MULTISCALE FINITE ELEMENT ANALYSIS OF DELAMINATION GROWTH IN A DOUBLE CANTILEVER BEAM SPECIMEN MADE OF WOVEN FABRIC COMPOSITE

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Abstract

Delamination growth in a double cantilever beam (DCB) specimen made of a five harness satin weave fabric composite is simulated by a multiscale finite element model in order to provide a better understanding of toughening mechanism of fabric composites. To accomplish this, a meso-scale model of five harness satin weave fabric composite is placed at the delamination zone in order to model the toughening caused by the fabric structure. R-curves and load-displacement curves from the analyses are compared with those of experiments which agree with the lower bound of experimental results. The numerical results revealed two major types of toughening mechanisms: 1) inter-yarn locking causing stress relaxation at delamination front 2) the creation of sub-surfaces via weft yarn bridging which is observed after the delamination grows. By including and observing these two toughening mechanisms, a more realistic simulation of delamination in fabric composites is achieved.

1 Introduction

Toughening behavior, which implies an increase in total fracture toughness during delamination growth, has been experimentally observed in fabric composites [1, 2]; however, the source of this toughening behavior can not be experimentally determined. In order to shed light on this phenomenon, a multiscale finite element (FE) analysis with Cohesive Zone Material Model (CZM) [3] is used in this study. This model provides information on the state of internal damage during the delamination growth. CZM properties are set based on experimental results on mode I delamination of a double cantilever beam specimen made of a 5-harness satin weave carbon fiber composite.

In this paper, first, experimental results are presented and a hypothesis is put forward relating the toughening mechanisms to the architecture of the fibers. A multiscale finite element model is then created to examine this hypothesis and to study the contribution of different toughening mechanisms. In order to evaluate the effect of the fiber architecture on toughening behaviour, the multiscale model is compared with a homogeneous model of delamination. Comparison of the results obtained from experiment, multiscale FE model, and the homogeneous FE model are used to identify the main toughening mechanisms.

2 Experimental Results on DCB Specimens

Seven Double Cantilever Beam (DCB) specimens similar to what is schematically shown in Figure 1 are used in this study. The specimens are made using resin transfer moulding (RTM) and are tested under pure mode-I delamination [1] following ASTM standard D5528 [4]. The Modified Beam Theory (MBT) is used to calculate the critical energy release rates (G_{IC}) as shown in Figure 1. The significant increase in G_{IC} observed during the first instants of crack growth is believed to rely on the fact that the initial delamination, which has a straight front, requires less energy to develop compared to the developed crack front, which includes a non-straight front and may involve yarn bridging and interlocking. The aim of the finite element analysis presented in the following sections is to validate this hypothesis and to determine the contribution of each mechanism in total fracture energy.

