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A Unique Numerical Model to Evaluate the Influence of Adherends' Misalignment on Adhesive Joint Strength

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Industry 4.0 needs to have a digital representation of the real manufacturing and assembly processes to foresee the effects of modifications on equipment, tools and processes. Assembly processes often use adhesive to keep together the components because it has many advantages. The simplest example of adhesive assembly is a single lap joint. In the literature, the attention is focused on nominal adhesive assemblies, that do not represent the real products and that are tested to evaluate the product's strength. Therefore, the obtained mechanical performances are far from those connected with the real products.
The present work takes into account the geometric deviations of a single lap joint, as the adherends' misalignment, due to the manufacturing process and used equipment on its strength. A numerical tool of the literature was modified to deal with adherends' misalignment to estimate both the tensile and the bending strength. The numerical results were validated through experimental tests. The developed numerical model shows a very low deviation from experimental results.
The original contribution of this work is that the developed numerical model simulates the adhesive process of a real joint with adherends' misalignment and not of its nominal geometry; thus, providing a tool more useful in optics Industry 4.0 to represent a process closer to the real.

Keywords: Adhesive Joint, Adherends' Misalignment, Strength, Tensile Test, Bending Test

1 Introduction

Adhesive joints characterise many industrial applications because they have some advantages: they allow uniform distribution of the applied load, avoid concentration of stresses, reduce product weight and increase fatigue resistance in comparison with the traditional drilled and threaded connections [1].

Single-lap joints (SLJ) are commonly used to bond two sheets. Some works of the literature studied and modelled nominal single-lap joints submitted to tensile tests [2]. The influence of further parameters on the strength of nominal SLJs was studied in the literature, such as the fillet, the length of overlapping, and the surface treatment [3-6]. The cohesive parameters of the adhesive were experimentally investigated to model cohesive contacts [7]. Structural analyses deepened the effects of cohesive parameters, the failure mechanisms, the distribution of shear stress and the use of composite adherends [8-12]. A methodology to take into account both adhesive and cohesive properties was proposed to model the strength of adhesive joints [13].

It was proposed to a scarf or tape the adherend [14], use a fillet of adhesive [15], non-flat surfaces of the adherends [16] or the extreme interfaces [17] to increase the strength of nominal SLJs.

Bending moments are strongly connected with the tensile strength of nominal SLJs [18]. The bending strength of nominal SLJs was studied experimentally through four-point [19-20] and three-point tests [21]. Manufacturing imperfections and surface defects significantly reduce joint strength [22].

However, in all these cases the fact that the adherends are not aligned and that the manufacturing process and the manufacturing equipment involve further contributions to geometric deviations of the manufactured product was not taken into account [23]. In this way, the quality connected with the manufacturing process may be evaluated [24]. In previous works a numerical model of the literature was adapted to deal with the effects of adherends' misalignment on tensile [24], 3-point bending strength [25] or 4-point bending strength [26].

This work aims to put together the two previous models in a unique one to relate the misalignment between the adherends and the mechanical performance of the joint. The misalignment is due to the rotation of one adherend around one axis about the other one. The developed numerical model simulates the adhesive process of the real single lap joint and not of its nominal geometry; thus, providing a tool more useful in optics Industry 4.0 to represent a process closer to the real. This work shows the correlation between tensile and bending strength.

Section 2 presents the proposed model and the considered case studies. In Section 3 the results were presented and put into relationship; in Section 4 a partial experimental validation was carried out.

2 Material and method

2.1 Material

This work studies a single-lap joint constituted by two adherends, whose length is 102.5 mm and whose thickness is 3 mm with an overlap of 25 mm. The material of the adherends was AA6082 T651 aluminium alloy, while that of the adhesive was Araldite® AV138, i.e. a brittle epoxy resin [27]. 2D plane-strain elements were used as mesh. The Cohesive Zone Model (CZM), which is a well-known model of the literature applied to adhesive nominal joints, was applied to joints with adherends' misalignment. The zone with adhesive (of 0.80 mm thickness) had a layer of 0.005 mm thickness, a layer of 0.79 mm thickness and a layer of 0.005 mm thickness. The layers of 0.005 mm serve to simulate the cohesive failure; they detach from the adherends during the cohesive failure. The adhesive had one element along the thickness and 125 elements along the adherend direction. Each adherend had 15 elements along its thickness and 125 elements along its axis direction in the overlapping, while proceeding towards the extremes, the elements of the mesh increased in size. The mesh dimension is 0.2 mm x 0.2 mm in the overlap zone and 1.02 mm x 0.2 mm at the extremes.

