INVESTIGATION OF BULK ADHESIVE MATERIAL AND THICK ADHESIVE JOINTS FOR WIND TURBINE APPLICATIONS

Jialiang Fan[a], Javane Karami[b], Ali Kojouri[b], Danny Van Hemelrijck[b], Anastasios Vassilopoulos[c], Veronique Michaud[a].

a: Laboratory for Processing of Advanced Composites (LPAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland – jialiang.fan@epfl.ch.
b: Vrije Universiteit Brussel, Brussel, Belgium.

c: Composite Construction Laboratory (CCLab), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland.

Abstract: *Adhesive joints connecting the outer shells of wind turbine blades can reach up to several cm in thickness. This leads to particular requirements in terms of processing and assessment of the mechanical properties and resistance to damage of these joints. In this paper, a commercial epoxy adhesive designed for wind turbine blades, Sikapower®-830, was characterized. Rheological and mechanical properties were assessed on the bulk resin, which were obtained during this study. The yield stress of the uncured adhesive is about 400 Pa, which is required by the manufacturing process. The fracture toughness of the cured resin, K_{IC}, is 2.79 MPa√m. Its Young's modulus is about 2.5 GPa and tensile strength is about 40 MPa. Based on its rheological properties, double cantilever beam (DCB) specimens were produced with thick adhesive layers by adding and removing spacers during production. During the DCB tests, stick-slip and crack-kinking occurred, changing from stable to unstable crack propagation. Defined sample manufacturing methods and commercial epoxy adhesive results are shown in this paper and will be used for the development of novel adhesive formulations.*

Keywords: Adhesives; Thick joints; Fracture; Mode I

1. Introduction

Thick adhesive joints are widely used in wind industry, shipbuilding, and bridge construction [1]. For example, wind turbine blades are usually made with two skins and webs that are connected with a structural adhesive. The length of blades keeps increasing over the last decades to favor power extraction, which also leads to an increase in the adhesive layer thickness [2]. The bond thickness varies along with the shape of the blades, from several millimeters to centimeters. Adhesive formulations for wind turbine blades need to have sufficient viscosity and yield stress to maintain the shape of the layer after being applied to the composite skin surface during manufacturing. During operation, these adhesive joints endure mixed-mode static and fatigue loading [3,4]. As a result, the bulk adhesive should also have excellent mechanical properties, such as high ultimate strength, high E-modulus and high fracture toughness.

Limited research has been focused on the behavior of thick adhesive joints. Lopes Fernandes et al. [5] studied the mode I fracture behavior of DCB joints with varying adhesive thickness, from 0.4 mm to 10.1 mm. The critical mode I strain energy release rate (G_{Ic}) of joints with 10.1 mm thick adhesive layer was much higher than the G_{Ic} of joints with 0.4-2.6 mm thick adhesive layers, by about 46 %. Crack path, fracture surface and the stress field ahead of the crack tip are the reasons for this increase. Rosendahl et al. [6] tested DCB joints with 6 mm and 12 mm thick silicone sealant adhesive layers. They suggested that when the joints were thick enough, the G_{Ic} values became independent of adhesive thickness. In this case, they could determine the bulk material fracture toughness from joints with 6 mm and 12 mm thick adhesive layers. Xu et al. [7] carried out fatigue tests with DCB joints with 0.2 mm and 1 mm thick adhesive layers. Thicker ones showed lower fatigue growth rates. So far, thick adhesive joint behavior is not well understood.

This study focuses on the investigation of adhesives for wind turbine blades by conducting bulk material and thick adhesive joint tests, including rheology yield stress, tensile, single edge notch bend (SENB), and DCB joint tests. Sample preparation protocols are defined for these tests with preliminary test results given in this paper.

2. Materials and experimental methods

2.1 Materials

The material used is the epoxy adhesive, Sikapower®-830 (SP830) delivered by Sika Technology AG. It is a two-component epoxy adhesive specifically designed for wind turbine rotor blade connections. The two-component weight mixing ratio is 100:47. The demolding agent for bulk material sample fabrication is Sika liquid wax-815.

Adhesive joints were produced using the SP830 adhesive and glass fiber reinforced epoxy adherends. Unidirectional glass fabric with 425 g/m^2 areal weight from P-D interglas technologies GmbH was used as the reinforcement. EPIKOTE Resin MGS RIMR 135 and EPIKURE Curing Agent MGS RIMH 137 from Hexion Inc were used as two-component infusion epoxy resin to produce the composite adherends.

