Understanding Failure of Adhesively Bonded Joints

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June 2015

Abstract

This research was developed together with Optimal Structural solutions, a company from the automotive and aerospace engineering fields, to analyze the strength and performance of the commercial epoxy adhesive 3M 9323 B/A. Developing 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. On this preliminary approach the interest was to create a simple and realistic procedure able to produce practical results that could be used for standard bonded models calculations. Revising literature on this subject it was detected that most have the intent to reproduce perfect results. On the contrary for this research the objective was to find results to be implemented on the daily basis, adjusted to the imperfections made when manufacturing bonded joints. It starts by tests to determine the young modulus of the adhesive, as well as its resistance to peel solicitations. The determination of a practical failure envelope to be applied when using this specific adhesive, comparing with the computational results taken from the Finite Element analysis realized. At last, simple and double adhesively bonded joints will be tested and analyzed. As results, there are several to be used when sizing this kind of joints, but most important, numerous conclusions and notes will be taken for further review and to keep the development growing.

1. Introduction

Bringing structures and structural similar or dissimilar materials together can be a very complex action that involves several studies and a rational weighing of the advantages and disadvantages associated.This is a very contemporary subject that is receiving a lot of attention and popularity from the industry in general and specially the Automotive and Aeronautical Engineering companies. With the increasingly demand for greener and efficiently vehicles as well as lighter structures, the conventional joining techniques such as bolting, pinning or riveting do not present the necessary performance specially when loaded, concentrating stresses at the fastener holes and leading to structural degradation [1]. For this reason many researchers and engineers are seeking for alternative joining methods as adhesive bonding. Although there have been an intensive investigation on the adhesive joints field for the past 70 years [2], the increasing adhesives popularity demands for an evolution in the analyses techniques and numerical models which turns this subject into an actual engineering problem. Analyzing specifically the application of adhesives to the aeronautical field and aircraft manufacture,from several decades now bonding techniques have been very important for aircraft production. Reasons as the high durability in terms of lifetime, the high resistance to dynamic loads as well as fast changes and extreme temperatures are responsible for a largely implementation of bonding solutions to aircrafts. Combining these with the reduced operating and production costs, turns the bonding process an extremely attractive and useful manufacturing method that eases the eternal quest for lightweight low-cost structures. The main objective of this research was to realize computational analysis of adhesively bonded joints,understanding how to transport these results to the daily basis applications where the cares taken do not include high level of tooling as it was necessary to obtain no defects bonding. This way, a practical approach to a complex problem applicable on several structural solutions was implemented.

2. Fundamentals

2.1. 3M Scotch-Weld Paste Adhesive 9323 B/A

It is a very high performance 3M structural epoxy adhesive with a bi-component constitution and a mix ratio (Part A:Part B) of 27:100 by weight. It is particularly used for situations where a resistance to difficult environmental conditions, including temperature, oils and gasoline for instance, is required. It also has an high impact and shear strength resistance, and presents a good capability to bond metals, plastics, rigid rubbers and, of course, composites. This type of adhesive has a service temperature from -55^oC to 80^oC and a cure cycle of 2h at 65^oC or 15 days at 23^oC ([3], [4]). Some problems were found using this type of adhesive: extremely dependent on user ability and high viscosity. On the other hand, it is a super qualified adhesive used all over Europe by Aerospace manufacturers.

2.2. Adhesion Constraints - Adhesive Voids

One of the biggest problems found was the formation of voids within the adhesive layer. These voids can have several sizes and are extremely difficult to handle with. The entrapment of this kind of voids between the adhesive and substrates allows the stresses to be concentrated on the gas bubbles, which are the weakest adhesive zones which reduces the adhesive strength. For two part adhesives, it was studied that mixing and applying techniques are the main reasons for the air entrapment [5]. Solutions to deal with this problem were studied on [6], but all of them need advanced equipment and resources.

