NUMERICAL CALIBRATION OF THE MECHANICAL PROPERTIES OF AN ADHESIVE MATERIAL

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Abstract

For a number of years the aerospace industry has been making increasing use of composite materials for manufacturing many aircraft parts, with the different parts being joined by means of adhesives. The verification of an aircraft design requires establishing the response of all of its components under the various loading scenarios, a verification that strongly relies on computational tools. In this context, one of the challenges faced by the finite element analyses performed is to ensure that the actual behaviours of the different parts of the global structure are adequately represented in the simulation. The objective of the present work is to produce reliable analyses, using the finite element method, of the response of structures made of composite materials and bonded by means of adhesive materials.

1. Introduction

The increasing use of composite materials in the aircraft industry is explained by the reduction of weight and the structural response achieved. As a consequence of those advantages many components are being manufactured using composite materials and linked to each other by means of adhesives. It is therefore crucial to have a good understanding of the behaviour of such structures including their post-failure response.

The finite element method (FEM) is well-established in the aeronautical industry as a tool that allows studying the response of various aircraft parts subjected to hundreds of different loads cases. The more critical ones tend to require detailed analyses that include sophisticated mechanisms like crack evolution, post-buckling response, etc. The correct simulation of at least the main phenomena is essential for achieving realistic results from the analyses.

In the present work a number of coupons are studied using Abaqus [6] in order to correlate the results of analyses and physical tests, and to characterise the fracture toughness of a specific adhesive.

2. Object

As already mentioned, the primary object of the present work is to correlate the results of finite element analyses with the actual test observations in order to achieve an accurate characterisation of the adhesive layer. The tests performed are standard tests conducted to establish the response to tensile, shear and mixed mode demands:

- Double cantilever beam (abbreviated DCB, mode I opening)

- Calibrated end loaded split (abbreviated C-ELS, mode II opening)
- Mixed mode bending (abbreviated MMB, mode I and II opening)
- Four point bending (abbreviated 4PB)

3. Description of the tests

The tests were performed on coupons made of two or three “co-bonded” plates of composite material. The geometrical configurations and the loads applied in order to activate the various damage modes are described in the following sections.

3.1. Double cantilever beam (DCB)

The ISO 15024 standard [1] provides the specifications for this test, intended to determine the mode I interlaminar fracture toughness, G_{IC}, of unidirectional fibre-reinforced plastic. The mode I crack opening develops as shown in Figure 1, with the load *P* applied in a direction normal to the delamination plane. The DCB specimen contains a thin, non-adhesive starter film, embedded at the midplane, to simulate an initial delamination.

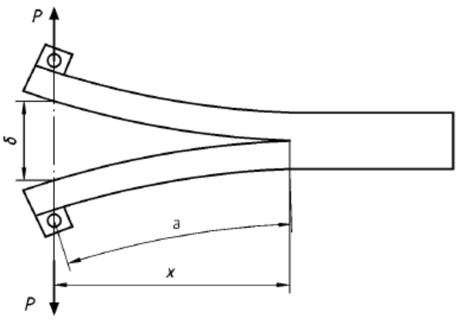

Figure 1. Configuration for DCB test.

3.2. Calibrated end loaded split (C-ELS)

This method is used to determine the delamination resistance of unidirectional fibre-reinforced polymers under mode II shear loading [2]. As in the previous case, a region is already debonded initially and the response of the structure to the load allows obtaining the interlaminar fracture toughness, G_{IIC}.

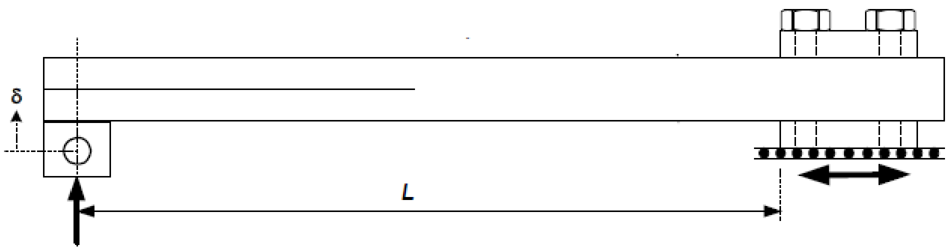

Figure 2. Configuration for C-ELS test.

3.3. Mixed mode bending (MMB)

This test [3] aims to determine the delamination fracture toughness at different ratios between modes I and II. As in the previous tests, the specimen contains a non-adhesive insert at the midplane which serves as initiator for the delamination. As shown in Figure 3, the forces are applied near the ends of the delamination section and through rollers that bear against the specimen in the non-delaminated region.

