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# Study on mechanical characteristics of accordion metallic damper

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ABSTRACT

This paper presents Accordion Metallic Damper (AMD) as a unique energy dissipating system that originated from the concept of thin-walled tubes used in machinery as the shock absorber. The AMD can perform as a repairable hysteretic fuse in structural frames to enhance the lateral ductility, energy-dissipation and damping potential of the frame systems during earthquakes. The AMD consists of the corrugated thin-walled tubes installed at the brace connection to the frame. The lateral displacement of the braced frame causes yielding of the AMD in axial deformation mechanism and dissipates energy due to forming of plastic hinges along the corrugated tubes in reversed cyclic deformations. In order to evaluate the performance of the AMD for upgrading the seismic behavior of the structures a series of quasi-static cyclic tests were conducted on pre-fabricated corrugated thin-walled tubes and hysteretic load-deformation response, lateral strength, initial stiffness, and dissipated energy was investigated. Numerical studies were also carried out to provide a large parameter results to explore the effect of geometry parameters such as shape, thickness, diameter and length of the corrugated tube on the mechanical properties. The analytical model was created based on finite elements method and non-linear inelastic analysis with considering large deformation capacity was employed for these studies. The results showed that the AMD exhibited enhanced energy-dissipation and damping potential with stable hysteresis loops and confirmed that the AMD is an excellent energy-dissipating device that can be used for upgrading the seismic behavior of framed structures.



## 1. Introduction

Traditional methods for seismic resilient structures are gradually losing their significance by developing the modern control systems such as energy dissipating systems [1]. Energy dissipating systems such as metallic dampers have been developed during the past four decades for controlling the structural vibrations due to earthquake. Tensional and bending beam and U shape bands were among the first dampers. Balendra conducted several works in this area from 1990 to 1997 [27]. X-shaped and V-shaped bending plates, known as ADAS and TADAS dampers are other types of dampers which take advantage of uniform yielding of steel and have been developed and are used in industry [2,3]. Using this system decreases the seismic vulnerability of the buildings significantly and provides enhanced performance and balance of energy absorption in the structural elements [4,5]. Also, there are many studies performed regarding the use of energy dissipating systems for retrofitting the reinforced concrete frames. Sahoo and Rai used aluminum shear links for seismic strengthening of non-ductile reinforced concrete frames [6]. The ring elements are the new flexural fuses which can be installed in CCBF's. Abbasnia, Vetr and Kafi conducted a testing program on ductile steel ring elements attached to braces [7]. Maleki, Bagheri and Mahjoubi studied pipe damper and dual-pipe systems in the frame connection and showed the potential of the system in energy dissipation during an earthquake [8,9]. Tagawa and Gao proposed a new vibration control system with U-shaped steel damper and evaluated the stiffness and strength of the system [10]. Motamedi and Ventura tested steel ring connections at mid-joint of X-brace steel frames and showed an enhanced energy-dissipation and damping potential for this system [11]. Furthermore, metallic dampers were suggested for timber structures with new mechanism such as rocking. Wrzesniak et al. investigated applicability of High-Force-to-Volume damping devices in rocking timber structures [12]. On one hand, there are so many experimental and analytical studies on using and application of metallic dampers for seismic retrofitting of structures [13]. On the other hand, certain studies performed on the energy-dissipation of thin-walled tubes due to impact loads. Many researchers have studied the plastic deformation mechanisms in axially compressed metal tubes used as impact energy absorbers [14–16]. Also square metal tubes were investigated under axial impact [17] while some studies were focused on the maximization of crushing energy absorption of cylindrical shells [18]. Moreover, study of behavior of axially crushed corrugated tubes under impact load was conducted [19]. Chen and Ozaki also performed numerical studies on axially crushed cylindrical tubes

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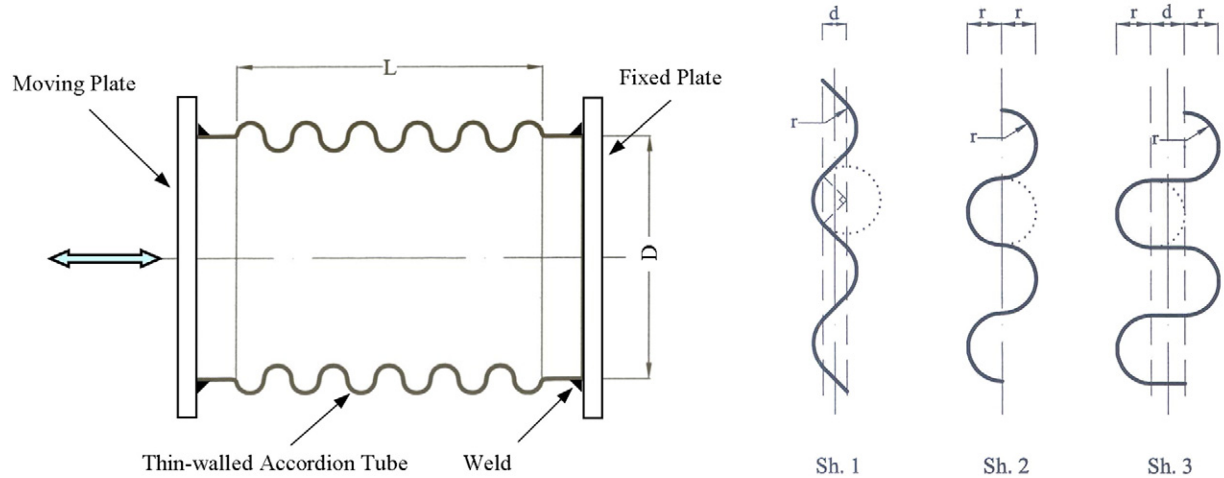



**Fig. 1.** Schematic view of Accordion Metallic Damper (AMD) device and the geometry parameters.

with corrugated surface [20]. Thin walled tubes under axial compression are considered as one of the best methods for absorbing the energy because of the large deformation capacity and long crippling length. However, these systems can deform and absorb energy only in impact condition.

In this paper, the performance of thin-walled accordion tubes has been studied under axial cyclic loading. The objective of this study was to explore the capability of this system as an energy dissipating system for upgrading the seismic behavior of frame structures. Therefore, a series of tests was planned and conducted to investigate the mechanical properties of Accordion Metallic Dampers (AMD) such as initial stiffness, ultimate load capacity and hysteretic energy-dissipation potential. Also, an analytical study was performed using a finite element model. The numerical models were verified with the experiments and employed in order to study the effect of geometry parameters on performance of the AMD.

