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Research Paper

Experimental and Numerical Investigation of The Effect of Wall Perforation Geometry on Absorption of Axial Impact Energy In Thin-Walled Metal Tubes

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ABSTRACT
In this research, the experimental and numerical analysis of the effect of the geometry of holes on the energy absorption of thin-walled tubes is discussed that its energy is applied by axial impact. Thin wall tubes, with and without side holes, are used to absorb the axial impact energy caused by a dropping weight. These tubes absorb the energy by asymmetric plastic buckling. If the force of the impacting object is greater than the minimum average buckling force, the tube will be dented and its length will decrease. The amount of tubes depression depends on amount of energy, the geometric characteristics and the material of the tubes. In this research, it is shown that by perforating the thin-walled tubes in different shapes, in order to absorb the same impact energy, the shortening length of the tubes increases. By increasing the shortening length of the tubes, the amount of initial force is reduced, and in other words, it is possible to control the force and reduce damage. There is a good agreement between experimental and simulation results.

Keywords: Energy absorption; Thin-walled tubes; Perforated; Axial impact.

1 INTRODUCTION

ONe of the interesting topics in mechanical engineering is energy absorption in structures that are deformed due to impact. Tubes whose diameter to thickness ratio (D/t) is greater than 90 are known as thin wall tubes.

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Depending on the application, these tubes are usually made of steel, aluminum, etc. If the collision of the impacting object is along the longitudinal axis of the tube and its other geometric characteristics are axially symmetrical, its buckling and wrinkling will be symmetrical along the longitudinal axis. As the impact energy increases, the length of the tube will be shortened more. Impact energy depends on the mass and height of the impacting weight.
The geometric characteristics of the tube, such as diameter and thickness, affect the shrinkage of the tube. Wrinkling of the tube wall, due to buckling in the wall, creates at least two plastic hinges in the tube wall. The axial force applied to the tube causes plastic moment and absorbs its energy by converting the impact energy into work required to create plastic moment. The length of the shrink arm depends on the geometric characteristics of the tube, including its diameter and thickness. Increasing the impact energy, increases the number of wrinkles along the length of the tube. The philosophy of using thin wall tubes is not only to absorb impact energy. The use of energy absorbing tubes with a perforated wall is suitable for controlling the impact force. If the striking force is absorbed in a longer time, the maximum initial force will decrease. So, if constant energy is applied to an object in a longer time, the damages will be reduced. This method is used in many shock absorbers such as car chassis and bumpers, elevator shock absorbers and other cases.

Szwedowicz [1] has investigated the experimental and numerical results about the energy absorption performance of a square tubular profile with circular discontinuities created along the structure. He used a direct profile model to compare the energy absorption between structures with discontinuities under quasi-static loads. In his research, holes were created symmetrically in two walls and placed in three different positions along the profile. Based on their results, there is a better performance in energy absorption for circular discontinuities located at the middle height of the sign, and a maximum increase of 7% in energy absorption capacity was obtained experimentally compared to the profile without holes. Baaskaran [2] investigated the energy absorption capacity and deformation of circular thin wall members with oval holes numerically and experimentally. In order to conduct the experiments, he designed a special fixture arrangement to place the sample in the pressure loading device and investigated the deformation mechanisms and the related collapse state along with its energy absorption from the thin wall tubes in detail for different ratios. They used ABAQUS finite element code to perform numerical studies. The experimental results and their simulations are in good agreement and show that the location and symmetry of the cuts had a significant effect on the collapse crushing behavior. Simhachalam [3] investigated the compressive behavior and energy absorption of AA6061 aluminum alloy tubes both experimentally and numerically. They have performed static and dynamic simulation using LS-dyna software for aluminum tubes and plotted the actual plastic stress-strain curves from the tensile test in static and dynamic simulation of AA6061 aluminum tubes. The energy absorption values are in good agreement between the experimental compression results and the numerical simulation, and the deformed states from the numerical simulation have been compared between the tubes with and without holes in static and dynamic conditions.