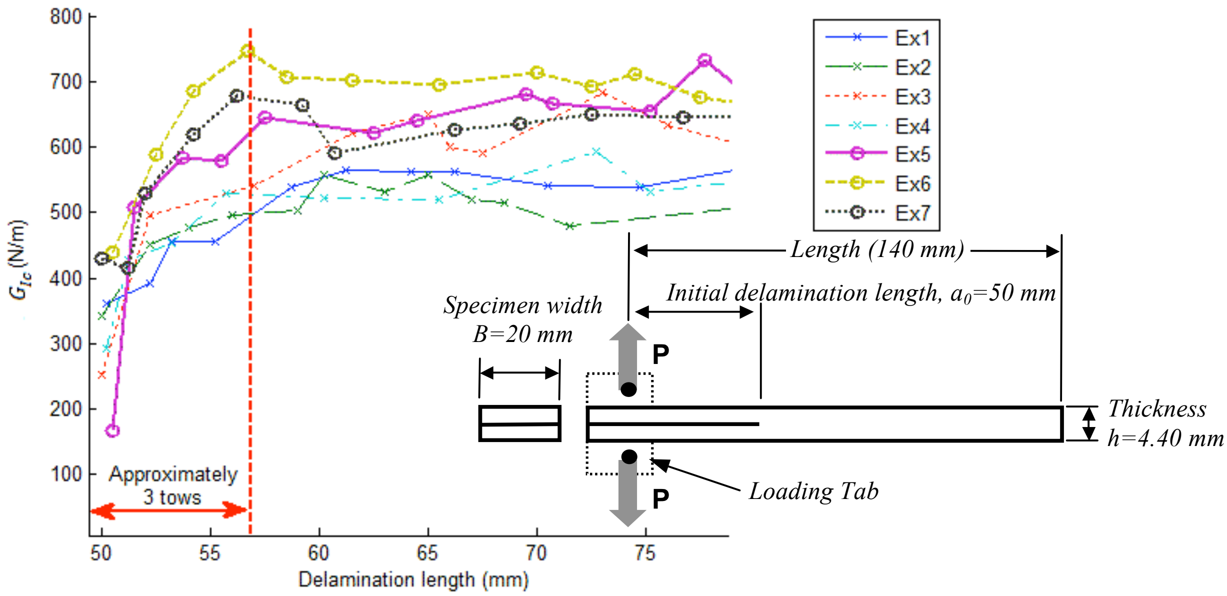


Figure 1. Mode-I critical energy release rate experimentally measured on seven DCB specimens made of 5HS weave carbon fiber composite.

3 Multiscale Modeling of Delamination Growth

Figure 2 shows the multiscale model of the DCB specimen used in this study. In order to reduce the computational time, the length of the non-cracked part of the specimen is shortened to 7 mm (the minimum length required to reach a plateau in G_{IC}, see Figure 1) and the width of the model is reduced to 9.28 mm. In order to study the effect of using a shortened specimen, real-size 2D and 3D plane-stress finite element models are analyzed and appropriate correction factors are derived.

The multiscale model includes a meso-scale model of the 5HS weave fabric composite at the delamination zone and a macro-scale homogeneous model at the regions farther from the delamination path. The homogenous parts are bonded to the meso-scale part through contact elements. To have a smooth transition from meso-scale parts to the homogeneous parts, the initial delamination front is placed at the half-width of the first weft yarn (see Figure 2).

To simulate the crack growth within the specimen, the meso-scale part of the model uses CZM elements with bilinear cohesive material law [5], which is defined by the critical strain energy release rate, G_{IC}, and the maximum normal stress, σ_n. Once the maximum normal stress is attained, the contact elements no longer have cohesive properties, but act as standard contact elements with no friction. Figure 3 shows bilinear cohesive material law and associated parameters used in this study. Similar cohesive properties applied in tangential direction, where the tangential contact stiffness is derived from the following equation:

$$K_{tCZM} = (\sigma_s / \sigma_n)^2 (G_{IC,Matrix} / G_{IIC,Matrix}) K_{nCZM} \quad (1)$$

σ_n and σ_s in this equation are normal and shear strength and G_{IC} and G_{IIC} are the mode I and mode II fracture toughness. Tangential contact stiffness property is defined in Figure 3.