## 2. Accordion metallic damper concept

Using thin-walled accordion tubes as an energy dissipating system has been currently suggested by Motamedi and Nateghi-A. [21]. They showed that thin-walled accordion tubes are suitable for using as hysteretic metallic damper if a proper inelastic deformation of corrugates occur along the tube during an earthquake. Schematic view of Accordion Metallic Damper (AMD) device and its geometry parameters is shown in Fig. 1. As it is shown, AMD is fabricated of a thin-walled accordion tube welded to a couple of plates at the ends. Energy dissipation in AMD device is based on plastic deformation of steel material mainly in flexural form. Relative displacement of the end plates generates axial deformation in the tube and flexural plastic hinges form in the corrugates. Formation of plastic hinges in several corrugates due to reversed cyclic loading dissipates energy. This behavior enhances the performance of the AMD in structures subjected to severe earthquakes. The accordion tube can be manufactured in different shapes; S-shape, C-shape and U-shape, (Sh. 1, Sh. 2 & Sh. 3, respectively shown in Fig. 1). Hence, L, D, t, r and N represent length of tube, diameter of tube, wall thickness, radius of wrinkles plate and number of corrugates along the tube, respectively. Obviously, the behavior and performance of the AMD and its mechanical properties severely depend on the shape of the tube. Therefore, an extensive parameter study is required to determine the optimal geometry parameters for the AMD to obtain the maximum energy-dissipation. The thin-walled tube should be fabricated from mild steel material with a minimum of 30% elongation in tensile coupon test to guarantee ductile behavior.

An applicable installation scheme of the AMD within a steel frame structure is illustrated in Fig. 2. The AMD is assembled either on top of an inverted-V brace and connected to the beam by two stiffened supports. When frame is subjected to lateral movement, lateral load on the frame is allowed to transfer to the braces and sever axial deformation concentrated in the AMD. In the shown position in Fig. 2 one accordion tube deforms in tension while the other one deforms in compression. This type called as “coupled AMD” in this paper.

## 3. Experimental studies

An experimental study was performed in order to investigate the behavior of thin-walled accordion tubes [26]. The objectives of this testing program were to study the behavior and performance of the AMD under cyclic large deformation, determine the mechanical properties of the AMD and collect valid data in order to validate the numerical models.

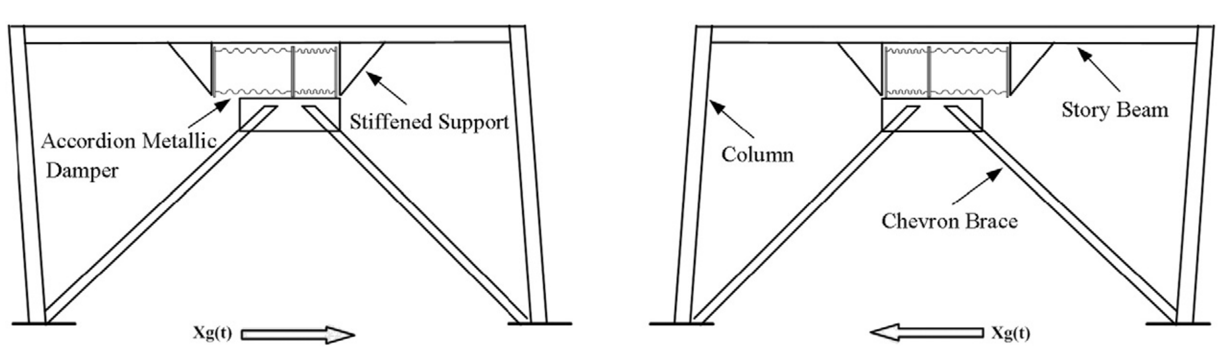



**Fig. 2.** Installation scheme for AMD and the deformation mechanism.

**Table 1**
Properties of the specimens used for experimental studies.

| Specimen type | Specimen no. | Shape type | D (mm) | L (mm) | t (mm) | r (mm) | d (mm) | n | Steel type |
|---|---|---|---|---|---|---|---|---|---|
| Coupled | 1 | Sh. 3 | 158 | 2 × 152 | 0.5 | 4 | 8 | 2 × 10 | A304 |
| Single | 2 | Sh. 3 | 136 | 152 | 0.5 | 4 | 8 | 10 | A304 |
| | 3 | Sh. 3 | 158 | 152 | 0.5 | 4 | 8 | 10 | A304 |
| | 4 | Sh. 3 | 217 | 190 | 0.6 | 5 | 8 | 10 | A304 |

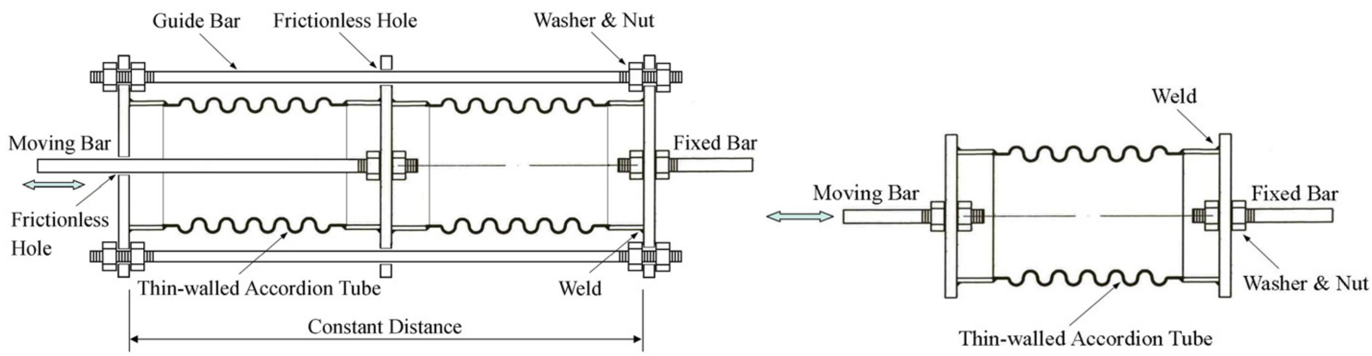



**Fig. 3.** Schematic view of the specimens prior testing: a) coupled specimen; b) single specimen.

### 3.1. Specimens and material properties

Four test specimens were fabricated in two types; one coupled and three single thin-walled accordion tubes and used for testing program. Table 1 presents the properties of the specimens used for the tests. Also, schematic view of the coupled and single specimens is exhibited in Fig. 3. This figure explains the mechanism of the AMD specimens, connections and shows how they perform.

The thin-walled tubes were made of structural steel material conforming to ASTM A653 (A6M3) with a galvanized coating for all sheet thicknesses [25]. Three tensile coupon tests were conducted for 0.5 mm thick sheet used for the specimens based on ASTM A370-97a Standard. The base metal material properties are given in Table 2. Fig. 4 illustrates the engineering stress-strain diagrams obtained from tensile material tests.

