Experimental and Analytical Study of Multilayer Accordion Metallic Damper

M.Torbat.E
Tafresh University, Iran

E.Izadi.Z, F.Nateghi.A
International Institute of Earthquake Engineering and Engineering Seismology, Iran

M.Motamedi
Islamic Azad University, South of Tehran Branch, Iran

SUMMARY:
In recent years, thin-walled accordion tubes under axial cyclic loading due to their appropriate energy absorption mechanism and behavioral characteristics were suggested as hysteretic metallic dampers. The effectiveness of accordion metallic damper (AMD) to protect and mitigate the response of structures under seismic loading is well established both experimentally and analytically.
In this paper for the purpose of improvement, the effects of increasing the number of accordion tube layers on the damping behavior of AMD investigated experimentally and analytically. Experimental studies were conducted on single layer and two layer specimens under axial cyclic loading by dynamic universal actuator. Using the experimental results, analytical studies based on finite element method and inelastic dynamic analysis have been carried out on a series of single and multi-layer AMD models.
The results obtained from studies conducted in this regard show that due to the more stable behavior and interaction effects, an increase in the number of layers has a great effect on the amount of dissipated energy, loading capacity and the other behavioral characteristics.

Keywords: Energy Absorption, Experimental Study, Finite Element Method, Multilayer Accordion Metallic Damper

1. INTRODUCTION

Earthquake risk mitigation through structural control has achieved significant progress over the last three decades. Structural control can be broadly classified into three categories: passive, active, and semi-active. Passive control systems include seismic isolation and supplemental energy dissipation devices. Among different developed dampers, hysteretic metallic is among the most common because of economic consideration, reliable performance and the convenience of their fabrication and installation.
In recent years thin-walled tubes are used for absorbing the impact energy in mechanical and transportation systems. Numerous studies have been carried out by Reid et al. (1993) on thin-walled tubes, their deformation mechanism and also their energy absorption potential under axial crushing. These studies indicate that after applying axial pressure force, thin-walled tubes are deformed with one pattern or a combination of diamond, Euler and concertina buckling mode. In addition, some studies have been carried out by Yamazaki and Hen (2000) using finite element method on aluminum thin-walled tubes under axial crushing in order to model the three axial crushing patterns mentioned above and evaluate the performance of tubes in each of these patterns. Experimental and analytical studies of thin-walled tubes under axial crushing that have been conducted by Bardi and Yan (2003) showed that among different bucking patterns, concertina buckling had higher energy absorption because it engages most of the materials in the process of plastic deformation. Thus, thin-walled tubes under axial crushing, because of their high capacity to absorb energy, received attention as one of the best methods of energy absorption. In order to obtain the best deformation mechanism and higher energy absorption capacity, concertina buckling may be applied as the major dominant pattern of axial crushing using the two methods of corrugation and grooving. By providing the conditions for the formation of concertina buckling pattern such as forming corrugations in the wall, thin-walled tubes can be suitable as absorbers of the earthquake input energy to the structure. Study of the behavior of axially crushed corrugated tubes under impact load was conducted by Singace and El-Sobky (1997).
In recent years, the idea of stimulating the concertina buckling mode of thin-walled tubes by creating accordion corrugations under axial cyclic loading was led to the development of accordion metallic damper (AMD) by Motamedi and Nateghi-A (2004). The effectiveness of AMD under axial cyclic loading and also seismic loading

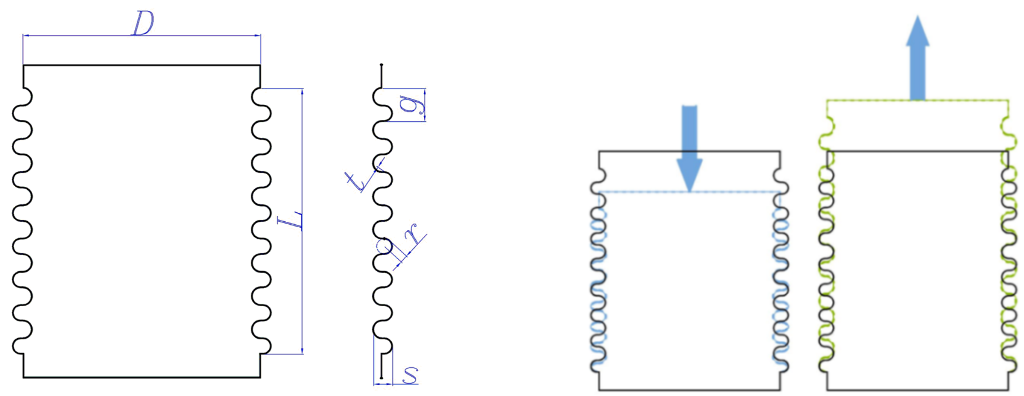
were established both analytically and experimentally by Motamedi and Nateghi-A (2005). This damper displays high energy absorption capacity and Stable behavior due to axial cyclic deformation.
For the purpose of improvement on AMD's, the effect of using flexible filling materials such as polyurethane foam on the main characteristic of damper has been investigated by Izadi et al. (2008) both experimentally and analytically. Based on the presented results, using hyper foam material such as polyurethane foam as filler inside AMD's is an efficient method to prevent destructive buckling modes such as diamond mode which in turn increases the low cycle fatigue strength of damper. Furthermore, using the appropriate filler improves some of the other important parameters such as the amount of dissipated energy and plastic capacity.
In the present study, the effect of increasing the layers of the damper has been examined in order to improve the behavior of accordion metallic damper. By causing higher behavior stability, modification of buckling modes, prevention from destructive buckling modes and desirable effects of intra-layer interactions, increasing the number of layers improves the damper's behavioral characteristics. To this end, single-layer, two-layer, and three-layer analytical models of damper are developed based on finite elements method and nonlinear dynamic analysis and then validated using the results obtained from the experimental studies conducted on single-layer and two-layer specimens. The effects of increasing the number of layers on behavioral characteristics of damper such as energy absorption, loading capacity and equivalent viscous damping is investigated under axial cyclic loading.

