Energy Absorption by Thin-Walled Tubes with various Thicknesses in Rectangular and Square Sections under Different Quasi-Static Conditions: Experimental and Numerical Studies

K. Hoseini Safari, **Y. Mohammadi**
Department of Mechanical Engineering,
Islamic Azad University, Qazvin Branch, Qazvin, Iran
E-mail: safari@dena.kntu.ac.ir, u.mohammadi@gmail.com

S. Dehghanpour*
Department of Mechanical Engineering,
Toyserkan Branch, Islamic Azad University, Toyserkan, Iran
E-mail: sajjaddehghanpour@yahoo.com
*Corresponding author

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Abstract: Impact is one of the most important subjects which always have been considered in mechanical science. Nature of impact is such that which makes its control a hard task. Therefore it is required to adopt a safe and secure mechanism for transferring the impact to other vulnerable parts of a structure, when it is necessary. One of the best methods of absorbing impact energy is using Thin-walled tubes, where the tubes collapse under impact by absorbing energy, while this prevents the damage to other parts. Purpose of the present study is to survey the deformation and energy absorption of tubes with different type of cross section (rectangular or square) and with similar volumes, height, mean cross section, and material under different speed loading. Lateral loading of tubes are quasi-static type and in addition to the numerical analysis, also experimental experiment has been performed to evaluate the accuracy of the results. Results from the survey indicates that at the same conditions which mentioned above, samples with square cross sections, absorb more energy compared to rectangular cross sections; also by increasing the loading speed and thickness, the energy absorption would be more.

Keywords: Energy Absorption, In-plane Loading, LS-DYNA, Quasi-Static

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Biographical notes: K. Hoseini Safari and **Y. Mohamadi** are Assistant Professor at Industrial and Mechanical Engineering, Qazvin Branch, Islamic Azad University. They received their PhD in Mechanical engineering at K. N. Toosi University of Iran. **S. Dehghanpour** is faculty member at Islamic Azad University, Toyserkan Branch and is pursuing his PhD in Mechanical Engineering at Department of Mechanical Engineering, Islamic Azad University, Qazvin Branch, Iran. His current researches include Impact mechanic and Energy absorption in thin–walled structures.

1 INTRODUCTION

Energy absorbers, because of their great applications, have a significant importance in industry. Energy absorbers devices transfer the kinetic energy to the other kinds of energy and their main purpose is to reduce the damaging force which is transferred to the structure. Survey of lateral load to tubes has been considered as an important group of energy absorbers by the researchers.

The impact energy-absorbing devices, such as brakes or shock absorbers, are capable of bringing a moving mass to a controlled stop depending on the absorption of energy by the production of plastic deformation. The use of tubes in energy-absorbing systems is an interesting topic and has been discussed by several authors [1-5]. Mutchler attempted to determine the energy absorbed by a tube compressed laterally between two plates by using a numerical integration technique [6]. DeRunts and Hodge carried out a limit analysis of a tube compressed between two rigid places for rigid perfectly plastic materials by assuming a model consisting of four plastic hinges which remain stationary relative to the rigid portions of the tube. Two kinks are formed in the center portion, and are known as the buckling of the tube [7].

Gupta and his colleagues surveyed the lateral load on the structures' with rectangular and square cross section and showed that the shape of cross section is influential to the amount of energy absorption [8]. Gupta investigated the parameters such as type of cross section, thickness, and also coefficient of friction, and showed that by increasing wall thickness, the rate of energy absorption increases. He also argued about effect of cross section on the rate of energy absorption and by surveying factor of friction, and its variation showed that, this factor does not have significant effect on the rate of energy absorption.

In the next researches, Gupta and his colleagues surveyed the lateral loads on the tubes. They simulated it by offering a theatrical model for tubes deformations and dividing the different region of tube's cross section from different types of deformation point of view, and compared the distribution of stress and strain in different parts of cross section. Then they analyzed the ratio of diameter to their wall thickness and found that by increasing this ratio, the energy absorption, decreases. Selection of the best shape of energy absorbers and reduction of harmful forces to the structure is valuable, and lot of research has been done for this subject. Recently, Niknejad et al. [9-12] studied quasi-static axial deformation of empty and polyurethane foam-filled intact and grooved tubes, theoretically and experimentally. Yan and Chouw [13] investigated crashworthiness characteristics of natural flax fiber reinforced epoxy composite circular tubes from the point of view of energy absorption. They showed that flax fabric reinforced epoxy composite tube has the potential to be a useful energy absorber device. Also, Yan et al. [14] studied effects of the polyurethane foam-filler on energy absorption of flax fabric reinforced epoxy composite tubes under axial quasi-static compression. Foam-filled tubes have better crashworthiness than empty tubes in total absorbed energy, specific absorbed energy and crush force efficiency. Mahdi et al. [15] introduced a four-phase program to improve the specific absorbed energy by axially crushed composite collapsible tubular energy absorber devices.