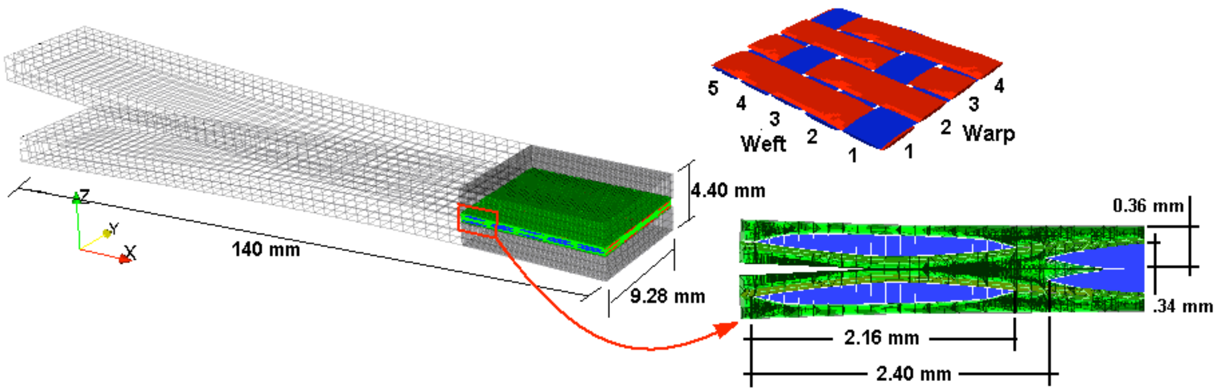


Figure 2. Multiscale FE model of the shortened DCB specimen including the meso-scale model of the fiber structure at the delamination zone.

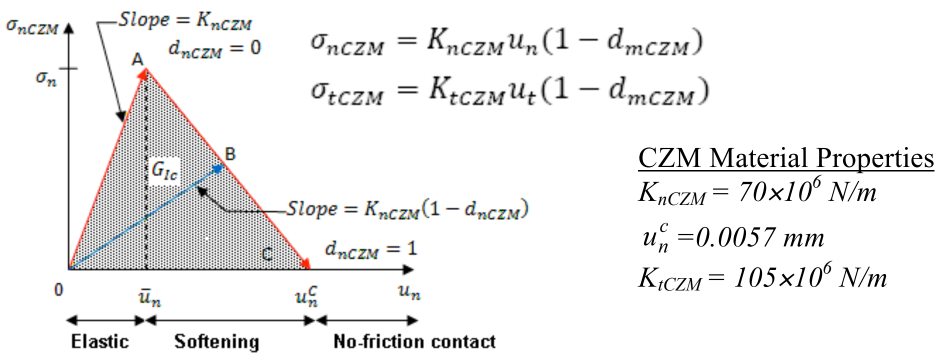


Figure 3. Contact elements used in finite element model and associated stiffness parameters in CZM bilinear material law

The different mechanical properties that are assigned to matrix, yarns and homogenous macro-scale regions are shown in Table 1. Mechanical properties of unidirectional and fabric composites are obtained from unit-cell analysis of a composite with hexagonal packing [6]. The unit-cell analysis assumes perfect bonding between the yarns and matrix, homogenous materials for the yarns, infinite repetition of the unit-cell in all directions, and exclusion of voids and damages. The effect of fiber misalignment on material stiffness is calculated to be less than 3% and is ignored without loss of accuracy.

In order to study the effect of fiber architecture on delamination toughness, a homogeneous finite element model of delamination was also developed. The homogeneous model simulates the DCB specimen as two parts made of homogenous orthotropic materials. The two parts are attached to each other in the non-cracked region using contact element with similar CZM properties used in the multiscale model. The difference between the delamination toughness in multiscale model and homogeneous model is used to identify toughening mechanisms in fabric composites.

Elastic Constant	Cured Epoxy [8]	Carbon Fiber [9]	Unidirectional	5HS fabric
Fiber vol. fraction	0	1.000	0.838	0.55
E11 (GPa)	3.1	230	195	60
E22/E33 (GPa)		22.0	13.7	60/8.73
ν12= ν13	0.3	0.30	0.301	0.0346/0.405
ν23	0.3	0.35	0.348	0.405
G12=G13 (GPa)		22.0	9.22	4.60/2.80
G23 (GPa)		8.15	5.13	2.80
G_{Ic} (N/m)	200			
G_{IIc} (N/m)	$1.5\times G_{Ic}$			
Density (g/cm3)	1.22	1.8	1.706	1.62
σ_n (MPa)	70			
σ_s (MPa)	$1.5\times\sigma_n$			

Table 1. Mechanical properties used in multiscale finite element model

4 Numerical Results

The finite element models are solved using ANSYS 12.0. Figure 4 compares the delamination toughness obtained from multiscale finite element model with the upper and the lower bounds of the experimental results. A good agreement is observed between numerical results and the lower bound of the experimental results. The smoother toughness curves from experiment are due to the limitations in measuring increment. Three major steps in delamination growth (marked by letters A, B and C) are shown in Figure 5.