Adhesive thickness had four values (see Table 1); it was discretized with 1, 2, 3 or 4 elements.

Four adherends' misalignments were considered. The following adhesive shapes were considered: the first one is characterized by a constant nominal thickness; and the second one by a not constant actual thickness. They are the same volume of adhesive.

Tensile, 3 and 4-point bending tests were considered.

Tab. 1 *Tensile plan*

Parameter	Value			
Adhesive thickness/ Misalignment	0.20 mm/ 0°	0.40 mm/ 0°	0.60 mm/ 0°	0.80 mm/ 0°
Loading scheme	displacement δ			
Tests	4			
Adhesive thickness / Misalignment	0.20 mm / 0.40°	0.40 mm / 0.78°	0.60 mm / 1.16°	0.80 mm / 1.50°
Loading scheme	• displacement δ • alignment ν and displacement δ			
Tests	8			

2.2 Model

The developed model uses Marc Mentat® and Matlab® software [28, 24]. At first, the single lap joint was modelled by considering a constant and not constant thickness of the adhesive through a cohesive model. Then, the strength of the joint is estimated through a finite element analysis and the obtained results (displacements, stresses, deformations, forces) are shown. A cohesive zone model (CZM) was used [29].

Shift between surfaces of the joint involves traction. The direction of the relative shifts may be normal or shear. The shift may be evaluated as [30]:

$$\begin{cases} \delta_n = u_1^{top} - u_1^{bottom} \\ \delta_s = u_2^{top} - u_2^{bottom} \\ \delta_t = u_3^{top} - u_3^{bottom} \\ \delta = \sqrt{\delta_n^2 + \delta_s^2 + \delta_t^2} \end{cases}, \quad (1)$$

With the displacement u, the normal shift (δ_n), the shear shift (δ_s) and the tear shift (δ_t). The bilinear law is:

$$T = \begin{cases} \dfrac{2G_c}{\delta_m}\dfrac{\delta}{\delta_c} \quad \text{if } 0 \le \delta \le \delta_c \\ \dfrac{2G_c}{\delta_m}\left(\dfrac{\delta_m - \delta}{\delta_m - \delta_c}\right) \quad \text{if } \delta_c < \delta \le \delta_m \\ 0 \quad \text{if } \delta > \delta_m \end{cases}, \quad (2)$$

Where:

G_c…The critical energy release rate,

δ_m …The maximum opening shift.

In the tensile test, two load conditions were considered according to ASTM D 1002-01. The first one submits one edge of the joint to a shift δ to generate a tensile condition, as shown in Fig. 1a. It was applied to both nominal and actual cases. The second one submits one edge of the joint at first to a shift ν

perpendicular to the joint and then a shift δ parallel to the joint, as shown in Fig. 1b. It was applied only to the actual case.

The shift v, which represents the alignment to the clamping system on the joint, was evaluated as:

$$v = K\tan\theta + \left(t_A - \frac{L_O}{2}\tan\theta\right), \quad (3)$$

Where:

θ…The angular misalignment of the adherend;

t_A…The nominal adhesive thickness;

L_O…The overlap length and K is the adherend length.

In total, 12 different joints were considered, as shown in Table 1.

The 3-point bending test is shown in Fig. 1c. Different values of span, support and nose diameter were studied (see Table 2). 64 joints, nominal and actual, were considered.

The used scheme of 4-point bending test is in Fig. 1d. A value of span, support and nose diameters and two distances between loads were studied (see Table 3). 16 joints, nominal and actual, were considered.

Adherend dimensions, overlap length and adhesive and adherend materials were fixed (see section 2.1).

