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Quasi-cup specimens as a new energy absorber part under the quasi-static axial loading

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Abstract
Some thin-walled structures such as frusta, dome, egg-box and cones are widely used in the aerospace applications. This article represents a novel energy absorber with quasi-cup geometry under the quasi-static axial compression loading between two rigid platens by the experimental method. For this propose, some quasi-cup specimens, that have been produced by shaping the circular blanks with Teflon-pad forming, were used in the in the axial compression tests. The quasi-cup specimens were prepared with different apex angles, thickness and material properties to investigate influences of the mentioned parameters on the energy absorption process. Diagrams of axial load-displacement and absorbed energy-displacement of each sample are sketched and its specific absorbed energy is obtained by calculating the ratio of total absorbed energy per mass of the structure. The experimental results show that when a quasi-cup specimen is filled by the polyurethane foam with density of 50 kg/m^3 and plateau stress of 0.26 MPa, specific absorbed energy by the specimens increases. Also, the tests demonstrate that by enhancing the apex angle of the quasi-cup specimens, ultimate displacement reduces and axial load enhances. Experiments indicate that there is an optimum value for apex angle and a quasi-cup specimen with the optimum apex angle has the highest specific absorbed energy, in comparison with the other ones. Furthermore, experimental measurements show that when thickness of the quasi-cup specimens increases, specific absorbed energy by the samples increases, too. Totally, the current research work introduces a quasi-cup specimen with apex angle of 90^o in thick-walled condition and with the polyurethane foam-filler as a suitable energy absorber structure.

Keywords: *Quasi cup specimen- Axial compression- Energy absorption- Experiment- Thin walled sample.*

Introduction

In aerospace industries, ratio of strength to weight is one the main parameters in design and manufacturing of different parts and structures. Furthermore, external impact loadings are applied on some parts of aerospace structures. Therefore, most of designed structures with aerospace applications should have high ratios of strength/mass and absorbed energy/mass. However, some materials have higher energy absorption capacity during the creation of plastic deformations under the impact loading, respect to the corresponding quasi-static loadings. Thus, investigation of mechanical behavior of thin-walled structures and their energy absorption processes under different loadings in the quasi-static conditions is valuable, in viewpoint of aerospace applications.

Hosseinipour and Daneshi [1] studied crashworthiness characteristics of thin-walled steel tubes with annular grooves. They performed quasi-static axial crushing tests and calculated some theoretical formulations for predicting energy absorption and mean crushing load. Tai et al. [2] used non-linear finite element software LS-DYNA to analyze axial compression behavior and energy absorption of a high-strength thin-walled member under an impact load. Tarigopula et al. [3] performed quasi-static and dynamic axial crushing tests on thin-walled square tubes and spot-welded top-hat sections made of high-strength steel grade DP800. Typical collapse modes of the sections and associated energy absorbing characteristics were examined. Hossain [4] described experimental and analytical investigations on behavior of thin-walled composite filled columns under axial compression. He presented details of the experimental investigation included description of test columns, testing arrangement, failure modes, strain characteristics, load-deformation responses and effects of various geometric and material parameters.

Lee et al. [5] presented an experimental investigation to study energy absorption characteristics of thin-walled square tubes subjected to quasi-static axial loading to develop optimum structural members. Ye et al. [6] investigated effects of partially foam-filled core on buckling behavior of a thin-walled cylindrical shell. Zhang and Yu [7] investigated effects of internal pressure on energy absorption of thin-walled structures and studied axial crushing of pressurized thin-walled circular tubes. In experiments, three groups of circular tubes with different radius/thickness ratios were axially compressed under different pressurizing conditions.

Gupta [8] investigated experimental and computational analyses of deformation behavior of thin-walled aluminum frusta subjected to axial compression between two parallel platens. The specimens were tested to identify their modes of collapse and to study associated energy absorption capacity. Aljawi et al. [9] performed an experimental investigation on the quasi-static axial inward inversion of right circular frusta. Effects of wall thickness, frustum angle and material on the inversion process were studied by quasi-static as well as drop hammer

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dynamic tests. Also, Finite element modeling and analysis of deformation modes were presented. Alghamdi [10] studied plastic deformation of aluminum frusta, experimentally. Effects of changing the angle of frustum as well as frustum wall thickness on absorbed energy were investigated. They gave details of experimental plastic inversion and reinversion. Ahmad et al. [11] investigated crush behavior and energy absorption response of foam-filled conical tubes subjected to oblique impact loading. Dynamic computer simulation techniques validated by experimental testing was used to carry out a parametric study of such devices.

