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Structural disconnection as a general technique to improve the dynamic and seismic response of structures: a basic model

Cristiano Fabrizio[a], Andrea M. de Leo[a], Angelo Di Egidio[a,*]

[a]Unversity of L'Aquila - DICEAA, via G. Gronchi, 18, 67100 L'Aquila, Italy

Abstract

The Base Isolation (*BI*) and the Tuned Mass Damper (*TMD*) represent two different techniques to reduce vibrations in building structures. Both these techniques may be considered as descending from an appropriate "disconnection" carried out on a given structure, whose global mass is subdivided in two parts, with a substantial difference in stiffness. The present work aims to study the characteristics of the disconnection and its effectiveness in reducing the dynamic response of a building structure subject to a base excitation. A simple 2-*DOF* "archetype" model has been developed to describe structural systems where a disconnection has been performed. This model has a constant total mass while stiffness and mass ratios, related to the two degrees of freedom, are taken as main variable parameters. Two distinct reference schemes (*BI*-scheme and *TMD*-scheme) have been adopted in order to identify the specific part of the structure (respectively upper or lower) whose dynamic response should take advantage from the disconnection. A measurement of such advantage has been then proposed by means of different "gain parameters", related to each scheme. The behavior of the gain parameters has been depicted in various maps, each one defined for different base accelerations.

Keywords: Base isolation, Tuned Mass Damper (TMD), archetype system, gain parameters and maps, seismic design.

1. Introduction

The Base Isolation (BI) and the Tuned Mass Damper (TMD) have always represented interesting solutions to reduce vibrations in structures. Until some years ago, the BI and TMD have been treated as two distinct opportunities to improve the dynamic behavior of structures, due to their different intrinsic characteristics. In the last

* Corresponding author. Tel.: +39-0862-434530; fax: +39-0862-434548.
E-mail address: angelo.diegidio@univaq.it

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years various studies have investigated the opportunity to move from the context described above towards new and more complex solutions. For example, in [1] it is investigated the use of the *TMD*, shifted down on the first floor above the isolation layer, in a base isolated structure, in order to reduce the base displacements. On the other hand, the condition that a "suitably heavy" *TMD* may well perform as a protection device against the earthquake action, has brought the basic idea that sufficient mass for the damper could be obtained from the structure to be protected itself, instead of adding supplemental mass. In [2] entire portions of the structure (the substructures) are turned into vibrating masses with a uniform disconnection, along the building's height, with respect to the rest of the structure (the superstructure). In [3] the mass of the damper is represented by the entire roof system of the building while the disconnection stands on top of the structure in a classical manner. In [4] new storeys (2 or 4) are placed on an isolation layer on the rooftop of an existing 12-storeys building, so that they can act as a *TMD* system to control the vibration of the lower portion. About the mid-story disconnection, various works [5, 6] have studied, analytically and experimentally, the dynamic behaviour of building structures equipped with an isolation layer, placed mainly above the 1st floor.

Regarding the possibility to disconnect the structure at different levels, to improve its overall dynamic response, it would be of interest to wonder what are the limits that exist between the *BI* and *TMD* and when the disconnection can be considered as a base isolation or a tuned mass damper system. This paper tries to give an answer to this question by introducing a simple two-degree of freedom model. Similarly to what performed in [7, 8], a simple two-degree of freedom model may be taken as representative of structures where a *BI* - or a *TMD* -scheme is used. This "archetype" 2-*DOF* system has a constant total mass while stiffness and mass ratios, related to the two degrees of freedom, are taken as variable parameters. Both external harmonic and seismic base excitation are considered. An extensive parametric analysis is performed to characterize the system. Two different types of behaviour maps, one referring to the *BI* and the other to the *TMD*, are introduced. To make them comparable, they are represented in the same parameters space. In these maps the regions where a base isolation or a tuned mass damper system works properly, are well recognizable and, beside them, it is also possible to point out some other regions of the parameters space where both systems may well perform. Some numerical simulations, conducted on shear-type systems, are perform in order to confirm the results provided by the simple 2-*DOF* model.

