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Adhesive thickness influence on a structural methacrylate adhesive behavior

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Introduction

Structural adhesive bonding importance has been growing steadily in the last decades as transport sector's current problematic is to there products' reduce mass. In addition, compared to riveting and welding, adhesive bonding offers better properties when joining dissimilar materials such as metals and composites which are a pair used more and more frequently. However, adhesive bonding suffers greatly from a lack of confidence from industries as validating the bond quality need either destructive testing or long and costly nondestructive testing. Both these solutions can hardly be implemented at an industrial level. Nevertheless, with the implementation of robotics it is possible to automate and control the entire bonding processes. In this context a collaborative project called S3PAC (Système de Supervision et de Simulation de la Production d'Assemblage par Collage) has been launched in order to offer a fully supervised and automated industrial bonding process. Each bonding steps from the cleaning of the adherends to the raw adhesive laying and the final thickness of the structure is controlled while monitoring curing time and temperature. Moreover, to assess the quality of the structure and to validate that its mechanical behavior is compatible with the part's specifications, the bonded joints characteristics are implemented in a numerical simulation.

One of this project purposes is to model a fracture behavior under complex loading of the SAF30MIB adhesive a methacrylate structural adhesive manufactured by AEC Polymers/Bostik.

In this work, the adhesive bond thickness influence will be investigated for pure modes and mixed-mode loadings. The experimental results in mode I will be compared to 2D plain stress finite element (FE) simulations and to the 1D-macro-element (ME) technique [1].

Experimental characterization of the methacrylate adhesive is carried out through the realization of tensile test on bulk adhesive, double cantilever beam (DCB) and ARCAN tests [2]. The bonded assembly tests were performed for two adhesive thicknesses 0.2mm and 1mm.

Experimentation

Experimental tests presented in this part were carried out using SAF30MIB adhesive a methacrylate adhesive manufactured by AEC Polymers/Bostik. It is a thermoplastic adhesive that polymerize at room temperature in less than 20 minutes. When testing bonded specimen, adherends are aluminum 2024 that has a measured Young's modulus and Poisson's ratio of respectively E=70GPa and υ=0.33.

a) *Tensile test on Bulk adhesive*

Bulk specimens were manufactured in a Teflon mold. According to the NF-EN ISO 527-2 standard, dog bone specimens with a length of 150mm, a width of 10mm and a height of 4mm were manufactured. The methacrylate adhesive polymerizes at room temperature but it is sensitive to oxygen and the methacrylate solvent tends to dissipate. As a consequence, once the mold imprints were filled, the adhesive overload was removed with a spatula and the imprints were recovered with a polypropylene film. The adhesive was left to cure at room temperature for 24 hours. Specimens have then been tested in monotonous tensile under a controlled displacement rate of 5mm/min on an Instron 100kN tensile machine. Displacement and strain field were obtained by 3D DIC (Digital image correlation) with two sets of Pike 505 B cameras.

b) *ARCAN tests*

Arcan specimens were manufactured using a bonding tool designed to be tailored to the adherends geometry (Figure 1a and b). Prior to bonding, the adherends surfaces were degreased with isopropanol. Adhesive bond thickness is assured with a metal calibration gauge for 1mm bond thickness and two layers of Teflon film for the 0.2mm bond thickness. Raw adhesive was applied on adherends screwed on the bottom half of the tool. The other half was then positioned on top of the latter. The excess of adhesive was removed with a plastic rod in order to reduce edge effects [2]. Specimens are left to polymerize for 24 hours.

Specimens were embedded in the modified arcan which is divided into two moon shape parts (figure 1c). Monotonous tests were performed on a Zwick 10kN machine under a controlled displacement rate of 0.1mm/min for 0.2mm-thick specimen and 0.2mm/min for 1mm-thick specimens. For each bond thickness two specimens were tested in tension, two specimens were tested in shear and two specimens were tested in tensile/shear.

