Journal on Mechanics of Solids, 1:1 (2022) 31-38
ISSN 2975-8262
DOI: 10.24840/2975-8262_001-001_001838

Received: 27 September, 2022
Accepted: 7 October, 2022
Published: 11 November, 2022

Effects of Mode Mixity on the Failure Mechanism of Aged Adhesive Joints

Guilherme Pedro do Vale
Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (guilhermevale@gmail.com). ORCID 0000-0003-3338-0110

Alireza Akhavan-Safar
Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Campus da FEUP, R. Dr. Roberto Frias 400, 4200-465 Porto, Portugal (aAkhavan-Safar@inegi.up.pt). ORCID 0000-0002-7168-7079

Frederico Vilaça Barbosa de Castro Lopes
Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (fclopes@inegi.up.pt)

Fernando Castro Sousa
Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (fmcsousa@fe.up.pt). ORCID 0000-0003-3642-5492

Rakesh Goyal
Deere & Company, Enterprise Technology and Engineering Center, Pune, MH, 411013, India (GoyalRakesh@johndeere.com)

Justin Jennings
Deere & Company, Intelligent Solutions Group, Moline, IL, 61265, USA, (JenningsJustin@JohnDeere.com)

Lucas FM da Silva
Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 PORTO, Portugal (lucas@fe.up.pt). ORCID 0000-0003-3272-4591

Author Keywords

Adhesives, Arcan Joint, Ageing, Failure Mechanisms, Mode Mixity

Type: Rapid Communication

Open Access

Peer Reviewed

Abstract

The strength and the performance of adhesive joints can be significantly influenced by the ageing procedure. However, the role of aging in the failure mechanism of adhesive joints as a function of loading conditions has not been studied yet. The current research aims to investigate the effect of mode mixity on the failure mechanism of aged adhesive joints using Arcan samples. Based on the results loading the tested joints in shear led to a higher percentage of interfacial failure than in tensile. However, it was also found that the shear loading mode is less sensitive (compared to tensile loading) to the ageing conditions.

1. Introduction

The application of adhesives is on the rise in various industries due to their mechanical characteristics and versatility. They also make a low-weight alternative to the traditional joining method which is a very important goal in top-notch industries (da Silva Lucas F. M., Öchsner Andreas, and Adams Robert D. 2011). Despite all these advantages they also come with some problems attached. One of them is their sensitivity to environmental conditions such as heat and humidity (Joviano António da Costa et al. 2022). The presence of humidity negatively impacts the properties of the adhesive and worsens the strength of the joint (Brandão et al. 2022; J.A da Costa et al. 2022) which can make them useless for some applications. There are three different types of failures on the joints: adhesive failure, cohesive failure, and substrate failure. The aim is always to have a substrate failure with signs of damage to the adhesive part since this shows that the weakest part of the connection is not the adhesive nor the interface between the adhesive and the substrate but the substrate itself. If no damage is seen on the adhesive part, it means the joint was overdesigned and therefore it is not ideal (Silva, Magalhães, and Moura 2007). However, when humidity is introduced into the system the predominant type of failure is mostly adhesive failure rather than cohesive failure (Borges et al. 2021; da Costa et al. 2021a). Water can enter the adhesive joints via the adhesive, the substrate, or the interface between these two (Brandão et al. 2022). Once the water gets into the joint it causes two major problems: the degradation of the adhesive and the degradation of the interface between the adhesive and substrate. Regarding the first one, a consequence of the humidity is also the expansion of the adhesive (da Costa et al. 2021b) which will cause internal tensions that damage the joint strength (da Costa et al. 2021a; da Costa et al. 2022).

To avoid joint failures in service, first, it is essential to study different failure mechanisms that occur in aged samples. Da Costa et al. (2022) showed that the strength of aged Arcan specimens would have a loss of up to 63% after 15 days of ageing on static tests. In another study, da Costa et al. (2022) concluded that aged adhesives joints would not be able to support significant fatigue loads. Similar aged and unaged samples were subjected to static and fatigue loading conditions to investigate the effects of aging on the failure modes. Both modes I and II loading angles were analyzed. The failure modes were finally investigated by the analysis of the fracture surfaces.