2. Archetype models

A main archetype two-degree of freedom model (2- *DOF*) (Fig.1) is used to describe the behaviour of general multi-degree of freedom systems related to structures where a disconnection is present. The vertical position of the disconnection is taken as a variable parameter of the problem. Moreover, two auxiliary single-degree of freedom systems (*S-DOF*) are introduced as reference cases (Fig.2). These latter ones are used to represent the behaviour of general systems before the disconnection is performed. The main structural model is a simple 2- *DOF* system (Fig.1) subject to ground acceleration a_g . The total mass $m = m_1 + m_2$ is considered constant, while the ratio of the two masses is considered variable. According to Fig.1, this configuration can be derived from an ideal block, with mass m, cut by a virtual horizontal plane at various heights. Both masses are linked to linear elastic springs whose stiffness are k_1 and k_2 and linear viscous dampers whose coefficient are c_1 and c_2 . Two dimensionless parameters are introduced to describe the variability of the disconnecting plane and of the stiffness of the linear springs. Specifically:

$$\mu = \frac{m_2}{m} = \frac{m_2}{m_1 + m_2}; \qquad \rho = \frac{k_2}{k_1} \tag{1}$$

where μ is the mass ratio and ρ is the stiffness ratio. The parameter μ is contained in the range $\mu \in [0.1, 0.9]$. It is of interest to note that when μ is equal to the extreme values of its definition range, the main 2- *DOF* may suggest some particular structural schemes. Specifically, these schemes describe two different vibration reduction strategies, the Tuned Mass Damper (*TMD*, $\mu = 0.1$) and the Base Isolation (*BI*, $\mu = 0.9$). Therefore the basic idea of this study is to analyse, by varying μ , ρ and the characteristics of the base acceleration, the evolution of the two schemes and to find out the conditions under which these schemes can effectively identify a vibration reduction system. For the purpose of developing a parametric analysis, the equations of motion will be written in a dimensionless form, in order to express the main characteristics of the various systems in terms of μ and ρ. Equations presented in the successive sections will be written on the basis of the following definitions and relations:

$$\omega_1 = \sqrt{\frac{k_1}{m_1}};\ \omega_2 = \sqrt{\frac{k_2}{m_2}};\ \xi_1 = \frac{c_1}{2\,\omega_1 m_1};\ \xi_2 = \frac{c_2}{2\,\omega_2 m_2} \tag{2}$$

where ω_1, ω_2 and ξ_1, ξ_2 are respectively the natural circular frequencies and the damping ratios evaluated considering the two masses of the main 2-*DOF*, together with their linking devices, as two isolated subsystems. The following dimensionless time τ and displacements $\tilde{x}_i$, $(i=1,2)$ are introduced:

$$\tau = \omega_1 t;\ \tilde{x}_1 = \frac{x_1}{\tilde{l}};\ \tilde{x}_2 = \frac{x_2}{\tilde{l}} \tag{3}$$

where $\tilde{l}$ is a length. For the sake of simplicity, in the following $\tilde{l}=1$ will be set, thus obtaining that $\tilde{x}_i = x_i, (i=1,2)$. The substitution of the variable t with the dimensionless variable τ, makes possible to write $\dot{x}_i(t) = \omega_1 \dot{x}_i(\tau)$ and $\ddot{x}_i(t) = \omega_1^2 \ddot{x}_i(\tau)$ $(i=1,2)$. The dimensionless Newton's equations of motion of the main 2-*DOF* in matrix form read:

