ON THE ANALYSIS OF A CONTACT FRICTION COMPOSITE-TO-METAL JOINT

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1 Introduction
Fiber reinforced composites are excellent materials for applications which require high stiffness and strength in combination with low weight and corrosion resistance. Hybrid structures require the transfer of loads from composite assemblies to metallic counterparts. Depending on the application and use, composites can be joined with metals mainly through adhesive bonding, mechanical fastening and friction-type techniques [1]. Decisions to use friction joints are mostly application oriented, with regards to e.g. anchoring a composite shaft in a metallic hub [2]. Previous studies have shown the effect of contact and friction on the pressure variation within a carbon fiber reinforced polymer (CFRP) rod/metal assembly, as well as the effect of surface treatment of the parts in contact [3]. Gripping conditions are affected by the geometry of the FRP rod, which has been investigated in previous studies, with circular [4] and rectangular [5] profiles. The metallic counterparts can be manufactured in different materials, but until now typical choices are to use copper or aluminum [6]. The aluminum has shown to provide higher grip, as well as increased shear stress. While the fracture behavior of joints made of the same material or by a combination of similar materials has been the subject of significant studies, the behavior of bi-material joints is less documented. For industrial applications of a joint consisting of aluminum wedges and FRP composite, which will exhibit differences in constitutive law, pressure and stress distributions, thorough analysis has to be conducted. The minimization of stress concentrations is essential for the lifetime behavior of FRP composites, and if unaccounted for, it can lead to premature failure. While it can be stated that bonded joints might deliver superior results, their performance is affected to a large extent by the quality of the surface preparation and other hard to control conditions. The current study will address the challenges of designing aluminum to Basalt Fiber Reinforced Polymer (BFRP) friction joint. The basalt has been chosen for its corrosion resistance, and the aluminum because it is easy to machine. The main technique used until now for obtaining such a joint has been crimping. Several studies focus on the optimization of crimping [7], non-linear FEM modeling [8] and geometry of the assembly [9]. Stress concentrations have been proved to limit the maximum pullout force. These solutions are attractive in the case of a circular FRP profile. This study concentrates on the development of a gripping solution where the composite is a thin rectangular strip. The influence of the friction coefficient in-between aluminum and carbon fiber reinforced polymers has been studied in the case of a bolted plate [10] for static and wear conditions [11]. The interaction of aluminum and BFRP represents a novelty, and the present study will concentrate on providing the design and numerical tools for assessing the efficiency of such joints. The joint has to ensure the structural integrity of the BFRP, without damaging the surface, as would be the case when using rivets, or twisting/crimping of the composite. Studies on the friction model and the setup of contact friction elements between two composite plates [12] have proven that the Coulomb friction law is a good approximation. The validity of this will be assessed with complementary pullout tests in future work.

2 Problem Description
The considered aluminum-to-BFRP joint, schematically shown in Fig. 1, consists of two aluminum wedges with the BFRP in the middle. The purpose of this joint is to transfer loads between a flange and the BFRP tape. By using BFRP instead of
steel, significant weight savings can be obtained in a series of load carrying structural components. The system is designed to work in two steps. First the pressure $P$ is applied by means of an external device. This will provide the initial clamping force. The second step consists of displacing the BFRP strip. If the friction coefficient in the AL/BFRP interface is higher, the lower wedge will slide relative to the upper wedge and provide additional pressure over the composite. This will result in a self-locking mechanism, which leads to the increase of the pullout force.

![Fig. 1: Schematic representation of the considered contact friction Al-to-BFRP joint. The model is symmetric with respect to the longitudinal axis and thus only half is modeled with representative boundary conditions applied.](image)

The boundary conditions allow the vertical displacement of the top wedge and the horizontal movement of the BFRP. The tilt angle influences the pressure distribution in the two interfaces, as well as the generation of extra pressure. By applying a displacement at the right end of the BFRP, the reaction pullout force can be measured. All plots for the two interfaces will have the x-axis oriented according to Fig. 1, with zero at the left hand side of the assembly.

The aim of this paper is to analyze the joint described in Fig. 1 and to optimize the stress fields in the interfaces. By achieving a stress field as uniform as possible, it is possible to ensure no premature failure of the composite.

### 3 Numerical Approach

Modeling of the wedge system shown in Fig. 1 will be done using the commercial finite element software ANSYS v.13. The material properties will be taken from literature, while others will be assumed. The assumed values refer to mechanical and frictional properties of the BFRP. This study is intended as a screening of different geometric and physical parameters, whose results will be used in the definitive wedge design. For this reason the results will be presented in a qualitative manner.

