SPECTRAL INVESTIGATION ON THE SEISMIC BEHAVIOUR OF VERTICAL MASS ISOLATED STRUCTURES AGAINST EARTHQUAKE

M. Nekooei[1] and M. Ziyaeifar[2]

[1] *Phd Student, Structural Engineering Research Centre, International Institute of Earthquake Engineering & Seismology (IIEES), Tehran, Iran*

[2] *Assistant Professor, Structural Engineering Research Centre, International Institute of Earthquake Engineering & Seismology (IIEES), Tehran, Iran*

Email: nekooei@iiees.ac.ir, mansour@iiees.ac.ir

ABSTRACT :

Most of the new techniques in seismic design of structures are based on changing the dynamic characteristics of buildings to receive less earthquake input force and energy and to dissipate the energy with lower damage and deformation in structural components of the system. Mass isolation of structures is one of this techniques that focuses on the mass of the structure as the main target for seismic isolation and reducing earthquake effects on buildings In this paper, the seismic behaviour of vertical mass isolated structures against the earthquake is studied. The analytical model used for this investigation is a dual mass-spring model which is an extended form of the three element Maxwell model. In this study, the ability of mass isolation techniques in reducing earthquake effects on buildings with two approaches, parametric and numerical approaches, is shown. In the parametric approach, by definition an isolation factor for structure and determination the dynamic characteristics of system, the relative optimum value of the isolator damping coefficient is obtained. The results provide an insight on role of relative stiffness and mass ratio of the two subsystems. Finally, in the numerical approach, the spectral responses of these structures due to the earthquake are investigated. The results show a noticeable decrease in earthquake input force to vertical mass isolated structures in comparison with non-isolated structures.

KEYWORDS: Seismic isolation, Mass isolation, Isolation factor, Damping factor

1. INTRODUCTION

One of the new techniques in seismic design of structures that has shown a great success in reducing earthquake effects on buildings, is base isolation. Using this technique that isolates the structure from its base, flexibility of structure in its dominant first mode of vibration increases and earthquake effects on building reduces (Fig.1) [1,2]. In this approach increasing the flexibility and damping ratio of building is concentrated within an isolation layer located at the base of structure. However, widespread application of this technique in seismic design of structures is limited due to the problems associated with base isolation technology.

To expand the application of isolation techniques it is proposed to focus on the mass of the structure as the main target for isolation. Mass isolation focuses on mass as the primary concern for isolation [3,4]. This view point is general and can seamlessly describe different seismic isolation techniques. For example, base isolation can be considered as a subordinate notion deriving from the idea of mass isolation where the whole mass of the system is indispensably isolated not from the ground, but from the high stiffness of the system through the flexibility of isolators(Fig.2-a and b).

A more desirable approach in mass isolation would be a technique in which lateral stiffness of the system is not abruptly affected by isolation. In building structures an isolation technique based on this idea requires the horizontal component of mass to be isolated from the lateral stiffness of structure. Figure (2-c) schematically shows one example of this technique in which the mass of the system, attached to a low stiffness-supporting frame, is connected to a stiff braced frame as the lateral stiffness of the system through an isolation mechanism. Here, the isolation device is not subjected to the weight of building and its prominent role is to reduce the level of force and displacement on the mass supporting frame [4,5].