**Table 2**
Material properties of steel thin-walled accordion tubes.

| Coupon test no. | Sheet thickness (mm) | Yield strength (MPa) | Ultimate strength (MPa) | Modulus of elasticity (GPa) | Elongation[a] (%) |
|---|---|---|---|---|---|
| 1 | 0.5 | 198 | 426 | 201 | 59.5 |
| 2 | 0.5 | 196 | 430 | 209 | 60 |
| 3 | 0.5 | 197 | 426 | 209 | 60.9 |

[a] Based on 50 mm gage.

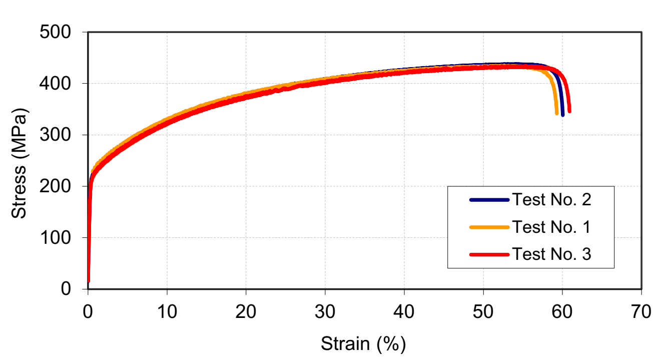



**Fig. 4.** Engineering stress-strain diagrams obtained from tensile material tests.

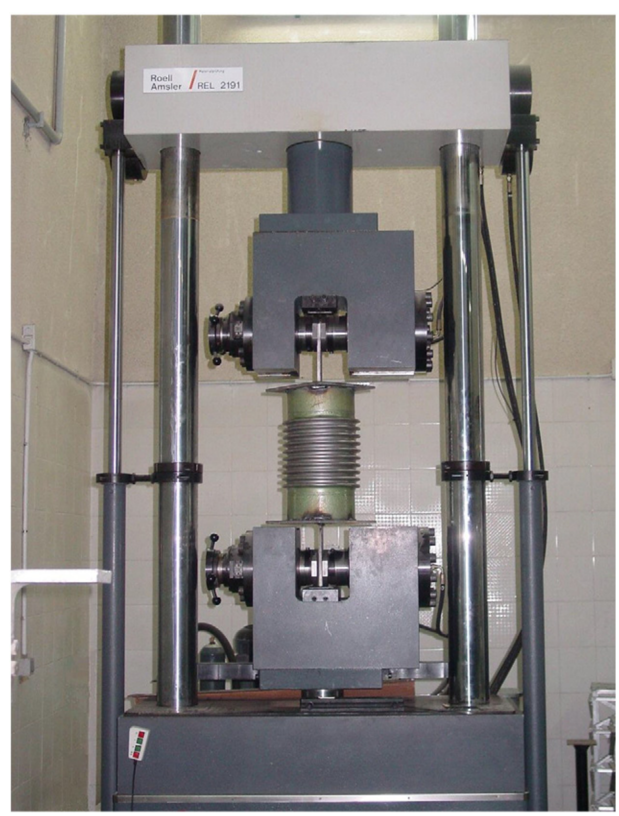



**Fig. 5.** Experimental test setup using uni-axial testing machine.

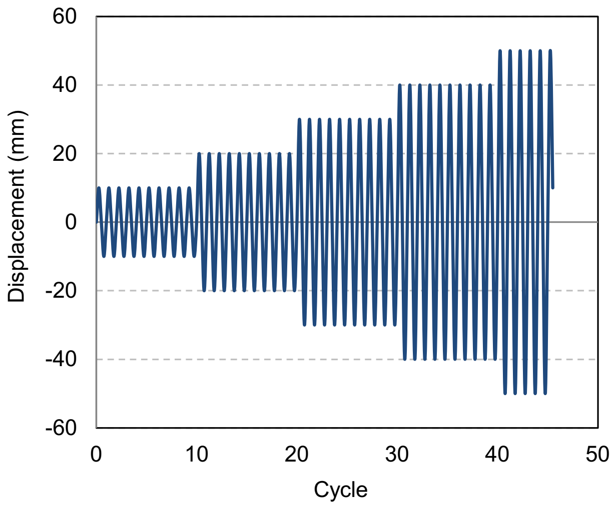



**Fig. 6.** Axial loading protocol for cyclic tests of thin-walled accordion tubes.

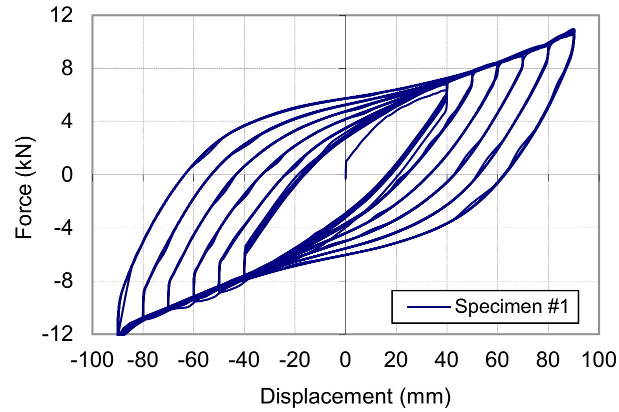



**Fig. 8.** Hysteresis loops of coupled Accordion Metallic Damper (Specimen 1).

### 3.2. Test setup and loading protocol

A series of quasi-static cyclic tests was conducted on AMD specimens. A uni-axial dynamic testing machine in the structures laboratory of International Institute of Earthquake Engineering and Seismology (IIEES) was used for cyclic tests. Fig. 5 shows the test machine, test setup and a specimen prior to testing. As shown, the end plates are welded to the tube and the connected bars would be fastened to the grips in the testing machine. The specimens were only subjected to axial deformation without any rotation at the ends.

A Loading protocol as shown in Fig. 6, was used for quasi-static cyclic testing of specimens based on existing experimental studies on energy dissipating system. This protocol was designed for displacement control and was including large cycles with gradually increasing amplitude from 10 to 60 mm.

### 3.3. Test results and discussion

#### 3.3.1. Coupled AMD

Fig. 7 illustrates the coupled AMD (Specimen 1) during the test. The specimen was subjected to tensile and compression axial movement of the test machine and deformed in axial direction. As seen in the figure, the specimen was extremely deformed, one tube in compression while the other tube deformed in tension. The severe flexural deformation was concentrated in peak area of all corrugates in the compressed tube. Whereas, in the tensioned tube the deformation was observed in the bottom of the corrugates along the tube. In the reversed cycle, inelastic deformation occurred in opposite direction. Thus, input energy was dissipated by forming of plastic hinges in peak and bottom points of the corrugates in reversed cyclic deformations. However, the premature instabilities of the accordion tubes, such as sudden overall or local buckling, transverse deformation of the tubes, bending or failure of plates, bars and welds were not observed at any amplitude levels up to 60 mm.

