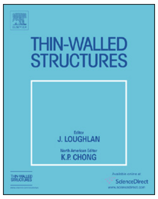
Thin-Walled Structures 94 (2015) 253–272

Contents lists available at ScienceDirect

Thin-Walled Structures

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



Theoretical, numerical, and experimental study of dynamic axial crushing of thin walled pentagon and cross-shape tubes

M. Ali*, E. Ohioma, F. Kraft, K. Alam

Department of Mechanical Engineering, 251 Stocker Center, Ohio University, Athens, OH, USA

ARTICLE INFO

Article history:
Received 26 April 2014
Received in revised form
23 March 2015
Accepted 9 April 2015
Available online 14 May 2015

Keywords:
Tube
Thin wall
Front rail
Crush
Plastic hinge
Crush force

ABSTRACT

Rectangular thin walled tubes are commonly used in front rail structures of automotive chassis, and are designed to absorb maximum amount of energy during frontal impact. With increasing emphasis over the last few decades on building lighter and faster vehicles by auto manufacturers, researchers are actively exploring opportunities to improve crashworthiness of vehicles by exploiting structural and material optimization approaches. In this paper, two new shapes, Pentagon and Cross, were studied for two materials, aluminum and steel, with the objective of improving the crashworthiness of automobiles without adding any additional weight (within the same type of material) to the chassis. The tubes were initially analyzed using finite element method. The performances of proposed tubes were compared with a rectangular cross-section tube by comparing the average mean force (required to crush the tube under 35 mph impact velocity) and the total specific energy absorbed. A theoretical plastic analysis was carried out by evaluating the folding mechanisms of tubes for Pentagon and Cross shapes and an analytical model was developed that predicted the mean force necessary to crush the tubes. The numerical and theoretical analysis showed that for equivalent tube wall areas, the aluminum and steel Pentagon and Cross tubes absorbed 31–60% and 48–92% more energy than the rectangular tube. The outputs of proposed predictive theoretical model for the Pentagon and Cross tubes were compared reasonably well with the mean force values calculated through numerical method. An experimental study was conducted on cross tube samples machined from Aluminum AA6061–T6511 blocks with the purpose of validating numerical and theoretical approaches used in the present study. Experimental results for the mean force demonstrated a good correlation with numerical and theoretical approaches with approximately 1% and 6% variation, respectively. In addition, the deformation modes observed in the experiment matches reasonably well with the ones observed in the finite element analysis (FEA) simulations.

1. Introduction

In designing chassis frames of vehicles to withstand impact in the event of an accident, the energy absorption characteristics of critical components of frames must be analyzed. The front rail in a vehicle chassis acts as the primary defense to frontal impact during vehicle collision. In the design of frontal rails, circular and rectangular cross section thin walled tubes have largely been used and their deformation behaviors under axial loading have been extensively studied by other researchers [1–7]. Hayduk and Wierzbicki [8] analyzed the crushing process of thin walled "L" shapes. In analyzing the deformation modes, they took into account both bending and extensional deformation, showing the importance of extensional deformation in energy absorption using analytical technique and experimental data. Abramowicz and Jones [3] carried out drop hammer rig tests on thin walled square steel tubes with varied cross sections and at varying lengths. They developed an appropriate theoretical analysis using a kinematically admissible method. From that analysis, 4 deformation modes were predicted for different ranges of side length to height ratio (c/h). Andrews et al. [9] carried out experimental work trying to determine axial crushing modes and energy absorbing characteristics of quasi-statically compressed aluminum circular tubes and also researched the influence of tube length. They observed the dependency of modes on tube length to diameter and tube wall thickness to diameter ratios and developed a classification band for varied tube geometric configurations and the observed deformation modes.

The elastic–plastic buckling of square tubes with emphasis on elastic–plastic stress wave propagation due to axial loading was studied by Karagiozova and Jones [10]. They observed that the plastic waves on impact were propagated at higher velocities for

---

* Corresponding author. Tel.: +1 740 593 1389.
E-mail address: alim1@ohio.edu (M. Ali).

http://dx.doi.org/10.1016/j.tws.2015.04.007
0263-8231/

List of symbols

C	side length
c	half of side length
Ψ_0	angle between adjacent sides
h	wall thickness
ω	angular velocity
E	Young's modulus
ν	Poisson's ratio
ρ	density
Δ	displacement
t	time
H	half of a fold length
s	displacements of side plates during deformation
E_1	energy dissipation along the toroid region in Mode I
E_2	energy dissipation along the horizontal hinge line in Mode I
E_3	energy dissipation along the inclined hinge in Mode I
E_4	energy dissipation in the trapezoidal region in Mode II
E_5	energy dissipation along the horizontal hinge line in Mode II
E_6	energy dissipation along the inclined stationary hinge in Mode II
Φ	coordinate of the toroid region in the circumferential direction
α	angle deforming current mode geometry
β	angle formed by Intersecting plates
γ	angle defining deformation process
$\sigma(y)$	static yield strength
N	$\sigma(y)$ h, fully yielding membrane force
M	$\sigma(y)$ h^2 $\frac{1}{4}$, fully plastic bending moment
L	axial length of tube
δ	end displacement
$\sigma(d)$	dynamic yield strength
ε'	strain rate
V	velocity
P	theoretical static mean force
$P(d)$	theoretical dynamic mean force

