A NOVEL MIXED-MODE COHESIVE ZONE MODEL FOR DELAMINATION WITH SEVERE FIBER BRIDGING APPLIED TO SANDWICH PANELS AND MONOLITHIC LAMINATES

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Abstract
Due to their very high stiffness to weight ratio, sandwich panels with honeycomb core and carbon fiber reinforced plastic facesheets are becoming increasingly popular in aerospace applications. However, the honeycomb topology also provides modelling challenges when the disbonding between facesheet and sandwich core is to be modelled.
The authors have previously shown that the disbonding between the facesheet and the honeycomb core of said sandwich panels cannot be accurately described by established cohesive zone formulations and a novel formulation was developed. The formulation requires a number of parameters which can be extracted from experiments by combining load displacement data on the one hand and digital image correlation strain data on the other hand. The parameter set was obtained for the interface between IM7/8552–1 prepreg tape and Hexcel 5052 aluminum honeycomb core bonded with FM 300K film adhesive, which constitutes the baseline design of the cargo fairing of the NASA Space Launch System (SLS).
The novel formulation is comprised of two cohesive components, one of which is related to the initial interface traction while the other one is related to the bridging tractions in the wake of the crack tip. So far, this formulation has only been used to describe the mode I dominated delamination of single cantilever beam specimens. Subsequently, the formulation has been extended to account for mixed-mode disbonding. The newly developed formulation is applied to monolithic laminates as well as sandwich panels.
Results obtained with the mixed-mode formulation are presented herein.

1. Introduction

Delamination is characterized by three different modes of delamination which can occur, see Figure 1. As most authors in the community, e.g. [1] [2] [3] [4], we focus on the modes I (opening) and II (sliding) as well as combinations of the two, i.e. “mixed-mode”. A number of tests to characterize delamination properties of specimens have been proposed and a short overview is presented in Section 2 along with the obtained experimental results.

The authors have previously shown that the Single Cantilever Beam test (ASTM D 5528) is very well-suited to describe the mode I interfacial failure of sandwich panels comprised of cores with high in-plane compliance [5] [6] [7]. The specimen geometry and model is shown in Figure 2.

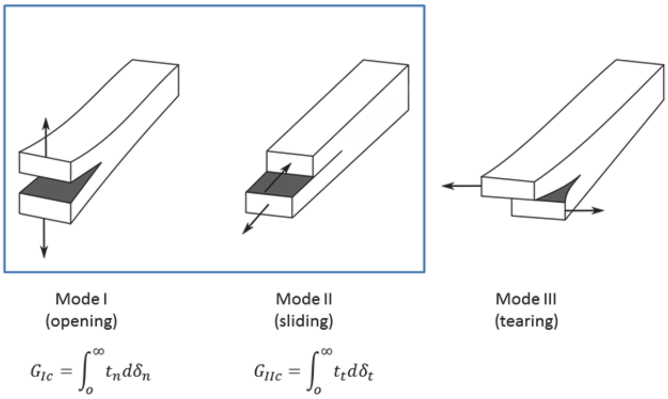


Figure 1. The three modes of delamination.

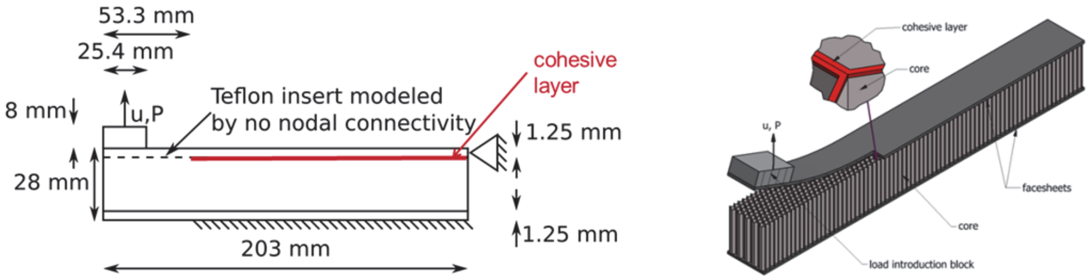


Figure 2. SCB geometry, boundary conditions and model topology.

