CONEM 2016
CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
21 - 25 AGOSTO DE 2016 FORTALEZA - CEARÁ
ABCM 40 anos
Associação Brasileira de Engenharia e Ciências Mecânicas

MODELING A SHAPE MEMORY ALLOY HONEYCOMB VIBRATION ABSORBER USING THE FINITE ELEMENT METHOD

Gabriel Averbug, averbugg@gmail.com[1]
Ricardo Alexandre Amar de Aguiar, ricardoaamar@yahoo.com.br[1]
Silvo Romero de Barros, silvio.debarros@ cefet-rj.br[1]
Pedro Manuel Calas Lopes Pacheco, pedro.pacheco@cefet-rj.br[1]
Marcelo Amorim Savi, savi@mecanica.coppe.ufrj.br[2]

[1] CEFET/RJ – Centro Federal de Educação Tecnológica Celso Suckow da Fonseca - Department of Mechanical Engineering
20.271.110 - Rio de Janeiro - RJ – Brazil
[2] Universidade Federal do Rio de Janeiro - COPPE – Department of Mechanical Engineering,
Center for Nonlinear Mechancis, P.O. Box 68.503 - 21.941.972 – Rio de Janeiro – RJ – Brazil

Abstract: *Shape memory alloys (SMAs) are smart materials employed in several applications due to their adaptive characteristics being of special interest in engineering. Pseudoelasticity effect occurs in austenitic SMAs where a hysteretic behavior is observed in the stress-strain curve. The area inside the hysteresis loop is associated with energy dissipation during loading-unloading cycles. Since the volumetric density of dissipated energy of nickel-titanium and copper-based alloys is significant, they have been broadly applied in vibration systems. In this regard, an optimized geometric design is a great challenge for the construction of shape memory alloy vibration absorbers. This work presents a numerical model based on the finite element method developed to study the energy dissipation capability of an SMA S-shape absorber connected to aluminum plates to form a honeycomb structure. A constitutive model with internal variables describes pseudoelastic behavior of SMA. The proposed model can be used as a tool for analyzing phase transformation distribution and to optimize the geometry of the SMA vibration absorbers in order to maximize the energy dissipation capability. Numerical simulations show that the SMA S-shape absorber can be used as an efficient absorber for vibration reduction.*

Keywords: *shape memory alloys, pseudoelasticity, honeycomb, vibration absorber, finite element analysis*

1. INTRODUCTION

Shape memory alloys (SMAs) are active materials that present complex thermomechanical behavior, leading to different physical processes. Under thermomecanical loads, SMAs are capable to develop significant displacements and/or forces (Lagoudas, 2008). The most common phenomena regarding this class of material are pseudoelasticity, shape memory effect, and phase transformation due to temperature variation. As a consequence of their special characteristics, shape memory alloys attract much technological interest, motivating different applications in several fields of science and engineering. Aerospace, automotive industry, biomedicine and robotics are some of the areas where SMAs have been applied (Nava *et al.*, 2014; Jani *et al.*, 2013; Lagoudas, 2008; Song *et al.*, 2006; Petrini and Migliavacca, 2011).

The mechanisms behind the behavior of SMAs are associated with phase transformation phenomena (Paiva and Savi, 2006; Lagoudas, 2008). Two main phases are presented: austenite, stable in a stress-free state at high temperatures; and martensite, which presents variants, twinned and detwinned martensites. For lower temperatures, below a critical temperature, twinned martensite is the only stable phase in a stress-free state, whereas the detwinned martensitic phase is associated with the presence of a stress field above a critical stress. Several alloys can develop strains related to phase transformation, but only those that can develop large strains are of commercial interest, such as nickel-titanium (NiTi) and copper-based alloys (CuZnAl and CuAlNi).

Pseudoelasticity, also known as superelasticity, is the effect responsible for the recovery of large strains induced by stress at a constant temperature (Lagoudas, 2008; Riagusoff, 2012). Pseudoelasticity takes place at high temperatures, above a critical temperature (A_F), where austenite is the stable phase in a stress-free state. As can be seen in the stress-strain curve (σ-ε) in Fig.1, an initial linear behavior is observed during the loading stage, until stress reaches a critical value at point *A*. Curve *A*-*B* is characterized for a non-linear behavior due to the phase transformation from austenite to detwinned martensite. A 100% of martensitic volume fraction is reached at point *B*. After this point, the loading promotes a linear behavior. For the unloading process, a linear curve is observed for stage *B*-*C*, followed by a non-linear curve *C*-*D*, where the reverse phase transformation occurs. Finally, when point *D* is reached, a condition of 100% of austenitic volume fraction is observed.

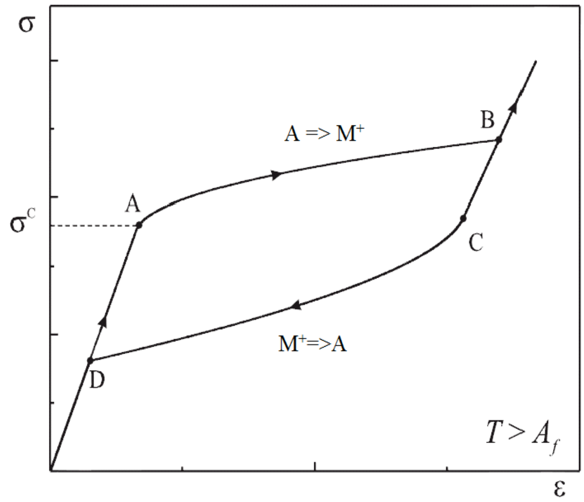


Figure 1 – Pseudoelastic behavior of SMAs (Riagusoff, 2012).