2. EXPERIMENTAL STUDIES

Laboratory test results (Motamedi & Nateghi, 2005) were used to validate the analytical model of the study. These tests were conducted on single-layer and two-layer specimens with geometrical properties as shown in Table 2.1. In this table D, diameter of the tubes; L, length of the tubes; t, thickness of layers; r, radius of corrugation; n, number of corrugation; s, depth of wrinkle and g are wall's corrugation length. A schematic overview of geometric characteristics and deformation manner of specimens has been illustrated in Fig. 2.1.
Stainless steel A304 based on ASTM classification was used as thin-walled tubes materials. Pure axial loading regime according to Fig. 2.2 has been subjected to specimens by dynamic universal actuator. The mentioned loading is displacement control and was applied to the specimens in different cycles and amplitude with the frequency of 0.1 HZ.

Table 2.1. Geometric characteristics of Experimental Specimens

Type No.	No. of Layers	D (mm)	L (mm)	t (mm)	r (mm)	n	s (mm)	g (mm)
A.D.1	1	200	224	1	7	8	16	28
A.D. 2	2	200	224	1	7	8	16	28



(a) (b)

Figure 2.1. Schematic Overview of Specimens: Geometric Characteristics (a), Acting Load and Deformation (b)

Specimens passed through cycles with different displacement amplitude and showed rupture for single-layer and two-layer samples at cycles 31 and 55.
Figures 2.3 and 2.4 indicate the hysteresis loops related to single-layer and two-layer specimens at the last cycle. It is obvious that energy absorption characteristics, plastic capacity and elastic stiffness of two-layer samples are increased more than two times of those of single-layer specimen.

