Determination of Mode I cohesive law of structural adhesives using the direct method

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Abstract

The use of adhesive joints in critical structures, makes it fundamental to develop precise methodologies, both experimental and numerical, in a way to predict and characterize joint behaviour [1]. In Mode I, the fracture toughness of the joint is usually measured with Double Cantilever Beam (DCB) tests [2], that enables the evaluation of the integrity state of bonded structures. Mode I fracture behaviour of adhesive joints, bonded with two different epoxies, was evaluated by means of Digital Image Correlation (DIC). In order to determine the critical energy release rate, the J-integral was considered, and the direct method was used to experimentally evaluate the tensile cohesive law. Furthermore, DIC measurements were analysed resorting to a new method programmed in Python, aiming to optimize the process. A direct comparison of the load-displacement curves between experimental and numerical results was used to validate the cohesive law.

Experimental details

Joint geometries

The specimens' geometry, for the different tests performed, are presented in Figure 1. The DCB specimen was used to perform fracture tests and characterize the fracture behaviour of two epoxy adhesives, adhesive A and adhesive B. The first is a one component structural adhesive with crash-resistant properties, and the second is a structural two-component adhesive, designed for high strength and impact-resistant bonding of metallic or composite substrates.

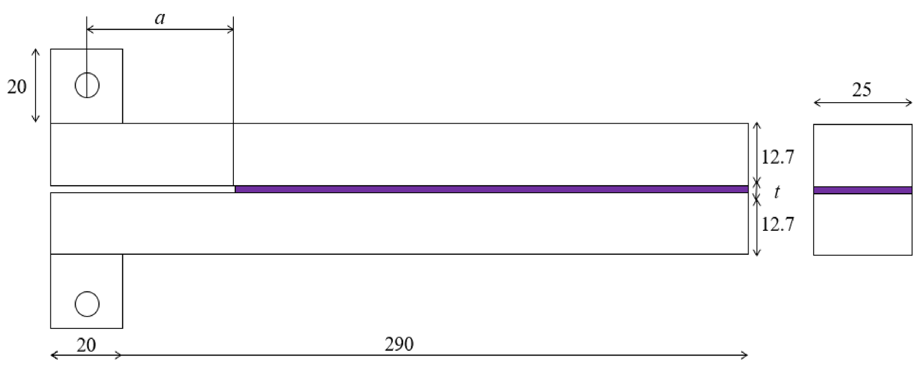

Figure 1 – Specimens' geometry, in mm.

Testing setup

For the fracture tests, as well as for the validation tests, a digital camera lens was placed in front of the specimens, with the lens perpendicular to the observation surface, to synchronously monitor the applied load and the displacement field of areas of interest. In order to ensure the perpendicularity between the digital camera and the DCB, a laser-beam was used. Figure 2 depicts a correctly aligned beam reaching the digital camera.

Figure 2 – Laser-based approach for perpendicularity (left) and laser detail (right).

DIC method

During the application of the DIC technique, both initial crack tip displacement and rotations in the loading points were registered. A method (ref) was used to calculate rotations from the displacements of the inspection points, in the DIC software, resorting to the expression $\theta = {}^{dy}/_{dx}$. In Figure 3 it can be observed the points in the positions where they are going to be analysed.

Figure 3 – Marked points in the DIC software (left) and displacement field of one test (right).

Traction-separation law (TSL)

The experimental law is obtained by combining the values of the fracture toughness, estimated using the J-integral approach, with the values of the crack tip opening displacement. Equations 1 and 2 represent the expressions for J-integral and the cohesive law, respectively.

$$J = \frac{P}{b} \cdot \left(\theta_{up} - \theta_{up}\right) \tag{1}$$

$$\sigma = \frac{J_{t+\Delta t} - J_t}{\delta_{n_{t+\Delta t}} - \delta_{n_t}} \tag{2}$$

Where P is the applied load, b is the width of the specimen, θ is the rotation of the substrate (upper and lower) in the loading point and δ_n is the crack tip opening displacement.

Results

Experimental results

The DCB were tested under quasi-static conditions and their fracture toughness was calculated using the J-integral and compared with the CBBM method, as it can be seen in Figure 4. A good agreement was found, with the difference between both being less then 7%. Additionally, a cohesive zone model (CZM) model was developed to predict the adhesive behaviour. The comparison between experimental and numerical results is presented in Figure 4, where a good correlation was observed.