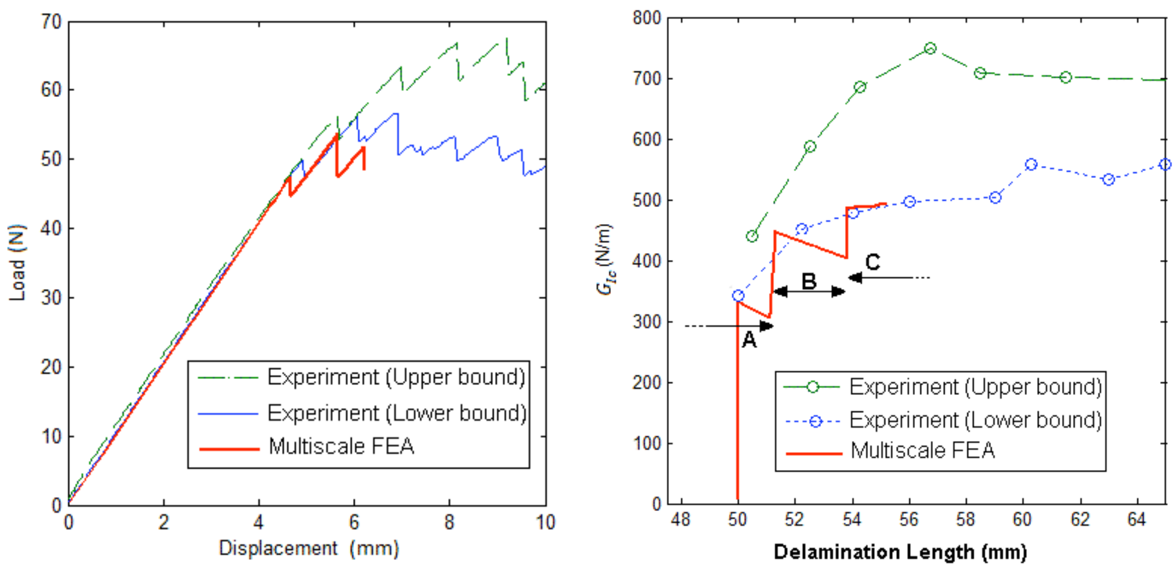
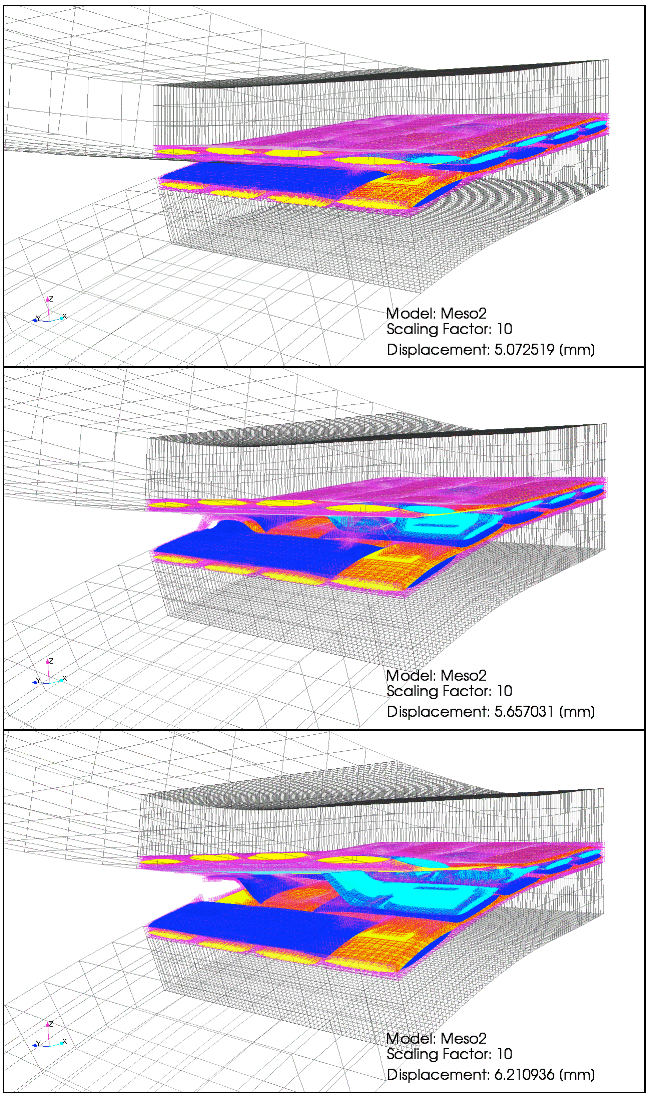


