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Improved Behaviour of Accordion Metallic Dampers Affected by the Increasing Number of Layers

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P A P E R I N F O

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A B S T R A C T

In this research for the purpose of the improvements, the effects of increasing the number of accordion tube layers of the Accordion metallic dampers (AMD) was studied. Damping behavior of AMD was investigated by the experimental, analytical and parametric studies. Experimental studies were conducted on single layer and two layer specimens under axial loading. Analytical studies have been carried out on series of single and multi-layer AMD models; then, those have been verified by the experimental results. Also, the effect of changing the geometrical parameters on the damping behavior with increasing the number of layer was evaluated and ideal geometric model was suggested . The results show increasing the number of layers influences the amount of dissipated energy that is due to a greater stable behavior.

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1. INTRODUCTION

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. [1] 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 [2] 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 have been conducted by Bardi, Yan and Kyriakides (2003). Their results show that among different bucking patterns, concertina buckling has higher energy absorption because it engages most of the materials in the process of plastic deformation. Thus, thin-walled tubes under axial crushing received attention as one of the best methods of energy absorption because of their high capacity to absorb energy. 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 [3].

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 [4]. The effectiveness of AMD under axial cyclic loading and also seismic loading well established both analytically and experimentally by Motamedi and Nateghi-A [5].

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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. [6] 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 increase 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 and two-layer 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 .

Parametric studies was performed to identify and assess the effect of different geometric parameters such as layer thickness, tube diameter, tube length and radius of the wave fold accordion on the energy absorption and behavior of multi-layer accordion metallic damper. Also, the specific model provided with the highest energy absorption with the best geometric parameters.

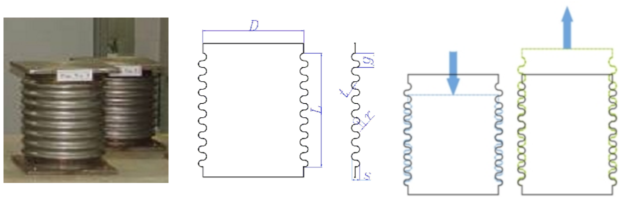
2. EXPERIMENTAL STUDIES

Laboratory test results (Motamedi & Nateghi, [5]) are used to validate the analytical model of the study. These tests are conducted on single-layer and two-layer specimens with geometrical properties as shown in Table 1. In this table, D is diameter of the tubes; L is length of the tubes; t is thickness of layers; r is radius of corrugation; n is number of corrugation; s is depth of wrinkle and g is wall's corrugation length. Specimens made of Accordion metallic damper and a schematic overview of geometric characteristics and deformation manner of specimens have been illustrated in Figure 1.

Stainless steel A304 based on ASTM classification is used as thin-walled tubes materials. Pure axial loading regime according to Figure 2 has been subjected to specimens by dynamic universal actuator. The mentioned loading is displacement control and applied to the specimens in different cycles and amplitude with the frequency of 0.1 HZ.

TABLE 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
2A.D.	2	200	224	1	7	8	16	28



(a) (b) (c)

Figure 1. Schematic Overview of Specimens: Specimens made of Accordion metallic damper (a) Geometric Characteristics (b), Acting Load and Deformation (c)