2.3. Analytical Solutions for Stress Distribution

Analytical solutions for adhesively bonded joints will be used for validation of the computational results taken. The study of closed-form solutions for joints started back on 1930s with the classical theories. These simplified methods are very useful since it allows the engineer, when developing a computational model of an adhesively bonded joint, to have a solution to compare with and this way verify the applicability of the computational model that will be employed on the study.

Volkersen

Introduced the concept of differential shear on 1938, assuming that the adherends are only deformable in tension and adhesive only in shear, not taking into account with the bending and shear effects of the adherends. Using this theory, shear stress distribution ($\tau(X)$) is defined as follows:

$$\tau(X) = \frac{P * w_v}{2 * b * l} * \frac{cosh(w_v * X)}{sinh(w_v/2)} + \\ + \frac{\psi - 1}{\psi + 1} * \frac{w_v}{2} * \frac{sinh(w_v * X)}{w_v/2}, \quad (1)$$

where w_v is a volkersen's parameter, ψ the adherends thickness ratio, P the applied load, b the joint width and l the overlap length. All the defining equations can be found on [7].

Goland and Reissner

Within this theory authors were a little further and considered the peel stress component of the adhesive stress distribution created by the adherends bending moment [8].This way, it was now necessary to take into account with the rotation of the joint and, in consequence, with the adherends effects of the large deflections that would turn the problem into a non-linear one. Instead of solving this non-linear problem, Goland and Reissner assumed the adherends to be integral but neglected the adhesive layer allowing them to calculate the loads at the overlap ends and then solving the plane strain problem that would give the shear and peel stresses on the overlap area. For this model, the expression for the shear stress ($\tau(X)$) distribution is defined as follows and all the other defining equations including for the peel stresses are described on [9].

$$\tau(X) = \\ -\frac{\bar{P}}{8c} * \left[\frac{\beta c}{t_s}(1+3k) \frac{cosh\left(\frac{\beta c}{t_s}\frac{X}{c}\right)}{sinh\left(\frac{\beta c}{t_s}\right)} \right] - \frac{3 * \bar{P}}{8c}(1-k), \quad (2)$$

where $\bar{P}$ is the applied tensile load per unit width, c half of the overlap length, t_s the adherend thickness and k the bending moment factor.

2.4. Joint Strength Prediction - Point Stress Criterion

To computationally predict the strength of adhesively bonded joints it is necessary to use a failure criterion. There are several types of failure criteria that can be grouped into the following categories: maximum stress or strain criterion, critical stress or strain at a distance or over a zone, limit state criterion,fracture mechanics criterion and damage mechanics criterion [10]. Each type of failure criterion presents its limitations which are very well described on [10]. On the Point Stress criterion it is used the concept of characteristic distance defined on [11], and that represents the distance between the point at which the Von Mises stresses equal the yield strength of the adhesive and the end of the lap length where the elastic stress singularity occurs. The methodology used within this criterion is shown on Figure 1. The great advantage of this type of criterion, when comparing with maximum stress/strain, is the smaller dependency of mesh because it deals better with the inevitable singularities. The great problem of this approach is the difficulty of predicting the strength on adherends and adhesives that still have not been characterized [10].

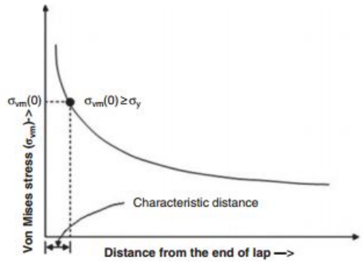

Figure 1: Point Stress Criterion Methodology.

3. Elasticity Parameters Test

The Elasticity parameters test is the only test realized with the purpose to mechanically characterize the material used as adhesive. Although there are some results in the literature for these parameters, it is not possible to find accurate results that allows for its use when doing a linear elastic analysis, not even on manufacture's datasheet [4]. For this testing procedure, ASTM D2370-92 [12] was followed but also adapted for this particular case of study.