#### 3.1 Modelling Considerations

The numerical 2D model consists of three areas, meshed with quadratic elements. Contact elements are used at the contact between the Al and BFRP elements, see Fig. 2. The mesh density can be modified through direct input in the contact area. Coulomb friction is used for the description of the contact constitutive equation. This model will allow for the study of the friction coefficient effects, the geometry effects and clamping pressure effects. Geometry effects include the wedges and BFRP thicknesses ($t_1$, $t_2$, $t_c$ and angle $\alpha$) and the Al/BFRP overlap length $L$. Literature studies have been focused on measuring the friction coefficient for Al to CFRP contact friction problems [13], and their values will be used here as well.

#### 3.2 FE Model

The three main areas, shown in Fig. 2, consisting of the BFRP material and aluminum wedges are all modeled with a 2D 8 node structural solid element, Plane 183. The contact elements used in the two contact areas, the Al/BFRP and Al/Al, are respectively Conta172 and Targe169. Over the top of the upper Al wedge, where the pressure $P$ is applied, spring elements (Combin14) are created for each node. Constraints in the $y$ direction are given to the bottom of the BFRP, and the top Al wedge is constrained in $x$ direction. Pressure can be applied to the top wedge, while the nodes on the right hand side of the BFRP are constrained together. Displacement can be applied to the master node, located in the right corner of the BFRP strip.

![Fig. 2: FE mesh. The mesh is coarser in the contact areas, and the number of elements is defined parametrically.](image)
3.2 Material properties

The aluminum wedges and BFRP strip are modeled as elastic materials. The wedges are isotropic, while the BFRP is orthotropic. Since the model uses a plane stress formulation, the non-major properties of the basalt are not necessary at this stage.

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFRP</td>
<td></td>
</tr>
<tr>
<td>Longitudinal elastic modulus (GPa)</td>
<td>40</td>
</tr>
<tr>
<td>Transversal elastic modulus (GPa)</td>
<td>16</td>
</tr>
<tr>
<td>Longitudinal shear (GPa)</td>
<td>2.7</td>
</tr>
<tr>
<td>Major Poisson ratio</td>
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</tr>
<tr>
<td>Assumed minor Poisson ratio</td>
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</tr>
<tr>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>69</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 1: Material properties

3.3 Model formulation

The contact formulation is based on the normal and tangential stiffnesses. For solving the contact problem, the pressure is applied as an external degree of freedom, with zero penetration at the surface. Thus the normal tractions are pressure distribution, and the tangential stiffness is given by the friction coefficient times the pressure in tangential direction.

The stick condition is fulfilled if the tangential tractions are below the value of the normal tractions, see Fig. 3. Normal traction is calculated as the pressure times the friction coefficient.

3.2 FEM Analysis

3.2.1 Model Configuration

A parametric 2D model has been created to simulate the three components of the system, namely two wedges and the BFRP strip, see Fig. 2. The boundary conditions are introduced as constraints applied to the BFRP tape in the y direction and to the top aluminum wedge in the x direction. In order to facilitate identification, the two contact interfaces will be called Al/Al and Al/BFRP. Pressure is applied uniformly over the top of the wedge, with a value of 9 MPa. The purpose is to simulate initial clamping pressure. The distribution of this pressure on the contact interfaces will be analyzed over a wide range of parameters, namely different friction coefficients, mesh discretization and tilt angle α. Initial analysis will investigate the influence of the mesh density in relation to pressure distribution in the two interfaces. It is necessary to differentiate between two models: one in which both Al/Al and Al/BFRP interfaces exist, and one with just the Al/BFRP.

Fig. 3: Contact formulation. δ_n and δ_t are the normal and tangential displacements, k_n and k_t are the normal and tangential material stiffnesses. The normal and tangential tractions are T_n and T_t.

Fig. 4: Pressure distribution Al/BFRP interface
In Fig. 4 and Fig. 5 the convergence analysis for the case where the aluminum wedges are allowed to slide relative to each other is presented. The aim is to investigate if, for static conditions, the wedge design has any influence over the pressure distribution. The overlap length is 30mm and the tilt angle $\alpha = 20^{\circ}$. The analysis is done with mesh discretization starting with 30 elements and up to 140 elements. This corresponds to an element size of 1 mm, 0.5 mm, 0.33 mm, 0.25 mm and 0.21 mm. The pressure distribution in Fig. 4 is for the AL/BFRP interface. The pressure value is the same along the entire interface, for all mesh discretization. The difference is in the value of the pressure over the last element. The pressure concentration is influenced to a large extent by the element size. Although the Al wedge does terminate with a rounded corner, it is clear that at the location a stress concentrator will appear.