Alexander [4] was the first researcher of circular walls, who calculated the average folding force as an approximate theory and for an ideal state by presenting a symmetrical collapse model around the tube. Pugsley [5] investigated asymmetric folding modes by experimental origami method. Johnson [6] developed the asymmetric mode theory based on the folding geometry and predicted the axial mean collapse force. Huang [7] studied numerically cylindrical shells with elliptical hole wall under shock loading and investigated the effect of wall on energy absorption capacity and collapse of the structure. The presence of these oval holes in the walls has reduced the initial maximum force. Song [8] investigated absorbers with a square section wall to reduce the weight of the structure. This pattern has reduced the initial maximum force and increased the amount of energy absorption and earlier exhaustion. Yang [9] investigated the energy absorption of circular tubes under axial impact loading and investigated the effects of material strain rate on the average crushing force. The obtained results show that the results of experimental test and numerical simulation are in good agreement. Niknejad [10] predicted the maximum crushing force in four-sided columns and compared it with a column filled with foam. The theoretical calculations performed in the displacement force diagram have been in good agreement with the experimental tests. Martínez [11] discussed perforated energy absorbers to apply quasi-static loading and calculate the collapse force and energy absorption capacity of the absorber. This study showed that the absorbent energy absorption capacity or reduction of initial maximum force depends on the number of wall cells and the type of cross section in terms of circular and square shape. It was also found that the behavior of the square absorber is similar to the behavior of the perforated cylinder absorber. Also, in the sample of the perforated tube, the response of the structure depends on the orientation of the window wall. The proper angle of the perforated wall helps to increase the absorption capacity and prevent Euler buckling. In other experimental tests, Nouri [12] showed that by using perforated columns, the energy absorption capacity increases. This experiment was carried out by the free drop of the weight and it was simulated numerically by Abaqus software. Song [13] investigated the wall effect on thin-walled square tubes. Experimental results showed that, in addition to lower weight, walled tubes have reduced the maximum force and increased energy absorption. Singace [14] used the preform mold to create a corrugated ring for the symmetrical collapse of thick wall tubes. Laboratory tests showed improved energy absorption. Bhuvaneshwari [15] investigated the behavior of the thick-walled tube inside which the polymer reinforced with glass fiber was placed under axial stress and found that this method has a positive effect on the final strength and ductility of the tube in causing buckling of hollow steel tubes. Yab [16] performed a quasi-static pressure test on thin-walled aluminum and square tubes and compared the obtained stress relations with other researchers. The results of the tests showed that the performance of circular tubes is 57% better than that of square cans, and the energy absorbed by circular tubes is twice that of the square section. Alavi Nia [17] and [18] investigated the energy absorption capacity of thin-walled tubes with circular, square, rectangular, hexagonal, pyramidal, and conical cross-sections experimentally and numerically. The results of quasi-static tests showed that the cross-section geometry has a significant effect on energy absorption. Experiments also showed that circular tubes have the highest absorption capacity. Supian [19] used composite fibers to strengthen the walls of tubes with circular and square sections, which were filled with aluminum foam to absorb energy. This structure has reduced the primary maximum force and energy absorption has been controlled in the form of symmetrical buckling. Ghamarian [20] did an experimental and numerical study of conical tubes and compared it with a tube filled with polymer foam. The results showed that the ability to absorb energy in polymer tubes has improved. In US documents [21] spindle-shaped absorbers are used in a car bumper system to absorb the energy caused by accidents. Kalashti [22] used aluminum square thin-walled cans as energy absorbers in the numerical simulation of dynamic and quasi-static axial loading to calculate the maximum force. Harte [23] used circular tubes covered with glass fibers/epoxy with polymer foam cores for energy absorption. The ratio of wall thickness to diameter in tubes filled with foam has been optimized and has a high ability to absorb energy. Peroni [24] used square cans whose cross-section was made of two-piece bent plates to absorb the dynamic energy of the impact. Two-piece bent plates are connected to each other by welding and with different composition. The creation of welding joints in the formation of the cross-section has a significant effect in reducing the maximum and average force. Mozafari [25] proposed a tube with a double-sided corrugated structure to absorb maximum energy, which improved energy absorption by 32% compared to the one-sided corrugated model. Xin [26] investigated the absorption law of thin-walled tubes with different materials in a numerical study and determined the ratio of height to diameter with thick walls in order to increase the specific energy. Zhang [27] investigated multicellular tubes with cylindrical tubes placed in the center of each cell. In this research, the six-cell tube with an octagonal wall has the highest performance in absorbing the energy caused by impact. Sun [28] investigated energy absorbing structures with thin walls made of aluminum and composite materials, which were placed at an angle on special fixers, and the appropriate angle for static loading was obtained. Liu [29] conducted a numerical and experimental investigation of thin-walled tubes with a star-shaped cross-section with aluminum material under axial impact and by proposing a new cross-section, the absorption of specific energy has increased by 40%. Eyvazian [30] investigated the effect of waves on the settlement behavior and energy absorption of aluminum tubes with a circular cross section. In this investigation, five plain and corrugated tube samples were subjected to quasi-static axial loading and it was found that in corrugated tubes, the subsidence mode is more predictable and controllable and is associated with improved energy absorption capability. Moradpour [31] addressed a new and efficient solution to increase the capacity of quasi-static axial energy absorption by thin-walled aluminum tubes. In this solution, by drilling multiple rows, in which the number of holes and the diameter of the holes can be changed in each row, the absorbed energy is improved to the weight of the symmetrical tube, and the experiments showed that if the tubes are in five rows and in each row If the holes are 12 and the hole diameter is 6 mm, the energy absorption performance is improved. This structure is also applied to mild steel tubes. Acar [32] optimized the specific energy absorption by using LS-DYNA software using thin-walled aluminum multi-cell tubes. Mansor [33] investigated the configuration of metal tubes reinforced with fiberglass layer under dynamic loading conditions at low speed. Parametric studies have shown that increasing the thickness of the aluminum wall causes higher specific energy absorption, and increasing the layers has increased the ability to absorb energy in an accident. Ha [34] showed by investigating corrugated tubes that corrugated thin-walled structures are more efficient and effective in absorbing energy and will be used more in advanced engineering structures in the future.