Zhang et al. [16] studied design issue of thin-walled bi-tubal column structures that were filled by aluminum foam under axial compression, numerically and experimentally. Also, some researchers investigated effects of different geometrical imperfections on axial crushing of thin-walled tubular structures. Arnold and Altenhof [17] examined the effects of geometrical imperfections in the form of circular holes, on the crashworthiness characteristics of axially loaded extruded aluminum tubes. The experiments results showed that circular discontinuities cause increment of the crush force and even large increment of energy absorption. Cheng et al. [18] investigated axial crush behavior of square aluminum tubes with different circular, slotted and elliptical discontinuities.

The results of their research show that by introducing crush initiators into the structural members, the splitting and cutting deformation modes were generated rather than global bending deformation which was observed for specimens without any dis-continuities. Alavi Nia et al. [19] studied the effects of cracks on mechanical behavior of cylindrical and square thin-walled aluminum tubes under the quasi-static axial compression. They found that the cracks change collapse processes, folding modes and energy absorption parameters of thin-walled tubular structures under axial compression. In this paper, more surveys has been performed on energy absorption of rectangular and square cross section because of different and varying thickness, experimentally and numerically.

2 EXPERIMENTAL SAMPLES

Sample of tubes with thin wall thickness and with different geometrical shapes (square, rectangular with dimension ratio of 1.5:1) with the height of 100 mm, mean area of 190 mm, from material of aluminum with yield stress of 130 Mpa according to characteristic in table 1 has been selected. The samples made are shown in figure 1.

Table 1 Specifications of the tubes

Environment Section (mm)	high (mm)	Thickness (mm)	
190	100	1,1.5,3	Specifications of the Tubes

Fig. 1 prepared samples with different sections for performing experiments

3 PERFORMANCE OF TENSILE TEST TO OBTAIN THE STRESS-STRAIN CURVE

Tensile test by using INSTRON device, model 8305 (figure 2) and based on ASME was performed on the samples which are made from aluminum sheet, which ultimately yields to stress equal to 130 MPa. Stress-strain curve from the tensile test has been shown in figure 3 and the samples tested in this experiment are shown in figure 4.

Fig. 2 Instron 8305

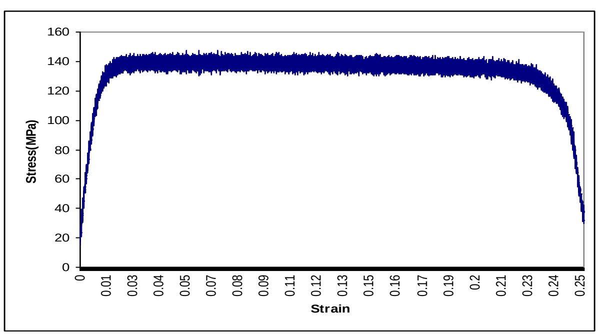
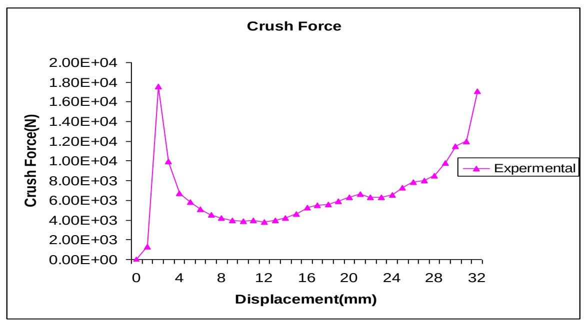


