COHESIVE ZONE MODELLING OF ADHESIVE IN BUTT JOINT SPECIMEN

Jarno Jokinen(*) , Mikko Kanerva
Department of Mechanical Engineering, Aalto University, Finland
(*)Email: jarno.jokinen@aalto.fi

ABSTRACT
Adhesively bonded joints are mainly designed to transfer loads in shear. The out-of-plane forces, or peel forces, can anyhow have a significant influence on joint loading. A type of specimen for experimental testing of adhesive performance in out-of-plane loading is the butt joint specimen. In this work, we performed finite element analyses for the butt joint specimen. First, mesh sensitivity effects on stress analysis results were studied. Second, the effects of several geometric and analysis features on the simulated specimen behaviour were analysed. The focus of the work was in failure behaviour when cohesive elements are utilized. The results of our study make clear the importance of an intact glue-line, the effect of glue-line thickness variation, and also establish an idea of a new butt joint specimen design.

Keywords: Cohesive elements, adhesive, butt joint, test design.

INTRODUCTION
Adhesively bonded joints have been utilized widely in different kind of structural applications. Adhesively bonded joints are mainly designed to transfer loading in shear. However, out-of-plane forces – namely peel forces, cannot be totally avoided. For example, the peel stresses emerge in typical shear dominated specimens, such as the single lap joint where peel stress effects on crack onset can be high.

A specimen type utilized in peel strength studies is the so-called butt joint specimen. In the butt joint specimen, the adhesive is applied between two cylindrical adherents. Upon testing, the bonded specimen is loaded using tensile loading. The stress state in the adhesive is three-dimensional. In the current literature, this three-dimensional stress state has been studied using different finite element procedures [Adams&Wake]. Firstly, the edge stresses differ from the ones found at the central part of the specimen (inside adhesive layer). Secondly, these free edge stresses are typically dependent on the element mesh created for the finite element model.

For practical purposes, a stress analysis is able to remark critical spots from where the damage is the most probable to onset. However, further analysing of the damage onset and propagation requires fracture mechanics methods. In general, adhesively bonded joints have been studied using cohesive elements. The elements are typically attached to the adhesive-adherend interface. The damage analysis is based on a traction-separation law (see e.g. [Turon]). The applied traction-separation law has a significant effect on the damage behaviour of the adhesive bond line [Volokh].

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In this work, our target is two-fold: Firstly, we perform sensitivity analyses of our numerical butt joint specimen model. Secondly, we study manufacturing defect and geometry effects on specimen behaviour.

In sensitivity analyses we studied how the finite element mesh fineness, position of the failure surface and the applied cohesive zone model affect analysis results. The response was interpreted using out-of-plane stresses and force-displacement curves of the specimen. Based on these sensitivity analyses, an applied model was defined for manufacturing defect and geometry effect analyses.

In manufacturing defect and geometric variation analysis, different scenarios of debond and geometric anomalies existing in the specimen were studied. This provides useful information for manufacturing and testing of butt joint specimens. Comparisons were carried out based on force-displacement-curves. In addition, damage onset patterns in the cohesive element plane were studied to find out whether the damage propagates gradually or occurs suddenly through-out the cross-section. Based on analyses, a new geometry for the specimen was innovated. The innovation was to use a partly hollow specimen to achieve crack propagation instead of extensive sudden damage.

MATERIALS AND METHODS

Materials

The adherends of the butt joint specimen were modelled as aluminium. Young’s modulus of aluminium was 70 GPa and Poisson’s ratio 0.33 in our analyses. Material properties of the adhesive were approximated to resemble the epoxy film adhesive Cytec FM-300-2K. Young’s modulus of adhesive was 2.45 GPa and Poisson’s ratio 0.38. The applied properties of the adhesive failure are collected into Table 1.

<table>
<thead>
<tr>
<th>$G_{IC}$ [J/m²]</th>
<th>1820</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_0$ [MPa]</td>
<td>53</td>
</tr>
<tr>
<td>$G_{IIC}$ [J/m²]</td>
<td>3200</td>
</tr>
<tr>
<td>$\tau_0$ [MPa]</td>
<td>30.1</td>
</tr>
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Cohesive elements for finite element methods

Cohesive elements are additional elements attached to the studied interface. The advantage of cohesive elements is in their ability to model crack onset and propagation. Cohesive elements are based on a traction-separation law, namely cohesive zone model. The simplest law is the bi-linear model, which can be extracted in mathematical form for fracture mode I as [Alfano]:

$$\sigma = \begin{cases} K\delta/a_0 & \text{if } \delta \leq a_0 \\ a_i - \delta/a_i & \text{if } a_0 \leq \delta \leq a_i \\ 0 & \text{if } \delta \geq a_i \end{cases}$$

where $a_0 = \sigma_0/K$ and $a_i = 2G_{IC}/\sigma_0$. 

