Experimental Investigation and Finite Element Modelling of the Influence of Hydrostatic Pressure on Adhesive Joint Failure

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Abstract

Structural adhesives have been increasingly used in automotive industries in conjunction with lightweight structural components to maximize weight reduction in modern car design. They are used to bond various kinds of lightweight materials such as FRP composites or metallic alloys and provide a good distribution of force across joining area without damaging the substrates. For automotive applications, bonded components have been often used in complex loading environments which brings failure prediction of adhesive joints a key of success for this technology. As polymer-based materials, hydrostatic pressure can have a major impact on adhesive joint failure in addition to temperature and strain rate. Its influence can be investigated using a specific test fixture known as a modified-Arcan fixture. This article presents the characterization of epoxy-based adhesive using a series of modified-Arcan tests to apply different loading taking in account effect of hydrostatic pressure onto adhesive joints. A high-order exponential Drucker-Prager failure criterion is chosen to interpret the yield and failure surface. Finally, the non-linear behaviour of adhesive is identified via 0° and 90° Arcan tests which correspond respectively to tri-axial and shear modes and the validation of this behaviour is carried out by mix-mode 60° and 120° Arcan tests. The simulation shows a good agreement only with the result in direction 60° while in direction 120° the divergence is obvious due to the different in damage mechanism of this mode.

Keywords: adhesive bonding, modified-Arcan test, The high-order Drucker-Prager criteria, FEM simulation
1. Introduction

Structural adhesive joining technology is currently one of the attractive methods to assembly lightweight structural components such as composites in automotive and aerospace industries. This method provides many advantages in comparison to conventional methods including a good distribution of force all over the bonded area, which noticeably decreases a local concentration of stress in components. It is also an available option for multi-material assembly and adds relatively low-weight onto structures, which is suitable for weight reduction philosophy to increase an efficiency of a car in automotive industrial design nowadays [1, 2]. For bonded multi-material structures, e.g. metal-composite joining, the optimize thickness of adhesives is suggested a certain structure (about 0.2-0.5 mm) to ensure that the adhesive layer is bonded all over the overlap area [3-5] so that the thickness control of adhesive layer is also a topic in industrial applications where more sophisticated geometric components are bonded. The adhesive SikaPower-497 designed to bond metal-composite structure was investigated in this study. The mechanical properties in manufacturer’s datasheet is insufficient to predict efficiently structural failures.

Since the adhesive presents a non-linear behavior under loading and its yield and failure domain also depend on hydrostatic pressure, a sophisticated experimental methodology is required to characterize its behavior. A modified-Arcan fixture is a specific test fixture that can be used to characterize an adhesive layer under hydrostatic pressure [6]. It can apply either tri-axial tension or compression and coupling with shear load to induce different state of hydrostatic pressure onto a specimen. In addition, a metallic substrate of modified-Arcan test has a special geometry to reduce the edge effects of adhesive layer [5]. With a good surface preparation, a cohesive failure, which is a failure in an adhesive layer, can be expected. This type of failure is preferable to ensure that the characterization is on an adhesive layer not on interfaces between adhesive and its substrate and confirm the good selection of adhesive. This paper investigates the effect of hydrostatic pressure on adhesive layer using a series of modified-Arcan tests.

An image correlation is used as a non-contact method to measure a strain field during the tests. The yield and failure surface are interpreted by a high-order exponential Drucker-Prager criterion. A non-linear behavior of adhesive is identified by tri-axial (0°) and shear (90°) mode of modified-Arcan test using FEM simulations and mix-mode direction (60° and 120°) are served as a model validation.