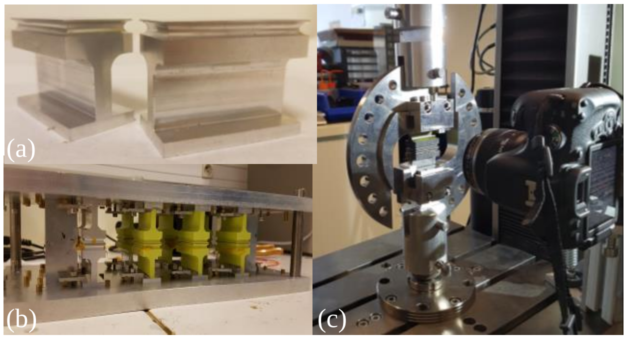

Figure 1. a) ARCAN test specimen; b) Experimental device to mold ARCAN specimens; c) Experimental ARCAN setup

c) *DCB tests*

DCB specimens were manufactured using tailored bonding too. The adherends were 195mm long, 15mm wide and 10mm thick. These dimensions were chosen in order to prevent plastic deformation in the adherends. Prior to bonding, adherends were degreased with isopropanol. Specimens' thickness was assured with calibrated Teflon films. For bond thicknesses of 0.2mm and 1mm, respectively two layers and 10 layers of Teflon film were used. Initial crack length was set to 35mm.for every specimen.

DCB test are carried out on a Zwick 10kN machine at a controlled displacement rate of 2mm/min for both adhesive bonds thicknesses. Displacement and rotation of the adherends were determined using DIC with two reflex cameras Canon EOS 750D. Both cameras took 1 picture every two seconds. Cameras are positioned on each side of the specimen in order to have images of the whole specimen and zoomed in on the initial crack.

Modeling

a) *Arcan Model*

A 2D plain stress FE model has been realized in order to investigate the stress concentrations in the adhesive layer and to validate that the experimental adherends geometry used is offering a homogenous stress distribution. The arcan specimen geometry has been simplified in order to reduce computation time and the plan strain hypothesis has been chosen. For tensile loading, 2 symmetry conditions have permitted the modelling of a quarter of specimen. For shear and tensile/shear loading, the whole specimen has been considered. Boundary conditions are applied on the middle line of the adhesive. Stresses and strains in the adhesive were investigated along the overlap at the contact between adhesive and adherend. For simplification purposes, a kinematic bonding has been set between the adhesive layer nodes and the adherends'. The adhesive behavior is supposed to be perfectly elastic.

In order to validate the specimen geometry, the model has been implemented for 2 adhesive layer thicknesses, 2 adhesive edge shape and for 3 adherends geometry (figure3): a simple model without beaks which is supposed to have the highest singularities, a model with straight edges beaks and one with round beaks. The adhesive geometry is either straight or lightly curved. Mesh is set to be the finest close to the high stress regions which are close to the edge. For both adhesive thicknesses the elements size is of 10µmx10µm.

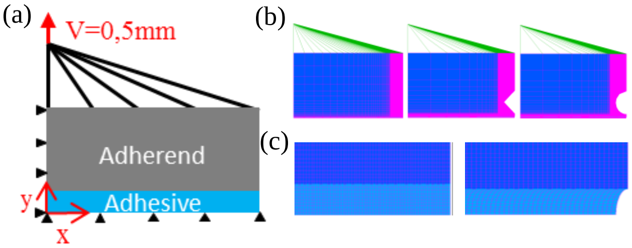

Figure 2. a) Quarter Arcan Model b) beak shapes studied c) Adhesive layer shapes studied

b) *DCB model*

A 2D FE model of a DCB specimen has been developed to compare to experimental data. The model dimensions are the same than the experimental ones (figure 3a). The model is implemented with plan strain hypothesis. Adherends are modeled with a linear elastic behavior and adhesive behavior has been implemented with a cohesive zone model (CZM). A classical bilinear traction-separation law has been chosen as a first approximation [3]. The traction separation law is defined by the initial adhesive modulus (Yt), the tensile stress at crack propagation (Smax) and the fracture energy (GIc). The parameters used are listed in table 1. Mesh is at its finest close to the initial crack with a size of 0.2mmx0.2mm. Loading is modeled by two reference points rigidly linked to the upper and lower adherends. The upper reference node is the one driving the load and the lower reference node is clamped.

Table 1. Cohesive zone model properties.

Bond thickness (mm)	**Yt (MPa)**	**Smax (MPa)**	**GIc (J/mm^3)**
0.2	610	10	2
1	610	10	4.3

A 1D-beam model based on ME technique is developed. It is based on simplified hypotheses to model the joint behavior and uses the minimization of the potential energy for solving. Both the adhesive layer and the adherends are gathered in 1 4-node element. Nonlinear adhesive material can be supported [1]. Boundary conditions are different than the FE model as the upper and lower adherends' nodes at the extremity of the specimen are blocked in the normal and tangential direction as well as in rotation (figure 3b)

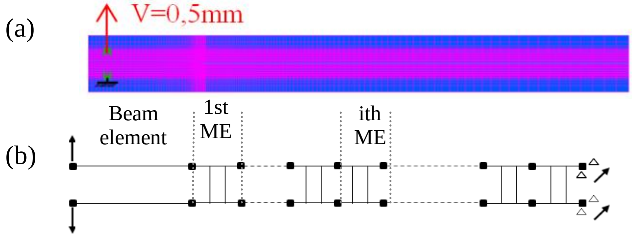

Figure 3. a) DCB FE model; b) ME model.