Cyclic load-displacement response of this specimen is presented in Fig. 8. The coupled AMD exhibited full, stable, and symmetric hysteretic loops with significant post-yield strain-hardening behavior. Further, the specimens did not show any degradation in strength and stiffness during the entire loading procedure. No pinching effect was observed in hysteresis loops and the overall shape of the loops confirmed that AMD in couple pattern is a perfect devise as energy dissipating system. However, this specimen exhibited very low stiffness and load capacity which is attributed to the very low thickness of plate (0.5 mm) used for thin-walled tubes.

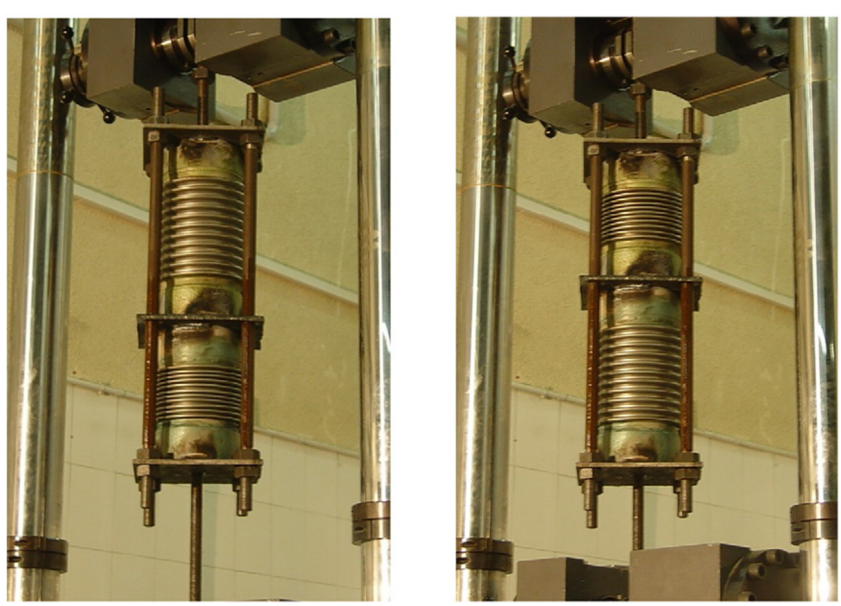
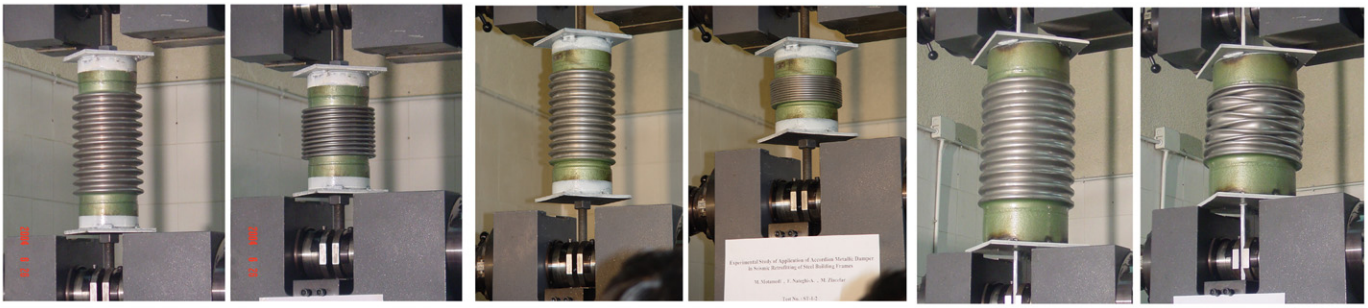


**Fig. 7.** Axial deformation of coupled Accordion Metallic Damper during cyclic test (Specimen 1).



(a) (b) (c)

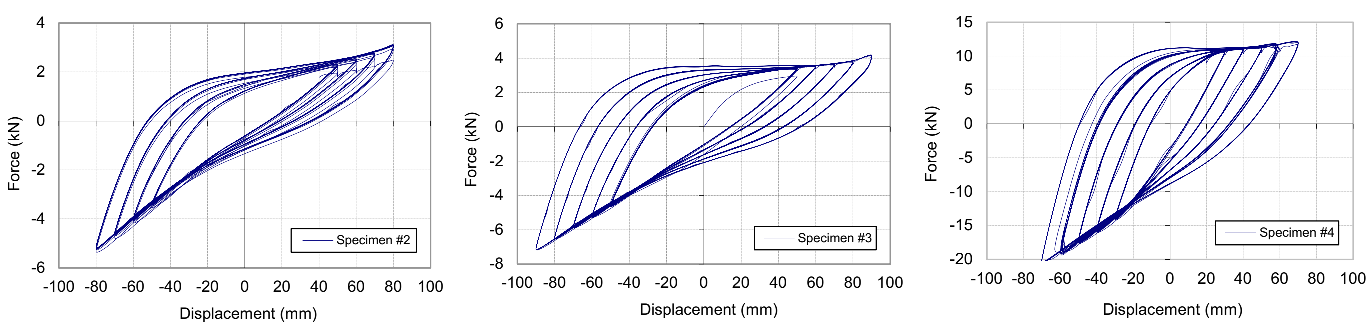
**Fig. 9.** Axial deformation of single thin-walled accordion tubes during cyclic test: a) Specimen 2, b) Specimen 3, c) Specimen 4.

*3.3.2. Single AMD*

Axial deformation of specimens 2, 3 and 4 are illustrated in Fig. 9 during the test. All the specimens have tolerated deflection about 60 mm and 70 cycles in a stable estate without any tearing or damage. Hysteretic behavior of single specimens are shown in Fig. 10. The area under hysteresis loops represents the amount of dissipated energy in cyclic deformation which is quite comparable with current dissipated devices. Reconciliation of hysteresis loops indicates no deterioration Such as strength reduction, stiffness degradation in axial deformation mechanism. Further, no pinching effect was observed in single AMD hysteresis loops. However, behavior of the tubes is not equal in tension and compression which is associated with large deformation and changing the geometry of the corrugates in tension state. Plastic capacity and amount of dissipated energy were increased by increasing the tube diameter and therefore the better behavior is obtained in larger specimen. The results obtained from testing program were used for verification of numerical models.

