Crashing analysis of end-capped thin-walled steel conical frusta containing cutouts

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Abstract: - Shells have exhibited significant advantages in energy absorption. We examine the crashworthiness of the end-capped thin-walled stainless steel conical frusta under axial load and evaluate the effect of cutouts on crashing behavior and energy absorption capacity of these structures. Experimental tests are done by INSTRON 8802 servo hydraulic testing machine. Numerical studies are carried out by simulation via the ABAQUS software. Several changes in shape, size, location and angle of cutouts are investigated to determine the influence of the cutouts on the crash behavior and energy absorption capacity. In addition, Effects of changing height of shells on crashworthiness are studied.

Key-Words: end-capped thin-walled conical frusta, energy absorption capacity, crashworthiness, cutout, Experimental method, Numerical analysis.

1 Introduction

The crashing behavior of conical and cylindrical shells of circular, elliptical and square cross-sections has been considered in recently, because of their possible application in the design of vehicles. These absorbers can be easily used in vehicles due to their light weight and simple geometry. For example, the crash box of an automotive body in white (BIW) is often made of thin-walled tubes which can absorb the kinetic energy of the vehicle during an impact [1]. Conical tubes are useful in impact and energy absorption due to their favorable response and energy absorption capacity [2]. A tapered thin-walled tube is preferable to a cylindrical tube because it has a stable load deflection response and minimizes the possibility of collapse by buckling in the Euler mode as found in previous studies [3].

Lots of research has been done to investigate the crushing behavior of thin-walled tubes through experimental, analytical, and numerical methods. A number of these studies have been performed on tubes with polygonal cross sections (e.g. rectangular, square, etc.) [4] and circular [5] cross-sections, while some researchers have tried to improve the energy absorption of thin-walled tubes by filling them with various materials such as polymer and metal foam [3, 6, 7, 8].

Gupta and Abbas developed a mathematical model for the axisymmetric axial crushing of thin conical shells [9]. Easwara Prasad and Gupta [10] experimentally studied the behaviour of conical shells of large semiapical angles at various strain rates. Gupta et al. [11] also performed experiments on aluminum conical frusta with semi-apical angles range of 16–29◦ and thicknesses between 0.7 and 1.62mm under axial compression.

Numerical and experimental investigations were performed to optimize the thin-walled tapered cone for use as an energy absorber by mohamed Sheriff et al. [12]. They considered geometrical parameters, such as height, bottom diameter and semi-apical angle to obtain the design space in their research.

Zhang et al. [13, 14] studied the effect of buckling initiators on the initial peak load of axially loaded thin-walled tubes. AlaviNia et al. [15] studied the effect of cracks on energy absorption characteristics of cylindrical and square tubes. Ghamarian and Tahaye Abadi [16] investigated the response of end-capped circular tubes under axial compression and determined the effects of end cap on the crushing load, crushing mechanism and capacity of energy absorption.

Fan et al. [17] performed numerical and experimental studies on thin-walled tubes with different cross-sectional shapes under Quasi-static axial compression. Qi et al. [1] investigated crashing behavior of axisymmetric thin-walled square tubes with two types of geometries (tapered and straight) and two kinds of cross-sections (multi-cell and single-cell) as energy absorbing components under oblique impact loading. Uzun [18] considered the compressive crush behaviour of spheres of closed-cell aluminum foams with different diameters and square tubes filled with these spheres. Rahi [19] studied the energy absorption capacity of thin-walled end-capped conical geometries and the collapse of the absorbers under different loading types. Patel et al. [20] presented the computational analysis of the crushing response of AA-1080 cap and open end hybrid frusta tube, with and without circular cut-outs subjected to the quasi-static axial loading. Kaczynski et al [21] studied the behavior and energy absorption of both dynamic and quasi-static axial crushing of foam filled thin-walled cylindrical tubes.

