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# INTERFACIAL CRACK PROPAGATION IN AXIALLY COMPRESSED SANDWICH PANELS - EXTENDED HIGH-ORDER SANDWICH PANEL THEORY APPROACH

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## 1. ABSTRACT

The investigation presents a nonlinear model for the analysis of the interfacial debonding propagation in sandwich panels. The model combines the Extended High-Order Sandwich Panel Theory with a cohesive interface modeling. The model derived using the first order shear deformation kinematic assumptions for the face-sheets and high order small deformations kinematic ones that include out-of-plane compressibility for the core. The cohesive interfaces join the three components of the sandwich panel and introduce the interfacial nonlinearity into the model. These interfaces are governed by nonlinear traction-displacement gap laws that allow capturing the failure mechanism of interfacial debonding propagation. This effect is combined with the geometrical nonlinearity and the instability associated with the buckling of the thin delaminated face-sheet. The cohesive interface parameters are calibrated to match to experimental results available in the literature. The results are compared with experiments of three specimens and loading configurations: Double Cantilever Beam (DCB), Cracked Sandwich Beam (CSB), and end-shortening (ES) test. In the DCB case, the crack tip is subjected to a global mode I and in the CSB case global mode II. This mode requires the consideration of interfacial contact conditions that prevent penetration of the delaminated face-sheet into the core. In the ES test case, the sandwich panel is subjected to an in-plane compression loading that introduces geometrical instabilities. This effect, along with the presence of pre-existing delaminated regions trigger buckling of the compressed face-sheet, evolution of a debonding mechanism, and a further growth of the delaminated region. The comparison of the analytical results with the experimental ones focuses on the linear response, the nucleation of the interfacial debonding crack, the phase of interfacial crack progression, and the local/global interfacial and geometrical instabilities. The analytical model, which is validated through the comparison with the experiments explores additional features of the debonding mechanism in sandwich panels that are beyond the capabilities of the experimental technique.

## 2. RESULTS

The experimental results of the DCB specimens in terms of load vs. displacement [1,2] and the numerical results of the extended high order model [3] appear in Fig. 1. The results are presented for two DCB specimens: one with a 15 mm thick core and other with a 20 mm core.

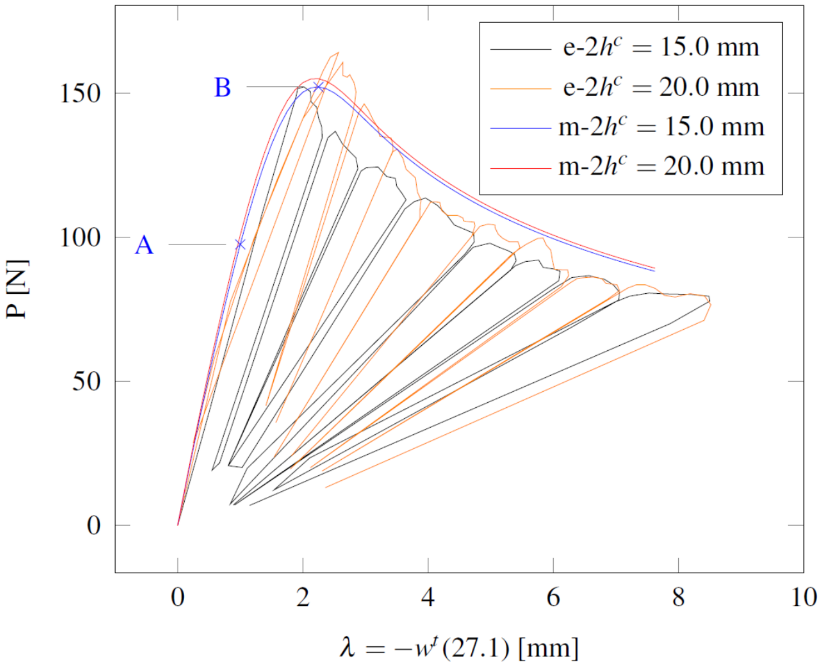

*Fig. 1: Experimental [1-2] and model [3] load-displacement curves of two DCB sandwich specimens (e-experiment, m-model).*