As a result of the hysteretic behavior, SMAs are able to dissipate mechanical energy in each loading-unloading cycle, making them appropriate to be used in vibration attenuation applications (Aguiar *et al.*, 2013; Asgarian and Moradi, 2011; Casciati and Faravelli, 2009; Desroches and Delemont, 2002; Fugazza, 2003; Hora *et al.*, 2013; Johnson *et al.*, 2008; Lagoudas, 2008; Ozbulut *et al.*, 2007, 2010, 2011; Ozbulut and Hurlebaus, 2011; Pacheco *et al.* , 2015; Savi *et al.*, 2011; Shook *et al.*, 2008; Youssef *et al.*, 2008; Zhang *et al.*, 2008; Zuo *et al.*, 2006, 2008, 2009; Zuo and Li, 2011).

Moreover, as austenite and martensite have different Young modulus values, during phase transformation the stiffness of an SMA element varies, affecting the system dynamical behavior. Another remarkable feature of SMAs is their ability to change their center point (recentering) trough phase transformation induced by temperature or by a pre-loading (Pugliese and Casey, 2012). Due to these combined effects, SMA pseudoelastic elements can be used as efficient vibration attenuators for mechanical components. Figure 2(a) shows a load-displacement curve for an SMA element subjected to an axial loading where the area inside the hysteresis loop represents the maximum energy dissipated during a loading-unloading cycle. Figure 2(b) shows a cyclic loading where oscillations occur between maximum and minimum load values (F_{max} and F_{min}). The energy dissipated in each cycle is associated with the highlighted area.

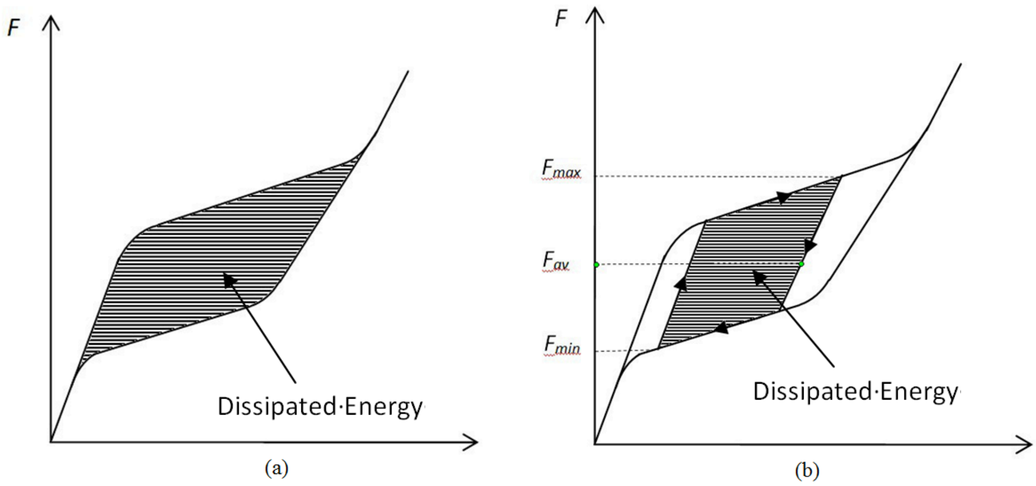


Figure 2 – Energy dissipation on pseudoelastic elements. (a) and (b) dissipated energy for a vibration situation (Pacheco *et al.*, 2015).

Over the past years, several energy absorber types have been developed with different forms. Each type is capable of dissipating energy in different modes, resulting in distinct energy absorption responses. Olabi *et al.* (2007) presented an overview of metallic energy absorbers in the form of tubes. Shaw *et al.* (2007) presented a study for the design and fabrication of superelasticity NiTi honeycombs cellular structures. Moreover, Michailidis *et al.* (2009) had investigated the use of SMA hexagonal honeycomb structures under in-plane compression for the analysis of superelasticty behavior and stability. Indeed, low density cellular solids, such as SMA honeycombs, present high stiffness-to-mass ratio and good energy absorption characteristics. Besides, the maximum tensile strain recovery and consequently the superelasticity of these thin-walled structures are substantially amplified in comparison with monolithic structures, making them appropriate for vibration damping (Michailidis *et al.,* 2009). The design of an optimized geometry and the joining methods with different materials become challenges for the construction of shape memory alloy vibration absorbers. Hot joining processes, such as welding, can affect the thermomechanical properties of these materials, whereas the adoption of screws and rivets can cause stress concentration. As an alternative, the usage of structural adhesives presents several potential advantages. Pacheco *et al.* (2015) presented an analysis of a bonded SMA vibration attenuator element using the finite-element method to study the element hysteretic behavior and experimental analysis to characterize the performance of an SMA-aluminum bonded joint.

The availability of existing numerical tools coupled with advanced constitutive models has permitted advances in the modelling of the complex behavior of SMA pseudoelastic vibration attenuation mechanical elements. Concerning the application of SMAs as vibration absorbers, the design of an optimized geometry presents technological challenges. This work presents a numerical model based on the finite-element method to study the behavior of an SMA S-shape absorber connected to aluminum plates forming a honeycomb structure. The proposed model considers the pseudoelastic behavior of SMA elements.

