Experimental and Numerical Study of Lateral Loadings on the Composite Tubes with SMA and Aluminum Wires and Without Wire

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Abstract: In this paper, crushing length, deformations and energy absorption of thin walled square and rectangular composite tubes which are reinforced with Aluminium and SMA wires and without wire have been investigated under a quasi-static lateral load, both experimentally and numerically. To experimental study, square and rectangular composite tubes have been fabricated with SMA wire, Aluminium wire and without wire. To validate the results, a finite element model is constructed and analysed under the same conditions by using FEM27 and LS-DYNA software packages for composite tubes with Aluminium wire and without wire. The numerical results are in a good agreement with the experimental data. The results show that section geometry and the types of reinforcement wires have a considerable effect on the energy absorption. Rectangular cross-section samples with SMA wires have the most energy absorption capacity.

Keywords: Absorbed-Energy, Composite Tubes, Quasi- Static Load, SMA Wires

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Biographical notes: Sajjad Dehghanpour is Associate Professor of Mechanical engineering at the IAU, Tuyserkan Branch. He received his PhD in Mechanical engineering from IAU, Qazvin Branch. His current research focuses on experimental investigation on the impact, composites, an energy absorber. **Mohsen Rahmani** received his PhD in Mechanical engineering at the IAU, Qazvin Branch. His current research interest includes vibration, dynamic behaviour of sandwich structures, shells, plates, beams, FGM, smart materials and nano-composites, where 18 papers are among his publications.

1 INTRODUCTION

Nowadays, thin walled composite tubes have been widely used in the advanced transport structures, aero-space and vehicle as energy absorbers. Fabrication of these structures is simple. They transfer the kinetic energy to the other kinds of energy and reduce the damaging force which is transferred to the structure by crushing deformation. Axial and lateral crushing are two common types of deformation methods which the thin walled metal tubes can waste plastic energy. Due to the lateral loading which caused the lateral crushing, plastic hinges are formed parallel to axial direction. Using energy absorbers is an appropriate option to increase the safety of passengers in the vehicle. These parts have different shapes and are made of different materials such as low density metals and composites. In the last decade, concept of smart materials has been interesting for researchers especially in the engineering applications like aerospace. Shape Memory Alloys (SMA) in comparison to other smart materials like piezoelectric crystals, electro-restrictive and magneto-restrictive materials are proper in the smart composite structures, because of their very high strain capability, flexibility and unusual properties of materials. Properties of SMA vary with tension, temperature and history of loading. Transforming the crystal-line thermos-elastic phase between high symmetric phase (Austenite) and low symmetric phase (Martensite) is the reason of SMA behaviour [1-2].

Many researchers have investigated the absorber energy and deformations in different structures. Dehghanpour et al. studied energy absorption of square and rectangular metallic tubes [3]. Cetin and Baykasoğlu studied the energy absorbing characteristic of thin-walled tubes enhanced by lattice structures [4]. Firouzi et al. studied energy absorption capability of H-shaped thin walled profiles and optimized the geometry by using the Taguchi method to improve the energy absorption performance [5]. Kaczyński et al. experimentally and numerically studied the energy absorption of foam-filled circular tubes under quasi-static and dynamic axial crushing [6]. Kheirikhah et al. studied experimentally and numerically the energy absorption, crushing length, and deformation of thin walled circular composite tubes under a quasi-static axial loading [7]. Gupta et al. investigated the deformation behavior of the round metallic tubes subjected to quasi-static condition experimentally and computationally [8]. Morris et al. examined the force-deflection response of mild steel short tubes subjected to the quasi-static lateral load with vertical and inclined side constraint both experimentally and numerically [9]. Dehghanpour and Rahmani investigated the lateral collapse of square and rectangular composite tubes experimentally and numerically [10]. Roger and Robertshaw investigated the composites reinforced with SMA and SMA hybrid composite [11]. SMA presents properties which are sensitive to temperature and strain. Also, it shows a significant operational properties in terms of strain or tension, which, although with limited applications, is placed in the smart materials category. To enhance the applications of SMAs which are produced in the form of wire or strips, as the smart materials, they should be combined, with a structural material. Now the production of composite materials with SMA is in a desirable step in the laboratory scale [12]. The experimental and numerical investigation of Alebrahim et al. were carried out on hybrid composite smart beam with SMA wire under quasi static loading [13]. Khalili and Saeedi studied the behavior of laminated hybrid composite beam with embedded SMA wires under the impact of multiple masses [14]. Khalili et al. by embedding the SMA wires between glass fibers reinforced by epoxy composite layers investigated the bending loading condition of sandwich compo-site panels [15]. Khalili and Ardali studied the dynamic response of thin smart curved composite panel reinforced by SMA under a low velocity transverse impact [16]. Shariyat and Niknami analysed the impact of temperature dependent rectangular composite plates with embedded SMA wires both numerically and experimentally [17]. Payandeh et al. studied the effect of martensitic transformation on the debonding propagation in Ni-Ti SMA wires. To obtain wires with different transformation characteristics, different heat treatment operations were performed [18]. Raghavan et al. studied damping, tensile and impact properties of super elastic SMA fiber reinforced polymer composites [19].