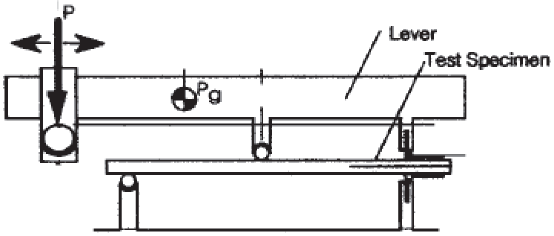

Figure 3. Configuration for MMB test.

3.4. Four point bending (4PB)

The object of this test is to evaluate the interlaminar shear strength [5]. A bar with rectangular cross-section is loaded in bending as a simple beam to induce a shear failure. The bar rests on two supports and the load is applied at two points, as shown in Figure 6.

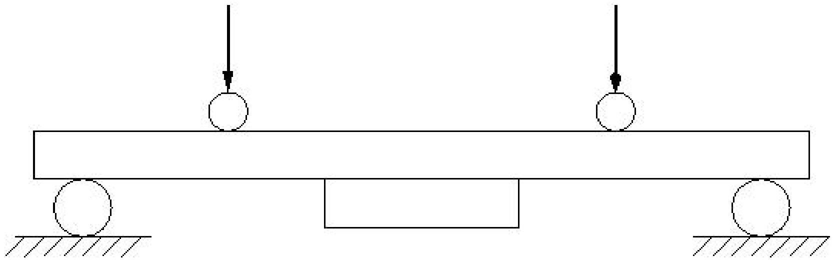

Figure 6. Configuration for 4PB test.

4. Numerical approach

Finite element models were built to study the response of the specimens under the different scenarios described in the previous section. The calculations were carried out with Abaqus/Standard [6].

4.1. Finite element model. Discretisation

The model constructed for the DCB test is shown in Figure 7, which includes a general view of the mesh and a more detailed one. The suitability of the model was confirmed by sensitivity analyses, varying mesh refinement, element type and boundary conditions. The model adopted uses solid elements C3D8R from the Abaqus library, with four elements across the thickness of each plate. Similar strategies were followed for the rest of the tests.

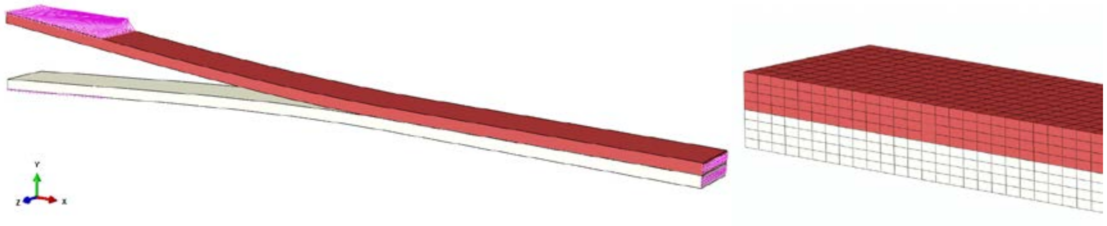

Figure 7. Finite element model for DCB test.

4.2. VCCT criterion

The Virtual Crack Closure Technique (VCCT) criterion models the adhesive layer between the plates and uses the principles of linear elastic fracture mechanics (LEFM). VCCT is based on the assumption that the strain energy released when a crack is extended by a certain amount is the same as the energy required for closing the crack by that same amount.

In Figure 8, nodes 2 and 5 will start to separate when:

$$\frac{G_I}{G_{IC}} = \frac{1}{2}\left(\frac{v_{1,6}F_{v_{2,5}}}{bd}\right)\frac{1}{G_{IC}} \geq \mathbf{1.0} \tag{1}$$

where G_I is the mode I energy release, G_{IC} is the critical mode I energy release, b and d correspond to the dimensions of the element at the crack front, $F_{v2,5}$ is the vertical force between nodes 2 and 5, and $v_{1,6}$ is the vertical displacement between nodes 1 and 6.

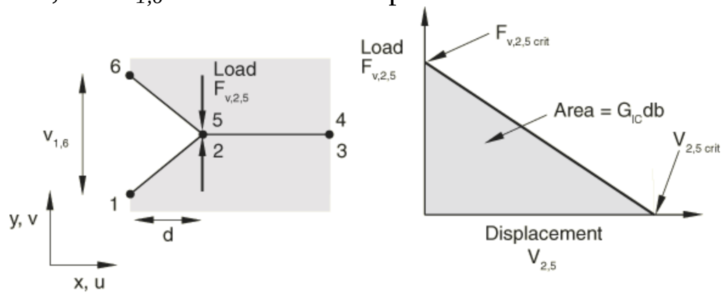

Figure 8. VCCT for pure Mode I.