2. FINITE ELEMENT MODEL

Different constitutive models can describe shape memory alloys thermomechanical behavior. Paiva and Savi (2006) presented an overview of constitutive models for SMAs and, in this work, the constitutive model proposed by Auricchio *et al.* (1997) is employed. This three-dimensional model is capable of describing the pseudoelastic behavior and considers the presence of two phases: austenite (A) and martensite (M). The internal variables ξ_A and ξ_M are introduced to represent, respectively, austenitic and martensitic volume fractions, which satisfy the following relation: $\xi_A + \xi_M = 1$. SMA is isotropic and phase transformation obeys a Drucker-Prager loading function. Elastic behavior for austenite and martensite is related to the Young modulus (E) and Poisson ratio (ν). The process of phase transformation is controlled by four critical stresses σ_s^{AM}, σ_f^{AM}, σ_s^{MA}, σ_f^{MA}, where "*s*" and "*f*" subscripts state for "start" and "finish" and "*AM*" represents austenite to martensite transformation, whereas "*MA*" represents martensite to austenite transformation; ε_L represents a parameter associated with the recoverable strain resultant from martensitic phase transformation. Figure 3 presents a one-dimensional stress-strain curve for the pseudoelastic behavior idealized by this model.

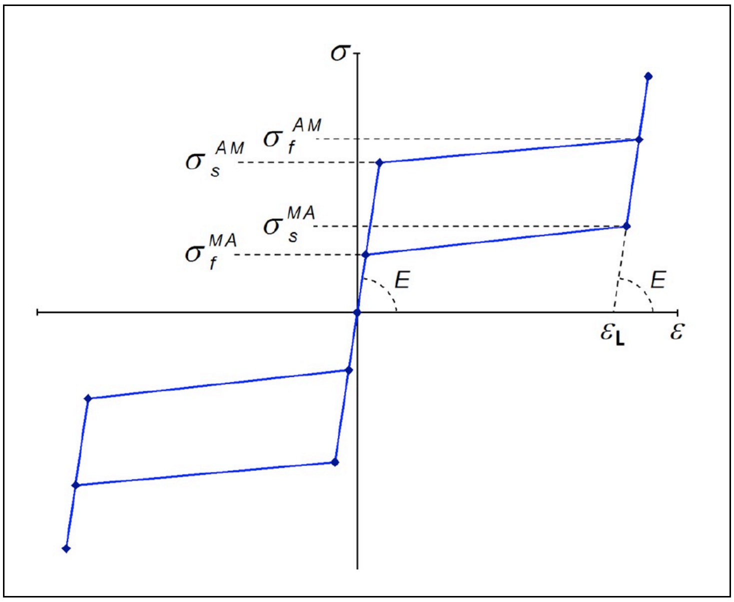


Figure 3 – Idealized one-dimensional stress-strain curve for pseudoelastic behavior (Auricchio *et al.,* 1997).

A numerical analysis of an SMA S-shape absorber behavior under a loading-unloading cycle is developed to assess the vibration attenuation element capability. Dissipated energy is related to hysteretic response of the SMA element, as shown in Fig. 2.

Table 1 presents the SMA pseudoelastic constitutive model parameters employed in the study, and obtained for room temperature after a training process developed to stabilize the hysteresis stress-strain loop. Note that high stress values need to be achieved to trigger phase transformation, inducing hysteretic behavior. Martensitic volume fraction ξ_M represents the amount of phase transformation, and can be used as an indication of mechanical energy dissipation. The proposed model permits to assess the phase transformation distribution that develops during the loading-unloading process of the SMA element.

Table 1 – SMA pseudoelastic constitutive model parameters (Pacheco *et al.*, 2015).

Parameter	Value
E (GPa)	53
ν	0.30
σ_s^{AM} (MPa)	297
σ_f^{AM} (MPa)	772
σ_s^{MA} (MPa)	306
σ_f^{MA} (MPa)	78
ε_L	0.07

Figure 4 presents a schematic representation of the SMA S-shape absorber geometry, displayed by the dark blue color, forming an assembling with aluminum plates, displayed by the purple color. The aluminum plates represent a structure or a machinery component connected to several repeated regular SMA S-shape absorbers, producing a low density cellular structure, such as a honeycomb. ANSYS Mechanical (ANSYS, 2015) is used for finite element simulations, using APDL (Ansys Parametric Design Language). Two different element types are adopted: SOLID186, applied for both SMA and aluminum plates; and MESH200, used to assist the mesh generation.

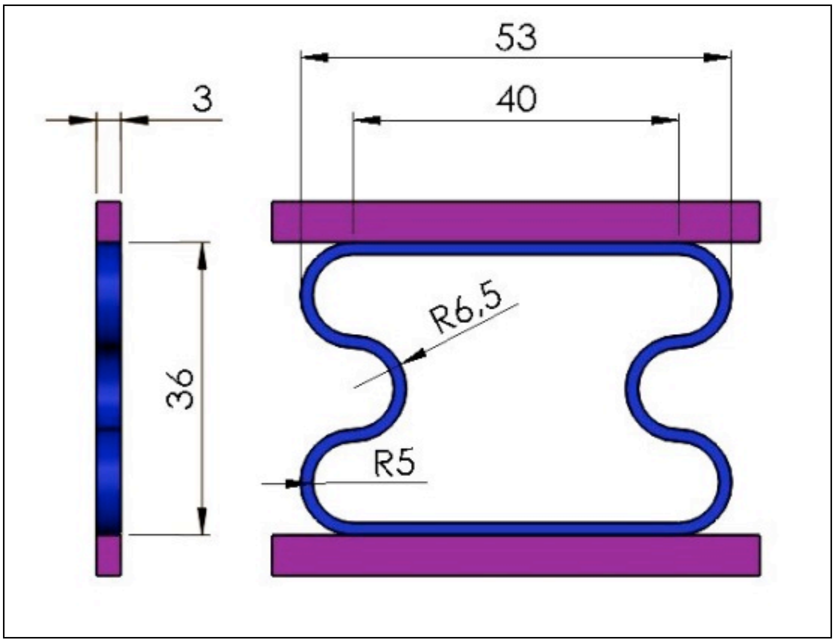


Figure 4 – SMA S-shape absorber element geometry. Dimensions in mm.