The load-displacement curves in Fig. 1 (black and blue curves) show that the numerical results are in good agreement with the global envelope of the experimental ones. The correlation includes the initial linear stage, the ultimate load, and the descending branch of the load. This branch, which reflects a decrease in load and is attributed to the interfacial crack propagation phase. In the experiment, this phase is associated with unloading and re-loading cycles which are not considered here. However, the theoretical results of the analysis match the envelope of those experimental cycles very well. The comparison with the experiments allow to calibrate the properties of the cohesive interface. In this case, the properties are calibrated using the experimental results of the thinner core. Using the same calibrated cohesive interface parameters for thicker core yields satisfactory results that well compare with the experimental measurements (orange and red curves in Fig. 1).

The analytical [3] and experimental [4] results of load vs. mid-span displacement for the CSB specimens appear in Fig. 2.

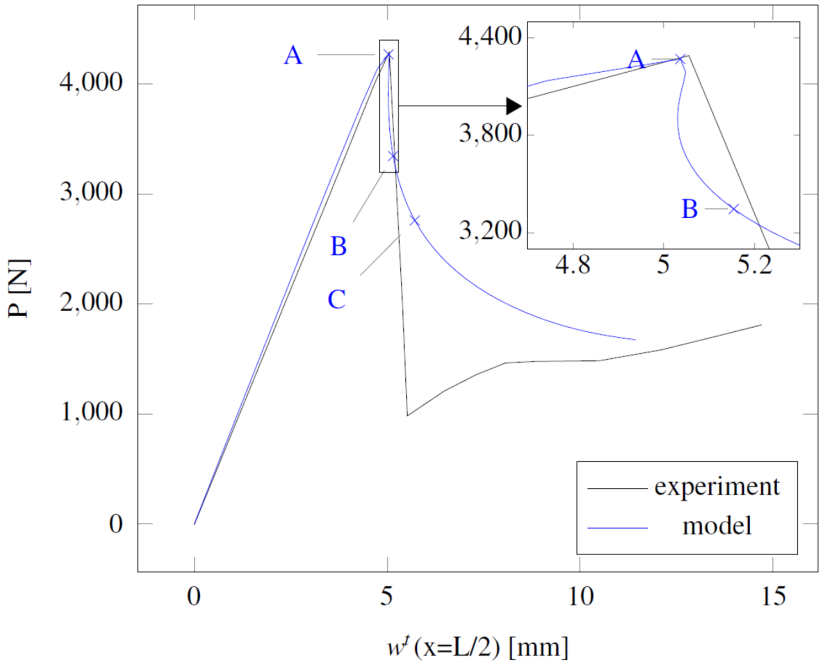

*Fig. 2: Experimental [4] and model [3] load-displacement curves for CSB sandwich specimen.*

The results of the model for the CSB case are in good agreement with the experimental ones, see Fig. 2. This correlation includes the linear phase, the ultimate load, and the initial phase of the debonding where the load drops. Notice that in the experiment, the load drop is sharper than in the model and it may be attributed to the dynamic effects of the response. Rinker et al. [4] noted that the crack propagation is not stable and it has occurred in one-step of expansion up to mid-span. This crack propagation drove the specimen into the dynamic regime, which is not discussed here. Yet, the model captures the instability reflected by the load drop and the snap-back of the response beyond the peak load.

The experimental setup of the ES specimen [5] appears in Fig. 3. In general, this setup reflects an axial compression test where a sandwich panel is axially loaded through stiffened clamps at its edges, denoted as edge-beam. Yet, the layout of the sandwich panel, the presence of pre-existing delaminated regions, the slenderness of the compressed face-sheet in the delaminated region, and the geometrical and interfacial nonlinearities yield a response of buckling instability, out-of-plane deformations, and evolution of a debonding process. The real boundary conditions (BCs) are modelled using the concept of an edge-beam with a rotation spring that enables a range of conditions from fixed edges to hinge ones.