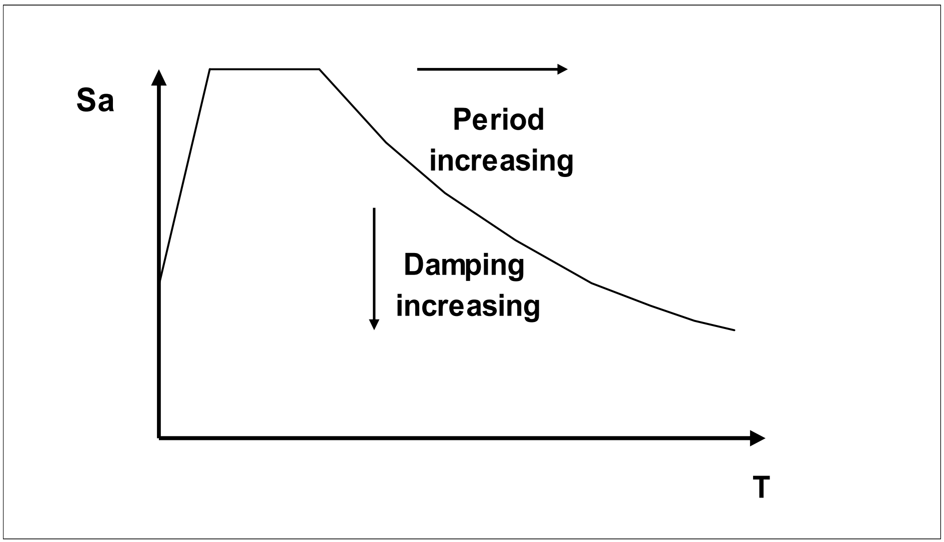

Figure 1 Isolation concepts

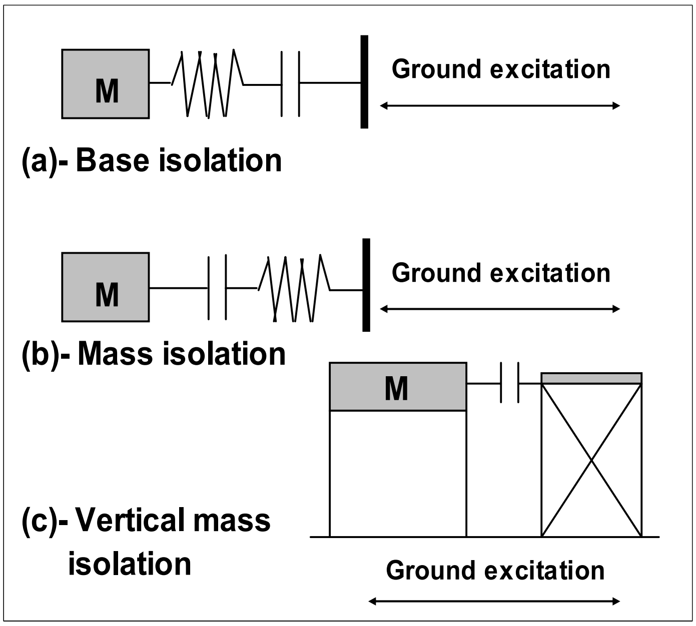

Figure 2 Isolation techniques

In this paper, the ability of this technique, entitled as *Vertical Mass Isolation*, in reducing earthquake effects on buildings with two approaches, parametric and numerical approaches, is studied.

2. ANALYTICAL MODEL

Vertical mass isolated structures are assumed to be consisted of two subsystems. Mass subsystem possesses low lateral stiffness but carries the major part of mass of the system. Stiffness subsystem, however, controls the deformation of the mass subsystem and attributes with much higher stiffness. The isolator layer is, therefore, located in between the mass and the stiffness subsystems and assumed to be a viscous damper layer. Figure (3) schematically shows the analytical model for non-isolated structure and vertical mass isolated structure. The parameters m, k and c are respectively the mass, the stiffness and the viscous damping coefficients of non-isolated structure model. The parameters m1 , k1 and c1 are respectively the mass , the stiffness and the viscous damping coefficients of the mass subsystem and the parameters m2 , k2 and c2 are respectively the mass , the stiffness and the viscous damping coefficients of the stiffness subsystem in vertical mass isolated structure model.