$$\begin{aligned}&\begin{bmatrix}1 & 0\\ 0 & \tilde{\mu}\end{bmatrix}\begin{Bmatrix}\ddot{x}_1(\tau)\\ \ddot{x}_2(\tau)\end{Bmatrix}+\begin{bmatrix}2\xi_1+2\xi_2\sqrt{\rho\tilde{\mu}} & -2\xi_2\sqrt{\rho\tilde{\mu}}\\ -2\xi_2\sqrt{\rho\tilde{\mu}} & 2\xi_2\sqrt{\rho\tilde{\mu}}\end{bmatrix}\begin{Bmatrix}\dot{x}_1(\tau)\\ \dot{x}_2(\tau)\end{Bmatrix}+\\ &\begin{bmatrix}1+\rho & -\rho\\ -\rho & \rho\end{bmatrix}\begin{Bmatrix}x_1(\tau)\\ x_2(\tau)\end{Bmatrix}=-\begin{bmatrix}1 & 0\\ 0 & \tilde{\mu}\end{bmatrix}\begin{Bmatrix}1\\ 1\end{Bmatrix}a_g(\tau)\end{aligned} \tag{4}$$

where $\tilde{\mu} = \mu/(1-\mu)$. Two auxiliary single-degree of freedom systems are considered as reference cases, strictly related to the main 2-*DOF*. In Fig.2 a representation of these two systems is shown. Specifically the System 1 (Fig 2a) is obtained from the main 2-*DOF* system by connecting through a rigid link the upper mass m_2 to the bottom mass m_1. Hence, the system works as single-degree of freedom of total mass $m = m_1 + m_2$. It can be also interpreted as the original system of total mass m, before that the intermediate disconnection is performed. The dimensionless equation of motion of the System 1 reads:

$$\ddot{x}_{S1}(\tau) + 2\,\xi_1\,(1-\mu)\,\dot{x}_{S1}(\tau) + (1-\mu)\,x_{S1}(\tau) = -a_g(\tau) \tag{5}$$

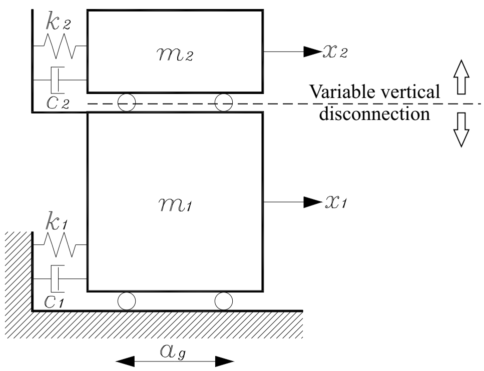

Fig. 1. Main two-degree of freedom system (2-*DOF*)

The System 2 (Fig.2b) is obtained by the main 2-*DOF* system by connecting through a rigid link the bottom mass m_1 directly to the ground. Also in this case, the system works as single-degree of freedom of mass m_2. The dimensionless equation of motion for System 2 is:

$$\ddot{x}_{S2}(\tau)+2\,\xi_2\sqrt{\frac{\rho}{\tilde{\mu}}}\,\dot{x}_{S2}(\tau)+\frac{\rho}{\tilde{\mu}}\,x_{S2}(\tau)=-a_g(\tau) \tag{6}$$