This behavior will be analyzed for the Al/Al interface as well. The result in Fig. 5 indicates that the same effect appears in the first and last element. This is due to the effect of the sharp corners of the interface.

The pressure distribution in the Al/BFRP interface must be compared between the model with the wedge and a model with a solid rectangular block. The purpose is to observe if the wedge has any influence over the pressure distribution in the static case. For obtaining this result, the nodes in the Al/Al interface have been joined. All other constraints have not been changed. From the results in Fig. 6 we can see that the pressure distribution is identical as the result in Fig. 4. The reason is that the friction coefficient in the Al/Al interface is sufficient to carry the pressure load through shear stresses, from one wedge to the other.
Since the pressure spike occurring in the last element is highly dependent on mesh density, this relation has to be investigated. By plotting the maximum pressure in the AB/BFRP interface and normalizing with the maximal value for the 140 element mesh, the result in Fig. 7 is obtained. On the x-axis the five coordinate points correspond to the mesh densities in increasing order, from 30 elements to 140 elements. On the y-axis the normalized maximal pressure in the last contact element is represented. The dependency is clear. As the number of elements in the mesh increases, so does the pressure. But the relation is not precisely linear. The increase in pressure becomes less and less as the number of elements is increased. It is possible that the maximal contact pressure will reach a plateau if even more elements will be used. Based on these results, a decision has been made to use 90 elements for further simulations. This is to ensure sufficient accuracy in the model, at the same time with keeping the model small enough and computational inexpensive.

3.2.2 Wedge system design

Now that the main parameters for the analysis have been set, it is time to start to design the joint. There are several parameters which have to be investigated separately.

The tilt angle between the two wedges will be investigated in two cases. First, a static case is considered, where just the pressure P is applied. Then, the pressure application is followed by a displacement of the BFRP. The static case will provide the optimal angle α for pressure distribution. The displacement case will show how the pressure distribution changes in the interface.

The results in Fig. 8 have been calculated for an overlap length of 50 mm, and consist of the normalized pressure distribution in the AL/BFRP interface. Normalized results are used, since they better indicate the quantitative change of the parameters. It is clear that the optimal angle has a value between 10° and 15°. The shallower 10° angle distributes the pressure over a larger overlap length, but the value towards the end of the interface drops. The 15° angle offers a more constant pressure over half of the interface, while reaching 95% in the first 30% of the overlap. The 5° angle offers the most rapid increase in pressure, but its value drops after reaching the maximum in between 20% and 30% of overlap. All the higher tilt angles lead to worst results, as they tend to move the pressure maximum towards the end of the interface, which could lead to premature failure in the composite.

Fig. 8: Tilt angle sensitivity. The pressure distribution in the AL/BFRP interface for tilt angles between 5° and 40°.

Fig. 9: Overlap length sensitivity. Pressure distribution in the AL/BFRP interface for overlap lengths between 30 and 80 mm.
The results in Fig. 8 will now be extended to an overlap length sensitivity analysis. An optimal tilt angle of \( \alpha=15^\circ \) is used for the results in Fig. 9. The number of elements used is 90. In the legend the lengths from 30 mm to 80 mm are recorded.

The optimal overlap length is 50 mm, when considering the pressure profile. The 30 mm length shifts the pressure towards the end of the interface, while all values larger than 50 create a less even pressure distribution.

### 3.2.3 Pull-out

![Fig. 10: Pull-out tests model](image)

Once the main geometrical parameters have been chosen, the analysis will concentrate on the response of the joint, in the case that displacement is applied at the right hand side of the BFRP. The difference between the model in Fig. 10 and the one in Fig. 1 is, that instead of applying static pressure, the top Al wedge is connected to springs. The stiffness of the springs can be modified, and its influence on the pullout force is given in Fig. 11.

For the data in Fig. 11, a 50 mm overlap length in the AL/BFRP interface was used, modeled with an element size of 0.55 mm and a tilt angle of \( \alpha=15^\circ \). It was found that the system could not converge for low stiffness values. This is because for very small k values, rigid body movement occurs. The reason is that the low stiffness of the springs does not stop the upper Al wedge. It displaces upwards and loses contact with the lower wedge. Thus, the friction in the interfaces goes to zero and relative sliding occurs. The first value at which convergence was achieved, is \( k=1\times10^4 \) N/m. The results in Fig. 11 have been obtained by applying a displacement of \( \delta=0.2 \) mm. As expected, the pullout force increases with increasing stiffness.

The pullout force reaches a plateau at \( 10^7 \) N/m, after which further increasing the spring stiffness will not result in a force increase, see Fig. 12.