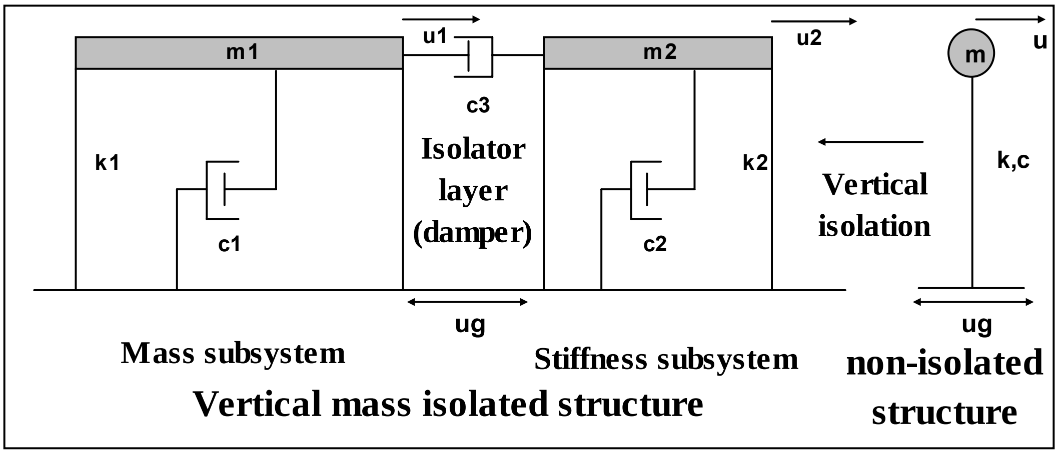

Figure 3 Analytical model

The analytical model, used for vertical mass isolated structure, is a dual mass-spring model which is an extended form of the Maxwell three element model that is a well-known model for non-classically damped systems [6]. If the parameters c1,c2 and m2 are negligible in this model (Fig.3), this model is converted to the Maxwell three element model (Fig.4).

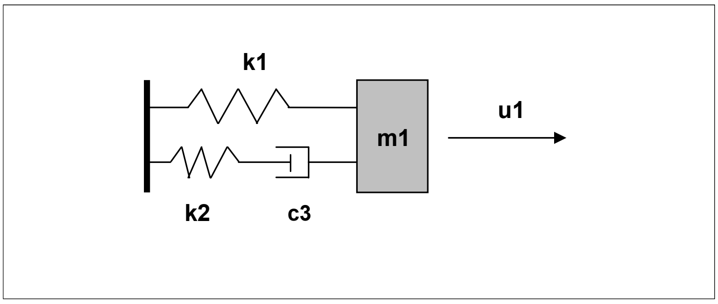

Figure 4 Maxwell three element model

The governing differential equations for a vertical mass isolated structure as shown in Figure (3) under earthquake excitation are given by

$$m_1\ddot{u}_1 + c_1\dot{u}_1 + k_1 u_1 + c_3(\dot{u}_1 - \dot{u}_2) = -m_1\ddot{u}_g \qquad (2.1)$$

$$m_2\ddot{u}_2 + c_2\dot{u}_2 + k_2 u_2 + c_3(\dot{u}_2 - \dot{u}_1) = -m_2\ddot{u}_g \qquad (2.2)$$

The displacement of the ground is denoted by ug, the relative displacement of the mass subsystem by u1 and the relative displacement of the stiffness subsystem by u2 (Fig.3). These equations can be written in matrix form:

$$\left[M\right]\left\{\ddot{U}\right\} + \left[C\right]\left\{\dot{U}\right\} + \left[K\right]\left\{U\right\} = -\left[M\right]\left\{1\right\}\ddot{u}_g \qquad (2.3)$$

by introducing the following notations,

$$\left[M\right] = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \tag{2.4}$$

$$\left[C\right] = \begin{bmatrix} (c_1 + c_3) & -c_3 \\ -c_3 & (c_2 + c_3) \end{bmatrix} \tag{2.5}$$

$$\left[K\right] = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \tag{2.6}$$

$$\left\{U\right\} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{2.7}$$

where [M],[C] and [K] are respectively the mass , the stiffness and the damping matrices and {U} is the displacement vector for the vertical mass isolated structure. Caughey and O'Kelly have shown [7] that if the damping matrix of the system satisfies the identity:

$$[C]\,[M]^{-1}\,[K] = [K]\,[M]^{-1}\,[C] \tag{2.8}$$

the natural modes are real-valued and equal to those of the associated undamped system. Equations (2.4),(2.5) and (2.6) do not satisfy the Caughey-O'Kelly condition (Eqn. 2.8). Such systems that do not satisfy the Caughey-O'Kelly condition, generally have complex-valued natural modes and are said to be non-classically damped systems. Their response can be evaluated by a generalization of the modal superposition method due to Foss [8,9].

3. PARAMETRIC APPROACH

In this approach, by definition an isolation factor for structure and determination the dynamic characteristics of system, the relative optimum value of the isolator damping coefficient is obtained. Substituting Eqn. 2.1 in Eqn. 2.2 without earthquake excitation gives

$$(m_1 m_2)\overset{(4)}{u_1} + [m_1(c_3 + c_2) + m_2(c_3 + c_1)]\overset{(3)}{u_1} + \left[m_1 k_2 + m_2 k_1 + (c_3 + c_1)(c_3 + c_2) - c_3^{\,2}\right]\overset{(2)}{u_1} +$$
$$[k_1(c_3 + c_2) + k_2(c_3 + c_1)]\overset{(1)}{u_1} + (k_1 k_2)u_1 = 0 \tag{3.1}$$

