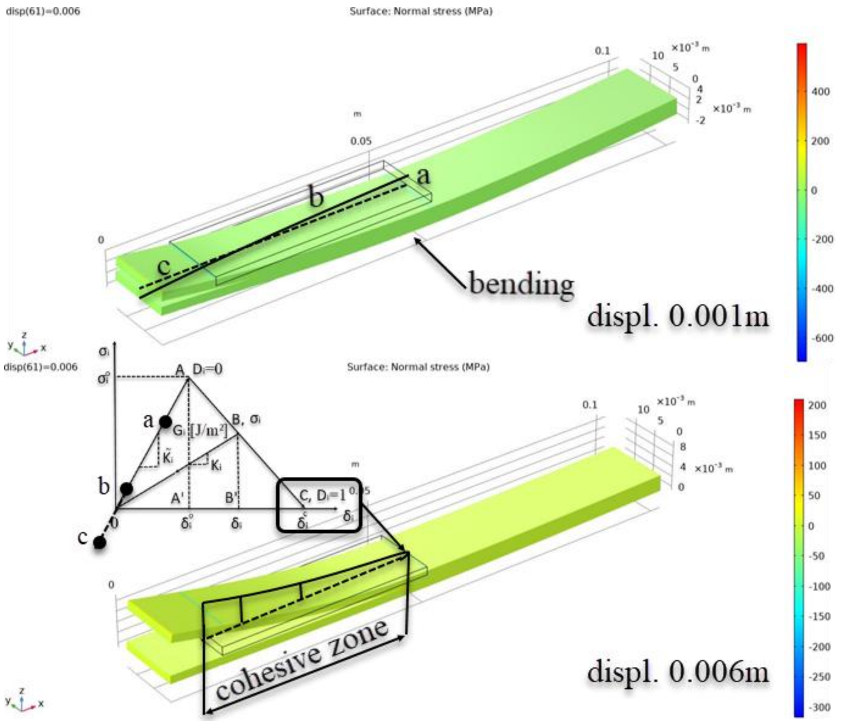
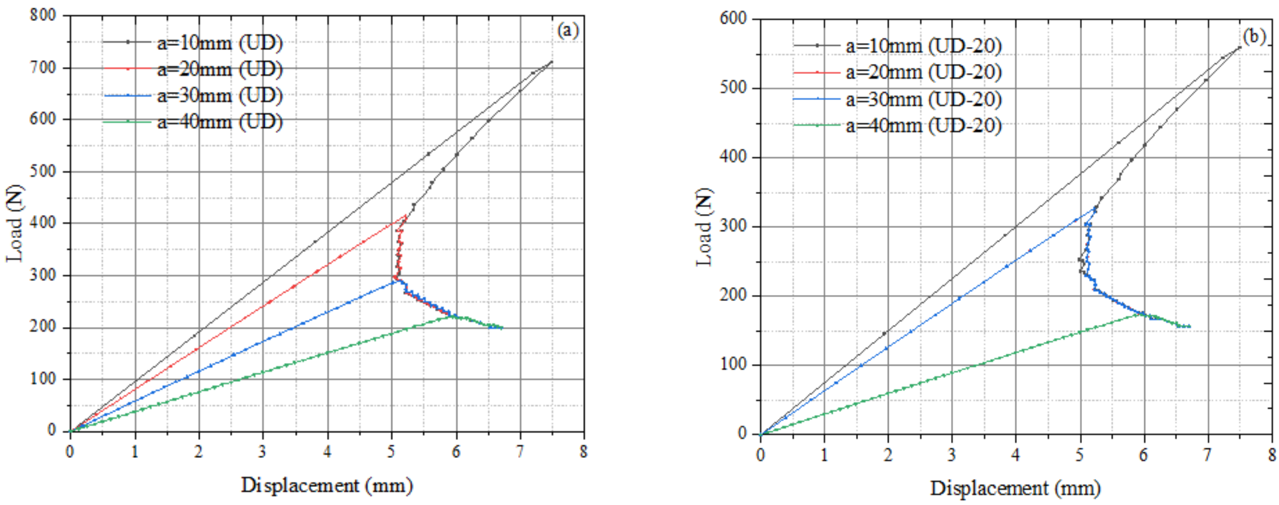