By reviewing the research, it was concluded that the absorption of axial impact energy by tubes is a practical issue in the industry. The most important innovation of this issue is the use of simple tubes with side holes of different shapes. The tubes have holes in one or more rows, and the number of holes in each row is different. In addition, the variety of tube geometry is another aspect of innovation in this paper that has not been investigated by researchers in previous research.

2 EXPERIMENTAL STUDY

In this part of the research, the experimental tests are discussed. The experimental samples are cylindrical tubes that are closed at one end and ringed at the other end in order to improve better energy absorption performance in uniform transfer of impact and uniform distribution of force on it. The mass of each thin-walled tube cylinders is about 95 grams, with a diameter of 110 mm, a height of 115 mm, and a thickness of 0.25 mm. In order to perform experimental tests, the weight dropping device was used in the impact laboratory of Imam Hossein university as shown in Fig. 1.

In order to achieve the appropriate height for experimental tests, samples have been tested at three different heights of 1, 2, and 3 meters with the free drop of a striking weight of 8.5 kg. Observations show that at two heights of 2 and 3 meters, the indentation of the cylinders is very high and the possibility of observing the effects of the side holes of the samples in the tests is reduced. At a height of 1 meter, the amount of indentation is such that the effects of side holes can be seen and evaluated more accurately in the tests. The force caused by the impactor from this height is the basis for conducting experiments and numerical simulations.

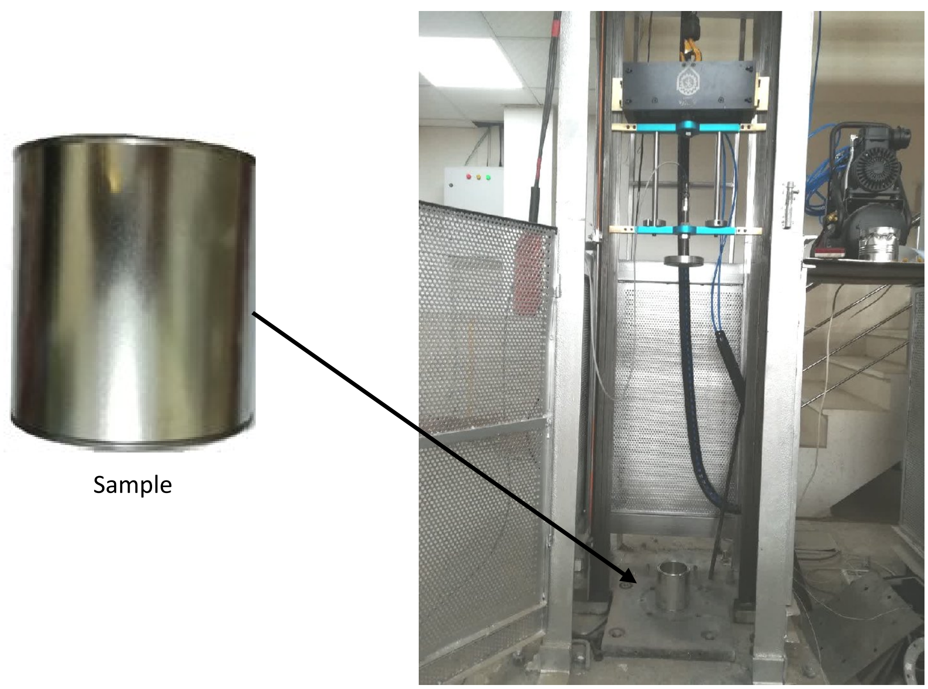

Fig. 1
Vertical impact test apparatus.

3 NUMERICAL SIMULATIONS

The LS-Dyna finite element program has been used for simulation and parametric studies. The simulation results have been compared and validated with experimental results. After validating the simulation results, a further parametric study has been carried out by numerical method to check the effective parameters in energy absorption in these structures. The simulation steps include modeling, configuration of the cylindrical tube of energy absorber and impactor, meshing of the model, application of boundary conditions, definition of materials and its properties, coefficient of friction between different parts of the energy absorber and initial conditions.

The material properties have been measured using a standard tensile test. The samples used for the tensile test are prepared from test cylinder. In Fig. 2, the diagram of force-extension of samples is presented which is determined experimentally.

