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Experimental Adhesive Failure Criteria for Analysis of Aerospace Structures

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Abstract

In order to develop a correct methodology that can be applicable when a standard aerospace bonded joint is being sized, first it is necessary to characterize adhesives through testing campaigns. For this preliminary approach the interest was to create a simple and realistic procedure able to produce practical but usable results that could be used for standard bonded models calculations. On the present research the main objective was to find results that can be implemented on the daily basis, adjusted to the imperfections made when manufacturing bonded joints. On this study two different tests were performed: an experimental calculation of the adhesive's elasticity modulus, and obtaining shear, tensile and combined failure stresses using a classical Arcan type fixture. From the Arcan tests it was possible to create a failure line of the adhesive tested. For the elasticity modulus an experimental value was calculated and compared with results found on the literature. It was observed a greater dispersion of combined test values in comparison with the pure tests results but, based on the assumptions with which this study was conducted, an accurate and practical curve was drawn that can be used safely when modelling adhesively bonded joints with this kind of adhesive.

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1. Introduction

The aerospace industry, as well as many other industries uses adhesives as connections between several different components. The great number of advantages on using this type of joints is consensual, but there are still several problems that need to be solved in order to increase the number of applications and cases where it is feasible to use adhesively bonded joints. Traditionally, adhesives are characterized using lap-shear testing campaigns, and sometimes peel or tensile mechanical tests but, considering that on real structural applications failure is on the regular basis due to a combination of these stresses, a more complex fixture will be employed for this characterization, the Arcan test. This specimen type allows drawing a failure line for each specific adhesive [1]. The non-linear behaviour of adhesives using a modified Arcan fixture and a Tast method was studied and presented by Cognard et al [2]. A practical analysis of a metal-adhesive composite adhesive-metal assembly was also studied [3] where tests, to

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characterize the mechanical behavior of adhesive joints for marine structures, were optimized . Altus [4] and Bresson [5] obtained failures envelopes for adhesive bonded joints using different approaches. Before this, in order to have a better understanding on the behaviour of the adhesive is going to be used and for effects of comparison with the available results, a mechanical characterization must be realized and the elasticity modulus is very important on that. Understanding a specific adhesive behaviour until fracture was also the intent of the study from Brensson [6]. Using different methods with the same objective was the work realized by da Silva and Adams [7], and then by Lim [8]. Most of these already realized experiments rely on complex procedures producing perfect results for adhesive characterization that do not account with the imperfections of the real manufacturing methods. The objective of the present study was to find an experimental failure envelope that could be almost directly employed when sizing bonded joints.

2. Elasticity Modulus Calculation

2.1. Production Method

The production method followed is the main difference between this research and the standard procedure. The suggested production methods are extremely complex. A simple procedure was designed and implemented, following next steps:

- The specimen production fixture was scrapped in order to prepare surfaces for the application of a multiple release coating that prevents adhesive to bond surfaces that are not supposed;
- Prepare the adhesive according to the manufacturer's indications [9], introducing it into the bonding fixture for drying and curing with prescribed geometry. Spreading the adhesive must be done with the most caution to avoid air entrapment;
- Close the fixture and wait for the prescribed curing cycle to be completed.

2.2. Test Specimen and Production Fixture

Production fixture was made of aluminium (AA2024 T6), working like a box that has two plates and a casting mold in the middle. It is a pratical and cheap to produce fixture that allows for good results maintaining the specimens dimensions.

The test specimen was produced according to the standard ASTM D2370-92 [10] recommendations, except for the thickness which there is no suggestion and was set to 0.5mm (Figure 1).

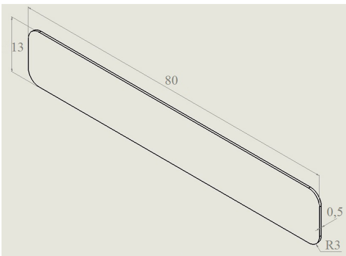

Fig. 1. Elasticity modulus testing specimen.

2.3. Testing Method

The testing method followed a tensile test procedure and measured the displacements within the specimens using a digital image correlation equipment - DIC (Figure 2). This equipment uses a camera to match the points on a pattern applied to the specimens (Figure 3) with the pixels from a photograph and calculate displacements. The elongation parameter used was 2%/mm.

Fig. 2. Digital Image Correlator.