2.2 Processing Methods

Rheology tests were conducted immediately after mixing the SP830 A and B components in order to explore the yield stress without the influence of epoxy polymerization. As for the other bulk material test specimens for the tensile and the SENB tests, SP830 was mixed and degassed under vacuum for 10 mins in order to reduce void volume. Degassed epoxy was poured and cured within aluminum molds, treated with a demolding agent. After pouring, the epoxy was cured at 70 degrees for 4 hours, according to the datasheet provided by Sika.

Tensile test dog-bone specimens were shaped following the ASTM D638 standard with Type I dimensions [8]. The dimensions of the SENB specimens were 10×20×130 mm. After curing, dog-bone specimen edges were polished with 220 grit SiC sandpaper. The 10 mm pre-crack of the SENB specimens was obtained by cutting the first 8 mm with a circular saw blade of 0.6 mm thickness and the next 2 mm with a thin saw with 0.16 mm blades.

The DCB joint specimen adherends were made by cross-ply composite laminates $[90/0]_{7S}$ fabricated by vacuum assisted resin infusion. The composite was cured at room temperature for 24 h and post-cured at 60 degrees for 9.5 h with a temperature ramp rate of 0.3 degrees per minute and 80 degrees for 6 h.

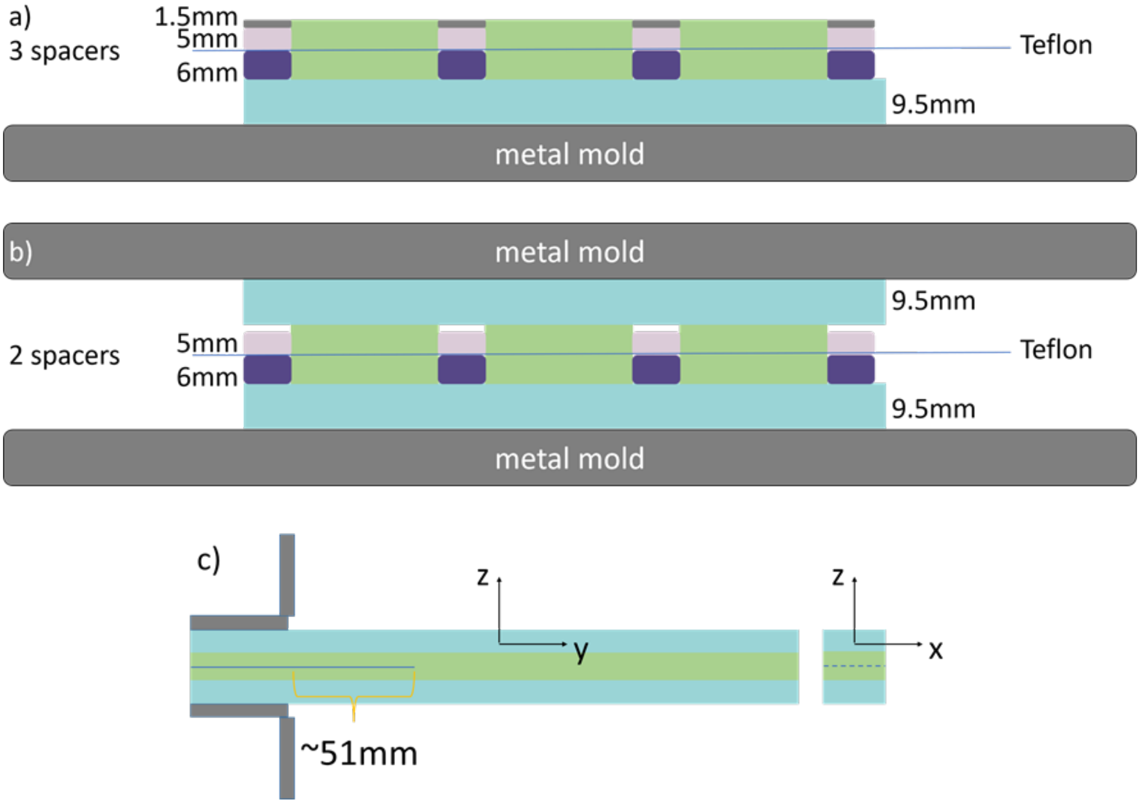

Figure 1 DCB joint production process: a) sketch after placing 3 spacers and controlling epoxy thickness. b) sketch after removing third spacers and placing top adherend and metal mold. c) sketch of DCB adhesive joint with piano hinges.

