Thin-Walled Structures 97 (2015) 140–153

Contents lists available at ScienceDirect

Thin-Walled Structures

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

A novel method for enhancing energy absorption capability by thin-walled sections during the flattening process

Mahmoud Zohrabi, Abbas Niknejad*, Sima Ziaee

Mechanical Engineering Department, Yasouj University, P.O. Box: 75914-353, Yasouj, Iran

ARTICLE INFO

Article history:
Received 6 May 2015
Received in revised form
25 August 2015
Accepted 15 September 2015
Available online 26 September 2015

Keywords:
Energy absorption
Thin-walled section
Open sections
Lateral compression
Flattening process

ABSTRACT

This article introduces a novel method to enhance energy absorption capability of thin-walled sections subjected to the quasi-static lateral loading by performing the saw cutting process on simple closed sections with rectangular columns and shaping them into open sections. For this purpose, some simple closed-sectional columns with square and rectangular cross-sections of aluminum were prepared and used to produce different types of open sections with different geometries and lip lengths through the saw cutting process on a face of the columns. Different paths were selected and performed for the saw cutting to obtain six types of square open section and five types of rectangular open sections with different forms of lips. Lateral compression tests between two rigid platens were employed to obtain variations of lateral load and absorbed energy versus lateral displacement and to calculate specific absorbed energy by thin-walled open sections during the flattening process. For each type of rectangular open sections, two similar specimens were prepared and one of them was compressed along the shorter edge and the other one was tested along the longer edge of the cross-section. Also, as benchmarks, some simple specimens with closed section were compressed in the lateral direction to compare their results with energy absorption capacity by the corresponding open sections. Experimental results show that in all types of square and rectangular open-sections, lip length has significant effects on energy absorption capability by the structure; and there is an optimum value for lip length of open section and the column with optimized length of the lips has the maximum absorbed energy. Furthermore, experiments reveal that rectangular open sections which are laterally compressed along their shorter edges absorb higher energy, in compression with the corresponding loaded specimens along the longer edges. Results show that maximum absorbed energy/mass belongs to a square open section of type A with rectangular lips and it is 2.68 times of the corresponding value of the similar closed section, as a valuable result.

1. Introduction

Automobile bumper subsystem is the frontal and rear structure of the vehicle that has the purpose of energy absorption during low velocity impact. Usually, bumper subsystem consists of bumper transverse beam, stays, impact-absorbing materials in the form of structural components and a cover. Among those elements, the bumper beam is the main structural component; it is expected to be deformable enough to absorb the impact energy, in order to reduce the risks of injury for pedestrians and other vulnerable road users, but, at the same time, it should also have sufficient strength to protect the nearby vehicle components [1]. So, one of the most important parameter in design of a bumper cross-beam is its high energy absorption capability under the concentrated and distributed lateral compression loadings. For this purpose, wide researches have been performed on lateral compression behavior of thin-walled sections.

Also, when the automobile is hit from the front or behind, the bumper beam collapses and applied force is transmitted to left and right front frames through the bumper beam and bumper stays. The kinetic energy is absorbed by plastic deformation of the bumper beam and bumper stays [2]. Usually, applied load on the bumper stays are in its axial direction and on the cross-beam is in the lateral direction.

Matulewicz and Szymczak [3] analyzed a thin-walled I-beam under the combined axial compression force and torsion torque by theoretical and numerical methods. Mohri et al. [4] investigated overall stability of unrestrained thin-walled elements of open cross-sections by theoretical and numerical methods. Veljkovic and Johansson [5] shaped a special open cross-section into a closed section by adding a thin cover plate connected discretely with self-tapping screws and studied influences of this process on mechanical behavior of the structure under the axial loading. Kolakowski and Kowal-Michalska [6] studied influence of axial

* Corresponding author. Fax: +98 74 33221711.
E-mail address: Aniknejad@yu.ac.ir (A. Niknejad).

http://dx.doi.org/10.1016/j.tws.2015.09.013
0263-8231/© 2015 Elsevier Ltd. All rights reserved.

extension mode on interactive buckling of a thin-walled channel as an open section with imperfections subjected to uniform compression, when a shear lag phenomenon and distortional deformations are taken into account. Young [7] briefly described experimental and numerical investigations of some cold-formed steel columns. Their investigations included plain and lipped channels, channels with inclined simple edge stiffeners, channels with complex edge stiffeners as well as plain and lipped angles, unequal lipped angles, and built-up closed sections with intermediate stiffeners. Miranda et al. [8] investigated the role of plastic deformation of metal foams on dynamic behavior of aluminum foam-filled columns with respect to their energy absorption capabilities. The influence of cross-section shape as well as other geometrical parameters was thoroughly studied under the axial loading.

