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Novel Mechanical Characterization Method Applied to Non-Structural Adhesives: Adherend Material Sensitivity

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Abstract
Adhesives are more relevant in the industrial world each day, and the need for fast, simple, and cheap mechanical characterization techniques is urgent. During the following work, a novel specimen that can perform four different tests in only one go, is used to numerically study the effect of downgrading the properties of the substrate materials allowing higher sensitivity when characterizing non-structural adhesives. This study showed that numerically the load displacement curves of fracture tests are the most influenced ones, but the actual change in the fracture toughness from steel to aluminum substrates is negligible for the mode I loading and penalizing for the mode II loading.

1. Introduction

Adhesives have been used for thousands of years, but only recently they started to be made with synthetic polymers. An adhesive consists, in a simplistic point of view, in a substance which the propose is to fill the space existing between two substrates and connected them (da Silva et al. 2018). These adhesives can be divided in two groups: structural and non-structural. Structural adhesives are more capable of resisting to higher stress and used, consequently, in applications that require structural load bearing components. Non-structural adhesives are used in more trivial applications and present much lower strength. As such, adhesive characterization is becoming more important each day, specially so when structural adhesives are involved. However, correctly understanding the properties of non-structural adhesives could also prove beneficial, even if it presents some challenges due to their reduced mechanical capabilities turning them more difficult to measure correctly, specially for more rigid adhesives which present very small displacements.

Four main tests must be performed considering different loading scenarios – tensile and shear strength, and mode I and mode II fracture. Tensile strength tests consist in the application of a uniaxial tension load on the material until failure occurs, this test considers one of several specimens: bulk tensile specimen, butt joints or butterfly joints, being the first the most reliable (da Silva et al. 2012). Shear strength tests, on the other hand, apply two parallel loads in opposite directions, with the objective of creating a shear load on the material that is being tested. For this kind of loading, specimens such as the thick adherend shear test (TAST) are the most common, nevertheless, others such as the modified TAST, butterfly joint and torsion butt joint are also used (da Silva et al. 2012). Facture toughness tests are also highly important measuring the minimum energy required to initialize crack propagation. Therefore, the use of an adhesive with a good fracture toughness will ensure the joint is able to resist damage, failing only in a predictable and safer way. This said, fracture tests can be used to characterize an adhesive in mode I loading using double cantilever beam (DCB) test, and for mode II the end-loaded split (ELS) test (Morais et al. 2010; Pereira et al. 2011).

However, in the industrial world, it isn't practical to make these four individual tests every time the need to characterize an adhesive arises. To reduce costs, time and complexity a unified specimen was designed to solve these problems, being capable of perform these four loading scenarios in just one test.

The proposed specimen, depicted in a scheme presented below (Figure 1), combines four of these tests into one. For tensile and shear loading, the butt joint and modified TAST, and for fracture in mode I and mode II, a modified DCB and an ELS test, respectively.

This work studied this novel specimen numerically to understand the influence of having a more compatible substrate material that would improve the characterization of two non-structural adhesives, a purely brittle and a brittle but flexible one, by going from the original steel substrates to aluminum.

2. Numerical Details

This numerical simulation of the unified specimen was done recuring to Abaqus® and considering four load steps, starting with shear, followed by tensile, then mode I and finally mode II loading.

Materials

Two different non-structural adhesives were used in this study, a brittle adhesive and a brittle but flexible one (Brandão et al. 2022), in order to have a wider spectrum of analysis. These materials were simulated recuring to cohesive elements and were defined as such by the input properties defined in the comparison tables presented in Section 2 - the Young's modulus, E, and shear modulus, G; maximum tensile strength, σ_f, and maximum shear strength, τ_f; and finally, critical fracture energies in mode I, G_{IC}, and mode II, G_{IIC}.

Since the main objective of this work is to understand how the change of substrate materials can change the way adhesives are characterize, two different substrate materials were used, steel and aluminum. Both of these were tested in the elastic domain using the following properties, a Young's modulus of 210 GPa, and 70 GPa, and a Poisson's ratio of 0.3 and 0.33, respectively.

Geometry

The geometry used is the one presented in Figure 1. According to the picture below, and explaining it, must be identified four adhesives' zones and the respective substrates.