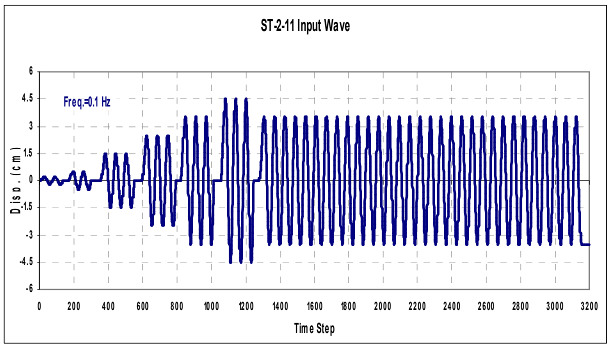


Figure 2. Axial CyclicLoading Regime Applied to Experimental Specimens

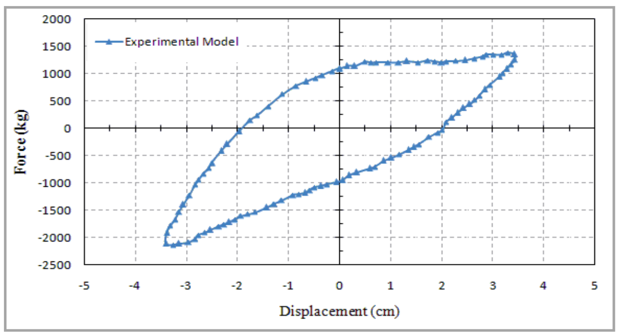


Figure 3. Last Hysteretic Loops of Single Layer Specimen

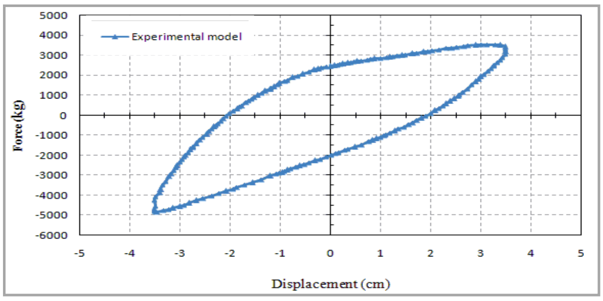


Figure 4. Last Hysteretic Loops of Two Layer Specimen

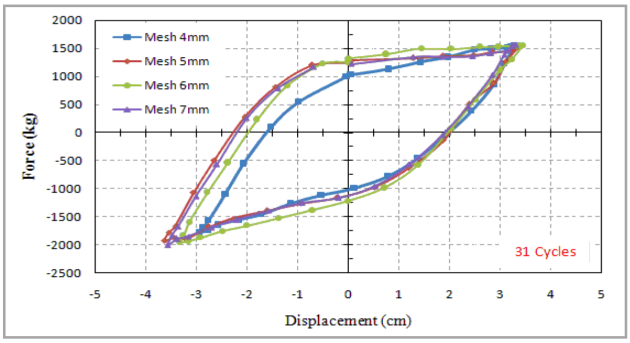


Figure 5. Hysteresis LoopsRelated to Single-layer Tube with Different Meshing Sizes

Specimens passed through cycles with different displacement amplitude and shows rupture for single-layer and two-layer samples at cycles 31 and 55. In both single-layer and two layer specimens, breaking occurred at the seventh fold from up the wave fold accordion, where stress concentration was started at the beginning of loading . Figures 3 and 4 show 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

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 is developed and validated using experimental results.

3. 1. Modeling and Validation the Single–Layer Model with Experimentally Specimen Results

According to the condition of experimental tests and specimens, analytical models of experimental specimens developed. Technical properties of the stainless steel A304 based on API standard in analytical model are provided in Table 2. 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. 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 Figure 2 was applied to 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 Figure 5.

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. Then, according to the later analyses conditions, it is directed toward a stable and reliable solution by modifying some variables.

TABLE 2. Technical Characteristics of A304 Stainless Steel Verified In Analytical Studies

Title Model	Modulus of Elasticity (kg/cm^2)	Yielding Stress (kg/cm^2)	Ultimate Stress (kg/cm^2)	Strain at the Beginningof Hardening (%)	Strain for Ultimate Stress (%)	Fracture Strain (%)
Analytical Model	$10^6 \times 1.35$	1950	4100	2	54	60

Figures 6 and 7 are assumed the hysteresis loops of final analysis model and the last loop of this set, respectively. In order to exhibit the validation, Figure 8 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 9 deals with the stress distribution in single layer of AMD on Von Misses criteria. It's assumed that the same stress distribution on 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.