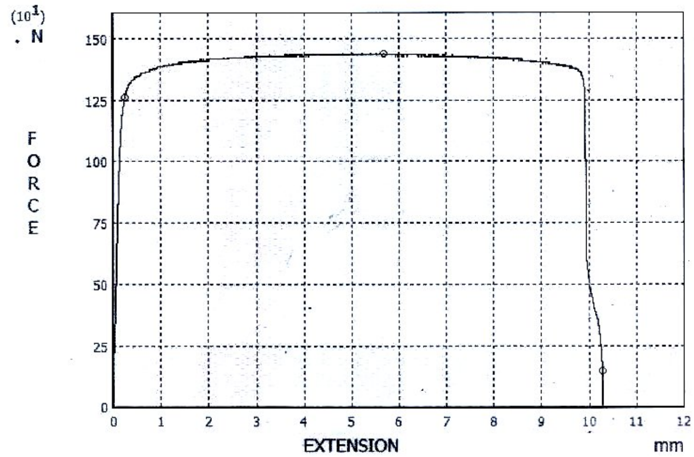

Fig. 2
Force-Extension diagram of material.

Table 1
Material properties.

ρ (Kg/mm3)	υ	E(Gpa)	σy(Mpa)	σu(Mpa)	Elongation (%)	(C)	(P)
7.12×10^{-6}	0.26	120	311	355	$0.6-14.2$	40	5

In Table 1, the mechanical properties of the material of tubes are presented which is used in FEM analysis. The material of the tubes is tinned St33 (1.0905) rolled steel and the material of the impactor is rigid steel. In this table, C and P are the parameters introduced in the well-known Cooper-Symonds dynamic yield stress relationship.

When the impactor released from a height of 1 meter, it has a speed and kinetic energy that increases from the moment of release and reaches the maximum value at the moment of impact with the sample. The amount of impact energy on the sample is the amount of kinetic energy of the impactor at the moment of impact. Energy is absorbed by the deformation and plastic buckling of the tube and its shortening.

One of the important problem in finite element method is the independence of the results from the mesh. The number and size of the mesh should be selected in such a way that in addition to the accuracy and convergence of the results. It also manages the execution time of the program in the analysis process. Preventing the increase in the program execution time is a cost that is achieved by checking and studying the independence of the results from the network and ensuring the accuracy of the results. In order to ensure the meshing of the numerical solution, several simulations were performed with the number of different elements, and finally, the size of the mesh was considered to be 1.5 mm.

The boundary conditions in the simulation are considered similar to the experimental condition. The install location of the tube is fixed and the direction of the hammer movement is along the longitudinal axis of the weight drop.

By performing mathematical calculations, the initial impact speed for the drop height of 0.5m, 1m, 2m, and 3m is 3.1, 4, 6, and 7.4 m/s, respectively. In these calculations, a 3% reduction in speed due to the friction of the device's rails has been considered, which obtained experimentally.

In the numerical analysis used in this research, the element type of thin walled cylinder is four node square shell and solid type for the impactor hammer.

The material model which is used in this analysis is piecewise linear theory of plasticity. the piecewise linear plasticity model is a popular elastic-plastic model, where both the stress versus strain curves and rate dependency are defined, combined with a single failure strain for all strain rates. The mesh type in this analysis is square mesh type and the mesh sensitivity of results are evaluated.

In Fig. 3, from top to bottom, the simulation results and effective stresses created in tubes without holes (dropping height of 1, 2 and 3m) are presented. Also, the corresponding results of their experimental tests are presented. Observations show that indentation in tubes occurs mostly longitudinally. Therefore, with the increase of impact energy, the longitudinal deformation of the tube also increases. In samples whose shortening is more due to impact, the time of applying the force also increases.