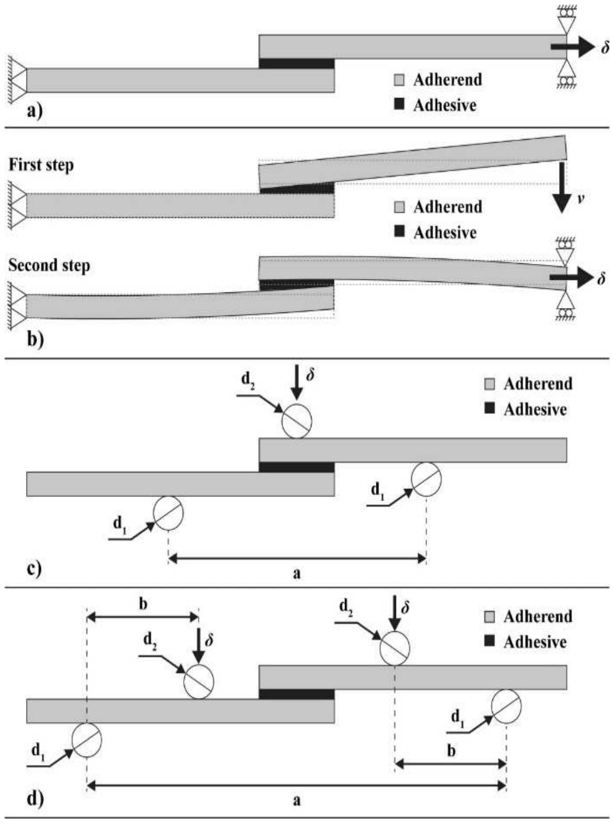

Fig. 1 *Loading condition: a)tensile test, b)alignment and tensile test, c)3-point bending case, d)4-point bending case*

Tab. 2 *3-point bending plan*

Parameter	Value			
Adhesive thickness/ Misalignment	0.20 mm/ 0°	0.40 mm/ 0°	0.60 mm/ 0°	0.80 mm/ 0°
Span (a)	60 mm	90 mm	120 mm	150 mm
Support and nose diameter	$d_1 = d_2 = 5$ mm $d_1 = d_2 = 10$ mm $d_1 = 5$ mm and $d_2 = 10$ mm			
Tests	48			
Adhesive thickness / Misalignment	0.20 mm / 0.40°	0.40 mm / 0.78°	0.60 mm / 1.16°	0.80 mm / 1.50°
Span (a)	60 mm	90 mm	120 mm	150 mm
Support and nose diameter	$d_1 = 5$ mm and $d_2 = 10$ mm			
Tests	16			

Tab. 3 *4-point bending plan*

Parameter	Value			
Adhesive thickness/ Misalignment	0.20 mm/ 0°	0.40 mm/ 0°	0.60 mm/ 0°	0.80 mm/ 0°
Span (a; b)	150; 30		150; 45	
Support and nose diameter	$d_1 = 5$ mm and $d_2 = 10$ mm			
Tests	8			
Adhesive thickness / Misalignment	0.20 mm / 0.40°	0.40 mm / 0.78°	0.60 mm / 1.16°	0.80 mm / 1.50°
Span (a; b)	150; 30		150; 45	
Support and nose diameter	$d_1 = 5$ mm and $d_2 = 10$ mm			
Tests	8			

3 Numerical results and discussion

3.1 Tensile test

Fig. 2 shows the results due to the tensile displacement δ. A difference among the results of nominal and actual cases occurred; the maximum value of load decreases concerning the nominal case and by considering an adhesive volume of 125 mm^3 of 1.35% and 1.20% when the displacement ν is and is not taken into account respectively. The maximum load decreases concerning the nominal case and by considering an adhesive volume of 250 mm^3 of 3.68% and 3.39% when the displacement ν is and is not taken into account respectively. The maximum load decreases concerning the nominal case and by considering an adhesive volume of 375 mm^3 of 7.12% and 6.75% when the displacement ν is and is not taken into account respectively. The maximum load decreases concerning the nominal case and by considering an adhesive volume of 500 mm^3 of 11.53% and 11.11% when the displacement ν is and is not taken into account respectively.

Table 4 reports an Analysis of Variance (ANOVA) results on the maximum load values obtained numerically. The displacement ν does not affect significantly the maximum load; while the adhesive volume is a significant factor: increasing adhesive thickness decreases the maximum load [31]. Moreover, the adherends' misalignment: is the most influential factor and increasing adherends' misalignment decreases the maximum load.

The conclusions are that adherends' misalignment causes a significant reduction of the maximum load supported by the joint: it can arrive at more than 11.5%.