Fig. 3. Pattern on the specimen's area of interest.

To calculate the material elasticity modulus, the stress was calculated using the loads from the tensile machine, and the strain using the displacements from DIC.

2.4. Results

For the modulus of elasticity the results are represented on Table 1. It is found on the results some dispersion for this parameter. The main reasons for this variation are the dependence of the test on the user's hability to handle the adhesive, and the quantity of air entrapment on the adhesive. The existence of voids turn the trials dependent on its distribution and quantity. These voids areas introduce weaker zones on the material, and allow for a high concentration of stresses around them. It is only possible to detect most of the voids after the adhesive is cured.

Table 1. Elasticity Modulus for each trial.

Trial Num.	1	2	3	4	5	6
Young's Modulus (MPa)	1639	1471	2052	1745	1820	2061

On Table 2 are presented some results found on literature for adhesive 3M 9323 B/A, as well as the relative errors to the experimental average value. It is possible to understand that there is no consensual value for this parameter, probably there is a great exposure of the elasticity modulus to the conditions of specimen production and testing. Nevertheless it is strongly believed that for a better analysis on these results it must be important to perform a study on the influence of the voids and micro-voids on the material behaviour.

Table 2. Young's Modulus relative errors.

Authors	Young's Modulus Literature Results (MPa)	Experimental Relative Error (%)
Photiou [11]	2100	16.79
O'Dwyer [12]	2440	35.71
O'Dwyer [13]	2800	55.72
Average	1798	

3. Failure Envelope Procedure

3.1. Specimen and Bonding Fixture

The specimens were bonded with a 3M 9323 B/A epoxy adhesive. The geometry of the specimens, namely the specimens thickness produced for the experimental tests, was selected into account previous researches [14]. It was decided to use an adhesive of 20x20x0.5 mm. Based on these dimensions, the already existent Arcan specimen was sized as present in Figure 4. Substrates manufacturing was made of common aluminium (AA2024 T69), using a Water Jet cutting method. For the experiment eight substrates were produced which constitute four different specimens.

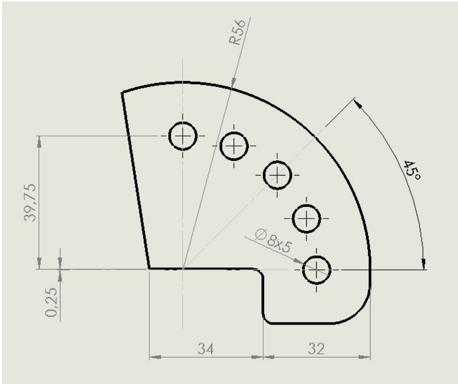

Fig. 4. Arcan Specimen Dimensioning.

3.2. Experimental Procedure

The experimental procedure realized for this test was the same as a simple tensile test. After gripping the substrates of the specimen it was necessary to push the head of the tensile up to reduce clearance between the substrates and the grips. The experimental tests were performed on an INSTRON Tensile Testing Machine with 50kN of maximum capacity and at a displacement rate of 2mm/min.

3.3. Experimental Results

In order to draw the failure envelope, yield and ultimate loads were obtained. (Table 3). The corresponding mechanical properties are listed in Table 4.

Table 3. Experimental failure loads for different loading cases.

	0^o - Pure Shear		90^o - Pure Tensile	45^o
	F_{yield} (N)	F_{UT} (N)	F_{UT} (N)	F_{UT} (N)
Specimen 1	8000	8688.63	6459.2	3724.7
Specimen 2	10900	12279.05	8108.6	6133.2
Specimen 3	8100	9362.84	8163	8842.4
Specimen 4	10100	10654.07	6459.6	-

Table 4. Experimental failure stresses for different loading cases.

	0^o - Pure Shear		90^o - Pure Tensile	45^o		
	σ_{yield} (MPa)	σ_{UT} (MPa)	σ_{UT} (MPa)	σ_{UT} (MPa)	σ_{UTx} (MPa)	σ_{UTy} (MPa)
Specimen 1	20	21.72	16.15	9.31	6.58	6.58
Specimen 2	27.25	30.70	20.27	15.33	10.84	10.84
Specimen 3	20.25	23.41	20.41	22.11	15.63	15.63
Specimen 4	25.25	26.64	16.15		-	

Drawing the failure envelope curves (Figure 5) it is demonstrated the limits obtained, as well as an average curve and a weighted average (Table 5). For the weighted average the higher value was not consider, which allows to calculate a more conservative average.