Figure 4. Comparison of load-displacement (left) and delamination toughness (right) during delamination growth in a 5HS composite laminate obtained by multiscale modeling and by experiment

The finite element analysis allows direct calculation of the released energy in the cohesive zone elements by normal and tangential delamination. The results presented in Figure 6 shows that the energy released by the multiscale model is higher than the one released by homogeneous model. The difference indicates the presence of additional energy release mechanisms in the multiscale model that must be related to the fiber architecture. In addition, the difference between the released energy calculated by MBT and CZM in homogeneous model is ignorable, while the difference between these two energies is significant in the multiscale model. These differences are used to identify different toughening mechanisms as follows.



(a) Delamination initiation

(b) Fibers bridging

(c) Extension of delamination

Figure 5. Delamination growth in a 5HS composite laminate simulated using a multiscale finite element model

4.1. Tangential debonding

Since the cohesive elements in the multiscale model are placed around the weft and warp yarns, tangential debonding is always present in multiscale model; however this term is absent in homogeneous model as shown in Figure 6. Contribution of the tangential debonding (U_t) towards total energy released is measured to be around 14% for the 5HS weave fabric composite used in this study.

4.2. Formation of Sub Surfaces

The normal energy released in multiscale model closely agrees with the homogeneous model, except a slight increase in the slope which is observed around delamination length of 53 mm (see Figure 6). The increase is due to the formation of sub-surfaces formed by lifting the weft yarns.

While the delamination is growing in zone B (zones A, B, and C are defined in Figures 5, 6 and 7), the delamination on some warps goes intra-ply, while on the others remains inter-ply. As a result, yarns are bridging between the upper and the lower plies and create extra delamination surfaces which are also observed by X-rays [2]. Measuring the area of the subsurfaces in all cohesive elements identifies the contribution of sub-surfaces towards the total energy released. This contribution is calculated to be around 3% in this study.