2. Experimental details

2.1. Materials

In this paper, a two-component epoxy adhesive was used. It is made for connecting metallic substrates, as well as composite materials, to provide high strength and impact resistance. Since the joints were planned to be exposed to moisture at high temperatures during the ageing process, stainless steel (AISI 304) substrates were used to avoid corrosion and therefore a reduction in its mechanical properties that would affect the data obtained on the considered tests.

2.2. Joint geometry and preparation

Arcan joints with the dimensions given in Figure 1 with widths of 10 mm were manufactured and tested. This form of the joint was used due to its versatility regarding tests on different loading modes. A mould was used (Sousa et al. 2020) to guarantee the adhesive alignment of the substrate during the curing process. The thickness of the adhesive layer was set to 0.2 mm with the assistance of calibrated metal spacers. The curing process consisted of 24 hours at room temperature followed by 1 hour at 80°C (da Costa et al. 2022).

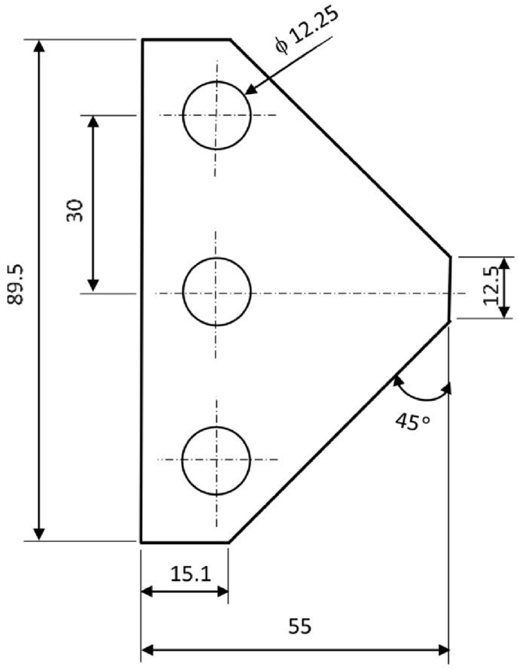


Figure 1. Dimension of an Arcan

2.3. Ageing conditions

To determine the rate of water uptake through the adhesive, the diffusion coefficient (D), as a key parameter is required. The parameter is obtained using a gravimetric analysis as discussed by da Costa et al. (2021a) using bulk plates. In this study, the plates were fully immersed in distilled water and were kept in an oven at 50°C. The weight of the samples was measured at specific time intervals. To age the Arcan joints, they were immersed in water for 15 days at 50°C. The joints then were taken out of the water and tested immediately.

2.4. Testing procedure

An Arcan apparatus (Sousa et al. 2020) was used to test Arcan joints in mode I and mode II loading conditions both for static and fatigue tests. For the fatigue test, a load-controlled test with a frequency of 10 Hz and an R ratio of 0.1 was used. In the static tests, a displacement rate of 1 mm/min was considered. A fractography analysis using microscopic pictures was conducted for all the tested joints.

3. Fick's Law

Fick's law is the most common model to simulate the diffusion of water into the adhesives. It is based on mass variation as a function of time. It does not, however, adhere to a universal paradigm for all materials and conditions investigated. As a result, numerous models for describing the water uptake behavior of materials have been presented (Borges et al. 2021). In this paper, the adhesive follows a dual Fick's law. This model consists of two stages of water absorption. Therefore, there will be different diffusion coefficients and saturation levels. The total saturation is calculated by adding each saturation level together (Loh et al. 2005). However, due to the short ageing time for the joints, the first saturation level of the adhesive was assumed for the ageing analysis of Arcan joints.

4. Finite Element Model

A numerical simulation was built using the Finite element method (FEM). To this end, Abaqus as a famous and robust FEM software was used. Two analysis steps were defined in this analysis. In a first step, using the data obtained experimentally out of the diffusion tests and by considering Fick's law results, the water uptake level in Arcan joints was simulated by the heat transfer analogy where the nodal temperature shows the amount of water at each point. The diffusion coefficient obtained by Fick's Law was set as the conductivity of the adhesive. The water uptake was simulated in the three-dimensional model for an Arcan joint. Due to the symmetry, an eighth of the joint was simulated to reduce the processing time. Eight-node thermally coupled brick elements (C3D8T) that measured trilinear displacement and temperature were used in the numerical simulation.

