Energy release rate of the fiber/matrix interface crack in cross-ply $[0^\circ_{2kn}, 90^\circ_n]_S$ laminates under transverse loading: debond-bimaterial interface interaction

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Abstract

The effects of crack shielding, fiber content and ratio of 0° to 90° ply thickness on fiber/matrix debond growth in thin cross-ply laminates are investigated with Representative Volume Elements (RVEs) of different ordered microstructures. Debond growth is characterized by the estimation of the Energy Release Rates (ERRs) using the Virtual Crack Closure Technique (VCCT) and the J-integral. It is found that

Keywords: Polymer-matrix Composites (PMCs), Thin-ply, Transverse Failure, Debonding, Finite Element Analysis (FEA)

1. Introduction

Since the development of the *spred tow* technology or "FUKUI method" [1, 2], significant efforts have been directed toward the characterization of *thin-ply* laminates [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] and their application to mission-critical structures in the aerospace sector [16, 17, 18, 19].

At the lamina level, the use of *thin-plies* leads to more regular and homogeneous microstructures but no significant imporvement in static properties except for an apparent improvement in compressive strength [12]. Improvements in fatigue life have been observed, although contrasting results can be found in the literature [4, 5, 6]. The beneficial effect of the use of *thin-plies* with respect to damage propagation has been instead commonly observed by different researchers under static [3, 6, 7, 8, 9, 10, 11, 12], fatigue [4, 6, 7, 8, 12] and impact loadings [6, 7, 8, 12]. It seems apparent that *thin-ply* laminates possess an increased ability to delay, and in some cases even suppress, the onset and propagation of transverse cracks (or matrix or micro-cracks).

The first appearance of transverse cracking phenomena is known to be characterized by the appearance of fiber/matrix interface cracks (also referred to as debonds), which grow along the fiber's arc direction, then kink out of the interface and coalesce forming a transverse crack [20]. Different approaches have been applied to model the initiation and growth of debonds. The Cohesive Zone Model (CZM) has been used to mimic the propagation of debonds along fibers interface; coupled with a failure criterion for the matrix, it has provided simulations of the growth of transverse cracks starting from a virgin material [21, 22, 23, 24]. The main advantages of this approach are the possibility to observe the development of a simulated crack path and to record a load-displacement curve to compare with experimental measurement. However, various observations cast a doubt about the applicability of the CZM: the bi- (for 2D models) and tri- (in 3D) axiality of the matrix stress state in the inter-fiber region that is linked with a cavitation-like failure of the polymer [25]; the locality and mode dependency of the interface failure; the problematic use at the microscopic level of properties measured in UD specimens at the laminate level.

2. RVE models & FE discretization

2.1. Models of Representative Volume Element(RVE)

We start by describing the different idealized micro-structures considered and the corresponding repeating element or RVE used to model them. Fig. 1, Fig. 2 and Fig. 3

2.2. Finite Element (FE) discretization

We describe the model implemented: schematic + description of parameters, formulation (LEFM, frictionless contact, VCCT, J-Integral), implementation of BCs, mesh. Fig. 5

(a) A debonded fiber every 2 fully bonded ones.

(b) Central debonded fiber with 1 fiber each side.

(c) A debonded fiber every 4 fully bonded ones.

(d) Central debonded fiber with 2 fibers each side.

(e) A debonded fiber every 6 fully bonded ones.

(f) Central debonded fiber with 3 fibers each side.

Figure 1: Models of $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminates in which the central 90° ply possesses a single layer of fibers and debonds repeating at different distances (left column), and corresponding Representative Volume Elements (right column) with symmetry applied on the lower boundary line. The interface crack is represented in red.

(a) 3 layers with a central line of debonded fibers.

(b) Central debonded fiber with 1 fiber above.

(c) 5 layers with a central line of debonded fibers.

(d) Central debonded fiber with 2 fibers above.

(e) 7 layers with a central line of debonded fibers.

(f) Central debonded fiber with 3 fibers above.

Figure 2: Models of $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminates in which the central 90° ply possesses a central line of debonded fibers (left column), and corresponding Representative Volume Elements (right column) with symmetry applied on the lower boundary line. The interface crack is represented in red.

We mention the validation of the model with respect to BEM results by referring to the other paper.

3. Results & Discussion

3.1. *Effect of Fiber Volume Fraction*

The effect is similar for all the different BC cases, it's enough to show some of them to exemplify. G_{I} in Fig. 6, G_{II} in Fig. 7.

