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Feasibility and effectiveness of exoskeleton structures for seismic protection

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Abstract

In this study, a self-supporting structure, namely an *exoskeleton*, is considered as set outside a main structure and suitably connected to it. From the structural point of view, the exoskeleton is conceived as a "sacrificial" appendage, called to absorb seismic loads in order to increase the performance of the main structure. From the architectural and technological point of view, additional functions may be associated through an integrated design approach, combining seismic with urban and energy retrofitting. Particular and attractive applications can therefore be envisaged for existing buildings.
A reduced-order dynamic model is introduced, in which two coupled linear viscoelastic oscillators represent the main structure and the exoskeleton structure, respectively, while either a rigid link or a dissipative viscoelastic connection is considered for the coupling. The equations of motion are set in non-dimensional form and a parametric study is carried out in the frequency domain to confirm that exoskeleton structures can be feasible and effective in reducing earthquake-induced dynamic responses.

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Keywords: seismic protection, structural control, external retrofitting, exoskeleton structure, coupling.

1. Introduction

The concept of seismic resilience (Bruneau *et al.* 2003) has been recently responsible for a paradigm shift in seismic design and risk management: other objectives beyond life and collapse safety, such as operational continuity (Parise *et al.* 2013, Parise *et al.* 2014), damage control and loss reduction, are considered as crucial to substantially enhance

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the resilience of the built environment. To this aim, structural control methods and systems (Housner *et al.* 1997, Spencer *et al.* 2003, Saaed *et al.* 2015) are a viable and effective means for reducing earthquake-induced vibrations and limiting structural as well as nonstructural damage on civil engineering structures. For existing structures, in particular, novel technologies for seismic retrofitting are strongly needed, to face performance requirements that are more stringent than in the past and continuously increasing (Nakashima et al. 2014). A promising approach to the seismic retrofitting of frame structures consists in employing external structural control systems, like reinforced concrete cores and walls (Trombetti and Silvestri 2007, Lavan and Abecassis 2015) and reaction towers (Impollonia and Palmeri, 2017). In this context, the present study explores the feasibility and effectiveness of exoskeleton structures for seismic protection: the exoskeleton structure is defined as a self-supporting structure, set outside and suitably connected to a main structure; it is conceived as a "sacrificial" appendage, called to absorb seismic loads in order to increase the performance of the main structure (Reggio *et al.* 2017). External seismic retrofitting via exoskeleton structures appears to be an advantageous strategy for a few reasons, among which: the possible strengthening of existing structural members is limited to those members locally interested by the connections to the exoskeleton; any service or business interruption during the retrofitting operations is kept to a minimum; additional architectural functions may be associated through an integrated design approach, combining seismic with urban and energy retrofitting.

2. Governing equations

2.1. Equations of motion

The dynamic behaviour of the coupled system composed of a main structure connected to an exoskeleton structure depends on the dynamic properties of each subsystem as well as on the mechanical features of the coupling device (Luco and De Barros 1998, Gattulli *et al.* 2013, Tubaldi 2015). A two-degree-of-freedom (2-dof) model, composed of two coupled linear viscoelastic oscillators as shown in Figure 1(a), is introduced here: the primary oscillator, with M_1, K_1 and C_1 as mass, stiffness and damping coefficients, represents the main structure; the secondary oscillator, with M_2, K_2 and C_2 as mass, stiffness and damping coefficients, represents the exoskeleton structure; $U_1(t)$ and $U_2(t)$ are the displacements relative to ground; $F(t)$ is the force exerted across the coupling device. The equations of motion of the system subjected to base acceleration $U_g''(t)$ are written as:

$$\begin{aligned} M_1 U_1'' + C_1 U_1' + K_1 U_1 &= -M_1 U_g'' + F \\ M_2 U_2'' + C_2 U_2' + K_2 U_2 &= -M_2 U_g'' - F \end{aligned} \tag{1}$$

with the symbol $(\cdot)'$ denoting differentiation with respect to dimensional time *t*.

