SIMULATION OF FRACTURE IN BONDED JOINTS WITH A COHESIVE ZONE MODEL

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Abstract

In this work, a Cohesive Zone Model (CZM) has been used to simulate the progress of fracture in a pre-cracked bonded DCB specimen. The CZM model has been implemented in the Finite Element (FE) code ABAQUS as a series of non-linear springs attached to the interface nodes of the cantilever. The influence of the cohesive zone parameters (shape, cohesive peak stress) on the simulated force-opening diagram was evaluated keeping the fracture energy as a constant. The CZM parameters of a commercial adhesive were identified by comparing FE analyses with fracture experiments performed on DCB. This set of parameters was used to simulate the failure of T-peel joints bonded with the same adhesive in order to assess the transferability of the model to a different joint geometry.

Introduction

Adhesive joining can offer significant advantages over traditional joining methods such as welding or mechanical fastening in structural applications. Automotive and aerospace industries are important examples. On the other hand, joint fabrication procedures, component service loads and environmental conditions may introduce or initiate defects, whose evolution will control the performance and the reliability of the bonded joint [1].

In those cases, Fracture Mechanics (FM) can be used to assess the structural integrity of a bonded joint [2, 3]. The FM approach consists in the comparison of a parameter, function of load and geometry of the cracked body (for example the strain energy release rate, G), with the fracture resistance (G_c). The simulation of fracture therefore requires to implement a criterion that triggers propagation when $G = G_c$.

An attractive way to simulate the effect of a defect on joint strength is to incorporate a model of the rupture process (i.e. the criterion to trigger propagation). In particular, the fracture of bonded joints has been successfully simulated using the Cohesive Zone Model (CZM) [4-10]. According to this model, the zone in front of the physical crack tip opens and then tears progressively following a given traction-separation behaviour (Fig. 1), where Γ_0 is the work of separation. In the case represented in Fig. 1 the other independent variable may be the maximum stress within the cohesive zone σ_m or the opening at fracture δ_c, besides the ratios δ_1/δ_c and δ_2/δ_c.

In this work, the CZM has been used to simulate the progress of fracture in a pre-cracked bonded DCB specimen. The CZM model has been implemented in the FE code ABAQUS as a series of non-linear springs attached to the interface nodes of the cantilever. The influence of the cohesive zone parameters (shape, cohesive peak stress) on the simulated force-opening diagram and crack resistance curves was evaluated keeping the fracture energy as a constant.

Experiments performed on DCB specimens [11] where aluminum cantilevers were bonded with a commercial adhesive were used as a target to identify a set of cohesive zone parameters for the adhesive under study. This set of parameters was then used to simulate the failure of T-peel joint bonded with the same adhesive in order to assess the transferability of the CZM to a different joint geometry.

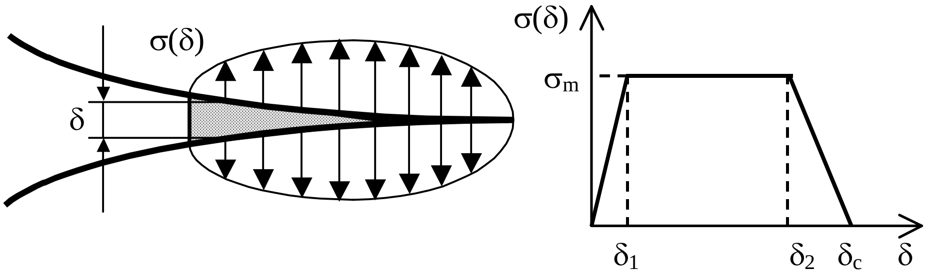

FIGURE 1. Outline of the cohesive zone and of a possible traction-separation law.

Methodology

FE model: bonded DCB specimen

The DCB specimen shown in Fig. 2 was used in [11] to evaluate the fracture toughness of the Loctite 330® structural adhesive.

The corresponding FE model is shown in Fig. 3. Symmetry conditions with respect to the bondline have been applied. Four-noded isoparametric elements have been used to simulate the adherend.