Fig. 3 Stress- strain curve, result of the tensile test

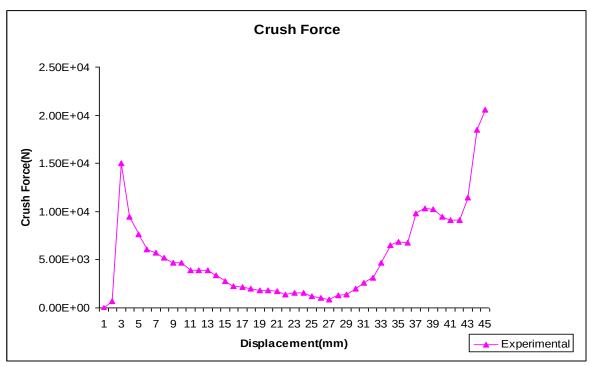
Fig. 4 The samples after tensile test experimental test

4 EXPERIMENTAL TEST

Experimental test of lateral loading with quasi-static method and with speeds of 100, 150, 300 and 450 millimeters per second has been performed with INSTRON test device and load-displacement curve which is obtained from this curve and the rate of absorbed energy in each sample were calculated by considering the cross sectional area. The curves which is obtained from samples with rectangular and square cross section, have been shown in figures 5, and also the samples with rectangular and square cross sections ,before loading and after loading have been shown in figure 6.



(Rectangular)



(Square)

Fig. 5 Load-displacement curve which has been obtained from experimental test on the rectangular and square tubes with loading speed of 100 mm/s (thickness:1.5mm)

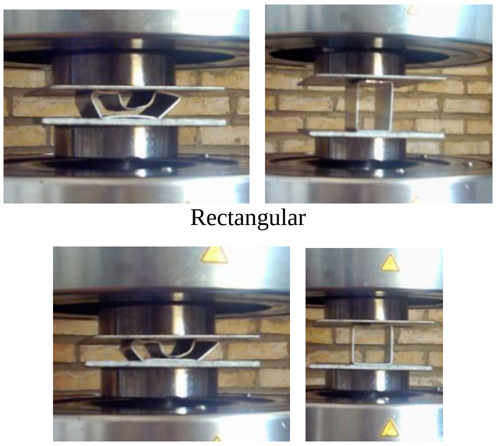


Fig. 6 Samples with rectangular and square tubes under loading Right: before loading left: after loading

After performing the tests and obtaining load-displacement curves, at the end of compression processing, energy absorption will be obtained from the area under load-displacement curve in tables 2 to 5. Crushing length, peak load, mean force and absorbed energy at the end of process for the samples with rectangular and square cross section and also with different thickness and loading speeds have been compared with each other.

Table 2 The comparison between rate of energy absorption, mean force and crushing length which has been obtained from experimental test by varying in the rate of loading with rectangular tubes

Specimen Code	Rate of loading (mm/s)	Crushing Length (mm)	Peak Force (N)	Mean Force (N)	Absorbed Energy (J)
$_{R}V_{\circ}$	100	30	17800	6166.6	185
$_{R}V_{1}$	150	30	11500	6433.33	193
$_{R}V_{2}$	300	30	9700	6966.6	209
$_{R}V_{3}$	450	30	8800	7266.6	218

Table 3 The comparison between rate of energy absorption, mean force and crushing length which has been obtained from experimental test by varying in the rate of loading with square tubes

Specimen Code	Rate of loading (mm/s)	Crushing Length (mm)	Peak Force (N)	Mean Force (N)	Absorbed Energy (J)
$_{S}V_{\circ}$	100	41	15000	4560.97	187
$_{S}V_{1}$	150	41	9400	4853.65	199
$_{S}V_{2}$	300	41	7800	5292.68	217
$_{S}V_{3}$	450	41	7300	5512.19	226

Table 4 The comparison between rate of energy absorption, mean force and crushing length which has been obtained from experimental test by varying thickness with rectangular tubes

Specimen Code	Thickness (mm)	Crushing Length (mm)	Peak Force (N)	Mean Force (N)	Absorbed Energy (J)
Rec1	1	45	5160	1377.7	62
Rec 1.5	1.5	30	17800	6166.6	185
Rec 3	3	12	77100	37500	450

Table 5 The comparison between rate of energy absorption, mean force and crushing length which has been obtained from experimental test by varying thickness with square tubes

Specimen Code	Thickness (mm)	Crushing Length (mm)	Peak Force (N)	Mean Force (N)	Absorbed Energy (J)
Squ 1	1	57	3790	1194.73	68.1
Squ 1.5	1.5	41	15000	4560.97	187
Squ 3	3	18	67500	27333.3	492

