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Dynamic behaviour of composite adhesive joints for the automotive industry

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ABSTRACT

The automotive industry has significantly increased the use of adhesive joints in vehicle construction, which can be explained in part by the widespread adoption of composite materials and structures. The combined use of composites and bonding allows the manufacture of structures with high mechanical strength and reduced weight. However, to ensure vehicle safety, these adhesive joints must be able to sustain large impact loads, transmitting the load to the structure without damaging the joint. This work aims to study the impact behaviour of composite adhesive joints bonded with a ductile epoxy adhesive, comparing different overlap lengths. For this purpose, a characterization of the behaviour of single lap joints was performed under quasi-static and impact conditions. Dynamic tests were also performed using vibration analysis to assess the damping capabilities of the studied joints. Numerical models were developed with cohesive elements in ABAQUS® software, including both quasi-static and dynamic models. It was demonstrated that joints manufactured with this type of adhesives and substrates can exhibit excellent impact strength and damping capabilities. It was also shown that the behaviour of these joints can be successfully modelled using static and dynamic finite element analysis.

1. Introduction

The wide use of fibre reinforced composite materials, such as carbon-fibre reinforced polymer (CFRP), in the automotive industry has led to lighter structures, with excellent strength and stiffness to weight ratios [1,2]. In order to satisfy mandatory safety requirements, structures used in this industry must be able to sustain dynamic load conditions, deforming and absorbing energy while at the same time maintaining their integrity. It is therefore important to ensure that carbon fibre structures can also bear impact loadings without premature failure.

The design of a composite adhesive joint for these conditions must be carefully considered, as geometrical parameters have a significant effect on the mechanical behaviour of bonded composite joints. Li et al. [3] analysed the influence of the overlap length, adherend thickness, width and scarf angle on single lap joints (SLJs), double lap joints (DLJs) and scarf joints, all using composite substrates and under static conditions. As the overlap increased, the ultimate failure also increased, as did the equivalent stiffness of the joint. In contrast, the overlap lap shear strength reduces with larger overlap lengths. Analysing the surfaces of the tested joints, the fracture modes changed from cohesive in the adhesive to cohesive in the adherend with an increase in the overlap length.

Neto et al. [4] further studied the effect of overlap length, performing a static strength comparison between a polyurethane adhesive and a two-component epoxy adhesive using CFRP adherends. In the case of the epoxy adhesive, the failure load increased until it reached a plateau from the overlap length of 30 mm. From this point further, the failure load was dictated by the composite. For the ductile adhesive, a linear behaviour of the failure load was noticed, since the failure mode was cohesive in the adhesive.

The effect of high strain rates in CFRP was studied by different authors. Harding and Welsh [5] showed that tensile properties of unidirectional carbon-epoxy were not influenced by strain rate. Taniguchi et al. [6] reached the same conclusion and also determined that the tensile properties in the transverse direction and the shear properties increased with an increase of the strain rate. Körber [7] showed that while strain rate had no significant effect on the longitudinal tensile modulus and strength, the same did not occur for the transverse tensile modulus and strength. A variation of the transverse tensile modulus and strength with the strain rate was observed. In this case, it is the resin that controls the failure, instead of the carbon fibres, which mostly influence

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the longitudinal properties. In 2000, Hou and Ruiz [8] tested woven CFRP using a split Hopkinson pressure bar (SHPB) apparatus under different strain rates and in tension, compression and in-plane shear. The authors concluded that the properties which are dominated by the matrix are: compression strength, Poisson's ratio, in-plane shear modulus, shear modulus and shear strength, being those properties strain rate dependent; the properties dominated by the fibres are: tensile modulus and strength which are virtually rate independent.

After understanding the mechanical behaviour of the CFRP substrate under impact loads, it is then fundamental to evaluate the adhesive behaviour under these same loads. Harris and Adams [9] compared the variation of joint strength in static and high rates of loading and the energy absorption by the structures under impact loads. In this research, different epoxy adhesives were used in the experiments. The first important conclusion was that the joint strength did not vary significantly when comparing static to dynamic loading of these adhesives. Concerning energy absorption by the structures, it was shown that in the case of bonded joints, energy absorption comes from the deformation of adherend material, and not from the adhesive itself. Bonded structures can withstand impact loads if the joints have sufficient strength to undergo plastic deformation in the adherend layers. In another study performed by Saldanha et al. [10] where low yield strength steel adherends and a high elongation and high ductility adhesive were used, drop weight impact tests were performed. It was possible to observe that in the impact tests the failure load increased and the elongation decreased. The adherends deformed less and absorbed less energy. Despite this, for both cases the failure occurred in the adherends. The behaviour of flexible adhesives under impact loads was studied by Kadioglu and Adams [11]. The authors determined that when the strain rate increased, the maximum tensile shear stress also increased and the tensile strain to failure decreased. This can be explained by considering that under high strain rates, the natural molecular rearrangement of the adhesive does not take place, because of the short period of load applications.