Within VCCT, Abaqus provides the BK (Benzeggagh and Kenane) law for dealing with mixed-mode phenomena. The BK law is described by (2):

$$G_{equivC} = G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_{II}+G_{III}}{G_I+G_{II}+G_{III}}\right)^{\eta} \tag{2}$$

The model requires defining the toughness in pure modes I and II, as well as the exponent η. As a result the energy release rates in modes I, II and III are combined into a single scalar fracture criterion.

A second possibility offered by Abaqus, also used in the present analyses, is the power law:

$$\frac{G_{equiv}}{G_{equivC}} = \left(\frac{G_I}{G_{IC}}\right)^{a_m} + \left(\frac{G_{II}}{G_{IIC}}\right)^{a_n} + \left(\frac{G_{III}}{G_{IIIC}}\right)^{a_o} \tag{3}$$

The power law (3) requires defining the exponents, only the first two in the present cas, a_m and a_n, since it was not used for combining with the third mode.

4.3. Materials

The coupons were manufactured using a composite material and an adhesive layer, following standard manufacturing and surface preparation processes of the aeronautical industry. From a numerical standpoint, an orthotropic elastic material is used to describe the plies through the thickness of the coupons; the toughness of the adhesive layer was taken from the tests.

5. Results and discussion

The numerical simulations of the tests are presented in the following sections, they generally provide a good representation of the tests.

5.1. Double cantilever beam (DCB)

A number of analyses were performed to evaluate the dependence on parameters such as coupon geometry, mesh size, element type, load point, and VCCT parameters. Figure 9 shows a comparison of the actual tests and the simulation, which describes well the evolution of damage. To achieve good results it is important to use realistic values of the thickness of the coupons, as the bending stiffness is very sensitive to this parameter.

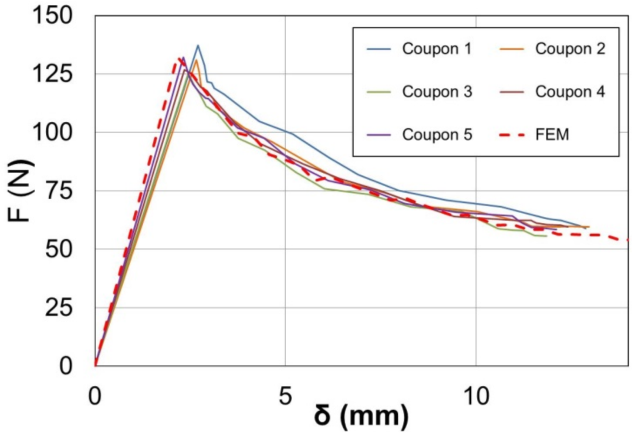

Figure 9. DCB test. Force vs displacement

5.2. Calibrated end loaded split (C-ELS)

As in the previous section, a number of tests served as baseline to calibrate the pure mode II behaviour. The response of the coupons under shear is well reproduced by the model, as shown in Figure 10. The stiffness discrepancies observed could arise from differences in thickness, load point location, and initial crack length. In any case, the peak force and damage evolution seem to have been correctly reproduced.

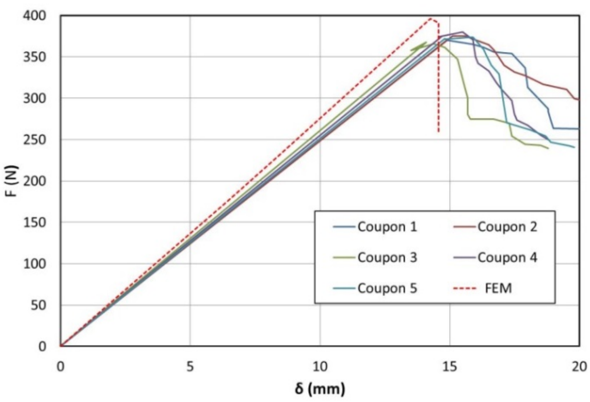

Figure 10. C-ELS test. Force vs displacement

5.3. Mixed mode bending (MMB)

This test combines damage modes I and II and was carried out for two different energy ratios G_{II}/G. Three coupons were tested with energy ratio G_{II}/G = 0.3 and three coupons with G_{II}/G = 0.7. Different values of η were obtained from each group of coupons, using the BK law equation. In particular, η = 3.8 was calculated for G_{II}/G = 0.3 while η = 4.5 was determined for G_{II}/G = 0.7. As shown in Figure 11, for coupons with G_{II}/G = 0.3 the results showed little sensitivity to the parameter η, at least for the range studied. The figure confirms again the quality of the simulation. Figure 12 compares the results of using the BK law and the power laws for the same group of coupons.

