Study of adhesive bonded joint failure in composite-metal joining

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Abstract. Currently, composites play an important role in the automotive industry where the weight reduction is a key of success due to its high strength to weight ratio. However, the replacement of metals with composites cannot be entirely archived, the joining between composite-metal is required. Bonding with adhesive is one of the most important methods in composite-metal joining. However, the accurate failure prediction of adhesive layers is still lacking due to the complicated state of stress at free-edges of specimens. The aim of this work is to investigate the failure behavior and analysis of acrylic adhesive which is particularly designed to provide superior bonding between composites and metals. Since an adhesive is generally a polymer, its failure depends on the hydro-static pressure. The chosen criterion needs to take into account this dependency. In this study, the Drucker-Prager failure criterion has been used. The parameters were characterized by tensile, compression and double lap shear tests. Then the FEM simulation was performed to predict a failure of single lap shear tests as a validation of model.

Keywords: adhesive bonding, Drucker-Prager failure criterion, composite-metal bonding, FEM simulation

1. Introduction
The environmental issue caused by carbon dioxide emission from fossil fuel usage effects directly to the modern automotive design. Consequently the automotive industry needs to find an appropriate solution and one of the best alternatives is the lightweight structure technology. The performance study tests claim that the reduction of automobile weight by 10% increase the fuel efficiency by 5-7%. Composites are attractive material candidates to be applied to this technology since these materials present a very high strength to weight ratio, especially CFRP composites. However, the composites cannot be used for all parts of a car and they are needed to be assembled with the other parts which are typically metals. Thus, in order to successfully integrate the lightweight composite structural part to the automobiles, the composite-metal joining technology is essentially required. In general the joining technologies for fiber reinforced thermosetting polymer composite (e.g. glass fiber/epoxy resin composite) and metal consist of adhesive bonding, mechanical fastening and hybrid using together.
these two technics [1]. In this study, we aim to focus on the adhesive bonding between glass fiber/epoxy composite and steel. The advantages of adhesive bonding include a uniform load distribution across the joint section and no fiber damage during the preparation phase since none of drilling or forming is pre-required on the composite. The behavior and failure of adhesive bonding under static loading have been investigated. A “cohesive” failure referred to a failure on an adhesive layer has been expected to ensure an appropriate adhesive selection and surface preparation. For the analysis of adhesive failure, the Drucker-Prager criterion has been chosen since this criterion includes the effect of hydrostatic pressure to its failure surface. The tensile test, compression test and double lap shear test have been carried out for the characterization of model parameters. The single lap shear test coupling with FEM simulations have been served as a validation of model.

2. Materials and Behavior

2.1. Adhesive
The adhesive chosen for this study is Maxlok MX/T18 acrylic adhesive manufactured by LORD. This adhesive has been recommended by the manufacturer for composite-metal bonding. Its cure requires 24 hours at room temperature. A full cure of this adhesive is justified by an equitable color visibility [2]. As a polymer based material, the mechanical behaviour of adhesive can complicate as elastoviscoelastic [3]. In addition, the failure of adhesive also depends on strain rate and hydrostatic pressure [18]. Since the scope of this work focus only on the non-linear behavior and the effect of hydrostatic pressure, the effect of strain rate is not taken into account therefore the strain rate in each experiment need to be identical in order to isolate the viscosity of behaviour and simplify the characterisation phase. The non-linear behavior of adhesive is assumed to be a contribution of plasticity and the Drucker-Prager yield criterion is used since this model takes into account the effect of hydrostatic pressure. The strains of plastic deformation are completely described by yield function, hardening rule, and flow rule [6]. Figure 1 shows the yield function in liner form plotting in Von Mises equivalent stress plane (\(\sigma_v-p\) plane) [7]. The parameters of model are identified by tensile test, compression test and double lap shear test. The yield point of each test can be plotted as shown in Figure 1. The Drucker-Prager yield criterion has the following form:

\[
f(\sigma_v, p) = \sigma_v - p \tan \beta - d = 0
\]

where \(\sigma_v, p\) and \(d\) are Von Mises equivalent stress, hydrostatic pressure and cohesion of the material.

