Effect of uniform distributions of bonded and debonded fibers on the growth of the fiber/matrix interface crack in cross-ply $[0^\circ_n, 90^\circ]_S$ laminates with different fiber contents under transverse loading

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Abstract

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1. Introduction

The structure is designed to very similar to the paper about UD, i.e. the line of thought is the same but applied to cross-plies. Maybe we could consider the two as part of one big work and call the two articles *Part 1* and *Part 2*. Thoughts?

1. We start with a few lines devoted to the spread tow technology and thin plies: what they are, what can be done, what are the possible applications.
2. By quoting the relevant references, we report on the observation that one of the main beneficial mechanisms in thin ply is the retardation of transverse crack propagation. We then enlarge by reporting the microscopical observations by Saito, in which debonds where also observed. We observe that available microscopic observations are just a few and mainly in 2D.

3. Propagation of transverse cracks has been widely investigated both analytically and numerically
4. Initiation at the level of fiber/matrix interface is instead a less researched subject.
5. cohesive elements are a possible choice, but have some drawbacks, which makes a LEFM approach valuable
6. With regard to LEFM studies of laminates under transverse loading, models can be found in the literature about: the single fiber in infinite matrix under different mode of loading, the effect of adjacent fibers on a fiber in infinite matrix under different mode of loading, the single fiber in an equivalent composite in transverse tension, the effect of adjacent fibers on a fiber in an equivalent composite in transverse tension. We mention these works more briefly.
7. We concentrate a little more on works with cohesive elements, as there is more of them on fiber/matrix interface crack in cross-ply
8. Initiation of transverse cracking at the fiber/matrix interface in cross-ply laminates under transverse tension hasn't been directly addressed with LEFM in the literature. We address this gap with this paper and we focus on (in analogy with the work on UDs): the effect of fiber volume fraction; the interaction of debonded and bonded fibers in micro-structured assemblies, i.e. no homogenization.
9. We conclude the introduction with a summary of the article's structure.

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

(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.

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

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

(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.

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.

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 (1 parameter: number of fibers in the horizontal directions) 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 $[0^\circ_n, 90^\circ]_S$ laminates in which the central 90° ply possesses a single layer of fibers at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$, 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 $[0^\circ_n, 90^\circ]_S$ laminates 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*

3.4. Interaction of debonds in a $90°$ *ply with multiple layers of fibers inside a* $[0^{\circ}_{n}, 90^{\circ}]_{S}$ *laminate*

4. Conclusions & Outlook