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Finite element analysis of adhesively bonded composite joints subjected to impact loadings

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ABSTRACT

The main concern of this paper is to explore the geometrical and material effects on composite double lap joints (DLJ) subjected to dynamic in-plane loadings. Thus, three-dimensional finite element analyses were carried out at quasi-static and impact velocities. The DLJ alone was used for quasi-static case while an output bar was added for impact case. Elastic behavior was assumed for both adhesive and adherends. Average shear stress and stress homogeneity were extracted and compared. It was observed that the adhesive shear stiffness increases the average shear stress. Moreover, it makes the stress heterogeneity more important. On the other hand, higher values of the substrates longitudinal stiffness make the average shear stress higher; whereas, the stress homogeneity in the joint is better achieved for lower substrates' shear stiffness.

1. Introduction

Adhesive bonding offers many advantages to mechanical joints such as low weight, cost and the ability to join dissimilar materials. It does not cause distortion or weld worms. For this reason, many works have dealt with this subject in the literature. Different aspects were considered such as static, dynamic and impact loadings. Stepped-lap joints under tensile impact were analyzed by Sawa and Ichikawa [1] and showed that peak stress increases with the increase of adherends young's modulus. Mechanism of damage formation in glass-epoxy composite joints under transverse impact was analyzed by Kim et al. [2]. Vaidya et al. [3] found that peak stress for bidirectional composite joint under transverse impact is 10 times higher than under in-plane quasi-static loading. Carlberger and Stigh [4] analyzed impact fracture in aluminum joints under tensile impact and showed that an increase of the strain rate can be achieved in the adhesive layer. Bonded cylinders under shear impact loading were modeled by Sawa et al. [5] to verify experimental split Hokinson pressure bars (SHPB) tests. Silberschmidt et al. [6] studied the effect of impact fatigue on the crack growth of bonded joints. High velocity transverse impact on composite joints was investigated by Park and Kim [7], plies delamination were observed at the highest peel and shear stresses. Challita and Othman [8] simulated the SHPB tests on double-lap bonded joints with metal substrates and concluded that the SHPB bar method gives a good estimation of the mean adhesive stress value and not for adhesive average strain and maximum stress and strain; a unified parameter was proposed to correct the SHPB results. Stress wave propagation in epoxy-steel cylinders subjected to impact push-off loads under small strain rates was analyzed by Liao and Sawa [9] and showed that normal stresses increase with the increase of adherend/adhesive stiffness ratio. Liao et al. [10] studied the single-lap joint (SLJ) subjected to impact tensile medium strain rate, as overlap length increases, maximum principal stress decreases while adherends young's modulus and loading rate have the opposite effect.

The aim of this paper is to present a numerical 3D parametric study on the stress distribution inside adhesive layer for composite DLJ under in-plane quasi-static and impact loading cases. Contrarily to Challita and Othman [8], we are dealing here with composite substrates.

2. Method

2.1. Sample geometry

In this paper, we were interested in the double-lap adhesive joints as depicted in Fig. 1. Since peel stresses are reduced in

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double lap joints comparing to single lap joints, we focused on the shear stress distribution inside the adhesive layer. A compressive rightwards load was applied on the central substrate which yields to a shear stress state in the adhesive layer. First, a reference model was studied. Subsequently, a parametric study considering the different geometrical and material parameters was carried out while maintaining adherends' similarity in the material and orientation.

2.2. Loading cases

Following Challita and Othman [8], we are interested in analyzing the accuracy of experimental testing of double-lap joints by using finite-element simulations. Contrarily to Ref. [8], we are dealing with composite substrates and not metal ones.

In the quasi-static range, the double lap joints are commonly tested by servo-hydraulic machines. The loading rate can be as slow as 0.1 mm/min. At impact loading rates, the split Hokinson pressure bars system is widely used. Strain rate can be of $10^4\ s^{-1}$. The specimen is sandwiched between two bars, termed respectively input and output bar; the incident wave splits into two other waves at the specimen-"input bar" interface, a reflecting wave through the first input bar and a transmitted wave through the specimen to the output bar. The reader is referred to Ref. [8] for further details on the SHPB method. Yet, Dharan and Hausser [11] introduced the direct-impact technique, whereas, the input bar is removed and the specimen is directly impacted by the incident bar.