3.1. Production Method

Due to the standard production method complexity, it was decided to change it on the present research. The procedure started scraping the specimen production fixture, preparing surfaces for the application of a multiple release coating that prevents it from bonding to the adhesive. Second step was comprised by mixing the adhesive following the manufacturers indications (see section 2) and introducing it into the fixture for curing. Careful is advised producing and handling the adhesive to avoid air entrapment. The production fixture was idealized for this experiment and manufactured using a common Aluminium. It functioned as a casting mold and allowed for the adhesive specimen to cure with the geometry wanted.

3.2. Testing Method

On the testing method, the objective was to elongate each specimen up to rupture to take out the curve stress vs strain of each test but, it was introduced a method of digital image correlation (DIC) for measuring the displacements on each sample, at the same time the test was happening. To synchronize the loads taken from the tensile machine and the displacements from DIC system, a small program was written. All the samples were measured before the test to calculate the applied stresses. For the test an elongation rate of 2% was used.

3.3. Results

In terms of trials results the values for the ultimate tensile stress and ultimate tensile strain are presented on Table 1.

For the young modulus parameter were found the results presented on Table 2.

Table 1: Ultimate tensile stress and ultimate tensile strain.

Specimen N.	Trial N.	σ_{UTS} (MPa)	ϵ_R(%)
1	1	17.85	3.8
	2	10.55	0.7
2	3	25.83	2.0
3	4	20.80	1.8
4	5	18.65	2.1
	6	28.4	1.6
5	7	28.85	1.8
6	8	22.75	1.9
7	9	26.2	1.7
8	10	20.6	1.5

Table 2: Ultimate tensile stress and ultimate tensile strain.

Specimen N.	Trial N.	$Young'sMod.$ (MPa)
1	1	1046
	2	1541
2	3	1639
3	4	1471
4	5	2329
	6	2327
5	7	2052
6	8	1745
7	9	1820
8	10	2061

3.4. Analysis and Comments

From the results taken, there were several comments and conclusions that are important to be stated relating the events of the test realized, the quality of the results and possible comparisons.

- Trials numbers 1/2 and 5/6 are concerned with the same specimen because, during the trial, the specimen started to slip from the grips;
- Results for the elastic parameters have a great dispersion because of the user's ability to correctly produce the quantity of air entrapped on the adhesive during mixing and spreading;
- Cancelling the trials from specimens 1 and 4, all the specimens present values close from each other, with specimen 3 (trial 4) presenting the greatest deviation;
- Results found on the literature (Table 3) present no consensual value for this parameter
- Calculating the averages for two analysis groups, the first only ignoring the slipped specimens and the other also not counting with specimen 3 (most deviated result), it is possible to present averages of 1798MPa and 1863.4MPa with maximum relative errors of

35.79% and 33.45%, respectively, which are not great results but, considering the deviation of the literature results, are much more possible;

- Results found on [13] can be a great support to certify the results here presented for the ultimate tensile stresses and strains

Table 3: Young's Modulus Literature Results.

Literature Elastic Mod. (MPa)		
2100 [14]	2440 [15]	2800 [16]

4. T-Peeling Test

Peeling stresses are maybe the most dangerous stresses for adhesives [17]. On these conditions it turns out to be important to understand the adhesives capabilities to withstand this kind of stress. T-peel tests are useful to provide comparative data but it can be inaccurate to calculate the actual fracture energy associated due to the plastic energy dissipation that can be involved [18]. There are numerous of already performed analyses ([19] and [20] for example) but this is an extremely difficult test to repeat because it really depends on the conditions where the specimens are produced and where the test is performed. Conditions as the tensile rate or the spew fillet of the joints also are very influential for the results [?]. Different ways to model and better understand the behavior of this type of test computationally are also being implemented ([21], [22] and [23]). For this test method it was used the ASTM standard D1876-01 [24] which was followed but also adapted.