Results and Discussion

a) Bulk tests results

Bulk tests experimental results have stressed out that the adhesive has a nonlinear behavior with an almost perfectly perfect plastic region. These tensile tests have also permitted the calculation of the Young's tensile Modulus which is of 610 MPa and the Poisson ratio υ=0.37.

b) Arcan finite element stress analysis

Simulations of the ARCAN specimen under tensile loading have been carried out in order to choose the geometry presenting the most homogenous stress distribution. The goal was also to decrease the stress singularities between adhesive and adherends close to the edge. Like Cognard et al [2], it was showed that a curved adhesive at the edge enables the reduction of the stresses. But, it is the adherends' geometry that has the most impact on adhesive stress peaks at the interface. Indeed, straight geometry generates high stresses in the adhesive whereas both beaks geometry enables a drastic reduction of stress singularities.

c) Arcan experimental results

A Matlab script has been developed for the analysis of the Arcan test results. It uses the displacement data calculated by DIC correlated to determine the real tangential and normal displacement. Indeed, the experimental set up tends to rotate during the tests. This rotation is taken into account and permits the correction of the displacement for each image.

The analysis of the 3 load cases have permitted to define the adhesive failure envelope where it can be seen that the adhesive bond thickness has little influence on the stresses at failure for shear and tensile-shear loadings (figure 4a). But for tensile loadings, a 1mm-bond thickness reduces the stress at failure by 20%. However, as it appears on figure 4b, the adhesive bond thickness has a large influence on the adhesive deformation when loaded in pure shear.

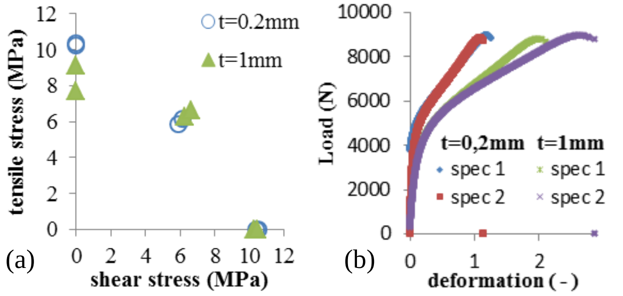

Figure 4. a) Stress at failure envelope; b) load-deformation curve for shear loading.

d) DCB experimental results

DCB experimental results showed an influence of the bond thickness on the load necessary to initiate the crack propagation, and the fracture energy, but the initial slope of the load-displacement curve is not affected by the variation of thickness. Numerical simulations are in good agreement for 0.2mm-bond thickness. However, for 1mm-bond the initial adhesive modulus and tensile stress at crack propagation determined for 0.2mm-bonds are not applicable for 1mm-bonds, as the FE model overestimates the load and both models underestimate the opening at the beginning of the crack propagation. Moreover, both numeric simulations overestimate the elastic modulus (figure 5).

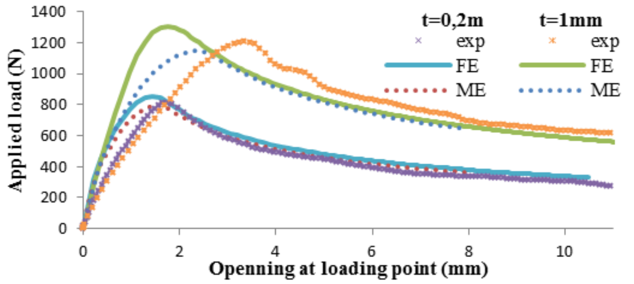

Figure 5. Comparison between experimental results and numerical prediction in terms of applied load versus opening at loading point for 2 thicknesses

Conclusions

The experimental and numerical analysis of the adhesive layer thickness has stressed out that bond thickness has an impact on the bonded assembly mechanical properties. Numerical simulation has permitted to validate the Arcan specimen geometry used experimentally. Moreover, numerical simulations of DCB tests highlights that the cohesive parameters determined for a 0.2mm-bonds are not assuring a good fit when used for 1mm-bond thickness.

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