Ahmad and Thambiratnam [12] studied dynamic response and energy absorption by aluminum foam-filled conical tubes under axial impact loading, using non-linear finite element techniques. Influences of geometrical, material and loading parameters on the impact response were investigated to compare validated numerical models. Alghamdi et al. [13] classified deformation modes of unconstrained capped end frusta when crushed axially between two parallel plates. Akisanya and Fleck [14] presented quasi-static plastic collapse of thin-walled frusta to determine shear and out-of-plane compression. Experiments and finite element calculations were conducted on conical metallic frusta to determine shear collapse response. Additional finite element predictions were given for compressive loading, and for combined shear-compressive loading. Niknejad and Tavassolimanesh [15] studied inversion process of capped-end frusta under the axial loading between a solid cylindrical punch and a rigid platen. They presented a theoretical analysis to estimate axial inversion load of the capped-end frusta versus axial displacement and verified the theoretical results with the corresponding experiments.

This paper studies energy absorption process on a metal part with geometrical shape of quasi-cup made of three kinds of galvanized iron by experimental method. The prepared specimens are compressed in the axial direction between two rigid platens during the quasi-static compressive loading. Also, effects of galvanized iron type and apex angle of conical part of the quasi-cups and influences of polyurethane foam-filler are studied on energy absorption capacity by the specimens.

Experiment

Nowadays, many researches are conducted on energy absorption capability of sheet metals to achieve pleasant results for decreasing the influences of unavoidable impacts and accidents. For this purpose, some galvanized metal parts with geometrical shape of quasi-cups were prepared to investigate their energy absorption behavior, experimentally. Figure 1a and b illustrates a quasi-cup specimen and a schematic specimen with its geometrical dimensions, respectively. In the figure, α and H are apex angle and height of the quasi-cup specimens and D_1, D_2 and D_3 show diameter of the specimens in different parts. R_1 and R_2 indicate curvature radius of the specimens in two different zones as shown in Figure 1. Thickness of the specimens is defined by t. All the quasi-cup specimens have been produced by shaping process of circular galvanized iron blanks with the same initial diameter of 50 mm into the quasi-cup samples during the Teflon-pad forming, using a punch and matrix system. The specimens were prepared with different thicknesses, galvanized iron types and apex angles. Then, the quasi-cup specimens were axially compressed between two rigid platens under the quasi-static compressive loading. Some specimens were compressed in empty conditions and the other ones were filled by polyurethane foam with density of 50 kg/m^3 and plateau stress of 0.26 MPa to study influences of the filler on energy absorption capability by the specimens. Axial load-displacement and absorbed energy-displacement of all the tests are sketched and ratio of absorbed energy per mass that called specific absorbed energy is calculated. Figure 2 illustrates an empty and a filled specimen before and after the energy absorption process. Loading rate was selected equal to 5 mm/min, in all the tests. Table 1 represents characteristics of the quasi-cups samples. Identified code of each specimen consists of four parts. For example, specimen code G035-E01 shows that the specimen has been produced by a galvanized iron sheet with thickness of 0.35 mm (G035) and it has been tested in the empty condition (E). Also, 01 determines apex angle of the specimen, according to Table 1. In specimen code, filled condition is specified by F. The initial blanks were prepared from thin plates of galvanized iron with three different types of G035, G060 and G070. The mentioned sheets have different thicknesses of 0.35, 0.60 and 0.70 mm, respectively. Table 2 gives material properties of three types of galvanized iron.

Results and discussion

The present work introduces the quasi-cup specimens as new energy absorber parts subjected to the axial loading. By producing the quasi-cup specimens with Teflon-pad forming and compressing them under the axial loading, effects of galvanized iron types, thickness and apex angle of the specimens and polyurethane foam-filler are studied on values of absorbed energy by the structures.