This paper investigates crash behavior and energy absorption capacity of the end-capped thin-walled stainless steel conical frusta during the axial compression, which are perfect or include cutouts. The specimens were produced by the spinning process. The effects of cutouts and changing shell's height on the crushing behavior of the end-capped thin-walled stainless steel conical frusta under compressive quasi-static load are investigated using experimental and numerical methods. Axial compression of specimens is done by compressing each specimen between two rigid plates. The numerical analysis is done using ABAQUS. Non-linear properties of material, geometry and contact are considered in the simulation. The load–deformation curves are obtained from the numerical analysis and compared with the quasi-static tests results.

The numerical and experimental results are used to determine energy absorption capacity due to the existence of cutouts. The performance of perfect shell is compared with perforated and slotted shells and It results that initial peak load can be controlled and better crash protection devices can be achieved using end-capped thin-walled conical frusta.

2 Geometry and Mechanical properties of the Shells

Axial compression experiments were conducted on steel truncated conical shells of semi-apical angle of 6.9°, bottom diameter of 68mm, height varying from 70mm to 150mm and 0.9mm thickness. Circular and notch shape cutouts were considered in this study. The geometry of the tested specimens is shown in Fig. 1.

In this study, conical shells were made of AISI Type 304 Stainless Steel. The engineering stress–strain curve of this steel was obtained using tensile test. Tensile tests were performed according to ASTM E8 standard through an INSTRON 8802 servo hydraulic testing machine at a controlled displacement rate of 5 mm/min. Mechanical properties obtained from tensile test, used in the FE simulations.

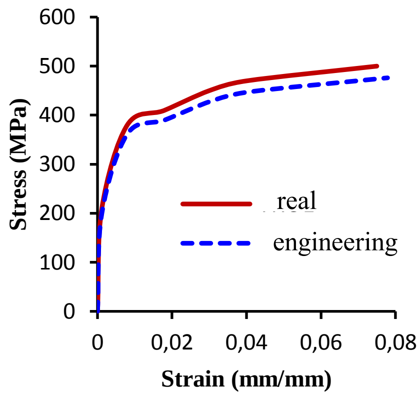
The stress-strain curves for the 304 Stainless steel are illustrated in Fig. 2. The Young's modulus is equal to the slope of the linear part of the stress-strain curve, therefore E=190GPa is obtained, which is accordant with reported value for this steel alloy. Furthermore, the value of Poisson ratio was assumed υ =0.3.

(a) Specimens include circular cutouts

(b) slotted specimens

Fig. 1 specimens before test

(a) Experimental test set-up with INSTRON 8802



(b) Engineering and real stress–strain curves

Fig. 2 Tensile Test Experiment

3 Specimens'specifications

Specimens' specifications and code of each specimen are presented in Tables 1 and 2. Table 1 presents the characteristic dimensions of perfect specimens and specimens with circular cutouts. Table 2 shows the characteristic dimensions of slotted specimens. Cutouts lengths for all of these specimens were considered 20 mm and cutouts were placed in mid-height of shells. Specimen code shows the shell's height, cutout number, cutout size and cutout position. Also, slotted specimens' codes are including angle of cutout. For example, H70-2d15-5 refers to the 70 mm height specimen with two opposite 15 mm diameter circular cutouts at mid-height of shell.

Table 1 Specimens' specifications and code of specimens with circular cutouts

Specimen code	Height (mm)	Number of cutout	Cutout diameter (mm)	Cutout position from shell base
H70	70	no cutout	------	-----
H100	100	no cutout	------	------
H150	150	no cutout	------	------
H70-d15-5	70	1	15	0.5 H
H70-2d15-5	70	2	15	0.5 H
H100-d15-5	100	1	15	0.5 H
H100-2d15-5	100	2	15	0.5 H
H100-2d20-3	100	2	20	0.3 H
H100-2d20-5	100	2	20	0.5 H
H100-2d20-75	100	2	20	0.75 H

Table 2 Specimens' specifications and code of slotted specimens

Specimen code	Height (mm)	Number of cutout	Cutout width (mm)	Angle of notch respect to central axis (deg)
H70-2-w1-A0	70	2	1	0
H70-2-w2-A0	70	2	2	0
H70-2-w3-A0	70	2	3	0
H70-2-w1-A45	70	2	1	45
H70-2-w1-A90	70	2	1	90

4 Experiments

The compression tests were performed using an INSTRON 8802 servo hydraulic testing machine under quasi-static loading (Fig. 3). A total of 15 specimens have been tested. The quasi static loading process was adjusted in speed 5 mm/sec. Total displacement of shells was considered to be about 60 percent of shells height. It is observed from experiments that all the specimens failed in local buckling mode. The force–displacement curves are presented later in Section 6.

