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Determination of dynamic shear stress – Strain relationship in adhesively bonded assemblies

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Abstract. In this paper, we are interested in the measurement of the shear stress-strain relationship in the adhesive layer of bonded assemblies. Precisely, we investigate the sensitivity of this relationship to strain rates. For this target, an M-shape specimen is tested with conventional split Hopkinson pressure bar (SPHB) system. Hence, we can reach impact velocities in the range of 20 m/s. The accuracy of dynamic tests is investigated by numerical experiments. Indeed, the experimental set-up (two Hopkinson bars and the M-shape) is modelled on ABAQUS 6.6. From the simulations, we deduce the strain at one cross-section of each bar as in a SHPB test. We apply then the conventional methodology to retrieve the strain and the stress in the adhesive layer under the homogeneity assumption. The retrieved strain and stress are compared to the mean strain and stress, respectively, in adhesive layer. Finally, we find that the SHPB methodology provides a good approximation of the stress however it over-estimates the strain. Fortunately, this over-estimation is quasi-independent of strain, i.e., the SHPB strain is quasi-proportional to the mean strain. A numerical coefficient can then be deduced from numerical simulations to correct the SHPB strain.

1. INTRODUCTION

Many studies have been developed on bonded assemblies and particularly engineering studies in order to determine the mechanical behavior and mechanical properties of the adhesive joints under many conditions of use (temperature, load, adherent material, specimen geometry...). In references [1] and [2], formulas for stresses in adhesively bonded joints were established. They assume that shear deformations are confined to a thin adhesive layer that separates the adherents, this for classical bonded joints. Goland et al. [3] presented a classical work in the area of static analysis of a single lap joint. On the other hand, Kaya [4] investigated stress distribution in single and double adhesive bonded lap joints under tension force by finite element procedure while Owen and Lee-Sullivan [5] studied the effect of surface roughness of a steel adherent for a lap shear joint. Kong et al. [6] analyzed, using 3D elastic-plastic finite element method, the stress distribution of adhesively bonded metal/metal single lap joints under cleavage loading. Many researchers were recently interested in studying bonded assemblies under impact loading, Sawa et al. [7] investigated the stress wave propagation in butt adhesive joints of similar hollow cylinders subjected to impact tensile loadings using a 3D finite elements method. Besides, they studied the effect of the adhesive thickness, the adhesive's Young's modulus and the inside diameter of hollow cylinders on the stress wave propagation at the interfaces. The comparison with the results of static loadings was also carried out. Wada et al. [8] investigated the impact tensile strength for dissimilar butt adhesive shaft joints using fracture toughness. Finite elements method at the fracture initiation time was used to study the joint strength at the interface between dissimilar substrates. The results were compared with static ones. Yokoyama [9] and Srivastava [10] proposed two different geometries of specimens to be tested under dynamic shear loading with SHPB device, but both geometries presented many variations of sections and thus impedance mismatch which induce errors to dynamic measurements, moreover the dynamic equilibrium was not reached. Furthermore, Zgoul [11] generated and presented experimental material data for rate-dependent adhesive. The

availability of such data allows the development of a numerical material model that can be used to predict the behavior of structures bonded with that adhesive. Crocombe et al. [12] predicted the rate-dependent response of adhesively bonded joints using an overstress-based viscoplastic model using ABAQUS finite element code. In another paper [13], considerable success has been reported by finding an almost uniform state of shear stress results with use of thick adherents which allows measurement of realistic material characteristics of the joint. Öchsner and Gegner [14], determined shear stress-strain diagrams (and hence the shear modulus) for different testing temperature. They calculated equally the Young's Modulus using an iterative finite element technique.

In this paper, we carried out experiments on bonded joint with an M-shaped specimen [15] and a split Hopkinson pressure bar set-up. In addition, we used numerical simulations based on FEM method using ABAQUS 6.6 to check the validity of the SHPB method. In our study, we varied many parameters to investigate their influence on the method accuracy: overlap length, adhesive thickness, adhesive's Young's modulus and impact velocity.