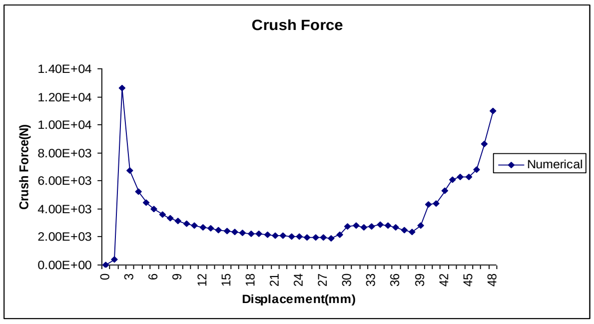
4 NUMERICAL SIMULATIONS

To perform quasi-static loading simulation in different samples, first the part of each sample, according to required dimension which is developed between two solid plates, is simulated by software package of FEM27, such that, the lower plate is fixed and the upper plate is moving downward and vertically with different speeds. Type of samples is shell with the thickness 1, 1.5, 3 mm and also the coefficient of friction between two end plates and each sample is taken 0.2. Material type for the end plates is No. 20 (rigid) and for experimental sample No. 24 (Mat-piecewise-linear-plasticity) has been selected.

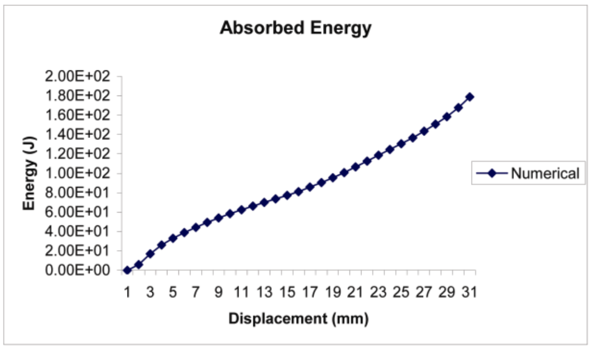
Mechanical characteristic of the experimental samples is shown in table 6. Lateral loading simulation on all the samples has been performed by using LS-DYNA package and the results of rectangular and square cross section were compared with the results of experimental method. Comparison for peak load and absorbed energy at the end of compression process has shown less than ten percent difference between these two methods, therefore we could use this package with more confident. Load-displacement curves and also the curve for energy-displacement of samples with rectangular and square cross sections which are obtained from simulations are shown in figures 7 and 8 and also the shapes for simulated samples, after applying the load and after compression process are shown in figure 9.

Table 6 Mechanical properties of specimens tested

Property	Mass Density (kg/m3)	Young Modules (GPa)	Poisson's Ratio	Yield stress (MPa)
Aluminum	2705	70	0.33	130

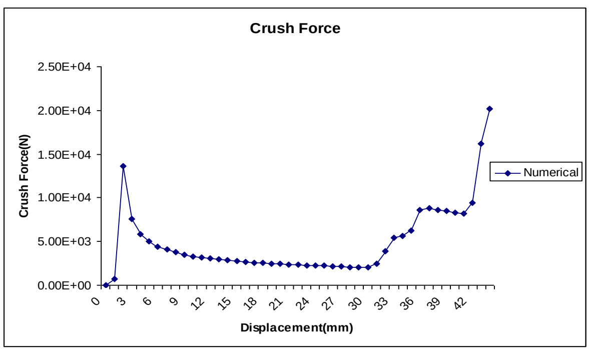


(Load-displacement)

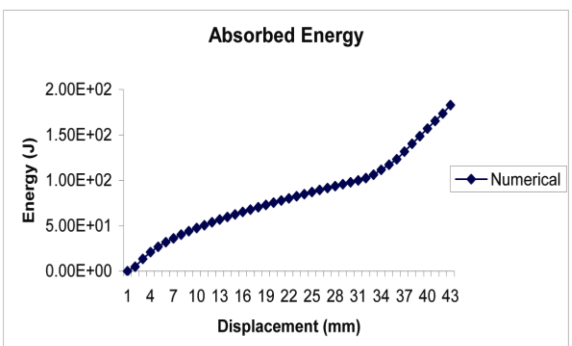


(Energy-displacement)

Fig. 7 Load-displacement and Energy-displacement curves which has been obtained from numerical Rectangular tube with loading speed of 100 mm/s (thickness:1.5mm)