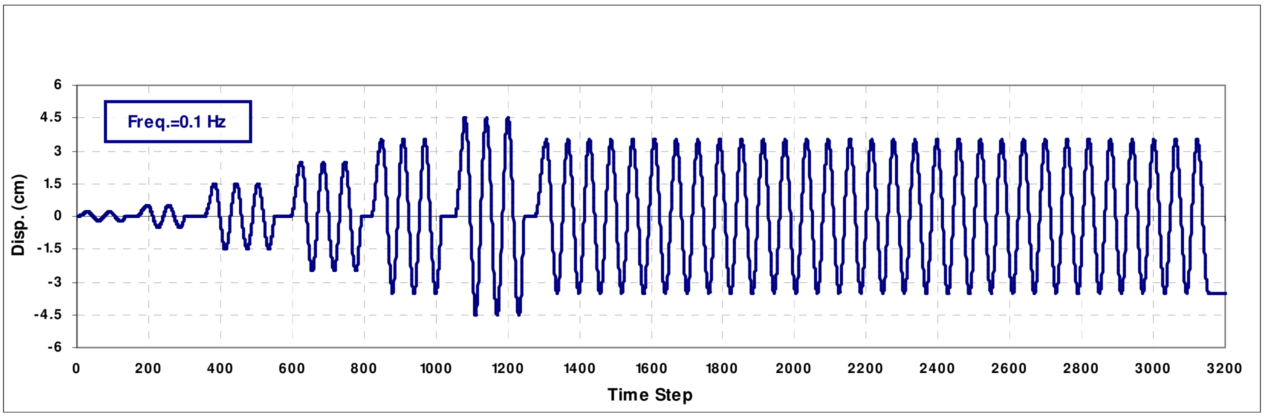


Figure 2.2. Axial Cyclic Loading Regime Applied to Experimental Specimens

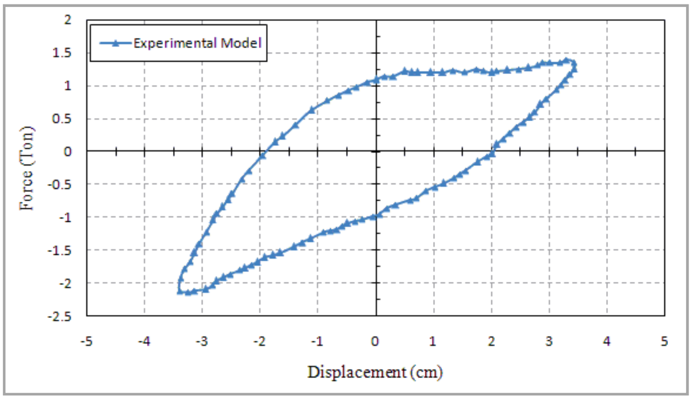


Figure 2.3. Last Hysteretic Loops of Single Layer Specimen

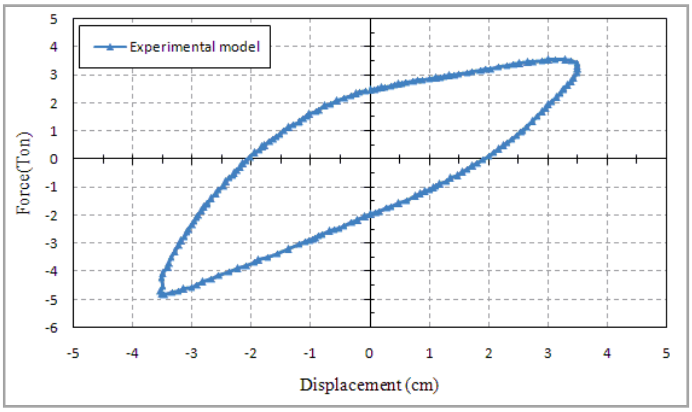


Figure 2.4. Last Hysteretic Loops of Two Layer Specimen

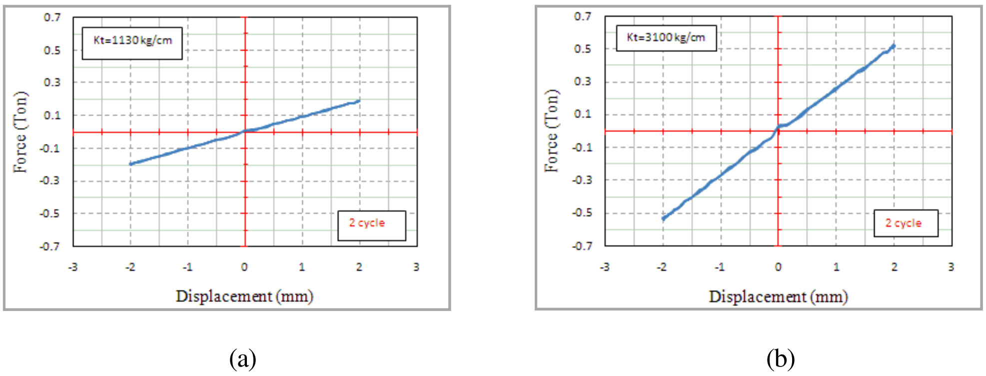


Figure 2.5. Axial Elastic Stiffness: Single-layer Specimen (a), Two-layer Specimen (b)

Fig 2.5 shows the axial elastic stiffness of single-layer and two-layer specimens. As shown in this fig 2.5 the two-layer accordion tube is more than two times stiffer than a single-layer tube. This could be attributed to the engagement and interaction of the two layers with each other and the reciprocal effect of layers as complementary forces.

3. ANALYTICAL STUDIES

In this section, the effect of increasing layers on the dissipation main characteristic of accordion metallic damper is investigated analytically. For this purpose analytical model based on finite element method and nonlinear dynamic analysis was developed and validated using experimental results.