2. EXPERIMENTAL SET-UP

The conventional configuration of a split Hopkinson pressure bar set-up consists of two elastic or viscoelastic bars (Figure 1). In our case, the two bars are made from the same material which is steel MARVAL and have the same diameter of 16 mm. On each bar, one strain gauge is bonded. A striker is launched on the first bar. This induces a compressive wave which moves through the input bar till the bar-specimen interface. At this interface, a first part of the wave is reflected back into the input bar as a tensile wave and a second part is transmitted through the specimen into the output bar as a compressive wave. The input gauge station measures the incident and reflected waves while the output gauge records the transmitted wave. In this case, the incident and the reflected waves are recorded separately with the input gauge.

Assuming one-dimensional wave propagation, dynamic equilibrium [16] and elastic bars, the shear stress in the adhesive joint is directly deduced from the conventional SHPB methodology, i.e.,

$$\tau(t) = \tau_{SHPB}(t) = \frac{F_{in}(t) + F_{out}(t)}{2 \cdot S_{overlap}} = \frac{E_b S_b (\epsilon_{inc} + \epsilon_{ref} + \epsilon_{tra})}{2 \cdot S_{overlap}} \quad (1)$$

where $F_{in}(t)$, $F_{out}(t)$, ϵ_{inc} , ϵ_{ref} , ϵ_{tra} , E_b , S_b and $S_{overlap}$ are the input force, output force, incident wave, reflected wave, transmitted wave, bars' Young's modulus, bars' cross-sectional area and overlap area, respectively.

On the other hand, the strain recovered by the SHPB set-up (the SHPB strain) is given by:

$$\gamma_{SHPB}(t) = \frac{U_{out}(t) - U_{in}(t)}{e_{adhesive}} = \int \frac{-c(-\epsilon_{inc} + \epsilon_{ref} + \epsilon_{tra})}{e_{adhesive}} dt. \quad (2)$$

where $U_{in}(t)$, $U_{out}(t)$, c and $e_{adhesive}$ are the input displacement, output displacement, the bar sound speed and the adhesive thickness.

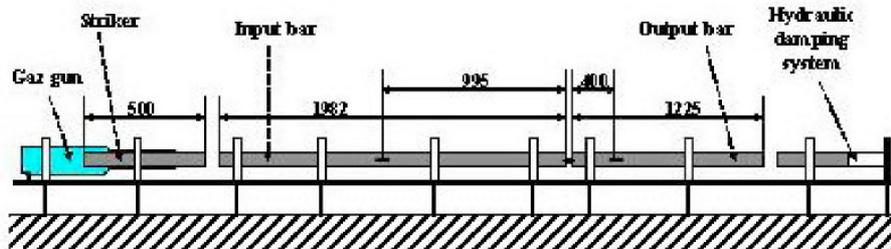


Figure 1. Split Hopkinson Pressure Bar (SHPB) device.

The M-shape specimen (Figure 2) consists of three metallic plates with the same length of 12 mm when the overlap is 10 mm, 14 mm when the overlap is 12 mm and 16 mm when the overlap is 14 mm, bonded together. The middle plate is shifted by 2 mm from the two others in order to convert the compressive load applied to the specimen into a shear stress inside the adhesive layer. All plates have the same width of 12 mm. The middle plate is 4-mm thick, while the upper and the lower plates are 2-mm thick. The adherents (plates) are made from steel S235 (Young's modulus $E = 200$ GPa; Poisson's ratio $\nu = 0.3$), while the adhesive is a toughened epoxy film on a glass carrier. Its elastic parameters are a Young's modulus $E = 3$ GPa and Poisson's ratio $\nu = 0.4$.

We were referenced to the cure cycle in the data sheet given by the manufacturer Gurit SP to achieve appropriately the consolidation of the adhesive film inside the assembly. Moreover, all the specimens are prepared in identical mountings [15]. After the cure cycle, they are removed from these mountings and kept for at least one week inside a conditioned room (Temperature of 20°C; Relative Humidity of 50%) and then they are ready to be tested.