The solution of Eqn. 3.1 can be taken as

$$u_1 = Ae^{st} \tag{3.2}$$

where s is a characteristic value. Substituting Eqn. 3.2 into the Eqn. 3.1, one obtains the characteristic value problem defined by

$$(m_1 m_2)S^4 + [m_1(c_3 + c_2) + m_2(c_3 + c_1)]S^3 + \left[m_1 k_2 + m_2 k_1 + (c_3 + c_1)(c_3 + c_2) - c_3^{\,2}\right]S^2 +$$
$$[k_1(c_3 + c_2) + k_2(c_3 + c_1)]S + (k_1 k_2) = 0 \tag{3.3}$$

If the parameters c1,c2 are negligible , Eqn. 3.3 gives

$$(m_1 m_2)S^4 + c_3(m_1 + m_2)S^3 + (m_1 k_2 + m_2 k_1)S^2 + c_3(k_1 + k_2)S + (k_1 k_2) = 0 \qquad (3.4)$$

This equation can be written in the form:

$$\left(S^2 + \frac{1}{2}\left[\frac{c_3}{m}\left(\frac{(1+\alpha)^2}{\alpha}\right) - \sqrt{\frac{c_3{}^2}{m^2}\left(\frac{(1+\alpha)^2}{\alpha}\right)^2 - 4\frac{k}{m}\left(\frac{1-\alpha}{\sqrt{\alpha}}\right)^2}\right]S + \frac{k}{m}\right) \times$$
$$\left(S^2 + \frac{1}{2}\left[\frac{c_3}{m}\left(\frac{(1+\alpha)^2}{\alpha}\right) + \sqrt{\frac{c_3{}^2}{m^2}\left(\frac{(1+\alpha)^2}{\alpha}\right)^2 - 4\frac{k}{m}\left(\frac{1-\alpha}{\sqrt{\alpha}}\right)^2}\right]S + \frac{k}{m}\right) = 0 \qquad (3.5)$$

by introducing the following notations,

$$m_2 = \alpha\ m_1 \quad \& \quad k_1 = \alpha\ k_2 \qquad (3.6)$$

$$m = m_1 + m_2 \quad \& \quad k = k_1 + k_2 \qquad (3.7)$$

where α is an isolation factor.

Generally, two isolation factors can be defined, the mass isolation factor α_m and the stiffness isolation factor α_s. Here, these are supposed the same for simplifying. Also m and k are the mass and the stiffness of non-isolated structure (Fig.3).

Eqn. 3.5 shows that if the value of c3, viscous damping coefficient of isolator layer (Fig.3), is equal to

$$c_{opt} = 2\frac{(1-\alpha)}{(1+\alpha)^2}\sqrt{\alpha}\, mw \qquad (3.8)$$

the circular natural frequencies of both modes of system are equal to

$$w = \sqrt{\frac{k}{m}} \qquad (3.9)$$

where w is the circular natural frequency of non-isolated structure, and the damping factor of the main mode of system is maximum and is equal to

$$\zeta_{\max} = \frac{(1-\alpha)}{2\sqrt{\alpha}} \qquad (3.10)$$

The variation of modal periods and damping factors due to the variation of viscous damping coefficient of isolator layer are shown in Figures (5) and (6) for $\alpha = 0.2$. In this figures, T is the period of non-isolated structure and d is a damping factor related to c3, viscous damping coefficient of isolator layer, defined by

