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# Equivalent linear elastic-viscous model of shape memory alloy for isolated structures

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ABSTRACT

In this investigation, the equivalent linear elastic-viscous model of shape memory alloy (SMA) is established for seismic analysis of base-isolated structures using system identification method. The necessary key parameters to express the hysteresis loop of SMA are austenite stiffness, transformation strength, ductility ratio, and stiffness ratio. These parameters are considered in the modeling. This model is developed based on the American Association of State Highway and Transportation Officials (AASHTO) isolation guidelines. In order to validate the proposed model, the base-isolated benchmark building is analyzed by using proposed equivalent linear SMA model as well as the different non-linear SMA models. The evaluation criteria given in the benchmark problem and time variation of top-floor absolute accelerations and base-displacements are considered for comparing the linear and nonlinear models of SMA. An excellent agreement is achieved between proposed equivalent linear SMA model and its nonlinear models. The seismic code recommends that the equivalent linear model of the nonlinear system can be used for carry out the response spectrum analysis of base-isolated structures. Furthermore, the non-linear model requires computationally more time and effort, especially for larger degrees of freedom system. The proposed model may be useful to design engineers in order to over come the disadvantage of non-linear models.



## 1. Introduction

Structures can be protected from the damaging effects of earthquakes by isolating them at ground level. A passive isolation system is one of the most effective and simplest representations to implement the above idea. By providing an isolation device between the superstructure and substructure, the time period of a base-isolated structure is elongated and shifted away from the energetic frequency content of an earthquake. Apart from the required flexibility, the isolation system also have an adequate energy dissipating mechanism and re-centering capacity. Further, it should be able to withstand under the action of vertical load coming from the weight of superstructure, and should provide lateral rigidity against in-service load condition, such as wind or blast or low intensity earthquake.

The isolation bearings can be broadly classified into two categories: elastomeric type and sliding type. Elastomeric bearings provide a flexible interface (rubber like material) between the structure and foundation. These bearings are also supplemented by lead core to enhance hysteretic damping and to provide lateral stiffness. Elastomeric rubber bearings (ERB) and lead rubber bearings (LRB) are the examples of this category. Sliding type isolation systems provide an interface to allow a structure to slide when the lateral load exceeds a threshold value. Friction pendulum systems (FPS) and resilient friction bearing isolators (RFBI) are the examples of this category.

Commercially available traditional isolation bearings such as ERB, LRB, FPS, RFBI etc. have some difficulty in replacing any device component after a strong seismic event. Moreover, they undergo large as well as residual deformations. Isolator displacement is the decision making parameter for the design of an isolation system. Large isolator displacement leads to failure of an isolation system, especially when it is subjected to a near fault earthquake. In order to over come these problems, American Association of State Highway and Transportation Officials (AASHTO) recommends that additional damping can be used to control the large isolator displacement. In this context, many investigations were carried out by researchers to control displacement of isolation bearings using semi-active Magnetorheological (MR) dampers [1–4]. The MR damper may partially solve the above-mentioned problem, but may not be entirely eliminated. Recently, many researchers have used SMA in the isolation systems to reduce its vulnerability against near fault

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motions [5–14]. SMA has many desirable properties such as super elasticity, durability and fatigue resistance. In addition to this, SMA has also an ability to reduce design displacement as well as re-centering capacity. Ozbulut et al. [15] have presented an excellent literature review on the super-elasticity of SMA and its applications in structural vibration control particularly in the area of seismic isolation.

Many international codes are available for designing the isolated structures by using traditional isolation bearings [16,17]. It is very crucial to predict the maximum displacement of an isolated structure for the design of an isolation system. It can be computed by a nonlinear dynamic (ND) analysis for the nonlinear isolation system. The ND analysis requires much effort and computational time for the analysis of base-isolated structures. Therefore, codes are recommended that the nonlinear model can be replaced by a equivalent linear model to carry out the equivalent linear dynamic (ELD) analysis or the response spectrum analysis. Thus, it is better to have an equivalent linear parameters of the nonlinear system to predict the approximate design displacement of the base-isolated structure.

Therefore, it is important to convert nonlinear system into linear one. The behavior of SMA wire is nonlinear. Linearization is a method to convert a nonlinear hysteresis into two analogues linear parameters such as effective stiffness and equivalent viscous damping. These two parameters can be computed from the area of the hysteresis loop. The contrast of non-linear model and its equivalent linear model were analyzed by many researchers for isolated structures [18–20]. The equivalent linear model of LRB for bridge structure was proposed by Hwang and Chiou [18]. This model was proposed based on AASHTO specifications. The results obtained from the equivalent linear model are comparable with the non-linear one. The comparison of bi-linear model and its equivalent linear model of LRB system for a building were studied by Matsagar and Jangid [19]. The modeling of the linear system was based on the International Building Code (IBC) and the Uniform Building Code (UBC) specifications. The study shown that equivalent linear model can predict comparable response as that of bi-linear one. The above-mentioned studies were limited to the friction, and lead based bearings. The equivalent linear model of SMA was proposed by Ghodke and Jangid [20]. In their work, the comparison of nonlinear SMA model and its equivalent linear model were carried out for five storeys framed structure. The results shown that the equivalent linear model of the SMA gives the comparable seismic response.

