Finite element modelling of mixed-mode delamination propagation in Abaqus/Explicit with nonlinear cohesive softening laws

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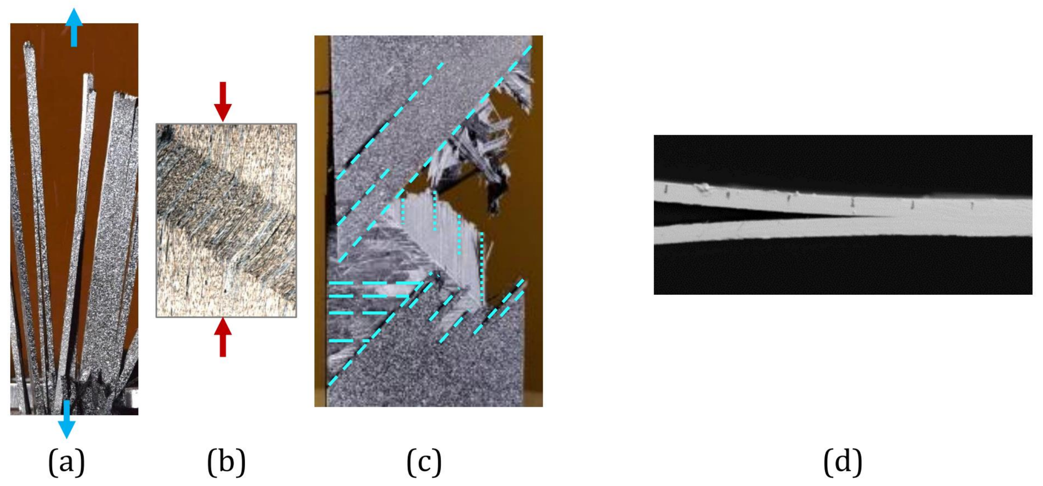
Introduction

- Delamination is an important type of failure in laminate composites, widely used in automotive & aerospace industries, where layers separate
- Onset & propagation of delamination can be predicted via finite element modelling (FEM), with special treatment of the ply-ply interface

▸ Fig. 1: Failure modes in laminate composites. (a) Fiber rupture; (b) Fiber kinking; (c) matrix failure; (d) delamination.



Background

The **Cohesive Zone Model (CZM)** models delamination:

- Non-linear finite elements used between plies
- Cohesive law represents local traction vs crack opening: traction ∝ displacement until critical value, then decreases until it vanishes & element fails
- Load-displacement depends on initial crack length, cohesive properties, traction-separation law shape, mode mixity ratio
- Cohesive law shape arbitrarily complicated; is usually approximated by triangle (elastic deformation, elastic recovery)

A **mixed-mode law** approximates mixed-mode cohesive properties from pure-mode properties:

- Power Law fits rule to data with fitting parameter α:

$$(G_I/G_{Ic})^{\alpha} + (G_{II}/G_{IIc})^{\alpha} = 1$$

- Benzeggagh & Kenane (B-K) Criterion fits rule to data with fitting parameter η:

$$G_c = G_{Ic} + (G_{IIc} - G_{Ic})(G_{II}/G_T)^{\eta}$$

ASTM-standard **Double Cantilever Beam (DCB), End-notched Flexure (ENF)**, and **Mixed-Mode Bending (MMB)** tests load a specimen under pure mode I, pure mode II, or mixed-mode conditions, respectively.