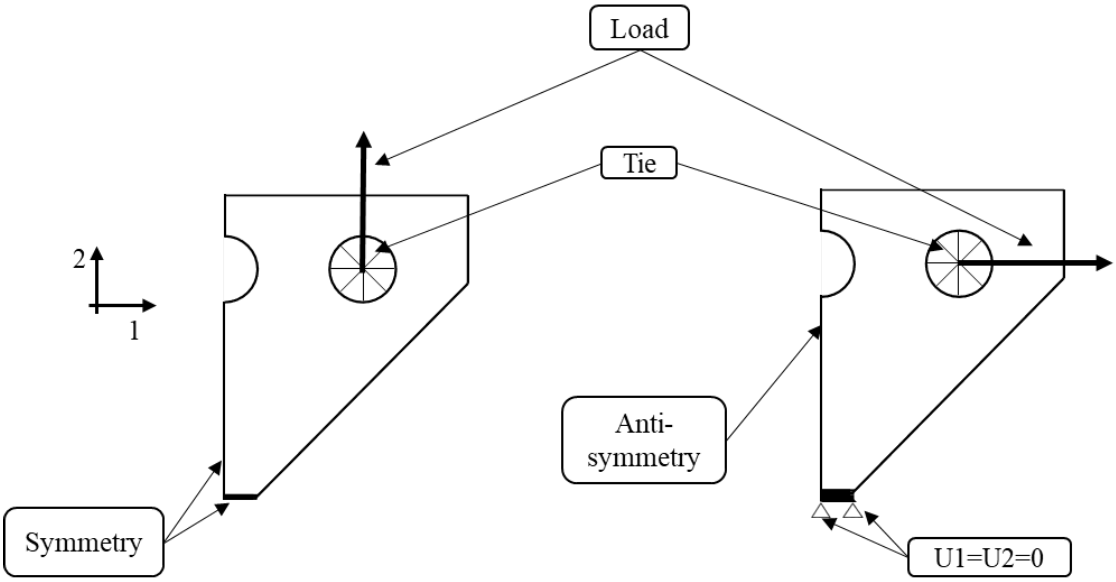


Figure 2. Boundary conditions for mode I (left) and mode II (right)

The second step consisted of a tensile or shear loading mode simulation. The properties of the adhesive on each node were defined by the amount of water present in the node. The type of nodes and the mesh were equal to the ones used in the previous step. The boundary conditions are shown in Figure 2 for both shear and tensile loading modes. From this step and by simulating for both loading modes the maximum principal stress distribution for each case was simulated. In this step, the properties of the elements were defined as a function of the level of water. To this end, the dogbone tensile test results for unaged and aged conditions were considered.

5. Results and Discussion

5.1. Test results

The rate of water uptake as a function of time was obtained from the gravimetric analysis. A two-step saturation behavior was found for this adhesive, which means that the considered material probably follows a dual Fickian low. However, due to the low ageing time considered for the Arcan joints, only the first saturation level corresponding to 3.15 % of water uptake was considered to calculate the diffusion coefficient. Accordingly, by using the Fick's law the rate of water uptake was obtained as $9.06E^{-12}\ m^2.s^{-1}$.

Static tests were performed for both aged and unaged joints. Two different types of loading modes were considered including pure shear and pure tensile. The average strength for unaged joints was 27.32 ± 3.06 MPa for mode I and 25.11 ± 3.60 MPa for mode II. Whereas for the aged joints, it dropped to 15.37 ± 0.80 MPa and 23.05 ± 2.15 MPa for modes I and II respectively. Comparing the results of the static tests, after ageing for 15 days the strength reduces by 43.8% for mode I and only 9.0% for mode II.