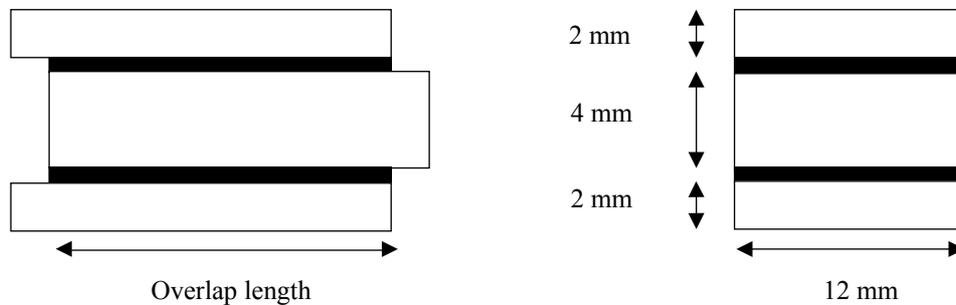


Figure 2. M-shape specimen, front view and side view respectively (Adherents in white; Adhesive layer in black).

3. NUMERICAL SIMULATIONS

3.1 Objective

Using ABAQUS CAE 6.6, numerical simulations were made on the whole system, i.e., the input and the output bars and the specimen. The experimental tests were exactly simulated with the same parameters we had during the test in order to measure the real values of the mean shear stress and mean shear strain inside the adhesive layer. On the second hand, we measure the bars deformations on the nodes corresponding to the positions of the strain gages of the SHPB device. Thus we can determine numerically the stress and the strain with the method based on the SHPB theory than the comparison with the real values will be done.

3.2 Stress measurement

The shear stress is measured on all adhesive nodes located in the middle plane parallel to the overlap length. A mean value over the overlap length is calculated at each time t of the numerical test. On the other hand, getting the bars deformations on the bars nodes corresponding to the gauges positions, we evaluated the forces on both interfaces specimen-bars, F_{in} and F_{out} , using the SHPB theory, hence the shear stress is determined from Equation (1). For a thorough wave processing, the software DAVID is used [17]. Comparing the two stress values, i.e., the mean stress value in the joint and the stress recovered by Equation (1), we found a little difference, This was observed for any set of parameters. For example, we plot in Figure 3 the shear stress curves form both methods for an overlap length of 14 mm and adhesive thickness of 100 μm .

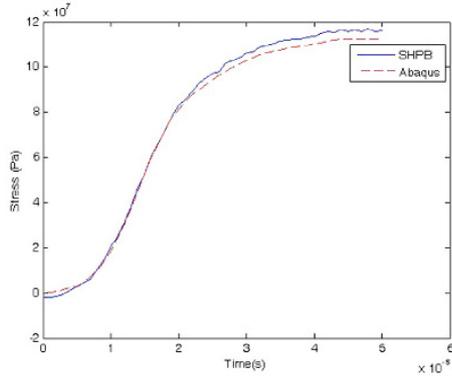


Figure 3. Graph of shear stress v/s time in both SHPB method and simulation.

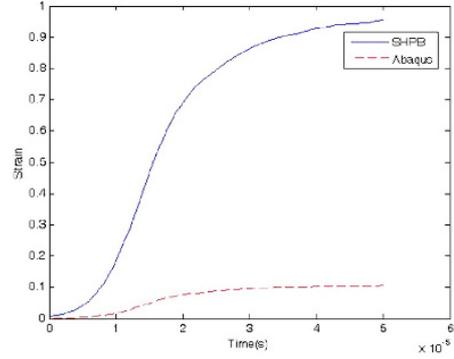


Figure 4. Graph of shear strain v/s time in both SHPB method and simulation.

3.3 Strain measurement

We did the same comparison for strain measurements. Precisely, we measured the mean value of the strain in the joint and by Equation (2). Both strains are compared. An example is plotted in Figure 4 (overlap length 14 mm and adhesive thickness 100 μm). The strain evaluated by Equation (2) over-estimates the mean strain value in the joint. In the following section 3.4 we present a correction to this over-estimation.

3.4 Correction of the strain

We carried out multiple numerical simulations for various material and geometrical parameter [18] and impact velocities. For each set of parameters we computed the ratio between the mean strain and the strain retrieved by Equation (2). It appears that, except the beginning of the test, this ratio depends only on specimen geometry and the materials parameters (Figure 5). Indeed, it depended neither on impact velocity nor on strain. Therefore, for each specimen geometry and material parameters we can define a correction coefficient β such as the real strain in the specimen can be retrieved by the following equation:

$$\gamma_{\text{real}} = \beta \cdot \gamma_{\text{SHPB}} \quad (3)$$

The coefficient β is determined by numerical simulations.