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The bi-linear traction-separation law includes three parameters for defining the law. The fracture toughness \( G_{IC} \) is given in the form of energy release rate, typically measured experimentally using double cantilever beam specimen [ISO25217]. In a graphical interpretation (Fig. 1), \( G_{IC} \) is the area under the traction-separation curve. The cohesive stiffness \( K \) defines the traction-separation law before damage initiation. Several methods for estimating stiffness have been developed, such as [Turon] and [Zou et al.]. We utilized a value of \( K=10^{15} \text{ N/m}^3 \) in this study. Third parameter in the model is cohesive strength \( \sigma_0 \) for defining damage initiation. The initiation is defined using a stress or strain criterion (in Abaqus). Cohesive strength is mainly considered as a numerical parameter fitted based on experimental results. Numerical fitting causes some issues, e.g. that the achieved strength is mesh-dependent. We utilized a linear stress criterion using strength values based on current literature. Linear stress criterion is simplified to a form:

\[
f = \frac{\sigma}{\sigma_0} + \frac{\tau}{\tau_0}
\]

where \( \sigma_0 \) and \( \tau_0 \) are cohesive strengths for mode I and II fracture.

**Finite element (FE) model**

The butt joint finite element analyses were performed using Abaqus, version 6.14. Analysis cases are shown in Fig. 2. The work was initiated by studying the mesh sensitivity for adhesive failure at one of two sections, A and B. The sensitivity was analysed in terms of out-of-plane stress and force-displacement curves when using cohesive elements at either of the sections. The choice of appropriate mesh for further analyses was based on these analyses. The effect of a specific traction-separation law on the force-displacement -curve was studied for the section A.

For simulating a manufacturing defect, a partly debonded specimen (case C) was analysed. The debond tip was defined as straight. The debond extent was defined by the maximum distance between the tip and free surface (\( \alpha \)). A real defect might not just occur during bonding but already during manufacturing of the adherends. Therefore, in cases D, E & F, the adherend interface (against adhesive) was not normal to the longitudinal free surfaces of the specimen. Both symmetric and asymmetric anomalies were studied. The defect size was exaggerated (\( \beta, \gamma \) & \( \eta \)) for clarifying the effect in results. The results were studied in terms of force-displacement –curves and the damage distribution over the cohesive elements plane. Damage distribution was of especial interest for the cases with abnormal adherend geometries.
The study of the adherend geometry raised an idea of controlling the damage propagation with specimens in which the adherends were hollow except for the distance $\kappa$ from the adherend-adhesive interface (case G). Thickness of the adherend at the adherend-adhesive interface was defined having the same value as the wall thickness of the hollow part.

![Diagram of adherend geometry](image)

The finite element model consisted of adherends, adhesive and cohesive elements. The adhesive and an adherend were joined using tie constraints, which allowed utilization of dissimilar meshes. This was beneficial for the mesh sensitivity studies where the main interest focuses on the mesh of the adhesive. The adhesive mesh effect on stress distributions was studied using a continuous adhesive layer. For fracture analysis using cohesive elements, the adhesive layer was divided into two pieces where cohesive elements were attached using tie constraints.
The adherend length was 45 mm and adhesive thickness 0.25 mm in the reference analysis. The specimen had a circular cross-section with a diameter of 15 mm. In an experimental specimen, the adherends would attach to the test machine via loading pins through the adherends. We did not model the holes for the pins. Instead, a partition was defined at the centre line of the hole in both adherends (Fig. 3). Boundary conditions were attached along lines representing the pin-adherend contact line in reality, which were perpendicular directed in each adherend allowing rotation over the axis of the line. In the lower adherend pin-contact line all displacements were restricted. The loading (displacement) was provided for the specimen at the upper adherend pin-contact line. For this line, a vertical enforced displacement was attached while other displacements were restricted. The enforced displacement was 0.075 mm in stress analyses. In fracture analyses, the enforced displacement value was modified to be adequate for achieving failure in the cohesive elements. The enforced displacement was performed using two analysis steps because load increase incrementation was modified between the steps in the fracture analyses. This modification allowed smaller incrementation when fracture occurs while the initial part was calculated using larger increments.