square tubes as compared to circular tubes. Various buckling types were developed in geometrically equivalent circular and square tube; the authors attributed that to differences in wave speeds and inertial properties of tubes. Furthermore, dynamic progressive buckling and plastic buckling were observed for the square tubes, but for the circular tubes, only dynamic progressive buckling was observed. It was concluded that lateral inertial effects had a significant effect on the crushing distance and energy absorption of square tubes. Tai et al. [11] analyzed the behavior and energy absorption of high strength thin walled steel members under compression impact loading. They carried out finite element analysis on these members in an effort to explain the effect of dynamic impact on strain rate. The models were measured for two materials, mild steel and dual phase steel (High strength steel). They found that thin walled members made of high strength steels had higher energy absorption as compared to thin walled members made of mild steel for equal cross-sectional area.

The research work on cross-sectional shapes other than conventional rectangular and round thin walled members is limited. Fan et al. [12] analyzed hexagonal, octagonal and 12 & 16 sided star cross sections. His work compared experimental data with FEA simulations. In another study, axial crushing behaviors of multi-cell tubes with triangular and kagome lattices were investigated to enhance energy absorption [13]. Yamashita et al. [14] explored the effect of number of side lengths on crushing behavior of tubes under axial compressive loading and determined that the crushing strength increases up to a polygon of six sides and saturates for higher numbers of sides. Liu studied the effects of strain hardening and strain rates on crash response of square tubes and numerically validated that mean crushing force of square tubes is independent of the impact velocity and tube length [15]. In above studies, finite element method was primarily used as one of the verifying tools. Other researchers have deployed finite element method successfully to verify preliminary theoretical results [16,17].

In order to establish the effect of cross sectional geometry on the energy absorption of thin walled structures loaded axially in compression, this paper, for the first time, theoretically and numerically analyzes two shapes, Cross and Pentagon, with potential applications in improving the crashworthiness of automobiles, locomotives, and other structures where impact mitigation is of prime interest. The study was performed on varying cross-sectional areas with fixed axial length. The finite element simulations were used to compare the performance and the deformation modes of each shape. The results showed a significant energy absorption enhancement over a typical rectangular cross-sectional member. A theoretical analysis was carried out using classical plastic models to predict the mean crushing force of these structures and the results of the analytical approach were compared with finite element outputs. Finally, a validation of the numerical and theoretical approaches was performed experimentally by conducting quasi-static compressive loading tests on aluminum cross-shaped tubes.

2. Numerical modeling details

2.1. Models

Fig. 1 shows three cross-sectional shapes of the tubes studied in present study. Fig. 1(a) shows the hollow Rectangle cross-section, Fig. 1(b) shows the hollow Pentagon shape, and Fig. 1(c) shows the hollow Cross shape. These shapes were modeled with three (cross sectional) wall areas of 774 mm^2, 929 mm^2, and 1239 mm^2 for a fixed axial length of 355.6 mm. The aforementioned wall area values are typically used in front rail designs of automobile chassis. Table 1 shows the linear and angular dimensions of each cross section for given area. Two materials, steel and aluminum commonly used in manufacturing of these members in automobile industry, were selected for the analysis with properties listed in Table 2.

The ABAQUS/EXPLICIT module was used to perform the dynamic analysis. The tubes were discretized by 4 node, reduced integration, hourglass control shell elements (S4R) with 5 integration points (through tube wall thickness). A separate convergence study was performed which revealed a global element size of 5. This size resulted in 71 elements along the axial direction of each model with a total number of elements of 3550, 4260, and 5680 for Rectangle and Pentagon, and 3408, 4260, and 5964 for Cross for wall cross-sectional areas of 774 mm^2, 929 mm^2, and 1239 mm^2, respectively. Two discrete shell square plates, A and B, of side dimension 150 mm were modeled using rigid elements. Plate B was completely fixed and plate A was allowed to move along the axial direction (Z-axis) of the tube as shown in Fig. 2. The moving rigid plate (Plate A) was assigned a mass of 1 t mimicking a weight of an average sized automobile in the United States, and it impacted the structure with a velocity of 15646.4 mm/s (35 mph) in the Z-direction (which is the speed at which vehicles crashworthiness is tested under the US