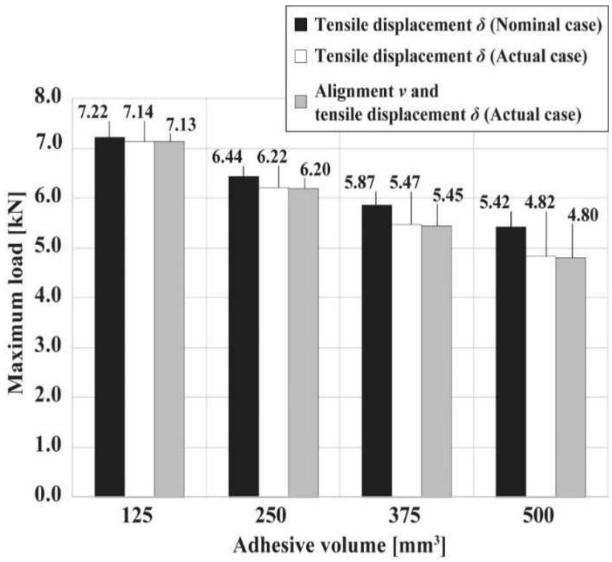

Fig. 2 *Results of the tensile test*

Tab. 4 *ANOVA results for tensile case*

Parameter	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	p-value
misalignment	4	6.3030	78%	0.3144	0.0786	6288.58	0.000
adhesive volume	3	1.8097	22%	1.8097	0.6032	48258.00	0.000
transverse displacement	1	0.0006	0%	0.0006	0.0006	49.00	0.006
error	3	0.0000	0%	0.0000	0.0000		
total	11	8.1133					

3.2 3-point bending test

First of all, an ANOVA allowed evaluating that support and nose diameter do not influence the maximum load, instead span (a) does (see Table 5). Therefore, only a diameter value for supports and nose was considered.

Tab. 5 *ANOVA results for 3-point bending case (nominal joints)*

Parameter	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	p-value
span (a)	3	1827113	99.8%	1827113	609038	27480.87	0.000
adhesive volume	3	2575	0.1%	2575	858	38.73	0.000
diameters for supports and nose	2	13	0%	13	6	0.29	0.753
error	39	864	0.1%	864	22		
total	47	1830564					

Fig. 3 shows the results with a span (a) of 60 mm (see Fig. 3a), 90 mm (see Fig. 3b), 120 mm (see Fig. 3c) and 150 mm (see Fig. 3d). The maximum value of load decreases with the increase of the adhesive volume. The actual cases present values always lower than those of nominal cases: from 1.31% to 2.18% for a span of 60 mm, from 1.04% to 1.78% for a span of 90 mm, from 1.01% to 1.64% for a span of 120 mm, from 1.14% to 1.69% for a span of 150 mm as the adhesive volume increases.

The conclusions are that adherends' misalignment involves a decrease of the maximum load supported by the joint. The bending strength decreases with adherends' misalignment of 1%-2% once fixed the adhesive volume.

