Composites Part B 105 (2016) 101–110

Contents lists available at ScienceDirect

Composites Part B

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

Parametric study of the bending properties of lightweight tubular metal/polymer foam hybrid structures

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ARTICLE INFO

Article history:
Received 11 January 2016
Received in revised form
4 July 2016
Accepted 23 August 2016
Available online 24 August 2016

Keywords:
Hybrid
Impact behaviour
Plastic deformation
Finite element analysis (FEA)

ABSTRACT

Hybrid structures of the structural epoxy foam Terocore® and circular tubes of different aluminium alloys (6060 T5, 6061 T6 and 7075 T6) were tested in dynamic three-point bending. Energy absorption, deformation and failure were compared to previous quasi-static tests and found to be similar. LS-DYNA was used to model the tube fracture using element erosion, with successful prediction of failure. A parametric study using the validated finite element model revealed the function of the foam and carrier tube is two-fold, both absorbing energy and also increasing the energy absorption of the outer tube by modifying the deformation.

1. Introduction

The automotive industry has seen significant improvements in vehicle crash safety over recent decades, with global regulatory bodies setting increasingly stringent requirements. In Australia, the number of new vehicles sold meeting a 5 star NCAP safety rating increased from nil in 2001 to 86% in 2014 [1]. At the same time, increasing fuel efficiency requirements and emissions standards favour more mass efficient designs. One area of opportunity for light weighting is by the use of hybrid structures (metal/foam) and lighter weight materials such as aluminium. Crashworthiness components have traditionally been made from high strength steels and provide occupant protection under large plastic deformation in bending by providing resistance force and kinetic energy absorption (EA). Hybrid structures employ foam to alter the deformation of the structure to increase EA. The mass efficiency of designs can be compared using specific energy absorption (SEA), which measures energy absorption per kg of weight.

Application of various foam materials have been described in the literature, including aluminium [2–16], and to a lesser extent polymeric foams such as polyurethane [17–21] and epoxy [22–27]. Polymeric foams have the advantage of a relatively simple manufacturing process, with products specifically designed to be placed in position as solid pieces that expand under heat in the vehicle paint shop process [28].

The initial work of Guo et al. [6] and subsequent continuation by Li et al. [7] with aluminium foam compared empty, fully filled and sandwich foam filled circular 6063 T6 tubes (outer tubes 38 mm diameter, 1 mm, 1.6 mm and 2 mm wall thickness with inner tubes of 20 mm, 22 mm and 24 mm diameter with 1.2 mm and 1.4 mm wall thickness). Both studies found that the sandwich tubes offered the highest SEA performance, and the fully filled single tubes offered a lesser increase in performance over the empty tubes, for dynamic and quasi-static bending. This was also in agreement with Li and Lu [8] who measured a doubling of SEA for aluminium 38 mm square sandwich tubes (6063 T6, 0.9 mm wall thickness) filled with aluminium foam with an inner tube of the same material (20 mm square with 1.2 mm wall thickness), compared with only a 16% increase in SEA for the same fully filled tubes. Duarte et al. [9] found that SEA could be increased by 84% by filling 6060 tubes (30 mm diameter and 2 mm wall thickness, 150 mm length) with 0.5 g/cm^3 aluminium foam. Kinoshita et al. showed a 17% increase in SEA for circular aluminium tubes (6060 T5, 40 mm diameter with 1.6 mm wall thickness) filled with aluminium foam [10]. Guo and Lu [11] observed a 50% increase in SEA for 38 mm square sandwich tubes (6063 T6, 0.9 mm wall thickness) using aluminium foam and a 25 mm square carrier tube with 1.2 mm wall thickness. Strano

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http://dx.doi.org/10.1016/j.compositesb.2016.08.030
1359-8368/

et al. [12] investigated circular and square tubes of steels and aluminium with aluminium foam filling and reported that a square high strength steel tube with aluminium foam filling provided the largest increase in SEA (20%) of all the configurations tested.

Partial filling of aluminium foam longitudinally has also been studied. Santosa [13] found that by limiting foam filling to near the midpoint of the beam span, an additional plastic hinge was encouraged to the point where additional energy could be absorbed compared with a fully filled tube, which allowed weight saving with only a minimal loss of bending resistance.

Published research on hybrid structures with polymeric foams covers mainly sandwich panels in bending and tubular structures under axial crush, but is limited for tubular structures under bending loads. In this area, Eksi and Genel [29] achieved a 47% increase in SEA when 6063 T5 tubes (30 mm diameter and 1 mm wall thickness, 217 mm span) were reinforced with 4 mm thick cast polyamide (PA6) on the inside of the tube. Park et al. [30] studied three-point bending of a closed 'hat' section of double layer high strength steel, employing a combination of a composite glass fibre insert in the large cavity of the section, or an epoxy foam in the small cavity between the two high strength steel panels. The structure was partially filled by the foam and/or reinforcement for about 1/3rd of the beam length, centred at the mid-span. SEA increased by 10% for the foam case, and 91% for the composite insert, compared with the empty steel beam. A combination of the two yielded a 96% increase in SEA. Butler et al. [23] conducted FEA crash simulations for vehicle bumper beams reinforced with Terocore® epoxy foam to reduce airbag deployment time. Herbst et al. [24] tested steel square tubes of 51 mm × 76 mm and 0.81 mm wall thickness in four-point bending with either empty, polyurethane foam (320 kg/m^3), or epoxy foam filling (700 kg/m^3). The beam span was 254 mm and indenter displacement 25.4 mm. The polyurethane foam increased SEA by an average of 234% and epoxy foam by an average of 257% over the unfilled case.