As a result of review in the accessible literatures, it is found that more investigation is needed on the effect of quasi static loads on the energy absorption of composite tubes. In this paper, the effect of adding SMA wire and Aluminum wire on the energy absorption of fiber glass composite tubes under a lateral loading is investigated both experimentally and numerically. The results of composites with wire are compared with the result of composites without wires. The composites are made with eight layers, their cross sections are square and rectangular. Square and rectangular fibers are in the form of cloth with [0-90] angles. SMA and Aluminum wires are embedded between fourth and fifth layers of the composite tubes in a helical form with one centimeter pitch. To verify the experimental results, the experimental conditions are simulated with a FEM software in the case of composites with Aluminum wire.

2 EXPERIMENT

2.1. Specification of Samples

It is not possible to buy the thin walled composite tubes with intended dimensions in the market, so the samples have been fabricated in the workshop. To investigate the collapse load and the energy absorption capability of composite tubes, some samples have been fabricated which SMA and Aluminum wires are embedded between the fourth and five layers of the E-glass/epoxy composite tubes, as shown in "Fig. 1(a)". Also, the wireless samples have been made, "Fig.1(b)". The cross sections of the structure are square and rectangular which have constant thicknesses. SMA wires is from Ni-Ti-0.16 heat activated type which are made by Highland company of USA, which are used as orthodontic wires in dentistry.


(a): with wires

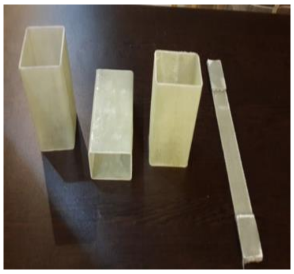
(b): without wires

Fig. 1 Composite tubes with different cross sections.

To determine the mechanical properties of the fabricated tubes, tensile test using INSTRON device model 8305, and based on ASME is performed on the samples which are made from of E-glass and Epoxy sheet, as shown in "Fig. 2" . Also, Stress-strain curve from the tensile test has been shown in "Fig. 3" . By averaging the results, the mechanical properties have been obtained which are depicted in "Table 1" .

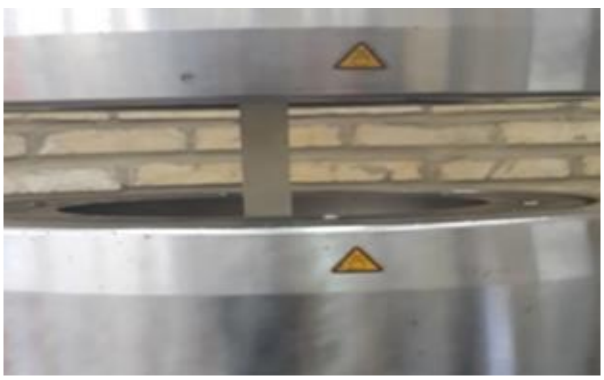
Fig. 2 Tensile test on a sample by INSTRON device.

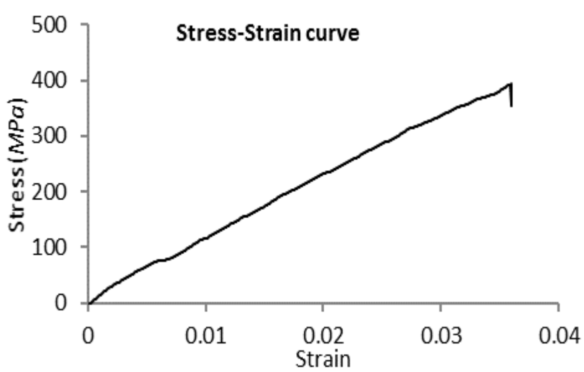

Fig. 3 Stress-strain curve the E-glass / Epoxy composite material.

