Effect of uniform distributions of bonded and debonded fibers on the growth of the fiber/matrix interface crack in UD laminates with different fiber contents under transverse loading

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Abstract

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1. Introduction

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.

5   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.

10   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.

7. For initiation of transverse cracking at the fiber/matrix interface in UD laminates under transverse tension, there is thus a gap regarding: the effect of fiber volume fraction; the interaction of debonded and bonded fibers in micro-structured assemblies, i.e. no homogenization. This article addresses these two points.

8. 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.

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.

2.3. Validation of the model

We mention once in this paper the validation of the model with respect to BEM results.

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(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 single-ply laminates with 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 single-ply laminates with multiple layers of fibers and 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.

(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 single-ply laminates with 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.

(b) Element with a single debonded fiber and free boundary on top.

(a) Single layer of debonded fibers.

(d) Element with a single debonded fiber and coupling of vertical displacements along the upper boundary.

(c) Infinite number of layers of debonded fibers.

Figure 4: Models of single-ply laminates with all the fibers 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.

Figure 6: Validation of the single fiber model for the infinite matrix case with respect to the BEM solution in [].

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

3. Results & Discussion

40 *3.1. Effect of Fiber Volume Fraction*

3.2. Interaction between debonds in UD laminates with a single layer of fibers

3.3. Influence of layers of fully bonded fibers on debond's growth in a centrally located line of debonded fibers

3.4. Interaction between debonds in UD laminates with multiple layers of fibers

45 *3.5. Comparison with the single fiber model with equivalent boundary conditions*

4. Conclusions & Outlook

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

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

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 10: 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.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 11: 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.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 12: 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.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 13: Effect of the interaction between debonds appearing at regular intervals on Mode I ERR in a single-ply laminate with multiple layers of fibers at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 14: Effect of the interaction between debonds appearing at regular intervals on Mode II ERR in a single-ply laminate with multiple layers of fibers at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 15: Comparison of Mode I ERR between the single fiber model with free upper boundary and the multiple fibers model with fibers only on the side at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 16: Comparison of Mode II ERR between the single fiber model with free upper boundary and the multiple fibers model with fibers only on the side at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 17: Comparison of Mode I ERR between the single fiber model with coupling conditions along the upper boundary and the multiple fibers model with fibers above and both above and on the side at different levels of fiber volume fraction V_f.

(a) $V_f = 30\%$.   (b) $V_f = 50\%$.

(c) $V_f = 60\%$.   (d) $V_f = 65\%$.

Figure 18: Comparison of Mode II ERR between the single fiber model with coupling conditions along the upper boundary and the multiple fibers model with fibers above and both above and on the side at different levels of fiber volume fraction V_f.