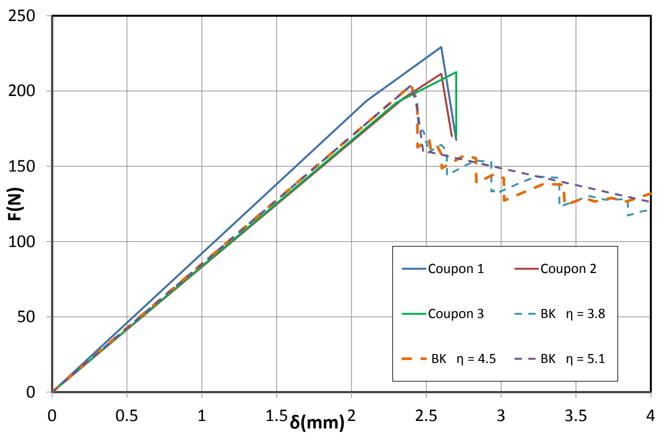

Figure 11. MMB. Force vs displacement, sensitivity to η

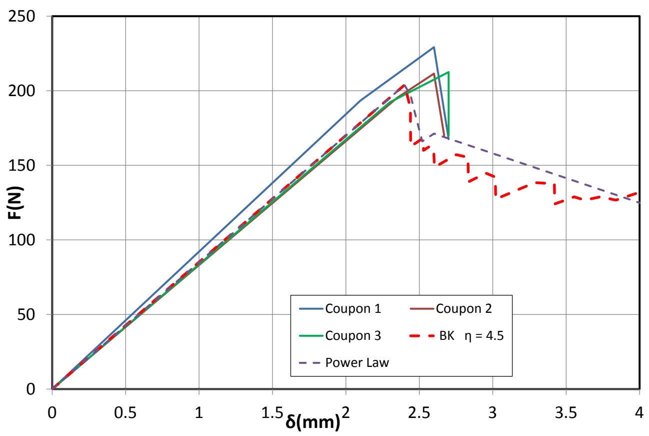

Figure 12. MMB. Force vs displacement, sensitivity to η

5.4. Four point bending (4PB)

As shown in Figure 13, the test stiffness is well represented in the numerical model, though the onset of damage is underpredicted by the simulation. This could arise from the fact that the VCCT technique needs an initial crack to start the propagation, while the test specimen was not pre-cracked in the present case.

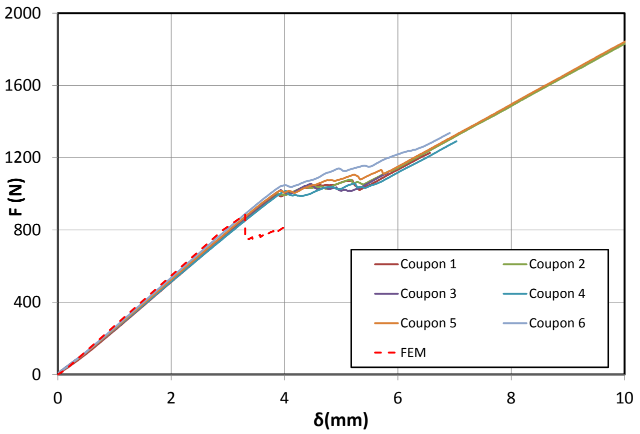

Figure 13. .4PB. Force vs displacement

6. Conclusions

Four different tests have been modelled to simulate the debonding of structures made of composite materials joined with adhesives. The numerical calibration of the material was based on a series of tests specifically designed to evaluate the response of the adhesive. The main interest here is to identify the most promising approaches to analyze adhesive joints in models of aeronautical industry components.

As a result of the work performed the following conclusions can be offered:

a) A good agreement was generally found between the numerical simulations and the actual tests. Hence the numerical strategies described must be considered suitable for simulating the debonding process in structures formed by composite materials glued with adhesives.
b) Sensitivity analyses were performed in respect of various parameters, such as mesh refinement, element type and tolerances used by VCCT. One observation is that the mesh in the region surrounding the adhesive needs to be sufficiently fine to capture the softening associated with the debonding process.
c) Special care must be exercised when defining the initial crack length and the locations at which the loads are placed; such parameters influence the initial flexural stiffness in both DCB and C-ELS tests and, if not sufficiently accurate, could impair the quality of the simulation.

References

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