The applied FE model (its half) is shown in Fig. 3. In the model, the adherends were meshed using continuum elements C3D8R. Typical element dimension in the adherends was 0.5 mm. The total number of elements in the adherends was 155,520. In the mesh effect studies, the element dimensions in cohesive elements and adhesive mesh were changed per analysis case. Typically, the element dimension was kept the same in the adhesive and cohesive elements. The element dimension range was from 0.05 mm to 0.2 mm. The adhesive was modelled using elements C3D8R and C3D8, from which the former is a reduced integrated element and the latter is a fully integrated element. The number of elements in the adhesive was from 17,936 to 849,600.
RESULTS

Mesh effects on stress analysis

Finite element mesh effects on stress distribution were studied in two sections of the adhesive, A and B (Fig. 2). The section A is located in the middle of the adhesive. The section B is located at 0.05 mm distance from the (upper) adhesive-adherend interface. Mesh effects on peel stress distributions at the sections A and B are illustrated in Figs. 4 and 5, respectively. Figs. 4 and 5 show that the mesh mainly affected the stresses close to the free edge ($r = 7.5$ mm) of the adhesive. The stress level was rather constant and mesh effect was low closer to the centre of the cross-section. The utilization of a fine mesh provided lower stress values compared to a coarse mesh at the free edge. The fully integrated C3D8 elements provided higher stress values than comparable meshes with the reduced integrated element C3D8R. The comparison of results for sections A and B shows that the free edge stresses are lower for the section B than for the section A. The values at the centre were comparable in both sections.

Fig. 4 - Mesh effects on stress distribution at the section A.

Mesh effects on cohesive zone modelling

The mesh sensitivity results using cohesive elements for the sections A and B are shown in Figs. 6 and 7, respectively. The results were obtained using cohesive elements with the bilinear traction-separation law. The force-displacement-curves provided by the models were...
relatively similar. The force increases linearly until the maximum force is reached and decreases suddenly after the maximum, critical force. This states that damage is unstable after reaching a sufficient load state.

However, some essential differences existed. For two coarsely meshed (C3D8R 0.2 mm & 0.125 mm) reduced integrated models, the force did not drop to zero, which remarks that a connection is still existing at the section (in this case section A). The finest mesh models with reduced integrated elements had severe convergence challenges and the analysis was not fully run to end for the sections A and B. The analysis of the two finest models using reduced integrated elements were aborted. The convergence difficulties became worse when using reduced integrated elements and when studying the section B. These analyses were also aborted after some hundreds of increments. The convergence could be achieved by further modifying incrementation and other numerical parameters.

The magnification of the curves remarks interesting differences. The reduced integrated elements utilize a smaller increment at the failure, which results to smoother curves at the turning point. The only exception is C3D8R with 0.125 mm element dimension for the section A, for which incrementation decreased during the descent path. Based on the analyses, the main difference between the element meshes is the analysis convergence and (time) efficiency. Consequently, C3D8 element using 0.125 mm typical dimension was chosen for further analyses.

![Fig. 6 - Mesh effects on cohesive element analysis force-displacement curves at the section A.](image1)

![Fig. 7 - Mesh effects on cohesive element analysis force-displacement curves at the section B.](image2)
Cohesive zone model effects

The cohesive zone model is the key element in cohesive element analyses. We performed analyses using two different cohesive zone models, a bi-linear and trapezoidal (definitions in Fig. 8). The trapezoidal law involves a cohesive strength plateau over a larger distance and the degradation occurs over a smaller distance of separation compared to the case with the bi-linear law. The results of the cohesive zone model comparison are shown in Fig. 9. The force-displacement curve with the trapezoidal law resulted in a force plateau, resembling more ductile behaviour. The trapezoidal law was defined using a discretized, table format in Abaqus. The discretization was found overly coarse, which was seen evident based on the oscillation of the force-displacement curve.

Fig. 8 - Traction-separation curves for applied cohesive zone models.
Fig. 9 - Cohesive zone model effects on the force-displacement curve at the section A.
Partly debonded adhesive section

For the case C (Fig. 2), a partly debonded specimen was analysed and the results are shown in Fig. 10. Load response is seen to be nonlinear, especially for the two specimens with large initial debonds. The behaviour of the models with small initial debonds is interesting. The force-displacement curves indicate a linear response before failure initiation that is presented by a clear force drop. However, in contrast to all previous simulations, the force drop does not result in total failure of the cohesive elements. The behaviour is supported by the cohesive element damage, which is wide at that point of the curve but not throughout the cross-section. The unsymmetric debond results in rotation of the adherends around the boundary condition axis as shown in Fig. 12a.

Adherend geometric variation effects

The results of the analyses with changes in the adherend geometry (cases D, E & F in Fig. 2) are shown in Fig. 11. The curves do not present major differences between the different simulation cases. The models D and F have a lower stiffness (linear region) when compared to the reference model and model D. These models have also larger (in displacement) nonlinear part than the reference model. Likewise, the failure for these models is delayed and the maximum force is decreased approximately 10%. While the force-displacement curves do not remark significant differences, the crack onset and propagation are different for the different simulation cases. Damages in the cases D and F are illustrated in Fig. 12. The image of the cohesive element damage characterizes the damage form in the failure plane of the adhesive. The change of the adherend geometry shifts the damage initiation to the centre part for the case D and to the outer (free-edge) region for the case F. This is a significant difference when compared to the reference model A, where damage occurs merely at once and throughout the cross-section. The different damage propagation occurring for the cases D and F can be seen in Fig. 11 as a larger nonlinear part of the force-displacement curves.
Fig. 11 - Adherend geometry effects on force-displacement curves.