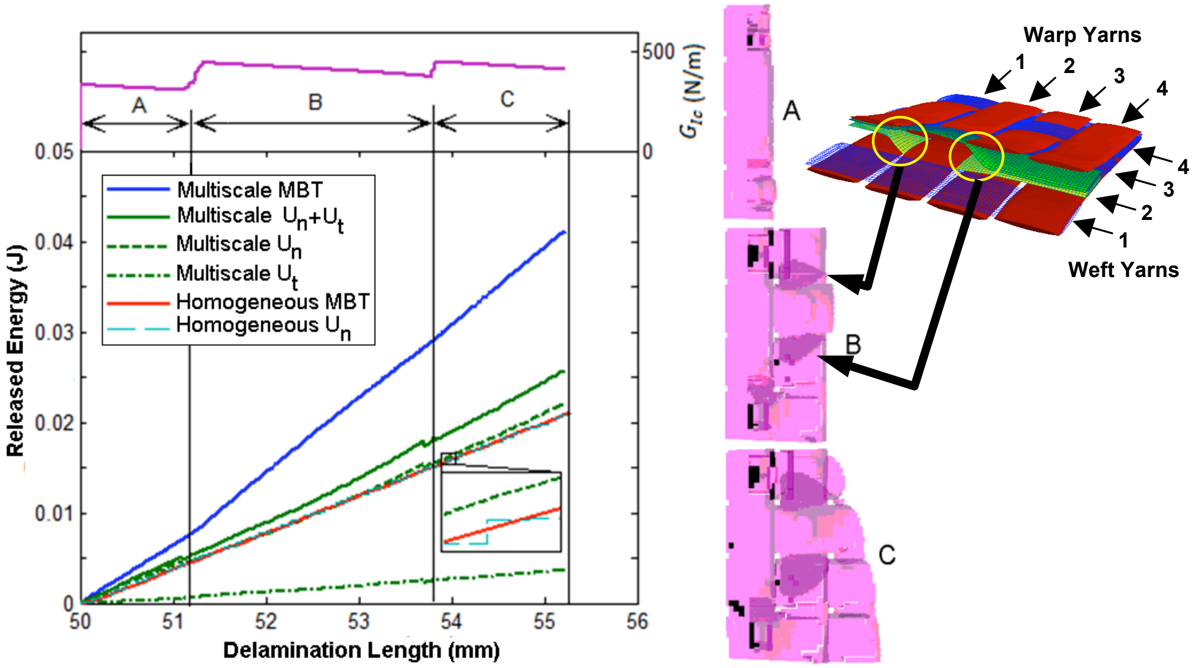


Figure 6. Released energies (left) calculated in different finite element models of delamination growth. Delaminated areas at different delamination zones (right), darker spots show multiple delaminations (formation of sub surfaces), black spots are the elements killed to alleviate convergence difficulties.

4.3. Inter-yarn locking and stress relaxation

Relaxation of stress concentrations ahead of the delamination front caused by inter-yarn locking is another toughening mechanism observed in this analysis. The difference between the released energy calculated by MBT and the one directly obtained from CZM elements (see Figure 6) is caused by this mechanism. The inter-yarn locking can be demonstrated by the presence of a compressive contact pressure at the overlapping area of a warp and a weft yarn. Figure 7 shows the contact stress at an intersection ahead of the delamination front. The contact pressure at the overlapping area consists of a relatively flat compressive pressure. This compressive pressure helps relaxing the separating stresses ahead of the delamination front. This figure also shows a situation where the matrix near an overlap has positive normal stress indicating that the stress concentration due to the delamination front is slightly relaxed forward along warp yarn 3.

The inter-yarn locking ahead of the delamination front plays a significant role in the toughening in zones A and B; however, it does not seem to continue in zone C as weft yarn 3 has no crimping warp yarn. Accordingly, there is no significant amount of inter-yarn locking effect expected ahead of delamination, but the effect of weft yarn bridging gradually appeared at the beginning of zone B and continues into zone C.