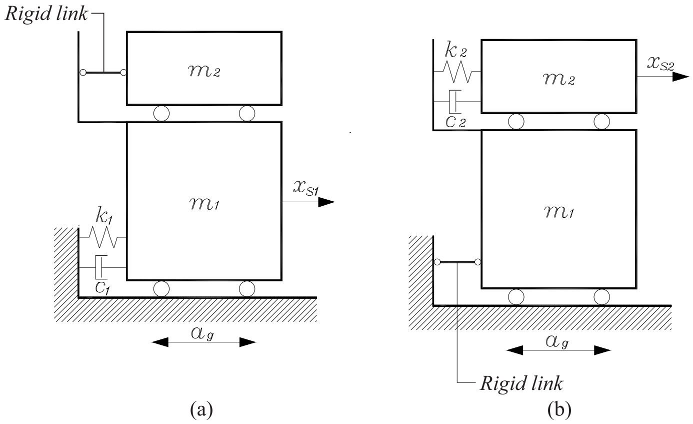

Fig. 2. Auxiliary single-degree of freedom systems: (a) System 1; (b) System 2

3. Analysis of the response under seismic excitation

For brevity, only the seismic excitation will be discussed in the following. The main objective of the seismic analisys has been to build gain maps, capable of driving the design of a intermediate disconnection. In order to have maps of wider and more general significance, the analisys have been carried out considering groups of different accelerograms that could be somehow related to each other. This kind of relation has been identified in the spectrum-compatibility criterion, defined for a code based design response spectrum. Thus, in this context, the aim of the analisys has been to create gain maps related to a specific design spectrum. Two different sets of seven natural, non-scaled seismic registrations (total 14) have been considered. Each set of seven records has been selected to be spectrum-compatible with the elastic design spectrum for the site of L'Aquila, provided by the Italian Seismic Code (ISC) [9]. Specifically, this design spectrum is related to the Life Safety Limit State (SLV) and is based on a exceedance probability of 10% in 50 years, equivalent to a return period of 475 years. Moreover it should be specified that the design spectrum refers to a site class A and a topogrphic category T1, according to ISC definitions. The spectrum compatibility requires that, for each period, in a specific range, the mean value of the spectral ordinates, obtained from a group of seismic registrations, must not be lower than 10% of the design spectrum (target spectrum), while there's no upper tollerance. The selection of the seven signals of each set has been performed using the software Rexel [10]. Using this software it has been possible to obtain two differet sets of signals that do not share any seismic event, while in each set more than one record comes form different registrations of the same earthquake. In Fig.6 the spectra of the two sets of seismic registrations are shown. In particular, in this figure, the spectra of the single earthquake (thin lines), the target spectrum (thick line) and the average spectrum of the seven registrations (dashed thick line), are reported.

A parametric analisys has been carried out, by varing the main parameters μ, ρ and $T_1 = 2\pi/\omega_1$ and using the same value of the damping ratios $\xi_1 = \xi_2 = 0.05$ in all the computations. For the pourpose of the analisys two gain parameters have introduced. Specifically:

$$\alpha_1=\frac{\left|\overline{\delta}_{1_{\max}}\right|}{\left|\overline{x}_{S1_{\max}}\right|};\;\alpha_2=\frac{\left|\overline{\delta}_{2_{\max}}\right|}{\left|\overline{x}_{S2_{\max}}\right|} \tag{7}$$

where $\overline{\delta}_{1_{\max}}$ is the mean of the maxima drifts of the frame in *TMD* -scheme ($\delta_1(t)=x_1(t)$) obtained for the seven earthquake registrations and $\overline{\delta}_{2_{\max}}$ is the mean of the maxima drifts of the frame in the *BI* -scheme $(\delta_2(t)=(x_2(t)-x_1(t)),$ see Fig.1) ; $\overline{x}_{S1_{\max}}$ is the mean of the maxima displacements evaluated in the System 1 (Fig.2a);

$\bar{x}_{S2_{max}}$ is mean of the maxima displacements evaluated in the System 2 (Fig.2b). On the basis of these definitions it is possible to assert that α_1 and α_2 can express a measure of the effectiveness of the two mitigation strategies, namely of the *TMD* -scheme and *BI* -scheme, respectively. Specifically, α_1 indicates the possibility to get benefit by subdividing the structural mass of the frame and utilizing part of it as a *TMD* instead of considering it as a whole. On the other hand, α_2 indicates a comparison between the drifts related to a frame, the superstructure one, placed respectively on a fixed or on an isolated base. The objective of the parametric analysis is to built two gain maps, each one referring to the two gain parameters α_1 and α_2. In Fig.4 the gain maps of the first set of earthquakes are shown. In these maps, inside the dark grey regions, the values of α_1 and α_2 exceed unity, thus no advantages on the use of the disconnection of the system is obtainable. On the contrary, inside the light grey regions the gain parameters are less than unity and an advantage of the use of the disconnection on the system is encountered. As it is possible to observe, in wide common ranges of the parameters μ and ρ both the gain indicators α_1 and α_2 are less than unity. From the analisys of the results it has been possible to observe that the gain maps obtained by using the second set of earthquakes are very similar to those obtained using the first set. This specific result can be attributed to the linearity of the problem, remembering the meaning of sprectrum-compatibility and taking into account that the two sets of seven registrations are compatible with the same spectrum. As a matter of fact the gain parameters (Eq.(7)) are defined using the mean of the maximum responses, just as it happens in the construction of the average spectrum.