2. Material and Behavior model

An adhesive structural for composite-metal bonding in this study is a SikaPower-497 Epoxy adhesive manufactured by Sika. It is a one-part structural adhesive based on epoxy. Its cure requires 50 minutes at 160°C to form a high-performance thermoset adhesive [7]. As a polymer-based material, the adhesive mechanical behavior is a type of elasto-visco plasticity which depends on temperature, strain rate and also hydrostatic pressure [8]. In this study, the material is treated as elasto-plastic and only the effect of hydrostatic pressure is investigated. As can be seen in Figure 1, the effect of hydrostatic pressure on adhesive yield and failure function, \( f(\sigma_y, p) \) can be explained by high-order exponential Drucker-Prager criterion for more accuracy at the state of negative hydrostatic pressure (Eq.1) [9]:

\[
f(\sigma_y, p) = a\sigma_y^b - p - p_i = 0
\]

where \( \sigma_y \) is Von Mises equivalent stress (eq.2), \( p \) is hydrostatic pressure (Eq.3), \( p_i \) is hardening constant, \( a \) and \( b \) are material parameters that are independent to plastic deformation:

\[
\sigma_y = \sqrt{3J_2} = \sqrt{\left((\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{13}^2 + \sigma_{23}^2)\right)/2}
\]
\[ p = -\frac{1}{3} I_1 = -\frac{1}{3} (\sigma_{11} + \sigma_{22} + \sigma_{33}) \]  

where \( \sigma_{11}, \sigma_{22} \) and \( \sigma_{33} \) are the normal stress components, \( \sigma_{12}, \sigma_{13} \) and \( \sigma_{23} \) are the shear stress components, \( I_1 \) and \( J_2 \) are the first invariant and the second deviatoric stress of the stress tensor respectively [10]. The functions for plastic flow follow the Equation 4 and 5.

\[ d\varepsilon_p = d\lambda \frac{\partial g}{\partial \sigma} \]

\[ g(\sigma_y, p) = \sqrt{\left(\xi \sigma_y \tan \beta\right)^2 + (\sigma_y)^2} - p \tan \beta \]

where \( d\lambda \) is the plastic multiplier, \( g \) is the flow potential, \( \beta \) is the dilation angle measured in the \( p - \sigma_y \) plane, \( \xi \) is an eccentricity of hyperbolic function defined an approaching rate of function to its asymptotes. Since the flow function, \( g(\sigma_y, p) \) is different from yield function, \( f(\sigma_y, p) \), the plastic flow is non-associated \((g(\sigma_y, p) \neq f(\sigma_y, p)) \). The flow direction will not be normal to the yield surface. To simplify the calculation, the constant \( \xi \), which refers to the eccentricity of hyperbolic function in equation 5, is tuned to provide the flow direction as close as possible to the associated flow \((g(\sigma_y, p) = f(\sigma_y, p)) \) which means that the flow direction is normal to yield surface. Then, the non-linear isotropic hardening from the theory of plasticity is used to interpret its non-linear behaviour [11]. Its response is described by the following equation:

\[ \sigma_y = \sigma_y + q \left(1 - e^{-\frac{c e^{\varepsilon_{eq}^p}}{q}}\right) + H \varepsilon_{eq}^p \]

where \( \sigma_y \) is the Von Mises equivalent stress, \( \sigma_y \) is the yield stress, \( \varepsilon_{eq}^p \) is the equivalent plastic strain and \( H, q \) and \( c \) are material parameters. All material parameters are identified using a series of modified-Arcan tests.

\[ \sigma_y (MPa) \]

\[ p (MPa) \]

\[ \sigma_y (MPa) \]

\[ p (MPa) \]

\[ \sigma_y (MPa) \]

\[ p (MPa) \]

3. Modified-Arcan fixture

The modified-Arcan fixture is a specific fixture for testing adhesives. It was inspired by the work of Arcan [12] and followed by the modified version of Arcan-Mines testing fixture [13, 14]. The updated version for adhesive testing allows the fixture to vary the angle to impose a different state of stress onto the adhesive layer as shown in Figure 2 [15]. The tri-axial and pure shear state of stress can be obtained when testing at the direction 0° and 90°. The combination of the tensile-shear state of stress...
can be found at direction 30° and 60° and the compressive-shear state of stress occurs when testing at direction 120°. All stress combinations are calculated using Equation 7 [14].

\[
\sigma_{11} = \frac{F \cos(\theta)}{S}, \sigma_{22} = \sigma_{33} = \frac{\nu F \cos(\theta)}{1-\nu}, \sigma_{12} = \frac{F \sin(\theta)}{S} \text{ and } \sigma_{13} = \sigma_{23} = 0
\]  