Figure 5 exhibits the mesh used in the numerical simulations, obtained after a convergence analysis. Symmetric conditions are applied treating one-quarter of the geometry. Figure 6 presents loading and boundary conditions, where light blue and orange triangles represent null displacement and rotation conditions, respectively, whereas green triangles represent non-null prescribed displacement applied to generate in plane loading in Y direction. In-plane loading-unloading process is composed by two stages: (1) a prescribed displacement loading, (2) followed by a prescribed displacement unloading. For each stage, 40 steps are used. Numerical analysis considers both geometric and constitutive nonlinearities representing large displacements and pseudoelastic behavior of SMA.

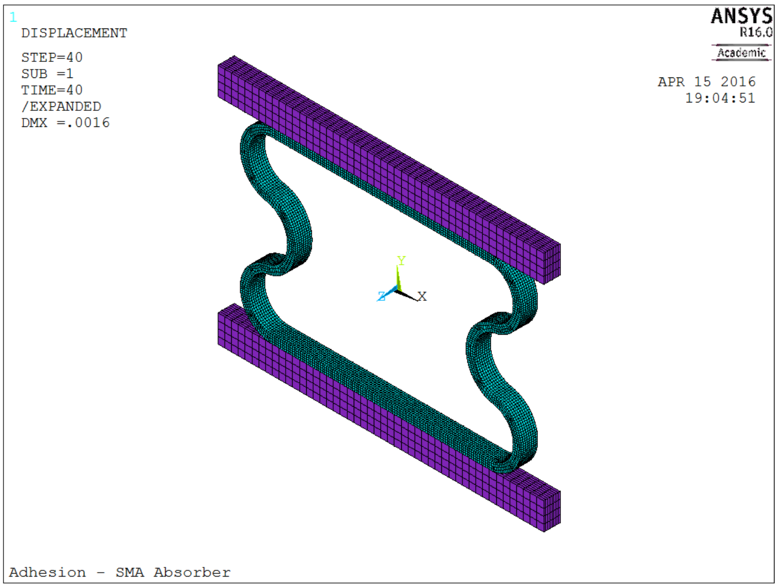


Figure 5 – SMA S-shape absorber mesh.

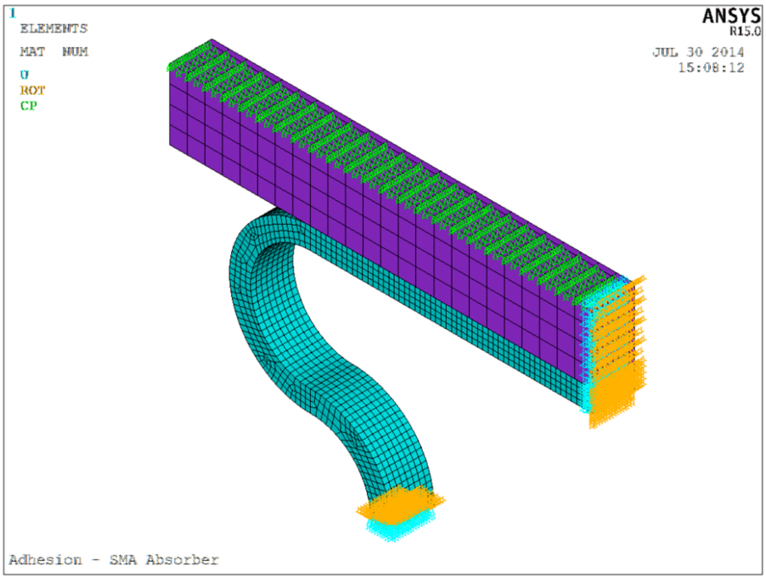


Figure 6 – Boundary conditions and loadings.

3. NUMERICAL RESULTS

Loading process is composed by a prescribed vertical (*Y* direction) in-plane displacement with amplitude of 3.25 mm, applied directly to the aluminum plate. Deformed and undeformed configurations are presented in Figure 7. Undeformed configuration is represented by the dotted line while deformed configuration is represented by the geometry with mesh, being associated with a condition of maximum load (upward vertical displacement).

Figure 8 presents the load-displacement curves for the SMA S-shape absorber considering upward (traction - red dot line) and downward (compression - black line) loadings. Note that system response is related to hysteresis loops that represent the dissipated mechanical energy due to SMA pseudoelastic behavior. A comparison between tension and compression hysteretic loops shows a difference associated with nonlinear geometric effects that promote different final configurations at the maximum load. Tension behavior has an area of 0.193 J per cycle, leading to a volumetric density of energy of 0.246 MJ/m^3, whereas the compression hysteretic curve furnishes an area of 0.125 J per cycle, which yields a volumetric density of energy of 0.160 MJ/m^3. Results show that the in-plane tension furnishes roughly 54% larger values than the in-plane compression. If an axial SMA element is employed, the maximum volumetric density of energy is 19 MJ/m^3, being associated with a complete phase transformation in the whole volume.