(a) 3 layers with a debonded fiber every 2 fully bonded ones in the central line of fibers.

(b) Central debonded fiber with 1 fiber on each side and 1 above.

(c) 3 layers with a debonded fiber every 4 fully bonded ones in the central line of fibers.

(d) Central debonded fiber with 2 fibers on each side and 1 above.

(e) 5 layers with a debonded fiber every 4 fully bonded ones in the central line of fibers.

(f) Central debonded fiber with 2 fibers on each side and 2 above.

(g) 3 layers with a debonded fiber every 6 fully bonded ones in the central line of fibers.

(h) Central debonded fiber with 3 fibers on each side and 1 above.

Figure 3: Models of$[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminates in which the central 90° ply possesses multiple layers of fibers with debonds repeating at different distances in the central line of fibers (left column), and corresponding Representative Volume Elements (right column) with symmetry applied on the lower boundary line.

(a) Single layer of debonded fibers inside a cross-ply laminates.

(b) Element with a single debonded fiber and, on the top surface, coupled vertical displacement and linearly distributed horizontal displacement.

Figure 4: Models of $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminates in which fibers belonging to the central 90° ply are all debonded (left column), and corresponding Representative Volume Elements (right column) with symmetry applied on the lower boundary line.

(a) Schematic of the model with its main parameters.

(b) Detail of the mesh in the crack tip's neighborhood.

Figure 5: Details and main parameters of the Finite Element model.

Graphics of ERR vs $\Delta\theta$, one curve for each V_f, one graphic for each selected BC. Selected BC: free, coupling, some examples with fibers (see captions).

(a) Single fiber model with free boundary on top.

(b) Single fiber model with coupling of vertical displacements along the upper boundary.

(c) 1 fiber each side.

(d) 1 fiber above.

(e) 5 fibers each side.

(f) 5 fibers above.

(g) 10 fibers each side.

(h) 10 fibers above.

(i) 1 fiber each side, 1 above.

(j) 3 fibers each side, 1 above.

(k) 2 fibers each side, 2 above.

(l) 5 fibers each side, 2 above.

Figure 6: A view of the effect of fiber volume fraction on Mode I ERR across different models.

(a) Single fiber model with free boundary on top.

(b) Single fiber model with coupling of vertical displacements along the upper boundary.

(c) 1 fiber each side.

(d) 1 fiber above.

(e) 5 fibers each side.

(f) 5 fibers above.

(g) 10 fibers each side.

(h) 10 fibers above.

(i) 1 fiber each side, 1 above.

(j) 3 fibers each side, 1 above.

(k) 2 fibers each side, 2 above.

(l) 5 fibers each side, 2 above.

Figure 7: A view of the effect of fiber volume fraction on Mode II ERR across different models.

3.2. Interaction between debonds in a 90° *ply with a single layer of fibers inside a* $[0^\circ_n, 90^\circ]_S$ *laminate*

We start with a simpler (2 parameters: number of fibers in the horizontal directions + bounding ply thickness) but more extreme model: central 90° ply with one line of fibers. What's the effect on G_I and G_{II}? What's the effect of $0°$ ply's thicknesses? Reference to Kies strain magnification. G_I in Fig. 8, G_{II} in Fig. 9.

One graphic for each V_f (30%,50%,60%,65%) and thickness ratio (1, 10), one curve for each case of fibers on the side (1, 2, 3, 5, 10, 50, 100) + curve for equivalent BC ()(Fig. 8, Fig. 9). Focus is effect of debond distribution in the horizontal direction.

(a) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(b) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(c) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(d) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(e) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(f) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(g) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(h) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

Figure 8: Effect of the interaction between debonds appearing at regular intervals on Mode I ERR in a $[0^\circ_n, 90^\circ]_S$ laminates in which the central $90°$ ply possesses a single layer of fibers at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(b) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(c) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(d) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(e) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(f) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(g) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(h) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

Figure 9: Effect of the interaction between debonds appearing at regular intervals on Mode II ERR in a single-ply laminate with a single layer of fibers at different levels of fiber volume fraction V_f.

One graphic for each V_f (30%,50%,60%,65%) and selected cases of fibers on the side (1, 3, 10), one curve for thickness ratio (1, 10) + curve for corresponding UD model + curve for equivalent BC (vertical displacement coupling+linear horizontal displacement)(Fig. 10, Fig. 11). Focus is effect of thickness of bounding plies.

(a) $V_f = 30\%$, 1 fiber on each side.

(b) $V_f = 30\%$, 3 fibers on each side.