4.1. Production Method and Specimen Dimensions

For the production method, the standard did not specify any procedure, a few resources consuming method was created. Two panels from a common Aluminium, 1mm of thickness and the dimensions prescribed on the standard, except the length that was changed from 152mm to 270mm because two stripes were added to each specimen in order to help controlling adhesive thickness, were cut and then the front parts bended to make a 90^o degrees angle with bonding area. Before bonding the specimens, both substrates were polished to enhance adherence. One of the substrates from each specimen was fixed to some blocks, and after mixed and spread the adhesive, the upper substrate was placed on the correct position, in contact with the adhesive, and fixed with some pressure to reduce clearances on the adhesive layer thickness. After curing, added edges were cut using a guillotine and the specimens measured.

4.2. Testing Method

The testing method was suggested on the standard [24]. The loading rate used was 254 mm/min. During the peeling test it was recorded the curve load vs tensile machine head displacement for further analysis.

4.3. Results

For this test the results are normally presented using the curve of the Load vs Distance Peeled but it is also common practice to use instead of load, load per unit of width. The curve of Load per unit of width vs Distance Peeled is presented on Figure 2.

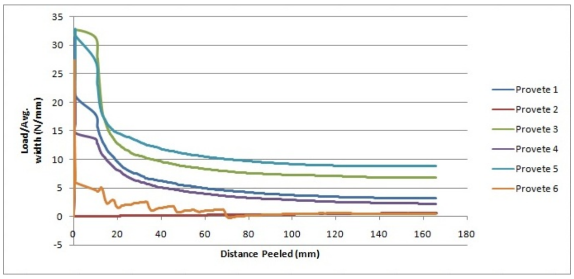

Figure 2: Results for the T-Peel test - Curve Load per unit of Width vs Distance Peeled.

The standard method [24] suggests also a determination of the average peeling load per unit of width for the first 127mm of peeling after the initial peak. Results for the maximum or peak load corresponding to the initiation failure are also used sometimes for effects of comparison [25]. Results are on Table 4.

Table 4: T-peel peak load for each specimen.

Specimens	Avg. of 127mm (N/mm)	Peak Load (N)	Peak Load per Width (N/mm)
1	6.27	791.0	31.6
2	0.25	192.9	6.6
3	9.16	912.7	31.6
4	4.74	843.9	29.0
5	10.64	918.5	29.4
6	1.54	710.3	25.5

4.4. Discussion

Analyzing the results from the test trials, there are several issues that need special attention in order to be fully clarified.

- There are some width variations on the specimens due to some difficulties found during the specimen production and from the cutting method that proved to be inaccurate;

- Width variations led to specimen misalignment which made that the area that was supporting the applied load was variable, changing the applied stress during test;

- Specimen 2 have completely different results because a different loading rate was used and will, therefore, excluded from the analysis rate of peel is very important [17];

- Specimen 6 had a cohesive failure but, other specimens had adhesion failure, probably there was a different type of fracture initiator, which are probably directly connected;

- Critical loads for every specimen are very similar, but then the evolution of each trial until the stabilization load are very different, having standard deviations in percentage of between 30.2% and 49.8% (depending on the analysis type) for the average load per unit of width of the first 127mm of distance peeled, and only between 4.0% and 7.61% of standard deviation for peak load per unit of width;

- There were great difficulties on finding similar testing conditions results

5. Failure Envelope Test

The most important type of test for this project was an implementation of an ARCAN test to calculate the failure envelope of the adhesive 3M 9323 B/A. ARCAN specimen [26] is very versatile and allow to test the adhesive, loading it from different angles. The objective was to realize a testing campaign and compare it with the experimental result from the Finite element analysis (FEA). This subject was already studied but, it is not a completely developed matter, since it relies on complex modelling (p.e. [27]) that are not applicable on a complete structural model.

