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Transverse impact loading of aluminum foam filled braided stainless steel tubes

Ryan Smith, William Altenhof *, Matthew Lapain

Department of Mechanical, Automotive and Materials Engineering, University of Windsor, 410 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4

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ABSTRACT

The findings from an experimental study investigating the mechanical response and deformation mechanisms of empty and aluminum foam filled braided stainless steel tubes are presented within this manuscript. Tube specimens were impacted using a custom built pneumatic gun and projectile at incident velocities ranging from roughly 21 m/s to 27 m/s. Deformation and failure mechanisms resulting from the impact process were identified through the use of a high speed, high-resolution camera. Forces arising during the impact event were measured using ICP load cells and a modular DAQ system mounted within the projectile. The braided tubing utilized within this study was woven from AISI 304 stainless steel possessing a nominal wire diameter of 0.51 mm, nominal external diameter of 64.5 mm, and a length of 330 mm. Aluminum foam cores of density levels ranging from 179.22 kg/m^3 to 520.47 kg/m^3 were incorporated within the braided tubes having rectangular foam core geometry. Failure of tube specimens, for foam core densities typically less than 400 kg/m^3, was observed to initiate within the vicinity of the annular clamps as a result of the elevated tensile forces and localized bending present within the clamped regions. For foam core densities greater than approximately 400 kg/m^3, failure was noted to shift the initiation of failure to the tube mid-span as a result of localized wire failure. Levels of absorbed energy were noted to range from 1.78 kJ to 2.95 kJ for the tube specimens examined within this study.

1. Introduction

It is estimated by Ref. 1 that the cumulative annual cost as a result of injury is roughly 19.8 billion dollars within Canada alone. When examining strategies to prevent the occurrence of injuries engineering plays an important role, particularly the development of energy absorbing structures. Composite structures incorporating materials such as braids and various interior core materials have shown promise as versatile and effective energy absorbing structures owing to their lightweight, sound mechanical properties, and high impact with damage tolerance.

Jenq et al. [2] performed an experimental study examining the ballistic limit of two-step braided three-dimensional textile composites. The specimens examined within the study were constructed from unidirectional E-Glass fiber roving and infiltrated with an epoxy resin. Impact tests involved firing a 36 g, 12.7 mm diameter hemispherical tipped cylindrical projectile toward the specimen at incident velocities ranging from 70 to 180 m/s utilizing a pneumatic gun. The ballistic limit of the textile composites was determined to be 74 m/s where it was noted that the prominent damage modes of the specimen were indentation, matrix failure, and fiber breakage. Similar damage development was noted in an experimental study completed by Gong et al. [3], examining the mechanical response of braided panels subjected to impact loading by means of a pendulum and gas operated gun. Gning et al. [4] performed drop weight impact tests on ±55° filament wound glass/epoxy tubes at incident velocities ranging from 1.7 to 8 m/s using a 1.6 kg, 50 mm diameter hemispherical tipped projectile dropped from a 4 m height drop tower producing impact energies ranging from 2 to 45 J. It was observed that low energy impacts resulted in delamination and debonding of braid layer surface interfaces while high energy impacts caused delaminations to propagate and resulted in intralaminar cracking. The influence of prior damage due to lateral impact on the progressive crush behavior of composite tubes was investigated by Karbhari et al. [5]. Crush tests were completed on a total of 14 different braid architectures. It was noted the presence of prior damage had a pronounced effect on further damage evolution observed within the crush zone during progressive deformation. Bambach et al. [6] completed an experimental and

Abbreviations: AISI, American Iron and Steel Institute; ASTM, American Society for Testing and Materials; BIP, black iron pipe; CNC, computer numeric controlled; CNRB, constrained nodal rigid body; FE, force efficiency; FEA, finite element analysis; FFTI, foam filled transverse impact; LVDT, linear voltage differential transducer; NFTI, no foam transverse impact; RC, rectangular core; SEA, specific energy absorption; TEA, total energy absorption; TTL, transistor–transistor logic.

* Corresponding author. Department of Mechanical, Automotive and Materials Engineering, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4. Tel.: +1 (519) 253 3000 ext. 2619; Fax: +1 (519) 973 7007.

E-mail address: altenh1@uwindsor.ca (W. Altenhof).

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Nomenclature

$E_{(absorbed)}$	sum of energy absorbed by tube specimen and machine frame [kJ]
$E_{(elastic\ frame)}$	energy absorbed by long stroke machine frame [kJ]
$E_{(FE\ sim)}$	computed estimate of energy absorbed by long stroke machine frame [kJ]
$E_{(projectile)}$	projectile kinetic energy prior to impact [kJ]
$F_{(measured)}$	reaction force measured by projectile load cells [kN]
m	projectile mass [kg]
TEA	energy absorbed by tube specimen [kJ]
TEA^*	energy absorbed by tube specimen computed from FEA findings [kJ]
v	incident projectile velocity [m/s]

analytical investigation on hollow and concrete filled steel (C350) square section beams subjected to low velocity, high mass, transverse impact. The test specimens were subjected to impact at the beam mid-span using a drop rig at an incident velocity of 6.2 m/s. A 50 mm wide rigid load point applicator was utilized for all tests. Upon examination of the mechanical responses of both the hollow and concrete filled specimens, it was observed that the concrete filling led to a reduction in the transverse failure deflection due to the formation of tensile tears at the beam's mid-span.