The thickness of the epoxy adhesive layer was controlled by aluminum spacers. Due to the interaction between the scraper and the high viscosity material, the scraped surface was not flat, excess epoxy was dragged out by the scraper. As a result, the top composite adherend could not touch the entire epoxy surface. In this study, DCB joints were produced successfully using an additional spacer, which was removed in a second stage after scraping to ensure better contact between the adhesive and the composite skins. Figure 1 illustrates the process of making DCB joints with 12 mm thick adhesive layer. First, epoxy was mixed and degassed, 6 mm spacers were placed and epoxy was poured into the cavity. After flattening the surface with a scraper, a Teflon sheet was inserted for pre-crack positioning. Then, the other two spacers were added and further epoxy was poured into the cavity. Afterward, the third spacers were removed, and the top composite and metal mold were placed on the top. The whole mold and joints were cured at 70 degrees for 6 hours and then the DCB joints were cut into 25.4 mm×250 mm dimensions. The specimens were polished with 220 grit SiC sandpaper and painted for the DIC technique. The piano hinges were also glued on the specimens before testing. The fabric direction of the layer in contact with the adhesive was parallel to the x-direction, as shown in Figure 1c.

2.3 Test procedures

A rheometer (Anton Paar, MCR 302e) equipped with 25 mm aluminum plates was employed for the yield stress tests. Experiments started with mixing two components and immediately filling epoxy in between two plates. After setting the gap to 1 mm, there was a relaxation period of 2 mins and 5 s pre-shear with 0.01 s^{-1} shear rate. The shear rate sweep was from 0.01 to 10 s^{-1}. In the end, shear stress at 0.1 s^{-1} was considered as the yield stress.

Tensile tests were performed with a universal testing machine (Walter + Bai AG, LFM-125 kN, Switzerland) using a 10 kN load cell with ±0.5 % accuracy. The test speed was 2 mm/min. Tensile test specimen elongation was measured with a clip-on extensometer.

SENB tests were carried out with a universal testing machine (Instron 4505) equipped with 10 kN load cell having ±0.5 % accuracy and 20 mm diameter support. The loading spam was 80 mm and the test speed was 1 mm/min.

DCB joint tests were conducted with the same machine as that used for the tensile tests. DCB joints were tested with the initial loading and reloading process and the test speed was 2 mm/min. All the tests were executed at room temperature.

3. Results and discussion

3.1 Bulk material test results

Bulk material test results are illustrated in Table 1. SP830 has sufficient yield stress to avoid spontaneous flow of a few cm thick layer. The presence of a silica filler and other ingredients forms a network that resists flow, but this also results in high viscosity for the epoxy adhesive. This high viscosity further causes some problems during specimen manufacturing, such as the presence of porosities and the difficulty of precisely controlling thickness.

Figure 2a shows the obtained stress-strain curves. High ultimate strength and E-modulus are the prerequisites of the envisaged applications. Voids are found on the fracture surface (Figure 2b). The possible source could be the trapped air from mixing and from transferring epoxy to the mold. The adhesive is highly viscous and the degassing procedures during sample preparation still leave lots of trapped air inside.

SENB test curves are presented in Figure 3a. The average max load is around 360 N and the K_{Ic} of epoxy adhesive is 2.79 MPa√m, while the fracture toughness of most nanomaterial toughened epoxy is within 0.5-2 range [9]. Figure 3b presents one SENB fracture surface, the white color surface area is rough and created under stable crack propagation, while the green color area results from the manual fracture after the test.

Table 1: Bulk material test results for SP830.

Rheology test	Viscosity [Pa·s at 10s^{-1}]	71.60
	Yield stress [Pa]	428.27
Tensile test	elongation at break [%]	2.87±0.31
	ultimate strength [MPa]	41.59±1.15
	E-modulus [GPa]	2.57±0.12
SENB test	Max load [N]	362.97±13.41
	K_{Ic}[MPa√m]	2.79±0.07