5.1. Experimental Part

ARCAN specimens need to be designed for specific bond line thickness because the holes are placed with angles relative to the adhesive middle line. Specimens were manufactured using common aluminium using the water jet as production method. Bonding substrates, it was necessary to idealize a bonding fixture that would allow the specimens to be fixed while the adhesive was curing. This bonding fixture was only constituted by one rectangular solid base that allowed the specimens to be screwed. Controlling adhesive layer thickness was not easy with this fixture and the only way found was to place the specimens and mark its position on the solid base. Taking one of the substrates the adhesive was placed and the substrate placed again. Before bonding, the multiple release coating needed to be spread on the metal surfaces that were not supposed to bound anywhere. The experimental procedure followed was similar to a simple tensile test. On this specific case, grips were produced with the necessary dimensions to grasp the specimen. After placing the specimens, it was necessary to pull the tensile machine head until the clearances between substrates and grips were reduced. The loading rate was of 2mm/min.

5.2. Computational Analysis

The numerical model for computational failure envelope solution was based on the finite element method and was implemented using the software Simulia Abaqus CAE. On this model three distinct types of elements were used for effects of comparison: a solid 20 node quadratic brick element with reduced integration (C3D20R), a quadratic 8-node doubly curved thick conventional shell with reduced integration (S8R), and a linear 8-node quadrilateral in-plane general purpose continuum shell also with reduced integration (SC8R). Creating the FE linear elastic model for this test, the materials were defined as it is expressed on Table 5.

Table 5: Elastic constants of the materials used modelling the Failure Envelope test.

	Substrates	Adhesive
Young's Modulus (MPa)	70000	1798
Poisson's Ratio	0.35	0.4

One of the most important aspects for this analysis is the way the connection between adhesive and substrates is done. The mechanism that was used was the Tie Constraint that prevents different surfaces that are tied from having relative motion between them. The Boundary Conditions were applied using another constraint mechanism named Multi-Point Constraint (MPC) from the type Beam. MPC constrains the displacements and rotations of the slave nodes to the displacements and rotations of the Master node, as if a rigid beam was placed between the slave node and the master one. To simulate the experimental test there was only need to place a load and to fix another point (All DOF = 0). At last, to complete the model, it is necessary to generate a suitable mesh that produces quality results and that costs the less computational effort possible. On the mesh convergence study several aspects were tested to reach a final mesh to be used on every computational analysis. Aspects as the adhesive proximity, element aspect ratio and stress distributions on the adhesive layer were taken into account when meshing. To note that the solution did not converge with only one element on the adhesive thickness. Final mesh characteristics are expressed on Table6.

After mesh convergence it was necessary to validate the computational model to be assured of the solution quality. Analyzing the comparing study, all three elements show good agreement, as well

Table 6: Lines Element Size and Number of Elements.

	Substrate			Adhesive	
	FA	NA/AC	NA tips	Tips	Centre
Ele. Size	4	0.25	0.17	0.17	0.25
Total Ele.	3422			288	
Note: FA=Far from Adhesive; NA/AC=Near Adhesive and Adhesive Center					

as Volkersens and GolandReissners theories. Solutions for Solid and Continuum Shell are similar having the greater difference on the adhesive tips. About the analytical solutions, Volkersens is only able to demonstrate a decent average value for stress but, on the other side, Goland and Reissners give a better match with the computational stress variation. This was not expected due to the assumptions made by each theory and the computational models but, each way, both theories present good agreement with the numerical solutions.

5.3. Results and Discussion

Experimental Results

Experimental results for yield and ultimate tensile stresses were taken from the procedure already stated Table.

Table 7: Experimental limit stresses for different loading degrees of the Failure Envelope Test.

Spe.	0^o		90^o	45^o	
	σ_{yield}	σ_{UT}	σ_{UT}	σ_{UT}	$\sigma_{UTx/y}$
1	20	21.72	16.15	-	
2	27.25	30.70	20.27	9.31	6.58
3	20.25	23.41	20.41	15.33	10.84
4	25.25	26.64	16.15	22.11	15.63

Difficulties on controlling the adhesive thickness and the voids that appear on the adhesive layer are maybe the main reasons for some variation observed on the experimental results. A problem with one of the specimens during the test of 45 degrees, reduced the number of obtained results. With a standard deviation of 11.51% and 33.57%, respectively, it is possible to understand that the 90 degrees was the test with the most consistent results and the 45 degrees with the most variable.