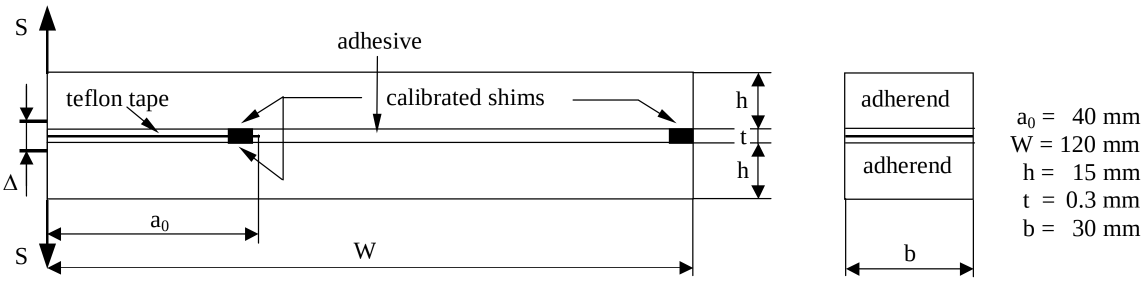

FIGURE 2. Outline of the bonded DCB specimen [11].

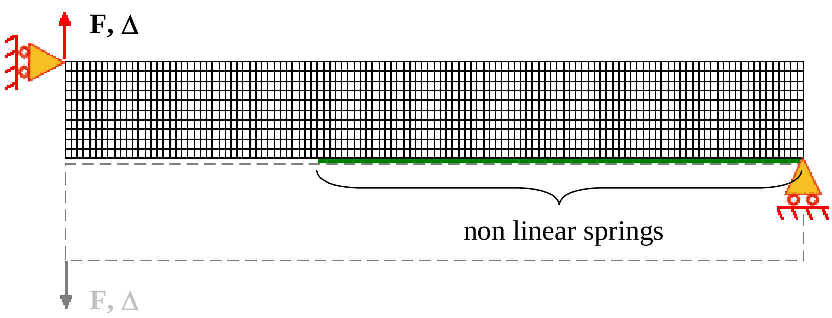

FIGURE 3. FE model of the DCB specimen.

The cohesive zone has been introduced as a series of non-linear springs connected with the adherend at one side and with the ground at the other side. This kind of approach has been adopted because of the easiness of implementation with respect to user-specified cohesive finite elements. It is worth to remark that this approach was already used successfully in [5] to model the fracture of bimaterial interfaces.

FE model: T-peel bonded joint

The T-peel joint configuration may be representative, for example, of tubular structures obtained by assembling folded metal sheets. A series of tensile tests was conducted at the Polytechnic of Turin [12] on the UNI Fe 360 construction steel T-peel joint represented in Fig. 4. Metal sheet thicknesses of 1.5 and 3mm respectively, were investigated. Due to the lack of information on the development of permanent deformations after testing, the two limiting conditions of purely linear elastic and elastic-perfectly plastic behaviour with a yield stress of 240MPa (typical for this material) have been considered. The adhesive used is again the Loctite 330®. A bondline thickness of 0.1mm was realized in this case.

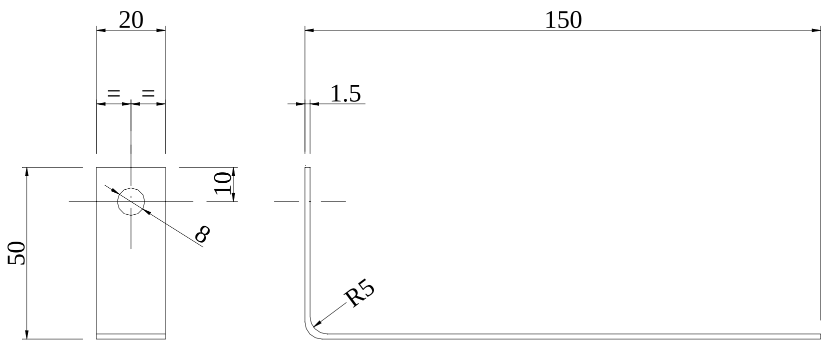

FIGURE 4. Outline of half of the 1,5mm-thick T-peel joint tested in [12].

The corresponding FE model is shown in Fig. 5. Symmetry conditions with respect to the bondline have been applied. Eight-noded isoparametric elements have been used to simulate the adherend. Again, the cohesive zone has been introduced as a series of non-linear springs.