In the present study, SMA supplemented ERB isolation device is used for the base-isolated benchmark building developed by Narasimhan et al.[21–23]. The aim of this study is to compare the seismic response of base-isolated benchmark building for different non-linear SMA models with the equivalent linear model through the mentioned evaluation criteria.

## 2. Outline of base isolated benchmark building

Fig. 1 (a) and (b) show plan and elevation of an eight-storied steel-braced frame of the base-isolated benchmark building. The floor plan of the building is L-shape up to the sixth floor and rectangular shape for remaining floors. The overall plan of the building is 82.4 m long and 54.3 m wide. The superstructure steel frame is mounted on a concrete base slab. The concrete base slab is monolithic with concrete beams. Drop panels are provided below each column. The SMA supplemented bearings are installed in between each drop panel and the sub-structure. The building is idealized as a three-dimensional linear elastic structure. In this study, the isolation system consists of 92 isolation devices as shown in Fig. 1(a). In the benchmark problem, these bearing locations are adopted to get equal contribution of all the isolation bearings in the response of the base-isolated building. Therefore, it is considered that the SMA does not deform beyond its maximum strain limit due to the adopted distribution. Although, SMA can sustain the larger forces beyond its maximum strain limit (hardening effect), but it is not necessary to use maximum strength of the SMA. Several assumptions are made for the structural system under consideration (i) the superstructure remains linear during seismic loading, (ii) the floors are assumed to be rigid and the masses are lumped at the center of mass of the floors, (iii) three degrees of freedom (DOF) are assumed at each floor at lumped mass location, (iv) fixed base structure consists of 24 DOF, and all modes are considered in the analysis, (v) the surrounding temperature is greater than the temperature at the manufacturing of SMA, and (vi) the inherent viscous damping of SMA is ignored.

The equations of motion are developed with the fixed-base properties used for the linear superstructure. With linear behavior of the superstructure, the equations of motion can be written as

$$[M_s]\{\ddot{U}_s\} + [K_s]\{U_s\} + [C_s]\{\dot{U}_s\} = -[M_s][r](\{\ddot{U}_g\} + \{\ddot{U}_b\}) \tag{1}$$

where $[M_s]$, $[C_s]$ and $[K_s]$ are the lumped mass, damping, and stiffness matrices of size 24 × 24 for the fixed base structure, respectively; $\{U_s\} = \{U_1, U_2, ....U_8\}^T$, $\{\dot{U}_s\}$ and $\{\ddot{U}_s\}$ are the unknown relative floor displacement, velocity, and acceleration vectors, respectively of size 24 × 1; the subscript numbers 1–8 represents the floor numbers; $U_1$ represent the vector of size 3 × 1 for considered three DOF at first floor level; $\{\ddot{U}_g\}$ and $\{\ddot{U}_b\}$ are the acceleration vectors of ground and base mass, respectively of size 3 × 1; and $[r]$ is the influence coefficients matrix of size 24 × 3.

The non-linear behavior of SMA is modeled using the Graesser–Cozzarelli model, and the forces in the bearings are transformed to the center of mass of the base using a rigid base-slab assumption. All the SMA supplemented isolation bearings can be modeled individually or globally by equivalent lumped elements at the center of mass of the base. The governing equation of motion for the base mass is written as

$$[r]^T[M_s][\{\ddot{U}_s\} + [r](\{\ddot{U}_g\} + \{\ddot{U}_b\})] + [m_b](\{\ddot{U}_g\} + \{\ddot{U}_b\}) + \{F_{rs}\} + \{F_{rb}\} = 0 \tag{2}$$

where $[m_b]$ is the diagonal mass matrix of the base mass of size 3 × 3; $\{F_{rs}\}$ is the vector of size 3 × 1, representing the resultant restoring forces of SMA wires, it can be linear or non-linear; $\{F_{rb}\}$ is the vector of size 3 × 1, representing the resultant restoring forces of ERBs; and $[r]^T$ represents the transpose of the influence coefficients matrix $[r]$.

## 3. Isolation system

The philosophy behind an SMA supplemented ERB isolation device is to control the large isolator displacement with nearly zero residual deformation, in which, the ERB provides horizontal flexibility and vertical stiffness. ERB consists of steel and rubber layers alternatively. The rubber layer provides relatively low shear stiffness in the horizontal plane. The steel shims provide high vertical stiffness which helps to control the rocking effects of the structure due to vertical vibrations caused by the earthquake. SMA is used along with the ERB due to its super-elasticity and damping capabilities which minimize the peak and residual isolator deformation. The SMA is wound along the corners of the ERB to provide hysteretic damping and also to add lateral stiffness along the direction of the seismic force (refer Fig. 1(c)). If $f_{rsi}$ is the restoring force of SMA wire in $i$th isolator, then

$$f_{rs} = \sum_{i=1}^{92} f_{rsi} \tag{3}$$