Digital image correlation (DIC) analysis indicated that two zones of high interfacial traction exist, one close to the crack tip and one in the wake of the crack tip, where severe fiber bridging is observed, see Figure 3 (left).

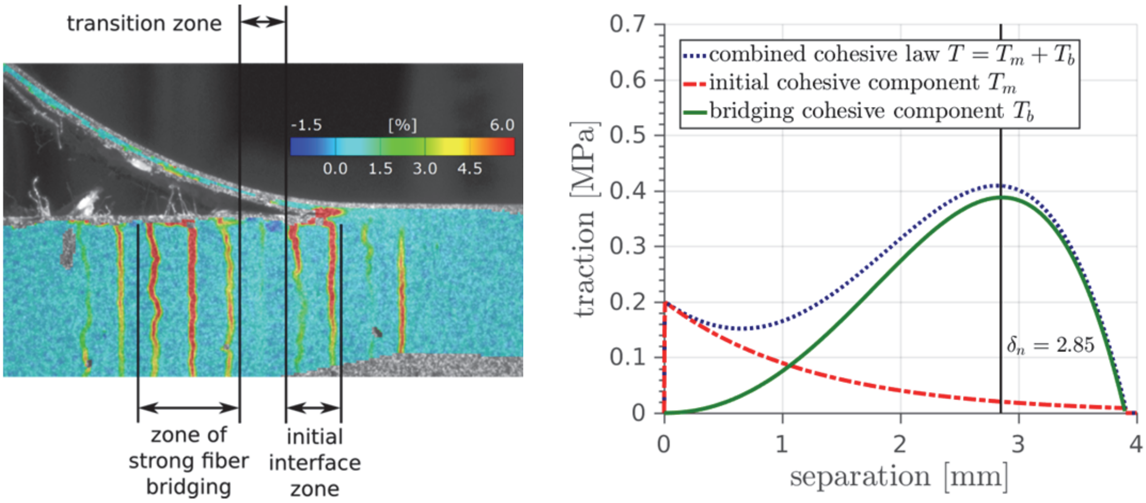


Figure 3. DIC results (left) and novel proposed cohesive law (right).

Therefore, the novel formulation is comprised of two cohesive components, one of which is related to the initial interface traction while the other one is related to the bridging tractions in the wake of the crack tip, see Figure 3 (right). The newly developed formulation greatly increased the accuracy of the numerical load-displacement prediction compared to standard cohesive formulations, see Figure 4.

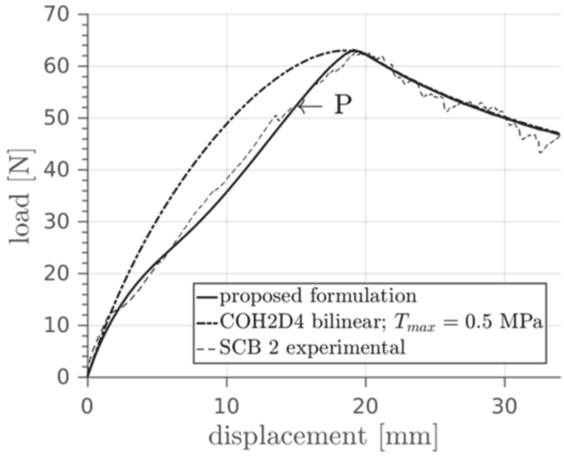


Figure 4. SCB load-displacement curve predicted with new CZ-formulation and bilinear CZ-formulation.

The obvious next step is to extend this formulation to also account for mixed-mode behavior. However, testing the mixed-mode interface disbonding of sandwich panels poses a number of challenges [8] [9]. For instance doublers become necessary in order to shift the neutral axis of bending such that in coincides with the fracture plane. The very thick core (25.4 mm) which is used in the current case for instance requires an excessively thick doubler at the top, even if no doubler at the bottom facesheet is used. However, simulations showed that due to the risk of core crushing in compression, doublers at the top and bottom would have to be used, which further increases the doubler thickness at the top, see Figure 5.