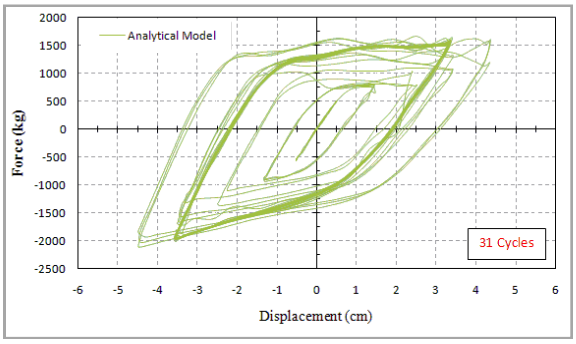


Figure 6. Hysteresis Loops of the Analytical Model in Single-layer Model

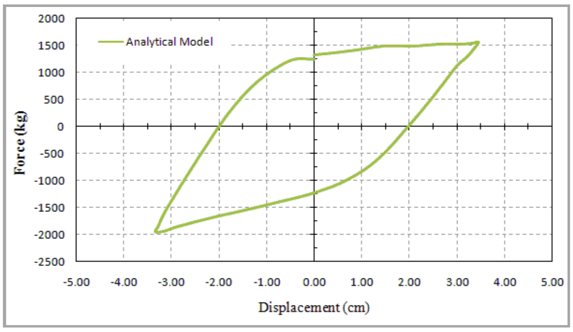


Figure 7. Last Hysteresis Loop of Analytical Model in Single-layer Model

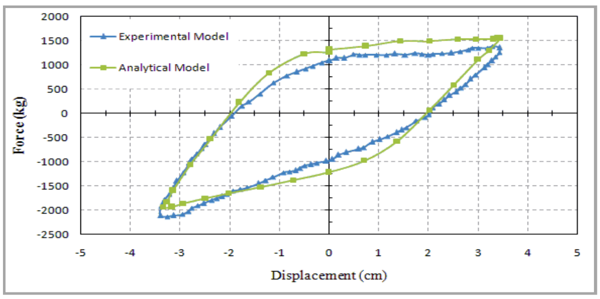


Figure 8. Analytical and Experimental Hysteresis Loops of Single-layer Model

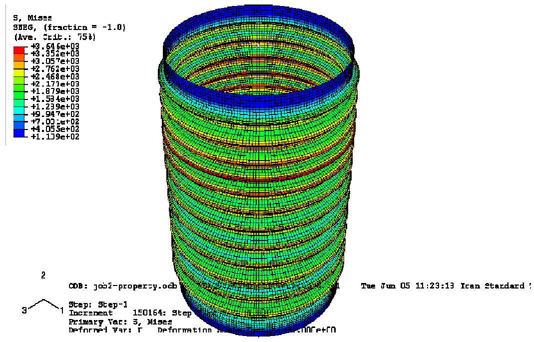


Figure 9. Stress Distribution in Single Layer Model Based on Von Misses Criteria

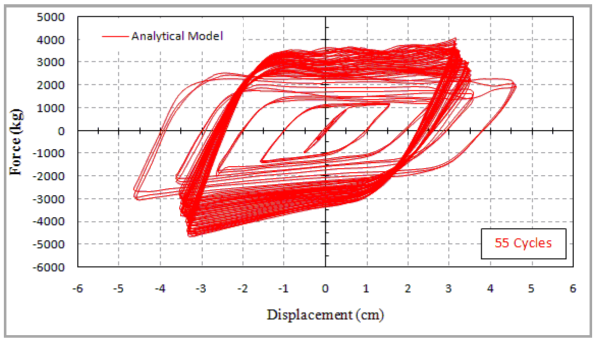


Figure 10. Hysteresis Loops of the Analytical Model in Two-layer Model

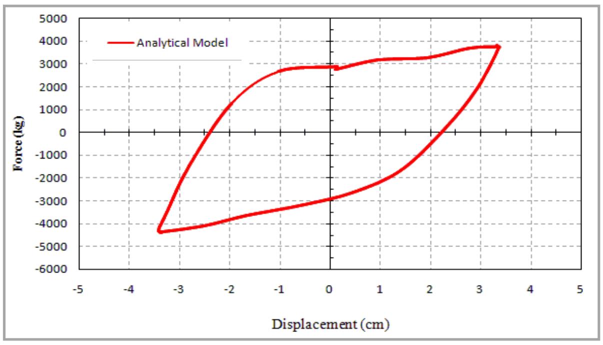


Figure 11. Last Hysteresis Loop of the Analytical Model in Two-layer Model

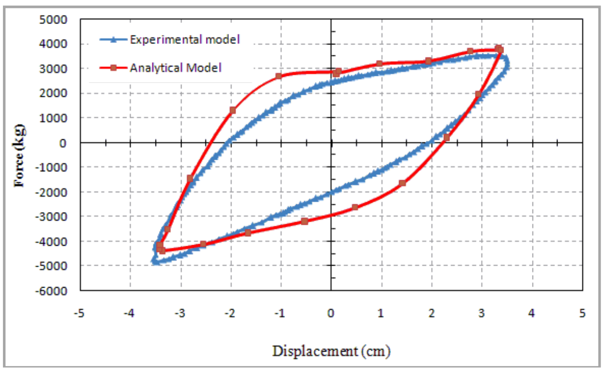


Figure 12. Analytical and Experimental Hysteresis Loops of the Two-layer Model

3. 3. Modeling and Validation the Two–layer Model with Experimentally Specimen 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. Figures 10 and 11 show the hysteresiscycles of two-layer analytical model and the last cycle of this set, respectively.

A comparison is made between the last loop resulting from analytical and experimental studies in Figure 12. This figure shows a good agreement which 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 also increase.

4. COMPARING THE BEHAVIORAL CHARACTERISTICS OF SINGLE AND TWO-LAYER MODELS

With respect to the results obtained from single-layer, two-layer and three-layer models, different behavioral Characteristics are compared. For the purpose of comparison, plastic capacity and energy absorption of different models extracted and showed in Figures 13 and 14. The shaded area shows the increasing of absorbing energy due to adding one and two layer.