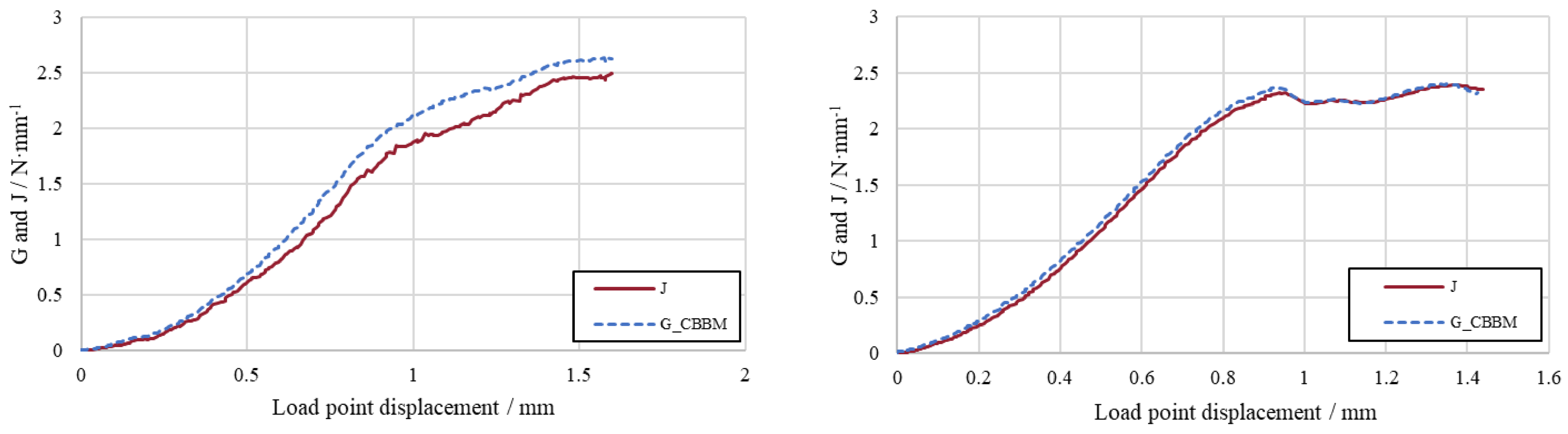

Figure 4 – Fracture toughness for adhesive A (left) and adhesive B (right).

A Savitzky-Golay filter was employed, resorting to a python script, on the experimentally obtained data to generate a smoothened cohesive law for both adhesives. The results were found to be sensitive to the parameters used in the filter, so this procedure was carefully executed to prevent the loss of important information. Figure 5 depicts the obtained cohesive laws for both adhesives.

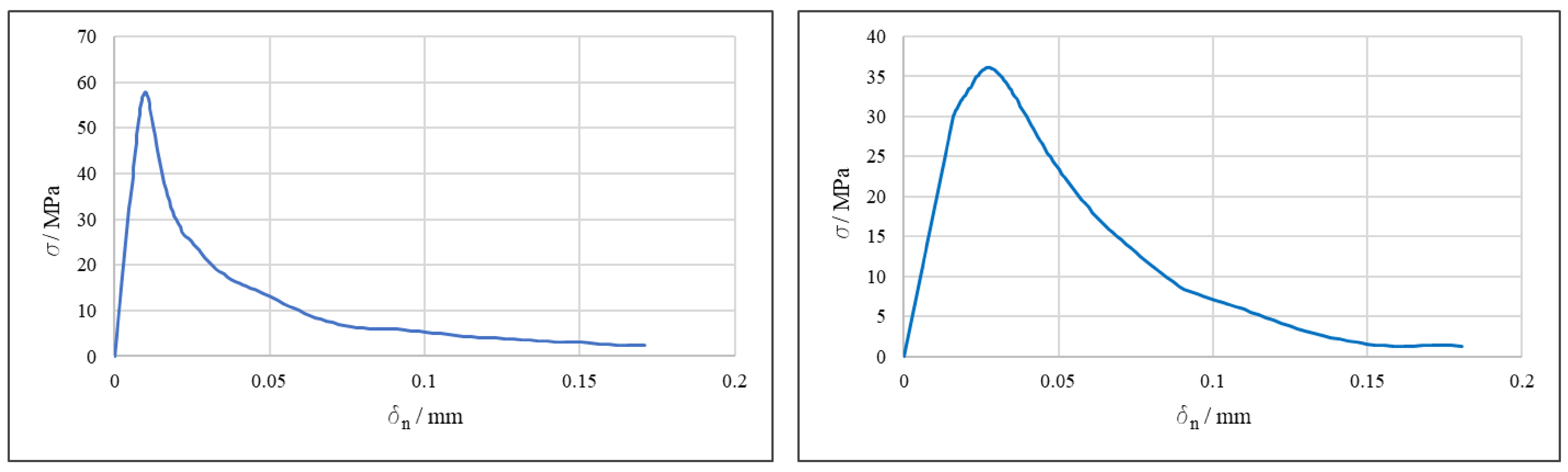

Figure 5 – Cohesive law of adhesive A (left) and adhesive B (right).