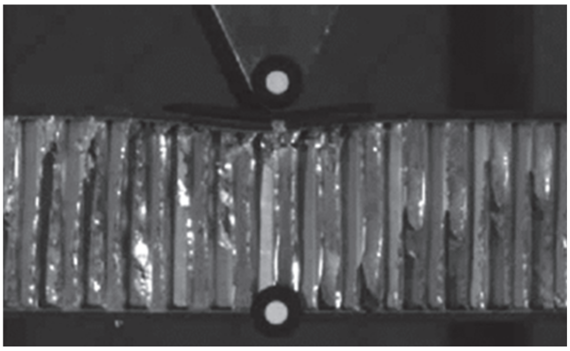


Figure 5. Example of core crushing for the current material system.

All of the aforementioned points introduce features the effects of which need to be investigated before reliable conclusions can be drawn. This complicates the determination of the interfacial fracture parameters significantly. Nonetheless, further investigations on monolithic laminates indicated that the novel cohesive law shape can also be observed in the delamination of monolithic laminates, c.f. Section 2.1.3.

2. Experimental Setups and Results

2.1. Mode I

The mode I critical energy release rate G_{Ic} is determined by conducting the standardized double cantilever beam test (ASTM D 5528) in the case of monolithic laminates. In this test, a notched specimen is pulled apart on piano hinges which are attached to the notched end, see Figure 6. For the testing of sandwich panels, the lower facesheet is clamped to a foundation, see Figure 2.

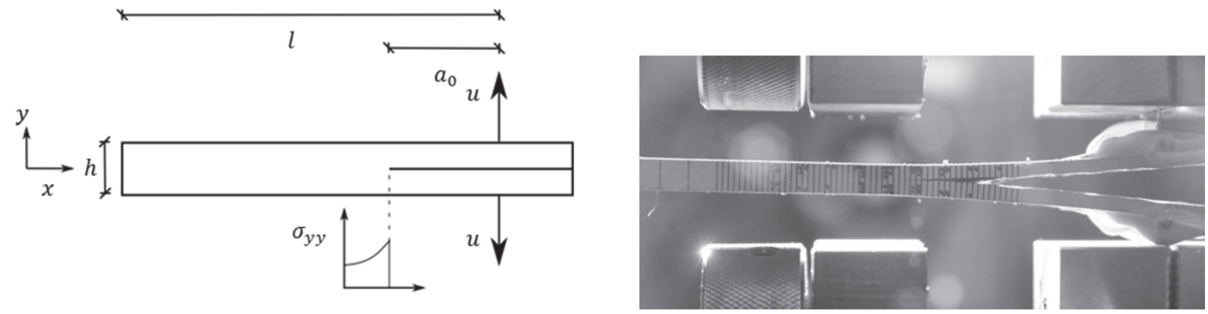


Figure 6. DCB setup schematic (left) and experimental realization (right).

2.1.3 Traction-Separation Comparison of Mode I experiments

The normal traction-separation law was extracted from the experimental data using the J-integral approach [10] [11] [12] [13]. It can be seen that the extracted traction-separation curve has two peaks, just like the SCB sandwich panel traction-separation law, see Figure 7.

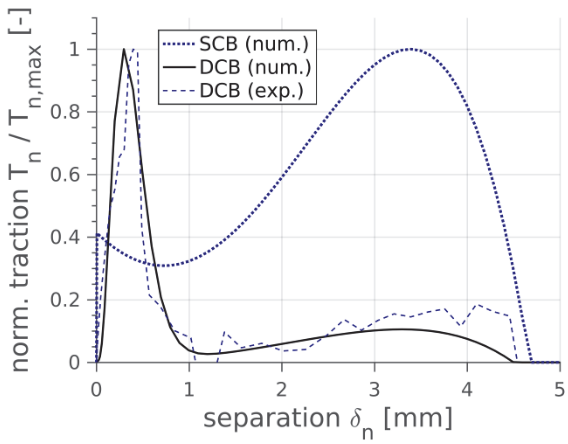


Figure 7. Normalized traction-separation plots for DCB and SCB.

The significant difference is that in the case of the investigated sandwich panels the bridging traction peak (at high separations) is higher than the initial peak (at low separations) whereas the reverse situation is observed in the investigated monolithic laminates. Therefore, the novel mixed-mode formulation is in this work validated with monolithic laminates and the comparison with mixed-mode sandwich panels is planned when the experimental uncertainties have been overcome.