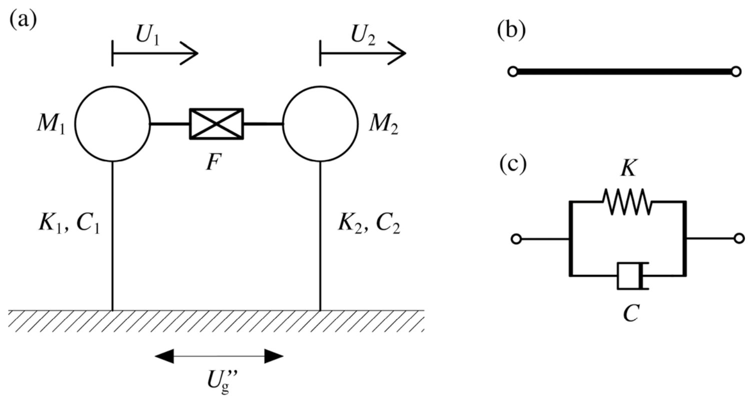

Fig. 1. (a) Structural model of the coupled system; (b) rigid connection; (c) viscoelastic connection (Kelvin-Voigt rheological model).

For a more general description of the problem, Equations (1) are set in non-dimensional form by introducing the following characteristic values of frequency, displacement and force:

$$\Omega^* = \sqrt{\frac{K_1}{M_1}} = \Omega_1, \qquad U^* = \frac{M_1 g}{K_1}, \qquad F^* = M_1 g \tag{2}$$

in which Ω_1 is the uncoupled natural frequency of the primary oscillator and g is the acceleration due to gravity. The following non-dimensional variables:

$$\tau = \Omega^* t, \qquad u_1 = \frac{U_1}{U^*}, \qquad u_2 = \frac{U_2}{U^*}, \qquad f = \frac{F}{F^*} \tag{3}$$

and the parameters:

$$\zeta_1 = \frac{C_1}{2\sqrt{K_1 M_1}}, \qquad \zeta_2 = \frac{C_2}{2\sqrt{K_2 M_2}}, \qquad \mu = \frac{M_2}{M_1}, \qquad \alpha = \frac{\Omega_2}{\Omega_1} \tag{4}$$

are defined, being $\Omega_2 = \sqrt{K_2/M_2}$ the uncoupled natural frequency of the secondary oscillator, while base acceleration becomes:

$$\ddot{u}_g(\tau) = \frac{U''_g(t)}{g} \tag{5}$$

the over-dot indicating differentiation with respect to non-dimensional time τ. Equations (1) are therefore rewritten in non-dimensional form as:

$$\begin{aligned} &\ddot{u}_1 + 2\zeta_1 \dot{u}_1 + u_1 = -\ddot{u}_g + f \\ &\mu \ddot{u}_2 + 2\zeta_2 \alpha \mu \dot{u}_2 + \alpha^2 \mu u_2 = -\mu \ddot{u}_g - f \end{aligned} \tag{6}$$

2.2. Constitutive model of the coupling device

The definition of force $F(t)$ in Equations (1), and hence of non-dimensional force $f(\tau)$ in Equations (6), depends on the constitutive model adopted to describe the mechanical behaviour of the coupling device between the main structure and the exoskeleton structure. Both a non-dissipative and a dissipative behaviour are investigated in this work. In the former case, a rigid connection (Figure 1(b)) is considered between the primary and the secondary oscillator; in the latter case, a viscoelastic connection is considered and modelled according to the Kelvin-Voigt rheological model (Figure 1(c)).

Rigid connection. A rigid connection can be viewed as the limit case of a linear purely elastic connection, i.e. a Hooke spring, when its stiffness coefficient K tends to infinity. The constitutive law of the Hooke model is given for $F(t)$ as:

$$F = K(U_2 - U_1) \tag{7}$$

which becomes in non-dimensional terms:

$$f = \beta_K (u_2 - u_1) \tag{8}$$

with $\beta_K = K/K_1$. As the spring stiffness tends to infinity, or $\beta_K \to \infty$, it follows $u_2 \to u_1$ and Equations (6) are to be replaced by the equation of motion of a 1-dof system:

$$(1+\mu)\ddot{u}_1 + (2\zeta_1 + 2\zeta_2\alpha\mu)\,\dot{u}_1 + (1+\alpha^2\mu)\,u_1 = -(1+\mu)\,\ddot{u}_g \tag{9}$$

Viscoelastic connection. The Kelvin-Voigt rheological model is made of a linear spring, of stiffness *K*, and a linear dashpot, of viscous constant *C*, placed in parallel. The corresponding constitutive law is given for $F(t)$ as:

$$F = K(U_2 - U_1) + C(U_2' - U_1') \tag{10}$$

It is expressed in non-dimensional terms as:

$$f = \beta_K(u_2 - u_1) + \beta_C(\dot{u}_2 - \dot{u}_1) \tag{11}$$

where $\beta_K = K/K_1$ and $\beta_C = 2\zeta_1\, C/C_1$ are the non-dimensional parameters that describe the mechanical properties of the viscoelastic connection.