(7)

where \( F \) is a force from the tensile test, \( S \) is a surface area of the substrate, \( \theta \) is the angle of fixture and \( \nu \) is Poisson’s ratio of the material. The direction 0° and 90° are called the triaxial and shear mode respectively while the other directions are named as the mix modes, as shown in Figure 3. In addition, this fixture has the advantage of using the universal testing machine. The specimen’s substrates for this test have a specific geometry called a beak, around their edge as shown in Figure 4. The adhesive layer bonds these two substrates together forming a specimen for testing. The 45° beak decreases remarkably the edge effect on the adhesive layer due to the substrate’s geometry [5]. A stress field in the adhesive layer is more uniform especially in shear stress and maximum stress appear in the center of the joint.

![Figure 3](image1.png)

**Figure 3.** Modified-Arcan test mode: (a) triaxial mode, (b) mix modes: tensile-shear, (c) shear mode, (d) mix modes: compression-shear

![Figure 4](image2.png)

**Figure 4.** The substrates geometry with the beak

4. **Experimental investigation**

All tests have been carried out statically using an Instron 5567 universal testing machine with a load cell of 30 kN capacity (accuracy ± 0.5%) and a crosshead speed of 0.5 mm/min [16]. The strain measurement was done by an image correlation system, ARAMIS manufactured by GOM, which has a strain measurement ranged to 0.005 % - 2000 % [17]. All tests were performed at room temperature.
The substrates for adhesive bonding are made of steel with a rectangular cross-sectional bonding area of 70x10 mm. The bonding surface of substrates is sanded and degreased according to manufacturer’s recommendations. The thickness of the adhesive layer and substrate’s alignment are precisely controlled by the assembly fixture. This fixture consists of a shim plate for thickness control, four straight columns to control a substrate’s alignment and coil spring to apply a clamping force, as shown in Figure 5. Specimens with a single component adhesive were cured at 160°C for 50 minutes to ensure a complete cure of adhesive layer. In order to utilize an image correlation strain measurement, a white-matte surface coating with a cloud of black points is required on the side of the specimen (see Figure 6). The deformation measured from point 1-10 was performed on steel substrates to capture the entire deformation field of the specimen. With a rigid substrate assumption, the average strain was calculated from the average deformations between points 1&6, 2&7, 3&8, 4&9, 5&10 and divided directly by the adhesive thickness (see Equation 8).

![Figure 5. Specimen’s assembly fixture](image)

![Figure 6. Image correlation for strain measurement](image)

$$\text{Average strain} = \frac{\sum_{i=1}^{n} (\delta_i / t_i)}{n} \quad (8)$$

where $\delta$ is a deformation between the two points, $t$ is an adhesive thickness, $n$ is a number of measured deformation.

5. Experimental results

The results from the modified Arcan test show a non-linear behavior in all modes. The limit elastic was identified by loss of linearity of experimental curves. The recorded force from load cell was transformed to stress components using Equation 7 with relating to testing mode. Then, Von-Mises equivalent stress and hydrostatic pressure were obtained via Equations 2 and 3. The yield and failure surface plots obtained experimentally from Arcan tests were shown in Figure 7. It can be seen that the dependence of hydrostatic stress on yield and failure stress can be represented well with the higher-order Drucker-Prager. The corresponding criteria’s parameters are summarized in Table 1. Table 2 and Table 3 summarize the parameters of the plastic model and plastic flow. They were identified using iteration method and FEM simulation to complete with experimental results (see Table 2 and Table 3). The results obtained from all testing mode show a cohesive failure on the specimen except in the direction 120° which is a combination of compression-shear mode. Regarding the direction 120°, the tested specimen was found out to be an adhesive failure. This can be explained by the nature of polymer behavior that becomes stronger under compressive loading (positive hydrostatic pressure) while the strength of interface remains the same (see Figure 8).

| Table 1. Summary of identified parameters for the adhesive. |
|-------------------------------------------------------------|
| $F = a c^{b} - p - p_i$ | $a$ | $b$ | $p_i$ (MPa) |
|------------------------|-----|-----|------------|
| Yield surface          | 1.3×10$^{-2}$ | 2   | 19.7       |
| Failure surface        | 4.3×10$^{-5}$ | 3.2 | 32.8       |
Table 2. Summary of identified parameters for plastic model.