FIGURE 2: Traction-separation law

IV. RESULTS AND DISCUSSION

Fig. 2 a-d and 3 a-d presents the load-displacement curves for unidirectional carbon/epoxy and woven carbon epoxy composite specimens for different crack lengths, width, and thickness of the sub laminates. A significant effect of the crack length can be observed, independently to the type of the material. Crack initiation appears where the first change of the slope in the diagrams is visible. The load-displacement curve shows that the load increases up to a certain point. After that point, it gradually decreases for both cases. To be more specific, in the case of unidirectional composites an average 69.5% decrease of the load can be observed when increasing the crack length from 10 to 40 mm. For the case of the woven composites is almost 70.5%. The value of displacement is chosen in a way that the specimens remains elastic everywhere.

However, the effect of geometric nonlinearity on the mode I fracture toughness of composite materials is suffice for long cracks [75, 76]. However, according to Figures 2a-d.there must be a limit of the crack length in double cantilever beams, especially for unidirectional composites. In other words, it is more benefit to manufacture specimens with crack length up to 20mm (figure 2d and d). Such limits must be defined by the selection of the appropriate normal and shear strength behavior and the geometry of the specimen. Further on, to avoid the sawing teeth in load-displacement curves, a finer mesh should be employed.



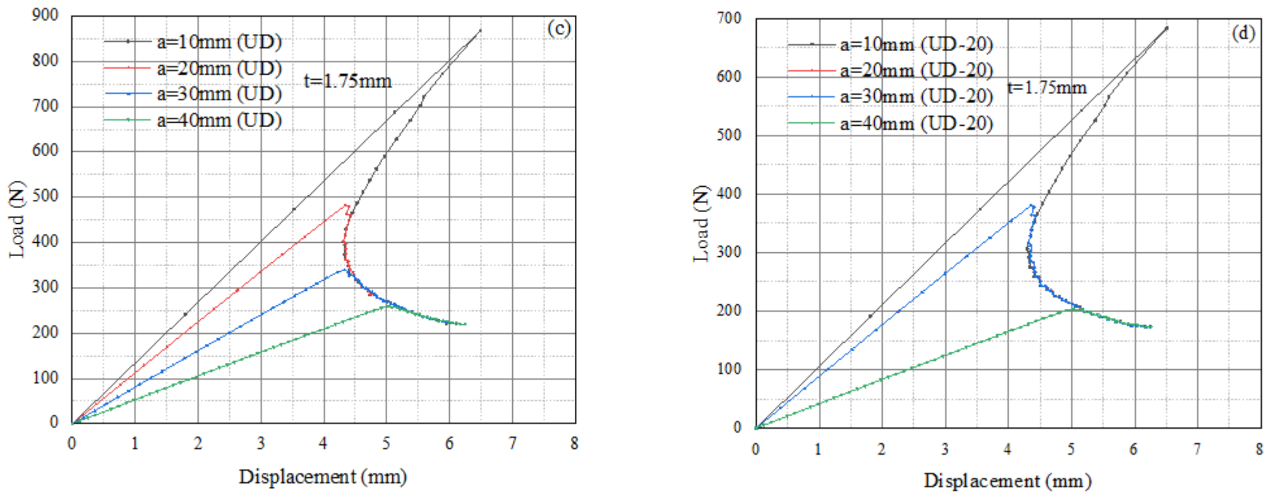


FIGURE 3: Load - Displacement curves for unidirectional carbon epoxy composites with different crack lengths of model with : case a) t=1.5mm and w=25mm, case b) t=1.5mm and w=20mm, case c) t=1.75mm and w=25mm, and case d) t=1.75mm and w=20mm.