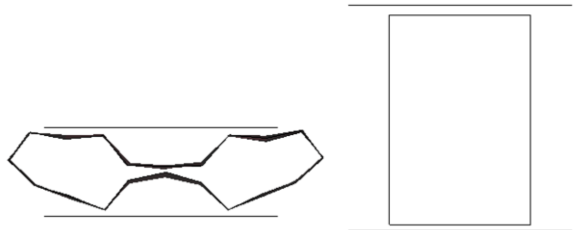


(Load-displacement)

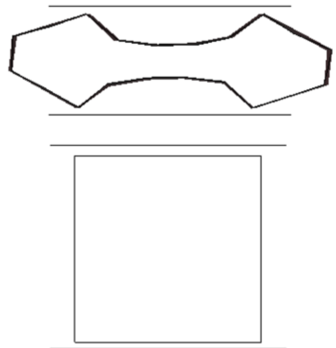


(Energy-displacement)

Fig. 8 Load-displacement and Energy-displacement curves which has been obtained from numerical Square with loading speed of 100 mm/s (thickness:1.5mm)



(a) (Rectangular) (b)



(a) (square) (b)

Fig. 9 Simulation of sample with rectangular and square cross section under loading condition, (a): before loading (b): after loading

5 COMPARISON AND CONCLUSION

After performance of quasi-static tests, results are compared and the rate of effect in amount of loading, the change in thickness and the geometry of cross section in absorbing energy, peak force and mean force were surveyed which their results are given in table 7 to 10, and also Load-displacement curves for samples with rectangular and square cross section with loading speed of 100 mm/s and thickness of 1.5 mm which is obtained from numerical analysis and experimental test are compared in figure 10. To compare the deformation, during the collapse process these tubes which are taken from numerical analysis and experimental test at the same moment, are compared in figure 11.

Table 7 The comparison of result of numerical simulation and experimental loading in a rectangular tube

Specimen Code	Rate of loading (mm/s)	Absorbed Energy (J) (Numerical)	Absorbed Energy (J) (Experimental)	Difference (%)
$_{R}V_{0}$	100	179	185	3.24
$_{R}V_{1}$	150	182	193	5.69
$_{R}V_{2}$	300	197	209	5.74
$_{R}V_{3}$	450	203	218	6.88

Table 8 The comparison of result of numerical simulation and experimental loading in a square tube

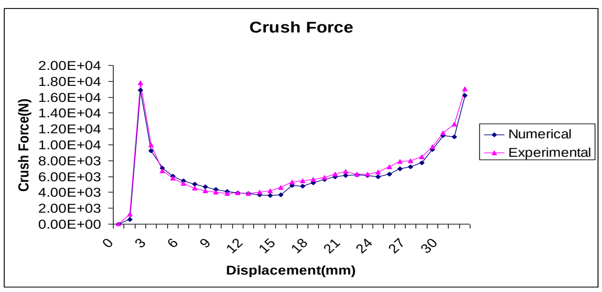
Specimen Code	Rate of loading (mm/s)	Absorbed Energy (J) (Numerical)	Absorbed Energy (J) (Experimental)	Difference (%)
$_{S}V_{0}$	100	183	187	2.13
$_{S}V_{1}$	150	186	199	6.53
$_{S}V_{2}$	300	204	217	5.99
$_{S}V_{3}$	450	211	226	6.63

Table 9 The comparison of result of numerical simulation and experimental loading in a rectangular tube

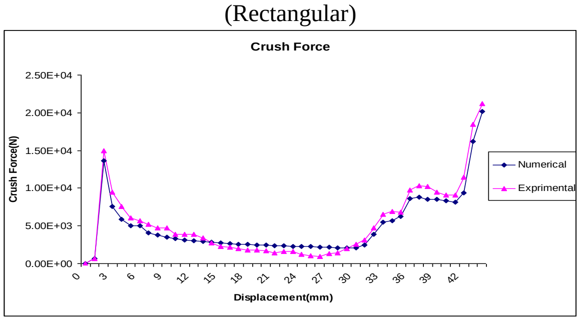
Specimen Code	Thickness (mm)	Absorbed Energy (J) (Numerical)	Absorbed Energy (J) (Experimental)	Difference (%)
$Rec1$	1	59.8	62	3.54
$Rec1.5$	1.5	179	185	3.24
$Rec3$	3	425	450	5.55

Table 10 The comparison of result of numerical simulation and experimental loading in a square tube