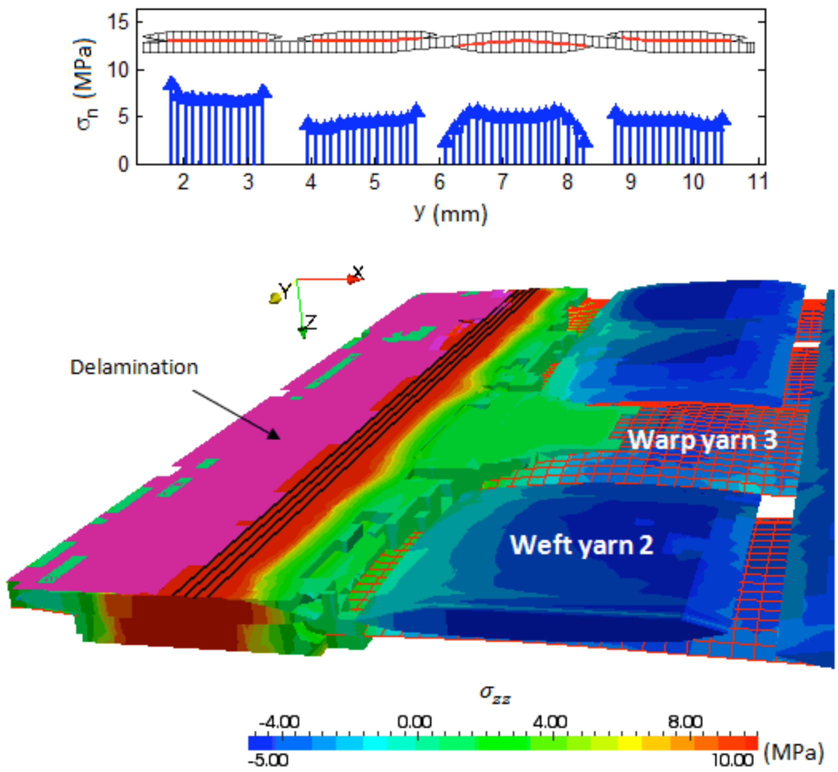


Figure 7. Contact pressure distribution at the overlapping yarns and the effect of this compressive stress in relaxing stresses in the delamination front at warp yarn 3

Weft yarn bridging, an example of which can be seen in Figure 6, not only creates sub-surfaces but also reduces the stress concentration ahead of the delamination front if the arrangement and strength of the bridging fibers allows for their contribution in load carrying between the separating laminates. In the multiscale model studied here, σ_n at the CZM elements located on the warp yarns at the delamination front are in the range of 60 to 70 MPa. This distribution does not seem to show a significant amount of stress relaxation at the delamination front indicating that there is no evidence of stress relaxing due to weft yarn bridging.

4.4. Discussion

In contrast to the conclusion drawn by Alif et al. [7] based on their experimental investigations on a similar composite architecture, the presented multiscale finite element analysis reveals that the weft yarn acting as periodic obstacles for delamination growth is not the main source of the toughening behaviour observed during delamination of fabric composites. In the analysis presented here, the delamination growth was restricted to the paths specified by the embedded CZM elements, which did not include delamination within the weft yarns. The FE model would likely cause delamination arrest by the weft yarn if these yarns would act as obstacles. The model yet is able to closely correlate with the lower bound of the experimental results. The conclusion in [7] was drawn based on experimental results, which are intermittent data on the side edge of the specimen and delamination surfaces. This limited amount of information might have blinded other sources of toughening mechanisms.

Finite element models analyzed here demonstrated a good agreement with the lower bound of the experimental results. The experiments indeed showed more variable damage types, such as fiber breakage that suggests fiber bridging [1, 2] and transverse cracks within the weft yarns [2]. These types of damage are omitted in the FE model in order to clarify the effect of meso-scale structure of the 5HS weave fabric composite. Adding the above-mentioned damage mechanisms may provide a result reaching the upper bound of the experimental results.

5. Conclusions

A multiscale finite element model of a double cantilever beam specimen made of 5HS weave carbon fiber fabric composite was developed in order to study the toughening mechanisms during delamination of this type of composite. The only damage considered in the model is delamination within a pre-defined grid inside the matrix, the interfaces of yarns and matrix, and the interfaces of warp yarns and weft yarns. The cohesive zone modeling element in ANSYS is used with a bilinear cohesive law and material properties of an epoxy resin. Accordingly, there is no consideration of fiber-matrix interaction, transverse matrix cracks within the yarns or fiber breakages within the tows.

The result of the multiscale finite element analysis is in a good agreement with the experimental results and closely correlates to its lower bound, which is predicted as the multiscale finite element model does not consider all possible energy dissipation mechanisms. The model is able to capture a significant amount of toughening caused by the fabric structure and identified two major toughening mechanisms: 1) inter-yarn locking causing stress relaxation at the delamination front and 2) creation of sub-surfaces via weft yarn bridging. The multiscale finite element analysis allowed investigating the delamination growth in detail, which could not be captured by experimental observations.

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