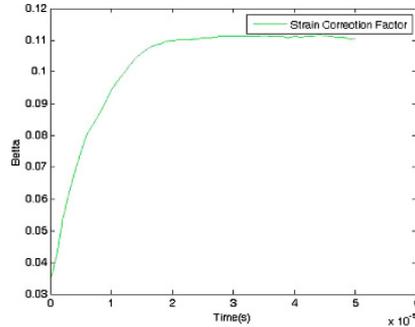


Figure 5. The ratio between the strain mean value and the strain recovered by Equation (2).

4. EXPERIMENTAL STUDY

4.1 Description

The thicknesses of the three plates are measured at five specified points, and then their surfaces are simply cleaned with ethanol to remove grease and dust. The epoxy bond layer is cut in small parts which have the dimensions of the overlap, each part is bonded on the upper and lower surface, and then the three plates are assembled as shown in Figure 2 using a special mounting device [15] that ensures the alignment of the plates. The whole assembly is introduced to a special oven where the cure cycle of the epoxy bond SA80 is programmed. The specimen is removed from the mounting and kept in a conditioned room where local temperature 20°C, relative hygrometry 50% for at least one week. The total thickness of the specimen is measured at the same five points as we did for the plates, and the thickness of the adhesive layer is estimated as the half of the difference between the average thickness of the specimen and the sum of the average thicknesses of the plates. The specimen is tested after no more than two hours after picking it up from the conditioned room.

4.2 Results and discussion

The shear strain rate is estimated as the ratio of the corrected shear strain (Equation (3)) at the failure over the time at the failure. Figure 6 represents the maximum mean shear stress for three different overlap lengths (10 mm; 12 mm; 14 mm) in function of the strain rate on a log scale axis. The maximum shear stress is between 40 and 70 MPa. Normally, the maximum shear stress increases with strain rate; but for very high strain rates, we observe a drop of the stress level; the reason might be explained by the heat effect produced in the polymers at high speeds which will cause a decrease in the shear strength.

This study considered simply a mean value of the stress in the joint; for more accuracy, the true profile of the shear stress with peak values at the overlap ends should be taken into account. This approximation becomes more applicable for an adhesive with low Young's modulus, high thickness and low overlap length because the stress field inside the joint will be more homogeneous.

We notice that the coefficient of strain correction β influences this graph since it is included through the correction of the strain rate. It will increase with the increasing of the adhesive thickness and the decreasing of the overlap length. Thus, the stress homogeneity and the strain correction factor will improve in the same way.

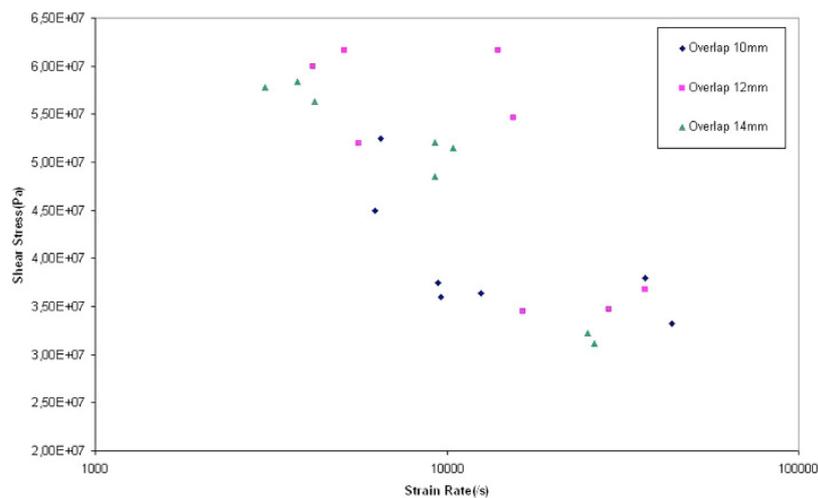


Figure 6. Graph of shear stress v/s logarithmic strain rate for different overlap lengths.

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