The Von Mises equivalent stress can be calculated following this equation

\[
\sigma_v = \sqrt{3J_2} = \sqrt{\left(\sigma_{11} - \sigma_{22}\right)^2 + \left(\sigma_{22} - \sigma_{33}\right)^2 + \left(\sigma_{33} - \sigma_{11}\right)^2 + 6\left(\sigma_{12}^2 + \sigma_{13}^2 + \sigma_{23}^2\right)} / 2
\]

and the hydrostatic pressure is

\[
p = -\frac{1}{3} I_1 = -\frac{1}{3} \left(\sigma_{11} + \sigma_{22} + \sigma_{33}\right)
\]

where \(\sigma_{11}, \sigma_{22}\) and \(\sigma_{33}\) are the normal stresses. \(\sigma_{12}, \sigma_{13}\) and \(\sigma_{23}\) are the shear stresses. \(I_1\) and \(J_2\) are the first invariant and the second deviatomic stress of the stress tensor respectively.
The Drucker-Prager yield and failure surface

The Drucker-Prager model is then applied for failure criterion with other set of parameters identified at the ultimate state of tensile test, compression test and double lap shear test. This decision is based on the assumption that these two surfaces are related to each other, the yield surface expend symmetrically to complete with failure surface (Figure 7) [17].

2.2 Adherends

Steel and composite adherends were used in this study. JIS SS400 carbon steel (non-alloy) is used as a steel adherend. As the steel, the mechanical behavior is isotropic. Another type of adherend is glass fiber-reinforced composite. The mechanical behaviour of this composite is orthotropic elastic and obeys the relationship written in the form of matrix notations as follows.

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\gamma_{23} \\
\gamma_{13} \\
\gamma_{12}
\end{bmatrix} = [S]
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{23} \\
\sigma_{13} \\
\sigma_{12}
\end{bmatrix}
\]

where \( \{\varepsilon\} \), \( \{\sigma\} \) are the column matrix notation of stress and strain tensor and \( [S] \) is the compliance matrix.

\[
[S] = \begin{bmatrix}
\frac{1}{E_1} & -\frac{\nu_{12}}{E_2} & -\frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{23}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}}
\end{bmatrix}
\]
The behavior of steel adherends is identified by tensile testing while a series of tensile tests in different fiber orientation ([0, 90], [±45]) and a short-beam 3-point bending test are used to identify the behavior of glass fiber-reinforced composites adherends.

3. Experimental investigation

3.1. Material characterization tests

An Instron 5567 universal testing machine was used for all tests with a load cell of 30 kN capacity (accuracy ± 0.5%) and extensometer with gage length of 25 mm (accuracy ± 0.5%) for strain following propose [11]. All tests proceed under environment laboratory conditions.

3.1.1. Adhesive test

The adhesive requires the three difference tests in order to identify the parameters of Drucker-Prager yield criterion as stated previously. The tensile specimens were casted by silicone mold with the geometries according to ASTM D638[4] (Figure 2a). The compression specimens were casted by PVC mold with cylindrical geometries of 12.7 mm in diameter and a height of 25.4 mm according to ASTM D695-96 [5] (Figure 2b). The double lap shear specimens were produced according to ASTM D3528 [9] (Figure 2c). The adhesive was mixed with mixing gun and applied on both contact surfaces of double lap shear adherends. The specimens were then clamped by a paper clip to maintain the position and overlap distance of adherends. The adhesive thickness was controlled by 0.3 mm wires [10]. The specimens were cured 24 hours at room temperature conditions (28 ± 3°C and 75 ± 10% relative humidity).

3.1.2. JIS SS400 carbon steel tensile test

JIS SS400 structural carbon steel is a carbon steel (non-alloy). The tensile specimens were fabricated from a steel sheet with a thickness of 1.5 mm according to ASTM E8 [12] using a laser cutting machine. The specimens were loaded up to failure to characterize both of elastic and plastic behaviors.

3.1.3. Glass fiber-reinforced composite tests

The composite adherend in this study is made from E-Glass glass fiber woven fabric (WR600) and epoxy resin. The composite tensile specimens were fabricated with respect to the standard ASTM D3039 [13] using vacuum infiltration process. The composite specimens contains 8 woven fabric layers with stacking of [0, 90]_8 and [+45, -45]_8. The tensile test on [0, 90]_8 specimen characterizes the elastic modulus in longitudinal (E_{11}) and transverse (E_{22}) direction while a shear modulus in direction 12 (G_{12}) is identified from the [+45, -45]_8 specimen. The short-beam specimens for 3-point bending test were fabricated according to ASTM D2344 [14] with the same process as tensile specimens. The number of layers was 12 and the stacking was [0, 90]_12. This test characterizes a shear modulus in direction 13 (G_{13}) and 23 (G_{23}). All composite specimens are cured at room temperature (28 ± 3°C and 75 ± 10% relative humidity) for 24 hours.