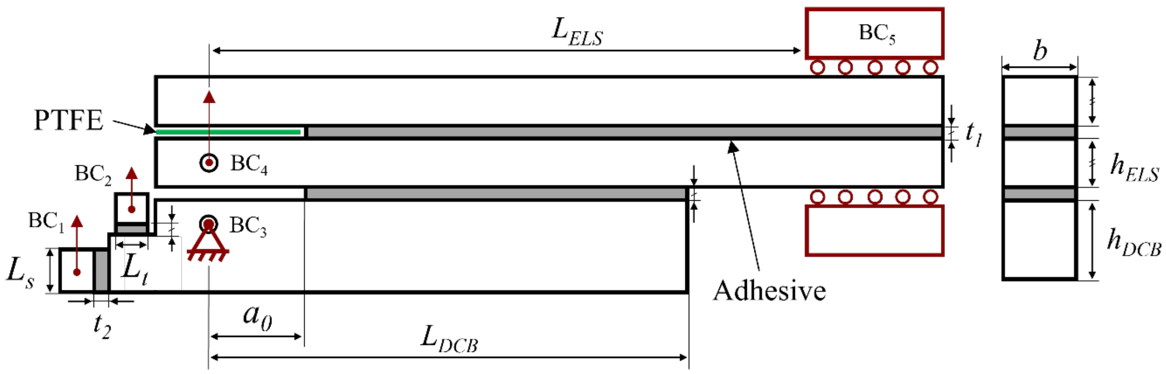

Figure 1: Boundary conditions used in the numerical simulation

Each adhesive layer is tested sequentially and can be identified in relation to Figure 1 by the boundary conditions (BC) that define it, starting by the shear test resultant of BC1 (loading displacement), and then the tensile test of BC2 (loading displacement), being both supported by BC3 (double support). Following that, the mode I test is comprised of both BC3 and BC4 (loading displacement). And finally, the ELS can be recognized by BC4 and BC5 (moving clamp). An additional element (PTFE) was used to consider a frictionless contact between the ELS substrates.

Mesh

The mesh used to simulate this specimen is composed of quadrilaterals of 0.5 mm side to void convergence problems. Since this is a 2D simulation, the elements considered for the substrates were 4-node bilinear plane strain elements (CPE4R) and for the adhesive layers 4-node two-dimensional cohesive element (COH2D4).

Boundary conditions

According to the nomenclature used in Figure 1, the boundary conditions presented different conditions in each simulation step, as presented in Table 1.

Table 1: Boundary conditions used in the numerical simulation defined for each load step.

Condition	Shear	Tensile	Mode I	Mode II
BC_1	(0; u_y ;-)	Deactivated	Deactivated	Deactivated
BC_2	-	(0 ; u_y ; -)	Deactivated	Deactivated
BC_3	(0; 0 ;-)	(0; 0 ;-)	(0; 0 ;-)	Deactivated
BC_4	-	-	(0; u_y ;-)	(0; u_y ;-)
BC_5	(- ; - ; 0)	(- ; -; 0)	(- ; -; 0)	(-; 0 ; 0)
PTFE	-	-	Contact interaction	Contact interaction

These boundary conditions identify the connections made by one of three scenarios, blocked (0), free (-) or active recuring to the respective variable (u_x u_y, θ_z).

In order to simulate, the non-friction condition between the ELS substrates, necessary for both the mode I and the mode II steps a discrete rigid wire – PTFE – bound by frictionless contact interactions.

Data treatment

The moduli and failure stresses of the shear and tensile tests were extracted from the respective stress-strain curves of each test.

The adhesive's G_I and G_{II} was determined using the compliance-based beam method (CBBM), a data reduction scheme whose advantage is not needing to measure the exact crack length, as well as considering the fracture process zone. For this method, the fracture energy is given by Formula 1 and Formula 2 (de Moura, Morais, et al. 2008):

$$G_I = \frac{6P^2}{b^2h}\left(\frac{2a_{eq}^2}{h^2E_f} + \frac{1}{5G_{13}}\right) \quad \textbf{(1)}$$

$$G_{II} = \frac{9P^2a_{eq}^2}{4b^2E_fh^3}F_2 \quad \textbf{(2)}$$

where for both equations *P* is the load applied, *b* the specimen width, *h* the thickness of the substrates, a_{eq} the equivalent crack length, E_f the corrected flexural modulus, and additionally for Formula 1, G_{13} is the substrate's shear modulus, and for Formula 2, F_2 is a large displacements correction factor.

3. Numerical results

In this section the results were presented starting by the brittle non-structural adhesive with both steel and aluminum. Followed by the brittle/flexible adhesive with both steel and aluminum substrates. The results can be seen in the Figure 2 – brittle adhesive – and Figure 3 – brittle/flexible adhesive.