Table 1 Mechanical properties of the composite tube without wire

Young modulus (GPa)	Poisson's ratio	Yield Strength (MPa)	UTS (MPa)
210	0.3	433	460

The samples have been made as four layers and eight layers. Composite tubes with wires have eight layers. The geometrical properties of the square and rectangular samples are depicted in "Table 2" .

Table 2 Geometrical properties of the Samples

	Square	Rectangle
Length(mm)	47.5	57
Width(mm)	47.5	38
Height(mm)	100	100
Thickness(mm)	1.5	1.5
Number of layers	8	8
angle	0-90	0-90
Fiber	E-glass AF252	E-glass AF252
Epoxy	LY5052	LY5052

3 QUASI-STATIC TESTS

Quasi-static lateral loading tests have been performed by using INSTRON device with speeds of 20 mm/s. This device has two jaws which the upper one is stationary and the lower one can move with a predefined velocity in a specific distance. The load is exerted by the hydraulic system up to 600 KN. To perform the experiment, the sample is placed between the jaws by a rigid steel plate, and quasi-static loadings is exerted by a plate. Maximum force, average force and crushing length after finishing the loading are measured. During the crushing, the load displacement curve is plotted by the sensors of upper jaw, processor and device software (Merlin), and the rate of absorbed energy in each sample are calculated by considering the cross sectional area. In "Fig. 4 and Fig. 5" , the samples with square and rectangular cross sections, before and after lateral loadings have been shown, respectively.

Fig. 4 Square composite tube before and after lateral loading.

Fig. 5 Rectangular composite tube before and after lateral loading.

The force-displacement curves which are obtained from experimental tests for the rectangular and square composite tubes without wire, with Aluminum wire and with SMA wire, and loading speed of 20 mm/s have been shown in “Figs. 6-11” , respectively.

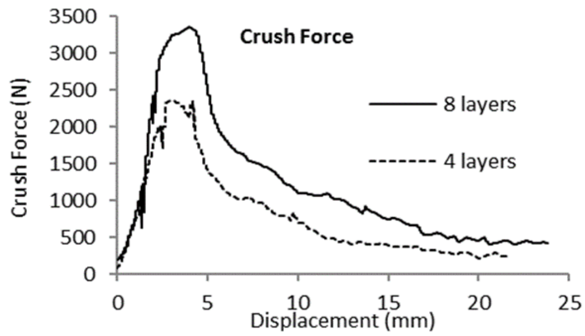

Fig. 6 Force-displacement curve of rectangular tubes without wire.

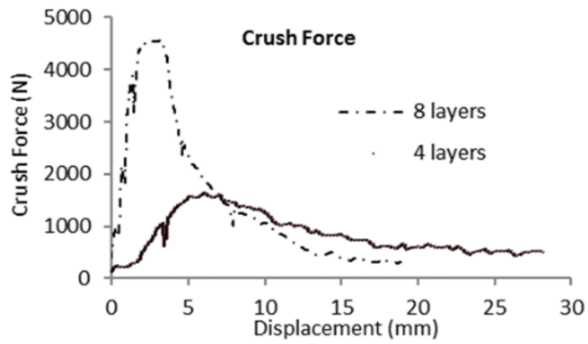

Fig. 7 Force-displacement curve of square tubes without wire.

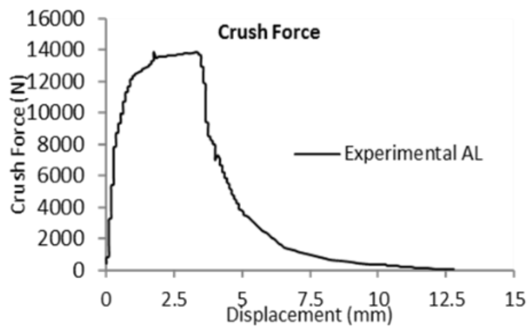

Fig. 8 Force-displacement curve of rectangular tubes with Aluminum wire.