$$d = \frac{c_3}{2\, mw} \qquad (3.11)$$

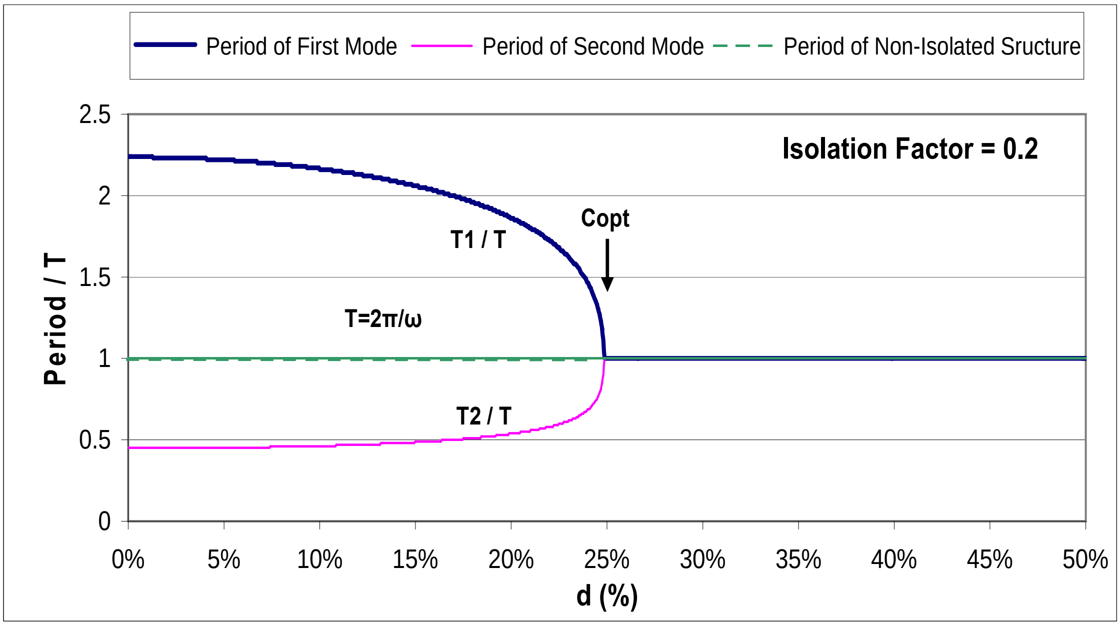

Figure 5 Variation of modal periods versus damping factor of isolator layer

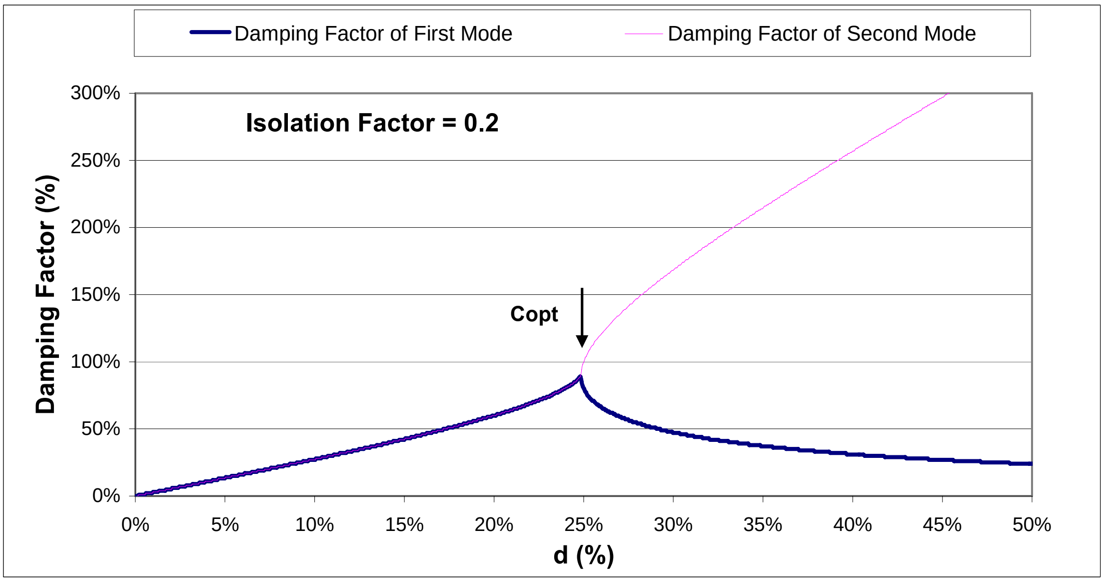

Figure 6 Variation of modal damping factors versus damping factor of isolator layer

4. NUMERICAL APPROACH

In this approach, the spectral responses of non-isolated structure and vertical mass isolated structure due to Tabas earthquake (Fig.7) are studied. The periods of structures considered for this study are respectively 0.5 , 1.0 , 2.0 and 3.0 (sec). The isolation factor used for vertical mass isolated structures is equal to 0.1 ($\alpha = 0.1$). Also the damping factor of non-isolated structure is equal to 0.05 (SDF5%) and the value of c3, viscous damping coefficient of isolator layer, for vertical mass isolated structures is equal to Copt (Eqn. 3.8). The comparison of the spectral responses of non-isolated structure and vertical mass isolated structure are shown in Figures (8), (9) and Table 1. The results show a noticeable decrease in earthquake input force to vertical mass isolated structures in comparison with non-isolated structures and also show more decreasing for vertical mass isolated structures with low periods.