3.1. MODELING

According to the condition of experimental tests and specimens, analytical models of experimental specimens were developed. Technical properties of the stainless steel A304 based on API standard in analytical model were provided as it is observed in Table 3.1. Based on the procedure of finite elements method, it is highly important to mesh the model in order to reach logical and stable results with sufficient precision and appropriate solution time. In this research, nonlinear four-node Shell elements with reduced integration procedure (two-dimensional element) were used for modeling thin-walled tubes. Figure 3.1 illustrates an overview of an analytical model of multi-layer accordion metallic damper. Isotropic tangential contact state was chosen for modeling the contact between layers considering the slipping of layers on each other and absence of dissipation state and lack of complete adhesion of layers to each other. Furthermore, considering that the two surfaces have frictional resistance toward each other, penalty function method with friction coefficient of 0.3 was chosen to introduce the degree of engagement. Dynamic analyzer with explicit solution method was chosen by considering load conditions, nonlinearity of the problem in terms of nonlinear geometry and materials, contact conditions and performance of sample in terms of changes in stress area.
Loading regime of Fig 2.2 was applied to the model. According to the number of cycles tolerable by each experimental specimen, 31 cycles were given to single-layer sample and 55 cycles to two-layer sample with maximum displacement amplitude of 35 mm. Thus, by applying this number of cycles, it is possible to validate analytical models. Mesh optimization and convergence test were performed on the models by breaking down the size of elements and examining the results and behavioral changes in hysteresis loops according to Fig. 3.2.

Table 3.1. Technical Characteristics of A304 Stainless Steel Verified In Analytical Studies

Title Model	Modulus of Elasticity (kg/cm2)	Yielding Stress (kg/cm2)	Ultimate Stress (kg/cm2)	Strain at the Beginning of Hardening (%)	Strain for Ultimate Stress (%)	Fracture Strain (%)
Analytical Model	1.35×10^6	1950	4100	2	54	60

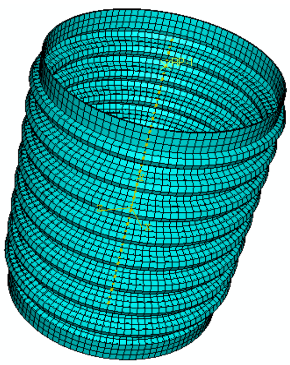


Figure 3.1. Single Layer Analytical Model Based on Finite Element Method

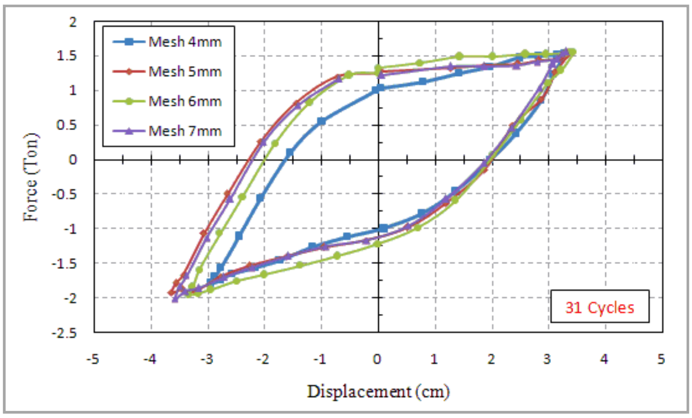


Figure 3.2. Hysteresis Loops Related to Single-layer Tube with Different Meshing Sizes

3.2. VALIDATION THE SINGLE–LAYER MODEL WITH EXPERIMENTALLY SPECIMEN RESULTS

In this section, results from analytical and experimental model were compared and analyzed regarding the single-layer sample. Figures 3.3 and 3.4 are assumed respectively the hysteresis loops of final analysis model and the last loop of this set.