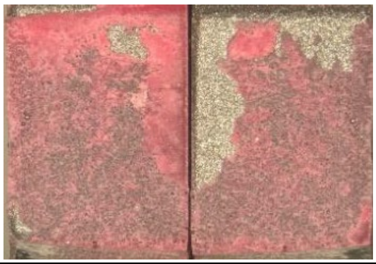
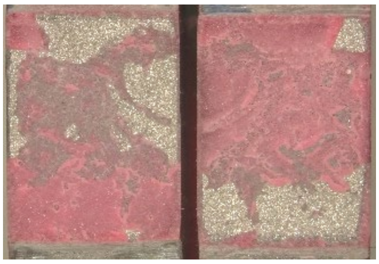
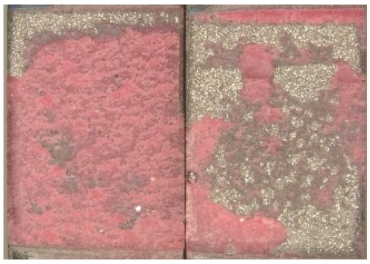
Fatigue tests were also conducted for both aged and unaged joints and for both mode I and mode II loading conditions. For mode I, for unaged joints at a load level of 2754 N the life was 982 cycles. A similar life (1741 cycles) was obtained for aged joints subjected to 1400 N maximum fatigue load. For mode II, for unaged joints to reach around the same life, a fatigue load of 2679 N was applied while for aged samples the load should be reduced to 2088 N for a similar fatigue life (1184 cycles). To maintain an approximate number of life cycles, the joints at mode I need a 49.2 % reduction in load after ageing for a similar fatigue life while in pure shear loading a smaller reduction (22.1%) would be enough for similar fatigue lives. This means that shear strength is less sensitive to the ageing environments than tensile strength.

5.2. Fracture Surface Analysis

One of the main parts of this research is the fractography analysis of the joints after failure. Ageing procedure degrades the adhesive properties. Also, the presence of water at the interface reduces the adhesion quality between the adhesive and the substrates leading to the reduction of the joint's performance which is in alignment with the conclusions of da Costa et al. (2022). It can also lead to an interfacial failure, which reduces the effective load-bearing area leading to a significant reduction in joint strength and reducing the number of fatigue cycles that the joint can experience. When comparing the strength results of modes I and II it can be concluded that joints loaded in mode II are less sensitive to the ageing conditions as they have a lower reduction in strength. On the other hand, the fracture surface for unaged joints showed a complete cohesive failure mechanism. While a mixed adhesive/cohesive failure mode was observed for the aged samples. The adhesive failure happened mostly at the edges of the joint while the center of the overlap is mostly dry. This is what forces the joint into a mixed failure mode with the edges being weakened by ageing tending to interfacial failure and the center remaining with cohesive failure. If the surfaces from Table 1 are compared it can also be concluded that mode II has a higher percentage of interfacial failure than mode I for both fatigue and static loading conditions.

A possible reason for this phenomenon is the different rate of property degradation in the adhesive layer and the interface due to the ageing. On the other hand, the sensitivity of the aged adhesive and the aged interface differs in mode I and mode II loading conditions. These differences in the behavior of the interface and adhesive after ageing change the failure mechanism of the joints loaded in modes I and II as shown in Table 1. Accordingly, it can be concluded that if the joint has a cohesive failure in mode I loading conditions it can’t be assumed that cohesive failure will happen when it is loaded in mode II and vice versa.

Table 1. Fracture surfaces of the tested joints

		Mode I	Mode II
Static	Unaged		
	Aged		
Fatigue	Unaged		
	Aged		

5.3. Numerical results

As mentioned before a water absorption simulation using FEM was performed to predict the distribution of water through the adhesive layer in bonded Arcan joints. The results are presented in Figure 3 where due to the symmetry only a quarter of the bonded area is shown. Due to the ageing process, the properties of the adhesive are degraded. Accordingly, in this analysis, the properties of the adhesive are defined as a function of the percentage of water at each material point.