Sensibility Studies

Due to some doubts about the model used for the study it was decided to realize some sensibility studies computationally to understand the influence of some parameters on adhesive stress distribution. The first parameter tested was the Young's modulus from adhesive. For this parameter, stress distribution within adhesive keeps very consistent, with only a greater variation of 36% on the adhesive tips (where the solution is harder to get), if there is a parameter change from the experimental value of 1798MPa to the 2800MPa found on [16], higher result found on literature.

Then, the next parameter tested was the substrate's Young's modulus. The analysis was realized for an interval between 60000 and 80000MPa, which covers all the range of values for the majority of Aluminium alloys. The conclusion of this sensibility test is that the stress distribution is even less sensitive to changes in this parameter. Increasing this Young's modulus in 33% will only increase the relative error in 23% for Peel stress on overlap free ends. Even though, it is important to note that an error on both parameters exists, it can be more important in terms of the solution quality.

At last, it is important to see the results variation changing the adhesive thickness because there is no sufficient control over this parameter. For analyses with adhesive layers between 0.3mm and 1.5mm, stresses increases on the centre of the adhesive and decreases on the edges, which turns the stress distribution much more regular and smooth both for peel and shear stresses. The smaller the adhesive, the higher stress concentration would be found inside the adhesive. Otherwise, increasing adhesive thickness will decrease joint strength [28]. A result validation can be made using the results presented on [29], where the results obtained for a finite element study of the stress distribution for different adhesive thickness on a single-lap joint, have the same variation trend as the one observed in here.

5.4. Computational Results

In order to present computational results for failure loads, it is necessary to implement a valid failure criteria able to determine the at which applied load/stress, the specimen will fail. The failure criteria used, starts from the point that the adhesive is characterized in terms of its characteristic distance. This is not the case of the 3M 9323 and so, the results found on literature for other specific cases possible to be compared were used ([30] and [31]). For the implementation of the point stress criterion on the computational analyses, it was necessary to decided where should the characteristic be measured. Thus, it was observed that on the experimental tests (45 and 90 degrees), failure was happened on the adhesive/substrate surface, and on the shear test it was more cohesively but very close to the contact surface. From the literature consulted for this problem ([32] and [33]) it was also concluded that adhesion failure was probably the most common path on failure. This way it was decided to measure stresses on the interface of adhesive with adherend. Failure loads were investigated on a range of characteristic distances, from the minimum (MinCD) to the maximum (MaxCD) values found on the literature, and based on three different yield adhesive strength: data sheet shear yield strength (ADS), minimum yield strength (MYS) found on the mechanical tests and an average value (AVG) taken from the same tests (Tables 8 and 9).

Table 8: Computational Failure Loads (N) - Shear and Tensile Test.

	Shear Test		Tensile Test	
	MinCD	MaxCD.	MinCD	MaxCD
ADS	7646	7646	22160	22045
MYS	4892	4880	9850	9791
AVG	4265	4250	11225	11050

Table 9: Computational Failure Loads (N) - 45 Degrees Test.

	MinCD	
	Abs. Value	$Load_{x/y}$
ADS	9930	7021.6
MYS	2622	1854
AVG	4140	2927.4

	MaxCD.	
	Absolute	$Load_{x/y}$
ADS	10380	7339.77.6
MYS	2735	1933.9
AVG	4325	3058.2

It is possible to see that depending on the strengths used, adhesive failure loads have a great variation, which makes necessary to choose this parameter extremely carefully.

5.5. Experimental and Computational Failure Envelopes

One of the main objectives of the present research was to find the experimental and computational failure envelopes for the 9323 adhesive and aluminium adherends. Figures 3 and 4 represent the failure envelopes in terms of Shear and Tensile components for the experimental and computational failure envelopes.