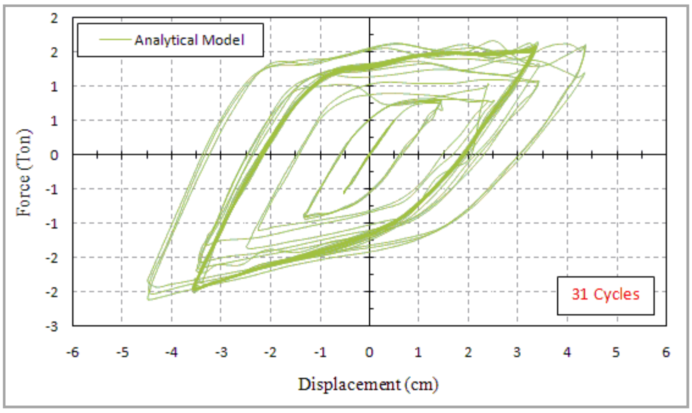


Figure 3.3. Hysteresis Loops of the Analytical Model in Single-layer Specimen

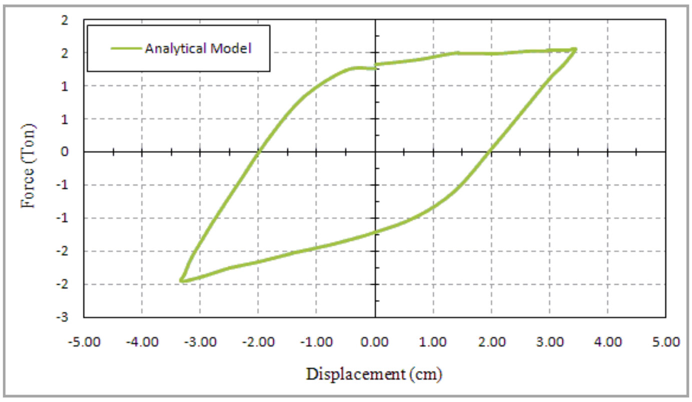


Figure 3.4. Last Hysteresis Loop of Analytical Model in Single-layer Specimen

In order to validate the analytical model against the experimental model and with respect to the type of the analyzer and the estimative nature of the solving the problem using finite elements method, after obtaining the result of the first solution, the resultant hysteresis loop is examined and according to the later analyses conditions, it is directed toward a stable and reliable solution by modifying some variables.
Figure 3.5 shows the fitted analytical hysteresis loop by experimental result of A.D.1 specimen which proofs the reliability of this model for parameter studies.

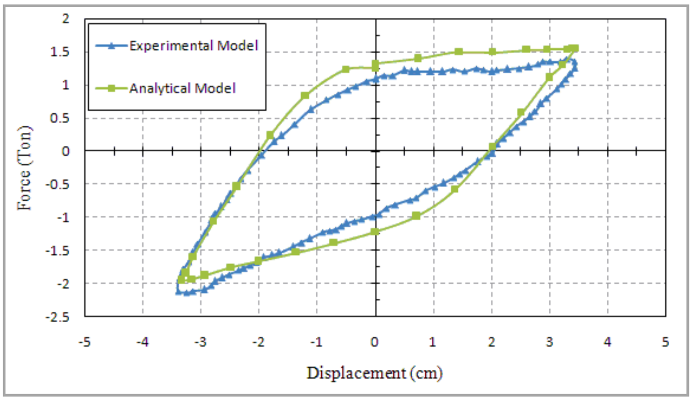


Figure 3.5. Analytical and Experimental Hysteresis Loops of Single-layer Specimen

Fig 3.6 deals with the stress distribution in single layer of AMD on Von Misses criteria (Timoshenko 1970). It's assumed that the same stress distribution on the whole model and the stress ratio in peak points of corrugates and their closed regions have been reached to yielding limit. Yielding regions have been developed by acting the more axial force and it means more energy dissipation in axial deformation of tube.

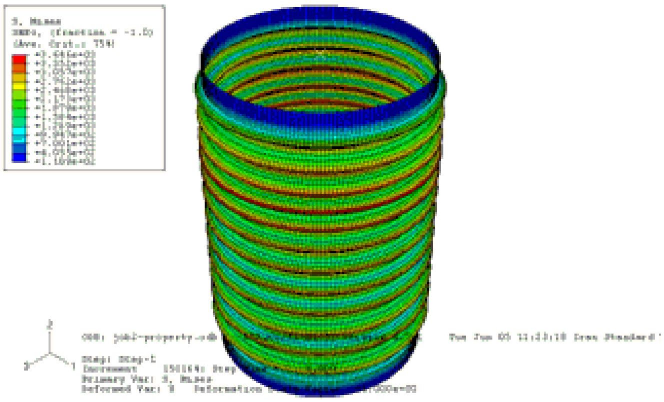


Figure 3.6. Stress Distribution in Single Layer Model Based on Von Misses Criteria

3.3. VALIDATION THE TWO–LAYER MODEL WITH EXPERIMENTALLY MODEL RESULTS

After the validating of the single-layer model, the multilayer model should be validated using experimental results. The two-layer model is built exactly according to the single-layer one but with two layers. Figure 3.7 and 3.8 show the hysteresis cycles of two-layer analytical model and the last cycle of this set, respectively.

