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Comparing Deformation Modes of Composite and Aluminum Columns with Square Cross–Section during Flattening Process

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Abstract
Square and circular sectioned tubes are one of the most commonly used structural elements due to their prevalent occurrence and easy manufacturability. For example, square 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. In this paper, a comparative experimental study on the lateral compression of square aluminum and composite columns is presented. The aluminum specimens were made of available commercial columns and composite specimens were fabricated from E-glass fibers and epoxy resin. The angles between fibers and tube axis were 30˚/-30˚. The ends of fabricated columns were cut out to ensure that the columns are free from burrs or uneven ends. The fabricated columns were cut out to the desired length. Three aluminum specimens had 35 mm side length and the other aluminum specimens had 45 mm side length. Also, all of the composite specimens had the same side length of 60 mm. The deformation modes of aluminum and composite specimens and the effects of deformation modes on their energy absorption capacities are investigated and compared. Also, the load-displacement diagrams of aluminum and composite specimens are sketched and the influences of deformation modes on the corresponding load-displacement diagrams are investigated. Meanwhile, lateral compression tests were carried on some aluminum and composite square columns with different geometries. Six aluminum specimens and five composite specimens were prepared and compressed laterally between two rigid plates in a DMG machine model 7166 and the experimental appearances of the tests are discussed.
Keywords: *flattening, composite, aluminum, column, deformation*

Introduction

Today, the use of composite materials in different kinds of applications is accelerating rapidly. Composite materials are common engineering materials which are designed and manufactured for various applications. As a part of engineering applications, composite tubes are capable of replacing metal products on many structures. High attention has been given to produce composite tubes and test them [1]. It is worth noting that tubes with square and rectangular cross-sections are frequently used as energy absorbing structural elements. Collapse behavior of these tubes under different loading conditions has been studied in the past by several authors [2]. Gupta et al. [2] presented experimental and computational investigation of the deformation mode and energy absorption behavior of rectangular and square tubes made of aluminum and mild steel under lateral compression. Load–compression and energy–compression curves obtained for tubes with different width, height and wall thickness. Also, a finite element model of lateral compression of these tubes was proposed. The results of simulated model were compared with experiments and it was shown that they were in good agreement. Gupta and Sinha [3] studied collapse behavior of square-section tubes which are made of aluminum and mild steel, placed orthogonally in two layers and sandwiched between two rigid platens, experimentally. Gupta and Khullar [4] carried out experiments to determine the collapse load of rectangular aluminum and mild steel tubes which are placed between parallel rigid platens. A two stage stability analysis of the vertical arm showed that when one or all of the geometric imperfections are large, the tubes collapse at loads much smaller than the buckling load of intact specimens and exhibit large bending deformations. Abosbaia et al. [5] investigated the effects of segmentation on the crushing behavior of quasi-static laterally compressed composite tubes. The load–deformation curves and failure mechanism histories of typical specimens were presented and discussed. Calme et al. [6] presented an analytical model for elastic stress state inside RTM-moulded braided composite cylinders under lateral compression. Taking into account the radial stresses, their modeling was based on the Fourier series development of the p-periodic symmetric loading derived from the Hertzian contact law. The experimental part described the quasi-static delamination under lateral compression of RTM-moulded carbon–epoxy rings fabricated from braided two-dimensional (2D) tubular preforms and DGEBA-IPD resin. The theoretical part showed that a mesoscopic computation of transverse shear stresses was needed in order to explain the locations of the brittle failures. Mahdi and EL Kadi [7] investigated the implementation of artificial neural networks (ANN) technique in the prediction of crushing behavior and energy absorption characteristics of laterally loaded glass fiber/epoxy composite elliptical tubes. The predicted results compared with actual experimental data in terms of load carrying capacity and energy absorption capability showing good agreement. Niknejad et al. [8] studied lateral compression of square and rectangular metal columns.