3.2. Criterion validation test: Single lap shear test

A single lap shear test was used for validation of the Drucker-Prager yield criterion. The specimens were carried out according to ASTM D1002 [15] Figure 2d. For composite adherend, the number of layers were 10 layers with [0, 90]_10 stacking. A metallic adherends were cut with a hydraulic press cutting machine. The two adherends were assembled for 20 mm overlap distance with an adhesive. Adhesive thickness was controlled by wires [10]. Paper clips were used to keep the adherends in place. The specimens were then cured for 24 hours at room temperature (28 ± 3°C and 75 ± 10% relative humidity).
4. Static tests results

4.1. Adhesive test
The results of tensile tests are shown in Figure 3 and the identified parameters are summarized in Table 1. The linear slope of the experimental curve is a Young’s modulus (E). A negative ratio of transverse and axial strain is a Poisson’s ratio (v). The tensile stress-plastic strain relation is also used for a hardening model. In order to implement into FEM simulation, a true stress-true plastic strain plot is required (Figure 4). The eqs. 5-7 is used to calculate these true stress and true plastic strain. The result of compression tests are presented in Figure 5 and Table 1. Since the strain exceeds 5%, the stress-strain curves are used to describe its mechanical properties: The elastic modulus (E_1) is the linear slope between $\varepsilon = 0$ to 0.05. The post-yielded modulus (E_2) is identified by the tangential linear slope as show in Figure 5. The yield point is characterized by the intersection of slope E_1 and E_2. The inflection point is defined as a divergence of E_2 [16]. This point is considered to be a failure point of compression test. For double lap shear tests, the state of pure shear was assumed at the adhesive layer. However the deformation measured from the extensometer (Figure 6) is not an adhesive deformation alone but a combination of adhesive and adhered deformation. Hence, only maximum shear stress was preliminary achieved from the experiments (Figure 6 and Table 1). A cohesive failure has been observed as expected (Figure 8). This confirms a good adhesive selection. The Drucker-Prager yield and failure criteria can be finally identified from these three tests (Figure 7 and Table 2).
Figure 5. Compression test: stress-strain curves of adhesive

Figure 6. Double lab shear test: shear stress-strain curves

Figure 7. Drucker-Prager failure surface

Figure 8. A cohesive failure of double lap shear test

Table 1. Mechanical properties of adhesive.

| Specimen          | E-modulus E1 (MPa) | E-modulus E2 (MPa) | Yield strain $\varepsilon_y$ (-) | Yield stress $\sigma_y$ (MPa) | Failure strain $\varepsilon_{fail}$ (-) | Failure stress $\sigma_{fail}$ (MPa) | Poisson’s ratio $\nu$ (-) |
|-------------------|--------------------|--------------------|----------------------------------|-------------------------------|---------------------------------------|--------------------------------------|-------------------------|
| Tensile           | 1424.266           | -                  | 0.451                            | 6.476                         | 1.760                                 | 13.987                               | 0.324                   |
| Compression       | 348.432            | 44.139             | 0.041                            | 9.061                         | 0.403                                 | 22.888                               | -                      |
| DB-lap shear      | -                  | -                  | -                                | -                             | 0.00023                               | 12.128                               | -                      |

(*) 3 specimens per test

Table 2. Summary of identified parameters for the adhesive.

| $F = t - p \tan \beta - d$ | $\beta$ (degree) | $d$ (MPa) |
|---------------------------|------------------|-----------|
| Yield surface             | 34.2             | 7.544     |
| Failure surface           | 34.2             | 18.622    |

\[
\sigma_{true} = F/S = Fl/S_{0}\sigma_0 = F (\Delta l + l_0)/(S_0 l_0) = F/S_0 (1 + \Delta l/l_0) = \sigma (1 + \varepsilon) \tag{5}
\]

\[
\varepsilon_{true} = \int_{l_0}^{l} \frac{\Delta l}{l_0} = \ln \left(\frac{l}{l_0}\right) = \ln \left(1 + \frac{\Delta l}{l_0}\right) = \ln \left(1 + \varepsilon\right) \tag{6}
\]

\[
\varepsilon^p = \varepsilon - \varepsilon^c = \varepsilon - E\sigma \tag{7}
\]

4.2. JIS SS400 carbon steel test results

The Young’s modulus ($E$) was identified from the tensile test and equals to 188.21 GPa (Figure 9, Engineering stress-strain curves). The Poisson’s ratio ($\nu$) was assumed as a typical value of metal and equals to 0.3. For the hardening characterization, a true stress-true plastic strain plot is required (Figure 10) using the eqs. 5-7. The curve from Figure 10 will be implemented directly in FEM simulation.
4.3. Glass fiber-reinforced composites test results