| Parameter | Value |
|-----------|-------|
| $\sigma_y$ | $\sigma_y + q\left(1 - e^{-\frac{q}{p}}\right) + H\varepsilon_{eq}^p$ | 29.6 |
| $q$ | 9.2 |
| $c$ | 19.5 |
| $H$ | 62.8 |

Table 3. Summary of identified parameters for plastic flow.

| Parameter | Value |
|-----------|-------|
| $g = \sqrt{\left(\zeta \sigma_y \tan \beta \right)^2 + \left(\sigma_y \right)^2 - p \tan \beta}$ | 29.6 |
| $\zeta$ | 18 |
| $\beta$ | 14.6 |

Figure 7. The Drucker-Prager yield and failure surface
Figure 8. The failure of modified Arcan specimens in different directions: (a) direction 0°, (b) direction 30°, (c) direction 60°, (d) direction 90°, (e) direction 120°

6. FEM simulation

6.1. Structural analysis

The simulation of the modified-Arcan test was performed to identify and validate the Drucker-Prager model. Concerning the CAD model of the fixture, its boundary conditions and geometries of the specimen are shown in Figure 9. Since the fixture deforms under loading due to the strength of the adhesive layer, the simulation needs to be performed on the entire fixture taking into account of the deformation. However, the fixture can still be simplified to increase the efficiency of simulation since its symmetries in the x-y plane. A 3D 8-noded solid element with reduced integration type (C3D8R) was used to ensure the accuracy of the results. Taken together, the fixture model consists of 46,344 elements and 58,838 nodes. The adhesive layer has 1,600 elements and 2,525 nodes with the mesh refining zone at the edge of the adhesive layer. The mesh sizes are in the range of 9.375x10^-3 to 4.688x10^-2 mm^3. The FEM simulations were performed using ABAQUS software with Young’s modulus (E) = 2120 MPa and Poisson’s ratio (ν) = 0.36 acquired from the previous work [11] and taken into account the nonlinear behavior of the material.
6.2. Identify of model

The tests simulation in direction $0^\circ$ and $90^\circ$ were used to identify the plastic model’s parameters for the non-linear behavior of adhesive. These two modes apply completely different states of stress onto the adhesive layer, which is suitable for the identification phase. Figure 10 demonstrates the comparison between experiments and simulation results using the parameters of the plastic model and plastic flow in Table 2 and Table 3.

6.3. Validation of model

The model validation was carried out using the mode mix tests, which are the tests in the direction $60^\circ$ and $120^\circ$ corresponding to tensile-shear and compressive-shear, respectively. These complex states of stress are perfect for validation phase. Figure 11 provides the comparison between simulation results and experiments. The simulations agree well with experimental results in direction $60^\circ$ while show an obvious divergence in direction $120^\circ$. This disagreement can be explained by the type of failure in this mode, which is an adhesive failure at the interface. As discussed previously that the adhesive layer becomes stronger under compressive loading and exceeds the interface strength between the adhesive layer and metallic substrates. With this scenario, the damage is localized at the interface rather than the adhesive layer, which is contrast from the other modes. Thus, the non-linear behavior observed from the experiment is a result of interfacial damage, which did not implement in the simulation. Since the effect of interface strength plays an important role in this mode, it needs to be analyzed by other approach [19].
7. Conclusions

The investigation of hydrostatic pressure effect on structural adhesive SikaPower-497 clearly shows how it varies the yield and failure surface of the material. The strength of adhesive increases with hydrostatic pressure but greatly declines under negative hydrostatic pressure, which corresponds to tensile tri-axial state. The high-order exponential Drucker-Prager criterion is suitable to interpret the experimental results in both yield and failure scenarios in comparison to the original linear Drucker-Prager criterion. The numerical validation of non-linear behavior identified from tri-axial and shear modes show a good agreement with experiments only if damage takes place at the adhesive layer which relates to cohesive failure. For interfacial damage, the different simulation approach is required in order to predict its behavior more precisely.

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