Investigation of joint behavior of a bonded aluminium structure using flexible adhesive

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Abstract: In the EU project BONDSHIP adhesive bonding has been introduced into shipbuilding for joining of similar or dissimilar lightweight materials. Numerical simulations of mechanical tests on a bonded aluminium structure have been performed with ABAQUS Standard. The adhesive layer has been modeled either by 3D solid elements with hyperelastic material models, or by 1D spring elements with equivalent stiffness. The structural behavior under both bending and shear loads was investigated by inductive measurement. A comparison of two modeling methods with the test results is presented in this paper.

1. Introduction

The European research project BONDSHIP - Bonding of lightweight materials for cost effective production of high speed craft and passenger ships - is a three-year project funded under the GROWTH Program of the European Commission. The project has 13 partners from 7 European nations and is a major European initiative to introduce into ship building adhesive bonding as an industrial process for joining lightweight materials. The aim is to make European shipyards more competitive by achieving considerable cost savings in the production of passenger ships and high speed craft. Focus is on aluminium-aluminium, aluminium-steel and aluminium-composite joints.

Therefore, an adequate modeling technique is required for the prediction of joint behavior of large bonded structures using flexible adhesives. For the refined capturing of local stress and strain gradients in the joint the adhesive material is described as a rubber-like, nearly incompressible and isotropic hyperelastic material which is characterized by a strain energy function. For the efficient representation of the joints in large structures a special substitute system of spring models has been developed to take into account the stiffness contribution of the adhesive layer.

Numerical simulations of mechanical tests on a bonded aluminium structure were performed by ABAQUS Standard. In different modeling methods the adhesive layer has been modeled either by 3 dimensional solid elements with hyperelastic material models, or by 1 dimensional spring elements with equivalent stiffness. For the used adhesive material multiple test data, for example uniaxial tension, and simple shear test, are required for the fitting of the material parameters.
A comparison of both modeling methods with experimental results for bending or shear load cases, respectively, will be presented in this paper.

2. The test problem

A frame of $2000 \times 1000 \, \text{mm}^2$ is welded from aluminium extrusions CH 47670. An aluminium plate of $1944 \times 944 \times 3 \, \text{mm}^3$ is bonded to the frame using the flexible adhesive Sikaflex 292. The bonding area has a thickness of 4 mm and a width of 20 mm (Figure 1).

The test sample is fixed via the C-channel, e.g. the flange of the extrusion (Figure 2). In the middle of the short edge (position A in Figure 1) the length of fixation is 160 mm, whereas the length of fixations at both long edges (positions B and C in Figure 1) is 350 mm. The panel is positioned horizontally, with the plate on the upper side. The origin of the coordinate system is located at the center of the plate which is in the $xy$-plane. The $x$-axis is parallel to the long side of the extrusion profile. The $z$-axis points upwards.

Shear force $F_y$ in negative $y$-direction was applied via an adapter in the plane of the test sample (Figure 3). The maximum in-plane force is 6 kN. The out-of-plane force was applied from the lower side of the frame (Figure 4). The bending force $F_z$ in positive $z$-direction (upwards) was applied perpendicular to the plane of the test panel. The maximum out-of-plane force is 1.5 kN.

For both in-plane shear test and out-of-plane bending test the maximum force was subdivided into 10 steps. In each case, the test sample was loaded in 10 steps and then unloaded in 10 steps.

Under both bending and shear loads, the structural behavior of the test sample was investigated experimentally. At each step, the resulting displacements in the loading direction were measured with inductive gauge at four points: in the middle of the plate (point “o” in Figure 1), in the middle of the short edge (point “a”), in the middle of the long edge (point “c”), and at the corner (point “e”).

3. Modeling methods

The flexible adhesive layer is presented in the finite element analysis either by 3 dimensional solid elements using hyperelastic material models, or by spring elements with equivalent stiffness. Both linear and (material and geometrical) nonlinear analyses have been performed.

3.1 Hyperelastic material models

In a detailed analysis the flexible adhesive is modeled with 3 dimensional solid elements to enable a refined capturing of local stress and strain gradients. The adhesive material is described as a rubber-like, nearly incompressible, and isotropic hyperelastic material characterized by a “strain energy potential” $U(\varepsilon)$, which defines the strain energy stored in the material per unit of reference volume (volume in the initial configuration) as a function of the strain at that point in the material. In the following the strain energy forms employed in the study are described.
Figure 2. Test configuration.