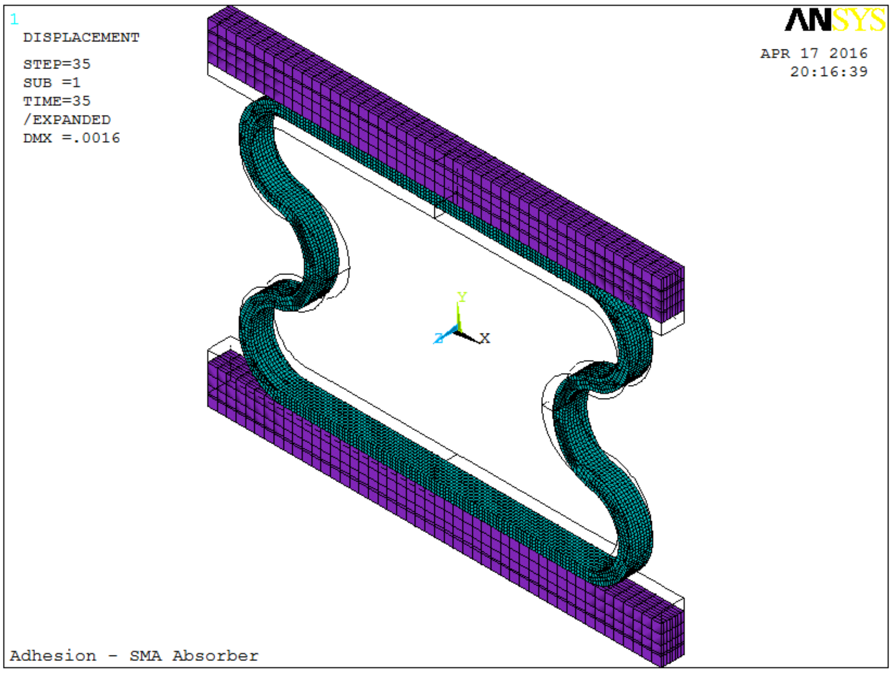


Figure 7 – Deformed and undeformed configurations of the SMA S-shape absorber at maximum load.