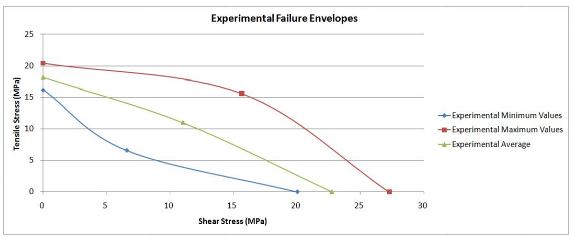

Figure 3: Experimental Failure Envelops.

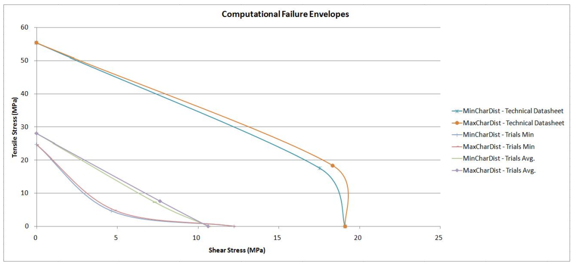

Figure 4: Computational Failure Envelope.

For the Shear Test and considering that this computational analysis is a perfect model without imperfections, it seams logical to use the values obtained by the manufacturers data sheet for lap shear. On the Tensile test the variation is much higher because a small variation on the applied force produce a great change on the stresses, which makes this test more difficult to be analysed and therefore makes it reasonable to use the minimum strength value. A comparison between the minimum (Computational 1) and the average strength value (Computational 2) will be presented. The results are the following (Figure 5):

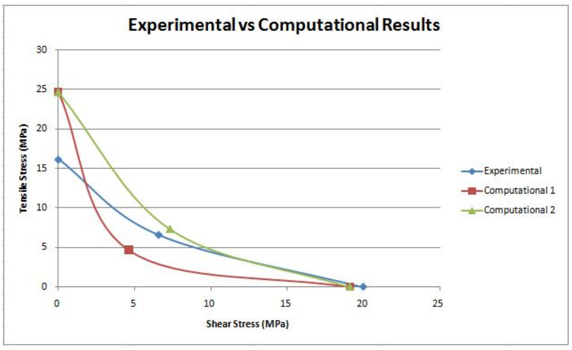

Figure 5: Comparison between experimental and computational failure envelopes - Minimum and Average Values for 45 Degrees Test.

Analysing the results presented for the 45 degrees test, a great variability is noted, for this reason it would make sense to take an average value for this test more reasonable than the minimum value;

The result for the computational shear test would be expected to be bigger than the experimental value, thus it has only a small error of approximately 4.45% when comparing with the experimental. Using perfect conditions for the computational analysis, it would be expected that the computational failure envelope would present a greater difference from the experimental one.

These are results that are perfectly usable on a real analysis, but to obtain a more accurate relation between computational and experimental results it was necessary to have more consistent experimental results and realise a more complex computational analysis.

The great confidence obtained with these results is that they were taken using very practical analysis, which means that if the procedures here described are reproduced this failure envelope can be implemented with great confidence.

6. Aluminium to Composite Adhesively Bonded Joints

On the present research it was sought to study both single (ASTM D5868 [34]) and double-lap (ASTM D3528 [35]) joints with dissimilar substrates, Aluminium and Carbon-fiber-reinforced plastic (CFRP). The study of joints with dissimilar adherends is interesting because of the importance of CFRP for aerospace and high-techs industries while Aluminium still have an important role as structural material across all industries.The Company interest for this type of connection was the reason for this joint composition. For this type of joints, researches with different objectives were already performed, using different theories and studying the influence of some parameters ([36] and [37]).