Figure 3. In-plane load introduction.
The form of the Ogden strain energy potential is

\[ U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i} \left( \lambda_i^{3\alpha_i} + \lambda_i^{3\alpha_i} + \lambda_i^{3\alpha_i} - 3 \right), \]  

(1)

where \( \lambda_i \) are the principal stretches: the ratios of current length to length in the original configuration in the principal directions. They are related to the principal nominal strains, \( \varepsilon_i \), by

\[ \lambda_i = 1 + \varepsilon_i. \]  

(2)

\( \mu_i \) and \( \alpha_i \) are material parameters which are determined by adhesive material test data.

The form of the reduced polynomial strain energy potential is

\[ U = \sum_{i=1}^{N} C_{\alpha i} (I_i - 3)^2, \]  

(3)

where \( C_{\alpha} \) are material parameters. \( I_i \) is the first deviatoric strain invariant defined as

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\[ I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2. \]  

(4)

The form of the **neo-Hookean** strain energy potential is

\[ U = C_{10} (I_1 - 3) \]

(5)

which can be obtained as a special case from the reduced polynomial function for \( N = 1 \).

As adhesive Sikaflex 292 was used in the test sample to bond the plate to the frame. For its modeling as a hyperelastic material stress-strain curves for the uniaxial tension test, for the uniaxial compression test and for the lap shear test were considered.

![Figure 5. Single lap joint, Sikaflex 360 HC.](image)

An initial modeling study within the BONDSHIP project revealed the importance of the proper choice of the material model for describing flexible adhesives. A single lap joint (Figure 5) loaded in tension was modeled using different hyperelastic and elastic models. Very good results were obtained (Figure 6) when both tension and shear test data were used for fitting the material constants. Large deviations were derived in the case of parameter fitting only by uniaxial tension test data. Therefore, the conclusion was to use test data from more than one test.

### 3.2 Modeling method by substitute systems of spring elements

In the global finite element analyses a special substitute system of spring elements was developed to take into account the stiffness contribution of the adhesive layer. Three translational springs represent a substitute model for the adhesive continuum in global models:

- Spring stiffness for tension/compression:
  \[ k_1 = \frac{(E' \cdot l \cdot b)}{h}, \]
  \[ (6) \]

- Spring stiffness for shear:
  \[ k_2 = k_3 = \frac{(G' \cdot l \cdot b)}{h}, \]
  \[ (7) \]
where \( b \), and \( h \), denote the width and the thickness of the adhesive layer, respectively. \( l \) is the length of the finite element adjacent to the adhesive layer. Therefore the stiffness of the spring elements depend on the joint geometry and on the size of the elements adjacent to the adhesive layer. The elasticity constant \( E' \) is derived from the butt joint test, whereas the shear constant \( G' \) is determined by lap shear tests of joints with the same adhesive and adherend materials as the test sample. The spring behavior can be linear or nonlinear, depending on the test results. In this way, the complex dependency and the nonlinearity of the adhesive material on the loading rate, temperature, load type and cross section geometry is considered.

4. Material properties

4.1 Material properties of aluminium alloy

The test sample consists of the welded frame and the plate which is bonded to the frame. Following aluminium alloys were used:

- Extrusion: EN A-W 6005A T6 (AlMgSi0.7)
- Plate: EN A-W 6082 T6 (AlMgSi1)

For both alloys we used the same elastic constants:

- Young´s modulus \( E \): 70000 N/mm\(^2\)
- Poisson´s ratio \( \gamma \): 0.3
4.2 Material properties of the adhesive Sikaflex 292

The flexible adhesive Sikaflex 292 was used to bond the plate to the frame. The adhesive supplier Sika delivered nominal stress - nominal strain curves for the uniaxial tension test, for the uniaxial compression test, for the simple lap shear test, and for the butt joint tension test.

4.2.1 Tensile, compression, simple shear, and butt joint tension test

In the uniaxial tensile test, a dumpbell shaped specimen of the adhesive is tested under tensile load. The dimensions of the specimens are given in Figure 7, whereas the resulting curve for the nominal stress and the nominal strain is shown together with the corresponding curves of the other tests in Figure 9.

In the compression test, the cylindrical specimens (Figure 8 a)) made of adhesive Sikaflex 292 are tested under compression loading. Samples have a diameter of 30 mm and a height of 10 mm. The measured nominal stress – nominal strain curve is shown in Figure 9.