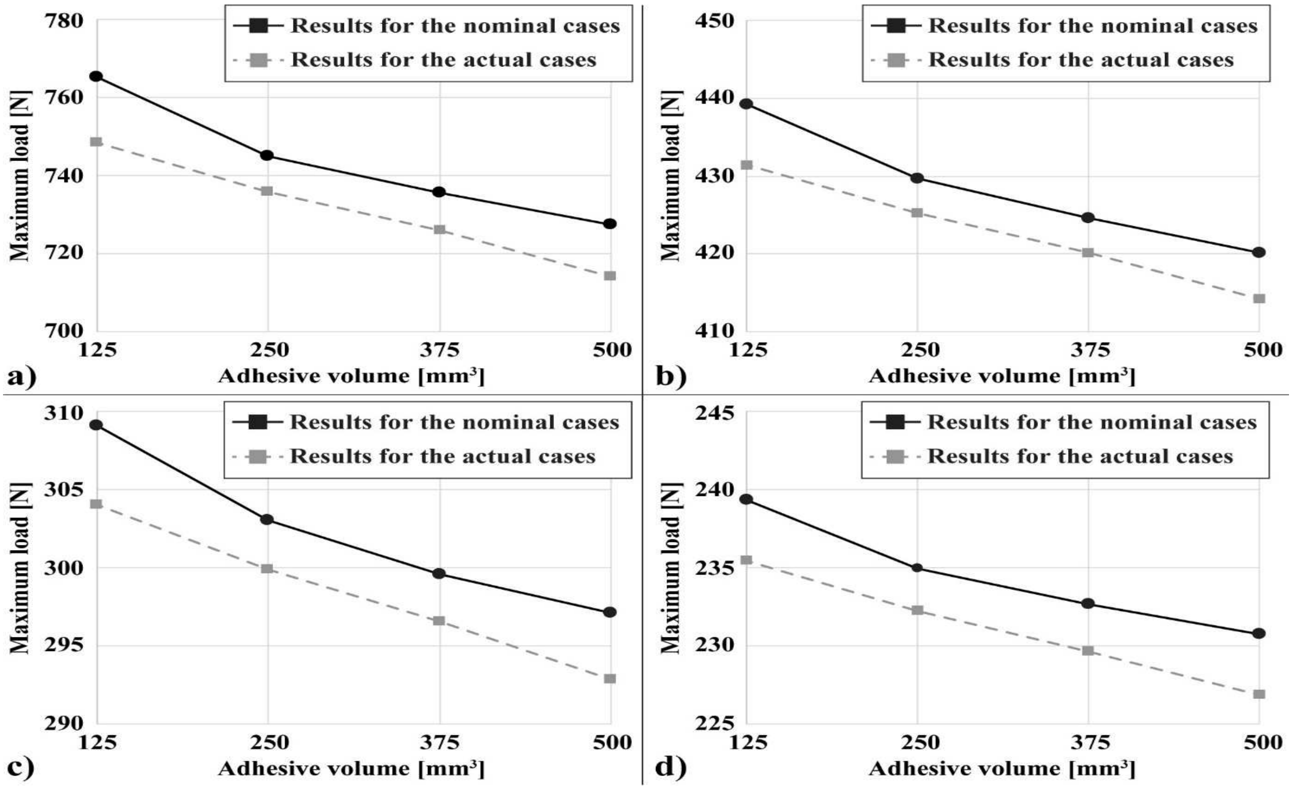

Fig. 3 *3-point bending test results for a span of a) 60 mm, b) 90 mm, c) 120 mm, d) 150 mm*

3.3 4-point bending test

Fig. 4 shows the results with a span of 30 mm (see Fig. 4a) and 45 mm (see Fig. 4b). The maximum value of load decreases with the increase of the adhesive volume. The actual cases present values always lower than those of nominal cases: from 0.44% to 0.95% for a span of 30 mm, and from 0.13% to 0.58% for a span of 45 mm.

ANOVA results show that adherends' misalignment and adhesive volume do not significantly influence the maximum load, instead span (b) does.

The conclusions are that adherends' misalignment involves a decrease of the maximum load supported by the joint. Adherends' misalignment reduces 1% bending strength, once fixed the adhesive volume.

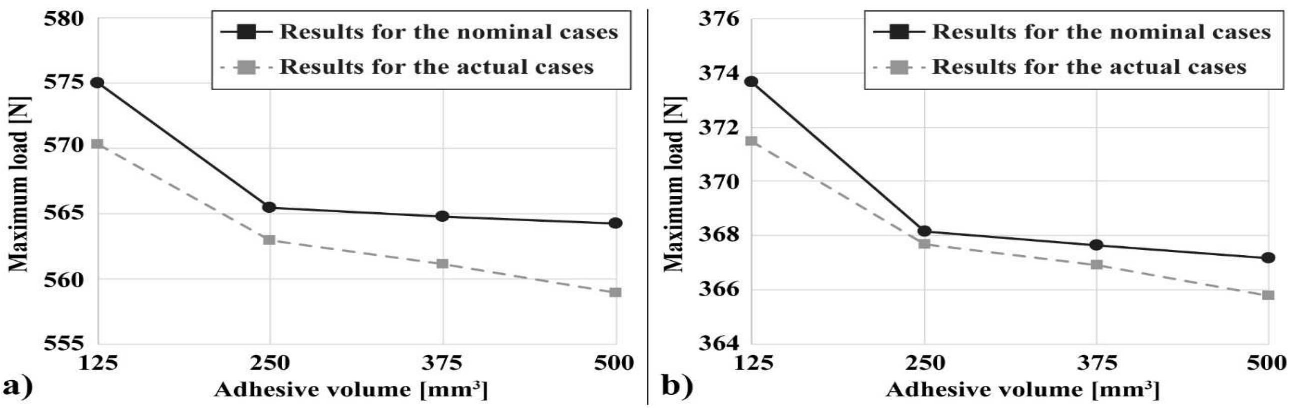

Fig. 4 *4-point bending test results for a span of a) 30 mm, b) 45 mm*

Correlation between 3-point and 4-point bending and the tensile results are visualized in Fig. 5, where the Pearson index is shown. The obtained values are near to 100% in both the cases, where R is equal to:

$$R = \frac{\bar{\sigma}_{xy}}{\bar{\sigma}_x \bar{\sigma}_y}, \quad (4)$$

Where:

$\bar{\sigma}_{xy}$…The sample covariance,

$\bar{\sigma}_x$ and $\bar{\sigma}_y$ …The sample standard deviations. Based on the results achieved, a significant correlation exists.