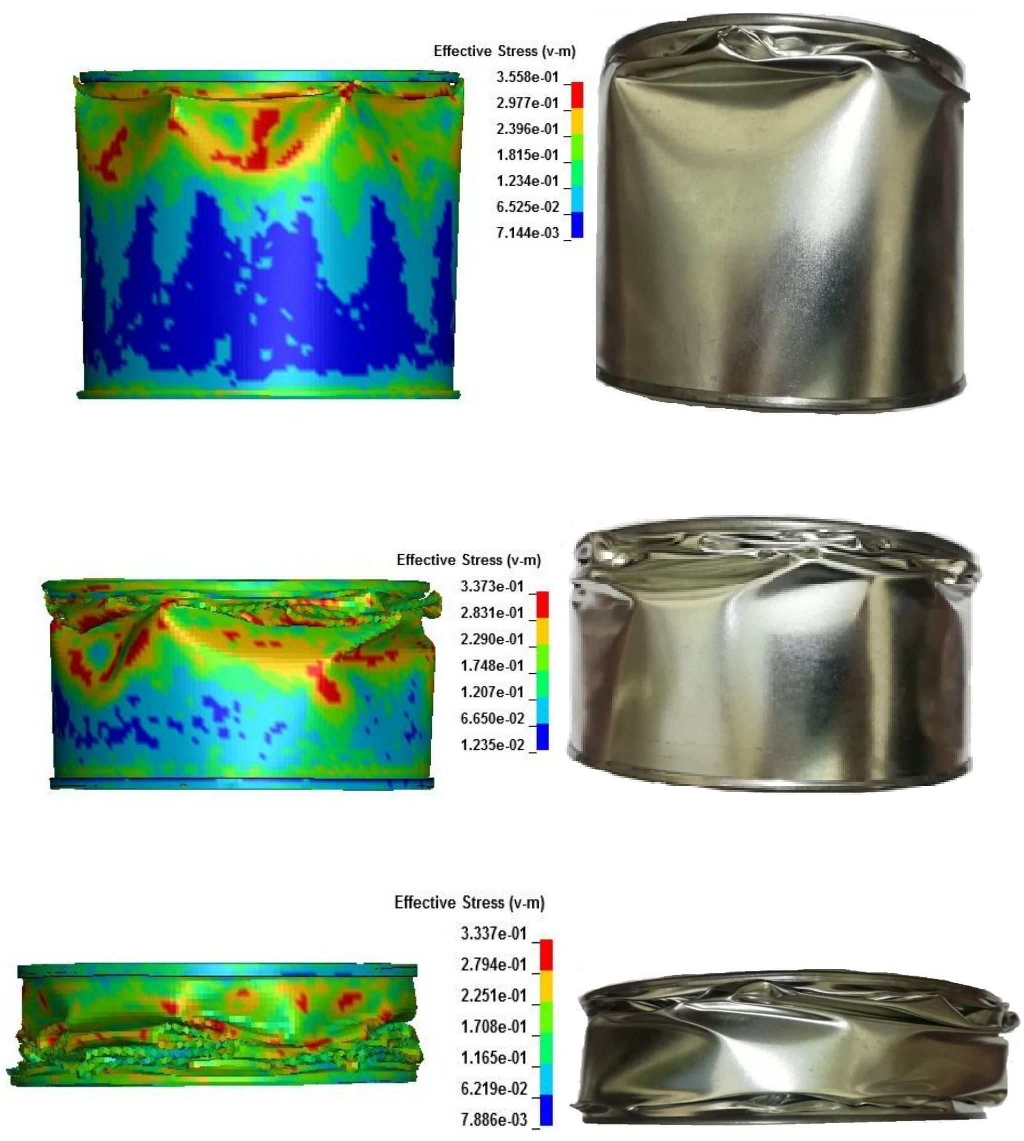

Fig. 3
Tested samples at a height of 1 (top), 2 (middle) and 3 (bottom) meters with the corresponding numerical simulation.

As shown in Table (2), the experimental and simulation results are in good agreement. The result of simulations is validated with the experimental results. After verifying, the energy absorption of tubes with different hole shapes is analyzed parametrically.

In order to study the effect of the shape of the wall holes of the thin-walled tube, numerical simulation has been done for eight different shapes. In each of the samples, the reduced area of tube wall (caused by perforation) is exactly 20% of the total side area. In addition to lightening the samples, this will reduce the effective cross-sectional area of the sample against impact.

In Fig. 4, the simulation is presented for 8 different types of hole shapes as well as for the tube without holes. In all simulations, the impactor's weight is 8.5 kg and the fall height is 0.5 meters. In this figure, the geometries of the holes are presented as follows: T0 is the sample without holes. T1 to T8 are samples with triangular, vertical oval, hexagonal, vertical bean-shaped, rectangular, circular, horizontal bean-shaped and horizontal oval holes, respectively.