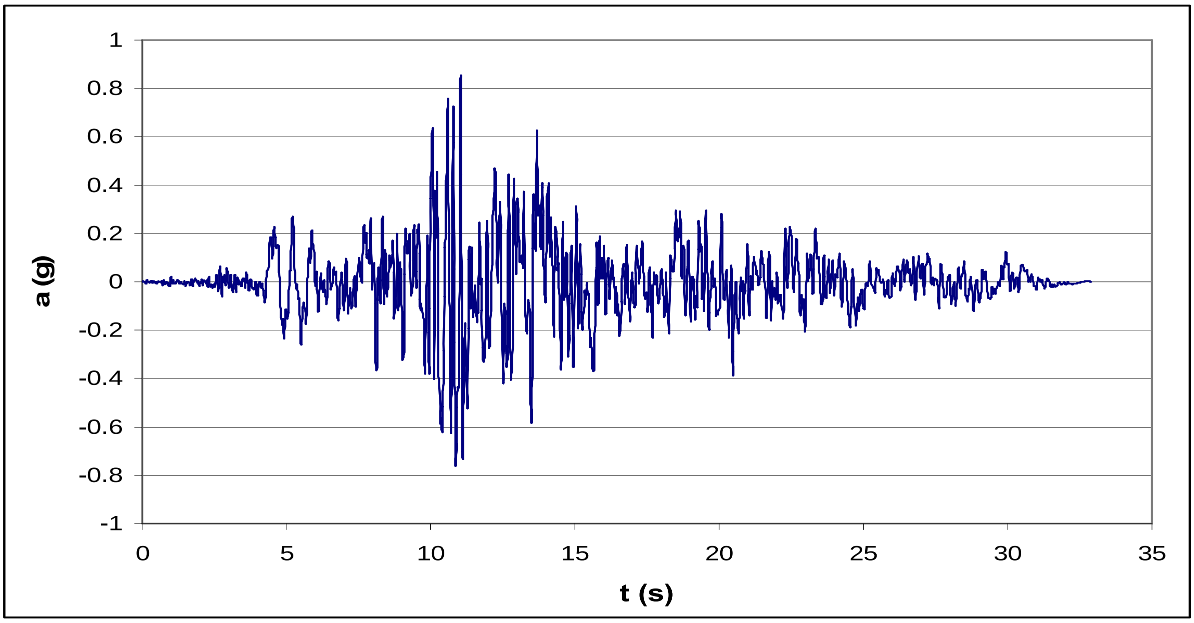

Figure 7 Acceleration history of Tabas earthquake (1978, Iran)

Table 1 The ratio of the spectral responses of vertical mass isolated structures to the spectral responses of non-isolated structures

$\alpha = 0.1$ T(s)	Displacement Ratio	Force Ratio
0.5	0.93	0.25
1.0	1.71	0.40
2.0	1.26	0.40
3.0	1.26	0.54