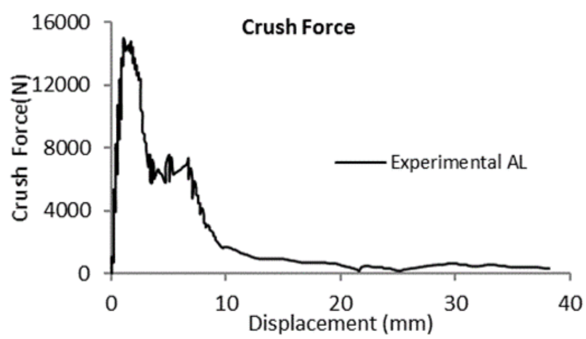

Fig. 9 Force-displacement curve of square tubes with Aluminum wire.

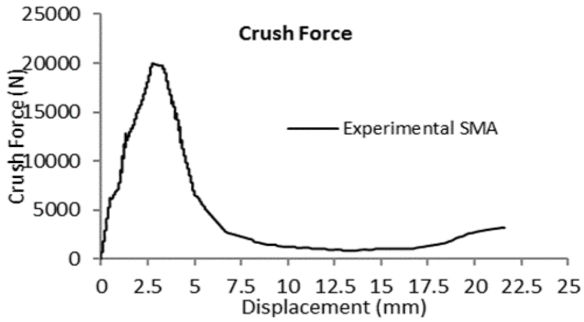

Fig. 10 Force-displacement curve of rectangular tubes with SMA wire.

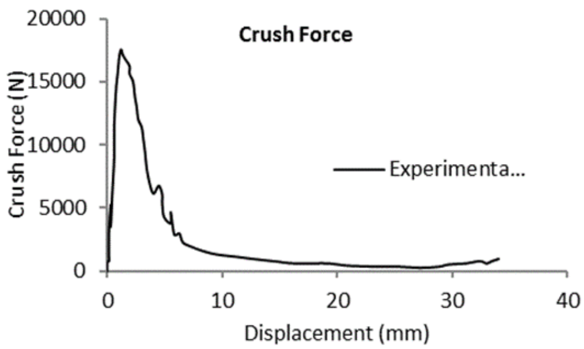

Fig. 11 Force-displacement curve of square tubes with SMA wire.

After conducting the tests and obtaining the curve for force-displacement, the rate of energy absorption at the end of compression process is obtained by calculating the area under force-displacement curve. In "Table 3" , crushing length, maximum force, average force, and absorbed energy, at the end of process, for 4 layers (R4) and 8 layers (R8) rectangular samples without wire, 8 layers' rectangular samples with Aluminum wire (R8-AL) and with SMA (R8-SMA) and for 4 layers (S4) and 8 layers (S8) square samples, 8 layer square samples with Aluminum wire (S8-AL) and with SMA wire (S8-SMA) are compared with each other.

Table 3 Comparison of the experimental results of rectangular and square composite tubes with SMA wire, Aluminum wire and without wire

Sample code	Crushing length (mm)	Maximum force (N)	Average force (N)	Absorbed energy (J)
R4	21.46	2364.23	803.26	17.243
R8	23.76	3350.2	1203.66	28.607
R8-AL	12.7826	13852.6	4648.87	59.4247
R8-SMA	21.6223	19898.5	4382.10	94.7512
S4	28.11	1659.49	851.24	23.925
S8	18.80	4564.01	1533.24	28.835
S8-AL	38.159	14923.1	2250.66	85.883
S8-SMA	34.04236	17509.39	2299.65	78.28556

4 NUMERICAL SIMULATION

The experimental tests are expensive and difficult, and the theoretical analysis of plastic deformation problems is complicated, so the researchers preferred to analyse the problem numerically with FEM soft wares. To verify the results of the experimental tests, the quasi-static crush tests of composite tube samples with same dimensions are simulated in FEM27 software package. First the part of each sample, according to required dimension which is developed between two solid plates, is simulated by software package of LS-DYNA 970, such that, the lower plate is fixed and the upper plate is moving downward and vertically with speed of 20 mm/s. Due to high capability in defining the material properties to create a model, FEMB27 software package is used, and 3D simulation is done to establish an accurate condition coincident with experimental tests.

The geometrical characteristics of the sample are presented in "Table 2" . Samples include thin-walled tube which two rigid plates are placed at the ends of them. The tube is crushed between these two rigid plates and is modelled based on Belytscho-Tsay four node element shells with the thickness of 1.5 mm. The coefficient of friction between two end plates and each sample is taken 0.2. Material of the end plates is considered No. 20 (rigid) as Matpicewise_linear placticity (24). Boundary conditions are considered similar to the experimental tests. According to the situation of upper and lower jaws in INSTRON device, upper rigid plate is fixed and the lower plate moves upward, only in vertical direction with the speed of 20mm/s. Mechanical properties of Aluminum wire which are embedded to the layers are presented in "Table 4" .