Fig. 3 Experimental test set-up (INSTRON 8802)

5 Numerical simulation

ABAQUS/Explicit was employed to numerically simulate the quasi-static axial crushing process of the thin-walled end-capped conical frusta. Generally, a 1mm×1mm S8R5 element was selected for meshing the geometry of the specimens. The conical shell was rested on a fixed bottom base, while a total vertical displacement of 60 percent of shell height was gradually applied to the top rigid plate. Axial compressive force was created by moving the rigid plate at a constant speed along the longitudinal axis of the shell. The contact between the top surface of the end-capped specimen and the moving rigid plate was considered. The coefficient of friction was considered to be 0.25. In order to prevent penetration between the wrinkled surfaces of the shell wall during crashing phenomena, self-contact conditions were considered on the external and internal surface of the shell wall. The deformed shapes for three specimens are presented in Fig. 4.

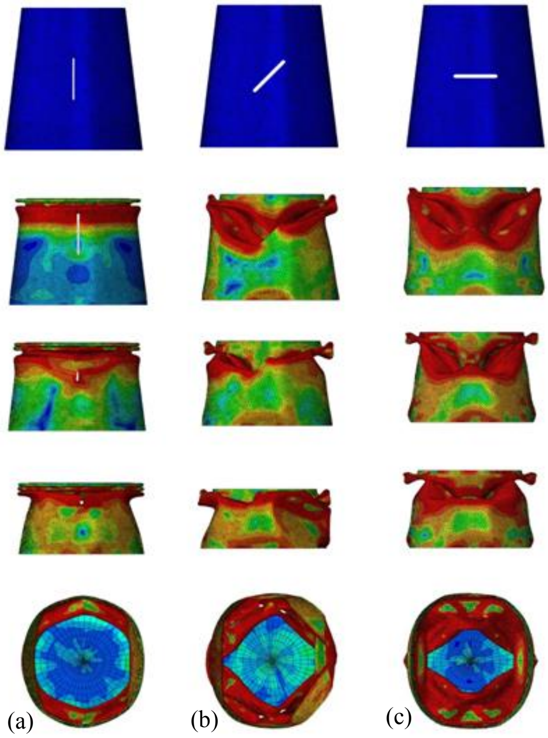


Fig. 4 Shell deformation during crashing phenomena for specimen (a) H70-2-w1-A0, (b) H70-2-w1-A45, (c) H70-2-w1-A90, form FEA.

6 Numerical and experimental results

6.1 Comparisons between experimental and numerical results

In this section, a number of force-deformation curves from the tests are compared with the corresponding numerical results in Fig. 5. In addition, a comparison between experimental and numerical results is performed in Table 3. The initial peak load and energy absorbed during the compression process are obtained from experiments and numerical analysis for all specimens, which are given in this table.

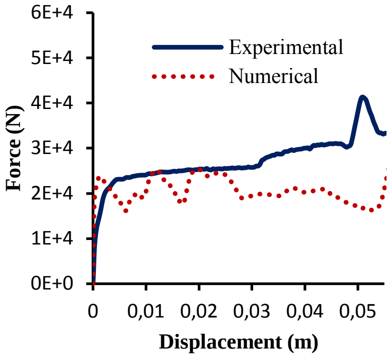
Absorbed energy is the area under load-deformation curve obtained during crashing process for each specimen. Initial peak load, refers to initial maximum load during loading after which the first local deformation of the shell occurs. This is an important parameter in optimum design of energy absorbers and attempts are made to reduce its value with respect to residual energy absorption capacity [22].