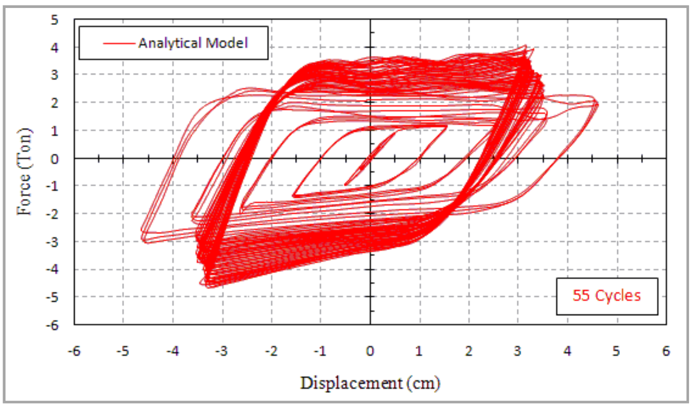


Figure 3.7. Hysteresis Loops of the Analytical Model in Two-layer Model

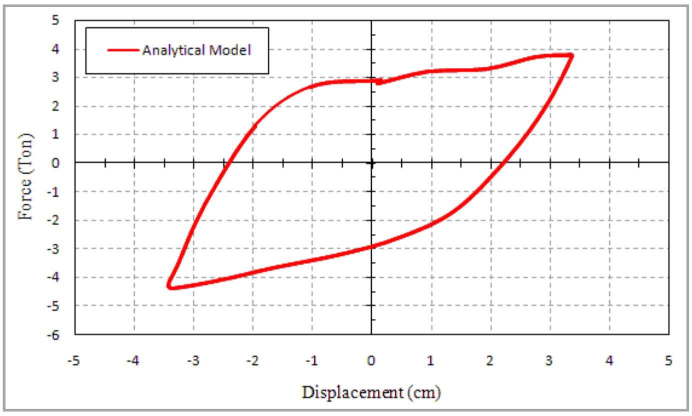


Figure 3.8. Last Hysteresis Loop of the Analytical Model in Two-layer Model

A comparison was made between the last loop resulting from analytical and experimental studies in Fig 3.9. This figure shows that a good agreement is observed between the two results. From the hysteresis loops related to single layer and two-layer models presented in the previous sections it is clear that load capacity in the two-layer model has increased to more than two times than that of the single-layer model. Hence, other behavioral characteristics of the damper including the degree of absorbed energy will be increased too.

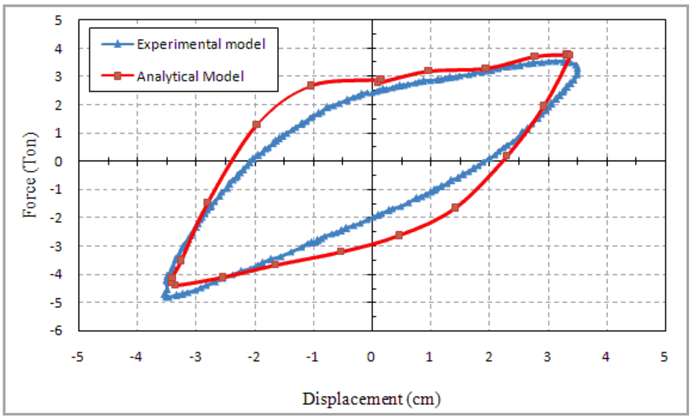


Figure 3.9. Analytical and Experimental Hysteresis Loops of the Two-layer Model

3.4. RESULTS FROM THE THREE-LAYER MODEL

Following the modeling of single-layer and two-layer models, the three-layer model is also built based on the same geometrical conditions, materials, meshing and friction coefficient. The hysteresis loops related to the three-layer model to the 31st loading cycle are given in Fig 3.10.

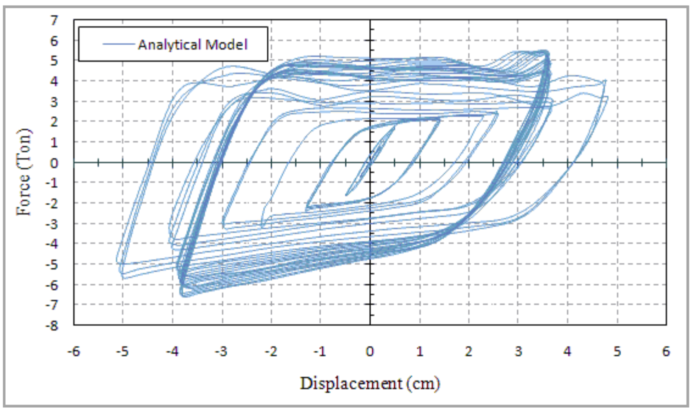


Figure 3.10. Hysteresis Loops of Three-layer Analytical Model

As the hysteresis loops shown above indicate, load capacity has increased to more than three times compared to that of the single-layer model. Obviously, this increase in load capacity will result in increased energy absorption. In the next section, the effects of this multilayer structure on the behavioral characteristics of the accordion metallic damper were compared.

4. COMPARING THE BEHAVIORAL CHARACTERISTICS OF SINGLE AND MULTILAYER MODELS

With respect to the results obtained from single-layer, two-layer and three-layer models, different behavioral characteristics were compared. For the purpose of comparison, plastic capacity and energy absorption of different models extracted and showed in figures 4.1 and 4.2. The shaded area shows the increasing of absorbing energy due to adding one and two-layer.
According to the results, the energy absorption of two-layer model has increased 163 percent compared to the single-layer model. It means that its absorption has increased 63 percent more than the expected degree; the reason for this increase may be attributed to the interaction effects of layers. In addition, energy absorption of three-layer model has been increased 302 percent compared to the single layer model. This result also indicates that energy absorption has increased 102 percent more than what was expected.
In order to identify its performance during loading time, we examined damper's crucial behavioral characteristics such as energy absorption, load capacity and equivalent viscous damping according to the time elapsed from the loading of the model or according to the number of loading cycles. To achieve this, 3 curves, each corresponding to one of the characteristics of energy absorption, load capacity and equivalent viscous damping, were created (as shown in figures 4.3, 4.4 and 4.5) based on the number of loading cycles. Using these diagrams, we can evaluate different single-layer, two-layer and three-layer models.