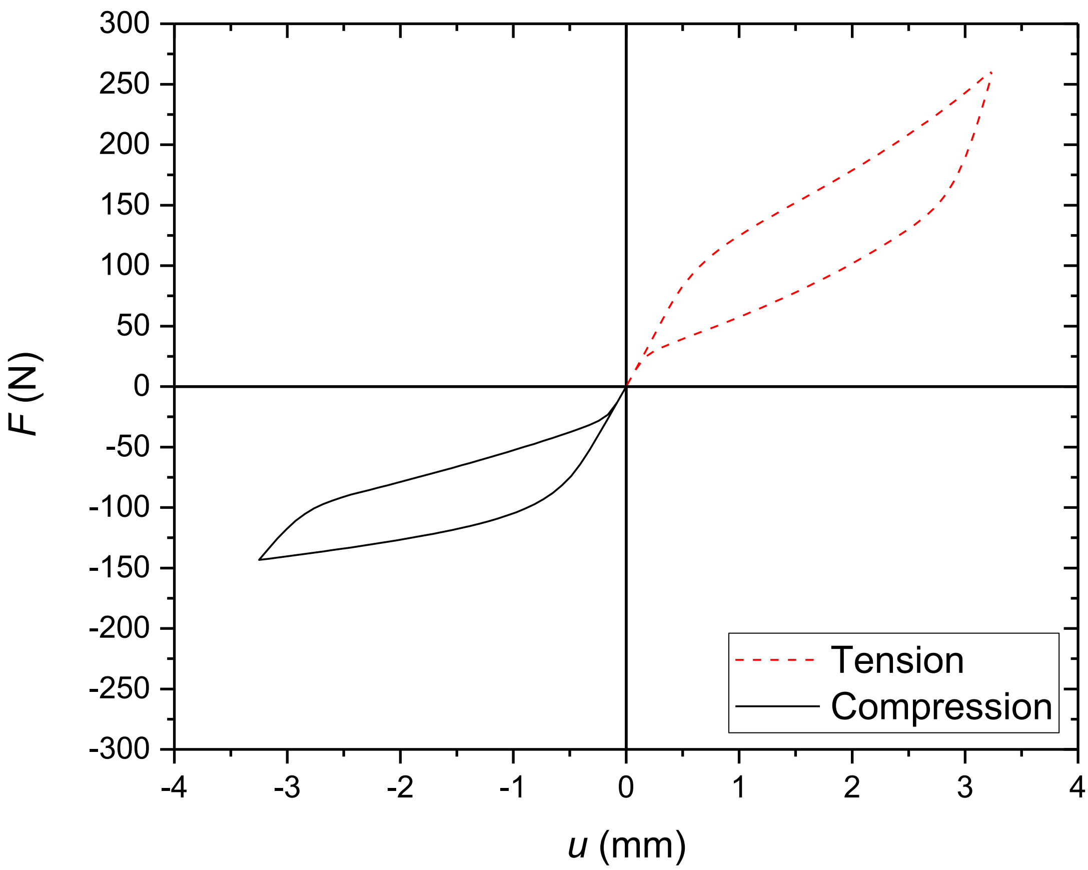
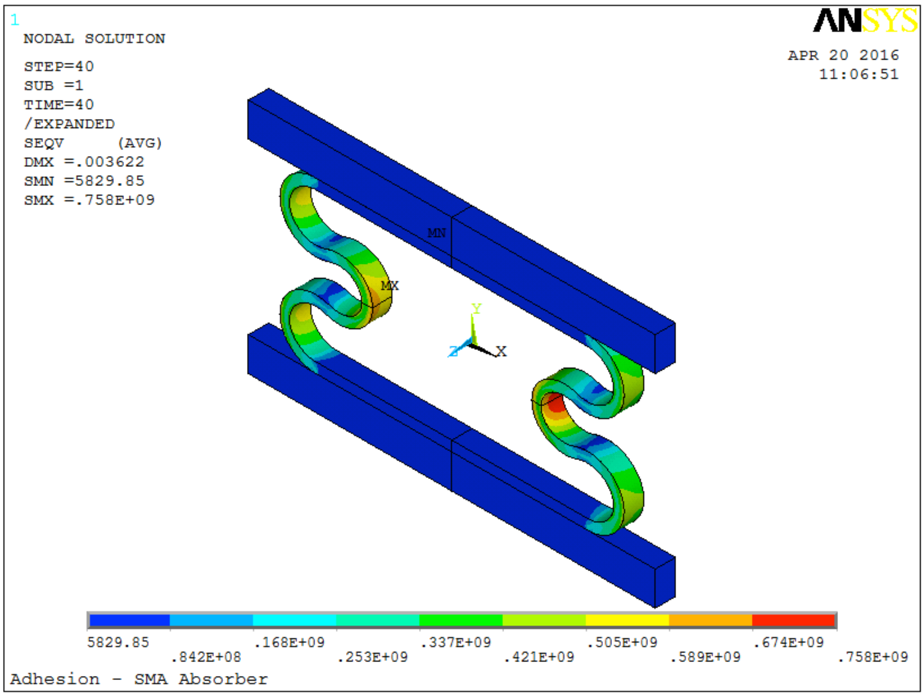
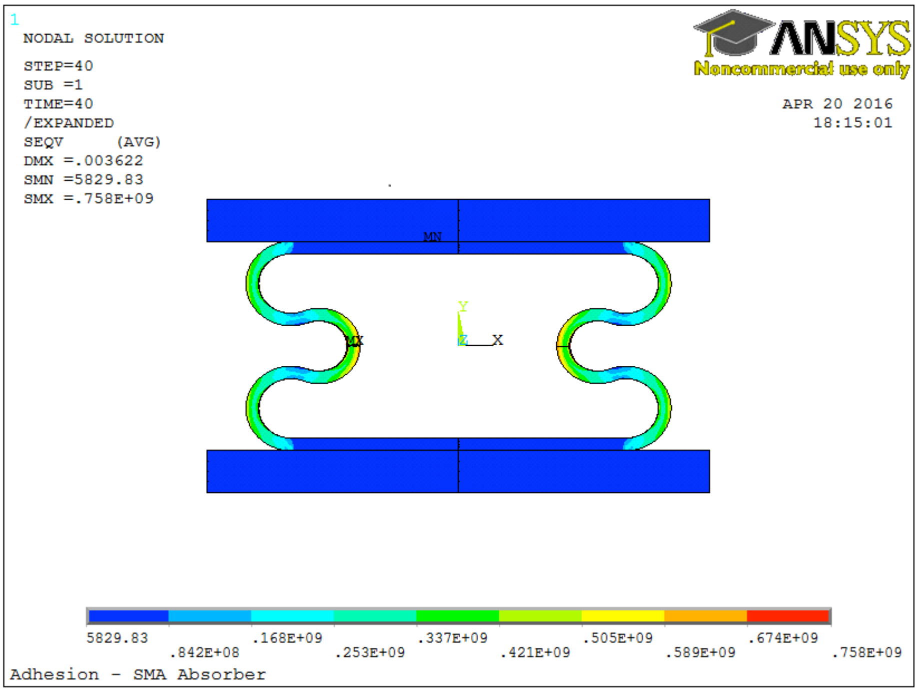


Figure 8 – Hysteretic behavior under tension and compression loadings.

Figure 9 presents the *von Mises* equivalent stress distribution and Fig. 10 the martensitic volume fraction distribution at the maximum load on the isometric and front views for the downward load (compression). Significant values of stress have been achieved, with a maximum of 758 MPa in a region associated with stress concentration. This stress value is near the σ_f^{AM} stress and values of phase transformation volume fractions of 97 % are produced at these regions. However, as the largest values of stress only concentrate at specific regions, only a small part of the volume experiences phase transformation, which produces only a low volumetric density of dissipated energy. Therefore, the proposed methodology using a finite element model can be used as a tool to analyze the phase transformation distribution and to optimize the geometry of SMA vibration absorbers in order to maximize the SMA volume that experiences phase transformation. As SMAs phase transformation critical stresses present a dependence on the temperature, the proposed model can also be used to study the effect of temperature variation in the amount of dissipated energy associated to the pseudoelastic SMA element hysteretic behavior.