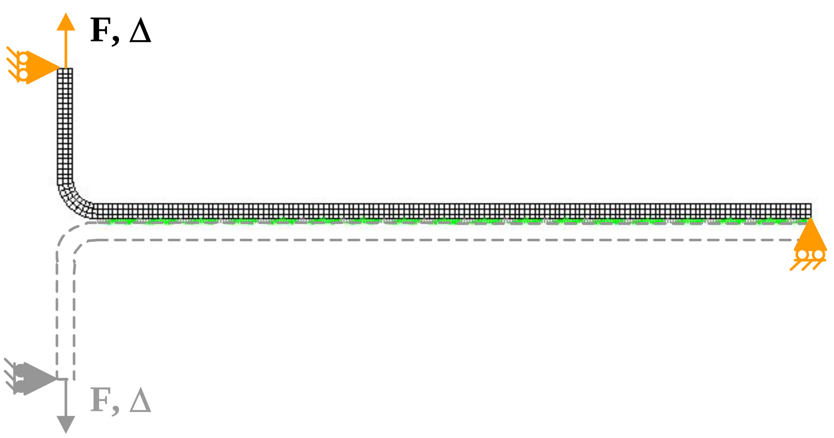

FIGURE 5. FE model of the T-peel joint.

Cohesive law

A trapezoidal cohesive law alike the one in Fig. 1 was adopted in all of the simulations. Negative opening were limited imposing that the stiffness of the non-linear springs under compression was three orders of magnitude greater than under tension.

The relationship between the parameters of the law is:

$$\Gamma_0 = \frac{1}{2}\sigma_m \delta_c \left[1 + c_2 - c_1\right] \tag{1}$$

where $c_1 = \delta_1 / \delta_c$ e $c_2 = \delta_2 / \delta_c$. The cohesive energy Γ_0 was taken equal to fracture toughness measured in [11], that is $\Gamma_0 = G_c = 550 J/m^2$. This value has been used for both DCB and T-peel joints even though the bondline thickness is different. A lower thickness as in the case of the T-peel in fact, should promote adhesive strength but, at the same time, limit plastic deformation at the crack tip and therefore the energy dissipated to break the bond.

Results and discussion

Influence of the value σ_m on the simulation of bonded DCB specimen

Referring to studies conducted in [5] and[6], the values $c_1 = 0.15$, $c_2 = 0.85$ were fixed. A series of simulations with σ_m ranging from 2 to 40MPa was then performed in order to define an envelope of possible results. That range of σ_m is representative in fact of the tensile strength of structural bonded joints. The results are summarized in Fig. 6.

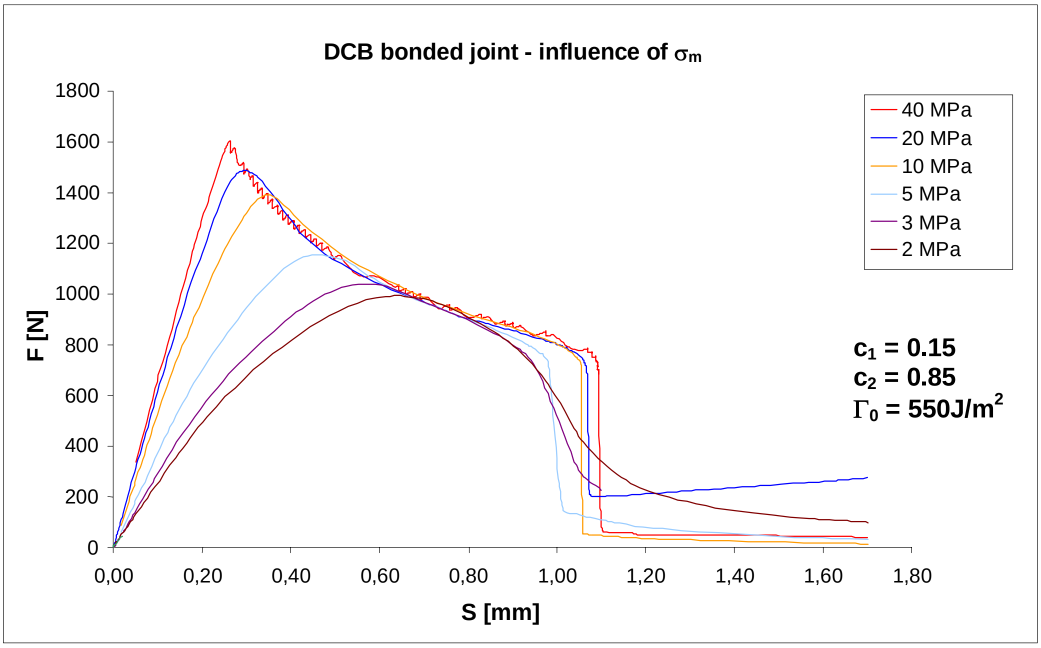

FIGURE 6: results of simulations of DCB bonded joint for varying σ_m.