Table 4 Mechanical properties of Aluminum wire

Yield Stress (Mpa)	Poisson's ratio	Young modulus (Gpa)	Density (Kg/m3)
130	0.33	70	27.5

FEM model of deformation of square tube with Aluminum wire during loading is shown in "Fig. 12". In "Fig. 13", numerical crush-displacement curves and energy-displacement curves of square tube without wire and with Aluminum wire are shown with a speed of 20mm/s loading. Figure 14 depicts the deformation of square tube with Aluminum wire under transversal loading in both numerical and experimental models. Finite element model of rectangular tube with Aluminum wire during loading is shown in "Fig. 15". Numerical crush-displacement curves and energy-displacement curves in rectangular tube with Aluminum wire and without wire in speed of 20mm/s loading are depicted in "Fig. 16".

Figure 17 shows the numerical and experimental deformation of rectangular tube with Aluminum wire under lateral loading.

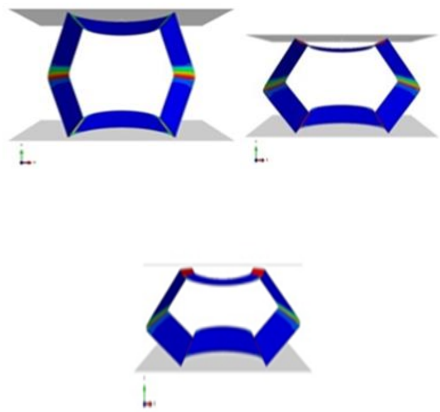

Fig. 12 FEM model of deformation of square tube with Aluminum wire during loading.

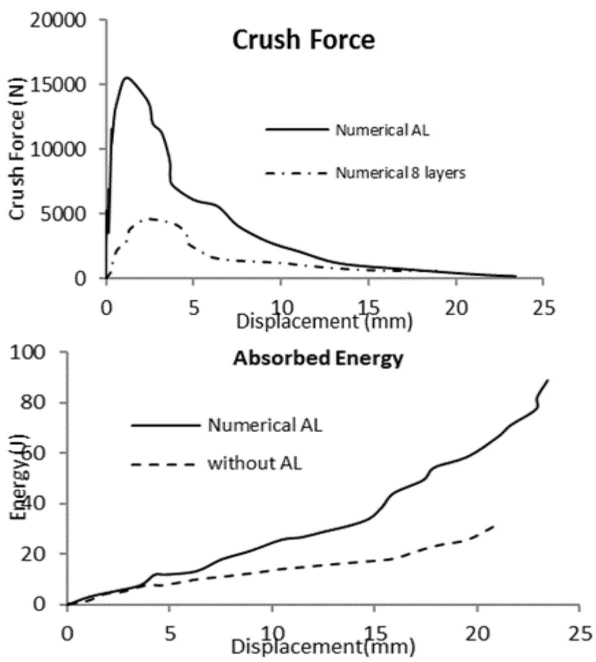

Fig. 13 Numerical crush-displacement curves and energy-displacement curves of square tube without wire and with Aluminum wire.

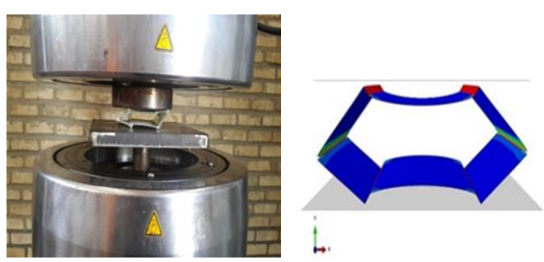

Fig. 14 Experimental and numerical deformation of square tube with Aluminum wire under lateral loading.

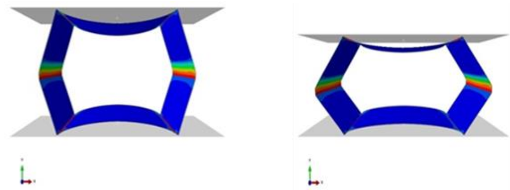

Fig. 15 FEM deformation of rectangular tube with Aluminum wire during loading.