The results of tensile test are present in Figure 11 and 12. The linear slope of specimens [0, 90] in Figure 11 defines as elastic modulus in longitudinal (E₁₁) while the transversal modulus (E₂₂) is assumed to be equal to E₁₁ due to the cross-ply stacking. The linear slope of specimens [+45, -45] in Figure 12 represents E₁₂ and can relate to the in-plan shear modulus (G₁₂) using eq.8 [20]. The results of short beam 3 points bending test are shown in Figure 13. The linear slope in Figure 13 refers to ΔP/Δδ in eq.9 [20] and can be used to calculate the out of plan shear modulus (G₁₃) and (G₂₃) which assumed to be equal due to the cross-ply configuration. All identified parameters are summarised in Table 3.

\[
\frac{1}{G_{12}} = \frac{4}{E_{45^\circ}} - \frac{1}{E_1} - \frac{1}{E_2} + 2\nu_{12} \frac{E_2}{E_1}
\]  
\[
\frac{1}{E_1} + \frac{6h_0^2}{5E_1} = \frac{4}{E_1} \frac{\Delta \delta}{\Delta P} \frac{b_0h_0^3}{L^3}
\]
Table 3. Summary of identified parameters for the composite.

| Composite          | $E_1 = E_2$ (GPa) | $E_3$ (GPa)[19] | $G_{12}$ (GPa) | $G_{13} = G_{23}$ (GPa) | $\nu_{12}$ [19] | $\nu_{13} = \nu_{23}$ [19] |
|--------------------|-------------------|-----------------|----------------|--------------------------|-----------------|-----------------------------|
| Glass/epoxy        | 19.16             | 3.5             | 2.93           | 0.83                     | 0.04            | 0.38                        |

5. FEM simulation

5.1 Structural analysis

The single lap shear test simulation was performed to validate the Drucker-Prager model. Dimensions and boundary conditions of single lap shear specimens are shown in Figure 14. A 3D 8-noded solid element (C3D8) was used. A model has totally 165888 elements and 186120 nodes with the refinement zone at the edge of adhesive layer. The mesh sizes of adhesive layer are progressively increased from 7.5x10^{-4} to 0.037 mm\(^3\). ABAQUS software was used to simulate the numerical test and taken into account the material nonlinearity. This test showed non-linear deformations due to the bending effects during the applied load.

![Figure 14. Single lap joint](image)

5.2 Validation of model

Figure 15 shows a deformation of single lap shear specimen by simulation. The red-circle zone of steel adherend proceeds a plastic deformation. The comparison of simulation and experiment is demonstrated in Figure 16. A good agreement was found up to 8 MPa after that the simulation appears to be slightly higher. The different can be explain by the failure of testing specimens which have been fail at the composite adherend (delamination) rather than adhesive layer as expected.(Figure 17) This means that the selected adhesive is stronger than the strength of composite intra-plies. It is confirmed a good adhesive selection.

![Figure 15. Finite element model of the single lap joint](image)
6. Conclusions
In this study, the adhesive behavior was found to depend on hydro-static pressure. Drucker-Prager yield criterion with isotropic hardening was used to define the plastic behavior of the adhesive. This criterion was also adapted experimentally as a failure criterion to estimate failure loads of adhesive. The numerical simulation has shown a good agreement of using Drucker-Prager for a yield criterion. For a failure prediction, the Drucker-Prager failure criterion has accurately predicted failure load (0.22% error) when considering all adhesive elements satisfied a failure criterion as a failure of structure (using post-processing method without any degradation rule on elements). However, for a high local stress concentration field, the characteristic length or even characteristic volume [21,22] were often used to predict a failure of structure rather than all elements failure. In that case, the single lap shear test can be used to identify a characteristic length and some other test needs to be proceeded in order to validate the identified length. The linear Drucker-Prager yield criterion model proposed in this study significantly differs from the higher order model e.g. hyperbolic Drucker-Prager model [17,18] at tri-axial state of stress (negative hydrostatic stress) which is a weakest state of stress for adhesive (Figure 18). However, all tests proceeded in this study cannot identify that tri-axial failure, a sophisticated Arcan-Mines test is required [17] in order to justify a suitable failure criterion.

*Error in strain measurement at 7 MPa, the maximum stress of this test is 15.33 MPa*
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