(c) $V_f = 30\%$, 10 fibers on each side.

(d) $V_f = 50\%$, 1 fiber on each side.

(e) $V_f = 50\%$, 3 fibers on each side.

(f) $V_f = 50\%$, 10 fibers on each side.

(g) $V_f = 50\%$, 1 fiber on each side.

(h) $V_f = 50\%$, 3 fibers on each side.

(i) $V_f = 50\%$, 10 fibers on each side.

(j) $V_f = 65\%$, 1 fiber on each side.

(k) $V_f = 65\%$, 3 fibers on each side.

(l) $V_f = 65\%$, 10 fibers on each side.

Figure 10: Effect of 0° ply's thickness on the interaction between debonds appearing at regular intervals on Mode I ERR in a $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminate in which the central 90° ply possesses a single layer of fibers at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$, 1 fiber on each side.

(b) $V_f = 30\%$, 3 fibers on each side.

(c) $V_f = 30\%$, 10 fibers on each side.

(d) $V_f = 50\%$, 1 fiber on each side.

(e) $V_f = 50\%$, 3 fibers on each side.

(f) $V_f = 50\%$, 10 fibers on each side.

(g) $V_f = 50\%$, 1 fiber on each side.

(h) $V_f = 50\%$, 3 fibers on each side.

(i) $V_f = 50\%$, 10 fibers on each side.

(j) $V_f = 65\%$, 1 fiber on each side.

(k) $V_f = 65\%$, 3 fibers on each side.

(l) $V_f = 65\%$, 10 fibers on each side.

Figure 11: Effect of 0° ply's thickness on the interaction between debonds appearing at regular intervals on Mode II ERR in a $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminate in which the central 90° ply possesses a single layer of fibers at different levels of fiber volume fraction V_f.

3.3. Interaction between layers of fully bonded fibers and a centrally located line of debonded fibers in a 90° ply inside a $[0^\circ_n, 90^\circ]_S$ laminate

We then move to a ply with multiple lines of fibers and only debonded fibers in the central one (2 parameters: number of fibers in vertical direction + bounding ply thickness, a bit closer to real plies). G_I in Fig. 12, G_{II} in Fig. 13.

One graphic for each V_f (30%,50%,60%,65%) and thickness ratio (1, 10), one curve for each case of fibers on top (1, 2, 3, 5, 10, 50, 100) + curve for equivalent BC (Fig. 12, Fig. 13). Focus is effect of debond distribution in the vertical direction.

(a) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(b) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(c) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(d) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(e) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(f) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(g) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(h) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

Figure 12: Influence of layers of fully bonded fibers on debond's growth in Mode I ERR in a centrally located line of debonded fibers at different levels of fiber volume fraction V_f and thickness ratios.

(a) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(b) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(c) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(d) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(e) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(f) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(g) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$.

(h) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

Figure 13: Influence of layers of fully bonded fibers on debond's growth in Mode II ERR in a centrally located line of debonded fibers at different levels of fiber volume fraction V_f and thickness ratios.

One graphic for each V_f (30%,50%,60%,65%) and selected cases of fibers on top (1, 3, 10), one curve for thickness ratio (1, 10) + curve for corresponding UD model + curve for equivalent BC (vertical displacement coupling+linear horizontal displacement)(Fig. 14, Fig. 15). Focus is effect of thickness of bounding plies.

(a) $V_f = 30\%$, 1 fiber on each side.

(b) $V_f = 30\%$, 3 fibers on each side.

(c) $V_f = 30\%$, 10 fibers on each side.

(d) $V_f = 50\%$, 1 fiber on each side.

(e) $V_f = 50\%$, 3 fibers on each side.

(f) $V_f = 50\%$, 10 fibers on each side.

(g) $V_f = 50\%$, 1 fiber on each side.

(h) $V_f = 50\%$, 3 fibers on each side.

(i) $V_f = 50\%$, 10 fibers on each side.

(j) $V_f = 65\%$, 1 fiber on each side.

(k) $V_f = 65\%$, 3 fibers on each side.

(l) $V_f = 65\%$, 10 fibers on each side.

Figure 14: Effect of 0° ply's thickness on the influence of layers of fully bonded fibers on debond's growth in Mode I ERR in a centrally located line of debonded fibers in the central 90° ply of a $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminate at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$, 1 fiber on each side.

(b) $V_f = 30\%$, 3 fibers on each side.

(c) $V_f = 30\%$, 10 fibers on each side.

(d) $V_f = 50\%$, 1 fiber on each side.