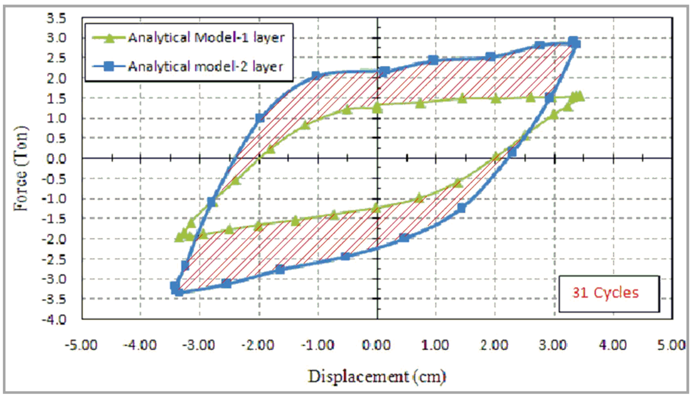


Figure 4.1. Comparison of the Hysteresis Loop of Single-layer and Two-layer Specimens

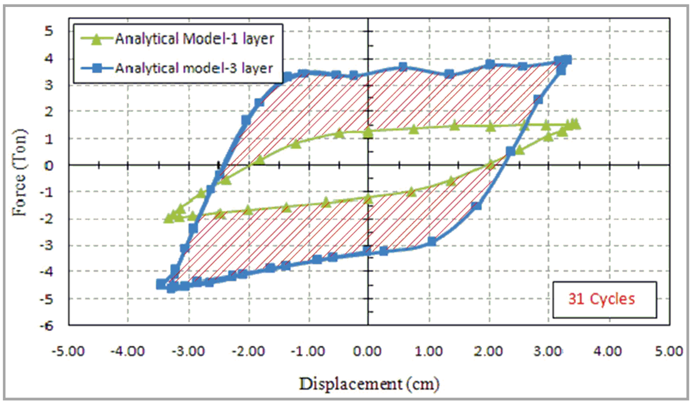


Figure 4.2. Comparison of the Hysteresis Loop of Single-layer and Three-layer Specimens

These loops show the stable behavior of accordion metallic damper both in the case of single-layer model and multilayer models. Indeed, energy absorption is increased with the number of layers. Increasing the number of layers will have major impact on accelerating the ascending trend of these parameters during the toleration of higher cycle numbers.

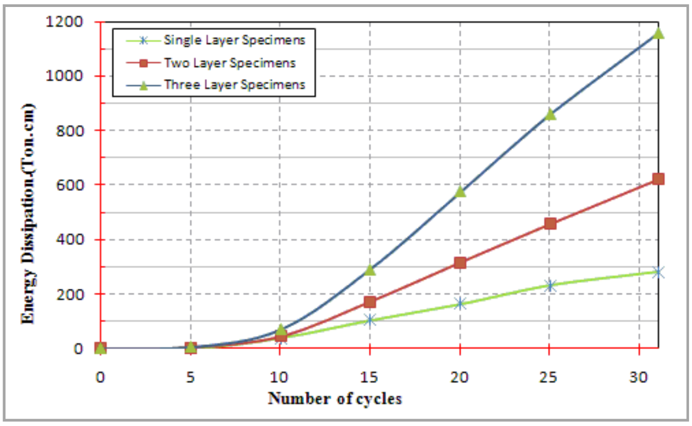


Figure 4.3. Dissipated Energy in Single-layer, Two-layer and Three-layer Models

From comparing the degree of energy absorption between the two-layer and single-layer models, we may say that the energy absorption of two-layer model is two times more than the single-layer model. We can argue that increasing the number of layers, doubles the thickness of the model which in return doubles energy dissipation. Furthermore, putting layers on each other and increasing the number of plastic joints are important factors in increasing energy absorption to more than two times. For the higher cycles, there is higher load capacity and it is intensified when layers are increased. The reason for this is that the interaction between layers is more sustainable at higher cycles.