Objectives

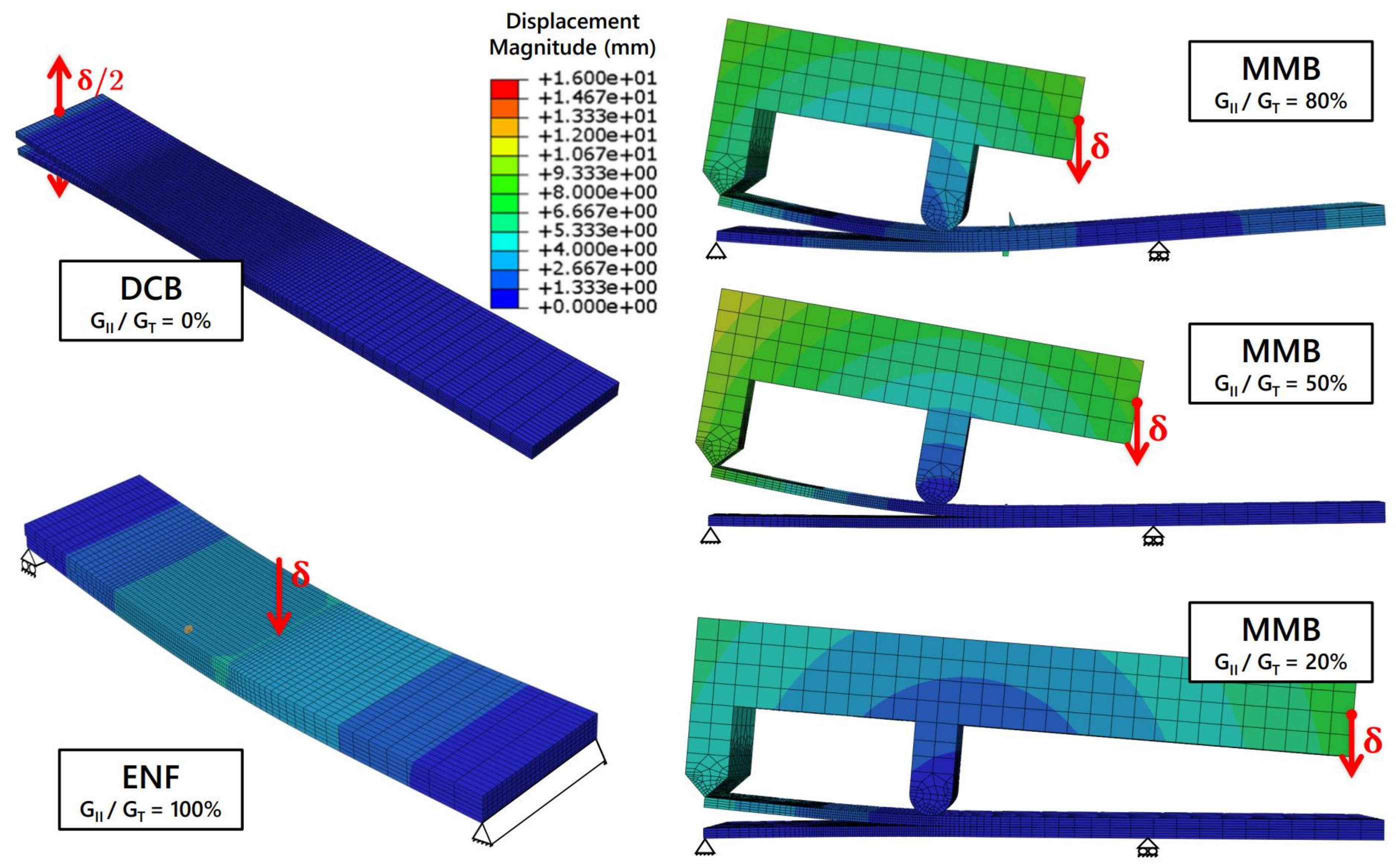
To build and test FEM models implementing CZM across several mode mixity ratios (G_{II}/G_T) in Abaqus, to study cohesive laws shape affect delamination behavior, and to validate a novel mixed-mode interaction formulation.

