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Numerical simulation of the adhesive interface

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This work shows possible approaches to modeling crack propagation in a thin adhesive layer in a simple double cantilever beam (DCB) sample. Materials of DCB samples consist of epoxy adhesive and carbonepoxid composite. Numerical simulation is modeled based on experiments done in work [2] where increased temperature's influence on pure modes I and II was observed. The further objective is to determine the sensitivity of models parameters to maximum force and fracture toughness.

The motivation for this work is the increasing interest of the industry in adhesive bonding of composite materials due to their advantages, such as nondestructive bonding, more uniform stress distribution, and high fatigue resistance. This leads to high interest in material research and its simulation research. Adhesive can be used on large surfaces where failure on sides is not necessarily a failure of the whole part, and crack propagation is of interest. The effect of demanding operating conditions is one of the other interests in the research community.

For numerical simulation, the finite element method was used. Two main approaches to crack propagation simulations are discrete crack models or smeared crack models [5]. In this work, three discrete methods were used, namely cohesive zone model (CZM) with element deletion, extended finite element method (XFEM), and classical finite element method (FEM) with element deletion [1].

DCB sample is fabricated from two prismatic strips, which are bonded on the part of the surface, and then two loading blocks, used for transferring loads from the universal test machine, are glued to the ends. The geometry of the DCB sample is shown in Fig. 1. Loading blocks are pulled in opposite directions, and the adhesive breaks cohesively, which corresponds with pure

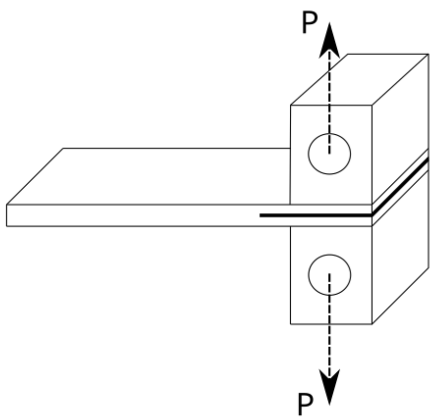

Fig. 1. Scheme of DCB sample and its loading points

mode I fracture. The effect of temperature was considered in the model by lowering all adhesive parameters in the same ratio of fracture toughness for mode I in elevated temperature (50° C) and room temperature. This temperature does not have any considerable effect on composite material. For this reason, the parameters of the composite have not been modified in any way.

Models were created in Abaqus/CAE and computed in Abaqus/standard. In the next bullet points, essential parameters are described for three models.

- *CZM model:* Due to the considerable thickness of the adhesive part, CZM elements with finite thickness were used (COH2D4). Cohesive behavior was described by traction-separation parameters. Quadratic nominal stress damage (Quads) initiation criteria were used to predict damage initiation in cohesive elements, and damage evolution was described by energy-based mixed mode behavior by Benzeggagh-Kenane. Adherends were modeled by plane strain element with incompatible modes enabled (CPE4I).

- *XFEM model:* The adhesive layer was enriched by XFEM, where plane strain elements were used (C4PE). The elastic behavior of adhesive was modeled as isotropic. Maximum principal stress (Maxps) initiation criteria were used to predict damage initiation in the XFEM enriched region. The same damage evolution model was used as in CZM. Also, adherends were modeled as in CZM.

- *Ductile model:* For the last method, plane stress elements with incompatible modes enabled (CPS4I) were used. This change from previous models was done because of ductile damage initiation criteria, which is based on fracture strain. The adhesive was modeled as elastic isotropic with plasticity. Damage evolution was modeled as energy-based with a mode-independent definition. This energy had to be scaled to match previous models in Force displacement output.

Viscosity in adhesive elements for CZM and ductile damage model was specified due to convergence issue. This improved numerical stability and computational time. For the XFEM model, a stable solution and correct crack propagation was achieved with a different adhesive mesh and adherend mesh so that most of the nodes do not connect directly. Further adhesive geometry near crack initiation had to be modified for each method to get a stable solution. Material parameters for adhesive 3M™ Scotch-Weld™ Epoxy Adhesive DP490, were taken from work [4] and for composite material KORDCARBON-CPREG200T3KEP142A from [3].

For further evaluation, adhesive fracture toughness for mode I was computed according to the modified beam theory as

$$G_I = \frac{3P\delta}{2B(a + |\Delta|)}\,, \tag{1}$$

where P is applied load during crack propagation with crack length a. δ is load point displacement, B is width of specimen and Δ is term for correction due to possible rotation, which was set to zero.

All methods are evaluated in Fig. 2, where numerical methods are compared with the experiment. On the left figure are Force–displacement ($P - \delta$) curves, and on the right are R–curves, which are fracture thougness – crack length ($G_I - a$). Force–displacement results were obtained from the top loading point and are consistent with the experiment. Fracture toughness was computed as in experiments where crack length was measured from the loading point. R–curve was then constructed for multiple time increments throughout the simulation. Inconsistent values of fracture toughness were observed, where CZM has the largest difference from the experiment. This leads to the conclusion that the three methods are not equivalent. Further study of mesh sensitivity should be performed.

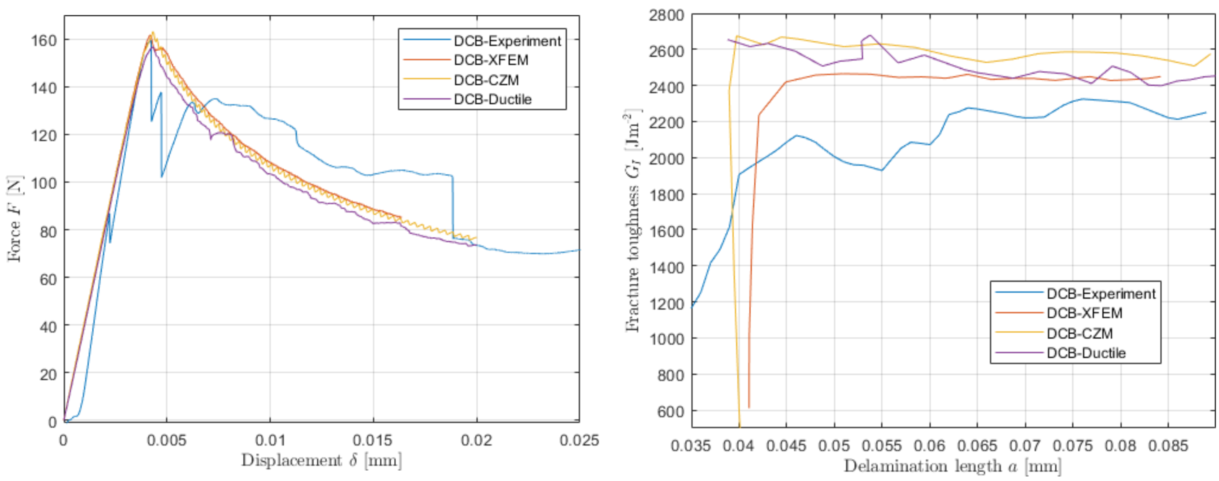

Fig. 2. Evaluation of numerical simulation and experiments: (left) force vs displacement, (right) resistance curve (R–curve)

In this work, three approaches for modeling crack propagation were compared. These methods are consistent for force–displacement evaluation but are not consistent for R–curve evaluation. Computational cost between XFEM and ductile model with element deletion were comparable, and CZM was the most efficient.

Acknowledgement

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