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Some theoretical relations were presented to predict the absorbed energy, the specific absorbed energy and the instantaneous lateral load during the lateral compression. Comparison of the theoretical predictions and experimental results showed a good correlation between the analytical and experimental results. Rouzegar et al. [9] investigated experimentally quasi-static lateral crushing of different tubular structures with geometric discontinuities. They focused on the effects of discontinuities in energy absorption parameters of tubular structures to find the best positions for discontinuities on the walls of energy absorbers and reduce their negative effects and even find ways to improve the capability of notched specimens.

The main objective of the present study is to compare deformation modes of aluminum and composite columns with square cross–sections during the flattening process. Also, the influence of deformation mode on the energy absorption capacities is investigated.

Experiment

Six aluminum specimens and five composite specimens with square cross-sections were compressed laterally between two rigid plates in a DMG machine model 7166. The tests were carried out in quasi–static condition with loading rate of 10 mm/min. The side lengths of three aluminum specimens were 35 mm with different column lengths and the other three aluminum specimens had 45 mm side length with different column lengths. All composite specimens were fabricated from E-glass fibers weaved at a 30/-30 configuration. The ends of fabricated columns were cut out to ensure that the columns are free from burrs or uneven ends. The fabricated columns were cut out to the desired length. All of the composite specimens had the same side length of 60 mm and different column lengths. Table 1 and 2 show the geometrical characteristics of aluminum and composite tubes with square cross-sections, respectively. Also, Table 2 shows the fiber fabric layers, resin type and fiber type of composite specimens.

In these tables a, b, t and L indicate outer height of cross–section, outer width of cross–section, wall thickness and length of the specimens, respectively.

Table 1. Geometrical characteristics of aluminum tubes with square cross-sections

Specimen NO.	*a* (mm)	*b* (mm)	*L* (mm)	*t* (mm)
AS-01	35	35	20	1.9
AS-02	35	35	35	1.9
AS-03	35	35	70	1.9
AS-04	45	45	20	1.8
AS-05	45	45	45	1.8
AS-06	45	45	90	1.8

Table 2. Geometrical characteristics of composite tubes with square cross-sections

Specimen No.	*a* (mm)	*b* (mm)	*L* (mm)	Fiber fabric layers	Resin type	Fiber type
CS-01	60	60	25	3	Vinylester	Granule
CS-02	60	60	50	3	Vinylester	Granule
CS-03	60	60	75	3	Vinylester	Granule
CS-04	60	60	50	4	Vinylester	Granule
CS-05	60	60	50	5	Vinylester	Granule

Results and Discussion

Based on the experimental results, deformation modes of composite and aluminum columns with square cross–section during flattening process are studied and their difference and influence on the load–displacement diagram are investigated.

Deformation mode of aluminum columns

By exerting lateral compression load on an aluminum square column, the lateral load is applied on the lower and upper edges of column. At commence of loading, each vertical edge is axially compressed and the buckling is started like a pin–ended column. Then, plastic hinge lines form at the mid–height of the vertical arms. By increasing the lateral compression, the vertical edges deform outwards while the horizontal edges bend inwards. Simultaneously, four hinge lines form at the four corners of the column cross–section. Finally, the column changes to a double layers plate. Figure 1 shows a schematic view of deformation mode of an aluminum column with square cross-section during the lateral compression test that is called flattening process.

Deformation mode of composite columns

By subjecting the lateral force on a composite column, at first each vertical edge starts buckling outward like two pin–ended columns and then, one hinge line forms at mid–height of one of the vertical edges. After that, a hinge line forms approximately at the top or bottom corner of the other vertical edge and four hinge lines form at the corners. By increasing the lateral compression, the column moves toward the vertical edge that its hinge line formed at the mid–height. It is seen that in the flattening process of aluminum columns, horizontal edges tend to bend inward but in the flattening process of composite column, horizontal edges remain straight. Figure 2 shows a schematic view of deformation mode of a composite column with square cross-section during the lateral compression test.