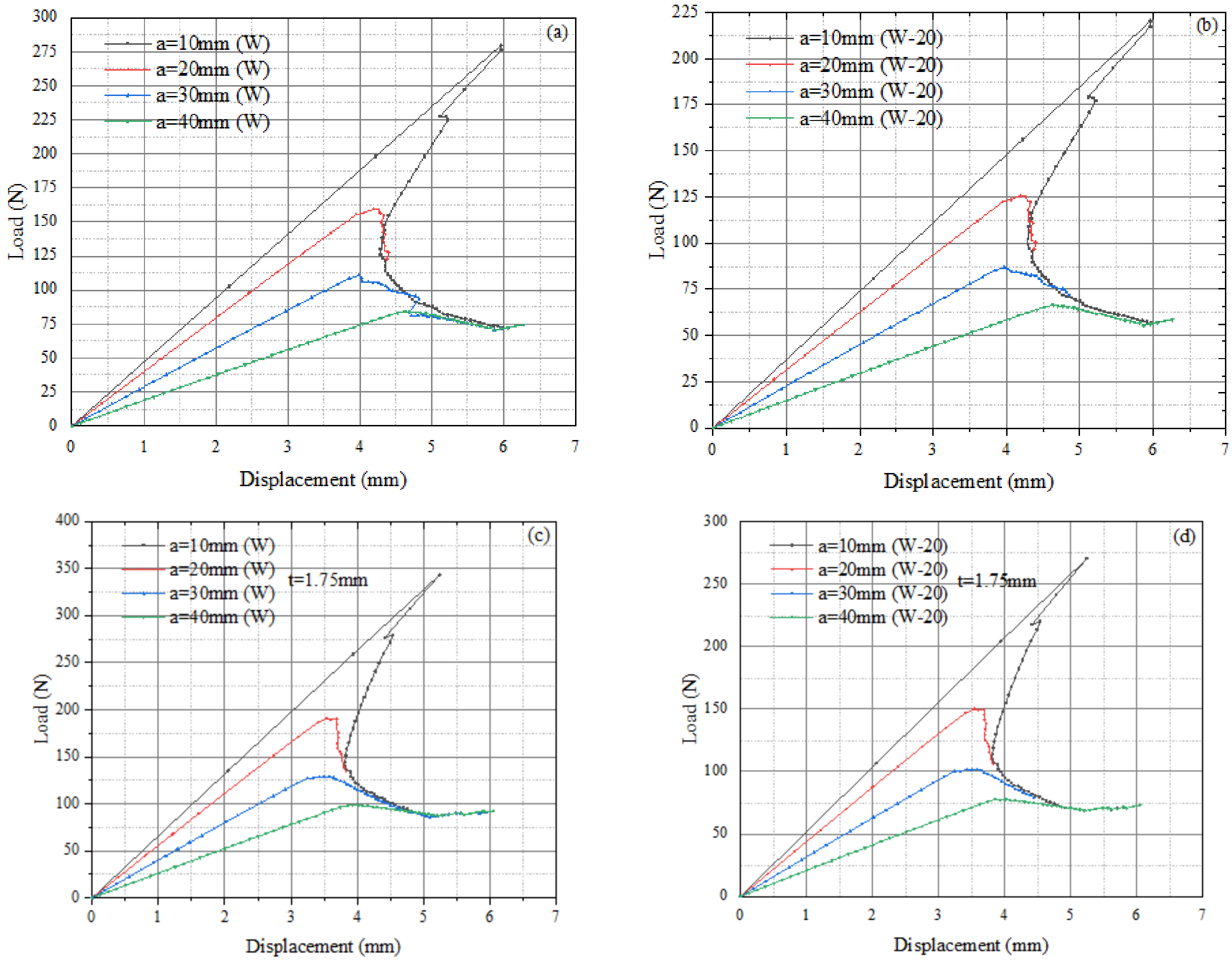


FIGURE 4: Load - Displacement curves for unidirectional carbon epoxy composites with different crack lengths of model with : case a) t=1.5mm and w=25mm, case b) t=1.5mm and w=20mm, case c) t=1.75mm and w=25mm, and case d) t=1.75mm and w=20mm.