The simulations for varying σ_m show two main features: i) the higher σ_m the higher the peak load and the global stiffness; ii) for σ_m > 5MPa the phase of stable crack propagation, characterized by a smoothly decreasing load, is followed by the sudden (unstable) rupture of the remaining ligament at a load level of about 800N and a displacement of 1-1.1mm.

Influence of the cohesive law shape (c_1, c_2) on the simulation of bonded DCB specimen

The results of simulations with four different values of (c_1, c_2) are reported in Fig. 7 in the case of a σ_m = 20Mpa. Higher or lower values of σ_m show qualitatively the same behaviour. The values of (c_1, c_2) have been choosen such as to have the same δ_c in all of the simulations.

The initial stiffness varies to a certain extent but a trend cannot not be extracted from the results. However, the maximum load is practically the same in all of the cases examined, therefore one can say that the influence of (c_1, c_2) on the simulation is quite low.

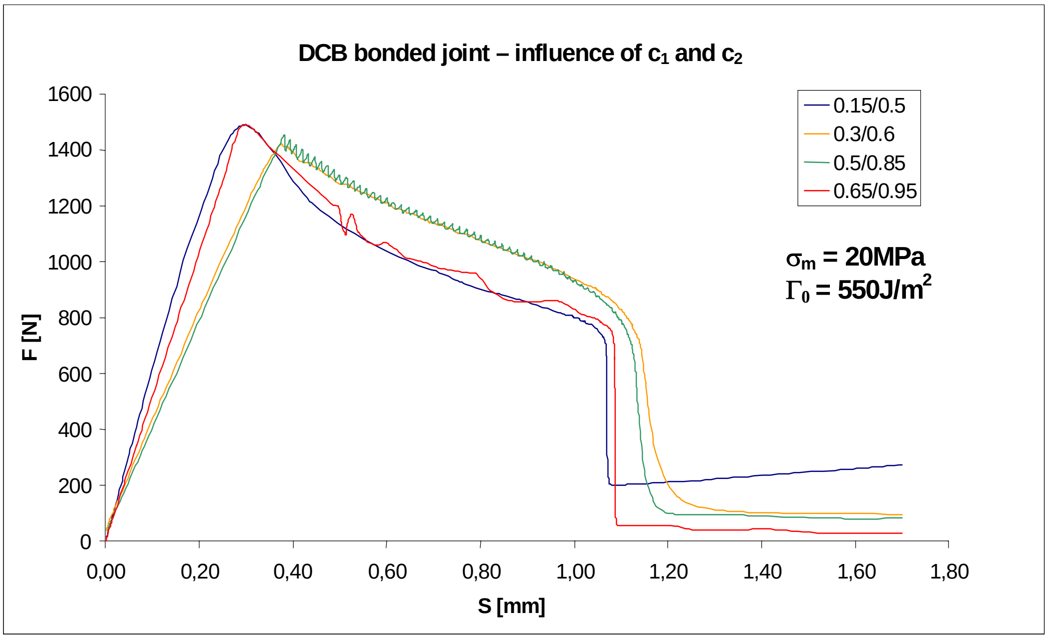

FIGURE 7. results of simulations of DCB bonded joint for varying c_1 e c_2.

Calibration of the cohesive law parameters and simulation of the T-peel joints

The parameters of of the cohesive law have been tuned by comparing the FE-simulated load-displacement behaviour with the experiments conducted in [11] on DCB bonded joints. Taking $\Gamma_0 = G_{Ic}$ = 550J/m^2 and accounting for the influence of σ_m and (c_1, c_2) on the results of simulations, a good correlation between experiment and simulation has been found with the values σ_m = 5MPa, c_1 = 0.2 and c_2 = 0.5, as shown in Fig. 8. The unloandings-reloadings visible in the experimental data were made in order to monitor the crack length with the compliance method.