3. Response in frequency domain

The dynamic response of the coupled system in frequency domain is considered and analysed with the aim of assessing the feasibility and the effectiveness of exoskeleton structures as a means for structural vibration control under dynamic loading.

Non-dimensional base acceleration (5) is assumed to be harmonic

$$\ddot{u}_g(t) = a_{g0}(\omega)\, e^{i\omega t} \tag{12}$$

with $\omega = \Omega/\Omega_1$ being its non-dimensional circular frequency. The dynamic response of the coupled system is characterised by means of complex Frequency Response Functions (FRFs), which express the ratio between the amplitude of steady-state responses and the amplitude of the excitation (Genta 2009). The responses of interest for the primary oscillator are, in particular, its displacement $u_1(\tau)$ relative to ground and its absolute acceleration $\ddot{u}_{a1}(\tau)$. From the viewpoint of seismic protection, they represent the engineering demand parameters to which structural damage (deformation-sensitive) and non-structural damage (deformation- and acceleration-sensitive) are correlated. The corresponding FRFs are determined in three different system configurations as described below.

No control **(NC).** The exoskeleton structure is absent and the dynamic response of the main structure is not controlled. FRFs of relative displacement and absolute acceleration of the primary oscillator are given by:

$$H_{u_1/\ddot{u}_g}(\omega) = -\frac{1}{-\omega^2 + i\omega 2\zeta_1 + 1} \tag{13}$$

and

$$H_{\ddot{u}_{a1}/\ddot{u}_g}(\omega) = 1 + \frac{\omega^2}{-\omega^2 + i\omega 2\zeta_1 + 1} \tag{14}$$

respectively.

Coupling via rigid connection **(RC).** The exoskeleton structure is coupled to the main structure via a rigid connection. FRFs of relative displacement and absolute acceleration of the primary oscillator are given by:

$$H_{u_1/\ddot{u}_g}(\omega) = -\frac{1+\mu}{-\omega^2(1+\mu)+i\omega\left(2\zeta_1+2\zeta_2\alpha\mu\right)+\left(1+\alpha^2\mu\right)} \tag{15}$$

and

$$H_{\ddot{u}_{a1}/\ddot{u}_g}(\omega) = 1+\frac{\omega^2\left(1+\mu\right)}{-\omega^2(1+\mu)+i\omega\left(2\zeta_1+2\zeta_2\alpha\mu\right)+\left(1+\alpha^2\mu\right)} \tag{16}$$

respectively. The independent parameters that govern the dynamic behaviour of the coupled system in RC configuration are four: mass ratio μ, frequency ratio α, damping ratios ζ_1 and ζ_2.

***Coupling via viscoelastic connection* (VC).** The exoskeleton structure is coupled to the main structure via a linear viscoelastic connection. The equations of motion (6) of the 2-dof coupled system can be rewritten in matrix form as:

$$\mathbf{M}\ddot{\mathbf{u}}+\mathbf{C}\dot{\mathbf{u}}+\mathbf{K}\mathbf{u} = -\mathbf{M}\mathbf{r}\ddot{u}_g \tag{17}$$

where $\mathbf{u}(t)=[u_1(t)\;\;u_2(t)]^T$ is the displacement vector with respect to ground, $\mathbf{r}=[1\;\;1]^T$ is the influence vector and

$$\mathbf{M}=\begin{bmatrix}1 & 0\\ 0 & \mu\end{bmatrix},\quad \mathbf{C}=\begin{bmatrix}2\zeta_1+\beta_C & -\beta_C\\ -\beta_C & 2\zeta_2\alpha\mu+\beta_C\end{bmatrix},\quad \mathbf{K}=\begin{bmatrix}1+\beta_K & -\beta_K\\ -\beta_K & \alpha^2\mu+\beta_K\end{bmatrix} \tag{18}$$

are the system mass, damping and stiffness matrices, respectively. In this case, FRFs of both the primary and the secondary oscillator are listed in the following matrices:

$$\mathbf{H}_{\mathbf{u}/\ddot{u}_g}(\omega) = -\left(-\omega^2\mathbf{M}+i\omega\mathbf{C}+\mathbf{K}\right)^{-1}\mathbf{M}\mathbf{r} \tag{19}$$

for the displacements relative to ground and

$$\mathbf{H}_{\ddot{\mathbf{u}}_a/\ddot{u}_g}(\omega) = \mathbf{r}+\omega^2\left(-\omega^2\mathbf{M}+i\omega\mathbf{C}+\mathbf{K}\right)^{-1}\mathbf{M}\mathbf{r} \tag{20}$$

for the absolute accelerations. The independent parameters that govern the dynamic behaviour of the coupled system in VC configuration are six: in addition to the four parameters μ, α, ζ_1, ζ_2 previously defined, two further parameters β_K and β_C are characteristic of the viscoelastic connection.