Previously, Gu and Li [7] developed a simplified structural model to analyze the penetration of three-dimensional braided composites by a 7.95 g, 7.62 mm hemispherical tipped conical projectile at incident velocities ranging from 240 to 670 m/s. The model was developed for simulation using the explicit FE code LS-DYNA and based upon the fiber inclination model which simulated the braid kinematics and deformation during loading. Predicted levels of absorbed kinetic energy were found to be in good agreement with previously gathered experimental data, however, the model failed to accurately duplicate the damage morphology of the composite structure. Lipa and Kotelko [8] developed an FEA model examining the behavior of singular and multi-member tubular structures subjected to lateral impact by a rigid plate. Results predicted by the FE model were found to be in good agreement with previously collected experimental data, however, it was suggested additional simulation trials examining larger impact velocities be completed. A parametric study was completed by Zeng et al. [9] which examined the influence of factors such as tube radius, tube thickness, and braid angle on the levels of energy absorbed by a composite tube struck axially by a rigid plate.

The focus of this experimental study is to examine the mechanical response of aluminum foam filled stainless steel braided tubes under the previously unexplored transverse impact loading condition. The experimental findings from this study are novel as transverse impact tests of aluminum foam filled braided stainless steel tubes have yet to be completed. With the findings collected from this study, metrics such as the total energy absorption (TEA), specific energy absorption (SEA), and force efficiency (FE) have been computed. The average force is defined as the area bound by the force/displacement response and the abscissa, normalized with respect to the total measured displacement of each respective test. The FE is defined as the average measured force normalized with respect to the largest measured force. The TEA is defined as the area bound by the experimentally recorded force versus transverse displacement curve. The SEA is defined as the total energy absorbed normalized with respect to the mass of the test specimen.

2. Experimental test program

2.1. Compressive testing of aluminum foam cores

The aluminum foam cores utilized within this experimental study were constructed from stabilized aluminum foam sheets manufactured by the Cymat Aluminum Corporation (Canada) [10]. The closed cell aluminum foam boards were manufactured using a unique process known as melt gas injection. Readers are encouraged to consult Refs. 11 and 12 for a comprehensive overview of the melt gas injection process. For the purpose of this study, the aluminum foam cores were classified as either low medium or high density and classified as either group A or B for each respective density level. On average, low density foam core specimens possessed a much larger cell size compared to both medium and high density specimens. Cell size decreased and the thickness of individual cell walls increased with increasing foam density.

Compressive testing was completed on rectangular and circular aluminum foam core specimens using a Tinius Olsen compression-testing machine. Three individual foam specimens of each respective density were tested to assess the engineering stress/strain response of the interior foam cores. The testing machine was equipped with a linear voltage differential transformer (LVDT) with a functional operating range of 150 mm, which was utilized to monitor the deformation of the foam specimens during compressive loading. Forces arising during the testing process were measured through the implementation of a PCB strain gauge based load cell within the testing machine with an appropriate measurement range for each respective specimen (PCB model numbers 1204-03A (220 kN), 1204-02A (90 kN), or 1203-03A (9 kN) as required). Signals from the load cell and LVDT were measured using National Instruments 9237 and 9215 modules mounted within an NI CompactDAQ chassis. Force and displacement measurements were acquired at a rate of 2 kHz. During each test, foam specimens were oriented such that the translational direction of the testing machine crosshead was parallel to the height of the test specimen. Each test was completed at a crosshead speed of 1.04 mm/s at room temperature. Five measurements (length, width and height) for rectangular and (height and diameter) for circular specimens were taken prior to each test. An average value was computed for each critical dimension and later utilized to compute the density of each respective specimen. The identification system utilized for rectangular specimens follows the convention $\gamma\rho$-RC, where γ is either 'H' or 'L' indicating a high or low foam density (ρ), and RC indicates a rectangular core test specimen. The identification system utilized for circular cores follows the convention $\alpha\phi$-$\beta\rho$-CC, where α is either 'H' or 'L' indicating whether the specimen is high or low diameter (ϕ), β is either 'H' or 'L' indicating whether the specimen is high or low density (ρ) and CC identifies the specimen as circular core.

2.2. Transverse impact of empty braided tubes

Braided tube specimens utilized within this experimental study were constructed from American Iron and Steel Institute (AISI) 304 stainless steel wires with a standard "2 over 2 under" braid weave configuration. Cylindrical braids were created by weaving 48 braid tows around the circumference of the tube. Braid tows consisted of 8 individual wire strands each possessing a nominal diameter of 0.51 mm. The nominal external diameters of the braided tubes were 64.5 mm. Prior to testing, the tube diameter was physically measured to ensure that it met with manufacturer specifications. The mechanical properties of AISI 304 stainless steel are listed in Table 1 [13].

Transverse impact tests were completed using the frame of a custom long stroke testing machine equipped with transverse mounting fixtures as well as a custom fabricated pneumatically op-