2.2. Mode II

While there has been some debate about whether G_{IIc} is a true material parameter [14] [15], G_{IIc} has also become well-accepted for quasi-static testing. This is reflected by the current standards (AECMA prEN 6034, JIS 7086) which govern its experimental determination.

2.2.1 Symmetrical End-Notched Flexure (SENF)

The testing is accomplished by subjecting an end-notched specimen to three point bending (end-notched flexure, ENF). The ENF specimen geometry is similar to the DCB specimen geometry.

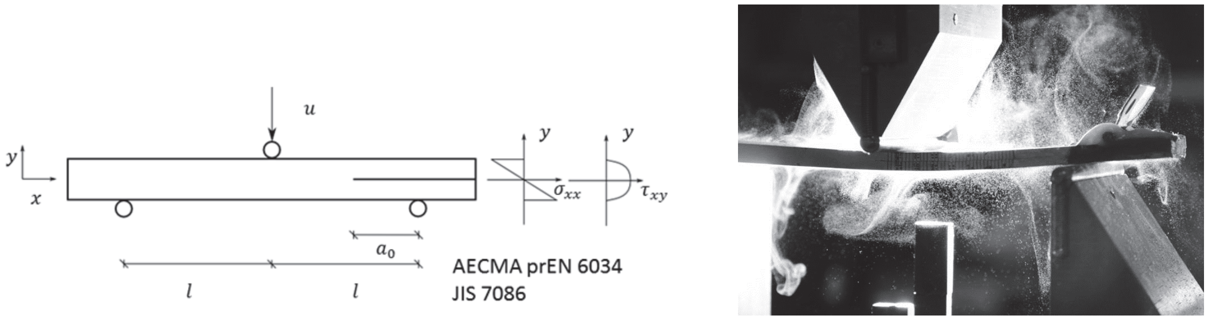


Figure 8. ENF setup schematic (left) and experimental realization (right).

2.2.1 Asymmetrical End-Notched Flexure (AENF)

Finite element simulations showed that the effective prevention of core crushing should ideally be accomplished by the use of stiff vertical supports introduced at the loading points and a significant reduction of the core thickness, see Figure 9.

Figure 9. AENF setup schematic including the proposed support locations.

2.3 Mixed Mode Bending (MMB)

The experimental determination of the mixed-mode fracture toughness G_c for various ratios of e.g. G_I/G_c is performed with mixed-mode bending (MMB) tests according to ASTM D 6671, see Figure 10. Again, the same specimen geometry is used. A comprehensive overview of existing tests and data reduction techniques is given in [16].

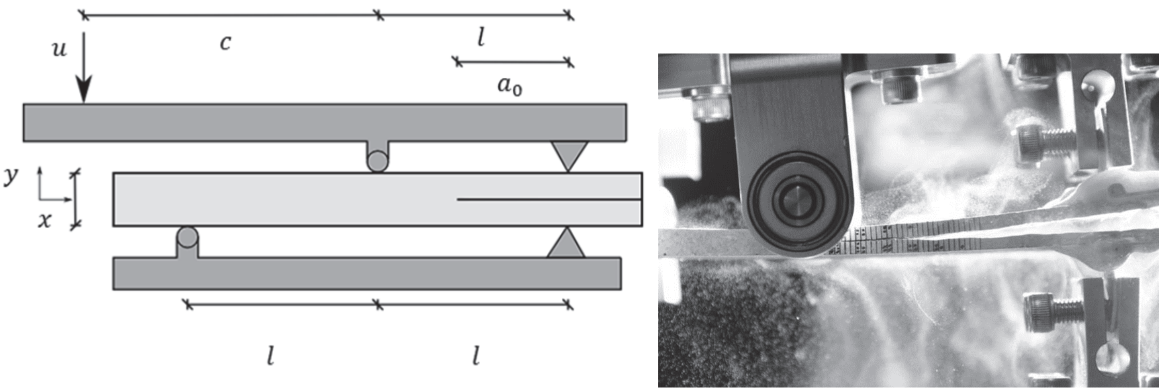
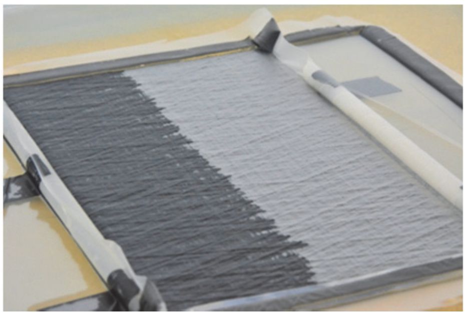


Figure 10. MMB setup schematic (left) and experimental realization (right).