Deformed shape of specimen H100 obtained from experimental and finite element methods are illustrated in Fig. 6. It is observed that the numerical results are close to experiments. However, there are some differences between experimental and numerical curves, probably due to the frictional effect and strain hardening, which may not be suitably captured.

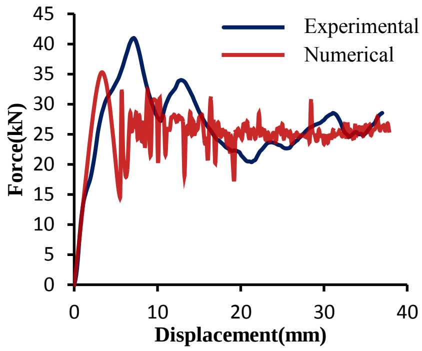
6.2 Effects of shell height on crashworthiness of conical shells

To study the effect of shell height on the energy absorption ability and initial peak load of end-capped thin-walled conical frusta, three specimens with 70mm, 100mm and 150 mm heights were considered. The analysis results are presented in Table 3. The load – displacement curves obtained from the FEA, are illustrated in Fig. 7. The areas under these curves determine the absorbed energy by related shell.

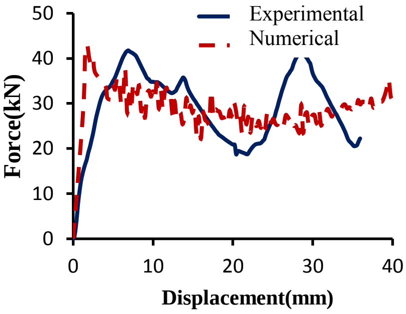
Comparison of results in table 3 eventuates that with increasing the shell height, the initial peak load increases and energy absorption ability decreases. Therefore, the crashworthiness of end-capped conical shell with the height of 70 mm is higher than the crashworthiness of two other shells.



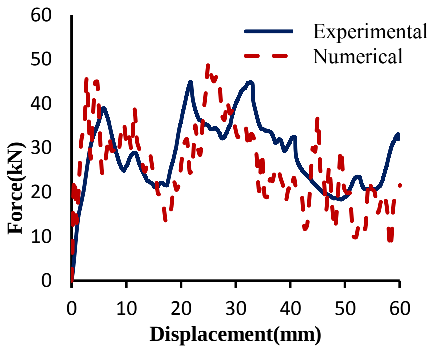
(a) H-70



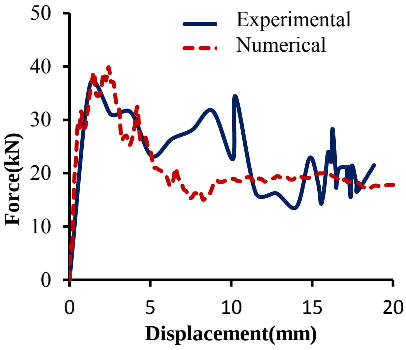
(b) H70-2d15-5



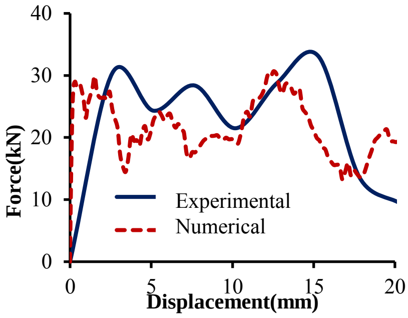
(c) H70-d15-5



(d) H100-2d10-3



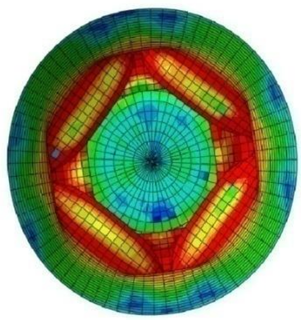
(e) H70-2-w3-A0



(f) H70-2-w1-A0

Fig. 5 Comparison of experimental and numerical load–deformation curves of specimen