Cohesive zone models (CZM) are a very powerful tool for studying the behaviour of adhesive joints under static or impact loads. These numerical models are extensively used and give accurate predictions of failure loads. Authors such as Needleman [12], Tvergaard et al. [13] and Camacho et al. [14] were among the first to demonstrate the validity of this technique. A CZM combines the elastic stress calculations with classical fracture mechanics, being able to fully model the fracture process and location. A CZM model uses cohesive elements, which contain both strength and energy parameters to simulate the nucleation and advance of a fracture crack [15,16]. A traction separation law is used to establish a relation between the stresses and displacements. Fig. 1 shows a triangular traction separation law, typically available in many finite element software packages such as ABAQUS®. In Fig. 1, σ_n and τ_s are the cohesive strengths in tension and shear, respectively, E and G correspond to the stiffness in tension and shear, and G_{IC} and G_{IIC} are the critical fracture energies in mode I and mode II.

The work of Carlberger et al., published in 2007 [17] was the first that demonstrated the validity of using this type of approach to predict impact strength of adhesive joints. Authors such as Haufe et al. [18], May et al. [19], Clarke et al. [20], Avendaño et al. [21], Neumayer et al. [22] and Morin et al. [23] employed similar approaches and have shown that modern commercial software packages enable accurate prediction of failure loads, using complex dynamic cohesive models with strain rate dependent data.

The damping of adhesive joints is also an important property for the automotive industry, as manufacturers demand stiff structures that are still able to absorb vibrations. Damping of an adhesive joint can be expressed by different parameters such as specific damping capacity, damping ratio, logarithmic decrement and loss factor. Limited research has been undertaken on the damping behaviour of SLJs by studying the effect of variables such as the overlap ratio, temperature and bondline thickness. One of the earliest works on this subject, performed by Saito et al. [24] found that damping of SLJs is highly dependent on vibrational mode and overlap length. Adams et al. [25] studied four different adhesives with five different overlap lengths, employing a high strength low-damping steel for adherends This research determined that the optimum overlap ratio (overlap length divided by total specimen length) is around 0.25 for SLJs and that the damping provided by adhesives in vibrating structures is relatively limited and cannot be expected to significantly enhance the damping of the complete structure.

The main aim of this work was to experimentally assess the impact behaviour of composite adhesive joints bonded with a ductile epoxy adhesive. The behaviour of SLJs with different overlap lengths was studied under quasi-static and impact conditions. The damping capabilities of these joints was also examined. Lastly, CZMs were used to develop numerical simulations, which were validated using the experimental quasi-static and dynamic results, ensuring their usefulness in the design of crash resistant composite structures.

2. Experimental details

2.1. Material and properties

2.1.1. CFRP

The SLJ specimens used in this work used CFRP substrates bonded with a high ductility, crash resistant adhesive (Nagase ChemteX® XNR6852E-3). The CFRP substrates were composed of stacked plies of a carbon/epoxy pre-preg (SEAL® Texipreg HS 160 RM). A unidirectional configuration was used, selected to ensure maximum strength in the loading direction of SLJs.

The properties of this material were previously determined in the work of Campilho et al. [26] in 2008, and are presented in Table 1.

As shown in the introduction, the tensile properties of unidirectional CFRP are known to not vary significantly with the strain rate along the fibre direction [6,7,27]. Due to this fact, the strain rate dependent characterization of the Young's modulus and the tensile strength was not performed in these experimental procedures. However, there is limited information regarding strain rate dependence of fracture energy, which prompted the use of fracture toughness testing to obtain this data. Additionally, some authors have demonstrated sudden drop-offs in fracture toughness due to adiabatic heating. In some cases, there is also pointed the absence of the effect of fracture toughness [28]. While the tensile strength in the off-axis direction and the shear strength are also known to be sensitive to the rate of loading [29], these effects were not considered on this study due to the loads being applied mainly in the fibre direction.

For mode I fracture testing double cantilever beam (DCB) specimens were used. The geometry of the CFRP DCB specimens was based on ISO 15024 [30] standard, from 2001, which is used to determine, in mode I, the interlaminar fracture toughness, G_{IC}, for unidirectional reinforced fibre-reinforced plastic composites.

Mode II fracture testing was performed using end notch flexure (ENF) specimens. The same manufacture procedure described for the DCB specimens was followed for ENF specimens. This test consists of a 3-point bending load, where the specimen is supported at both ends and loaded in the opposite side at mid-span, promoting a shear mode loading in the adhesive layer [31]. Since there is no standard defined for these experiments [32], the geometry of the