2.5 Specimen Preparation

The preparation of the sandwich panels is identical to the procedure described in e.g. [7]. The monolithic laminate specimens are prepared in a vacuum assisted matrix infusion process. The laminate consists of 110 Torayca T700SC 12k carbon fiber plies, see Figure 11 (left). A Teflon insert of 13 µm thickness and 45 mm width is added at the midplane. The individual specimens are then cut from the plate (Figure 11 right) with a diamond saw, to nominal dimensions of 25 mm width by 5 mm thickness by 150 mm length. The insert location is marked by the white line in Figure 11 (left). The insert is located to the right of the white line. The load point is 15 mm from the notched end and the total insert length is 45 mm, i.e. the insert extends 30 mm past the load point ($a_0 = 30$ mm).



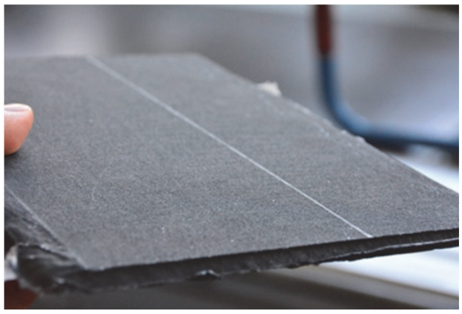


Figure 11. Vacuum infusion (left) and laminate prior to specimen cutting (right).

2.6 Measurement Equipment

The crack length is measured from both sides of the specimens simultaneously. One side is painted with a white brittle coating into which markings are cut every 1 mm. The crack propagation is monitored with a DSLR camera equipped with a high magnification lens. The other side is coated with titanium oxide spray on which graphite is speckled for contrast. This surface is monitored with the Aramis DIC system. The DIC measurements can be used to obtain the local strain field and to determine the crack propagation.

2.7 Summary of Experiments

The two peaks of the traction-separation law are observed across all mode-mixity ratios and the qualitative shape of the curve stays relatively constant, see Figure 12. Thus, this feature of the traction-separation law needs to be included in the modeling of the delamination process.

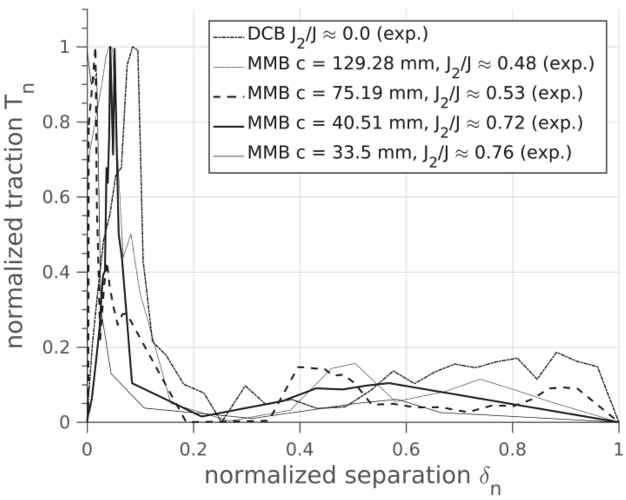


Figure 12. Normalized normal traction-separation curves for various mode ratios.

3. Modeling Method and Results

In a first step, the proposed pure mode laws are extended to account for mixed-mode modeling using a procedure proposed by Nguyen and Waas [2]. In a second step, the cohesive law is inversely stretched in traction and separation direction, based on an experimentally determined factor. The resulting normal tractions, T_n, and tangential tractions , T_t, prior to the stretching step are shown in Figure 13.

