Composite Structures 191 (2018) 168–179

Contents lists available at ScienceDirect

Composite Structures

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

An investigation of in-plane dynamic behavior of adhesively-bonded composite joints under dynamic compression at high strain rate

Sonia Sassi*, Mostapha Tarfaoui, Hamza Ben Yahia

ENSTA Bretagne, FRE CNRS 3744, IRDL, F-29200 Brest, France

ARTICLE INFO

Keywords:
Adhesive joints
In-plane dynamic compression tests
Dynamic properties
Damage mechanics
Hopkinson bar

ABSTRACT

This study examines the behaviour of adhesively-bonded composite joints under dynamic compression tests. The purpose of this work is to use the split Hopkinson pressure bar (SHPB) for the dynamic characterization of adhesively bonded joints subjected to in-plane compression loading and in particular, the effect of strain rate on the mechanical behaviour and the damage kinetics. These joints are studied using glass/vinylester composite materials which are frequently used in naval applications Compression tests are performed at different strain rates using SHPB and high speed camera has been used to follow the damage progression. The experimental results have shown that the dynamic properties change with respect to the change in strain rate. Fibre buckling and delamination are the main damage criterias seen in the specimens under in-plane compressive tests. Therefore, this study not only allows us to understand the dynamic response of the adhesively bonded joints under dynamic compression but also enables us to establish damage models based on strain rate effect, for structure design purposes.

1. Introduction

As the role of structural adhesives becomes more pronounced in composites used in technological applications such as aeronautics, military and naval etc, it has become necessary to understand the dynamic behavior of adhesively bonded joints. To design structures subjected to high impact loads in such applications, the knowledge of dynamic properties is required for developing constitutive models of the tested materials [1,2]. In addition, the link between the dynamic behavior and the dynamic damage evolution in adhesively bonded joints at high strain rates, is still far from being fully understood. Thus, it is significant to achieve an accurate description of damage under dynamic loading and effect of strain rate on the behavior of these materials for safety and design considerations. The split Hopkinson bar (SHPB) has been widely used to determine the dynamic properties of materials at high strain rates [3–12]. Significant efforts have been made to investigate the effect of high strain rate on the dynamic behaviour of polymers adhesives and composites laminates using the Split Hopkinson bar under various loading conditions [13–16]. Hosur et al. [17] investigated the dynamic response of unidirectional carbon/epoxy composite material subjected to in-plane dynamic compression tests using SHPB with different strain rates of 82, 164 and 817 s^{-1}. They compared the dynamic results with static compression tests and observed that strength and stiffness of the material are higher in dynamic compression than in static compression test. Kumar et al. [13] studied the dynamic compressive response of unidirectional glass/epoxy composite at various off-axis angles in the transverse and logitidunal direction.

They demonstrated in their study that the longitudinal compressive strength and failure strain increase however, the longitudinal modulus decreases with increasing strain rate. El-Habak et al. [14] examined the mechanical behaviour of woven glass fibre-reinforced composites at strain rates from 10^2 to $10^3\,s^{-1}$ for three types of matrix (polyester, vinylester and epoxy). They concluded that the vinyester matrix allows to obtain the highest strength. Tarfaoui et al. [5] studied the strain rate effect on the dynamic behaviour of glass fibre reinforced polymer under in-plane and out-of-plane dynamic compression tests using SHPB varying the fibres orientation and the loading conditions. The results showed that the dynamic strength of the material depends strongly on fibre orientation and impact pressure for in-plane tests and the material is significantly sensitive to fibre orientation for out-of-plane tests at the same impact pressure. Arbaoui et al. [9,10] studied the dynamic compressive behaviour of $[0/90°]_{26}$ glass/epoxy laminates in-plane and out-of-plane directions using (SHPB). They concluded that the dynamic properties are strain rate sensitive and the material is more resistant in the case of out-of-plane loading as compared to the in-plane loading case. Li et al. [18] studied the thermodynamic behaviour of unidirectional carbon/epoxy laminate subjected to in-plane and out-plane

* Corresponding author.
E-mail addresses: sonia.sassi@ensta-bretagne.fr (S. Sassi), mostapha.tarfaoui@ensta-bretagne.fr (M. Tarfaoui).

https://doi.org/10.1016/j.compstruct.2018.02.057
Received 5 September 2017; Received in revised form 24 January 2018; Accepted 19 February 2018
Available online 21 February 2018
0263-8223/

dynamic compression and tensile tests at different strain rates using (SHPB). It was concluded that the damage modes are responsible for heat dissipation in the material for both dynamic tests.