4 Experimental validation

The experimental activity designed and manufactured the tooling used to produce aligned and misaligned specimens. It was formed by two moulds in PLA manufactured by the extrusion material process [24].

A couple of moulds have flat planes for producing aligned adherends. Another couple has a mould with a flat plane and the other angled of 1.20° for a specimen of 0.60 mm and 1 mm thickness of adhesive for tensile and bending tests respectively (see Fig. 6). The adhesive was that indicated in section 2.1, while the material of adherends was AA7075-Ergal aluminium alloy.

The specimens were cut by the sheets and sanded on the areas to bond. Once the adhesive was placed between the adherends, it waited for the curing time. Therefore, the clamping elements were removed and the specimens were ready for measurement.

Leica microscope was used for measurement (magnification 10x).

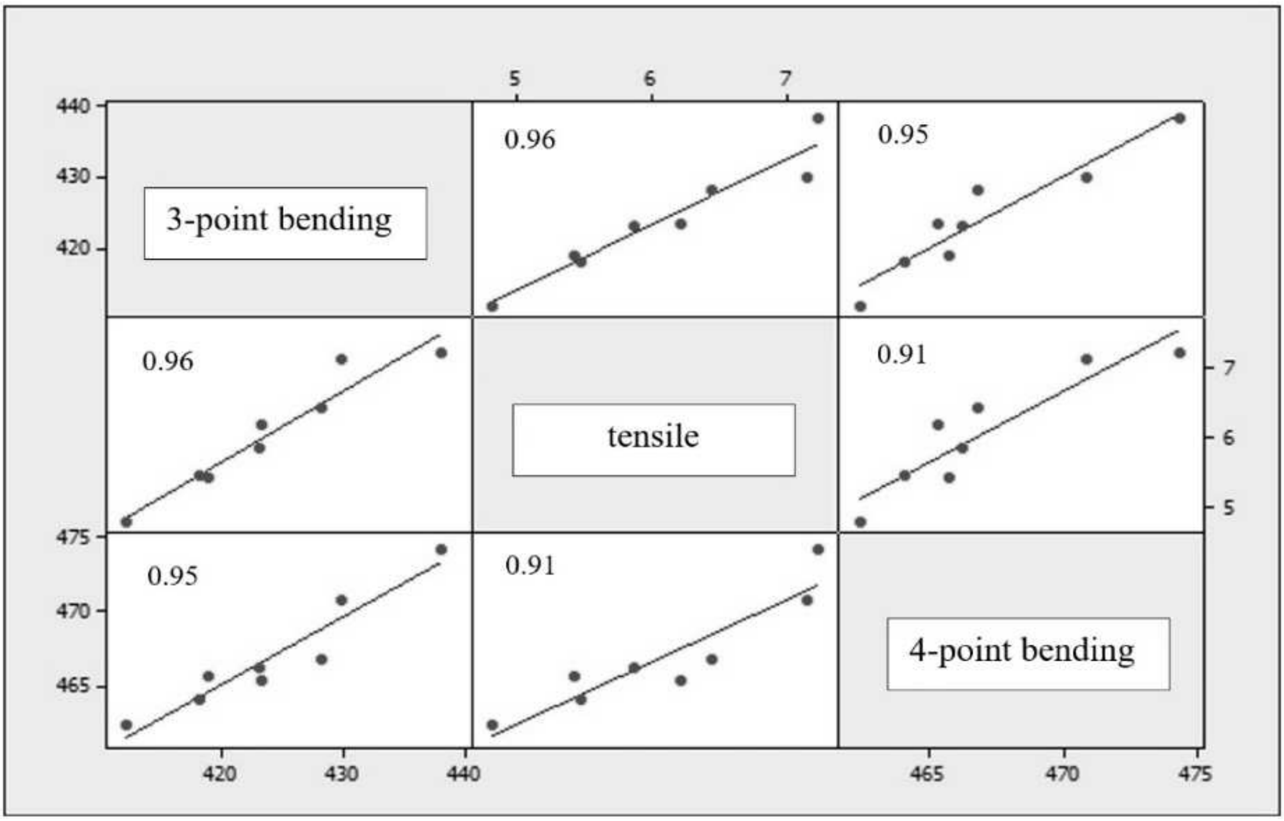

Fig. 5 *Correlation between the loads obtained by the three tests: 3-point flexural test, tensile test and 4-point flexural test (all values are in N)*

The tensile specimens presented a 1.02 mm of adhesive thickness and a misalignment of 1.04°. An adherends' misalignment of 0.19° characterized the nominal specimens for the tensile test, it was considered negligible.