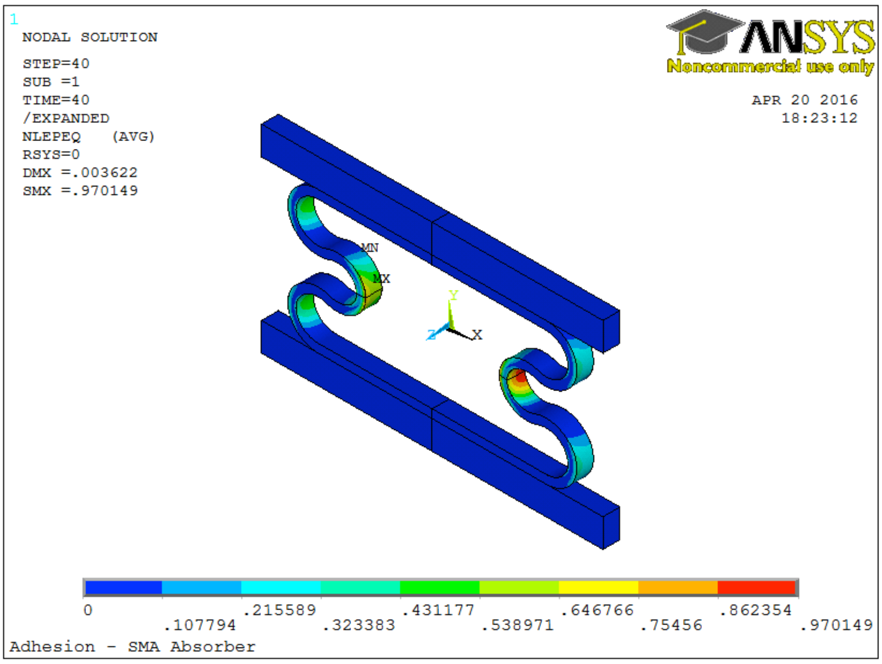


(a)

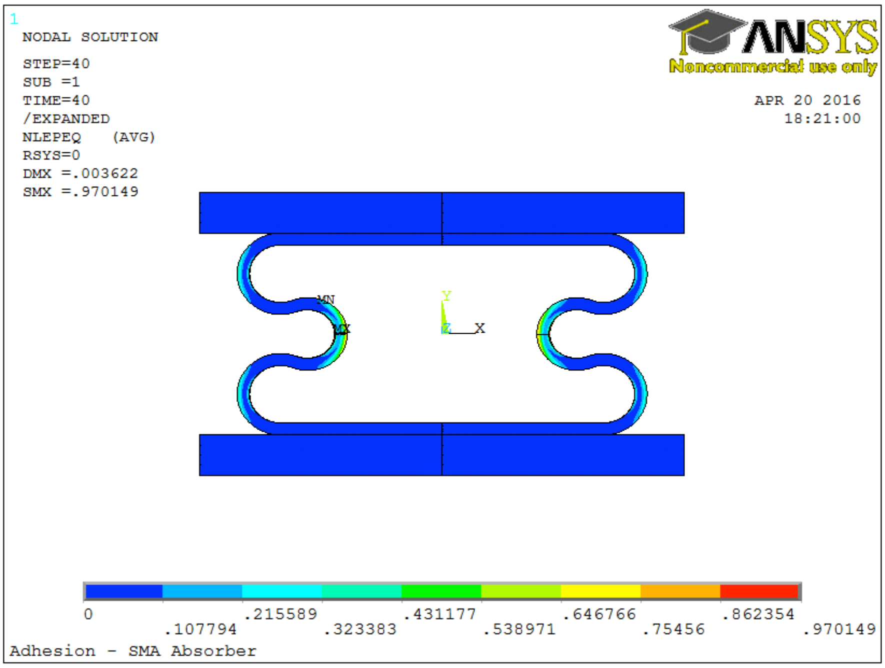


(b)

Figure 9 – *von Mises* stress distribution at maximum load: (a) isometric view and (b) front view.



(a)



(b)

Figure 10 - Martensitic volume fraction distribution at maximum load: (a) isometric view and (b) front view

4. CONCLUSIONS

Pseudoelastic SMA elements are able to dissipate mechanical energy as a result of their hysteretic behavior, making them appropriate to be used in mechanical vibration attenuation applications. In order to investigate an optimized geometry for the design of an SMA S-shape absorber, this work presents a numerical model based on finite-element method. Results show the amount of dissipated energy in each cycle, represented by the area of the hysteresis curve of the SMA element. Although large values of stress are produced, phase transformation only occurs significantly in small localized regions associated with stress concentration. Therefore, the proposed methodology can be used as a tool to analyze the phase transformation distribution and to optimize the geometry of SMA vibration absorbers in order to maximize the volume that experiences phase transformation.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Brazilian Research Agencies CNPq, CAPES and FAPERJ and through the INCT-EIE (National Institute of Science and Technology - Smart Structures in Engineering) the CNPq and FAPEMIG. The Air Force Office of Scientific Research (AFOSR) is also acknowledged.

6. REFERENCES

Aguiar, R.A.A., Savi, M. A. and Pacheco, P.M.C.L., 2013, "Experimental investigation of vibration reduction using shape memory alloys", Journal of Intelligent Material Systems and Structures, Vol. 24, pp. 247-261.

Asgarian, B. and Moradi, S., 2011, "Seismic Response of Steel Braced Frames with Shape Memory Alloy Braces", Journal of Constructional Steel Research, Vol. 67, pp. 65-74.

Auricchio, F., Taylor, R.L. and Lubliner, J., 1997, "Shape-Memory Alloys: Macromodeling and Numerical Simulations of the Superelastic Behavior", Computational Methods in Applied Mechanical Engineering, Vol.146, pp.281-312.

Casciati, F. and Faravelli, L., 2009, "A passive Control Device with SMA Components: from the Prototype to the Model", Structural Control and Health Monitoring, Vol. 16, pp. 751–65.