As one increases the crack length, the averaged normal stress between these two types of materials is decreased by 59.29% for the cases a and b, and 99.30% for the cases c and d, respectively (averaged). On the other hand, the averaged shear stress is further reduced at the surface of the sub-laminate, by 38.02% for the cases a and b, and 99.93% for the cases c and d, respectively (table 2).

TABLE 2
UNIDIRECTIONAL CARBON/EPOXY AND WOVEN CARBON/EPOXY COMPOSITES RESULTS: NORMAL STRESS AND SHEAR STRESS [MPa].

Crack Length	10 mm		20 mm		30 mm		40 mm	
Normal Stress	UD	W	UD	W	UD	W	UD	W
a	52.88	21.34	52.85	21.52	52.82	21.63	53.36	21.22
b	52.80	21.58	52.79	21.70	52.79	21.89	52.95	21.41
c	46.30	0.32	46.30	0.33	46.29	0.33	46.31	0.33
d	46.36	0.32	46.36	0.33	46.36	0.32	46.37	0.32
Crack Length	10mm		20mm		30mm		40mm	
Shear Stress	UD	W	UD	W	UD	W	UD	W
a	68.83	42.37	68.87	42.52	68.72	42.61	68.99	42.28
b	68.38	42.59	68.38	42.69	68.38	42.84	68.52	42.45
c	66.10	6.64	66.10	6.69	66.07	6.64	66.16	6.67
d	66.43	6.68	66.41	6.74	66.41	6.65	66.50	6.64

The results show that unidirectional laminates undergo significant fiber bridging when subjected to mode I fracture; [50] however, the weave in woven fabric composites limits the amount of fiber bridging which can occur [45]. The width of the specimens is another parameter that affects the fracture toughness of woven composites, but not for unidirectional composites [47]. Moreover, woven fabric composites exhibit relatively unstable crack growth compared to unidirectional laminates [45, 46].

Unstable crack growth in woven fabric composites can be observed as the crack scratches or jumps between transverse tows (fig. 5). Scratches means, load drops at the interface, which will be decreased or disappear due to the presence of the fiber bridging phenomenon [77]. Based on the traction-separation law, a new crack is formed once the critical force value is exceeded. This also means that subsequently a new critical force (but lower) must be surpassed again at the time of next crack propagation. It is hence necessary to accurately capture such progress of failure in a smooth manner. The bending of sub-laminates drastically changes both the normal stress and shear stress concentrations at the interface (fig. 2 and 6).