The 3-point bending specimens have a 0.77 mm of adhesive thickness and a misalignment of 1.38°. The nominal specimens manufactured for the 3-point bending test showed a slight adherends' misalignment of 0.13°, which was considered negligible, and a 0.88 mm of adhesive thickness.

The 20 specimens were tested on an Instron machine. The results presented an adhesive failure. The misalignment reduces the load by 17.6% and 2% for tensile and bending tests respectively (see Fig. 7a and 7c). These values are near the numerical results, which involved a decrease of 11% and 1% for the tensile and bending test (see Fig. 7b and 7d). The numerical model overestimates and underestimates the experimental results by about 20% for the tensile and bending tests respectively.

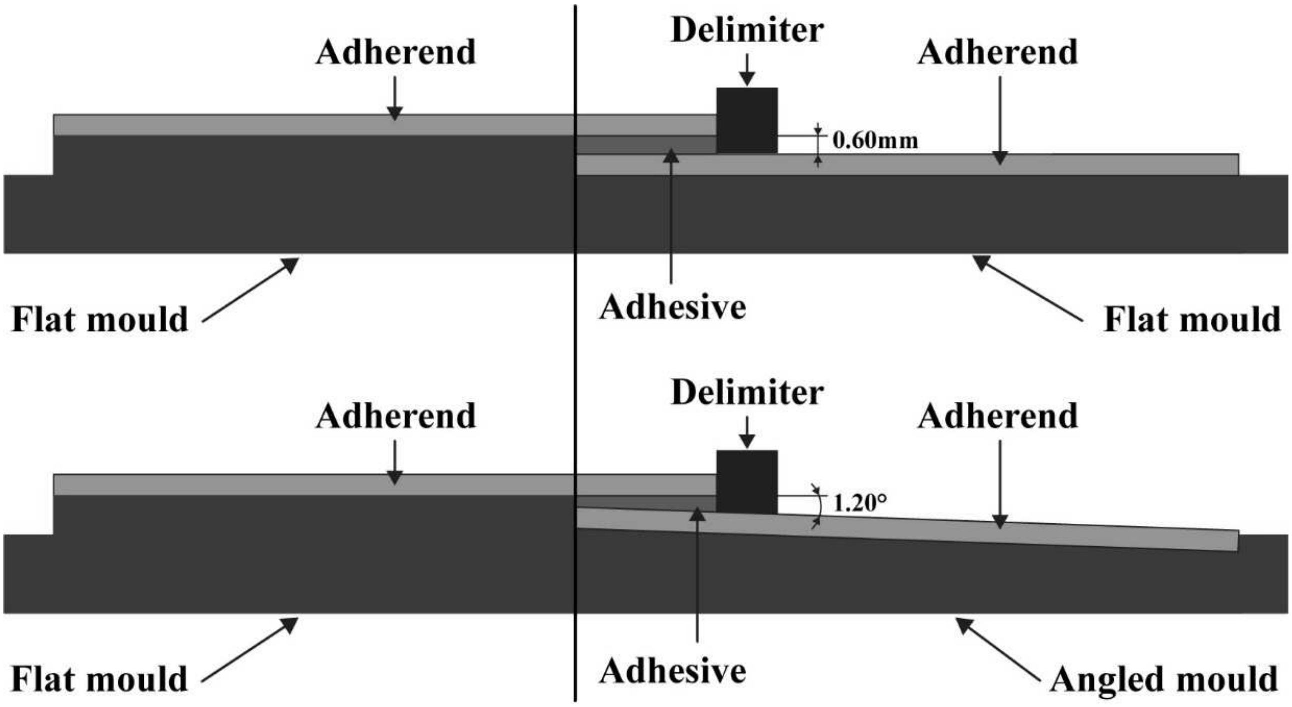

Fig. 6 *Scheme of aligned and angled adherends*

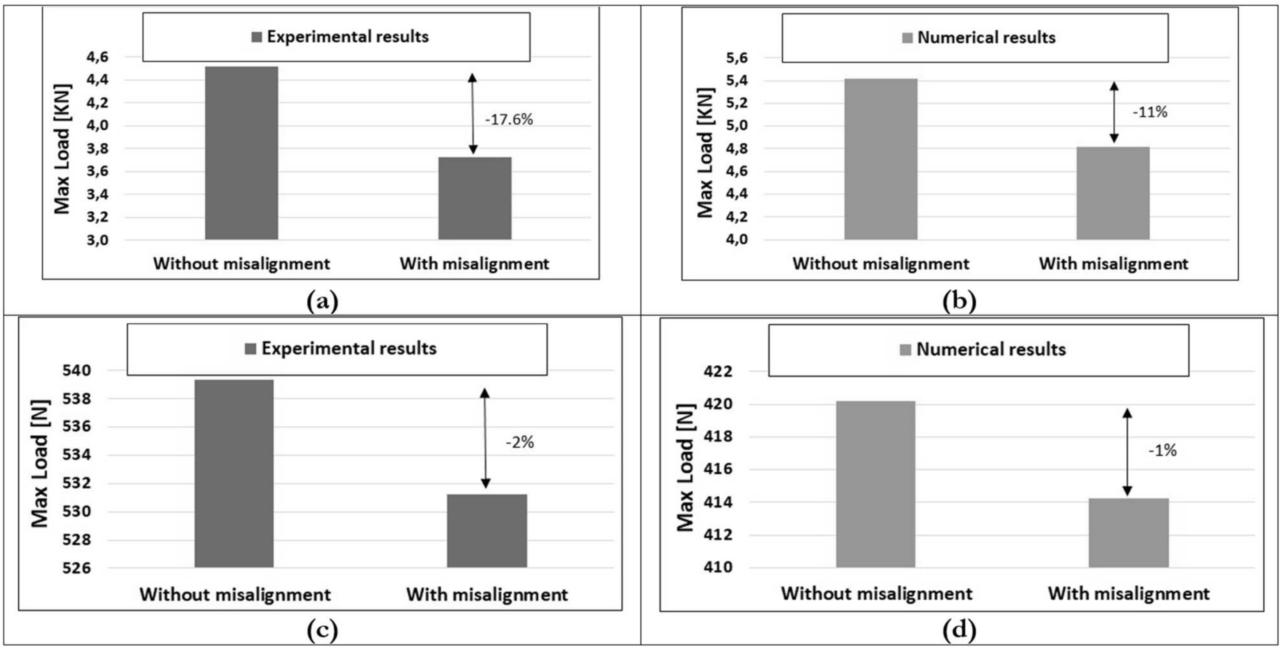

Fig. 7 *Results: a) experimental ones by tensile test; b) numerical ones by tensile test; c) experimental ones by 3-point bending test; d) numerical ones by 3-point bending test*

5 Conclusions

The quality of a product is becoming a very important aspect in the industrial field and, as well as affecting the aesthetic appearance of the product, it may reduce its strength. An example is a joint whose strength is commonly associated with the involved materials, but it depends on its actual geometry too. This work focuses on the effect of adherends' misalignment on the strength of a king of adhesive joints, the single lap joint.

A unique numerical model was developed in this work to put into relationship the tensile and bending strength of a joint with the materials of adherends and adhesive, the adhesive thickness, the length of the overlap zone and the adherends' misalignment.

This numerical model found that the adherends' misalignment reduces the maximum value of load that the joint may be submitted. In particular, the adherends' misalignment involves a significant reduction of the maximum tensile load supported by the joint: it can arrive at about 11% and 1% for tensile and bending tests respectively.

These values are lower than that found experimentally of 17.6% and 2% for tensile and bending tests respectively.

Industrially, the geometric deviations of adhesive joints may be very wide because no specific control is adopted. Therefore, a numerical tool is the key to improving the product performance.

Further studies considering more geometric deviations of adherends involved in a single lap joint are in progress, such as the variable thickness of the adherends or the adhesive and so on. Any product is generally connected to many sources of variations due to its manufacturing process and that qualifies its aspect. It is very critical to contain a product variability to identify all these sources of variations. This is a matter of further studies connected with adhesive joints.

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