Effects of polyurethane foam-filler

Nine pairs of quasi-cup specimens were prepared and in each pair, one of them was axially compressed in the empty condition and the other one was filled by the polyurethane foam and then compressed between two rigid platens to investigate influences of the filler on energy absorption behavior of the structures. Figure 3 compares axial load-displacement curves of the specimens G060-E03 and G060-F03 during the axial compression tests. The specimen G-060-E03 is empty and the sample G060-F03 is foam-filled. Both of the mentioned specimens have the same apex angle of 60°. The figure shows that by filling the quasi-cup specimen with the polyurethane foam, required load for compressing the specimen increases. As a numeric comparison, the experiments show that in the same axial displacement of 4 mm, axial compression loads of the mentioned empty end filled specimens are 720 and 1820 N, respectively. It means that in the same displacement of 4 mm, axial compression load of the filled sample is 2.53 times of the corresponding empty one. Absorbed energies by the specimens are obtained by calculating the area under the load-displacement curve. Experimental diagrams of absorbed energy-displacement of the mentioned specimens are sketched in Figure 4. The figure shows that total absorbed energies by the filled quasi-cup specimen G060-F03 and the corresponding empty sample G060-E03 are 26.88 and 16.61 J, respectively. The performed comparison indicates that when the quasi-cup specimen with apex angle 60º is filled by the polyurethane foam with density of 50 kg/m^3, energy absorption capacity of the specimen enhances up to 61.8%, respect to the empty sample. Furthermore, experimental results show that specific absorbed energies by the filled specimen G060-F03 is 2575 J/kg and it is 1.38 times of the corresponding value of the empty one. It means that when a quasi-cup specimen with apex angle of 60º is filled by the polyurethane foam, a new energy dissipater part is achieved and its energy absorption capability and specific absorbed energy increase respectively equal to 61.8% and 37.9%, respect to the empty one. The same results are considered in the other pairs of the empty and filled samples.

Effects of galvanized iron types

For investigating the influences of material type on the energy absorption process, three groups of quasi-cup specimens were prepared and tested. In each group, there are three specimens with different material types and thicknesses and with the same other characteristics were axially compressed between two rigid platens. Figure 5 compares axial load-displacement diagrams of the specimens G035-E01, G060-E01 and G070-E01 with the same apex angle of 120º during the compression tests. The figure shows that axial load of the quasi-cup specimens increases, when thickness and flow stress of the initial blanks of the specimens enhance. For better comparison, Figure 6 demonstrates diagrams of absorbed energy/flow stress versus axial displacement of the mentioned specimens during the axial compression tests. The figure illustrates that ratio of absorbed energy per flow stress of the specimen G070-E01 with thickness of 0.70 mm is the highest and the corresponding value of the specimen G035-E01 with thickness of 0.35 mm is the least. It means that when thickness of the quasi-cup specimens increases, their energy absorption capacities increase, too. As a numeric study, the results demonstrate that total absorbed energy/flow stress of the specimens G070-E01, G060-E01 and G035-E01 are 47.7, 44.3 and 17.8 J/kPa, respectively. It means that in the introduced quasi-cup specimens, thicker specimens are better energy absorber samples. Furthermore, the performed experiments show that specific absorbed energies by the quasi-cup specimens G070-E01, G060-E01 and G035-E01 are respectively equal to 1807.8, 1625 and 1256.3 J/kg. On the other hand, by increasing the specimen thickness, specific absorbed energy increases, too. The similar trends are considered in the other groups of the specimens.

Effects of apex angle

Three different groups of the quasi-cup specimens with the same material types and thickness were prepared and tested to investigate effects of apex angle of the energy absorption process. Three different specimens with different apex angles of 120, 90 and 60º were prepared in each group. Figure 7 illustrates load-displacement curves and Figure 8 compares experimental curves of absorbed energy/mass versus axial displacement of the specimens G060-E01, G060-E02 and G060-E03, respectively with different apex angles of 120, 90 and 60º during the tests. Figure 7 shows that, when apex angle of the quasi-cup specimens enhances, axial load increases and ultimate displacement reduces. Figure 8 demonstrates that specific absorbed energies by the mentioned specimens are 2300.7, 2659.3 and 1866 J/kg, respectively. It means that ration of absorbed energy per mass by the specimen G060-E02 with apex angle of 90º is higher than two other samples with apex angles of 120 and 60º. On the other hand, there is an optimum value for apex angle of quasi-cup specimens and a sample with the optimum apex angle has the highest specific absorbed energy.