4. Parametric analyses and discussion

The effectiveness of exoskeleton structures in reducing the dynamic response of the main structure is assessed by drawing a comparison between each control configuration (RC and VC) and the uncontrolled configuration (NC). Comparisons are made in terms of FRFs of the primary oscillator and with varying the independent parameters that govern the dynamic behaviour of the coupled system.

In Figure 2, the amplitude of the FRFs for both the relative displacement u_1 and the absolute acceleration $\ddot{u}_{a1}$ of the primary oscillator are shown in NC and RC configurations. Within the set of four parameters characterising the RC configuration, $\mu = 0.05$, $\zeta_1 = 0.05$ and $\zeta_2 = 0.02$ are assumed as constant, while frequency ratio α is varied in the range [0.1, 10]. Increments of frequency ratio α, for a constant mass ratio μ, are due to the stiffening of the secondary oscillator with respect to the primary oscillator. The resulting effect is a shift of the FRFs peak, corresponding to the natural frequency of the coupled system, towards higher values. Meanwhile, the FRF peak amplitude is reduced in the RC configuration as compared to the NC configuration, in terms of both relative displacement and absolute acceleration.

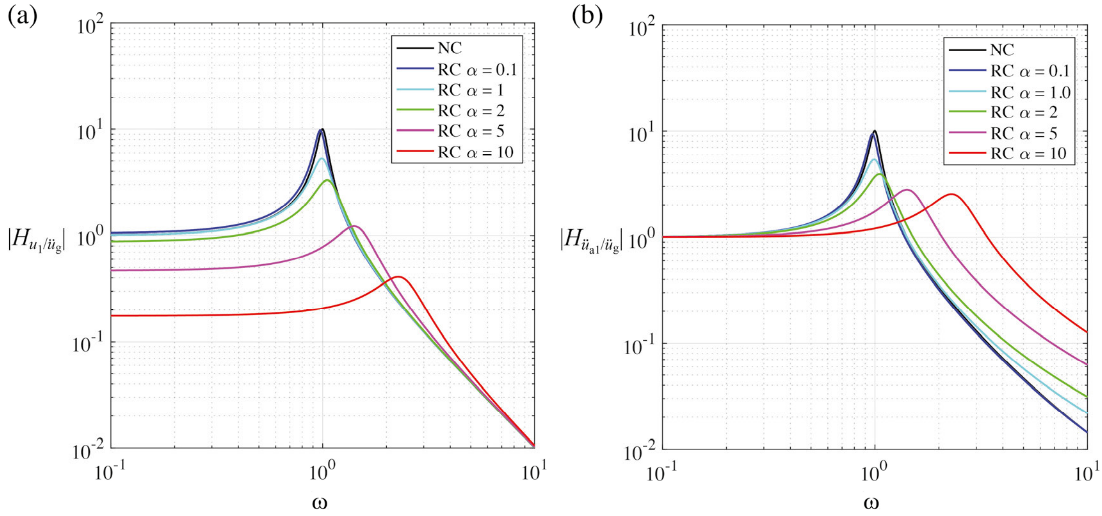

Fig. 2. Amplitude of FRFs to harmonic base acceleration for the primary oscillator, comparisons between NC configuration and RC configurations with varying frequency ratio α: (a) displacement u_1 relative to ground; (b) absolute acceleration $\ddot{u}_{a1}$. It is assumed: $\mu = 0.05$, $\zeta_1 = 0.05$ and $\zeta_2 = 0.02$.