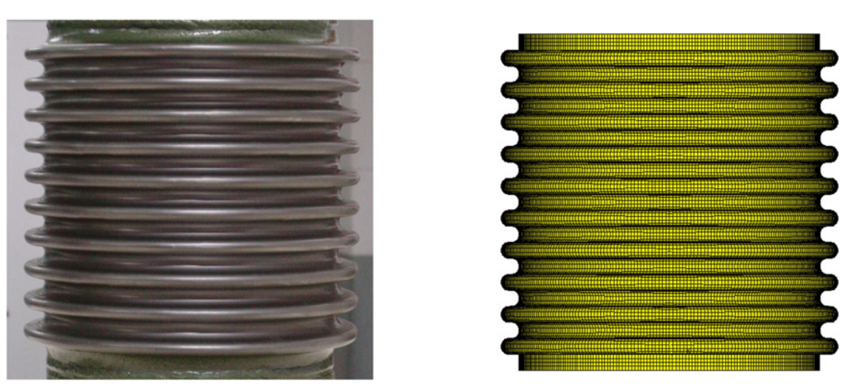
## 4. Analytical studies

Analytical studies were performed in order to investigate the performance of the AMD, stress distribution along the accordion tube and offering design equations for predicting the mechanical properties. The effect of geometry parameters on elastic stiffness, load capacity and dissipated energy was also studied.




(a) (b) (c)

**Fig. 10.** Hysteresis loops of single thin-walled accordion tubes: a) Specimen 2, b) Specimen 3, c) Specimen 4.



(a) (b)

**Fig. 11.** Finite elements model of the single thin-walled accordion tube with shell elements: a) test specimen (Specimen 4), b) finite elements model.

**Table 3**
Comparison of experimental results and computational analysis in Specimen 4.

| | Dissipated energy (kJ) | | | Ultimate compression strength (kN) | | | Axial stiffness (kN/mm) |
|---|---|---|---|---|---|---|---|
| Max. displacement (mm) | 20 | 40 | 60 | 20 | 40 | 60 | |
| Experimental model | 0.124 | 0.646 | 1.474 | 9.32 | 10.89 | 11.09 | 0.760 |
| Analytical model | 0.035 | 0.725 | 1.609 | 11.09 | 12.46 | 12.75 | 0.593 |
| Variation (%) | 71 | 12 | 9 | 16 | 13 | 13 | 22 |

### 4.1. Numerical models

A computational 3D model based on finite elements method was created for extensive analytical studies [22]. The material and geometric nonlinearities are both considered in the numerical models. Quadratic shell elements (Shell 181) have been used for mesh. Nonlinear analysis has been performed with considering the effect of large deformation. Actual characteristics of tensile coupon test result were used for material properties. Von Mises yield criterion was used for failure criteria of the materials [23]. The nodes along boundaries in one side of the model were restraint in all directions and in the other side were subjected to displacement. The displacement control loading protocol used for cyclic tests was applied to the numerical models to simulate the experimental study. The analytical model of Specimen 4 is shown in Fig. 11. The model was verified by experimental results of the same single specimen. Comparison of computational analysis and experimental results is illustrated in Table 3. Also Fig. 12 shows the fitted analytical hysteresis loops by experimental results of Specimen 4 which proofs the accuracy of the model for parameter studies.

### 4.2. Numerical results

Fig. 13 shows the stress counter plot that explains the distribution of stress in accordion tubes based on Von Misses criteria [23]. This plot suggests that the stress ratio in peak points of the corrugates and their close area have been reached to yielding limit. Yielding area has been developed by enforcing more axial deformation and this confirms more energy-dissipation in axial deformation of AMD.

### 4.3. Parameter study

An extensive parameter study was performed on single AMD devices in order to investigate the effect of geometry parameters on mechanical properties. Effect of wall thickness, diameter of tube and number of corrugates on axial elastic stiffness of C-shape thin-walled accordion tubes are illustrated in Fig. 14. The axial stiffness was increased by enlarging the wall thickness and decreased by enlarging the number of corrugates or tube's length. Also, the effect of *r*/*R* ratio, radius and number of corrugates on axial elastic stiffness of C-shape

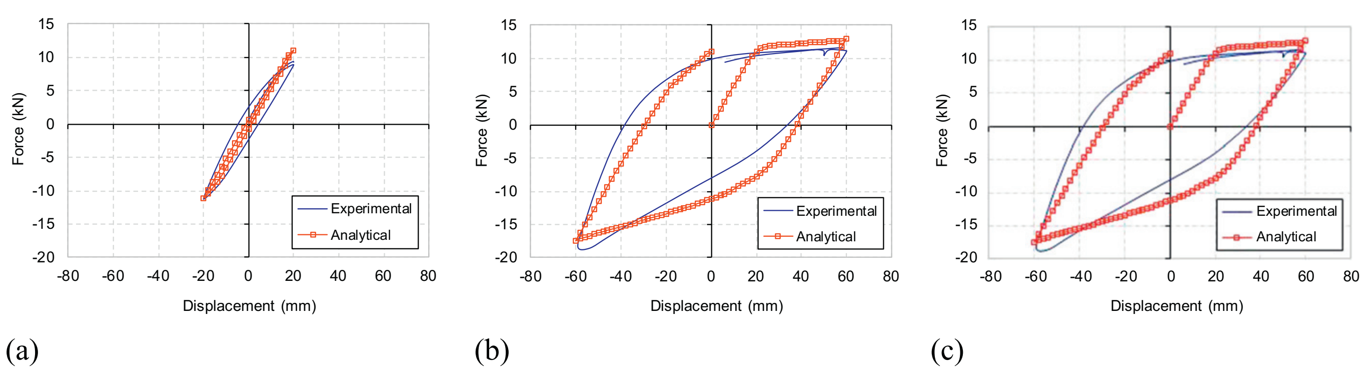



**Fig. 12.** Verification of analytical model with experimental results (hysteretic loops of Specimen 4 have been shown only in one fully reverse cycle with maximum deformation); at: a) 20 mm, b) 40 mm, c) 60 mm.

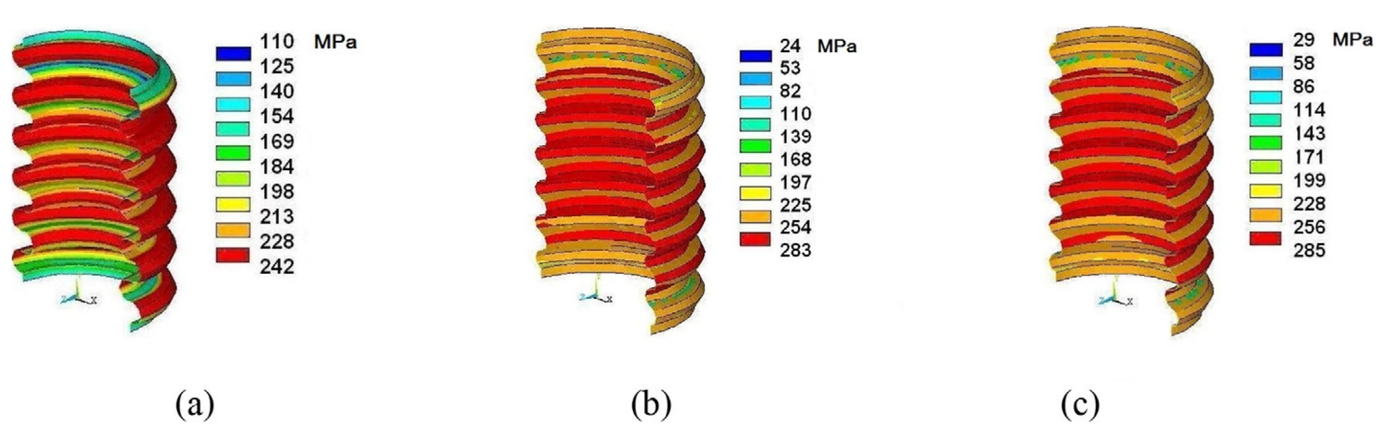



**Fig. 13.** Stress contour plot in thin-walled accordion tubes based on Von Misses criteria: a) shape type 1, b) shape type 2, c) shape type 3 (corresponding to Fig. 1).