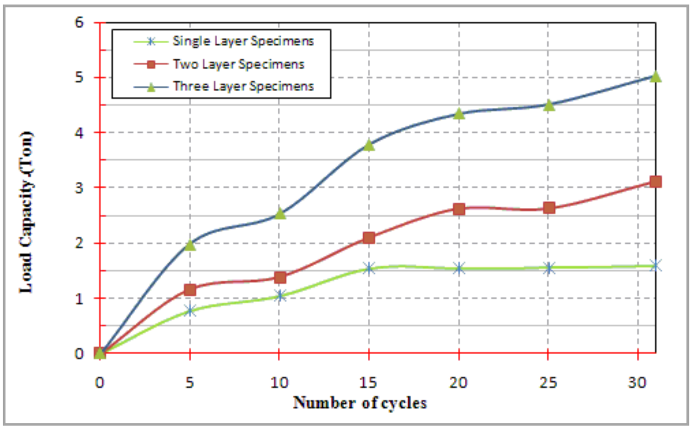


Figure 4.4. Plastic Capacity Level Curve in Single-layer, Two-layer and Three-layer Models

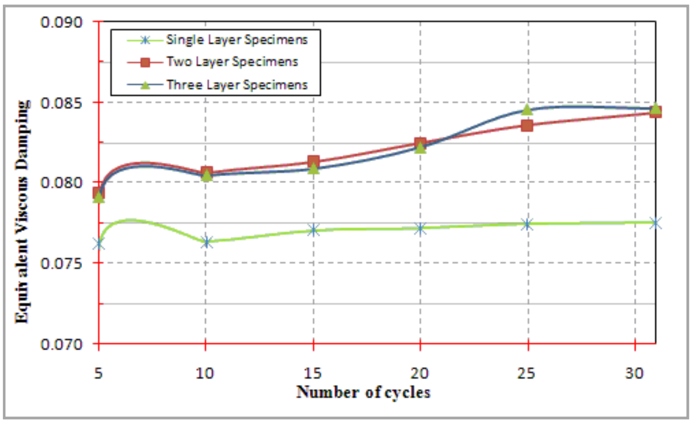


Figure 4.5. Equivalent Viscous Damping Level Curve in Single-layer, Two-layer and Three-layer Models

Equivalent viscous damping parameter has the least changes during loading and has only increased by adding layers. This uniformity stems from the good performance of the damper from the beginning to the end of the energy absorption operation.

6. RESULTS

- By comparing the energy absorption of two-layer and three-layer models with the single-layer model, evaluated that for a certain number of loading cycles, energy absorption of the two-layer model was two times more than the single-layer model and for the three-layer model three times more than the single-layer model.
- Increasing the number of layers, doubles the thickness of the model and this will lead to double energy dissipation. The favorable effects of the interactions between layers and increasing the number of plastic joints are factors which result in the doubling of energy absorption.
- The energy absorption of two-layer model has increased 163 percent compared to the single-layer model. It means that its absorption has increased 63 percent more than the expected degree. In addition, the three-layer model has had a 302-percent increase in absorbing energy in comparison to the single-layer model. This result also indicates that energy absorption has increased 102 percent more than what was expected.
- During the loading, energy absorption, load capacity and equivalent viscous damping parameters of the accordion metallic damper increase and this process is accelerated by increasing the number of layers. This indicates that the stability of the accordion metallic damper increases by increasing the number of layers.

REFRENCES

Reid, S.R., (1993). Plastic deformation mechanisms in axially compressed metal tubes used as impact energy absorbers. *International Journal of Mechanical Science*, **35:12**, 1035-1052.

Yamazaki, K., and Han, J. (2000). Maximization of the crushing energy absorption of cylindrical shells. *Journal of Advances in Engineering Software*, **31**, 425-434.

Bardi, F.C., Yan, H.D. (2003). On the axisymmetric progressive crushing of circular tubes under axial compression. *International Journal of Solids and Structures*, **40**, 3137-3155.

Singace, A.A. and El-Sobky, H. (1997). Behavior of axially crushed corrugated tube. *International Journal of Mechanical Science*, **39:3**, 249-268.

Motamedi, M., Nateghi-A., F. (2004). Using accordion thin-walled tube as a hysteretic metallic damper. *13 Th World Conferences on Earthquake Engineering*, Vancouver, Canada, Paper No.2264.

Motamedi, M. (2005). Experimental study of application of the accordion metallic damper in seismic retrofitting of steel building frames, Ph.D. Thesis, Islamic Azad University, Science & Research Branch, Tehran, Iran.

Motamedi, M., Nateghi-A., F. (2006). Experimental study of accordion metallic damper (AMD). *First European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, Paper No.38.

Nateghi-A., F., Motamedi, M. and Izadi-Z, E. (2008). Experimental behavior of the seismic filled accordion metallic damper. *14th World Conference on Earthquake Engineering*, Beijing, China, Paper No.2264.

Izadi-Z, E., Nateghi-A., F. and Motamedi, M. (2010). Stabilization and modifying the buckling behavior of accordion metallic Damper Using Polyurethane Foam. *14 th European Conference on Earthquake Engineering*, Ohrid, Macedonia, Paper No. 580.