Methodology

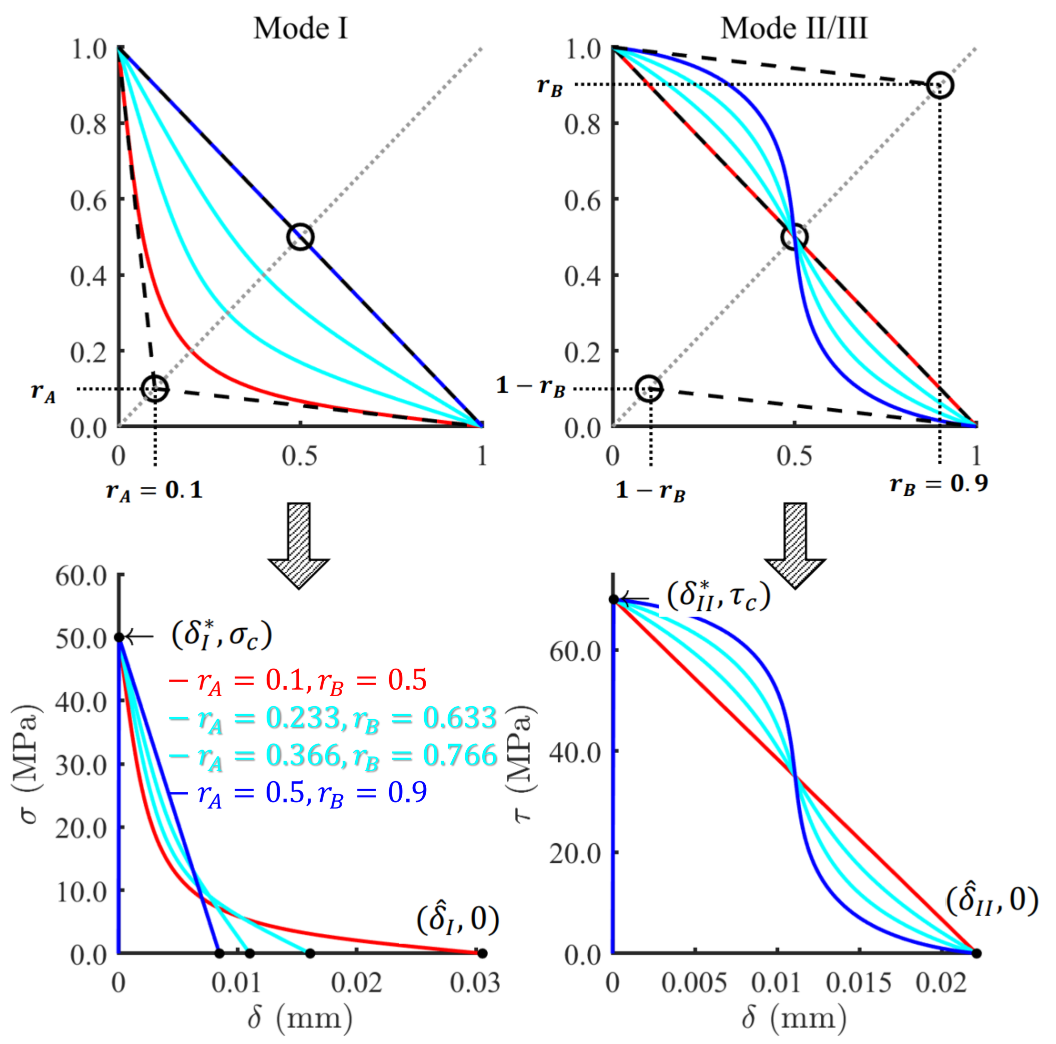
Models of specimens in DCB, ENF, and MMB conditions created in Abaqus/Explicit, for $G_{II}/G_T = 0\%, 20\%, 50\%, 80\%, 100\%$.

- Each ply discretely modelled with thin cohesive layer between laminae. In MMB, loading arm also modelled. See Fig. 2 for BCs.
- Laminae meshed with three C3D8I linear explicit elements through material thickness; cohesive layer meshed with COH3D8
- Parametric studies conducted to determine cohesive properties (strength, stiffness) which led models to best match benchmark results by Krueger, 2015

▸ Fig. 2: Deformed views of the four model geometries in Abaqus. Each model represents a specific mode mixity ratio. Boundary conditions are shown. Note the loading arms in the MMB models.