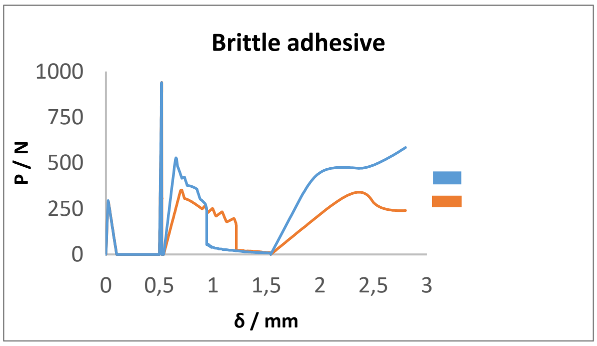

Figure 2: Simulation of Brittle Adhesive

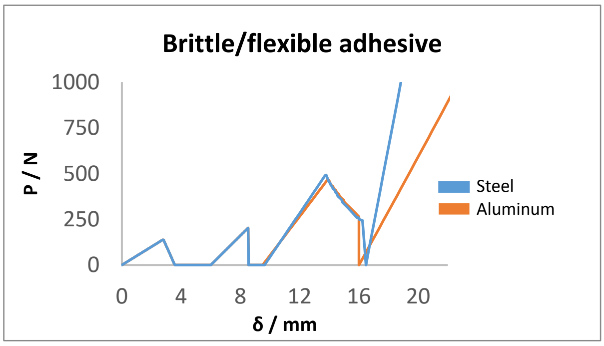

Figure 3: Simulation of Brittle/flexible adhesive

In this section the focus is not only on the behavior of the different adhesives, but the change of substrate materials.

The summary of the properties extracted from the load-displacement curves of this test are presented in Table 2.

Table 2: Propriety comparison of the non-structural adhesives.

Brittle adhesive	**E / MPa**	**σ_f / MPa**	**G / MPa**	**τ_f / MPa**	**G_{IC} / Nmm^{-1}**	**G_{IIC} / Nmm^{-1}**
Input value	800	16	300	8.0	0.15	0.30
Steel	188	16.8	105	6.9	0.21	0.29
Aluminium	171	16.1	95	6.7	0.18	0.19
Brittle/flexible adhesive	**E / MPa**	**σ_f / MPa**	**G / MPa**	**τ_f / MPa**	**G_{IC} / Nmm^{-1}**	**G_{IIC} / Nmm^{-1}**
Input value	1.34	3.4	1	2.8	3.3	5.0
Steel	0.3	3.1	0.5	2.2	6.5	-
Aluminum	0.3	3.1	0.5	2.2	6.5	-

4. Discussion

From Table 2, it can be perceived that both Young's modulus and shear modulus obtained are much lower than the theorical value, even though, this is a normal condition in adhesive characterization through joints since it englobes all the deformation of the adhesive joint and not only the adhesive itself. Both the maximum tensile stress and shear stress are close to the theorical values, as it is shown. The mode I fracture toughness test presented overestimated its values for both adhesives, and for mode II fracture, steel presented a better agreement with the input value for the brittle adhesive. The flexible adhesive did not present crack propagation in mode II, being unable to extract its fracture toughness.

It's simple to comprehend that using a substrate made of steel, the adhesive joint achieves a higher load for the same damage initiation since steel can present us with higher rigidity and, as such, lower substrate relative displacement which is an important factor for adhesive damage. But, by using aluminium, the lower rigidity and resistance, should make it possible to characterize better these adhesives, because the deformation and elongation are superior overall. However, this study showed that numerically, and in this novel specimen, even if the proprieties of the substrates are reduced which is noticed by the change in the load-displacement curves, the behavior of the adhesive is ultimately the same in terms of its properties.

Another important thing to refer is the fact that for the flexible adhesive the mode II fracture test did not propagate, as it is common for very flexible/ductile adhesives. The main reason for this situation might be the reduced dimensions of the specimen, becoming even more difficult to characterize the adhesive with this method.

5. Conclusions

From this study, the following conclusions were drawn:

- This novel specimen presents challenges that will be addressed with further research;
- The material change did not present any relevant change to the strength tests;
- The use of more ductile substrate materials in fracture tests does not present much numerical differences as the reduction methods consider these changes, but it is expected to be more relevant experimentally;
- To characterize adhesives with a very ductile or flexible behavior the use of bigger specimen is strongly recommended, in order to guarantee a full development of the fracture process zone allowing the correct characterization of the adhesive.

Additionally, it is relevant to note that in both cases the use of a modified DCB specimen, treated as pure mode I, overestimated the energy absorbed which is a point that has been noted and needs to be addressed in further development.

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