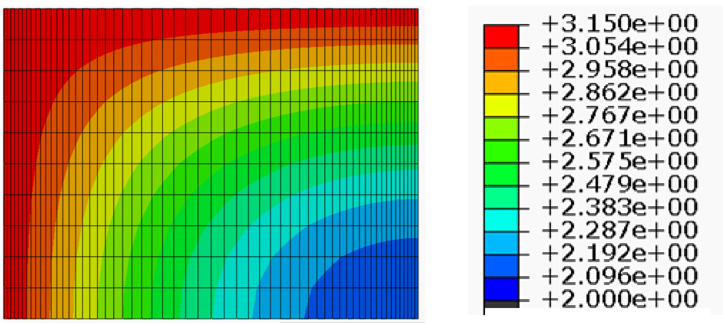


Figure 3. Water uptake simulation results

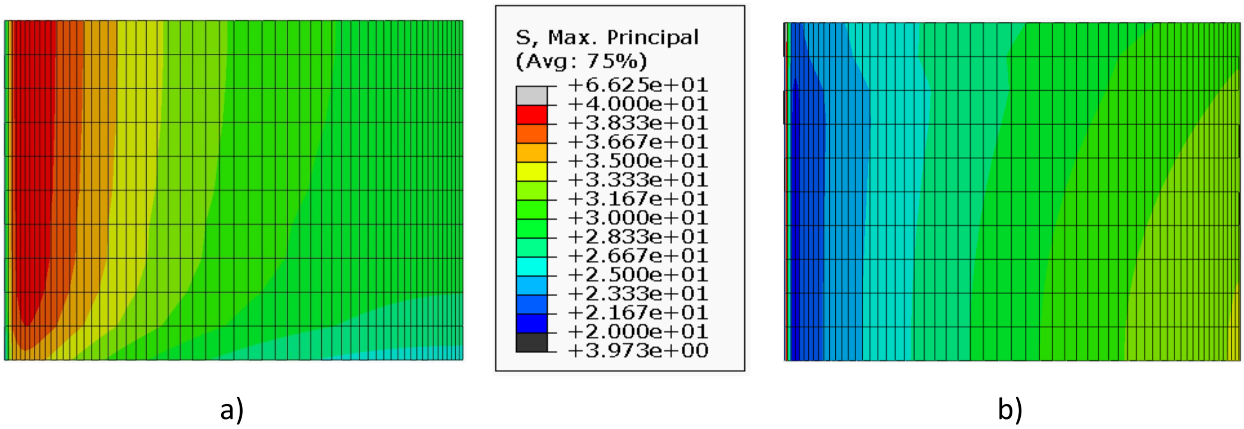


Figure 4. Maximum stress distribution a) Mode I b) Mode II

According to the numerical results shown in Figure 4, for mode I there is a higher maximum stress concentration at the edges of the adhesive layer while for mode II the tensions are more distributed by the whole area.

Authors (Da Costa et al., 2022) have shown that the adhesive/substrate interface experience a significantly higher rate of water uptake. This often leads to significant degradation of the adhesion property leading to the adhesive failure (or mixed adhesive/cohesive failure) of the aged joints if they are sufficiently exposed to a humid environment. The results obtained in the current study also showed that the aged samples experience an adhesive failure at the edges of the overlap. Based on the fracture surface analysis results, the crack in aged joints initiates at the edges of the joints at the adhesive/substrate interface. However, after initiation, the crack can follow different paths. It can directly kink to the adhesive layer or it can continue propagating through the interface. The crack path is a function of the loading angle. Results showed that in mode II loading, the crack propagates through the interface first, and then it kinks to the adhesive layer while when the joint is loaded in mode I an earlier crack kinking takes place after the crack initiation. However, further studies are needed to better understand the fracture mechanisms of aged bonded joints as a function of loading mode.

6. Conclusions

The performance of aged and unaged Arcan adhesive joints was studied both experimentally and numerically. Aging was found to decrease both the strength and fatigue performance of the tested joints, with the mode I result showing a higher susceptibility to aging than mode II. For joints of the same ageing conditions, different failure mechanisms were observed when the joints were subjected to mode I and mode II loading conditions. The results indicated that the ratio of interfacial failure to cohesive failure at the fracture surfaces is higher when the joints are loaded in mode II compared to mode I. It also showed that for mode II the maximum principal stress is more evenly distributed through the adhesive layer while for mode I it is more concentrated at the edges of the adhesive layer. Further studies on joints with different aging levels and different loading modes are required to better understand the relevant fracture mechanisms aged adhesive joints.

