Determination of Cohesive Parameters for Mode II of Epoxy Adhesive

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The paper deals with the determination of cohesive parameters of adhesive Scotch-Weld DP490 3M. Mode II of cohesive damage were examined. Experimental testing was performed on the test specimens to determine the mechanical properties of the adhesive according to ASTM D7905. The results of the experimental testing were compared with the numerical simulation of the same test. The cohesive parameters of the adhesive were obtained from the numerical simulation. Cohesive parameters of adhesive can be used to design real complex adhesive bonded joints. Cohesive models (specifically cohesive contacts or cohesive elements) are one of the most accurate methods of modeling adhesive bonded joints, so this method is mainly used for parts where it is necessary to ensure sufficient strength, such as in automobile, aviation, etc. Based on numerical simulation cohesive parameters of adhesive Scotch-Weld DP490 for mode II were obtained. Critical value of the strain energy release for Mode II conditions ($G_{IIc}$) was determined to be equal to 2 321.3 [J/m$^2$/N/m]. Stiffness of the adhesive ($k_{II}$) was determined to be equal to 140 [GPa/m].

Keywords: Cohesion, Strain energy, Scotch-Weld DP490 3M, Mode II, ENF

1 Introduction

Composite materials are becoming more and more used materials not only in aerospace and automotive industries but also in other industrial sectors where a high strength and stiffness at low weight is required [1], [2], [3], [4]. In aerospace and automotive industries (for luxury and sports car) the fiber reinforcement composite materials are most frequently used. For joining of those composite materials with metals the adhesive bond is most frequently the best option. The advantages of adhesive bonds are that they have no Heat-affected zone (such as welding [9]) and they do not need to drill holes (stress concentrators).

Within our research we are designing the methodology of predicting the strength of bonded composite material with metals when designing their structure. With the use of experimental testing and numerical simulations. In practice this methodology should be simply applicable to the majority of real components.

The overall quality of the adhesive bond is influenced by many factors. To the most significant ones belong: the material of adhesive components, the surface treatment of adhesive areas [10], the quality of degreasing of adhesive areas (These factors were examined [11]). Another, but no less important, factors are the type of adhesive, the thickness of adhesive layer, the technology of adhesion, etc.

On adhesion properties, specifically on influence material of adhesive components and the surface treatment of adhesive areas were focused the paper [11].

This paper is focused on cohesive properties [16] of adhesive, especially on critical strain energy release rate for mode II ($G_{IIc}$), stiffness of the adhesive ($k_{II}$) and maximum load force ($F_C$).

Cohesive properties of adhesive are linked with specific type of adhesive. Cohesive properties of adhesive are not dependent on the material of adhesive components, the surface treatment of adhesive areas and the quality of degreasing of adhesive areas. However, high strength adhesives can often cause adhesion failure. Therefore it is very important to design a suitable combination of „material-adhesive-surface treatment“.

The goal of this article is to determine the cohesive properties of epoxy adhesive Scotch-Weld DP490 3M. In this case it is the determination of cohesive parameters for mode II specifically.

2 Cohesive properties

There are three independent fracture modes. The crack opening mode (Mode I) is described in detail in [8]. The in-plane shear mode (Mode II) and out-plane shear mode (Mode III) always possess very similar values of fracture toughness and stiffness. That is the reason why only parameters for mode II are often determined and mode III is considered the same. There is also a combination of these modes called ‘Mixed-mode’. The individual modes of crack opening are shown in Figure 1. [6] Particular cohesive models are given in [5], [6], [13], [14]. Complex methodology of adhesive bonded joints design is described in [7].
3 Specimens

The dimensions of the specimens were defined by standard ASTM D7905 [15] for ENF test - mode II. ENF stands for End Notched Flexure. This standard does not define the exact dimensions of the specimen, but ranges of each parameters (Table 1). The shape of the specimens is shown in Figure 2.

**Tab. 1** Dimensions of specimen according to ASTM D7905

| Parameter | Name                          | Norm dimensions [mm] | Selected dimensions [mm] |
|-----------|-------------------------------|----------------------|--------------------------|
| L         | specimen half-span            | 50                   | 50                       |
| L<sub>c</sub> | Overhang closer to <i>a<sub>i</sub></i> | ≥15                  | 25                       |
| L<sub>u</sub> | Overhang further from <i>a<sub>i</sub></i> | ≥15                  | 55                       |
| <i>a<sub>i</sub></i> | initial delamination length | 30                   | 30                       |
| <i>a<sub>i</sub></i> | insert length in the trimmed specimen | ≥45                  | 75                       |
| R<sub>1</sub> | radius of the loading roller | 4.7 ± 9.6            | 5                        |
| R<sub>2</sub> | radius of the support rollers | 3.0 ± 6.0            | 5                        |
| B         | specimen width                | 19 ± 26              | 20                       |
| T         | specimen thickness            | 3.4 ± 4.7            | 3.5                      |

Fig. 2 Dimensions of specimens ENF test

The specimens were made using a water jet cutting machine. The advantage of using water jet cutting is that it achieves very good sample size accuracy. However, it is necessary to use the appropriate machine settings. In general, low pressure with gradually increased water pressure and early abrasive flow is optimal for composite laminate machining [12]. The individual parameters of the material are given in Table 2.