Numerical validation

The obtained TSLs were implemented in a cohesive zone model (CZM), by using an average law for each adhesive. The obtained load-displacement curves were compared to the experimental results. The model could predict the failure load with an error lower than 7%, although some differences were observed in the damage evolution, as shown in Figure 6.

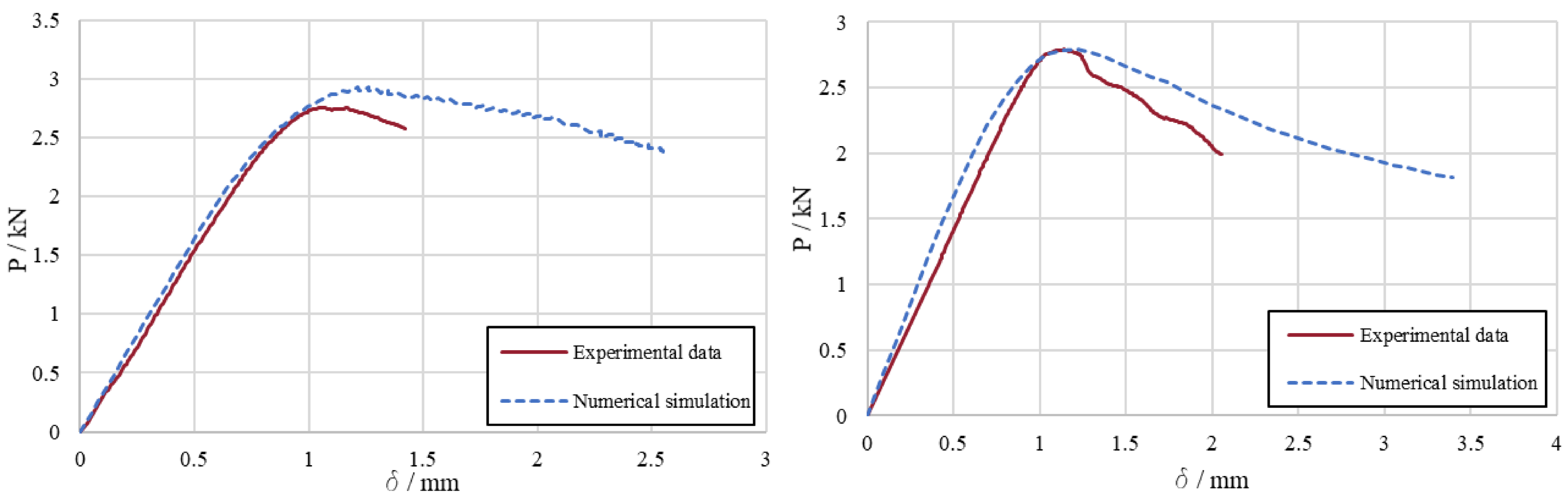

Figure 6 – Load-displacement curves for adhesive A (left) and adhesive B (right).

Conclusions

The python code, used as a post-processing tool, allowed a better analysis and preparation of the experimentally obtained data, seeking to minimize the dependency of the results obtained by the direct method on the data processing steps. The appropriate setup configuration and a thorough investigation provided the opportunity to compare the J-integral results with the CBBM method, as well as to extract the direct TSL for each adhesive. A comparison between the experimental TSLs and the numerical simulations showed difficulties in describing with precision the failure processes by the CZM modelling. However, the overall features were acceptable.

References

[1] M. Costa, G. Viana, R. Créac'hcadec, L. F. M. da Silva, and R. D. S. G. Campilho, "A cohesive zone element for mode I modelling of adhesives degraded by humidity and fatigue," International Journal of Fatigue, vol. 112, pp. 173-18 , 2018/07/01 2018, doi: 10.1016/j.ijfatigue.2018.03.014.

[2] F. Sun and B. R. K. Blackman, "A DIC method to determine the Mode I energy release rate G, the J-integral and the traction-separation law simultaneously for adhesive joints," Engineering Fracture Mechanics, vol. 234, p. 107097, 2020/07/01 2020, doi: 10.1016/j.engfracmech.2020.107097.

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