Specimen Code	Thickness (mm)	Absorbed Energy (J) (Numerical)	Absorbed Energy (J) (Experimental)	Difference (%)
$Squ1$	1	65.8	68.1	3.37
$Squ1.5$	1.5	183	187	2.13
$Squ3$	3	460	492	6.5

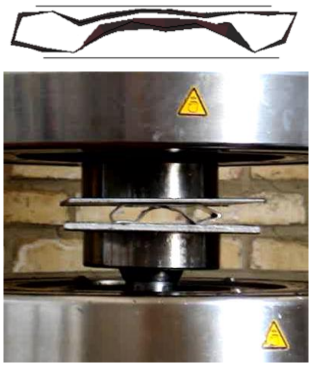


(Rectangular)

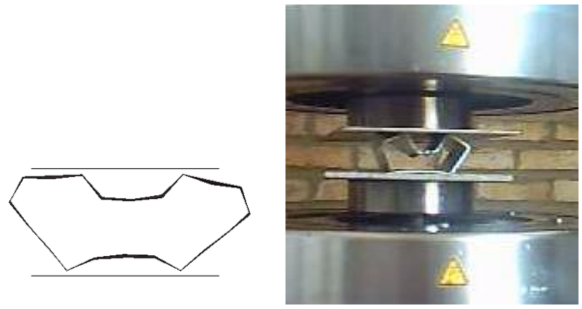


(Square)

Fig. 10 The load-displacement curves for rectangular and square section tubes obtained from experiments and simulations are compared with loading speed of 100 mm/s (thickness:1.5mm)



(Rectangular)



(square)

Fig. 11 Sample with rectangular and square cross section tubes under loading condition, during collapse process, right: numerical analysis, left: experimental test

6 CONCLUSION AND SUMMARY

By considering the results from the researches it is noted that:

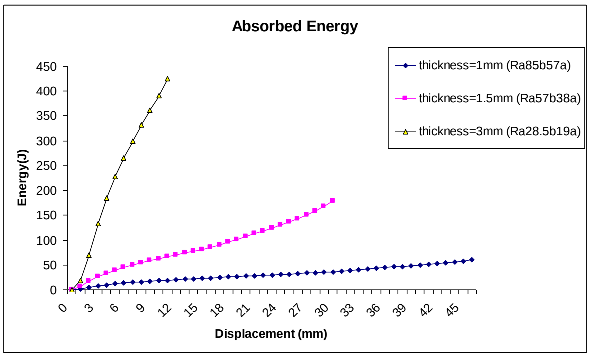
1- By changing the geometrical shape of cross section, the rate of absorbing energy changes and with changing the cross section from rectangular to square, absorbing energy increases.

2- As it can be seen from tables 7 and 8, with increasing the speed of loading, rate of absorption of energy also increases.

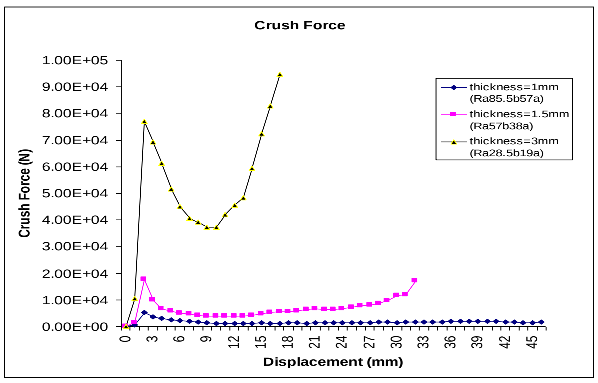
3- As it can be seen from tables 9 and 10, with increasing the thickness, rate of absorption of energy also increases. For a better comparison the Energy - displacement with rectangular cross-section of different thickness can be seen in Fig. 12.

4-With review of peak force with rectangular or square section under different loading condition, it is indicated that with increase of loading speed, peak force will be lowered and also by review of peak force on the sample with rectangular or square cross section peak force is less in the sample with square cross section, which is the optimum cross section for absorbing energy.

5- With review of peak force with rectangular or square section under loading, it is indicated that with increasing thickness, peak force will be increased and also by review of peak force on the sample with rectangular or square cross section peak force is less in the sample with square cross section, which is the optimum cross section for absorbing energy. For a better comparison, the Load -displacement with rectangular cross-section of different thickness can be seen in Fig. 12.



(Energy-displacement)



(Load-displacement)

Fig. 12 The Energy-displacement and load-displacement curves for rectangular section tubes with different thickness

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