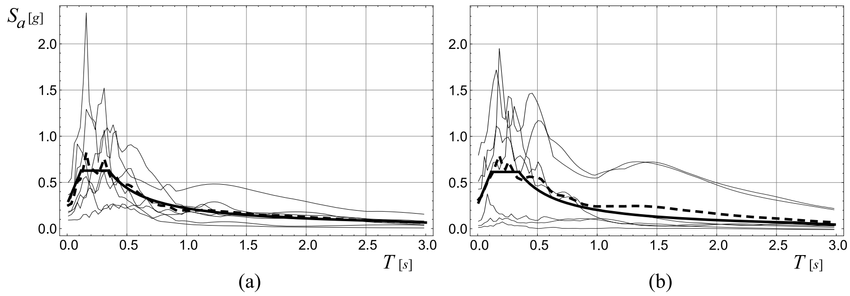

Fig. 3. Spectra of the seismic excitations: (a) First set of seven earthquakes; (b) second set of seven earthquakes.

If a *TMD*-scheme is used in a structure to improve its behaviour, a choice of the parameters inside the light grey zone of the map of gain indicator α_1 assures that a reduction of the amplitude of the displacement of the lower part of the structure occurs. If the parameters characterizing the system were also inside the light grey zone of the map of the gain indicator α_2, then further advantages could be obtained. Specifically, since the indicator α_2 refers to the drift of the upper oscillator, that represents the disconnected upper part of the structure, a reduction of the relative displacement between the lower and the upper part of the structure also occurs. In this last case it could be said that the lower part of the structure works as a base isolation for the upper part of the structure (the TMD system).

On the other hand, if a *BI*-scheme is used in a structure to improve its behaviour, a choice of the parameters inside the light grey zone of the map of the second gain indicator α_2 should be performed. This means that the upper part of the structure, which a base isolation system is applied to, undergoes oscillations of lower amplitude with respect the ones referring to the not isolated structure. Also in this case, if the parameters were inside the light grey zone of the map of the first gain indicator α_1, then further advantages could be obtained. Since the indicator α_1 refers to the displacement of the lower oscillator (the base isolated one), a reduction of the displacement of the oscillating base also occurs. In this last case it could be said that the upper part of the structure works as a tuned mass damper for the oscillating base of the structure (the BI system).

4. Conclusions

In the last years some studies have started to investigate the opportunity to improve the seismic behaviour of conventional structures by disconnecting one or more upper stories. It is of interest to wonder when the disconnection can be considered as a base isolation or a tuned mass damper system.

To give an answer to this question, an archetype model, constituted by a simple two-degree of freedom system, has been taken as representative of structures where a base isolation or a tuned mass damper scheme is used. The system has a constant total mass, while stiffness and mass ratios have been taken as variable parameters. The damping of the system has been always taken constant. An extensive parametric analysis has been performed to characterize the system. Two different types of behaviour maps, one referring to the base isolation and the other to the tuned mass damper, have been obtained. In these maps the regions where a base isolation or a tuned mass damper system works properly, are well recognizable and it has been also possible to point out wide regions of the parameters space where both systems show a good performance at the same time.