It is apparent from the available literature that little research has been carried out to study the dynamic behaviour of the adhesively bonded joints in comparison with the specimens made entirely in polymeric adhesives [19–24]. Although, obtaining reliable data regarding these adhesively bonded joints is complex and depends upon the combination of different materials but in general, most of the research is carried out to investigate either the adhesive formulation, or to study the effect of the strain rate and temperature on adhesive under dynamic impact using various simple ad hoc tests. For example, L. Goglio et al. [20] studied the effect of the strain rate on the dynamic tensile and compression strength of specimens made of adhesive «epoxy» using the SHPB. Their results showed that the adhesive strength increases substantially by increasing the strain-rate. Takeshi Iwamoto et al. [21] investigated the effect of strain rate on the compressive stress-strain behaviour of epoxy resin adhesive using SHPB. They concluded that in the elastic deformation, a semi-logarithmic approach could be established to link the peak stress in the low strain rate and nonlinear laws in high strain rates. To explained the non-linear behaviour, the authors have defined rheological models taking into account the plastic deformation of the glassy epoxy polymer. Sharon et al. [24] studied the effects of loading rate and temperature on the mechanical properties of four structural adhesives. They demonstrated that the yield stress and modulus decreased with temperature, while increase in loading rate resulted in an increase in yield stress with negligible influence on the modulus. Calberger et al. [19] studied the effect of the temperature and the strain rate on the cohesive properties of an epoxy adhesive. Their results showed a negligible effect of temperature on the fracture thoroughness from −40 °C to 80 °C (the glass transition temperature of the epoxy adhesive investigated is +90 °C) but the peak stress in peel loading decreased significantly with increasing temperature in this range and both cohesive parameters increased with increasing the strain rate. Srivastava et al. [25] investigated the effects of temperature and strain rate on the bond strength of lap joints in Ti-6Al-4 V and C/C-SiC composite. They concluded that the bond strength decreases by 40–50% at 300 °C, while it increases with the strain rate. So, it is clear that adhesive materials are high strain rate sensitive. Therefore, it can be expected that the dynamic response of adhesive joints would be strongly dependent on the strain rate under impact conditions.

In this study the effect of the strain rate on the dynamic behaviour of adhesively-bonded composite joints subjected to in-plane loading using SHPB is investigated. Compression tests were performed at four different impact pressures (1, 2, 3 and 4 bar). High speed camera was used to draw up the history of the dynamic damage in the specimens in response to the strain rate evolution. The failure modes of adhesively-bonded composite joints have been determined and also discussed. To summarize the experimental results, empirical models depending upon the strain rate effect, have been established. These empirical models will play a useful role in developing damage models for design optimization of adhesively-bonded composite structures.

2. Experimental procedure

2.1. Materials

The material used in this study is the one taken directly from a real superstructure of Fregate. It consists of a 45° Bi-axial fiber-glass mat of 0.286 mm thickness in a Polyester resin matrix. In adhesive bonding, a NORPOL Polyvinylester of 1 mm thickness has been used to assemble the composite substrate. The composite mechanical properties are given in Tables 1–3. For these dynamic compression tests, samples with 13 mm × 13 mm × 9 mm for in-plane tests are considered, as illustrated in Fig. 1. Before conducting the in-plane dynamic tests on the Hopkinson bars, it is necessary to ensure that these tests can be reproduced. With this objective in mind, a minimum of three tests were carried out at the same impact pressure in order to analyse tests reproducibility.

Table 1
Physical properties of the fiber glass mat.

Construction	Areal weight (g/m^2)	Tolerance (± %)	Material	Linear density (tex)
+45°	451	5	E-Glass	600
−45°	451	5	E-Glass	600
Stitching	12	5	PES 76 dtex	
Total area weight	912	5	Binder	Warp

Table 2
Mechanical properties of orthotropic layer (glass/vinylester).

Properties	Values
Density (kg/m^3)	1960
Young's modulus (MPa)	$E_1 = 48110$, $E_2 = E_3 = 11210$
Poisson's ratio	$\nu_{12} = \nu_{13} = 0.28$, $\nu_{23} = 0.34$
Shear modulus (MPa)	$G_{12} = G_{13} = 4420$, $G_{23} = 5000$
Longitudinal Tensile strength (MPa)	$X_t = 965.50$
Longitudinal compressive strength (MPa)	$X_c = 900$
Transversal tensile strength (MPa)	$Y_t = Z_t = 33.50$
Transversal compressive strength (MPa)	$Y_c = Z_c = 134$
Shear strength (MPa)	$S_{12} = S_{13} = S_{23} = 48.69$

Table 3
Mechanical properties of adhesive.

Properties	Values
Density (kg/m^3)	1960
Young's modulus (MPa)	$E = 3100$
Poisson's ratio	$\nu = 0.3$
Strength to final failure (MPa)	51.25

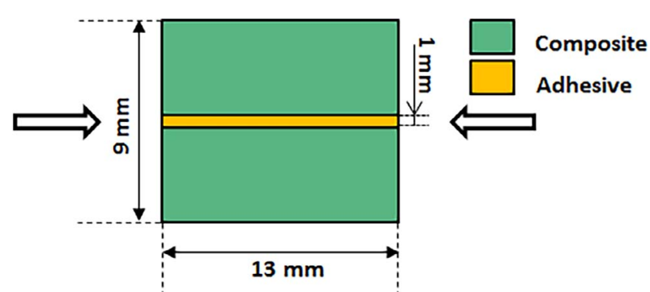

Fig. 1. Adhesively-bonded composite joints specimen subjected to in-plane loading.

2.2. SHPB method

In this study, the in-plane dynamic compressive loading is ensured using the SHPB apparatus (Fig. 2). Details of the SHPB experimental protocol are mentioned in [3–12].The SHPB apparatus basically consists of an incident bar, a transmitted bar and sticker bar. Both the incident and transmitted bars have a diameter of 20 mm and a length of 1.9850 m. A striker bar of 20 mm diameter and a length of 2 m is used to generate an incident stress via impact with the incident bar. Specimens of adhesively bonded assemblies are placed between the incident and transmitted bars without any attachment to prevent perturbations of measurements due to additional interfaces [26]. To vary the strain rates under different compressive tests, the striker velocity is adjusted by varying the pressure to achieve a range of incident load magnitudes.