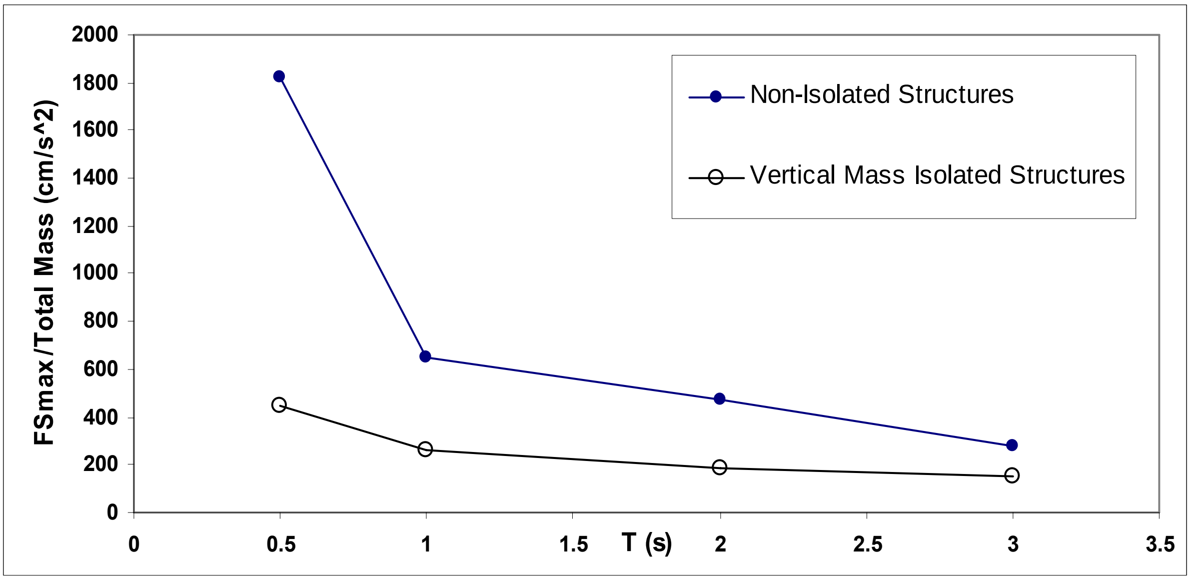

Figure 8 Comparison of spectral values of base shear forces from non-isolated structures and vertical mass isolated structures

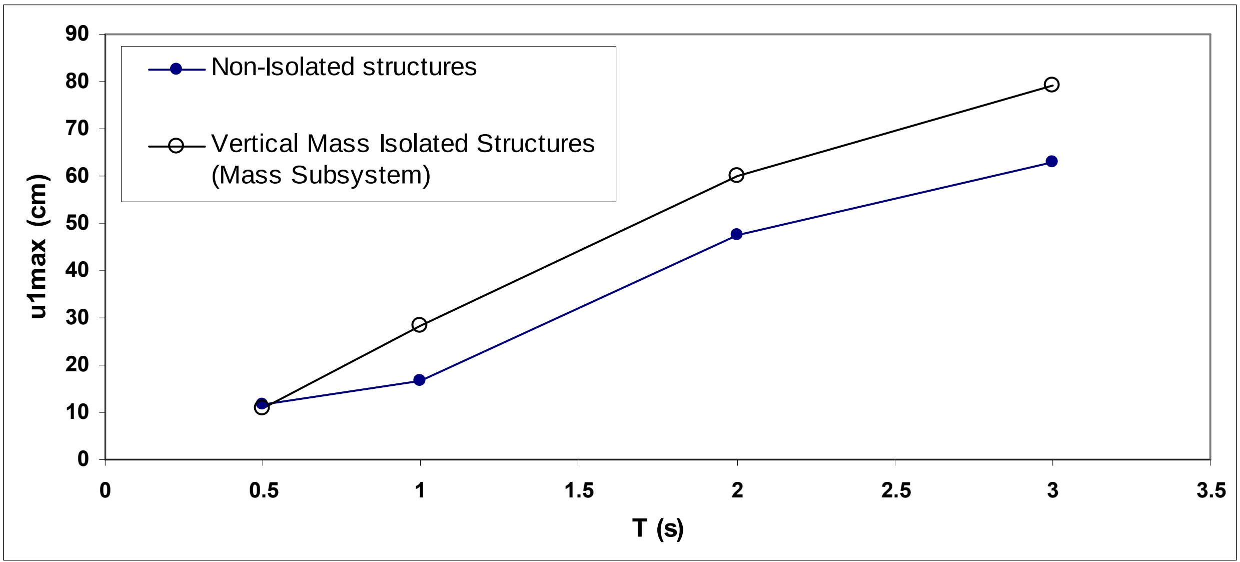

Figure 9 Comparison of spectral values of displacements from non-isolated structures and the mass subsystem of vertical mass isolated structures

5. CONCLUSION

Mass isolation is an intuition that attempts to rationalize the concept of vibration isolation by emphasizing on the mass as the main target for isolation. Using this approach, the main part of the mass of the system can be shifted to the zone of lower force and energy in the earthquake spectrum. This method also increases damping capability of the system to a relative optimum level without using complicated technologies. Vertical mass isolation technique, proposed in this study, demonstrates practicality of this approach in building structures and numerical examples represent its effectiveness in reducing earthquake effects in a variety of buildings. The potential of vertical mass isolation in seismic retrofit is also promising. Additional study is also required on the semi-active control systems, as well as low-power active control systems, to improve the performance of this technique.

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