References

Borges, C. S.P., E. A.S. Marques, R. J.C. Carbas, C. Ueffing, P. Weißgraeber, and LFM F.M.D. Silva (2021). "Review on the Effect of Moisture and Contamination on the Interfacial Properties of Adhesive Joints." *Proceedings of the Institution of Mechanical Engineers, Part*

C: Journal of Mechanical Engineering Science, 235 (3): 527-49. DOI: 10.1177/0954406220944208.

Brandão, R., C. S.P. Borges, E. A.S. Marques, R. J.C. Carbas, A. Akhavan-Safar, F. Schmid, C. Ueffing, P. Weißgraeber, and L. F.M. da Silva (2022). "The Influence of Humidity and Immersion Temperature on the Properties and Failure Mode of PBT-GF30/Silicone Bonded Joints." *Composite Structures,* 289 (June). DOI: 10.1016/j.compstruct.2022.115421.

da Costa, J. A., A. Akhavan-Safar, E. A.S. Marques, R. J.C. Carbas, and L. F.M. da Silva (2021a). "Effects of Cyclic Ageing on the Tensile Properties and Diffusion Coefficients of an Epoxy-Based Adhesive." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications,* 235 (6): 1451–60. DOI: 10.1177/1464420721994871.

da Costa, J. A., A. Akhavan-Safar, E. A.S. Marques, R. J.C. Carbas, and L. F.M. da Silva (2021b). "Cyclic Ageing of Adhesive Materials." *Journal of Adhesion*. DOI: 10.1080/00218464.2021.1895772.

da Costa, J.A, A. Akhavan-Safar, E.A.S. Marques, R.J.C. Carbas, and L.F.M. da Silva (2022). "The Influence of Cyclic Ageing on the Fatigue Performance of Bonded Joints." *International Journal of Fatigue*, Volume 161. DOI: 10.1016/j.ijfatigue.2022.106939.

da Costa, J. A., Alireza Akhavan-Safar, Eduardo A.S. Marques, Ricardo J.C. Carbas, and Lucas F.M. da Silva (2022). "The Influence of Interfacial Failure on the Tensile S–N Response of Aged Arcan Joints." *Journal of Applied Polymer Science,* 139 (16). DOI: 10.1002/app.51991.

Heshmati, M., R. Haghani, and M. Al-Emrani (2016). "Effects of Moisture on the Long-Term Performance of Adhesively Bonded FRP/Steel Joints Used in Bridges." *Composites Part B: Engineering,* 92 (May): 447-62. DOI: 10.1016/j.compositesb.2016.02.021.

Heshmati, M., R. Haghani, and M. Al-Emrani (2017). "Durability of Bonded FRP-to-Steel Joints Effects of Moisture, de-Icing Salt Solution, Temperature and FRP Type." *Composites Part B: Engineering,* 119 (June): 153-67. DOI: 10.1016/j.compositesb.2017.03.049.

Loh, W. K., A. D. Crocombe, M. M. Abdel Wahab, and I. A. Ashcroft (2005). "Modelling Anomalous Moisture Uptake, Swelling and Thermal Characteristics of a Rubber Toughened Epoxy Adhesive." *International Journal of Adhesion and Adhesives,* 25 (1): 1-12. DOI: 10.1016/j.ijadhadh.2004.02.002.

da Silva L. F. M., Öchsner Andreas, Adams Robert D. (2011). *Handbook of Adhesion Technology*. Heidelberg, : Springer-Verlag Berlin. DOI: 10.1007/978-3-642-01169-6.

da Silva, L. F. M., A. Gonçalves Magalhães, and M. Francisco S.F. Moura. 2007. *Juntas Adesivas Estruturais*. Porto: Publindustria. ISBN: 9789728953218.

Sousa, F. C., A. Akhavan-Safar, R. Goyal, and L. F.M. da Silva (2020). "The Influence of Mode Mixity and Adhesive System on the Fatigue Life of Adhesive Joints." *Fatigue and Fracture of Engineering Materials and Structures,* 43 (10): 2337–48. DOI: 10.1111/ffe.13301.