(e) $V_f = 50\%$, 3 fibers on each side.

(f) $V_f = 50\%$, 10 fibers on each side.

(g) $V_f = 50\%$, 1 fiber on each side.

(h) $V_f = 50\%$, 3 fibers on each side.

(i) $V_f = 50\%$, 10 fibers on each side.

(j) $V_f = 65\%$, 1 fiber on each side.

(k) $V_f = 65\%$, 3 fibers on each side.

(l) $V_f = 65\%$, 10 fibers on each side.

Figure 15: Effect of 0° ply's thickness on the influence of layers of fully bonded fibers on debond's growth in Mode I ERR in a centrally located line of debonded fibers in the central 90° ply of a $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminate at different levels of fiber volume fraction V_f.

3.4. Interaction of debonds within a 90° ply with multiple layers of fibers inside a $[0^\circ_n, 90^\circ]_S$ laminate

Finally models that are closer to real laminates and are more complex (3 parameters: number of fibers along the horizontal direction + number of layers in the vertical one + bounding ply thickness). G_I in Fig. 16, G_{II} in Fig. 17.

One graphic for each V_f (30%,50%,60%,65%) and thickness ratio (1, 10), one curve for each selected case of fibers on side and on top ([n. on side, n. on top]: [1,1], [2,1], [2,2], [5,1], [5,5], [10,1], [10,10]) + curve for equivalent BC (Fig. 12, Fig. 17). Focus is effect of debond distribution in the horizontal and vertical direction.

(a) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (b) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(c) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (d) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(e) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (f) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(g) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (h) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

Figure 16: Effect of the interaction of debonds within a 90° ply with multiple layers of fibers on debond's growth in Mode I ERR at different levels of fiber volume fraction V_f and thickness ratios.

(a) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (b) $V_f = 30\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(c) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (d) $V_f = 50\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(e) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (f) $V_f = 60\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

(g) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 1$. (h) $V_f = 65\%$, $\frac{t_{0^\circ}}{t_{90^\circ}} = 10$.

Figure 17: Effect of the interaction of debonds within a 90° ply with multiple layers of fibers on debond's growth in Mode II ERR at different levels of fiber volume fraction V_f and thickness ratios.

One graphic for each V_f (30%,50%,60%,65%) and selected cases of fibers on side and on top ([1,1], [5,1], [5,5]), one curve for thickness ratio (1, 10) + curve for corresponding UD model + curve for equivalent BC (vertical displacement coupling+linear horizontal displacement)(Fig. 18, Fig. 19). Focus is effect of thickness of bounding plies.

(a) $V_f = 30\%$, 1 fiber on each side.

(b) $V_f = 30\%$, 3 fibers on each side.

(c) $V_f = 30\%$, 10 fibers on each side.

(d) $V_f = 50\%$, 1 fiber on each side.

(e) $V_f = 50\%$, 3 fibers on each side.

(f) $V_f = 50\%$, 10 fibers on each side.

(g) $V_f = 50\%$, 1 fiber on each side.

(h) $V_f = 50\%$, 3 fibers on each side.

(i) $V_f = 50\%$, 10 fibers on each side.

(j) $V_f = 65\%$, 1 fiber on each side.

(k) $V_f = 65\%$, 3 fibers on each side.

(l) $V_f = 65\%$, 10 fibers on each side.

Figure 18: Effect of 0° ply's thickness on debond's growth in Mode I ERR within the 90° ply with multiple layers of fibers of a $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminate at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$, 1 fiber on each side.

(b) $V_f = 30\%$, 3 fibers on each side.

(c) $V_f = 30\%$, 10 fibers on each side.

(d) $V_f = 50\%$, 1 fiber on each side.

(e) $V_f = 50\%$, 3 fibers on each side.

(f) $V_f = 50\%$, 10 fibers on each side.

(g) $V_f = 50\%$, 1 fiber on each side.

(h) $V_f = 50\%$, 3 fibers on each side.

(i) $V_f = 50\%$, 10 fibers on each side.

(j) $V_f = 65\%$, 1 fiber on each side.

(k) $V_f = 65\%$, 3 fibers on each side.

(l) $V_f = 65\%$, 10 fibers on each side.

Figure 19: Effect of 0° ply's thickness on debond's growth in Mode II ERR within the 90° ply with multiple layers of fibers of a $[0^{\circ}_{n}, 90^{\circ}]_{S}$ laminate at different levels of fiber volume fraction V_f.

4. Conclusions & Outlook

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