The tests on T-peel joints performed in [12] were then simulated using the cohesive zone parameters tuned previously, except that the value of σ_m has been modified to account for the thinner bondline. In particular, two aspects have been considered: i) according to the technical datasheet given by Loctite, the tensile strength with a 0.1mm adhesive thickness (T-peel joint) should be about 30% higher than a 0.25mm thickness (DCB joint); ii) assuming a linearly elastic behaviour, the stiffness is inversely proportional to the thickness. Since the ratio of thicknesses is much more higher than the increase in strength, a value of σ_m = 5MPa*(0.25mm/0.1mm) = 12.5MPa has been adopted in the simulations of T-peel joints.

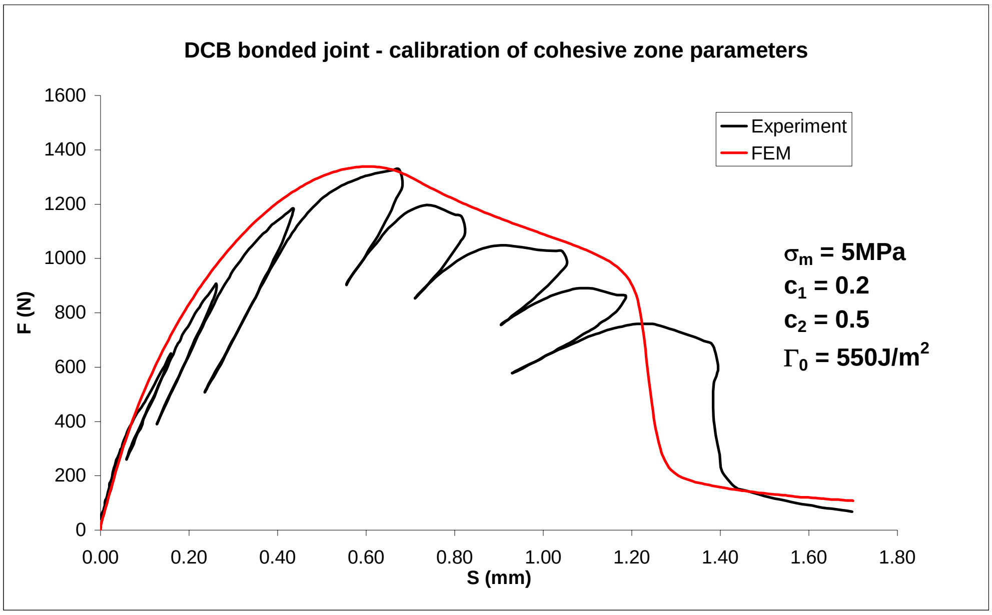

FIGURE 8. Calibration of cohesive zone parameters.

The results are summarized in Figs. 9-10. In both cases the initial stiffness is matched very well and the maximum load lies within the range ofound in the experiments. A difference is found instead during the propagation phase, where the load decreases more rapidly in the experiments than in the simulations. While in the case of the 3mm-thick joints this difference is quite lowin comparison to the absolute value of load, it becomes remarkable in the case of the 1.5mm-thick ones. Finally, it is worth to remark that the behaviour of the adherend influences greatly indeed the propagation phase. In the elastic-perfectly plastic case, conditions are such that plasticity develops in the adherend, requiring more work to be done to propagate the crack. The result is that the load for a given displacement is higher than in the linear elastic case and, therefore the difference with experiment is larger.

