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Determination of the impact tensile strength of structural adhesive butt joints with a modified split Hopkinson pressure bar

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A R T I C L E I N F O

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A B S T R A C T

The impact tensile strength of structural adhesive butt joints was determined with a modified split Hopkinson pressure bar using hat-shaped specimens. A typical two-part structural epoxy adhesive (Scotch weld® DP-460) and two different adherend materials (Al alloy 7075-T6 and commercially pure titanium) were used in the adhesion tests. The impact tensile strength of adhesive butt joints with similar adherends was evaluated from the peak value of the applied tensile stress history. The corresponding static tensile strengths were measured on an Instron testing machine using joint specimens of the same geometry as those used in the impact tests. An axisymmetric finite element analysis was performed to investigate the static elastic stress distributions in the adhesive layer of the joint specimens. The effects of loading rate, adherend material and adhesive thickness on the joint tensile strength were examined. The joint tensile strength was clearly observed to increase with the loading rate up to an order of 10^6 MPa/s, and decrease gradually with the adhesive thickness up to nearly 180 μm, depending on the adherend materials used. The loading rate dependence of the tensile strength was herein discussed in terms of the dominant failure modes in the joint specimens after static and impact testing.

1. Introduction

Over the last decade, there has been a growing interest in the impact behavior of structural adhesives and adhesive-bonded joints, largely due to the increasing use of adhesives in the aerospace and automotive industries. The mechanical performance of adhesive-bonded joints under essentially static loads can be assessed using a variety of ASTM tests. There are, however, no standard test methods available for determining the impact strength of adhesive-bonded joints, except for the block impact test using a pendulum-type impact machine (ASTM D950-94 [1]). In this test, the kinetic energy required to break a bonded specimen is measured in the typical manner with a pendulum-type impact machine without considering stress wave effects in the specimen. Adams and Harris [2] performed a critical assessment of the impact test method by finite element analysis, showing that the method does not provide the strength data on adhesive-bonded joints required for engineering design purposes. Since this time, many attempts have been made to determine the impact properties of several joints with different geometries using drop-weight impact methods or split Hopkinson pressure bar (SHPB) techniques [3]. Sato [4] provided an excellent review of the experimental methods used for the impact testing of adhesives and adhesively bonded joints. Yokoyama and Shimizu [5] evaluated the impact shear strength of adhesive-bonded joints with a modified SHPB using a pin-and-collar specimen. Bezemer et al. [6] developed a new rod-and-ring specimen to determine the impact shear strength and failure energy of adhesive-bonded joints using both a drop-weight tower and an air gun. Sato and Ikegami [7] measured the dynamic strength of adhesive-bonded butt joints under combined tensile and torsional loading using a clamped SHPB. Srivastava et al. [8] and Sen et al. [9] determined the dynamic compressive-shear strength of single-lap adhesive joints with a conventional SHPB. Kihara et al. [10] designed an experimental arrangement to determine the compressive-shear strength of adhesive layers under stress wave loading. Adamvalli and Parameswaran [11] measured the dynamic compressive-shear strength of single-lap adhesive joints with a standard SHPB at high temperatures up to 100 °C. Challita et al. [12] characterized the dynamic compressive-shear properties of double-lap adhesive joints with steel adherends using a conventional SHPB. Yokoyama [13] determined the impact tensile properties of adhesive butt joints with a tensile SHPB using a solid circular joint specimen. Wang and Xu [14] developed new convex-edged axisymmetric butt joints with dissimilar adherends to eliminate free-edged stress singularities and verified their efficiency using both a tensile SHPB and the commercial finite element software ABAQUS. Chen and

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Li [15] and Zhao et al. [16] evaluated the dynamic tensile-shear strength of single-lap adhesive joints with steel adherends using a tensile SHPB at temperatures ranging from −40 to 80 °C and at a low temperature of −40 °C.

In terms of weight reduction in adhesive-bonded joints, composite adherends have attracted much attention especially for aerospace and aircraft structural applications. Raykhere et al. [17] characterized the dynamic torsional-shear strength of adhesive joints composed of metallic and GFRP adherends with a torsional SHPB. Al-Zubaidy et al. [18] explored the effect of loading rate on the bond strength of CFRP/steel double-strap joints using a drop-weight impact machine. Galliot et al. [19] also studied the effect of loading rate on the failure load of adhesively bonded carbon/epoxy laminate joints using a similar machine.

He [20] recently presented a very comprehensive review of the finite element analysis of adhesively bonded joints under static, fatigue and dynamic loading. Sato and Ikegami [21] investigated the stress wave propagation in single-lap, tapered and scarf joints using a dynamic finite element method. Sawa and his co-workers performed finite element analyses of T-shaped butt joints [22], annular butt joints [23,24], single-lap joints [25–27] and tubular lap joints [28] subjected to impact tensile loading and compared their findings with experimental results obtained by strain-gauge techniques. Sato [29] analyzed the dynamic stress responses at the edges of adhesive layers in semi-infinite lap strap joints by a semi-closed-form approach. Challita and Othman [30] simulated standard SHPB tests on double-lap adhesive joint specimens using the commercial finite element code ABAQUS.