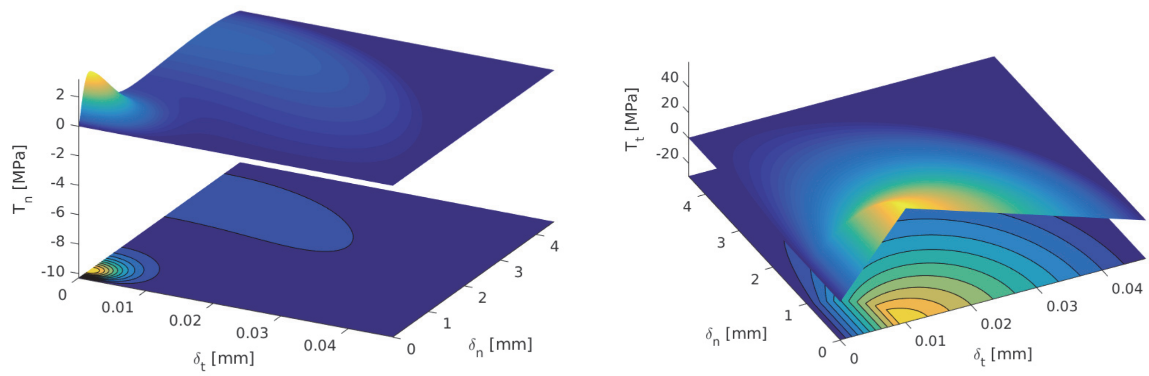


Figure 13. Vacuum infusion (left) and laminate prior to specimen cutting (right).

The predicted load-displacement curves for DCB , MMB, and ENF cases are compared to experimental results in Figure 14. Very close agreement between experiment and numerical predictions of the newly proposed formulation can be observed in both cases.

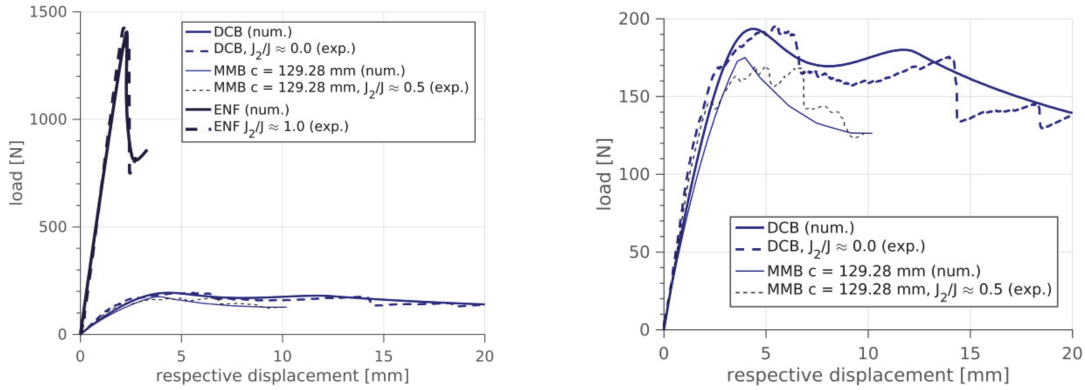


Figure 14. Load-displacement curves (experimental and numerical) for all considered cases.

4. Conclusions

Monolithic laminates show two normal traction peaks of the cohesive law, one close to the crack tip, one in the wake of the crack, similar to observations previously made in sandwich panels. This allows the extension and validation of a novel cohesive law originally derived for sandwich panels to the more general application of mixed-mode delamination of monolithic laminates. A number of propositions for specimen modifications which will allow similar mixed-mode tests for sandwich panels have been made, while mixed-mode tests with the current sandwich panel specimen geometry were unfeasible. The novel mixed-mode formulation is able to capture the load-displacement curves of DCB/SCB (mode I), ENF (mode II) and mixed-mode (mode I/II) experiments very well. The pure mode laws were calibrated based on experimental data by taking the derivative of the J-integral with respect to the separations. This led to comparatively low fitting effort. Another novelty of the current formulation is a scaling factor which has been introduced for the normal tractions and separations in the mixed-mode case. This was necessary as measurements indicated that the normal tractions tended to increase while the normal separations tended to decrease with increasing mode mixity.

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