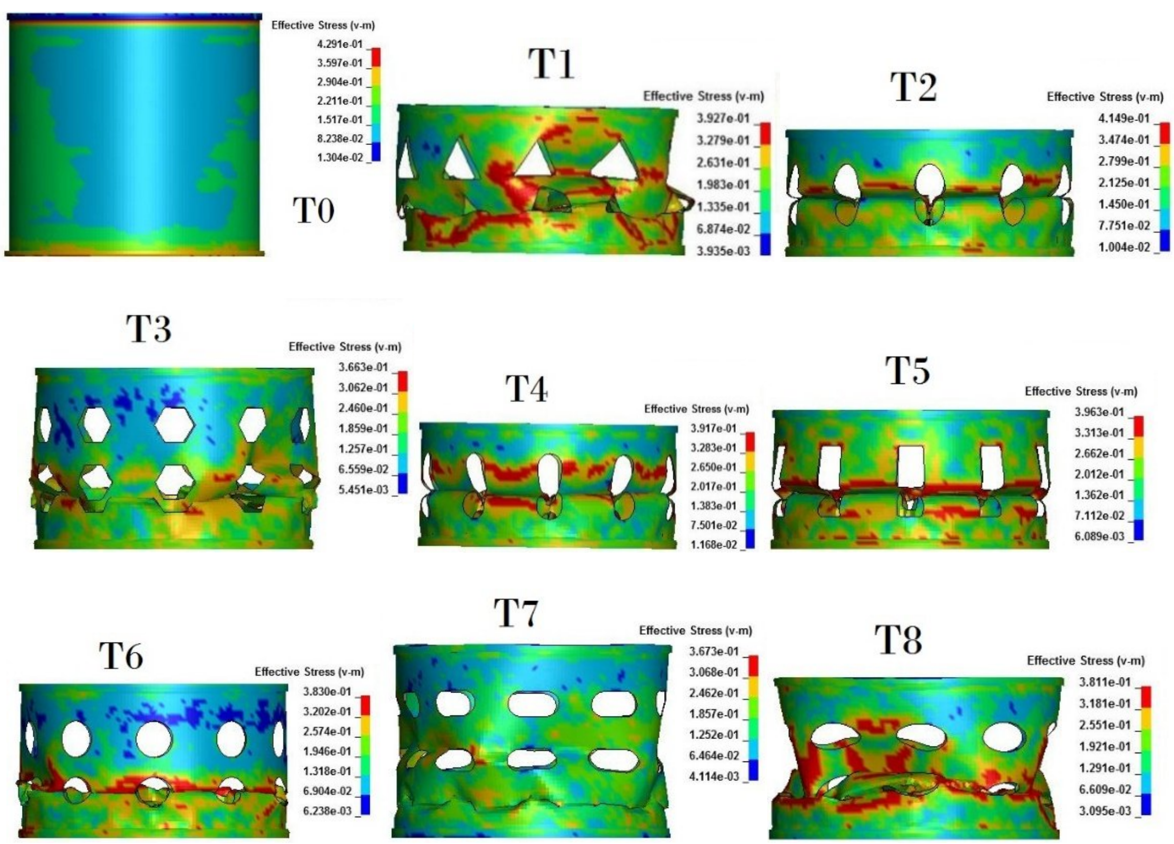

Fig. 4
Deformation of samples with different side holes caused by impact after 30 milliseconds.

4 ANALYSIS OF THE RESULTS

By examining and comparing the simulation and experimental results of samples without holes, the results according to the Table 2 have been obtained.

Table 2
Simulation and experimental results.

Experimental deformation(mm)	Numerical deformation(mm)	dropping height(m)	Relative error (%)
23	20	1	13%
49	57	2	16.3%
70	85	3	21.4%

In this table, the numerical and experimental deformations and their relative error are calculated and presented. It can be seen that for the conducted tests and simulations, the error value of the simulation method compared to the experimental method varies from about 13 to about 21% and the average error is equal to 16.9%.

Fig. 5 shows the displacement force diagram of samples without holes (T0) and with holes (T1 to T8). From this figure, it can be seen that in samples with holes, the maximum force decreases 62% compared to samples without holes. Also It can be seen that in perforated samples, the displacement increases by about 410% compared to the non-perforated sample.

Also, according to Table 3, it can be seen that the shape of the holes has an effect on maximum force and the change of location of the samples. In this table, the values and percentage of changes, compared to tubes without holes, are presented.

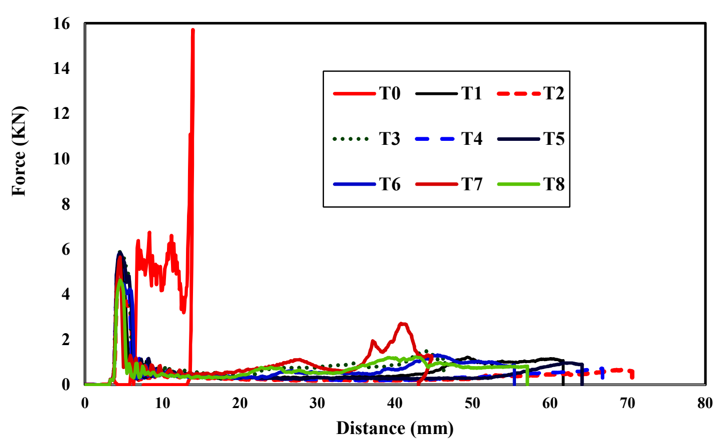

Fig. 5
Force-displacement diagram of samples (numerical simulation and dropping height of 0.5 meters).

Table 3
Effect of hole geometry on maximum force and displacement (compared to sample without hole, T0,).

Hole geometry	Triangular (T1)	vertical oval (T2)	Hexagonal (T3)	vertical bean-shaped (T4)	Rectangular (T5)	Circular (T6)	horizontal bean-shaped (T7)	horizontal oval (T8)
Reduction of maximum force (%)	6.1%	70.4%	62.5%	62.8%	62.7%	70.9%	64%	70.4%
Reduction of average force (%)	67.6%	81.1%	56.5%	78.9%	75.9%	63.7%	53.7%	65.3%
Displacement increased (%)	722%	841%	517%	790%	755%	647%	473%	677%

It can be seen that the sample with horizontal elliptical hole has the greatest decrease in maximum force by 70.4%. The average force in the sample with a vertical elliptical hole has the largest decrease of 81.1% compared to the sample without a hole. Also, the sample with a vertical elliptical hole has the largest increase in displacement by 841% compared to the sample without holes.

In addition to the force-displacement diagram, the average force and maximum force diagrams are also shown in Fig. 6 for a better comparison of the effect of holes on energy absorption parameters. In this graph, a significant reduction of the parameters compared to the tube without holes can be seen. In the damage caused in accidents caused by the collision of two bodies, the primary maximum force plays an important role in reducing the damage caused.