According to the results, the two-layer model's energy absorption 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 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 examine damper's energy absorption, according to the time elapsed from the loading of the model or according to the number of loading cycles. To achieve this curve, each corresponding to energy absorption is created (as shown in Figure 15) based on the number of loading cycles. Using this diagram, we will evaluate different single-layer, two-layer and three-layer models.

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

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 model which in return doubles energy dissipation.

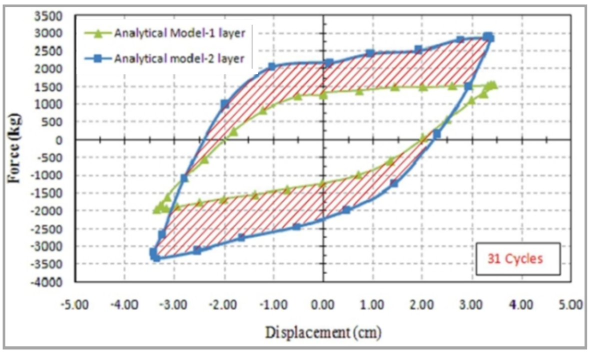


Figure 13. Comparison of the Hysteresis Loop of Single-layer and Two-layer Models

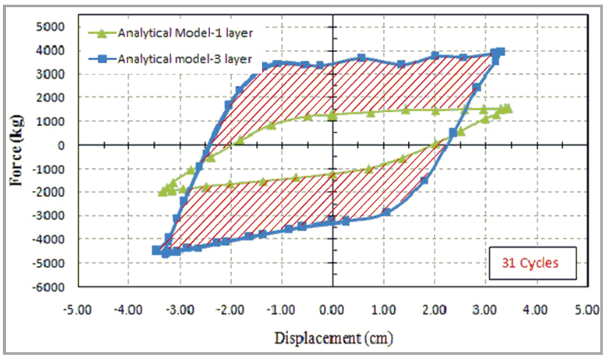


Figure 14. Comparison of the Hysteresis Loop of Single-layer and Three-layer Models

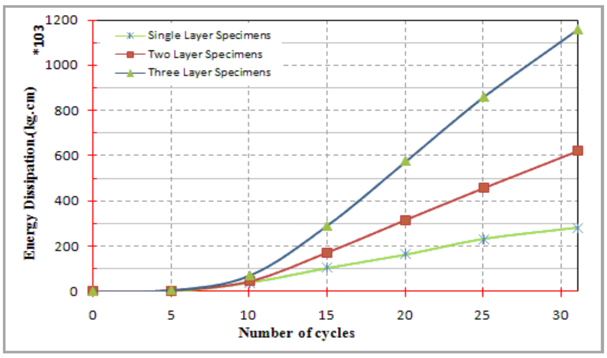


Figure15. Dissipated Energy in Single-layer, Two-layer and Three-layer Models

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.

5. EVALUATING THE DISSIPATION BEHAVIOR OF DAMPERS AFFECT OF GEOMETRIC PARAMETERS

In order to have a model of multi-layer accordion metallic damper with maximum energy absorption, determine the effect of various parameters such as wall thickness, tube diameter and radius of the wave accordion wall are considered in this section. These are the most important geometric parameters that affect the damper's geometry.

Performance evaluation of changes in the geometric parameters of the multi-layer damper with the damper can be optimized and presented a model with the best energy dissipation, stable against reciprocating loads and applicable at the different level of seismic vibrations. In this regard, by changing one of the parameters listed and fixed the other geometric parameters, dissipation behavior of dampers will be discussed in the states of single-layer, two-layer and three-layer. Similarly, at the first by changing in wall thickness parameter, changes in the rate of energy absorption is evaluated as the most important characteristic of the dissipation behavior of dampers. Due to the static load with variable amplitude, it is clear that increasing the wall thickness from 1 mm to 3 mm require greater force to achieve a given constant displacement. An increase in the amount of force with a constant displacement in both tension and compression causes an increase in the area under the hysteresis loops and dissipated energy.