![Fig. 12: Stiffness sensitivity analysis](image)

The desired result of the analysis is to see when the BFRP will slip out of the joint. Since the results above have not achieved this, it is reasonable to investigate the effect of displacement. By taking into account the plot in Fig. 12, the stiffness value \( k=1\times10^8 \) N/m is considered. The friction coefficient in the two interfaces is \( \mu_{\text{AL/AL}}=0.02 \) and \( \mu_{\text{AL/BFRP}}=0.6 \).

Several simulations have been conducted, in which the displacement is gradually increased from 0.1 to 5 mm. The wedge system is designed to slide and thus ensure increasing amounts of pressure for increasing displacement. The results in Fig. 13 are the reaction force obtained in the BFRP when displacement is applied. The stepwise linear response of the joint correlates to the ratio between the force and displacement to an almost constant ratio.
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Fig. 13: Displacement sensitivity analysis

Preliminary tensile tests indicate a failure load for the BFRP of 15 kN. Due to safety considerations, it is desired that the composite fails before pull-out occurs. This does not take into consideration the through-thickness max stress for the composite. Compressive material tests have not been done until this stage for the composite.

Fig. 14: Pullout simulation. The 0 MPa pressure corresponds to the case where just displacement is applied, and the 9 MPa pressure corresponds to the case in which pressure and displacement are applied at the same time.

If the only criterion is the max stress in the longitudinal direction, the results for pullout are given in Fig. 14. Until now all the tests have aimed at showing how the wedge works, without applying any pre-tension. A clamping pressure of 9 MPa is applied for one of the simulations in Fig. 14 in the first load step. The pressure is applied as in the model in Fig. 1, at the top aluminum wedge. During this load step the spring stiffness is set to zero. Once the load step is solved, the pressure is removed and spring stiffness is introduced. This succession of conditions would represent the effect of an outer casing installed over the wedge. The applied displacement is 7 mm. The data in the legend of Fig. 14 indicates the maximum BFRP failure force, while the ‘p0’ and ‘p9’ are the data set for the simulation without and with pre-clamping force. The pull-out force for both cases is identical. It was expected that the pre-clamping condition will lead to superior pressure, which in turn will raise the pullout force.

Fig. 15: Pressure distribution no pre-tension. ΔT = 1, 1.3 and 1.6

To understand the effect of clamping, the pressure distribution in the Al/BFRP interface will be analyzed at three ΔT time steps while the BFRP is being pulled out of the clamp. The results are normalized since the analysis is at this stage a qualitative analysis. For the first time step in Fig. 15 the pressure is evenly distributed in the interface. The intermediate time step, at ΔT=1.31, shows that with increasing displacement, the pressure begins to

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fluctuate towards the right hand part of the interface. This fluctuation indicates that the BFRP has started to slip out of the wedge along that overlap length. The remaining 0.6 of the interface length provides the grip. At $\Delta T=1.6$ the pressure distribution becomes more scattered over the part where the BFRP slides. The pressure profile over the 0 to 0.6 of the overlap length also begins to exhibit a pressure increase towards the left side, where the joint begins. This build-up could lead to local crushing of the BFRP.

If pre-tension is applied, and the pressure distribution is plotted for the same time steps as previously, the results can be seen in Fig. 16. The difference between these results and the ones in Fig. 15 is larger overall pressure at $\Delta T=1.6$. This means that the application of pre-clamping pressure has no discernible influence on the behavior of the joint.

![Pressure distribution Al/BFRP wedge](image)

Fig. 16: Pressure distribution pre-tension. $\Delta T = 1, 1.3$ and 1.6

### 4 Conclusions

The behavior of a self-locking composite-to-metal joint has been analyzed from a conceptual standpoint. The aim of this paper has been to establish the optimal geometric parameters for achieving a reliable load transfer between two dissimilar materials. A two-dimensional finite element model has been developed to calculate the pressure distribution between the aluminum wedges and the BFRP composite. Initial parameter screening has determined the optimal mesh element size to be 0.33 mm. Overlap length analysis has resulted in a 50 mm long interface, and an optimal angle of 15° between the wedges. Pullout simulations have been used to validate the stiffness of the system, and to confirm the behavior of the wedge. The normal pressure distribution in the Al/BFRP interface has been analyzed over a series of time steps, considering a case where pre-clamping pressure and displacement are applied, and another where only displacement is applied. No significant differences between the two have been observed.

The design has been found to be functional and easy to use. Further tests will be used to verify and fine-tune the model, after which a full 3-D analysis should be conducted.

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### References


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