From the results, it can be seen that the circular geometry has the most effect in reducing the initial maximum force by 70.3%. It is also easier and cheaper to make circular holes in thin-walled tubes. Therefore, the effect of the diameter and number of these holes, including the number of rows and the angles of the holes, will be investigated in order to achieve the maximum reduction of the initial maximum force. Table 4 shows the geometric characteristics of tubes with hole diameters of 6, 8, 10 and 15 mm. It should be noted that in all samples, the amount of total surface area which is reduced in the process of perforation is exactly 20% of the total side area of the tube and is equal to 29500 square millimeters.

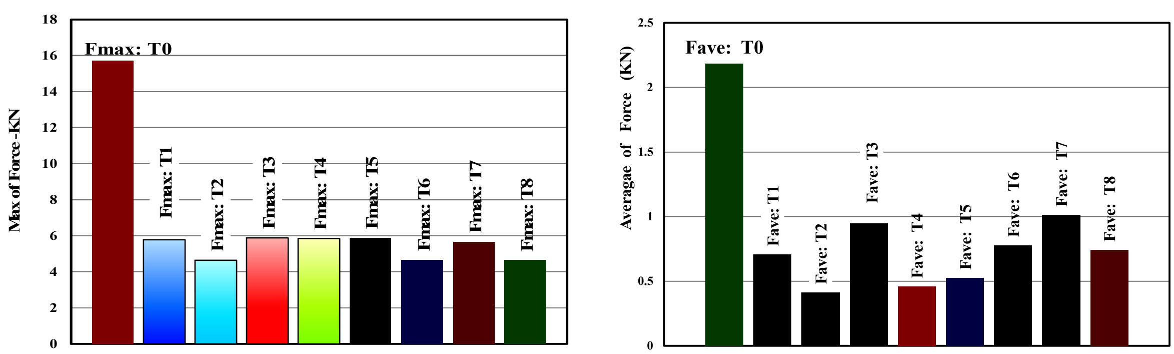

Fig. 6
Average force diagram (right) and maximum force diagram (left) - numerical simulations.

Table 4
Size, number and arrangement of circular holes (Total Area of holes: 29500mm2).

Number per Row	Rows Number	Diameter(mm)
36	7	6
29	5	8
23	4	10
10	4	15

The results of the numerical simulation for the sample with the diameter of the side holes of 6, 8, 10 and 15 mm are shown in Fig. 7.

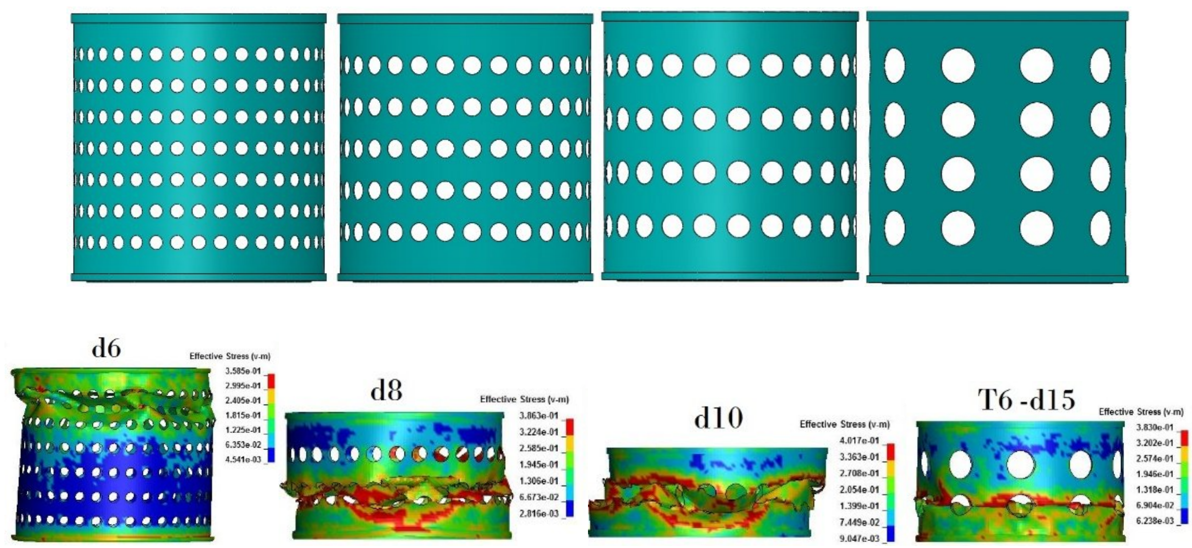

Fig. 7
Numerical impact simulation for holes with diameters of 6, 8, 10 and 15 mm.

Fig. 8 and Fig. 9 show the results of displacement force diagram and average and maximum force, respectively. The diameter of the holes in these results is 6, 8, 10 and 15 mm. In all the tests, as mentioned previously the decrease in surface due to the creation of the hole is constant and is equal to 20% of the side area of the tube.

