INFLUENCE OF EDGE-BOUNDARIES ON THE COHESIVE BEHAVIOUR OF AN ADHESIVE LAYER

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ABSTRACT

In comparison with other adhesives e.g. epoxies, polyurethane adhesives (PUR) are soft. In automotive applications, the thickness of PUR-adhesive layers is between about 2 to 5 mm. Since these adhesives cure by moisture, the width of the joints is limited. Often, the width is only marginally larger than the thickness of the layer.

In numerical FE-simulations it is now common to represent epoxy adhesive layers by cohesive elements. With this model, both stress distribution and fracture can be modelled using mesh sizes that allows for large-scale analyses. Material properties are usually the result from experiments with coupon type specimens, e.g. the double cantilever beam specimen (DCB). With PUR-adhesives this approach is problematic. The adhesive is very flexible and effects from the edge-boundaries cannot be ignored.

In order to study the influence of the edge-boundaries in peel loading, experiments with the DCB-specimens are performed. Specimens with a layer thickness of 3 mm and three different widths between 10.6 mm to 40.6 mm are studied. The PUR-adhesive *SikaFlex-UHM* is used. All the experiments are performed at a constant loading rate. The cohesive law is measured.

The experimental results show that the maximum peel stress is increasing with an increasing width of the specimen, i.e. when the influences from the edges decrease. When the width increases from 10.6 mm to 40.6 mm, the maximum evaluated peak stress increases from about 5 MPa to about 7 MPa. From visual inspections during the experiments it is conjectured that crack growth starts with voids initiating inside the adhesive. At a critical point, the voids rapidly reach the surface and crack growth starts.

NOMENCLATURE

- \( l \) (m): Length of the specimen
- \( x \) (m): Distance from the start of the adhesive layer
- \( t \) (m): Thickness of the adhesive layer
- \( w \) (m): Peel deformation of the adhesive layer
- \( \Delta \) (m): Displacement of the loading points
- \( \sigma \) (Pa): Peel stress
- \( \sigma_{\text{max}} \) (Pa): Maximum peel stress
- \( \theta_1 \) (m): Rotation of loading point
- \( \theta_2 \) (m): Rotation of loading point

INTRODUCTION

Experimentally determined cohesive laws are usually found to be unaffected by influences from the free edge boundaries. In the central parts of the joint, the in-plane strain can often be ignored due to the large difference in stiffness between the polymeric adhesive and the stiffer, often metallic adherends. This can be shown in asymptotic analyses, cf. e.g. [1]. The result of the constraint is substantial in-plane stresses. However, at the free edges, these stresses are zero. The size of the boundary zone is of the order of the thickness, \( t \), of the adhesive layer. Thus, if the in-plane size of the joined area is large as compared to its thickness, the effect of the free boundary can be expected to be small and possible to ignore. This is often the case with structural adhesive joints in industrial applications. However in e.g. the automotive industry, thick and soft adhesives are used in a number of applications. These layers are substantially softer and more ductile than the structural adhesives. A layer thickness of about 2 to 5 mm is common. Young’s modulus of some MPa and engineering strain to failure of several thousand per cent are also common. Since the smallest in-plane size of the joined area is only some centimetres, it is expected that the effects of the free boundaries cannot be ignored. For epoxy adhesives it has been shown that the fracture energy increases with the width of the specimen up to about 30 to 40 mm, cf. [2].

In numerically simulations it is preferable to represent an adhesive layer by a cohesive law cf. Fig. 1. Instead of trying to capture all details of the geometry and micromechanics of the
adhesive, its mechanical properties are homogenized and represented by a cohesive law giving the tractions exerted on the adherends interfaces to the adhesive due to the separation of the interfaces. This gives a considerable gain in computational efficiency, cf. e.g. [3].

In this paper, we report a study of the influences of the boundaries for an adhesive layer loaded in peel. The outline of the paper is to first give a brief background to the method used to measure the cohesive law. The second section presents the experimental results. These results are discussed in the third section. The paper ends with some conclusions.

**METHOD**

A commonly used geometry to determine cohesive laws in peel for adhesive layers is based on the use of the double cantilever beam specimen (DCB). The specimen geometry is shown in Fig. 2. The specimen is used both in linear and non-linear fracture mechanics. To determine cohesive laws, two methods are utilized; adaption of a traction-separation curve in order to fit the recorded load-displacement curve, cf. e.g. [3] or the use the $J$-integral approach, cf. e.g. [4].

Utilizing the $J$-integral approach the energy release rate for a DCB-specimen is given by,

$$J = \frac{F(\theta_1 + \theta_2)}{b} \quad (1)$$

where, $F$ is the force, $\theta_1$ and $\theta_2$ is the rotation of the loading points and $b$ is the width of the specimens. The relation is derived in e.g. [4]. Utilizing the path-independence of the $J$-integral, $J$ can be shown to equal the area under the traction-separation relation, cf. [5]. With a cohesive law representing the adhesive layer, one of the conditions for path-independence is fulfilled. By differentiating with respect to the peel deformation, $w$, the cohesive stress at the start of the adhesive layer is derived,

$$\sigma = \frac{dJ}{dw} \quad (2)$$

The method is derived in 2D. It should be noted that the equation is independent of the geometry and the material properties of the beams. The equation is valid even if the adherends deform plastically. The method is used frequently to measure cohesive properties, cf. e.g. [6,7,8].