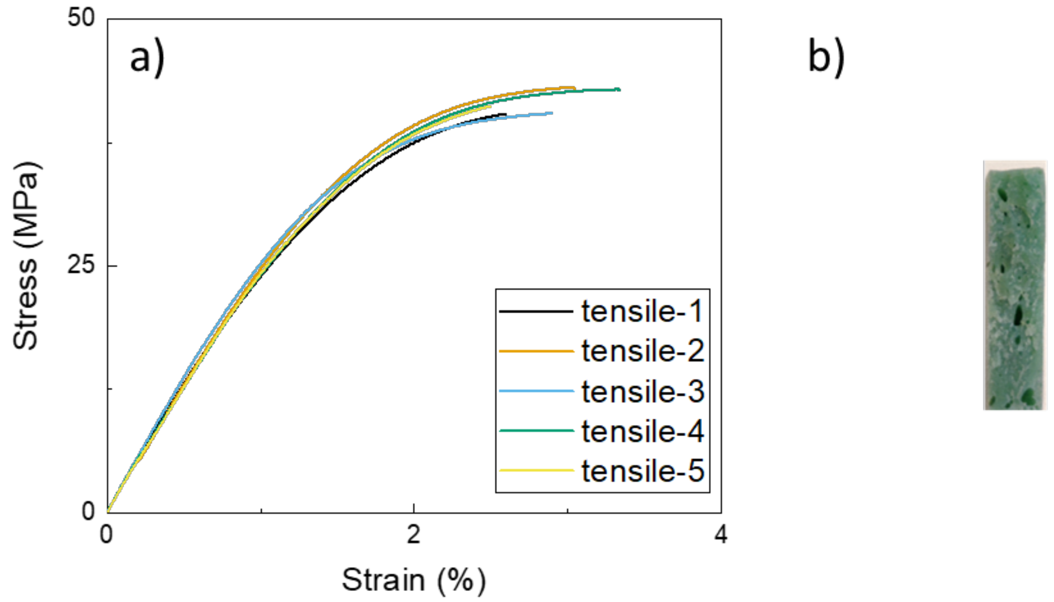

Figure 2 a) Tensile test stress-strain curves for SP830. b) Fracture surface of a tensile test dog-bone specimen.

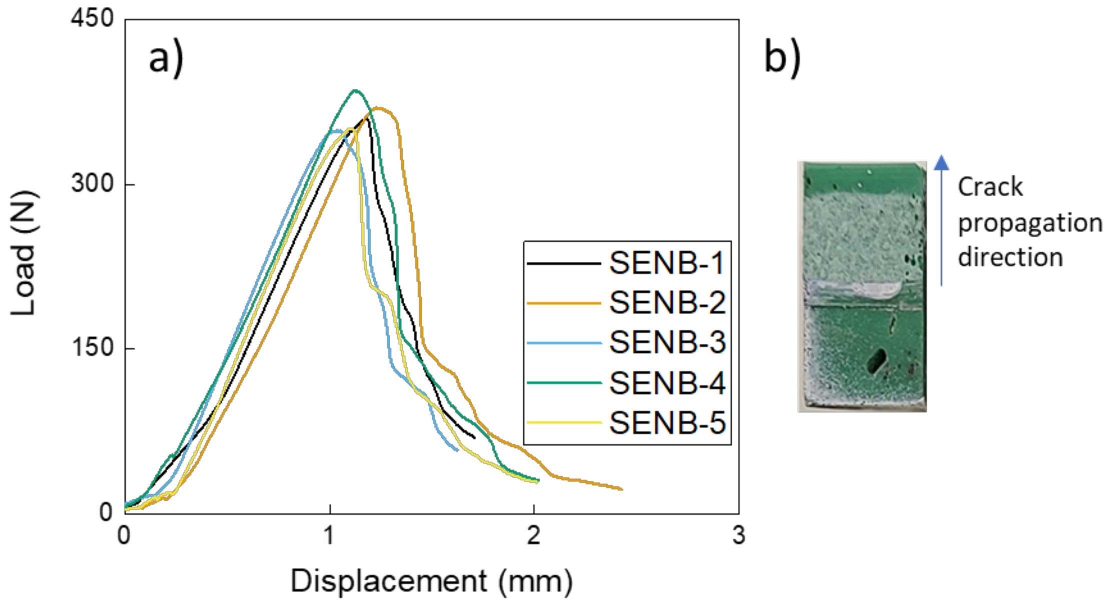

Figure 3 a) SENB test load-displacement curves for SP830. b) Fracture surface of a SENB specimen.

3.2 DCB joint test results

Figure 4a illustrates a typical load-displacement curve obtained during the DCB tests. At first, there was a short stable propagation within the adhesive layer. Afterward, stick-slip and crack kinking occurred during DCB joint tests. The crack was initially arrested within the composite adherend, and then, propagated in between the first and second layers of fabric.

The two propagation regions are also observed from the fracture surface (Figure 4b). The white region, which is very limited in length, corresponds to the stable propagation, and the green region to the stick-slip propagation. As a result, limited relevant data points with the information on crack propagation inside the adhesive layer were obtained.