Comparison of deformation modes and energy absorption

By subjecting lateral load on an aluminum or composite specimen, at first each vertical edge starts buckling outward like two pin–ended columns in both of them. After that, by increasing the compression load two hinge lines form at the mid–height of aluminum column but in the composite column at first one hinge line form at the mid–height of one of the vertical edges and then the next hinge line form approximately at the top or bottom corner of the other vertical edge.

In the aluminum columns, horizontal edges bend inward. So, by increasing the load two bent horizontal edges reach to each other and they start to bend outward. Figure 3 shows load–displacement diagram of specimen AS-06. According to this figure, by self-contacting the two horizontal edges to each other and also contacting the vertical edge to the bottom rigid plate, the sustained load increased suddenly. The configuration of specimen at this moment can be seen in Figure 3. As seen in this figure, load-displacement diagram of aluminum column is regular. This diagram has one pick point related to the forming two hinge lines at the mid–height of vertical edges and then the sustain load significantly reduces.

However, in the case of composite column, horizontal edges remain straight. Figure 4 shows load–displacement diagram of specimen CS-05. In this figure first pick point of load is related to forming the first hinge line at the mid–height of left vertical edge and the second pick point is related to the forming second hinge line at the bottom of right vertical edge. Afterward, the sustained load decreases suddenly and then the curve shows some disturbances because of contacting the vertical edges to the rigid plates at different displacements.

Comparing load–displacement diagrams of aluminum and composite column shows that this diagram for aluminum column has fewer disturbances. Also, comparing the first part of the related diagrams (before forming the first hinge line) shows that this part for composite column has softer slope. This results show a higher area under the load–displacement curve for the composite specimen in comparison to the aluminum one. Also, in aluminum column hinge lines in vertical edges are formed simultaneously but in composite columns hinge lines in the vertical edges are formed separately. Identically, this leads to higher area under the load–displacement diagram of composite specimen. So, it can be concluded that composite columns are better energy absorbers than aluminum columns. Figure 5(a) and (b) show deformation modes of specimen AS-01 and CS-03, respectively. According to this figure, aluminum column under flattening process deformed symmetrically but composite column has not deformed symmetrically.

Conclusions

In this paper, deformation modes of aluminum and composite columns with square cross–sections during the lateral compression tests are discussed. Investigations show that when an aluminum column is subjected to lateral compression, two hinge lines form at the mid–height of vertical edges and four hinge lines form at the corners. Friction between plates and the specimen causes tension in the horizontal edges when the load begins to act at the corners. So, the horizontal edges bend inward. Also, it is seen that aluminum columns under flattening process deform symmetrically. In the case of composite columns, when these columns are subjected to lateral compression, one hinge line forms at mid–height of one of the vertical edges. Then, the second hinge line forms approximately at the top or bottom corner of the other vertical edge. Investigation of the load-displacement diagrams of aluminum and composite columns reveals that this diagram for aluminum column has fewer disturbances. Also, comparing the first part of the diagrams (before forming the first hinge line) demonstrates that this part for composite column has a softer slope. Furthermore, in aluminum columns, hinge lines of vertical edges form simultaneously but in composite columns hinge lines of vertical edges form separately. Hence, load-displacement diagram of composite tube has more area under the curve and it can be concluded that composite columns are better energy absorbers in comparison with aluminum columns.