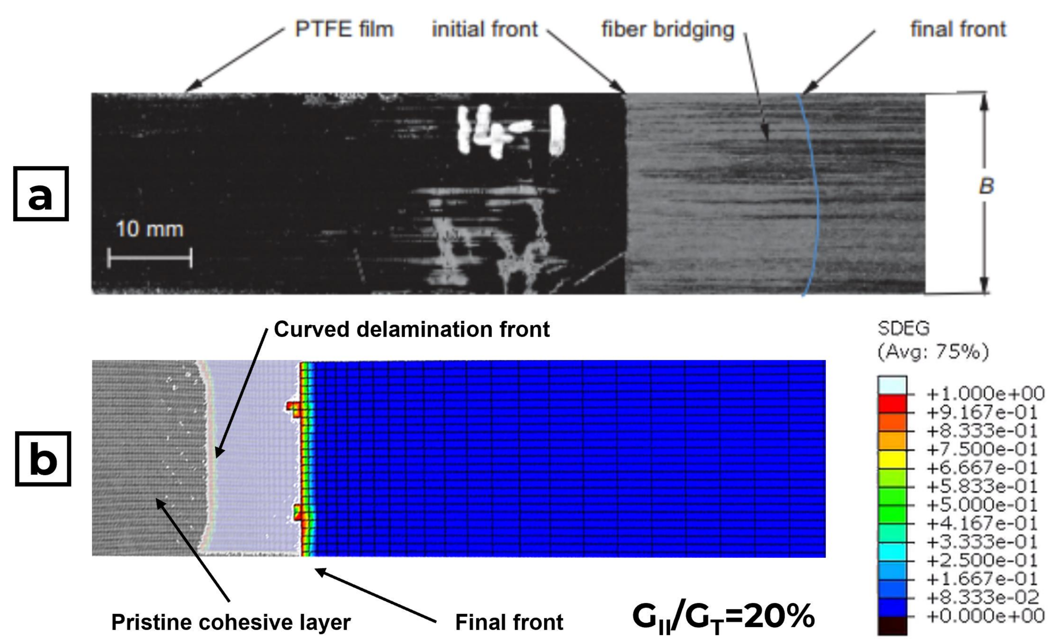


▾ Fig. 3: [Top] Set of Bezier curves used to generalize softening law shape. [Bottom] Cohesive laws based on each Bezier curve.



Cohesive Laws

- Bezier curve allows arbitrary softening law shape based on parameters r_A, r_B (see Fig. 3)
- Assumptions based on experiments by Girolamo et al., 2015: mode II law begins, ends with horiz. tangent, is symmetric; mode I law ends with horiz. tangent.
- Implemented novel mixed-mode formulation sensitive to shape of softening law & based on an effective separation, proposed by Nguyen & Waas, 2021.
- Bezier parameter sweep conducted to find those best matching benchmark, using novel formulation (see Fig. 3)

