ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 13 (2013) 449–464

Available online at www.sciencedirect.com

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

Original Research Article

Theoretical and experimental study on the flattening deformation of the rectangular brazen and aluminum columns

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ARTICLE INFO

Article history:
Received 29 August 2012
Accepted 21 April 2013
Available online 25 April 2013

Keywords:
Energy method
Lateral compression
Column
Energy absorption
Thin-walled structure

ABSTRACT

This paper presents a theoretical and experimental study on lateral compression of square and rectangular metal columns. Some theoretical relations are derived to predict the absorbed energy, the specific absorbed energy and the instantaneous lateral load during the lateral compression. Analytical relations are obtained in two stages: elastic and plastic parts. In the plastic zone, the total absorbed energy by the column is calculated, based on the energy method. Then, an analytical equation is derived to predict the instantaneous lateral load. In the elastic part, the instantaneous load is obtained by linear behavior assumption. To verify the theoretical formulas, some lateral compression tests were carried out on square and rectangular columns and the experimental results are compared with the theoretical predictions, which shows a good agreement. Also, based on the experiments, effects of geometrical dimensions and material properties of the columns on the energy absorption capability are investigated. The results show that the absorbed energy by a column increases proportional to the column length. Also, columns with the thicker wall have the higher specific absorbed energy and so, rectangular columns with the thicker wall are the better energy absorbers during the flattening process. Also, the absorbed energy increases when the length of the column edge along which the load is applied decreases. Also, it is found that the specific absorbed energy by the aluminum columns is higher than the brazen ones and therefore, flattened columns with the high ratio of the flow stress/density are the better energy absorbers.

1. Introduction

The function of an energy absorber is absorbing the kinetic energy and dissipating it in some other forms of energy, ideally in an irreversible manner. Non-recoverable (inelastic) energy can exist in various forms such as plastic deformation, viscous energy and friction or fracture energy. Circular or square sectioned tubes are one of the most commonly used structural

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1644-9665/$ - see front matter
http://dx.doi.org/10.1016/j.acme.2013.04.008

elements due to their prevalent occurrence and easy manufacturability. For example, circular tubes can dissipate elastic and inelastic energy through different modes of deformation. Such methods of deformation include lateral compression, lateral indentation, axial crushing, splitting and tube inversion. Energy absorption characteristics and mean crushing loads of the mentioned deformations are important in viewpoint of applications and design of the safe machines. Such practical cases may consist of energy absorbers in the aircraft, automobile and spacecraft industries, nuclear reactors, steel silos and tanks for safe transportation of solids and liquids [1]. Gupta and Khullar [2] investigated collapse load of aluminum and mild steel tubes with square and rectangular cross-sections between parallel rigid platens. They showed that when one or all of the geometric imperfections are large, the tubes collapse at loads much smaller than the buckling load. But, when their geometric shapes are nearly true, the tube collapses at the buckling load. Gupta and Abbas [3] presented a detailed experimental investigation of the quasi-static lateral crushing of composite cylindrical tubes between flat platens. The metallic tubes fail by plastic buckling; however, the GFRE tubes collapse by a combination of fracture processes. Gupta et al. [4] introduced experimental and computational investigations of deformation and energy absorption behavior of rectangular and square tubes under lateral compression. A finite element model of lateral compression of the tubes was proposed. The predictions of simulated model were compared with experiments that showed a good agreement. Zeinoddini et al. [5] described an experimental study in which axially pre-loaded tubes were examined under lateral dynamic impact loads. The experimental tests showed that pre-loading has a substantial effect on the level of damage in tubes subjected to lateral impacts. Karamanos and Eleftheriadis [6] examined the collapse of tubular members under lateral loads in the presence of pressure. In particular, it emphasizes on the effects of external pressure on the ultimate load and the energy absorption capacity. It is found that the presence of internal pressure increases both the ultimate load and the energy absorption capacity. Liu et al. [7] presented an experimental and numerical study on the dynamic behavior of ring systems subjected to pulse loading. Experiments for the stress wave propagation in ring systems were performed using a modified split Hopkinson pressure bar test system. Numerical simulations of the stress wave propagation in the ring systems were conducted by using LS-DYNA. The numerical results showed a reasonable agreement with the experimental results. Karamanos and Andreadakis [8] examined the structural response of tubular members subjected to lateral quasi-static loading, imposed by wedge shaped denting devices, in the presence of internal pressure. Based on numerical study, it was concluded that the presence of internal pressure causes a substantial increase of the denting resistance force. Morris et al. [9] numerically and experimentally investigated the quasi-static lateral compression of nested systems with vertical and inclined side constraints. Different variations of external constraints were used as a means of increasing the energy absorbing capacity of the nested systems. The numerical results showed a reasonable correlation, comparing with the corresponding experiments. Niknejad et al. [10–12] investigated the energy absorption capability of the metal columns with circular, square and rectangular cross-sections under the axial loading and then, studied the effects of polyurethane foam-filler on mechanical behavior of specimens. Then, Niknejad et al. [13] investigated the effects of polyurethane foam-filler on the lateral plastic deformation of the circular tubes under radial quasi-static loading. Experimental results showed that the polyurethane foam-filler increases the lateral load during the compression tests and this effect in thinner tubes is more than thicker specimens. Nemat-Alla [14] introduced a simple technique and based on an inverse analysis, he predicted the hoop stress–strain behavior of tubes by using lateral compression test. Also, a finite element simulation of the quasi-static lateral compression of tubes between two rigid flat platens was carried out using the estimated stress–strain curve. To confirm theoretical predictions of the stress–strain curves, some uniform compression tests were carried out under the same testing conditions. Fan et al. [15] conducted desirable experiments to investigate the lateral crushing behavior of double-walled tubes with aluminum foam-filler. Sandwich tubes with different diameter to thickness ratios were laterally compressed. To validate the numerical solutions by ABAQUS/Explicit, the corresponding experimental results were performed. Different crushing patterns were revealed and classified. Hall et al. [16] carried out some lateral compression tests on aluminum foam-filled tubes with circular cross-section. They performed the flattening tests with the different strain rates and indicated that the results are not strain-rate dependent. Abosbaia et al. [17] considered behavior of segmented woven roving laminated composite tubes subjected to quasi-static lateral loading. Experimental measurements showed that the segmented composite tubes consisting of cotton fiber/epoxy and carbon fiber/epoxy are particularly efficient crush elements. Mahdi and Hamouda [18] examined the effect of hexagonal angle, loading direction and packing system on the crushing behavior, energy absorption, failure mechanism and failure mode of composite hexagonal rings. Deruntz and Hodge [19] performed a simple rigid plastic analysis on the lateral compression of a circular tube and obtained load–deformation curve of the tubes crushed between two rigid parallel plates. They quantitatively discussed the effects of direct stress and shear on the yield condition.

The present article investigates the flattening process on metal columns with square and rectangular cross-sections subjected to lateral compression load by theoretical and experimental methods. Some theoretical relations are derived to predict the lateral force, absorbed energy and specific absorbed energy by the specimens, based on the energy method. Also, some lateral compression tests are performed on the aluminum and brazen columns with square and rectangular cross-sections to verify the theoretical formulas and to study the effects of geometrical characteristics and material types of the columns on their energy absorption capability.

2. Theory

By exerting lateral compression load on a rectangular column vertically, the lateral load applies on the lower and upper column edges. At the commencement of loading, both the left and right edges are axially compressed, in the elastic zone. Then, plastic hinge lines form at the mid-height of the vertical arms. By increasing the lateral compression, the