Also, according to the results of Table 5, it can be seen that the size and number of circular holes have an effect on the maximum force and displacement compared to the sample without holes.

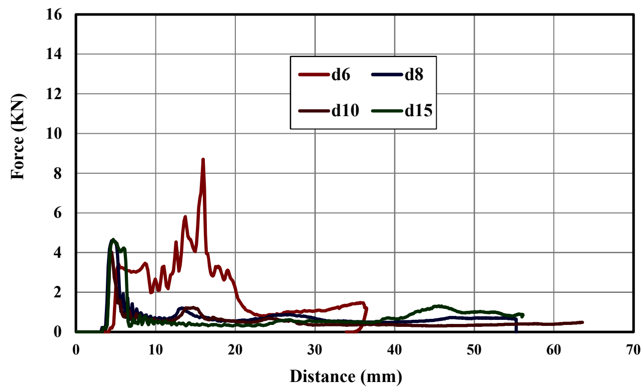

Fig. 8
Displacement force diagram for a tube with a circular side hole with diameters of 6, 8, 10 and 15 mm.

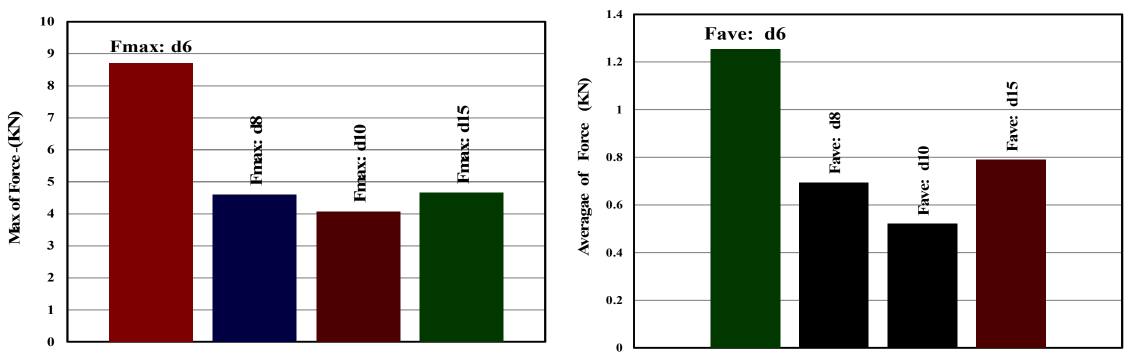

Fig. 9
Average force diagram (right) and maximum force diagram (left) for a circular hole with a diameter of 6, 8, 10 and 15 mm.

Table 5
Effect of diameter, number of rows and number of circular holes on maximum force, average force and displacement (shortening) of the sample.

	Sample without holes	252 holes with diameter of 6 mm in 7 rows	145 holes with diameter of 8 mm in 5 rows	92 holes with diameter of 10 mm in 4 rows	40 holes with diameter of 15 mm in 4 rows
Maximum force (KN)	15.7	8.70	4.60	4.07	4.66
Average force (KN)	2.18	1.25	0.695	0.521	0.79
Tube shortening (mm)	7.50	34	55.3	74.1	56

It can be seen that by increasing the diameter of the holes from 6 to 15 mm and consequently by reducing the number of holes from 252 to 40, the maximum force decreases from 15.7kN to 4.66kN (70.3 percent reduction). find Also, the average force decreases from 2.18kN to 0.79kN (63.7% decrease). The shortening of the tube increases from 7.5 mm to 56 mm (646% increase in length).

Also, from the comparison of the results of this table, it can be seen that by reducing the number of holes (increasing their diameter), the maximum force and average force do not always decrease, and with the decrease of holes from 92 to 40, the values of maximum and average force increase with the change of trend. Such a result can be understood for the shortening of the tubes.

4 SUMMARY AND CONCLUSION

In this research, the experimental and numerical study of the effect of the shape of the side holes on the absorption of axial shock in thin metal tubes has been discussed. It can be seen that the results of numerical simulations and experimental tests are in good agreement. By examining the effect of the geometry of the holes, it can be seen that the sample with a horizontal elliptical hole has the greatest reduction in maximum force and average force compared to the sample without holes. Also, the sample with a vertical elliptical hole has the greatest increase in displacement (shortening) compared to the sample without a hole. In the sample with a vertical elliptical hole, the greatest decrease in average force occurs compared to the sample without holes. From the results of this research, it can be seen that by increasing the diameter of the circular holes and consequently by decreasing their number (the sum of the area of the holes is constant in all samples), the value of the maximum force and the average force decreases and the shortening of the tube increases. By reducing the number of holes (increasing their diameter), the maximum force and the average force do not always decrease. By further reducing the number of holes, the maximum force and average change increase. This is also visible for the shortening of the tubes, and the maximum and average force decreases with the further reduction of the number of holes. In these investigations, the area of the created holes is fixed and equal to 20% of the total area of the side wall of the tube.

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