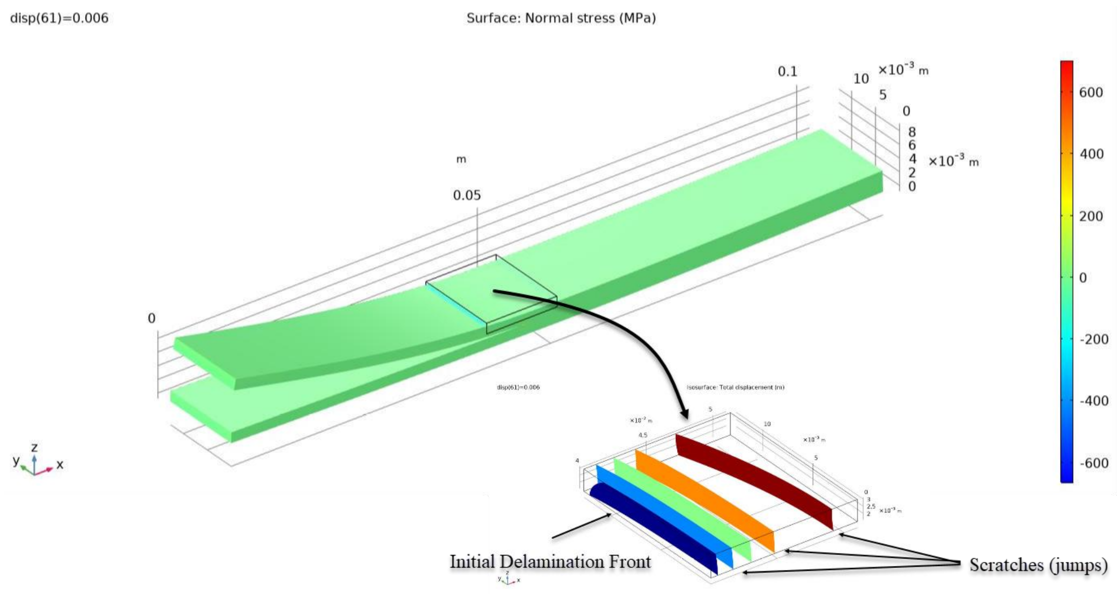
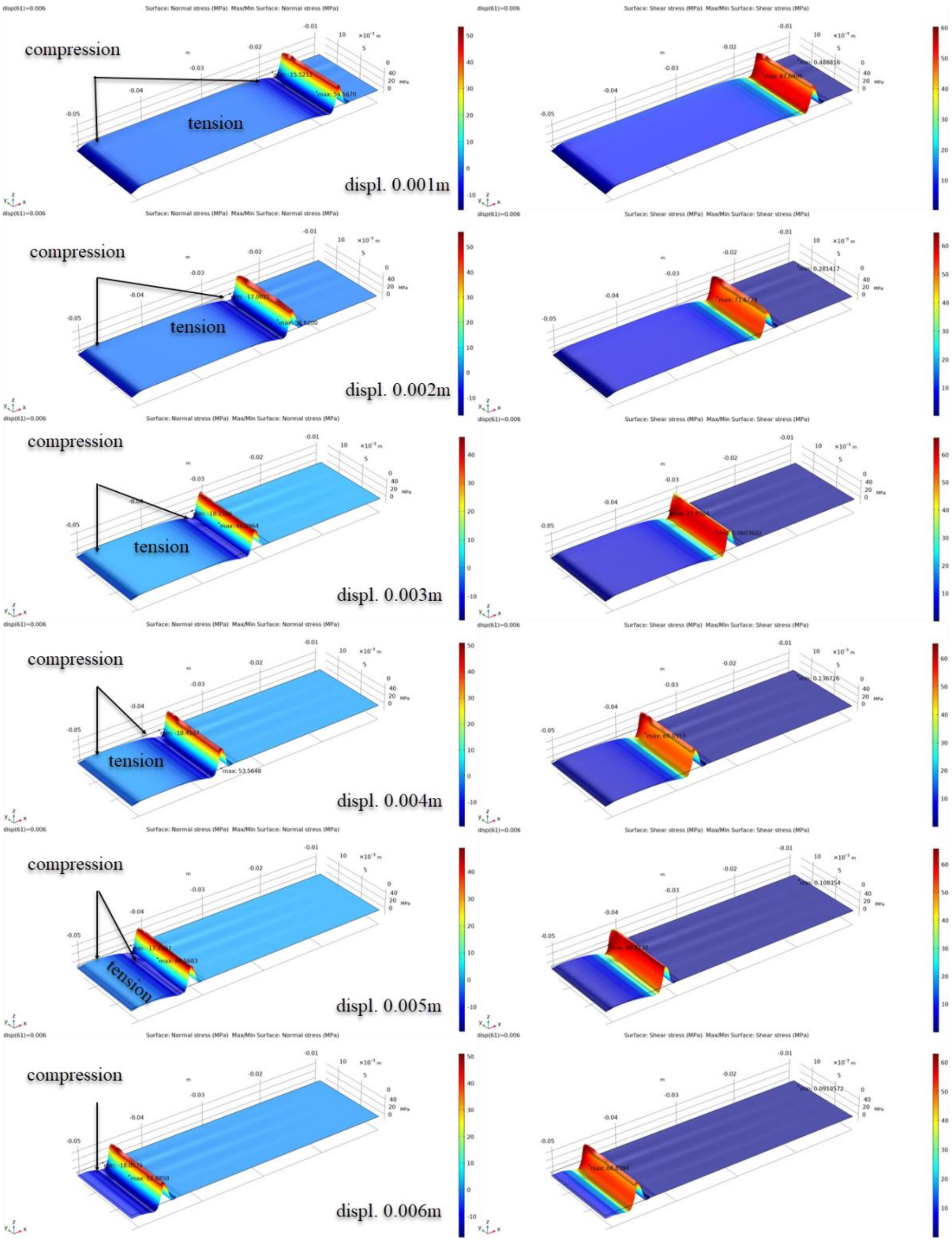