Much of the published research in hybrid structures has covered 6000 series aluminium for tubes of relatively thin wall thickness (less than 2 mm). Tubular structures using 7000 series aluminium in bending are harder to come by. Hilditch [31] studied three-point bending of empty tubes of 15 mm diameter and 1 mm wall thickness for materials including 7075 T6, however this did not include any study of hybrids.

The current study deals with dynamic three-point bending of hybrid tubular structures made with a structural epoxy foam and aluminium alloys 6060 T5, 6061 T6, and 7075 T6 with wall thicknesses up to 4.1 mm. The structures tested were also tested quasi-statically by Rathnaweera et al. [26–28,32]. A correlated dynamic FEA model was developed which successfully predicted EA and failure. The previously correlated quasi-static FE model was then used in a parametric study to investigate the contribution of each component of the hybrid structure to the overall EA, while predicting performance of hybrid structures of varying outer tube wall thicknesses and carrier tube diameters. The quasi-static FE model was chosen because EA and deformation were observed to be similar to dynamic experiments, and physical verification testing is easier to perform with less noise in the measurements due to inertial effects. Performance of the structures was measured in EA, SEA and performance index which is a representation of SEA per mm displacement.

2. Materials and experimental procedure

An epoxy based polymer foam Terocore® was used as a filler between the outer and carrier aluminium tubes to create hybrid sandwich structures as shown in Fig. 1.

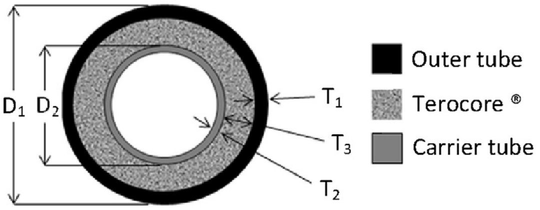

Fig. 1. Cross sectional view and dimensions of a typical Aluminium/Terocore® hybrid structure.

The hybrid structures had varying outer tube diameters and wall thickness, of either 7075-T6 or 6060-T5 aluminium alloys, whereas the carrier tube in all hybrid structures was of 6061 T6 aluminium, of 16 mm diameter and 0.9 mm wall thickness. The structures were cured in a fan-forced oven for 30 min at 168 °C. Uncured Terocore® density was 0.75–0.88 g/cm^3 compared to cured density of 0.5 ± 0.02 g/cm^3. Micro cells were created due to expanding of microspheres in polymer matrix. The materials and dimensions of tubes are listed in Table 1.

The bending performance of empty and hybrid structures was evaluated in both quasi-static and dynamic three-point bending using 340 mm long tubes with a span length of 260 mm and a maximum displacement of 60 mm. The diameter of the indenter and supports was 19.05 mm (3/4′). Quasi-static testing was performed using a 250 kN MTS machine (model 819) with the indenter reaction force and displacement measured at data sample rate of 20 Hz for an indenter speed of 0.35 mm/s. Dynamic testing was conducted using a drop hammer with carriage displacement measured using a laser triangulation displacement sensor and the reaction force on the supports measured using a load cell. Force and displacement data were acquired at a sample rate of 50 Hz for an initial impact speed of 7.8 m/s, which corresponded to the maximum height of the drop hammer.

3. Experimental results and discussion

Within the range of testing speeds examined, it was found that overall, the dynamic force-displacement results were on average similar to the quasi-static results, but with oscillation in the force signal and a higher initial peak force, possibly due to the inertial effects of the indenter and structural response of the tube and test apparatus. This is shown in Fig. 2 with typical examples of dynamic and quasi-static tests obtained for both empty and hybrid tubes of the two alloy materials (7075 and 6060).

EA and SEA were computed from the experimental data up to D_{max} which was defined as either the maximum indenter displacement of 60 mm, or an earlier displacement in the case of catastrophic failure of the tube, or where all the energy of the indenter had been absorbed without tube failure. Since the total EA

Table 1
Summary of experimental structure materials and dimensions (mm).

Structure[a]	Outer tube			Terocore®[a]	
	Material	D_1	T_1	T_3	% volume
E_7075_36_2.8	7075 T6	36	2.8		–
H_7075_36_2.8	7075 T6	36	2.8	7.2	61%
E_7075_36_4.1	7075 T6	36	4.1		–
H_7075_36_4.1	7075 T6	36	4.1	5.9	47%
E_6060_38_3.4	6060 T5	38	3.4		–
H_6060_38_3.4	6060 T5	38	3.4	7.6	55%
E_6060_38_4.4	6060 T5	38	4.4		–
H_6060_38_4.4	6060 T5	38	4.4	6.6	44%

[a] Note: same 6061 carrier tube for all tests: $D_2 = 16$ mm, $T_2 = 0.9$ mm.