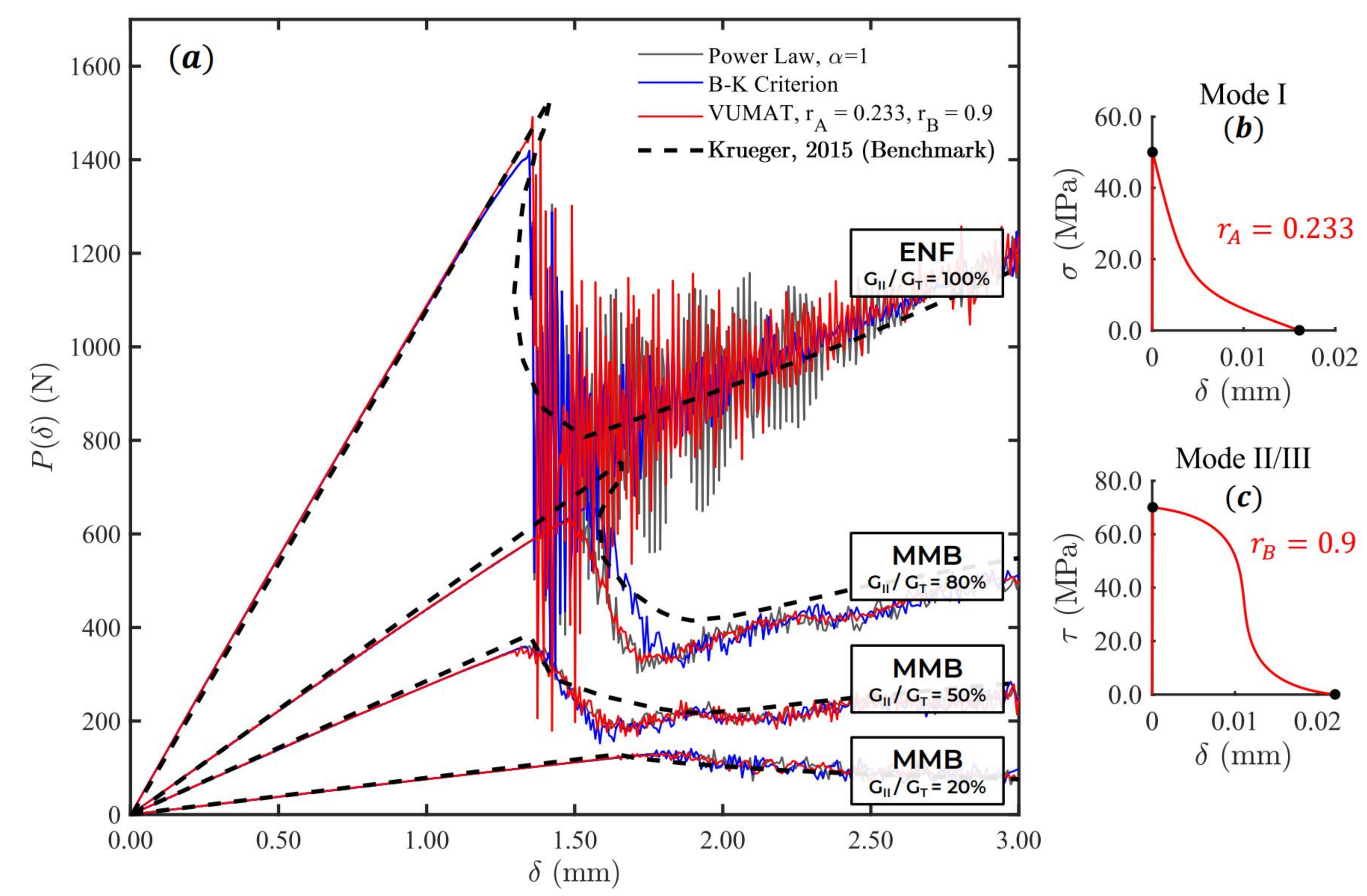


◂ Fig. 4: (a) Real photograph of delamination propagation front (Krueger, 2015). (b) Three superimposed views cohesive degradation in FEM model, which capture non-self-similar, curved delamination front.

Results & Discussion

- With a triangular law, custom formulation does not correctly capture peak load
- Non-linear law (more realistic to experiments) better:
  - Single set of Bezier parameters for all mixity ratios could not be found; $r_A = 0.233, r_B = 0.9$ best
  - Gives results on-par with Power Law ($\alpha = 1$), fails to capture peak load as consistently as B-K criterion

▾ Fig. 5: Load-displacement results for range of mode mixites, comparing results with various mixed-mode formulations (including the VUMAT with best parameters).



Future Work

Further studies are needed to obtain an empirical relationship between Bezier parameters and peak load. Constraints should be loosened on the Bezier parameters for the Mode II softening law.

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