(a) Experiment



(b) FEA

Fig. 6 Collapse mode for specimen H100

Table 3 Absorbed energy and initial peak load for specimens

	Experimental		Numerical	
Specimen code	Absorbed energy (J)	Initial peak load (kN)	Absorbed energy (J)	Initial peak load (kN)
H70	1740	34	1707.8	26
H100	1709	35	1689.4	26
H150	----	----	1449	29
H70-d15	1048.5	42	1052.1	43
H70-2d15	981.2	40	935.3	35
H100-d15	969.2	40	1058	45
H100-2d15	888.5	40	910.7	44
H100-2d20-3	1491.3	32	1414.6	35
H100-2d20-5	1166.3	34	1410	40
H100-2d20-75	1092	36	1349	36
H100-2d10-3	1703	40	1563	42
H70-2-w1-A0	470	32	450.5	30
H70-2-w2-A0	444	30	355	38
H70-2-w3-A0	440	38	426	38
H70-2-w1-A45	564.47	32	451	40
H70-2-w1-A90	338.9	24	348.5	26

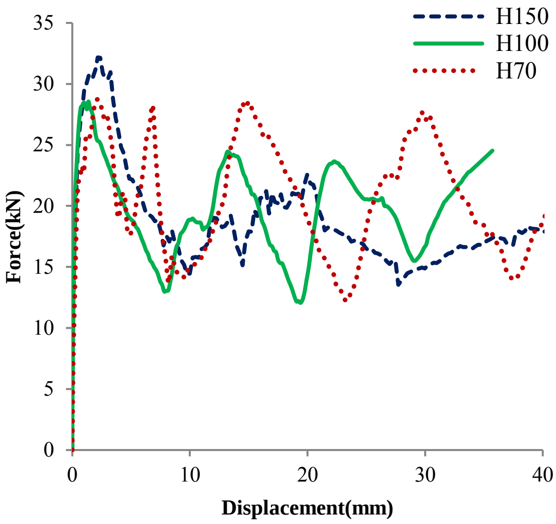


Fig. 7 Load-displacement curves for three specimens with different height from the FEA

6.3 Effects of circular cutouts on crashworthiness of conical shells

To investigate the influence of cutouts on the crashworthiness of end-capped thin-walled conical frusta, two specimens with height of 70mm and 100mm each containing a single circular cutout of 15mm diameter at mid-height of shell were analyzed. Also, two similar specimens each containing a double-sided circular cutouts with the same diameter at mid-height of shell were tested. The experimental and numerical results are presented in table 3. The load-displacement curves for these specimens are illustrated in fig. 8. Comparison of the results shows that generally cutouts decrease energy absorption capacity and increase initial peak load of shells. In addition, double-sided cutouts reduce energy absorption ability more than single cutouts.

In order to analyze the influence of cutout position on crush resistance of end-capped thin-walled conical frusta, three specimens with height of 100 mm were considered and one double-sided circular cutout with 20mm diameter was created on each specimen at 0.3, 0.5 and 0.75 shell height respectively. The results of the analysis are presented in Table 3. Comparison of the presented results in table 3 shows that increasing the distance of cutout from the base of shell decreases energy absorption ability and increases initial peak load. Therefore, decreasing the cutout distance from the base of the cone enhances the crashworthiness of thin-walled conical frustum containing cutouts.

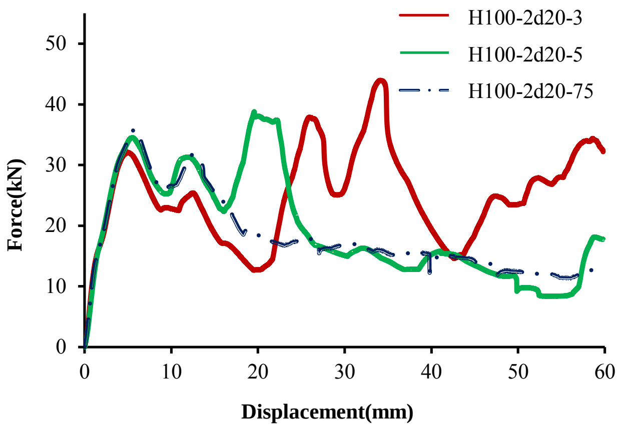


Fig. 8 Load-displacement curves for three specimens with different cutout position from the experiments