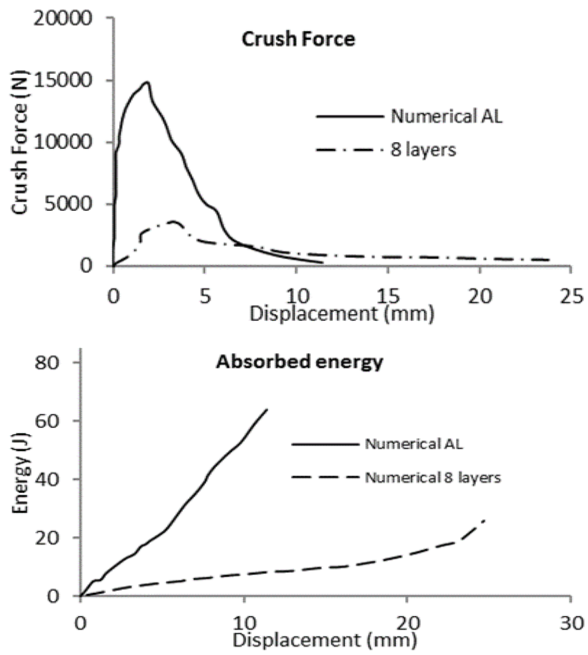

Fig. 16 Numerical crush-displacement curve and energy-displacement curve of rectangular tube without wire and with Aluminum wire.

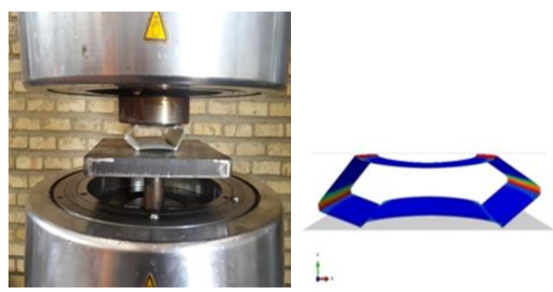

Fig. 17 Experimental and numerical deformation of rectangular tube with Aluminum wire under lateral loading.

5 COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

As depicted in "Table 5" and "Table 6" , numerical and experimental results of the square and rectangular samples without wire are compared with square and rectangular tubes with Aluminum wire. Also, these results are compared with square and rectangular samples with SMA wire, experimentally.

Table 5 Comparison of experimental and numerical results of rectangular tubes

Sample code	Number of layers	Absorbed energy (J) (numerical)	Absorbed energy (J) (experimental)	Difference
R4	4	17.731	17.243	%2.75
R8	8	27.287	28.607	%4.61
R8-AL	8	63.848	59.42	%6.9
R8-SMA	8	-	94.75	-

Table 6 Comparison of experimental and numerical results of square tubes

Sample code	Number of layers	Absorbed energy (J) (numerical)	Absorbed energy (J) (experimental)	Difference
S4	4	24.649	23.925	%3.02
S8	8	30.721	28.835	%6.54
S8-AL	8	88.91	85.88	%3.4
S8-SMA	8	-	78.28	-

6 CONCLUSIONS

In this paper, the effect of embedding SMA wire and Aluminum wire in the fiber glass composite tubes on the energy absorbing were investigated. Composites with wire had 8 layers which were made as square and rectangular cross-sections. Square and rectangular type fibers were in the form of cloth with [0-90] angles. SMA wires and Aluminum wires were helical form, with 1 cm pitch which were embedded between 4th layer and 5th layer of the structures. Square and rectangular tubes were subjected to lateral loadings. Wireless composites were fabricated as square and rectangular 4 layers and 8 layers tubes. There were good agreement between the numerical and experimental results. By comparing the numerical and experimental results of the samples, the following states are obtained:

1) Selecting the fabrication method and accuracy of fabrication have a significant role in improvement of the results.

2) Adding wire to composite tubes leads to significantly increase in the rate of energy absorption and maximum force.

3) In wireless tubes, increasing the layers of composites results in increasing the maximum force and the rate of absorption energy.

4) In the rectangular tubes, the rate of energy absorption in the tubes with SMA wire is more than tubes with Aluminum wire.

5) In the square samples, the tubes with Aluminum wire have a little more energy absorption in comparison with tubes with SMA wire.

6) Maximum force in the tubes with SMA wire is more than the tubes with Aluminum wire.

7) Rectangular cross-section samples with SMA wires have the most energy absorption capacity.

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