6.1. Substrates and Bonding Fixture Production

For both joint types CFRP substrates were produced using a Toray T300 2x2 Twill Prepreg. Vacuum bag and autoclave were the methods used to manufacture the substrates with a stacking sequence of [0/90, ±45, 0/90, ±45, 0/90, ±45, 0/90] for single-lap joints and the same sequence without the last two plies for double-lap. About the specimens dimensions, both standards were followed except for the adhesive layer dimensions that were set to a length and width of 20mm and a thickness of 0.5mm. Substrates thicknesses were a target of some modifications and, at the end, aluminium of 2mm and 5mm thicknesses were used for single and double-lap joints, respectively. The bonding fixture idealized needed to be able to keep the bonding layer dimensions, as well as the substrates still while the adhesive was curing.

6.2. Bonding Method

After scrapping both bonding fixtures and substrates, bonding fixtures needed to be covered with a sealant and a multiple release coating. Before applying the mixed adhesive, the composite substrate was fixed to the bonding base using scotch-tape. Then a plate was bolted and also fixed to the base to eliminate clearances, this plate was the adhesive thickness controlling part. At last the adhesive was placed on top of the composite substrate and the metal substrate placed in contact with the adhesive and fixed using, again, the scotch tape.

6.3. Testing Method

Both experiments were normal tensile tests that use pressurized grips, assuring a better traction without slipping. On the single-lap test, two different assemblies were used: the one suggested on ASTM D5868 and a similar assembly but with one shim enclosed on each substrate tip that is grasped by the grip, reducing the adhesive applied moments due to the substrates and adhesive thicknesses. Loading rate used was 6mm/min. On the double-lap joint test, ASTM D3528 standard suggested the test should be conducted at a specific velocity of 1.27mm/min, which was followed.

6.4. Results Demonstration and Analysis

This research part was far from a success because it was not possible to obtain the results wanted due to problems with the materials and the thickness of substrates. After measuring the final joints, it is possible to say preliminarily that the fixtures used worked very well and it was possible to obtain similar specimens for each joint type. About the practical results, single-lap joints test resulted on a fiber failure on the CFRP substrate near one of the lap tips, and it was not possible to really test the joint strength. Even when using shims on the joints (Specimens 5 to 7), the result was the same which says the moment applied on the adhesive due to the load deviation from the central line was not the reason for the failure. The only difference inflicted when inspecting joints with shims and without, is the failure surface, which is interlaminar on the specimens with shims and translaminar on the others. These results raises the need to make a better investigation on the reasons why this have happened, and suggests that probably it will be necessary to use a higher security factor when sizing these kind of joints. On the double-lap joints, even having substrates greater than what is suggested on the standard, the result was a metal substrate failure this time. The results for these trials are very consistent, which means the problem must not be from the bonding methodology.

7. Conclusions

From this research several investigations and researches can be developed. Of course the models followed in here are very simple but it is believed that this is the right way to follow in order to apply this on real applications.

- Work done on the peeling characterization of adhesive allows to have a good notion how the adhesive behaves in these conditions.
- In order to improve the relation between computational models and experimental results for the failure envelope, an extended work should be done on this where some things should be

developed: the control over the adhesive layer thickness, increase the number of trials realized and try other angles for loading. The most important method that should be implemented on future work, is the procedure to measure displacements during tests, to try for another failure criteria and test the results taken in here.

- If this last point is succeed, it is possible and can be extremely useful to apply this as a module on a finite element commercial code.
- Review the data taken from the tests realized on this thesis about testing joints, understand what went wrong, and resize both composite and metal substracts in order to test the joints. It is really necessary to take into account that probably the standards are not applicable on this adhesive case.

The objective of analysing the metal to composite adhesively bonded joints was not fulfilled and, although this study can serve as a starting point, the procedure needs to be done again. About the failure envelope that resulted from this research, it is possible to assure that it can be applied with great confidence, although it also can be considered to be very conservative. The computational models are very reliable and besides being simple, are a very good approximation to the problem. Adhesively bonded joints is still a very complex issue that despite all the advances that have been done on the last few years is still poorly applied on general applications. This is a research that can be hopefully used if that path is followed, contributing specially with different bonding methods and all the practical approaches taken to complex problems that really need to be simplified.

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