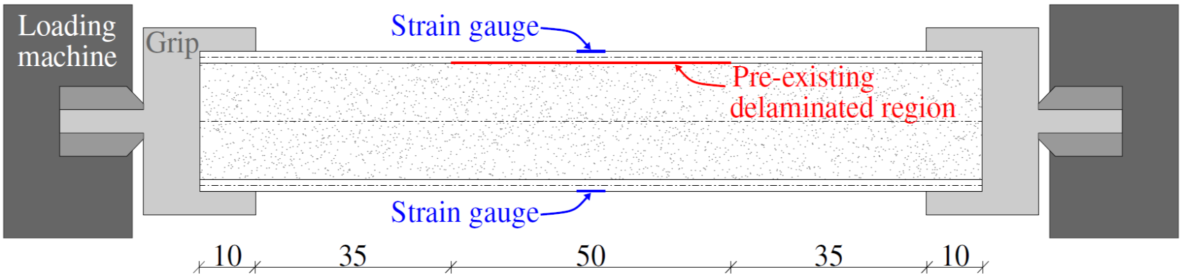

*Fig. 3: ES specimen [5].*

The numerical and experimental [5] results of the ES specimen in terms of load vs. strains of outer fibers of ES sandwich panel at mid-span appear in Fig. 4.

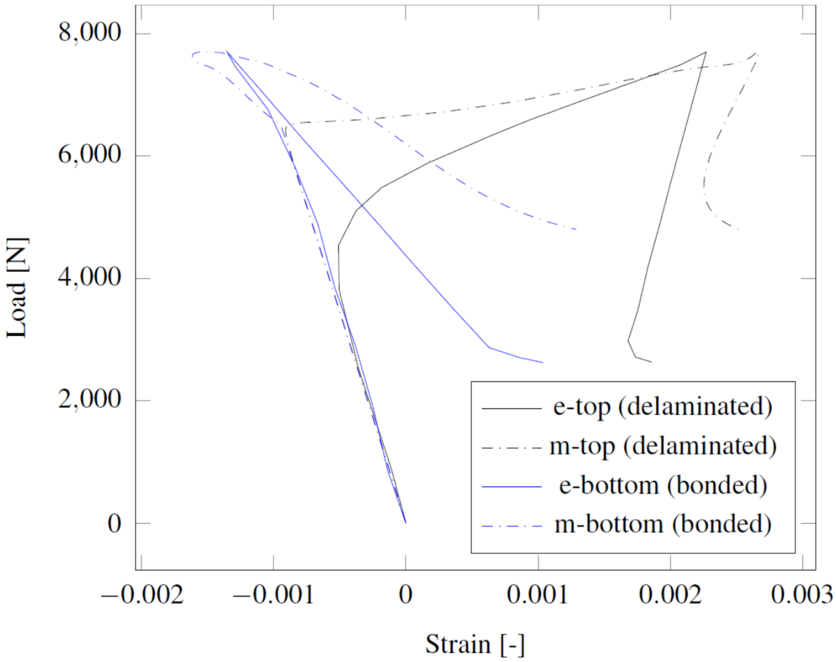

***Fig. 4: Load vs. strains of outer fibers of an ES sandwich panel at mid-span, experimental [5] and model results (e-experiment, m-model).***

The numerical results are in good agreement with the experimental ones, see Fig. 4. This comparison includes the linear phase and the ultimate load. In addition, the buckling and post-buckling behavior of the delaminated face-sheet that are observed in the experiment are reflected by the strains of the top face-sheet. The numerical results compare well with the experimental ones for the debonding phase where the load drops. The strains of the top face-sheet (delaminated) beyond the peak load alter their trend twice, similar to experiment's measurements. The strains of the bottom face-sheet (bonded) also follow the behavior of the experiment. Beyond the peak load, the strains are growing and even become positive. The deformed shape of the modelled sandwich panel consists of an "opening" mode, where the two face-sheets move in opposite directions similar to that of the experiment (see [5]). Please notice that the numerical results are highly sensitive to the exact definition of the BCs. Minor changes in the BCs may alter the response significantly. This sensitivity requires an enhanced investigation when modelling compressed delaminated sandwich panels of combined geometrical and interfacial instabilities.

## REFERENCES

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