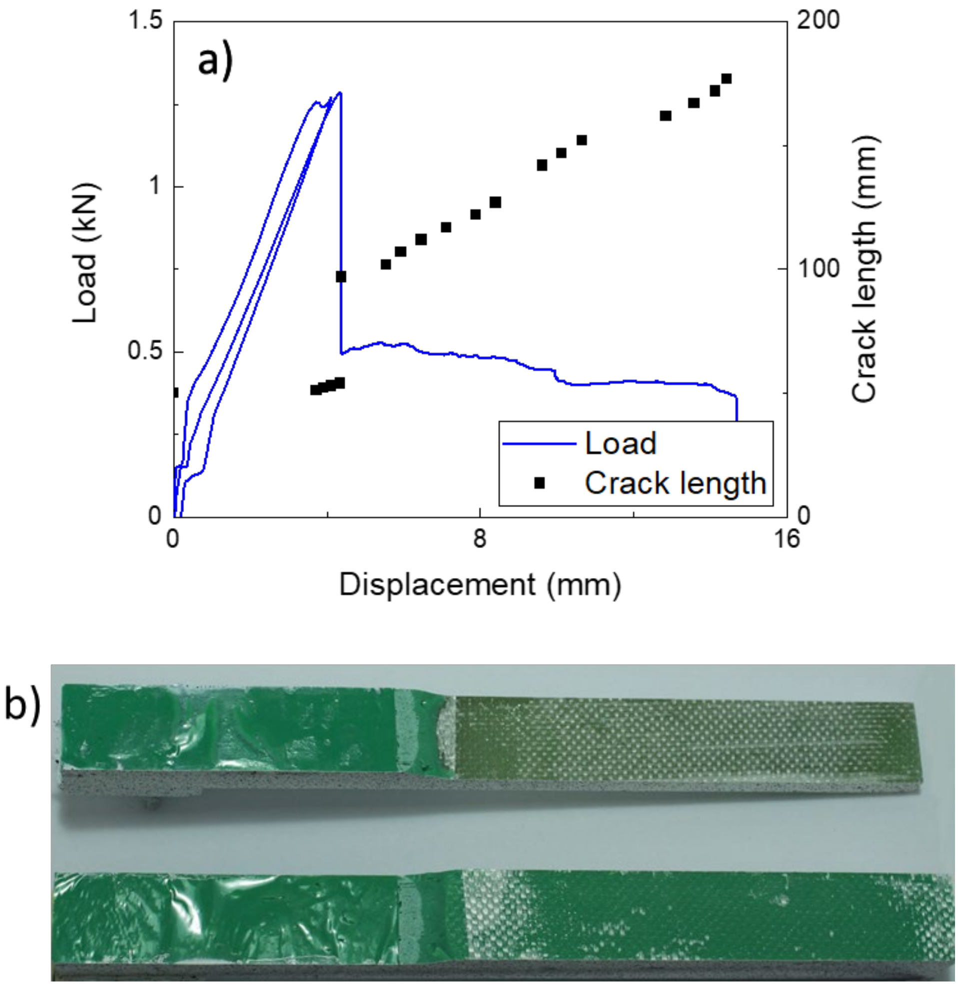

Figure 4 DCB joint with 12mm thick adhesive layer: a) load-displacement curve and b) fracture surface.

Voids are also observed on the DCB fracture surface. This could be one possible explanation of the stick-slip and crack kinking. A thin DCB joint with weak interface, i.e. very low $G_{interface}$ value, could have a similar behavior [10]. Assuming the voids as weak interface and the G_{void} to be zero, the stress field ahead of the crack tip would be influenced when the crack is near or going through the voids. This would further influence the crack propagation direction and when the void size is large enough, stick-slip occurs. More tests should be designed and conducted to prove this hypothesis.

4. Conclusions

SP830, a commercial epoxy used for wind turbine blade manufacturing has high E-modulus, high ultimate strength, and high fracture toughness. In addition, it has sufficient yield stress for the manufacturing process, which, however, leads to unwanted trapped air inside the bulk adhesive and joints.

DCB joint tests showed stick-slip and crack kinking. One possible explanation is the existence of voids leading to crack deflection. Also, the composite adherend intrinsic toughness seems to be lower than that of the adhesive, which also leads to further crack propagation into the composite. More dedicated procedures for making DCB joints will be proposed to study the influence of voids, and try to guide the propagation towards a more stable path within the adhesive phase. Nonetheless, bulk sample preparation protocols are defined and will be used for new material development.

Acknowledgements

The authors acknowledge funding under the Lead Agency scheme from the Research Foundation - Flanders (FWO Vlaanderen) through the project grant G031020N and the Swiss National Science Foundation (SNF) through the project grant 200021E_18944/1 with the title "Combined numerical and experimental approach for the development, testing and analysis of thick adhesive joints in large wind turbine blades”. The authors also acknowledge Sika Technology AG for providing materials and support.

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