FIGURE 5: Scratches (jumps) on the surface of the sub-laminate.

According to figure 6, on the length of the interface area exists where composites is under compression for all unidirectional carbon epoxy. But not for the case of woven composites. A comparative study of normal and shear stress variations for different crack lengths is made; it can be observed that, as the crack length increases, the maximum shear strength decrease in interface (table 2). Taking into account all these, the area where the normal stresses (tensile) appear is always confined almost to the ends of the cohesive zone. It exceeds typically 0.005m from the edge of the lever length for different crack lengths. This means that normal stresses are much more localized and are introduced mainly by the rotation and bending of the sublaminates. However, for woven composites (figure 7) shows that the maximum normal and shear stresses appears at the lever length. This difference is may be due to the amount of bridging, or to the amount of energy capable of being stored in the specimen.



(a) (b)

FIGURE 6: Normal (a) and shear (b) stress distribution at the interface, crack length of 10mm (unidirectional carbon/epoxy, case a) [MPa].

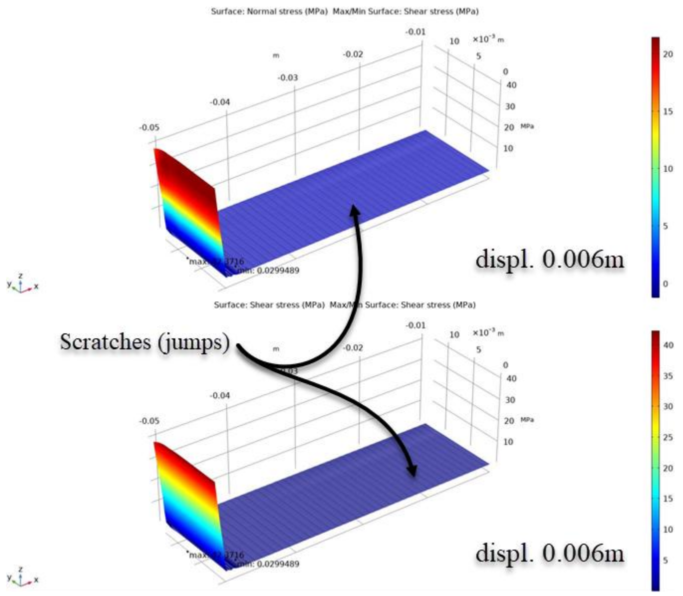


FIGURE 7: Normal (a) and shear (b) stress distribution at the interface, crack length of 10mm (woven carbon/epoxy, case a) [MPa].

V. CONCLUSION

As already mentioned, double cantilever beam is the most widely used test configuration for the study of crack propagation and arrest for composite materials. In this study, the following conclusions can be made,

- The durability of the double cantilever beam is affected by the sub-laminate surface quality and the service loads.
- There must be a limit of the crack length in double cantilever beams, especially for unidirectional composites.
- To avoid the sawing teeth in load-displacement curves, a finer mesh should be employed.
- The width of the specimens affects the fracture toughness of woven composites, but not for unidirectional composites.
- Unstable crack growth in woven fabric composites can be observed as the crack scratches or jumps between transverse tows.
- The bending of sub-laminates drastically changes both the normal stress and shear stress concentrations at the interface.

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