Kotelko and Mania [9] studied influences of strain rate on structural behavior of a top hat section and an open channel subjected to the axial compression. Theoretical analysis was performed using the finite element method and analytical solution based on the plastic yield-line analysis. In both cases, plastic strain rate was taken into account. Xu et al. [10] investigated axial crushing behaviors of tailor-welded blank thin-walled structures. A series of tailor-welded blank high-strength steel square tubes with different weld line locations was used to perform crushing tests for evaluating effects of different tailor-welded blank parameters, such as weld line locations and material combinations, on crushing characteristics. Feraboli et al. [11] studied influences of cross-section geometry on axial crush behavior of five different shapes of carbon/epoxy composite specimen such as open and closed sections with rounded corners. The specimens included a small and a large C-channel element, and a small and a large corner element, as well as square tube itself. Joosten et al. [12] described quasi-static crushing response of carbon/epoxy composite hat-shaped elements. A steeple-type triggering mechanism was used to ensure specimens exhibit a continuous stable crushing mode of failure. The explicit finite element software PAM-CRASH was used to predict crushing failure of these energy absorbing elements. Hou et al. [13] investigated effects of key shape and dimensional parameters on crashing behaviors of corrugated sandwich panels and optimized sandwich cores with trapezoidal and triangular configurations for crashworthiness criteria.

Loughlan [14] dealt with mechanics of interaction behavior between local and overall flexural buckling in thin-walled lipped channel column, and with effects on this behavior of column axis imperfection. Abedi et al. [15] studied absorbed energy and folding force of empty rectangular and square metal columns, and maximum axial force of empty and polyurethane foam-filled quadrangle columns, based on theoretical analysis and experiments. Yan and Young [16] performed a numerical investigation on axial compression process of fixed-ended cold-formed steel channel columns with complex stiffener. The complex stiffeners of channel open-sections consisted of simple lips with return lips. A nonlinear finite element model was developed and verified against experimental results.

Niknejad et al. [17] investigated influences of polyurethane foam-filler on mechanical behavior of filled circular tubes subjected to the lateral compression during the flattening process by quasi-static experimental method. Then, Niknejad et al. [18] represented quasi-static crushing performance of empty and polyurethane foam-filled E-glass/vinylester composite tubes with different geometrical characteristics during the lateral compression between two rigid plates. Leu [19] examined lateral compression of aluminum and clad tubes during a large deformation by an incremental elasto-plastic finite element method based on an updated Lagrangian formulation in which a sliding-sticking friction mode was especially considered. It was mainly expected to predict the buckling process and load-deflection curves for energy absorption capacity during the design stage. Baroutaji et al. [20] investigated energy absorption responses and crashworthiness optimization of thin-walled oblong tubes under quasi-static lateral loading. They experimentally compressed the oblong tubes by using three various forms of indenters named as flat plate, cylindrical and a point load indenter. Recently, Rouzegar et al. [21] studied effects of geometrical discontinuities on energy absorption characteristics of tubular structures under the quasi-static lateral loading and found a new way to enhance their energy absorption capacities.

This article represents a novel method to increase energy absorption capacity by thin-walled square and rectangular sections during the lateral compression tests between two rigid platens in the quasi-static condition. For this purpose, some simple square and rectangular columns with closed sections are prepared and by performing the saw cutting process through different paths on one face of the columns, different types of open sections with different lip forms and lengths are produced. The specimens are used in the lateral compression tests their energy absorption behaviors are compared with the corresponding closed-cell columns to suggest some new thin-walled columns with open section as suitable energy absorber parts.

2. Experiments

Some specimens with square and rectangular cross-sections are prepared and cut to desirable length. The square specimens have outer dimension of the square cross-section equal to 35 mm × 35 mm and the rectangular ones have the corresponding value equal to 35 mm × 55 mm. Wall thicknesses of the square and rectangular sections are 2.0 mm. Nominal lengths of all the samples are selected equal to 40 mm. The square and rectangular sections made from two different aluminum alloys were tested between two rigid platens in the quasi-static condition, laterally. Table 1 gives material properties of the square and rectangular sections, based on the tensile tests on dumbbell shape specimens, according to the standard ASTM E8M. The present research work investigates energy absorption behavior of open sections under the lateral loading so, some square and rectangular columns with closed cross-sections are laterally compressed; and in the other ones, some parts of the specimens are cut to produce open sections with different geometries and the prepared open sections are compressed between to rigid platens to study their plastic deformation behaviors and to compare energy absorption capacities of the closed and open sections. Totally, 188 different specimens are tested with constant loading rate equal to 10 mm/min. In each test, diagrams of lateral load–displacement and absorbed energy–displacement are sketched. Then, absorbed energy per unit of

Table 1
Material properties of square and rectangular specimens.

	Density (kg/m^3)	Elasticity modulus (GPa)	Yield stress	Ultimate stress (MPa)	Poisson ratio	Flow stress (MPa)
Square	2067.8	70	165	0.33	203.5	176.3
Rectangular	1795.1	70	71.6	0.33	108.3	85.1