Usually, in a servo-hydraulic mechanical test, the specimen (the double lap joint) is sandwiched between two rigid plates. One plate is moving at almost constant velocity whereas the second one is fixed. In order to simulate such loading case, a 0.1 mm/min steady-state velocity was applied on the inner substrate of the joint for a total time of 90 s. Therefore, a total displacement of 0.15 mm was imposed to the inner substrate by the end of the simulation. This loading case is referred hereafter as the quasi-static case. A second loading case was considered and is referred hereafter as the impact case. It simulates the loading to which a double-lap specimen is submitted during a direct-impact Hopkinson bar test. Therefore, a velocity impact pulse was applied on the inner substrate for a total duration of 20 µs. The impact pulse is shown in Fig. 2. Similarly to the quasi-static case, an almost total displacement of 0.15 mm was imposed to the inner substrate at the end of the numerical simulation.

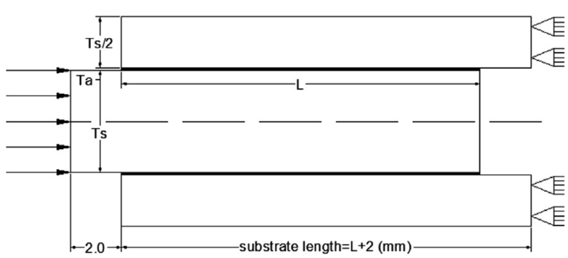

Fig. 1. Sample geometry with width *W*.

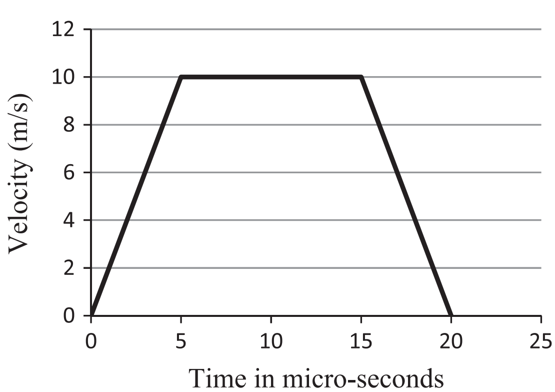

Fig. 2. Impact pulse.

2.3. Material properties

Both adhesive and substrates were assumed elastic as suggested by Higuchi et al. [17,18] and Sawa et al. [19] who compared their results to drop weight experiments. Indeed, elastic behavior is valid for elastic-brittle adhesives before failure and for ductile adhesives before yielding. The results of this study should be considered in this framework. Isotropy was assumed for the adhesive. However, as we were interested in composite laminate adherends, orthotropic elasticity was considered for substrates.

In the case of the reference numerical model, the material properties of Polyether ether ketone (PEEK) reinforced with 60% volume glass fiber were adopted. Moreover, we assumed that fibers are unidirectional and oriented parallel to the load with ply thickness of 0.2 mm. The adhesive is Araldite 2031, black epoxy system suitable for composite bonding. Material properties for reference model are shown in Table 1.

The material properties for the substrates are calculated using the mixing law.

2.4. Numerical model

For the quasi-static loading, the sole specimen was modeled with proper boundary conditions. For the impact case, the specimen and the output bar were modeled. Due to symmetry conditions, one-fourth of the system was modeled. The numerical models are shown in Fig. 3.

The commercial software ABAQUS was used with its implicit module for quasi-static case and explicit module for impact case. Tied node-to-surface was used between adhesive and substrates. The C3D8R 8-node solid element was used; each node has 3 degrees of freedom with reduced integration and hourglass control.

Since the thickness of the adhesive is a parameter, and we averaged stresses through the adhesive thickness, an element size of 0.025 mm through thickness was chosen to build-up any adhesive layer, which corresponds to 4 elements over adhesive thickness for the reference model. A $5 \times 100 \times 25\ \mu m^3$ smallest element was used at the joint edges. This mesh size was sufficient to achieve convergence as will be shown in Section 2.6.

Table 1
Material properties [12–16].

	Young's modulus (GPa)	Poisson's ratio	Rigidity' s modulus (GPa)	Limit stress (MPa)
PEEK	$E_m=4.1$	$\nu_m=0.4$	$G_m=1.3$	$\sigma=118$
Glass E	$E_f=72$	$\nu_f=0.22$	$G_f=30$	$\sigma=3300$
Composite ply: $V_f=60\%$ and $V_m=40\%$	$E_1=44.84$ $E_2=E_3=9.44$	$\nu_{12}=\nu_{13}=0.292$ $\nu_{23}=0.4$	$G_{12}=G_{13}=3.05$ $G_{23}=3.37$	$\sigma_R=2730$
Adhesive (Araldite 2031)	$E=1$	$\nu=0.4$	$G=0.35$	$\sigma=20$