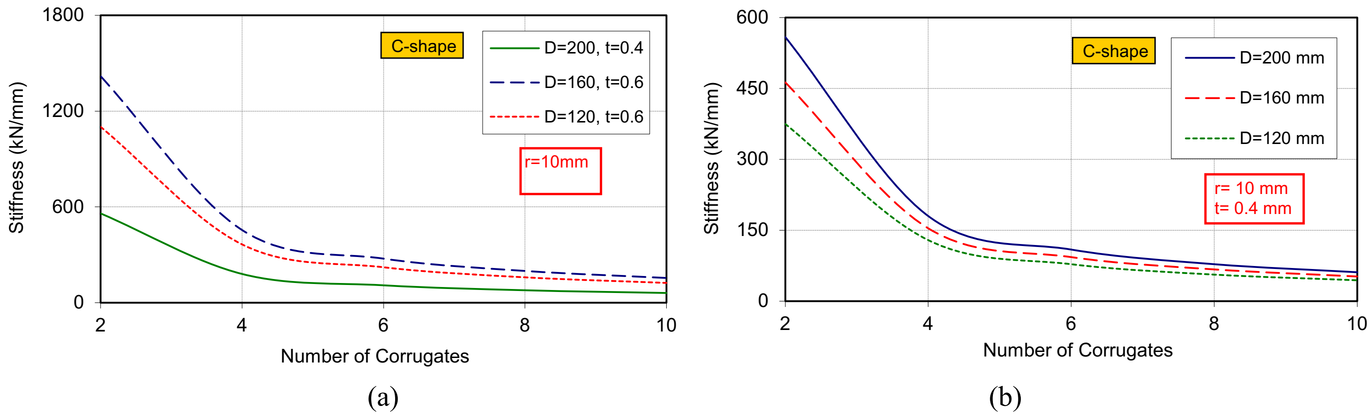



**Fig. 14.** Effects of wall thickness, tube diameter and number of corrugates on axial elastic stiffness of C-shape (Sh. 2) thin-walled accordion tubes.

thin-walled accordion tubes are shown in Fig. 15. Apparently, by enlarging the number of corrugates and $r/R$ ratio, no significant variation in stiffness was observed. Axial elastic stiffness is one of the most important mechanical properties of hysteretic metallic dampers which is required in design procedure of energy dissipating systems [24].

The effect of wall thickness and diameter of the tube on dissipated energy of C-shape thin-walled accordion tubes in a fully reverse cycle is shown in Fig. 16. As these diagrams show, the amount of dissipated energy was increased by enlarging the wall stiffness and diameter of the tube.

Also, the Fig. 17 illustrates the effect of number of corrugates and radius of corrugates on dissipated energy of C-shape thin-walled accordion tubes in a fully reverse cycle. The amount of dissipated energy was decreased by enlarging the number and the radius of corrugates. In all these parameter studies, the effective parameters assumed constant except one which was variable. Effect of collective parameters on dissipated energy is shown in Fig. 18. In this figure the dimensionless ratio of $tR/r^2$ versus dissipated energy was calculated and shown. By selecting the ratio of 4.25 the maximum amount of dissipated energy was derived.

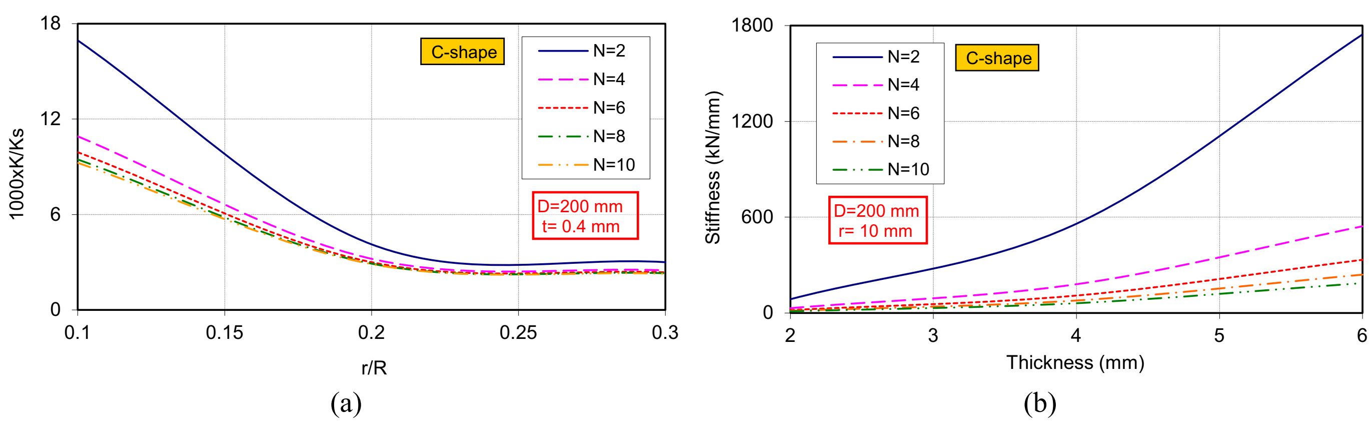



**Fig. 15.** Effects of $\frac{r}{R}$ ratio, wall thickness and number of corrugates on axial elastic stiffness of C-shape thin-walled accordion tubes.