The simple shear test is performed on a joint of two aluminium plates bonded with the adhesive Sikaflex 292. The plates have dimensions of 100 x 50 x 4 mm\(^3\). The joint has an overlap length of 20 mm, a breadth of 50 mm. The thickness of the adhesive layer is 4 mm (Figure 8 b)). The specimen is tested under shear force of the joint. During the test the thickness of the joint is hold constant. The measured curve of nominal stress and nominal strain is given in Figure 9.

The butt joint tension test is performed on samples shaped as shown in Figure 8 c). The used plates have dimensions of 50 x 20 x 4 mm\(^3\). The specimen is tested under tensile force (Figure 9).

![Figure 7. Dimensions of tensile test specimen.](image)

![Figure 8. Test specimens for compression test (a), simple lap shear test (b) and butt joint tension test (c).](image)
4.2.2 Hyperelastic parameters

The hyperelastic parameters were fitted on the basis of the uniaxial tension and compression test, and the simple shear test. The recommended planar test (pure shear) proved to be not suitable for samples made from flexible adhesives. Since ABAQUS does not accept test data from simple shear it became necessary to develop an user defined fitting routine for determining the hyperelastic constants.

Sikaflex 292 was modeled by the reduced polynomial form for N=1,...,6, and by the Ogden form for N=1,2. For each form the material constants were determined using all possible combinations of the above mentioned test data. By many one-element simulations the resulting parameters were tested and compared with the experimental data. The conclusions from these numerical tests are:

- The reduced polynomial, N=1,2, models the tension and the shear test quite well if at least two different experiments are used.
- The Ogden model, N=1,2, models the tension and the shear test quite well if at least two different experiments are used.
- The compression test is modeled in small accordance with the experiment.
- Higher order polynomials should not be used because of the small amount of experimental stress-strain-pairs available in this case.

In Figure 10 some results of one-element simulations for the simple shear mode are compared with the test data of the shear test. The used hyperelastic constants are derived from all available test data, from tension and shear test, and from only the shear test, respectively.
Figure 10. Comparison with shear test for the reduced polynomial, N=2, for Sikaflex 292.

4.2.3 Spring parameters

For the substitute systems of spring elements the necessary constants $E'$ and $G'$ are derived from the butt joint test and from the simple shear test, respectively. Following values were determined:

$$E' = 9 \text{ MPa} \quad \text{and} \quad G' = 0.6 \text{ MPa}$$

The Young’s modulus $E$ of the adhesive determined by the tension test (Figure 7) is 1.5 MPa which is significantly smaller than $E'$. The higher stiffness of the butt joint in tension (Figure 8 c)) is a consequence of the adherends. By their influence the adhesive is restrained from deforming perpendicular to the tensile axis. The shear modulus $G$ is almost the same as the constant $G'$.

5. Finite element analyses

According to the above explained modeling methods different finite element models of the test sample were developed. All finite element models used shell elements for the aluminium extrusion and for the plate whereas the consideration of the adhesive layer was different. The first author (Alcan MTS) used spring elements for the adhesive and linear quadrilateral shell elements with full integration for the plate and the frame. This model has following size:

- Number of elements: 15,188
- Number of nodes: 14,467
- Number of DOF’s: 86,802
The second author (IFAM) used solid elements for the adhesive layer and investigated the influence of different hyperelastic material models on the results. This approach yields a detailed model with larger size:

- Number of elements: 22,072
- Number of nodes: 21,999
- Number of DOF’s: 123,526

Because of the hyperelastic material properties of the adhesive hybrid elements had to be used. With only one exception the models were built by linear order elements.

### 5.1 In-plane shear load

Initially, the stiffening effect of the bonded plate was investigated by comparison of calculated magnitudes of deformation for the frame with and without the bonded plate. For an in-plane shear force of 6 kN we obtained in the middle of the loading edge a deformation of 43.6 mm and 6.1 mm in the simulation without and with the bonded plate, respectively. Therefore, the stiffness is increased by a factor of 7 due to the bonded plate.

Figure 11 depicts the deformation – force curve for two measurement points both from the measurement and from the analysis with the spring model. The analysis results are within the hysteresis of loading and unloading. Figure 12 shows the y-displacement calculated by the detailed model for the whole test sample whereas Figure 13 compares the finite element results for both models with the experimental curves for two points. For the middle point (“o”) the error of the simulated values is 6.8% and 13.7% whereas the error for the edge point (“a”) reaches only values of 7.4% and 0.2% for the detailed and the spring model, respectively.

