Composite Structures 185 (2018) 373–380

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Numerical study of the behaviour of composite mixed adhesive joints under impact strength for the automotive industry

J.J.M. Machado[a], P.M-R. Gamarra[b], E.A.S. Marques[a], Lucas F.M. da Silva[b],*

[a] *Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (INEGI), Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[b] *Departamento de Engenharia Mecânica, Faculdade de Engenharia (FEUP), Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

ARTICLE INFO

Keywords:
CFRP
Mixed adhesive joints
Single lap joints, Quasi-static
Impact
Numerical simulation

ABSTRACT

The increasing use of composite structures in the automotive industry is due to strict regulations regarding both fuel efficiency and safety standards, since this kind of structures allow to produce strong yet light vehicles. The main advantage of the use of adhesives is the possibility of joining dissimilar materials, particularly composite materials, representing an optimal method in comparison with more traditional ones such as fastening or welding. This work focused on the development and validation of numerical models able to simulate the performance of previously experimentally tested joints. The experimental tests were performed to assess the improvement of quasi-static and impact strength of composite adhesive joints, and with the focus of avoiding early delamination of the composite substrates. The technique selected for this purpose was the use of mixed adhesive joints. Mixed adhesive joints combine two or more adhesives in a single lap joint and combine these properties to attain mechanical performance superior to that obtained using those adhesives individually. The numerical results demonstrated to be able to simulate the experimental results with reasonable accuracy.

1. Introduction

The automotive industry requires increasingly lighter and stronger structures capable of withstanding an impact load without compromising its integrity. The increasing application of composite materials has the advantage of decreasing the weight of a vehicle, therefore, allowing to meet the strict regulations regarding fuel consumption and emissions. In this industry, one of the most important use of adhesives is in joining dissimilar materials, especially composite materials where other conventional methods are not adequate (bolts, rivets, etc). Nevertheless, several of the materials used in these structures exhibit some form of strain rate sensitivity, which adding to the presence of inertial effects causes the impact behaviour of an adhesive joint to be distinct from its quasi-static behaviour [1,2].

It is a general assumption that by decreasing the strength of an adhesive it is possible to obtain an increase in its ductility. Such compromise is still not clear in terms of optimization of joint strength. The concept of mixed adhesive joints aims to provide the best combination of strength and ductility using two distinct adhesives [3–7]. In the mixed adhesive joint configuration, the stiff and brittle adhesive should be in the centre of the overlap length, while the low-modulus and flexible adhesive is located at the ends of the overlap length, a region prone to high stress concentrations [8–11]. This method aims to delay the beginning of the failure and transfer the stresses from the ends of the overlap length to the centre.

Raphael [4] proposed the use of a more flexible adhesive at the ends of the overlap and a stiffer stronger adhesive in the section corresponding to the centre, attaining a more uniform stress distribution and delaying the occurrence of failure. Later work, by Fitton and Broughton [12] demonstrated that the right combination of adhesives with different modulus can reduce stress concentration in joints using carbon fibre reinforced polymer (CFRP) substrates. Similarly, changes in the mode of failure can be obtained. However, correct selection of adhesives for use in mixed adhesive joints should not only take the mechanical properties into account but also require the adhesives to exhibit a degree of compatibility [13]. The work of Hart-Smith [14] has also demonstrated that the mixed adhesive joint configuration can also be exploited to attain improvements in the strength of joints subjected to large thermal loads. Extensive experimental work on this subjected was performed by da Silva and Adams [15], which found significant improvements in the mechanical behaviour of a joint under a large temperature gradient. Analytical work performed by Neves et al. [16] enabled the assessment of the shear deformation in the substrates as well the nonlinear geometric effect which is characteristic of SLJs, comparing favourably the performance of this model with a finite element analysis. The same authors [17] later performed a parametric

---

* Corresponding author.
E-mail address: lucas@fe.up.pt (L.F.M. da Silva).

https://doi.org/10.1016/j.compstruct.2017.11.045
Received 31 August 2017; Received in revised form 6 November 2017; Accepted 16 November 2017

study of several joint parameters focusing on the stress distribution of mixed adhesive joints.

Further experimental work, performed by da Silva and Lopes [3] on mixed adhesive SLJs, used three different ductile adhesives. It was determined that if the joint strength of the ductile adhesive is lower than of the brittle adhesive, a mixed adhesive joint will lead to a joint strength higher than that of the adhesives used individually. Mixed adhesive SLJs using aluminium substrates were tested under quasi-static and impact conditions by Silva et al. [18]. The main conclusion of this work is that in configurations using a stiff epoxy with a room temperature vulcanizing silicone adhesive the results are not good, while, for the mixed adhesive SLJ combination using a stiff epoxy and an acrylic adhesive the results were superior to the individual use of both adhesives.

The performance of joints with composite substrates under impact was studied by Harding and West [19] and Taniguchi et al. [20], which have determined that while the tensile properties of unidirectional CFRP are not influenced by the strain rate, in the transverse direction the composite properties do have strong dependence of strain rate. This is because in the transverse direction the mechanical properties of the CFRP are governed by the resin.