Figures and Drawings

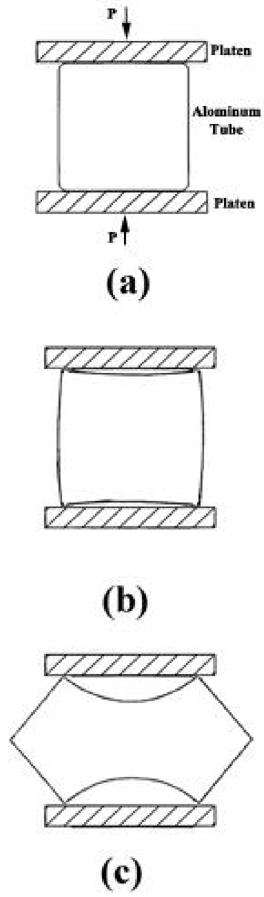

Figure 1: A schematic view of deformation modes of aluminum columns during the flattening process

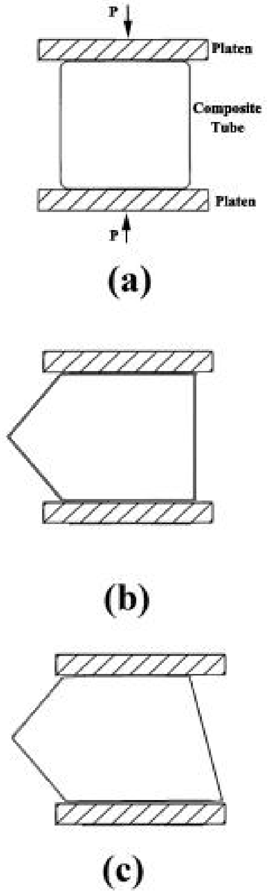

Figure 2: A schematic view of deformation modes of composite columns during the flattening process

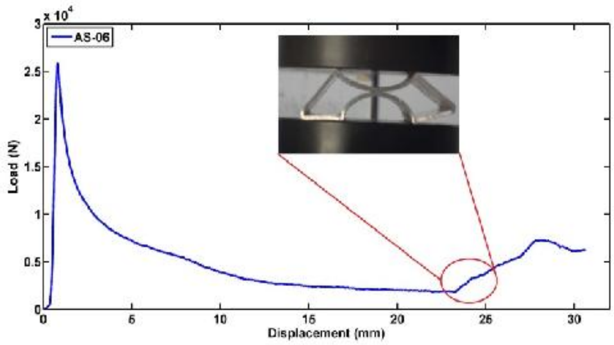

Figure 3: Load-Displacement diagram of specimen AS-06

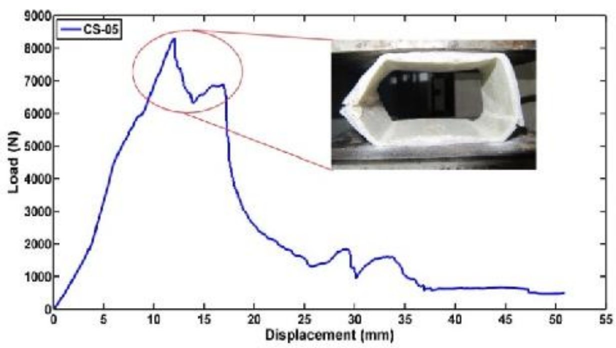

Figure 4: Load-Displacement diagram of specimen CS-05

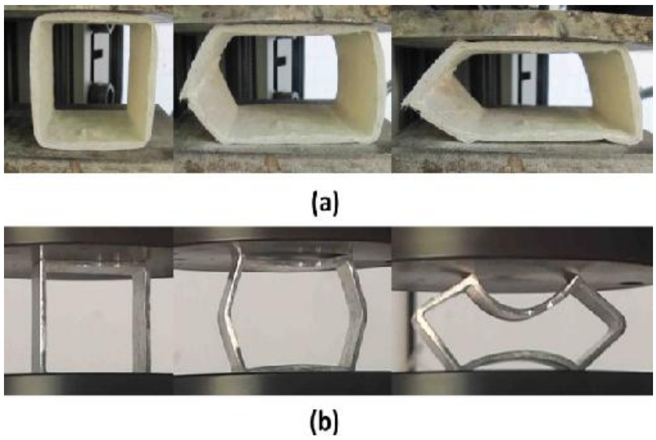

Figure 5: Specimens AS-01 and CS-03 during flattening process

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