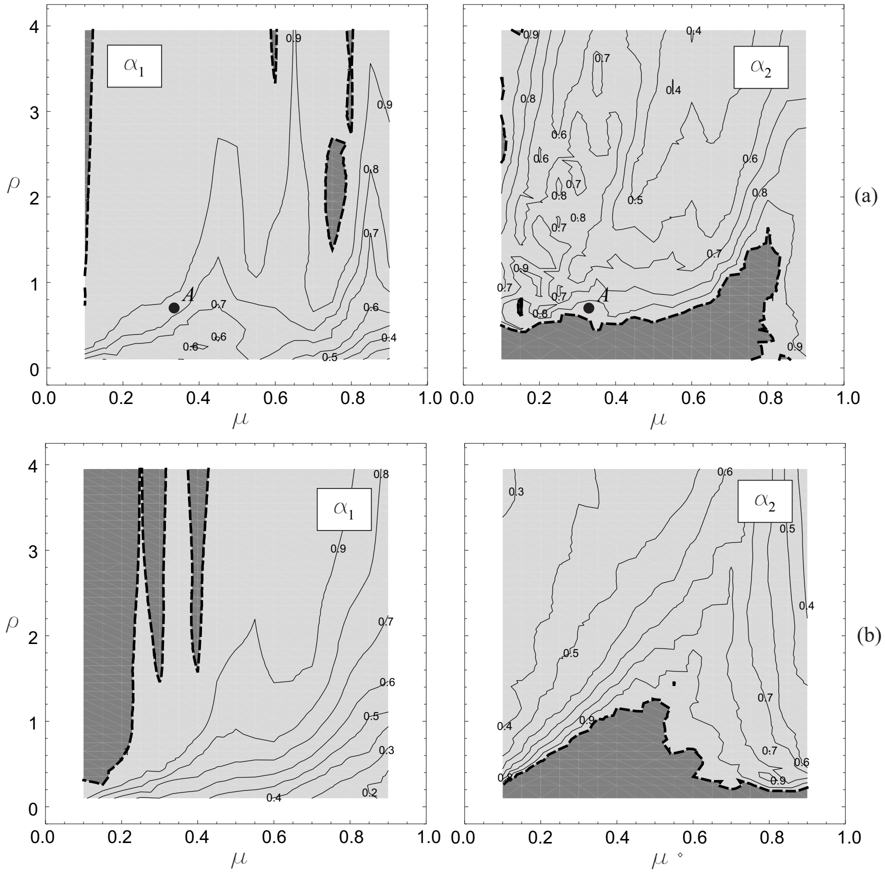

Fig. 4. Gain maps of the first set of seven earthquakes: (a) T_1=0.5s; (b) T_1=1.0s.

References

[1] T. Taniguchi, A. D. Kiureghian, and M. Melkumyan. Effect of tuned mass damper on displacement demand of base-isolated structures. *Engineering Structures*, 30(12):3478–3488, 2008.

[2] F. Sadek, B. Mohraz, A. W. Taylor, and R. M. Chung. A method of estimating the parameters of tuned mass dampers for seismic applications. *Earthquake Engng. Struct. Dyn.*, 26(6):617-635, 1997.

[3] R. Villaverde, M. Aguirre, and C. Hamilton. Aseismic roof isolation system built with steel oval elements. *Earthquake Spectra*, 21(1):225–241, 2005.

[4] M.H. Chey, J.G. Chase, J. B. Mander, and A.J. Carr. Innovative seismic retrofitting strategy of added stories isolation system. *Frontiers of Structural and Civil Engineering*, 7(1):13–23, 2013.

[5] S.-J. Wang, K.-C. Chang, J.-S. Hwang, J.-Y. Hsiao, B.-H. Lee, and Y.-C. Hung. Dynamic behavior of a building structure tested with base and mid-story isolation systems. *Engineering Structures*, 42:420–433, 2012.

[6] S.-J. Wang, K.-C. Chang, J.-S. Hwang, and B.-H. Lee. Simplified analysis of mid-story seismically isolated buildings. *Earthquake Engng. Struct. Dyn.*, 40(2):119–133, 2011.

[7] J. Kelly. Base isolation: linear theory and design. *Earthquake Spectra*, 6(2):223–244, 1995.

[8] R. Rana and T.T. Soong. Parametric analysis and simplified design of tuned mass damper. *Engineering Structures*, 20(31):193–204, 1998.

[9] Min. LL.PP. D.M. 14 gennaio (2008a). Norme Tecniche per le Costruzioni. *Gazzetta Ufficiale della Repubblica Italiana*, 29 (in Italian).

[10] I. Iervolino, C. Galasso, E. Cosenza. REXEL: computer aided record selection for code-based seismic structural analysis. *Bull. Earthquake Eng.* , 8:339–362, 2010.