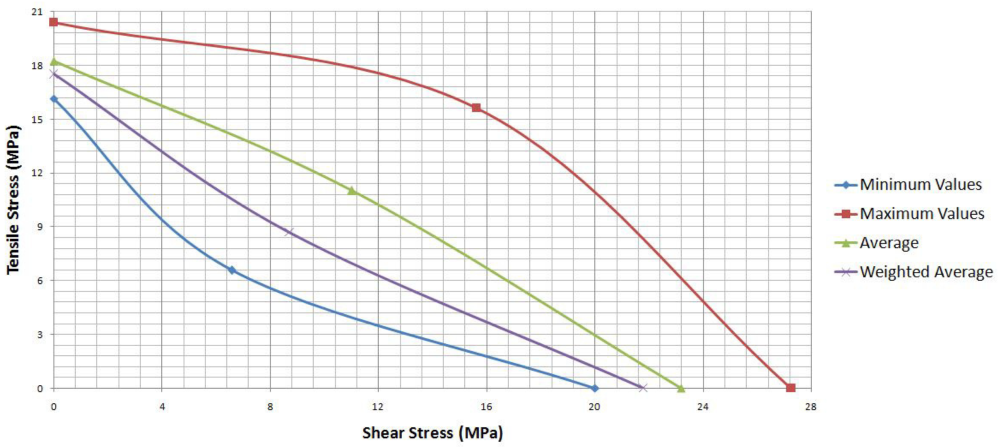

Fig. 5. Experimental Failure Envelopes.

Table 5. Average and uncertainties calculations for the experimental failure stresses.

	0^o - Pure Shear		90^o - Pure Tensile	45^o		
	σ_{yield} (MPa)	σ_{UT} (MPa)	σ_{UT} (MPa)	σ_{UT} (MPa)	σ_{UTx} (MPa)	σ_{UTy} (MPa)
Average	23.19±13.54%	25.62±13.39%	18.25±11.51%	15.58±33.57%	11.02±33.58%	11.02±33.58%
Weighted Average	21.8±11.1%	23.92±8.53%	17.52±11.07%	12.32±24.43%	8.71±24.45%	8.71±24.45%

3.4. Results Analyses

Looking at the results and from a global analyse it is observed that there is some variation within the results. On the 45 degrees test, the results cover a wide range of values presenting a percentage standard deviation of 33%. This deviation decreases for the shear test and presenting the most solid results for the tensile test. Explaining the variability of the experimental results, it is impossible not to state two aspects that are very influential and determinant on the results, voids and adhesive thickness. The first one is difficult to control and induce on the adhesive void areas which can be compromising for the structural integrity of the adhesive and are weak zones where there is stress accumulation. It was probably the main aspect that could reduce the adhesion strength of the adhesive. The control of the adhesive thickness was a problem that was tried to be solved the better way even though it was found to be very difficult to eliminate on this study. Both aspects change the adhesive stress distribution, inducing a higher level of uncertainty on the results ([15],[16]).

About the failure envelope that should be applied, it will always depend on the specific case that is being studied and what kind of approach is necessary.

4. Concluding Remarks

About the calculation of the elasticity parameter, numerous values were found. It would be really interesting to perform a study to understand the voids influence on this parameter. It is difficult to understand with certainty the real value for this parameter but, in order to realize a computational study, for example, of the Arcan test, it would be necessary to understand the influence of this parameter on the simulations and evaluate if further test would be necessary.

On this study a classical Arcan type fixture was used where besides the shear and tensile also combined failure stresses were obtained. Failure envelopes curves, of the 3M 9323 B/A epoxy adhesive, were obtained based on pure shear (0), pure tensile (90) and 45 experimental results.

A greater dispersion of values was observed in the combined experimental tests in comparison with the pure tests but, based on the assumptions with which this study was conducted, an accurate and practical curve was drawn that can be used safely when modelling adhesively bonded joints with this kind of adhesive. On 45 degrees test, the results cover a wide range of values presenting a percentage standard deviation of 33%. This deviation decreases for the shear test and presenting the most solid results for the tensile test.

This experimental Arcan test, in terms of future work, can be a base to calculate a relation between experimental and computational results on adhesive failure.

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