Fig. 12 – (a) Deformation (magnified) of a butt joint specimen with a partly debonded adhesive. (b) Cohesive element damage (SDEG) variable distribution (RED=debonded & BLUE=bonded) for different analysis cases.
Partly hollow specimen design

A partly hollow specimen was innovated based on the simulation analysis for the case F (see Fig. 11). The response of the new specimen design in the form of a force-displacement curve can be seen in Fig. 14. Firstly, the utilization of cylindrical (hollow) adherends decreases the stiffness of the specimen. The decrease in the wall thickness extends the nonlinear part of the curve. A comparison of case F and G force-displacement curves indicates a larger nonlinearity, or damage propagation potential, for the case G – the hollow specimen.

![Force-displacement curves for partly hollow specimens.](image-url)

**DISCUSSION**

A variety of butt joint analyses was performed. The stress analysis of a traditional butt joint specimen remarked that out-of-plane stress values remain at a relatively constant level along the centre part of the adhesive cross-section independent of the mesh. Out-of-plane stress has lower values at the free edges than at the centre part of the specimen and the decrease is clearly mesh and element dependent. For the centre part, the mesh effect on the out-of-plane stress was minor.

Another mesh sensitivity study was performed for a model with cohesive elements. The study showed that better results and convergence can be achieved using fully integrated elements in the adhesive layer. For the reduced integrated analysis, convergence problems were typical and failure was not always achieved. The element dimension effect on force-displacement response of the specimen was relatively low.
In the current literature, traction-separation law effects on finite element analyses have been discussed. In this study, we compared two different laws, a bi-linear and a trapezoidal model. The traction-separation law affected the force-displacement response of the butt joint. The shape of the law is shown in the response as a change in simulated ductility. The applied trapezoidal law was modelled in a table (discretized) form, which results in oscillation and tendency to incrementation leading to an increase in the CPU time.

Several manufacturing scenarios related to bonding and geometry of the specimen were analysed via the finite element model. The effect of an unsymmetric partial debond at the adhesive cross-section is seen clearly in the force-displacement response. The debond results in bending and nonlinear response of the specimen. An interesting feature of the specimen failure was a combination of a sudden force drop (partial failure) and a wide, smooth nonlinear part.

The adherend geometric effects on the force-displacement response did not provide as significant change as the partly debonded specimen did. The force-displacement curves with adherend geometry modifications were comparable to the reference specimen’s curve. The main change with a geometric modification of the adhesive-adherent interface was found in the damage pattern. The change in the adhesive thickness as a function of radius guides the damage. Using different geometries of the adherend/adhesive interface, the crack onset was shifted between the centre and free edges.

Utilization of a partly hollow specimen design enabled to control the damage onset to the areas under the cylindrical walls, or edges. In the force-displacement curve, a decreased stiffness was evident. As an important outcome, the decrease in the wall thickness increased the nonlinearity of the load response. Typically, the nonlinearity in the force-displacement response can be interpreted as crack propagation instead of sudden and uncontrolled failure of the adhesive, yet being length scale and time dependent in definition [Kanerva et al].

CONCLUSIONS

In this study, we performed stress and failure analyses for butt joint specimens. The finite element mesh was found to affect the stress values close to free edges of the adhesive glue-line. In the centre part of the specimen, the mesh effect on the out-of-plane stress component was relatively small. The section of stress analysis, or failure plane, did not remark any clear effect on the stress distribution prior to failure. The mesh had an effect on the cohesive element analysis of the adhesive failure. The main difference was seen when using coarse reduced integrated elements, where element distortion caused problems in running an efficient analysis. Convergence was also seen to be dependent on the applied mesh.

Another target of the work was to study manufacturing anomalies and defects suspected for the butt joint specimen. Based on our analysis, a partial debond has a significant effect on the force-displacement response. A debond can provide a totally nonlinear response, where force drop halts prior to the formation of a fully debonded cross-section. This was designated as a damage propagation behaviour influenced by the specimen rotation and bending. Already small debonds were observable in the force-displacement response. The adherend-adhesive interface geometry had a minor effect on the response compared to a debond. The main change caused by a change in the adherend-adhesive interface geometry is the shifting of the
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damage onset location. Based on the analyses, the damage onsets at a location where a low adhesive thickness exists. The analysis of a specimen design with partly hollow adherends indicated nonlinear response, i.e. damage propagation, which was controlled to evolve from the edge and towards the centre.

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