**EXPERIEMENTS**

The used adhesive is *SikaFlex-UHM*. This is a PUR-adhesive with Young’s modulus 31.9 MPa. The nominal thickness of the layer is $t = 3$ mm. The specimens are cured in a regulated humidity for a minimum time of two weeks.

Nineteen specimens with three different widths are manufactured, cf. Table 1. All the specimens are made of tool steel, *Uddeholm Rigor* with a yield strength greater than 500 MPa and a Young’s modulus of 200 GPa. For eleven of the specimens, the adherends have been hardened in order to further increase the yield strength. However, no influence has been observed due to this procedure. The length of the specimens is, $l = 340$ mm, the specimen height, $h = 10.6$ mm and the unbounded length, $a = 40$ mm. For the specimen width, $b = 40.6$ mm, the width is reduced to 34 mm at the loading point in order to fit the fixture. All the specimens are fixed to the experimental setup by M6 screws.

<table>
<thead>
<tr>
<th>Width, $b$ (mm)</th>
<th>Number of specimens</th>
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<tbody>
<tr>
<td>10.6</td>
<td>6</td>
</tr>
<tr>
<td>25.6</td>
<td>7</td>
</tr>
<tr>
<td>40.6</td>
<td>6</td>
</tr>
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</table>

The tensile test machine is oriented horizontally. In order to reduce any influence of weight the specimens are hanging downwards with the loading point at the top, cf. Fig. 3. The deformation of the layer, $w$, is measured with two LVDTs. Since one of the loading points is fixed and one is moving, the measurement length of the LVDT is adapted; on the fixed side the measurement length is 5 mm, on the moving side the measurement length is 10 mm. The deflection of the loading point, $\Delta$, is measured with a LVDT. The load cell is integrated in the test machine. At the loading points, the specimens are supported by ball bearings in order to minimize the friction. The bearings are oriented in such way that the centre of rotation
is in the neutral axis of the beams. The angle is measured both with an incremental shaft encoder and with two tilt sensors. All the experiments are performed with constant loading rate of 2 mm/min.

RESULTS

During an experiment necking is visible at the start of the adhesive layer or, when the crack starts to propagate, in front of the crack tip. At some distance from the start of the layer, compression is visible as the adhesive layer protrudes out at the edges. For all specimens, crack propagation occurs in the adhesive, i.e. all failures modes are cohesive. For the wider specimens it is observed that the crack starts to propagate inside the adhesive and propagate towards the start of the adhesive layer.

Compared to the other rates in the experiment the crack propagation is rapid. When the crack propagates, the adhesive will be unloaded. Small amounts of crack bridging is observed, cf. Fig. 4.

Figure 5 shows the force vs. load point displacement for all the experiments. For most of the experiments there is a sudden drop in the force displacement curve when the crack starts to propagate.

Figure 6 shows the cohesive relation evaluated by use of Eq. (2) together with an average cohesive relation later to be used in numerical simulations. Before differentiation, the experimental scatter is reduced by a first order Butterworth filter. The first linearly increasing part of the curves gives the stiffness of the layer. The apparent stiffness is increasing with the width of the layer. This is to be expected since the constrained stiffness is much larger than the less constrained stiffness close to the edges. This shows that the width of the specimen influences the cohesive relation. Also the apparent maximum stress is increasing with an increasing width of the specimen. Between about 0.5 and 2.0 mm in $w$, the deformation increases with a virtually constant stress. For many of the experiments crack propagation occur unstable.

Figure 7 shows the maximum peak stress vs. the width of the specimens. Similarly as in Fig. 6 it is shown that maximum peak stress is increasing with increasing width of the specimen. Figure 8 shows the fracture energy vs. the width of the specimen. The fracture energy appears virtually independent of the width of the specimen. For both graphs, there is an adaption to all the experimental data. This curve is shown in solid black. The scatter is more obvious for the smallest specimen with $b = 10.6$ mm. This is also obvious in Fig. 6. The average values are summarized in Table 2.

<table>
<thead>
<tr>
<th>$b$ (mm)</th>
<th>10.6</th>
<th>25.6</th>
<th>40.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_c$ (kN/m)</td>
<td>11.8</td>
<td>12.7</td>
<td>12.9</td>
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<tr>
<td>$\sigma_{\text{max}}$ (MPa)</td>
<td>5.0</td>
<td>6.1</td>
<td>7.0</td>
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</table>
DISCUSSION AND CONCLUSION

In this study it is shown that the evaluated cohesive properties of a soft adhesive layer depends on the width of the specimen. That is, to represent the behaviour of a soft and rubber-like adhesive layer only with a cohesive relation is to oversimplify the modelling. From the industrial point of view, it is still a demand for large-scale simulation capability. That is, more research is needed to develop simplified methods to model this type of adhesives. If the entire layer should be represented by one cohesive element this element has to take the edge boundary effects into consideration.

The scatter in the experimental results indicates that the adhesive layer is sensitive to small defects that initiate crack propagation. The scatter is larger for the specimens with the smaller widths. For these experiments the existence of a defect will have a larger influence. Moreover, the fracture energy decreases when the crack is formed. This gives unstable crack propagation.

Fig. 6 Peel stress vs. deformation of the layer. Blue curves are experimental; Solid black are an adaption to the experimental results.

Fig. 7 Peak stress vs. width of the specimen.

Fig. 8 Fracture energy vs. width of the specimen.
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REFERENCES