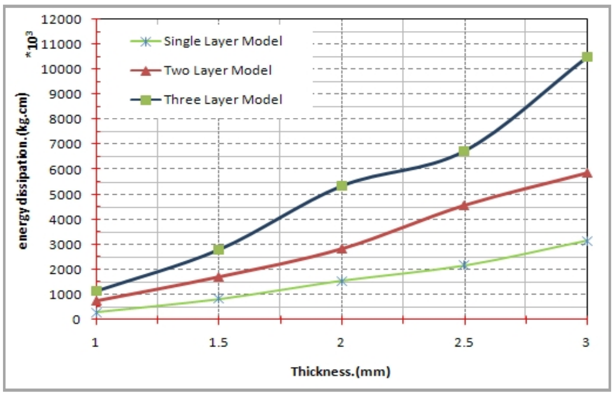


Figure 16. Dissipated Energy in Single-layer, Two-layer and Three-layer Models during the change of wall thickness

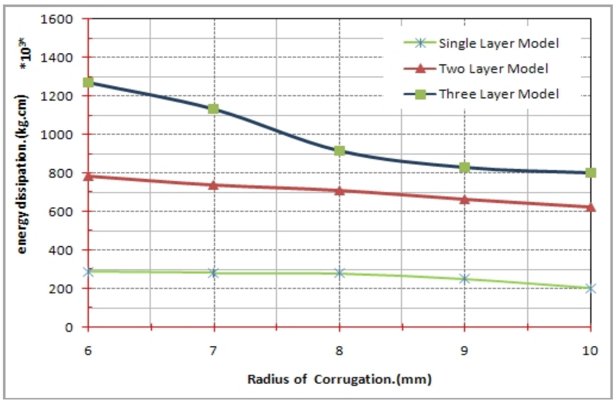


Figure 17. Dissipated Energy in Single-layer, Two-layer and Three-layer Modelsduring the change of corrugation's radius

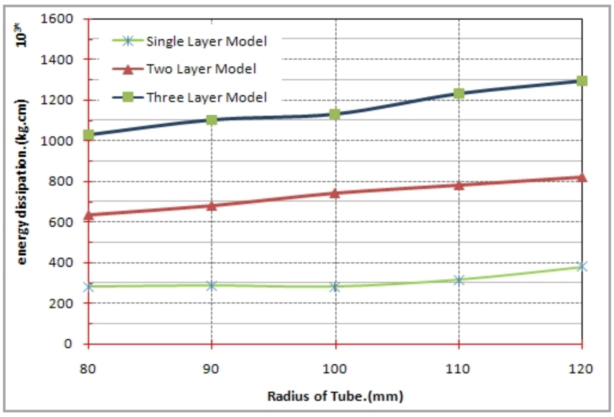


Figure 18. Dissipated Energy in Single-layer, Two-layer and Three-layer Modelsduring the change of tube's radius

According to Figure 16, rising trend in the energy absorption of single-layer, two-layer and three-layer dampers with an increase in layer thickness is observed.

An increase in the radius of corrugation reciprocating axially loaded from 6 mm to 10 mm causes the less likely of buckle accordion damper. In addition, according to Figure 17, the great reduction in energy dissipation, especially in multi-layer samples is observed. However, changing the tube's radius parameter according to Figure 18 has the multiplier effect on the rate of energy dissipation, but negligible.

6. RESULTS

- By comparing the energy absorption of two-layer and three-layer models with the single-layer model, it is 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.
- During the loading, energy absorption of the accordion metallic damper was increased and this process is accelerated by increasing the number oflayers. This indicates that the stability of the accordion metallic damper increases by increasing the number of layers.
- Parametric studies indicate the directly influence of geometric parameters such as wall thickness and the radius of the tube and reverse effect of radius burrs as an other geometric parameter on the energy dissipation of dampers.

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Improved Behaviour of Accordion Metallic Dampers Affected by the Increasing Number of Layers

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چکید

در این تحقیق، با هدف بهبود رفتار میراگر فلزی آکاردئونی به عنوان یکی از بارزترین میراگرهای فلزی جاری شونده، تأثیر افزایش تعداد لایه‌های جداره این میراگر مورد مطالعه تحلیلی و آزمایشگاهی و پارامتریک قرار گرفته است. مطالعات آزمایشگاهی بر روی نمونه‌های تک لایه و دو لایه انجام شده و مدل‌های تحلیلی تک لایه، دو لایه و سه لایه میراگر توسعه یافته و با استفاده از نتایج مطالعات آزمایشگاهی مورد صحت سنجی قرار گرفته است. همچنین تأثیر تغییر پارامترهای مهم هندسی جداره میراگر بر رفتار استهلاکی آن بررسی شده و مدل ایده آل هندسی ارائه گردیده است. نتایج نشان از تاثیر چشمگیر افزایش تعداد لایه های میراگر بر میزان جذب انرژی آن بعلت بوجود آمدن پایداری استهلاکی بیشتر برای میراگر دارد.

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