Desroches, R., 2002, "Seismic Retrofit of Simply Supported Bridges Using Shape Memory Alloys", Engineering Structures, Vol, 24, pp, 325-332.

Fugazza, D., 2003, "Shape-Memory Alloy Devices in Earthquake Engineering: Mechanical Properties", Constitutive Modeling and Numerical Simulations, Master degree thesis, Università degli Studi di Pavia.

Hora, R.B., Adeodato, A., Riagusoff, I.I., Aguiar, R.A., Pacheco, P.M, "Modeling Pseudoelastic Vibration Attenuators Elements Using the Finite Element Method", 22nd International Congress of Mechanical Engineering (COBEM 2013), 3-7, 2013, Ribeirão Preto SP.

Jani, J.M., Leary, M., Subic, A. and Gibson, M.A., 2013, "A review of shape memory alloy research, applications and opportunities". Materials and Design, Vo. 56, pp.1078–1113.

Johnson, R., Padgett, J. E., Maragakis, M. E., Desroches, R. and Saiidi, M. S., 2008, "Large scale testing of Nitinol shape-memory alloy devices for retrofitting of bridges", Smart Materials and Structures, Vol. 17, pp. 1-10.

Lagoudas, D, C, 2008, "Shape Memory Alloys - Modeling and Engineering Applications", Texas: Springer.

Michailidis, P.A., Triantafyllidis, N., Shaw, J.A. and Grummon, D.S., 2009, "Superelasticity and stability of a shape memory alloy hexagonal honeycomb", International Journal of Solids and Structures, Vol, 49, pp, 2724-2738.

Nava, N., Collado, M., and Cabás, R., 2014, "New Pin Puller Based on SMA Technology for Space Applications". Journal of Materials Engineering and Performance, Vol. 23(7), pp.2712–2718.

Olabi, A.G., Morris, E. and Hashmi, M.S.J., 2007, "Metallic tube type energy absorbers: A synopsis", Thin-Walled Structures, Vol, 45, pp. 706-726.

Ozbulut, O. E., Mir, C., Moroni, M. O., Sarrazin, M. and Roschke, PP. N., 2007, "A Fuzzy Model of Superelastic Shape Memory Alloys for Vibration Control in Civil Engineering Applications", Smart Materials and Structures, Vol. 16, pp. 818-829.

Ozbulut, O. E., Roschke, PP. N., Lin, PP. Y. and Loh, C. H., 2010, "GA Based Optimum Design of a Shape Memory Alloy Device for Seismic Response Mitigation", Smart Materials and Structures, Vol. 19, pp. 1-14.

Pacheco, P.M.C.L., Oliveira, P.S.F., Aguiar, R.A.A. and De Barros, S., 2015, "Modelling Bonded Shape Memory Alloy Vibration Attenuators Elements Using the Finite-Element Method", The Journal of Adhesion, Vol.91, pp, 883-908.

Paiva, A. and Savi, M. A, 2006, "An Overview of Constitutive Models for Shape Memory Alloys", Mathematical Problems in Engineering; Vol. 2006, pp. 1-30.

Petrini, L., and Migliavacca, F., 2011, "Biomedical Applications of Shape Memory Alloys". J. of Metallurgy, pp.1–15.

Riagusoff, I.I.T., 2012, Estudo de Dispositivos Pseudoelásticos para a Aplicação em Atenuadores de Vibração, Rio de Janeiro, M.Sc. Dissertation, Graduate Program in Mechanical Engineering and Material Technology, CEFET/RJ.

Savi, M.A., De Paula, A.S. and Lagoudas, D.C., 2011, "Numerical investigation of an adaptive vibration absorber using shape memory alloys", Journal of Intelligent Material Systems and Structures, Vol. 22, pp. 67-80.

Shaw, J.A., Grummon, D.S. and Foltz, J., 2007, "Superelastic NiTi honeycombs: fabrication and experiments", Smart Materials and Structures, Vol. 16, pp. s170-s178.

Shook, D., Lin, PP. Y., Lin, T. K. and Roschke, PP. N., 2007, "A Comparative Study in the Semi-active Control of Isolated Structures", Smart Materials and Structures, Vol. 16, pp. 1433-1446.

Song, G., Ma, N., and Li, H.N., 2006, "Applications of shape memory alloys in civil structures". Engineering Structures, Vol. 28(9), pp.1266–1274.

Zhang, Y., Camilleri, J.A. and Zhu, S., 2008, ''Mechanical Properties of Superelastic Cu-Al-Be Wires at Cold Temperatures for Seismic Protection of Bridges,'' Smart Materials and Structures, Vol. 17, pp. 1-9.

Zuo, X. and Li, A., 2011, "Numerical and Experimental Investigation on Cable Vibration Mitigation Using Shape Memory Alloy Damper", Structural Control Health and Monitoring, Vol. 18, pp. 20-39.

Zuo, X. B., Chang, W., Li, A. Q. and Chen, Q. F., 2006, "Design and Experimental Investigation of a Superelastic SMA Damper", Materials Science and Engineering A, Vol. 438-440, pp. 1150-1153.

Zuo, X. B., Li, A. Q., Chen and Q. F., 2008, "Design and Analysis of a Superelastic SMA Damper", Journal of Intelligent Material Systems and Structures, Vol. 19, pp. 631-639.

Zuo, X., Li, A., Sun, W. and Sun, X., 2009, "Optimal Design of Shape Memory Alloy Damper for Cable Vibration Control", Journal of Vibration and Control, Vol. 15, pp. 897-921.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.