**Tab. 2** Material properties of the samples

| Shortcut | Name                        | Value |
|----------|------------------------------|-------|
| E<sub>11</sub> | Young’s Modulus axial direction | 31 [GPa] |
| E<sub>22</sub> | Young’s Modulus transverse direction | 29 [GPa] |
| E<sub>33</sub> | Young’s Modulus normal (out-of-plane) direction | 15 [GPa] |
| G<sub>12</sub> | Shear Modulus axial direction | 4.4 [GPa] |
| G<sub>13</sub> | Shear Modulus transverse direction | 4.4 [GPa] |
| G<sub>23</sub> | Shear Modulus normal (out-of-plane) dir. | 3.9 [GPa] |
| ν         | Poisson’s Ratio in plane     | 0.13[-] |

4 Experimental testing

Experimental testing of samples was performed on the Zwick/Roell Z050 machine. It is a static material testing machine with a maximum force of 50 kN, equipped with extensometers and several types of jaws.
The samples are placed on two support rollers and by means of a load roller, the sample is pressed in the center. The testing happened quasi-statically. The speed of jaws’s shift was set to 1.5mm/min according to ASTM D7905 [15]. In this measurement, the loading force [N] and the displacement [mm] of the samples were subtracted using extensometers. The figure 3 shows the progress of the ENF test in several selected phases.

5 Numerical simulation

Cohesive model is created in software Abaqus 6.14. This is a nonlinear solution. Laminate beams are made of 3D elements (type BRICK). Dimensions and material properties are the same as for real test specimens (Figure 2, Table 2). A cohesive contact is set between two beams. The specimen is placed on two support rollers (with contact) and on set points is applied forced displacement. Lower surface of support rollers is fixed.

Computational model of ENF test is given in Figure 4. Examples of results of numerical simulation of ENF test are shown in Figure 5 and 6. Results of numerical simulation and experimental testing ENF tests are given in Figure 7.

![Numerical model](image)

**Fig. 4** Numerical model

![Example of results of numerical simulation ENF test](image)

**Fig. 5** Example of results of numerical simulation ENF test – results of displacement (m)

![Example of results of numerical simulation ENF test](image)

**Fig. 6** Example of results of numerical simulation ENF test – results of shear stress (Pa)

6 Summaries of the obtained parameters

We are interested in stiffness of the adhesive ($k_{II}$), maximum load force ($F_{CII}$) and critical value of the strain energy release for Mode II conditions ($G_{IIc}$) for design and simulation of the adhesive bonded joints.

Using experimental testing and numerical simulations, we obtained the necessary parameters:

$$k_{II} = 140 \text{ [GPa/m]} \quad (1)$$
$$F_{CII} = 335 \text{ N} \quad (2)$$
$$\Delta c_{II} = 11.7 \text{ mm} \quad (3)$$
$$G_{IIc} = 2.321.3 \text{ J/m}^2 \quad (4)$$

Where: $\Delta c_{II}$ is value of displacement appropriate to $F_c$.

We already know cohesive parameters for mode I for cohesive parameters of adhesive Scotch-Weld DP490 3M from [8].

$$k_I = 200 \text{ [GPa/m]} \quad (5)$$
$$F_{CI} = 26.66 \text{ N} \quad (6)$$
$$\Delta c_I = 21.393 \text{ mm} \quad (7)$$
$$G_{IC} = 905.5 \text{ J/m}^2 \quad (8)$$

Usually we require that the adhesive bonded joint is operated before the first failure. The first part (from 0 to $\Delta c$) of the chart (Fig. 7) describes the stiffness of the adhesive (to the first failure). The second part (after $\Delta c$) of the chart describes the damage progress. Therefore, the accuracy in the first part of the chart is more important to us. However, it may sometimes be useful to model the progress of material failure. We
can simulate progress of material failure using cohesive parameters.

Because we already know cohesive parameters for mode I and mode II and parameters for mode III can be considered identical to the parameters of mode II, we have everything you need for modeling complex adhesive bonded joints in numerical simulations. Comprehensive design methodology of adhesive bonded joint is described in detail in [7].

7 Conclusion

The goal of this article was to determine the cohesive properties of mode II of epoxy adhesive Scotch-Weld DP490 3M. Experimental testing of samples was performed and compared with numerical simulation of ENF tests.

Based on numerical simulation cohesive parameters of adhesive Scotch-Weld DP490 for mode II were obtained. Critical value of the strain energy release for Mode II conditions ($G_{IIc}$) is equal to 2321.3 [J/m^2=N/m]. Stiffness of the adhesive ($k_{II}$) is equal to 140 [GPa/m]. Critical force ($F_{cII}$) is equal to 335 N and displacement appropriate to critical force ($\Delta c_{II}$) is equal to 11.7 mm. Obtained cohesive parameters of adhesive can be used to design real, shape complicated adhesive bond. We have everything you need for modeling complex adhesive bonded joints in numerical simulations.

Acknowledgments

This paper is based on work sponsored by project SGS2019-001 (The complex support of designing of technical equipment IV).

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