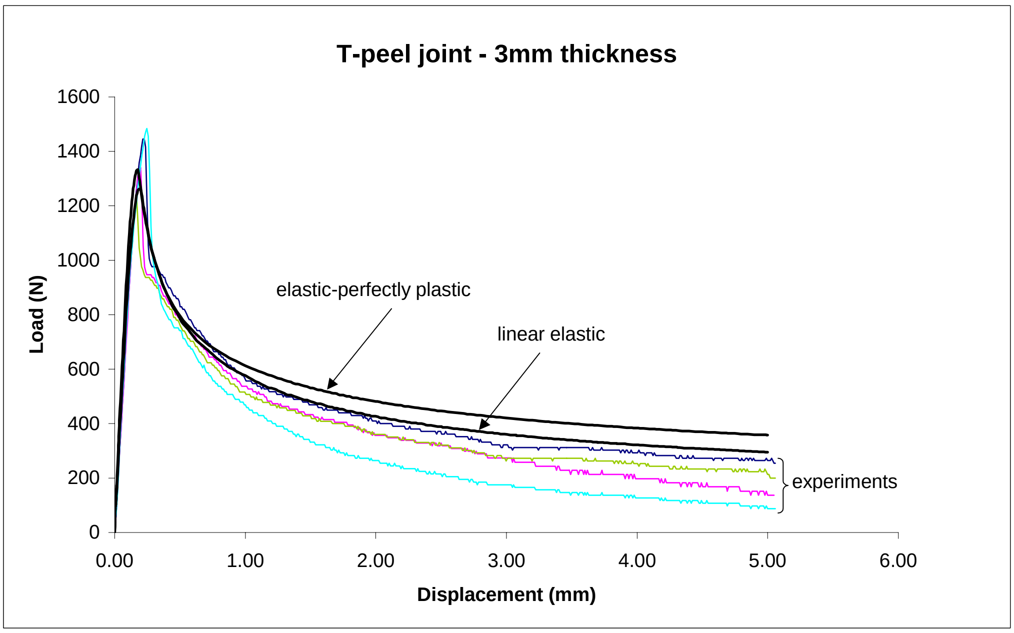

FIGURE 9. Comparison between experiments and simulation of 3mm-thick T-peel joints.

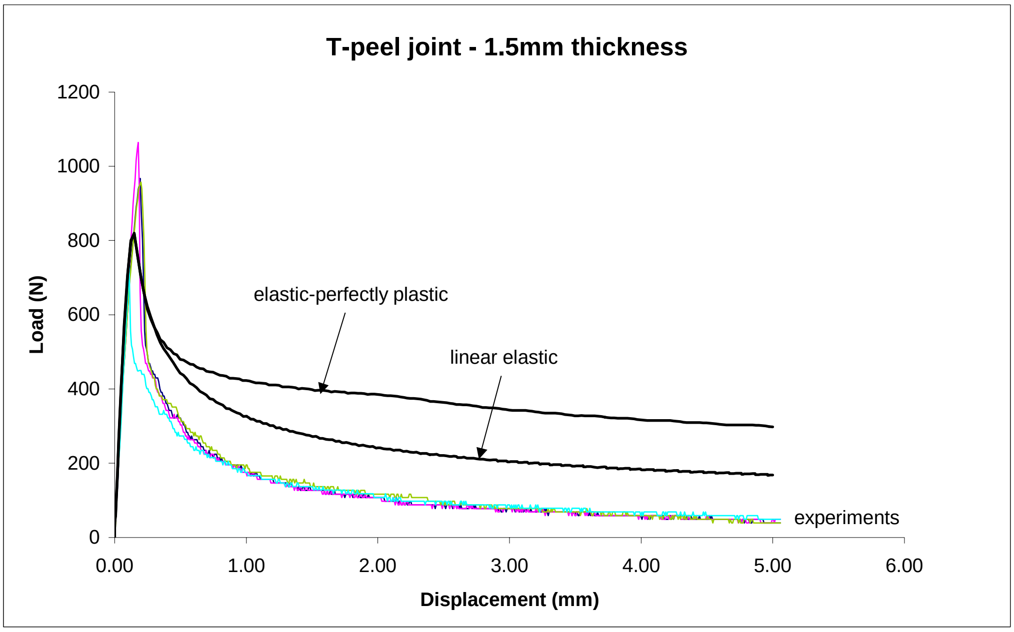

FIGURE 10. Comparison between experiments and simulation of 1.5mm-thick T-peel joints.

Conclusions

The fracture of a pre-cracked DCB joint bonded with a commercial adhesive has been simulated using a Cohesive Zone Model. The influence of the cohesive zone parameters (shape, cohesive peak stress) on the simulated force-opening diagram and crack resistance curves keeping the fracture energy as a constant was evaluated first. Then, the CZM parameters of a commercial adhesive were identified by comparing FE analyses with fracture experiments performed on DCB. This set of parameters was used, after a partial recalibration based on the thickness of the bondline, to simulate the failure of T-peel joints bonded with the same adhesive. The results showed a good agreement between experiments and simulations with respect to the stiffness and the peak load, while during the propagation phase the model overestimates the load for a given displacement. It is therefore believed that the CZM is an attractive way to simulate the beginning of fracture in a variety of bonded joints requiring only a partial recalibration of the parameters from one to the other.

Acknowledgements

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