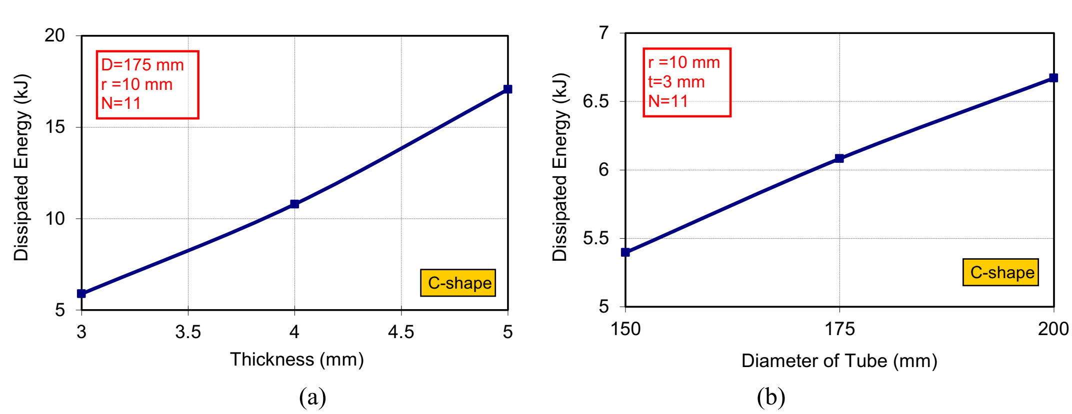



**Fig. 16.** Effects of wall thickness and tube diameter on dissipated energy of C-shape thin-walled accordion tubes in a fully reverse cycle with 40 mm deformation.

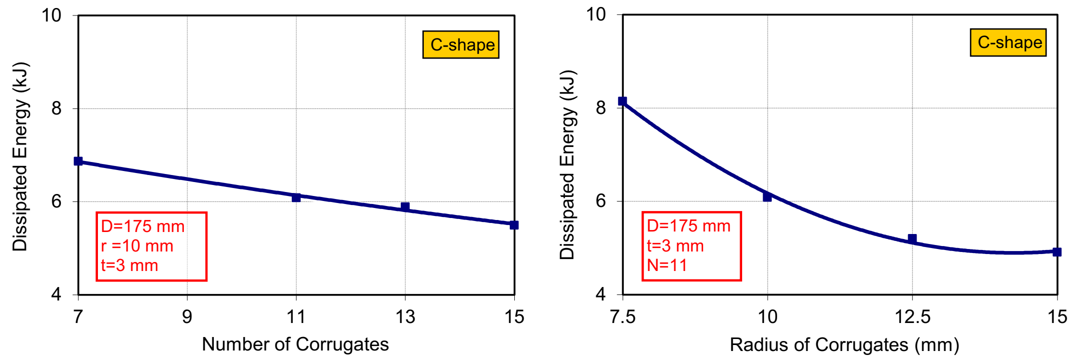



**Fig. 17.** Effects of number of corrugates and radius of corrugates on dissipated energy of C-shape thin-walled accordion tubes in a fully reverse cycle with 40 mm deformation.

*4.4. AMD characteristic formulation*

Axial elastic stiffness is one of the most important mechanical characteristics of thin-walled accordion tubes, which is required in design procedure of energy dissipating systems. A mathematical model was used for determining this character based on mechanics of materials principles. A curved strip by sinusoidal shape (S-shape type) is assumed as a wrinkle of the accordion tube, which is shown in Fig. 19. The geometry function is:

$$f(x) = \frac{s}{2}\mathrm{Sin}\left(\frac{2\pi}{g}x\right) \quad (1)$$

where s and g are presented in Fig. 19. $N_x$, $V_x$ and $M_x$ are axial force, Shear force and bending moment, respectively in this figure. By dispensing with effects of axial, shear and circumferential forces on axial stiffness of tube and by assuming the small deformations and also low thickness for wall, deformation in x direction under load, P is derived as below using the unit load method:

$$\delta = \int \frac{M_u M_L}{EI} dx \quad (2)$$

where $M_U$ and $M_L$ are bending moment under unit load and actual load, respectively. E is module of elasticity and I is inertial moment of section.

So that:

$$\delta = \frac{P}{EI}\int_{x=0}^{\frac{g}{2}} \frac{s^2}{4}\mathrm{Sin}^2\left(\frac{2\pi}{g}x\right)dx = \frac{Ps^2}{4EI}\left[\frac{x}{2} - \frac{g\mathrm{Sin}\left(\frac{4\pi x}{g}\right)}{8\pi}\right]_0^{\frac{g}{2}} = \frac{Ps^2 g}{16EI} \quad (3)$$

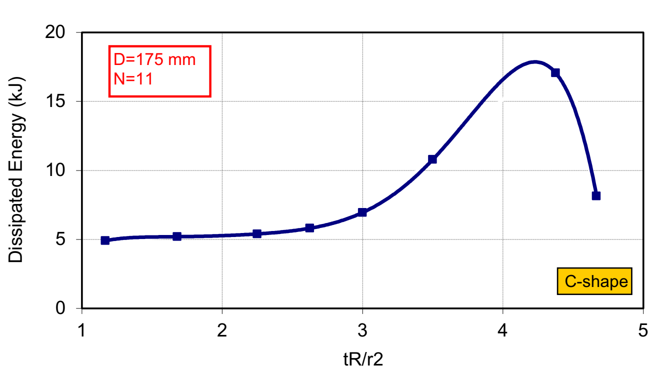



**Fig. 18.** Dependent effect of wall thickness, diameter of tube and radius of corrugates on dissipated energy of C-shape thin-walled accordion tubes in a cycle with 40 mm deformation.

and axial stiffness for one wrinkle is:

$$k = \frac{P}{\delta} = \frac{16EI}{s^2 g} \quad (4)$$

By considering the asymmetric shape for thin-walled accordion tube, axial elastic stiffness is derived as:

$$k = \frac{4\pi E\, t^3 D\alpha}{3(2n-1)s^2 g} \quad (5)$$

which $\alpha = 1$ for sinusoidal (S-shape) and 0.9 for circular shape (C-shape) of tube wall is suggested.

Fig. 20 presents the effect of geometry parameters of thin-walled accordion tubes on axial elastic stiffness obtained from proposed mathematical model and experimental results. As shown, there is a