Totally, the present research work introduces a quasi-cup specimen with apex angle of 90º and wall thickness of 0.70 mm in the polyurethane foam-filled condition as a suitable structure, in viewpoint of energy absorption.

Conclusion

This article introduces a novel energy absorber structure with the quasi-cup geometry subjected to the quasi-static axial compression loading between two rigid platens. For this purpose, some circular blanks with initial diameter of 50 mm form galvanized iron were prepared and shaped into the quasi-cup specimens with different geometries. Some of the specimens were axially compressed in the empty condition and the other ones were filled by the polyurethane foam and then compressed. Experimental results show that by filling the quasi-cup specimens with the polyurethane foam and by enhancing the blank thickness, specific absorb energy by the structure increases. Also, there is an optimum apex angle for the introduced specimens and an optimized quasi-cup specimen has the highest ratio of absorbed energy per mass. Therefore, this research suggests a quasi-cup specimen with apex angle of 90o, thicker wall and polyurethane foam-filler as a good energy absorber structure in the aerospace applications.

Tables

Table 1: The geometrical characteristics of the quasi-cups samples

Sample code	*t* (mm)	D_1 (mm)	D_2 (mm)	D_3 (mm)	R_1 (mm)	R_2 (mm)	H (mm)	Apex angle of conical part	Loading Type
G035-E01	0.35	14.1	30	48	8.1	4.6	4.95	120	Empty
G035-E02	0.35	14.2	30	45	8.1	5.7	7.44	90	Empty
G035-E03	0.35	14.1	30	42	8.1	8.0	10.79	60	Empty
G060-E01	0.60	14.1	30	48	8.1	4.6	5.67	120	Empty
G060-E02	0.60	14.2	30	45	8.1	5.7	8.20	90	Empty
G060-E03	0.60	14.1	30	42	8.1	8.0	10.99	60	Empty
G070-E01	0.70	14.1	30	48	8.1	4.6	5.50	120	Empty
G070-E02	0.70	14.2	30	45	8.1	5.7	8.17	90	Empty
G070-E03	0.70	14.1	30	42	8.1	8.0	9.81	60	Empty
G035-F01	0.35	14.1	30	48	8.1	4.6	4.95	120	Foam-filled
G035-F02	0.35	14.2	30	45	8.1	5.7	7.44	90	Foam-filled
G035-F03	0.35	14.1	30	42	8.1	8.0	10.79	60	Foam-filled
G060-F01	0.60	14.1	30	48	8.1	4.6	5.67	120	Foam-filled
G060-F02	0.60	14.2	30	45	8.1	5.7	8.20	90	Foam-filled
G060-F03	0.60	14.1	30	42	8.1	8.0	10.99	60	Foam-filled
G070-F01	0.70	14.1	30	48	8.1	4.6	5.50	120	Foam-filled
G070-F02	0.70	14.2	30	45	8.1	5.7	8.17	90	Foam-filled
G070-F03	0.70	14.1	30	42	8.1	8.0	9.81	60	Foam-filled

Table 2: Material properties of three types of galvanized iron

Blank code	Yield stress (MPa)	Ultimate stress (MPa)	Strain hardening exponent	Flow stress (MPa)
G035	400	505.7998	0.3921	381.227
G060	325	425.2036	0.2972	326.390
G070	450	604.0838	0.5256	422.118

Figures and Drawings

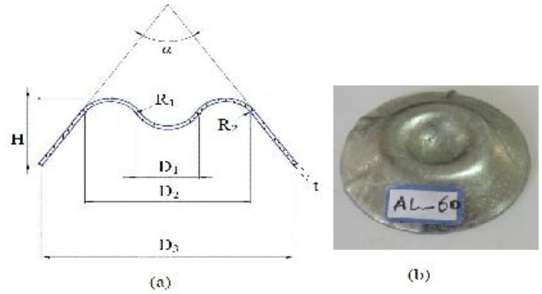

Fig. 1: a) A schematic specimen with its geometrical dimensions, b) A quasi-cup specimen.

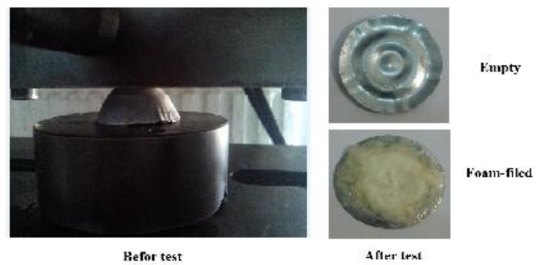

Fig. 2: An empty and a filled specimen before and after the energy absorption process.