The ability to simulate impact processes is fundamental for the design of crashworthy structures, minimizing the need for expensive experimental testing. A very powerful tool for simulating the behaviour of adhesive joints, including mixed adhesive joints, are cohesive zone models (CZM). Authors such as Needleman [21], Tvergaard et al. [22] and Camacho et al. [23] were among the first to adapt this technique to determine the failure load of adhesive joints. These elements have also been extensively used for modelling composite delamination [24,25]. The CZMs proposed by these authors completely model the fracture process, determining the crack location and advance, something which is not possible to achieve using classical continuum mechanics. The cohesive elements introduced in these models use both strength and energy parameters to simulate the nucleation and advance of a fracture crack [26,27], with the relationship between stresses and displacements being governed by a traction separation law. More recently, CZMs have also been combined with extended finite element method (XFEM) models, allowing more freedom in the location of the crack initiation [42].

The work of Carlberger et al., published in 2007 [28], was among the first that demonstrated the use of this approach to predict impact performance. Later, authors such as Haufe et al. [29], May et al. [30], Clarke et al. [31] Avendaño et al. [32] and Neumayer et al. [33] have performed similar analysis employing commercial software packages or custom elements, achieving accurate failure load predictions using complex dynamical cohesive models with strain rate dependent data.

Numerical simulations based on the mixed adhesive joints concept were already performed and proved experimentally. Kong et al. [34] developed a 3-D elastic finite element model to assess the influence in the stress distribution of different sequences and ratios of variable modules adhesives (bi-adhesive joints) in a bond line, in comparison to the use of a single adhesive. A decrease in the maximum stress of the adhesive layer occurred when using a suitable bi-adhesive combination, when meeting appropriate length ratios and bonding sequence of adhesives. From the simulations, it was concluded that the under different modes of loading, the optimization of the bonding parameters of bi-adhesives is required to be able to provide appropriate results. Similar results were obtained by Kumar and Pandey [35] (using also 2-D plane strain analysis) and Pires et al. [36]. Later, Pires at al. [37] performed a numerical study using Drucker-Prager plasticity model for the adhesives. Temiz [38] experimentally and numerically assessed that by using double strap joints subjected to bending moment, the use of two adhesives carried more loads as well higher strength. Akpinar et al. [39] studied experimentally and numerically (using a non-linear 3-D model) the effect of a mixed adhesive T-joint, in terms of normal and shear stress distribution. The finite element model could fit the experimental results, the peal stresses decrease with the use of mixed adhesives being the stresses carried into the inner regions, and the same behaviour was observed regarding shear stress. A numerical study to assess the effect of mixed adhesive joints with and without tapering plate on the interfacial stress in the adhesive layer was performed by Bouchikhi et al. [40] providing accurate results.

The present work focused on the numerical simulation with the aim of developing and validate models able to simulate loadings obtained experimentally in a previous work. The experimental tests were performed to assess the improvement of the static and impact strength of composite adhesive joints, and with the focus of avoiding early delamination of the composite substrates. The techniques selected for this purpose are the use of mixed adhesive joints and the use of crash resistant adhesives. Mixed adhesive joints combine two or more adhesives in a single lap joint and combine these properties to attain mechanical performance superior to that obtained using those adhesives individually. On the other hand, crash resistant adhesives are extremely strong yet ductile adhesives.

2. Experimental details

The mechanical properties of both substrates and adhesives tested experimentally are presented in this section. This data is of extreme importance for the numerical models, being defined for quasi-static and impact testing conditions. The geometry and all the adhesive configurations are also presented once they were used in all the numerical models created.

2.1. Mechanical properties of the materials

2.1.1. Adhesives

A total of five adhesives were tested experimentally in a previous work, two of those being considered as stiff and three being considered as flexible. The identification and type of adhesive is presented in Table 1, as well some of the authors who have determined the mechanical properties of these adhesives. It is also important to mention that the adhesives are ordered from the stiffest to the least stiff.

To perform accurate numerical simulation, it is essential to have the material properties at higher testing speeds, due to its strain rate dependency. The required value of high strain rate (3 m/s) the adhesives were not directly characterized. To determine these values, some of the adhesives were initially tested at 1 and 100 mm/min. An extrapolation process was then used, based in a logarithmic trend function able to estimate the properties at higher speeds [47,48] (Eq. (1)).

$$\text{Property to determine} = A\ln(\dot{\varepsilon}) + B \tag{1}$$

where A and B are constrains attained from experimental data, and $\dot{\varepsilon}$ is the strain rate in s^{-1}.

In Eq. (2), $\dot{\varepsilon}$ (strain) was determined:

$$\dot{\varepsilon} = \frac{v}{L_o} \tag{2}$$

Being v the velocity of the test and L_o the initial calibrated longitudinal deformation length of the specimen section where the strain is measured.

The mechanical properties of the adhesives (for room temperature)

Table 1
Types of adhesives studied.

Adhesive	Type	References
Araldite AV 138	Stiff	Silva et al. [41]
Nagase-Chemtex XNR6852 E-3	Stiff	Araújo et al. [42]
3M DP 8005	Flexible	Silva et al. [43] and Pinto et al. [44]
SikaFast 5211 NT	Flexible	Netusil et al. [45]
Momentive RTV 106	Flexible	Banea et al. [46]