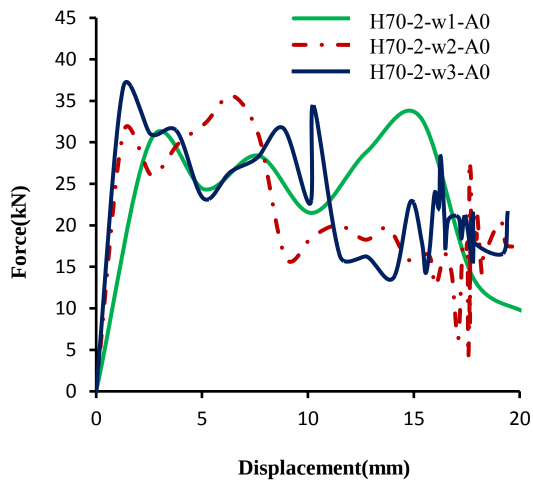
6.4 Effects of notches on crashworthiness of conical shells

In this section, the effect of changing the cutout width and cutout angle on the crashing phenomenon of slotted conical shells is studied. For this reason, five specimens with 70mm height each containing a cutout with a length of 20mm at mid-height of shell were considered. Cutouts angle respect to vertical axis for three specimens were 0◦ and cutouts width ranged from 1mm to 3mm. cutout width for the other two specimens was 1mm and cutout angles were considered to be 45◦ and 90◦. Obtained results are presented in Table 3. The load-displacement curves for these specimens are shown in fig. 9. The results indicate that increasing the cutout width decreases the energy absorption capacity and increases initial peak load. In other words, the crashworthiness decreases with increasing cutout width. It can be seen that the specimen with cutout angle of 45◦ has the higher energy absorption capacity than two other specimens.

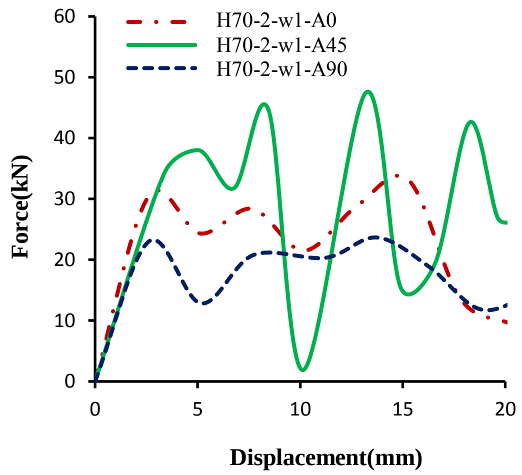
7 Conclusion

Experimental and numerical simulation procedures were developed to analyze the axial crushing of the end-capped thin-walled stainless steel conical frusta containing cutouts. The influence of the shell height, cutout position, and notch width and notch angle on the crashworthiness of specimens was investigated. Very good correlation was observed between the results of the experimental and numerical simulations. The numerical and experimental studies conclude the following characteristics for end-capped thin-walled stainless steel conical frusta with identical semi-apical angle:

1. Increasing the shell height, the crashworthiness decreases.
2. Cutouts decrease the crashworthiness.
3. decreasing the cutout distance from the base of the cone enhances the crashworthiness.
4. The crashworthiness decreases with increasing cutout width.
5. The specimen with cutout angle of 45◦ has the higher energy absorption capacity than two other specimens with horizontal and vertical cutouts.
6.



(a) cutouts with different widths



(b) cutouts with different angles

Fig. 9 Load-displacement curves for three specimens containing cutouts from the experiments

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Mahmoud Shariati was responsible for the oversight and leadership responsibility for the research activity planning and execution.
Babak Jahed carried out experimental tests and numerical simulations.
Masoud Mahdizadeh Rokhi: has analysed and interpreted the results and written the article.

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