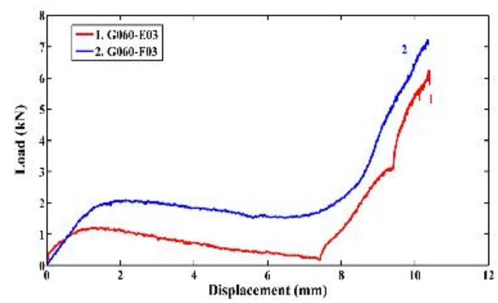

Fig. 3: Axial load-displacement curves of the empty and foam-filled specimens G060-E03 and G060-F03.

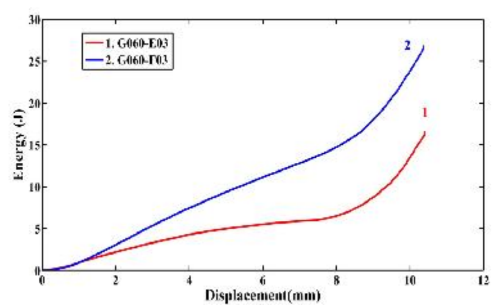

Fig. 4: Experimental diagrams of the total absorbed energy-displacement of the empty and foam-filled specimens G060-E03 and G060-F03.

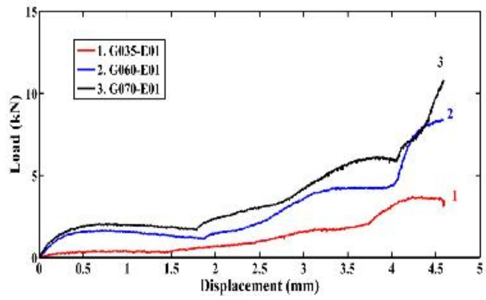

Fig. 5: Axial load-displacement diagrams of the specimens G035-E01, G060-E01 and G070-E01 with the same apex angle of 120º with different galvanized iron types.

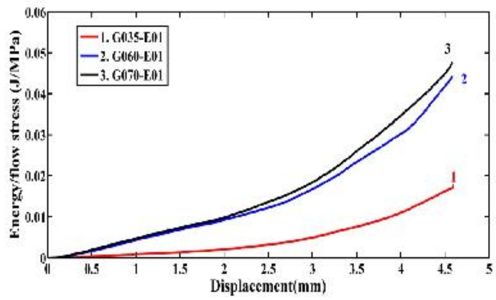

Fig. 6: Diagrams of absorbed energy/flow stress versus axial displacement of the specimens G035-E01, G060-E01 and G070-E01during the axial compression tests.

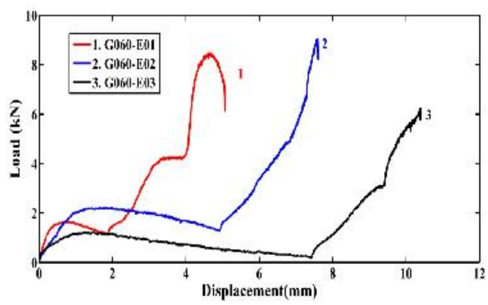

Fig. 7: Load-displacement curves versus axial displacement of the specimens G060-E01, G060-E02 and G060-E03, respectively with different apex angles of 120, 90 and 60º during the tests.

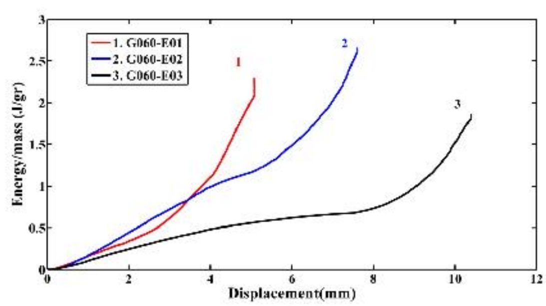

Fig. 8: Experimental curves of absorbed energy/mass versus axial displacement of the specimens G060-E01, G060-E02 and G060-E03, respectively with different apex angles of 120, 90 and 60º during the tests.

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