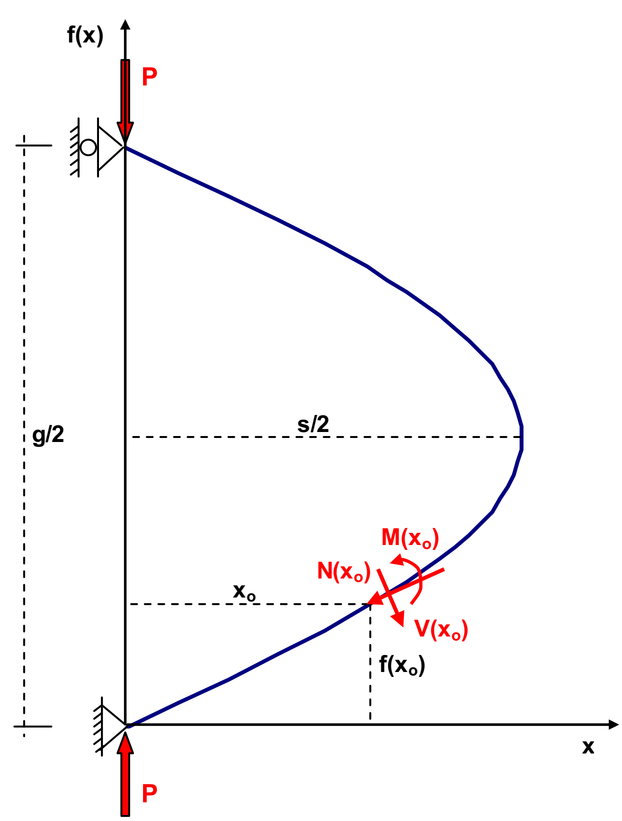



**Fig. 19.** Mathematical model for a corrugate of the thin-walled tube.

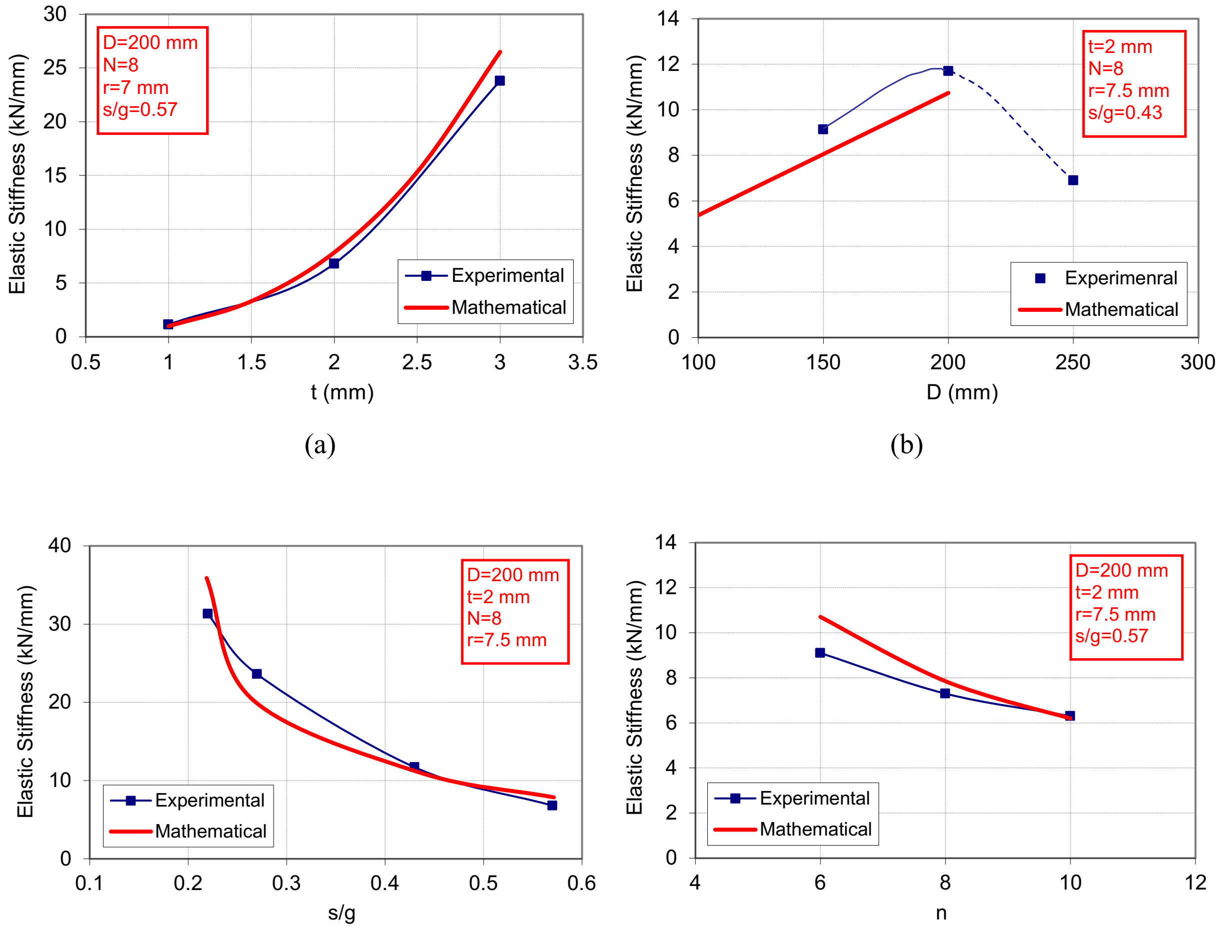



**Fig. 20.** Comparison of mathematical model and experimental results of thin-walled accordion tubes in elastic stiffness: a) effect of wall thickness, b) effect of tube mean diameter, c) effect of deep to step ratio, d) effect of number of corrugates.

good correspondence between the proposed numerical model and the test results for thickness (t), ratio of s/g and number of corrugated (n). However, the stiffness of the numerical model is not match with the test result for tube with 250 mm diameter. The large size tube demonstrated different mode of failure in test specimen and was not within the scope of the proposed model.

## 5. Conclusions

In this paper experimental and analytical studies were performed on metallic thin-walled accordion tubes to evaluate their performance as energy dissipating system. The proposed system is an inexpensive, simple to build and easy to install devise with efficient performance. The important conclusions obtained from these studies include:

1- Experimental studies on thin-walled accordion tubes showed that this system has large deformation capacity with adequate energy-dissipation. Energy dissipation in AMD is based on plastic deformation of steel corrugated tubes mainly in flexural form due to cyclic axial deformation mechanism of the devise. The specimens experienced deflection up to 70 mm and 70 cycles in a stable estate without any tearing or damage. Reconciliation of hysteresis loops showed no deterioration, stiffness degradation and strength reduction in axial deformation mechanism.
2- Analytical studies on calibrated models showed that axial deformation of the AMD created uniform stress distribution in thin-walled accordion tube. AMD models displaced very fat hysteresis loops with high ductility relative to many available metallic dampers.
3- Amount of dissipated energy, bearing capacity and elastic stiffness were controlled by varying the geometry parameters and the optimum shape for using these device according the seismic demand in a structure, could be attained by selecting the suitable parameters.
4- Wall thickness and tube diameter would increase and length of tube and radius of corrugates would decrease the dissipated energy. The wall thickness had the most effective rate in increasing the dissipated energy of thin-walled accordion tubes.
5- Optimum ratio for maximum energy-dissipation in thin-walled accordion tubes could be obtained from geometry parameters curves. This ratio for C-shape tubes is equal to 4.25.
6- The suggested mathematical model for axial stiffness which was compared with experimental results could be used for designing AMD as the energy dissipating system.

In conclusion, it seems that thin-walled accordion tubes can perform as energy dissipating system for seismic upgrading the structures based on studies carried out on their mechanical characteristics in this paper.

## Acknowledgments

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