![Figure 11. Comparison of experimental and FE results, spring model, shear load.](image)

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Further evaluation of the simulation results depends on the modeling method. For the method using solids for the adhesive layer, local stress and strain values for the complete 3 dimensional stress and strain state, and local results of the elastic strain energy density are available which can be compared to permissible thresholds.

In case of spring element models relative displacements and forces across the springs are provided. They correspond to nominal strains and stresses. The system of three springs SPRING2 yields two components of shear strain $\varepsilon_{13}$ and $\varepsilon_{23}$, and the tensile strain $\varepsilon_{33}$. For the evaluation the nominal strains are compared directly with the permissible nominal strains.
Figure 14. Elastic strain energy density of the adhesive, shear load (6.0 kN).

Figure 14 is derived from the detailed model. It shows the distribution of the elastic strain energy density for the adhesive layer which is symmetric about the $xz$-plane. On the last third (opposite to the load introduction) of both long sides the maximum value of $0.0863 \text{ J/mm}^3$ is reached. Also in this region the highest shear strain $\varepsilon_{23}$ of 37.5% is observed, corresponding to a shear stress of $0.259 \text{ N/mm}^2$. The shear strain $\varepsilon_{13}$ has maximum and minimum values on both long sides: 37.2% and -38.8%, respectively. The maximum tensile strains are quite small (6.1%, 6.4% and 2.6% for $\varepsilon_{11}$, $\varepsilon_{22}$, $\varepsilon_{33}$, respectively), the compressive strain of maximum magnitude is $-12.5\%$ ($\varepsilon_{13}$).

Qualitatively similar results are provided by the model using spring elements for $\varepsilon_{13}$ and $\varepsilon_{23}$. The maximum compressive strain $\varepsilon_{33}$ is only 1.1%, corresponding to a nominal compressive stress of 0.1 N/mm$^2$ which differ considerably from the results of the detailed model.

5.2 Out-of-plane bending

In the case of the out-of-plane bending the stiffening effect of the bonded plate is much smaller than in the case of shear loading. The stiffness is increased only by 9% due to the bonded plate.

The deformation of the whole test sample in $z$-direction calculated by the detailed model is shown in Figure 15. A comparison of the deformation at two measurement points for both analysis models and the mechanical test is contained in Figure 16. The correspondence of the finite element result with the measurement is better for the middle position at point “o” than for the boundary point “a” near the load introduction. For the middle point the error of the simulated values is only 3.7% and 6.8% whereas the error for the edge point reaches values of 14.6% and 16.0% for the detailed and the spring model, respectively.

Figure 17 shows the distribution of the elastic strain energy density for the adhesive layer which is derived from the detailed model. It is symmetric about the $xz$-plane as it was for the in-plane
loading. On the short edge opposite from the load introduction the maximum value of 0.0167 J/mm² is reached which is only 1/5 of the corresponding value for the shear loading.

In this region the highest shear strain $\varepsilon_{13}$ of 22.0% is observed, corresponding to a shear stress of 0.148 N/mm². The maximum magnitude of tensile strain and compressive strain is even smaller than they were for the shear load. Now they take values from 1.2% ($\varepsilon_{22}$) to 2.4% ($\varepsilon_{11}$) and from −1.3% ($\varepsilon_{11}$) to −3.3% ($\varepsilon_{33}$), respectively.

Figure 15. z-Displacement in mm, bending load (1.5 kN).

Figure 16. Comparison of different FE results, bending load.
6. Conclusion

In this modeling study of a bonded structure the flexible adhesive is presented either by solid elements with a hyperelastic material model, or by spring elements with substitute joint stiffness. The analysis results have been compared with the experimentally measured displacements of the mechanical tests. Both presented modeling methods provide satisfactory prediction of overall stiffness behavior of the investigated bonded structure compared with the measurement results.

The detailed analysis using the hyperelastic material model enables refined capturing of local stress and strain gradients in the adhesive layer. Only this approach provides information of the complete 3 dimensional stress and strain state in the adhesive layer. These local strain, stress and energy data can be used for the evaluation of the simulation results by comparing them with permissible thresholds. Comparatively large models and a longer calculation time of the nonlinear analysis are the disadvantage.

Therefore, for large bonded structures with flexible adhesives a combination of both modeling methods is recommended. The overall stiffness behavior is investigated in a global (linear or nonlinear) analysis where the joint is presented by spring elements with substitute joint stiffness. Nominal strain of the joint derived from this analysis can be compared with the permissible strain. For high loaded zones a detailed local analysis using a hyperelastic material model for the flexible adhesive is necessary in order to investigate the complex stress distribution in the adhesive layer.

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