In an effort to isolate the combined effects of adherend material and joint geometry on the dynamic response of adhesive-bonded joints, the dynamic stress–strain properties of bulk structural adhesives have been evaluated in compression [31,32,34] and in tension [32,33]. These studies demonstrate the importance of modeling the dynamic stress–strain behavior of bulk structural adhesives to readily perform numerical simulations of adhesively bonded structures under dynamic loading. Sancaktar [35] conducted a comprehensive survey of constitutive models for bulk adhesives and adhesively bonded joints. Fancello et al. [36], Iwamoto et al. [37] and Yokoyama et al. [38] derived rate-dependent constitutive equations for two different bulk structural adhesives under compression, based on elasto-viscoplastic models or a modified Ramberg–Osgood model. Nevertheless, the impact tensile or torsional properties of adhesive-bonded joints have not been well understood due to the experimental difficulties associated with high-rate test methods, including the need to fix the joint specimen and generate a well-defined tensile or torsional loading pulse.

The primary objective of the present study was to determine the impact tensile strength of epoxy adhesive butt joints with a modified SHPB using hat-shaped specimens. Impact tension tests were performed by utilizing the reflected tensile waves generated at the free end of the hat-shaped joint specimen. A typical two-component structural epoxy adhesive and two different metallic adherends were used in adhesion tests. Static indirect tension tests were run on an Instron 5500R testing machine using the same design of the joint specimens. The effects of loading rate, adherend material and adhesive thickness on the joint tensile strength were investigated in detail. Lastly, the limitations of the modified SHPB using the hat-shaped joint specimens were discussed.

2. Design and preparation of adhesive butt joint specimens

2.1. Adhesive and basic tensile properties of bulk adhesive

The adhesive used was a commercially available two-component structural thermosetting epoxy adhesive (Sumitomo 3-M, Scotch weld® DP-460) suitable for use with metallic adherends. According to the manufacturer's directions, the DP-460 was mixed in a volume ratio of 2 (base): 1 (hardening accelerator) to obtain optimum mechanical properties. Adhesive sheets with a thickness of 3 mm were fabricated by a special solidification technique based on the French Standard NF T76-142 [39] and cured for 24 h at room temperature, but not post-cured at higher temperatures. The geometry of a sheet tension specimen of the bulk epoxy adhesive is presented in Fig. 1. Tension tests were carried out on the Instron 5500R testing machine at crosshead speeds of 1 mm/min and 100 mm/min with a 5-kN—capacity load cell. Static and intermediate strain-rate tensile stress–strain curves up to fracture are shown in Fig. 2, indicating that the tensile strength increases appreciably; however, the ductility greatly decreases with increasing strain rate. The static tensile and physical properties of the bulk epoxy adhesive are summarized in Table 1. Two different adherend materials were used: Al alloy 7075-T6 (Furukawa Electric Co., Ltd.) and commercially pure titanium KS-50 (Kobe Steel Co., Ltd.). Their static tensile and physical properties are listed in Table 2.

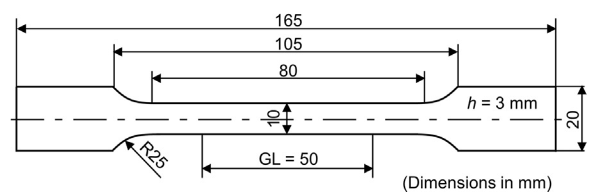

Fig. 1. Geometry of sheet tension specimen of bulk epoxy adhesive with thickness of 3 mm.

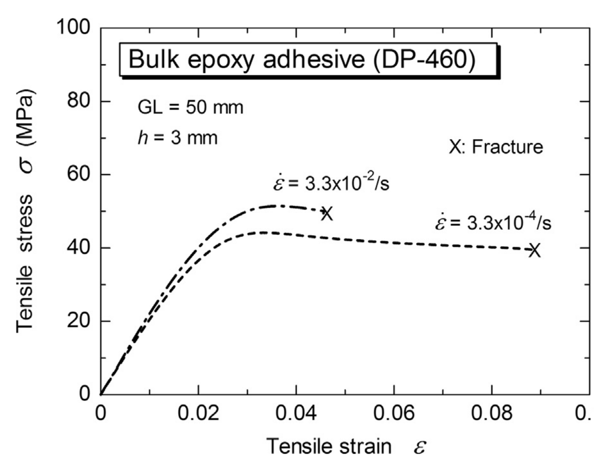

Fig. 2. Typical adhesive tensile stress–strain curves of bulk specimens at static and intermediate strain rates at room temperature.

Table 1
Static tensile and physical properties of bulk epoxy adhesive (Scotch weld® DP-460) at room temperature.

Adhesive	Initial modulus E_a (GPa)	Poisson's ratio n_a	Tensile strength σ_{UTS} (MPa)	Linear expansion coefficient β_a (1/°C)	Glass transition temperature T_g (°C)
DP-460	2.2 ± 0.06[a]	0.40	43.9 ± 0.11[a]	59×10^{-6}	80

[a] Mean ± standard deviation.