In consideration of these results, the effectiveness of the vibration control is explored by way of two performance indices, defined in terms of FRFs peak amplitude ratio between RC and NC configurations:

$$I_D = \frac{\max \left| H_{u_1/\ddot{u}_g} \right|^{RC}}{\max \left| H_{u_1/\ddot{u}_g} \right|^{NC}}, \qquad I_{AA} = \frac{\max \left| H_{\ddot{u}_{a1}/\ddot{u}_g} \right|^{RC}}{\max \left| H_{\ddot{u}_{a1}/\ddot{u}_g} \right|^{NC}}. \tag{21}$$

Based on definitions (21), values of I_D or I_{AA} smaller than one indicate a reduction of the resonance response of the primary oscillator, in terms of relative displacement or absolute acceleration, respectively, by virtue of the rigid coupling to the secondary oscillator. Contour plots in Figure 3 show performance indices I_D and I_{AA} versus mass ratio μ and frequency ratio α parameters, the former varying in the range [0, 0.2] the latter in the range [0.1, 10]. Damping ratios are assumed as $\zeta_1 = 0.05$ and $\zeta_2 = 0.02$. It is apparent that, although minima are not found, both I_D and I_{AA} assume values lower than one in a large part the spanned parameters space, confirming that a significant vibration control can be achieved by way of the rigid coupling. It is also worth noting that both performance indices I_D and I_{AA} are much more sensitive to variations in frequency ratio α than in mass ratio μ, meaning that a significant control performance can be obtained even with small mass ratios.

In VC configuration, parametric analyses have been carried out to highlight the influence of the mechanical properties, stiffness and damping, of the viscoelastic connection on the effectiveness of vibration control. Similarly to (21), two performance indices are defined in terms of FRFs peak amplitude ratio between VC and NC configurations:

$$J_D = \frac{\max \left| H_{u_1/\ddot{u}_g} \right|^{VC}}{\max \left| H_{u_1/\ddot{u}_g} \right|^{NC}}, \qquad J_{AA} = \frac{\max \left| H_{\ddot{u}_{a1}/\ddot{u}_g} \right|^{VC}}{\max \left| H_{\ddot{u}_{a1}/\ddot{u}_g} \right|^{NC}}. \tag{22}$$

Again, based on definitions (22), values of J_D or J_{AA} smaller than one indicate a reduction of the resonance response of the primary oscillator, in terms of relative displacement or absolute acceleration, respectively, by virtue of the

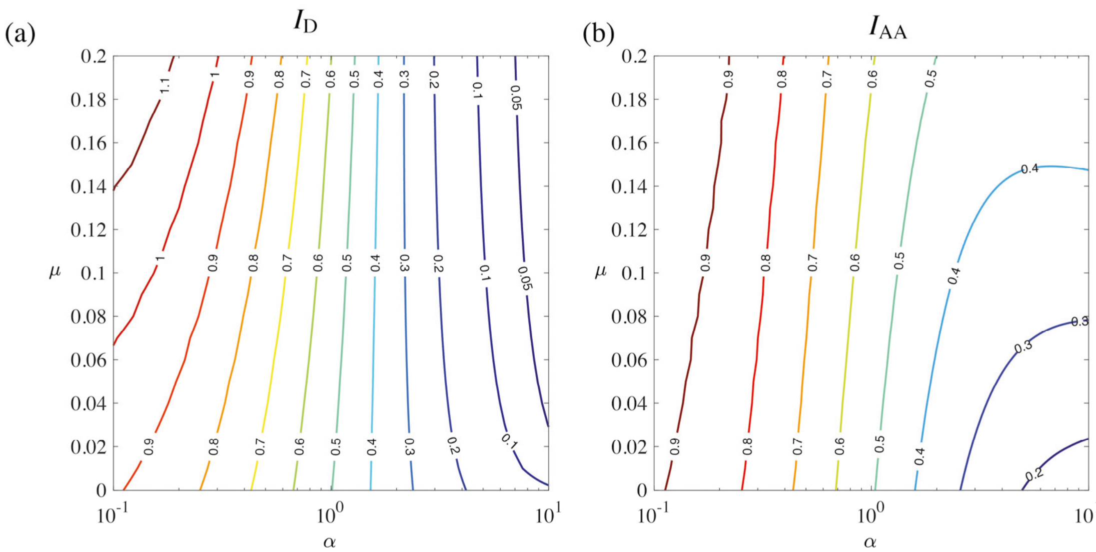

Fig. 3. Performance indices for the primary oscillator in RC configurations with varying frequency ratio α and mass ratio μ: (a) I_D for the displacement u_1 relative to ground; (b) I_{AA} for the absolute acceleration $\ddot{u}_{a1}$. It is assumed: $\zeta_1 = 0.05$ and $\zeta_2 = 0.02$.

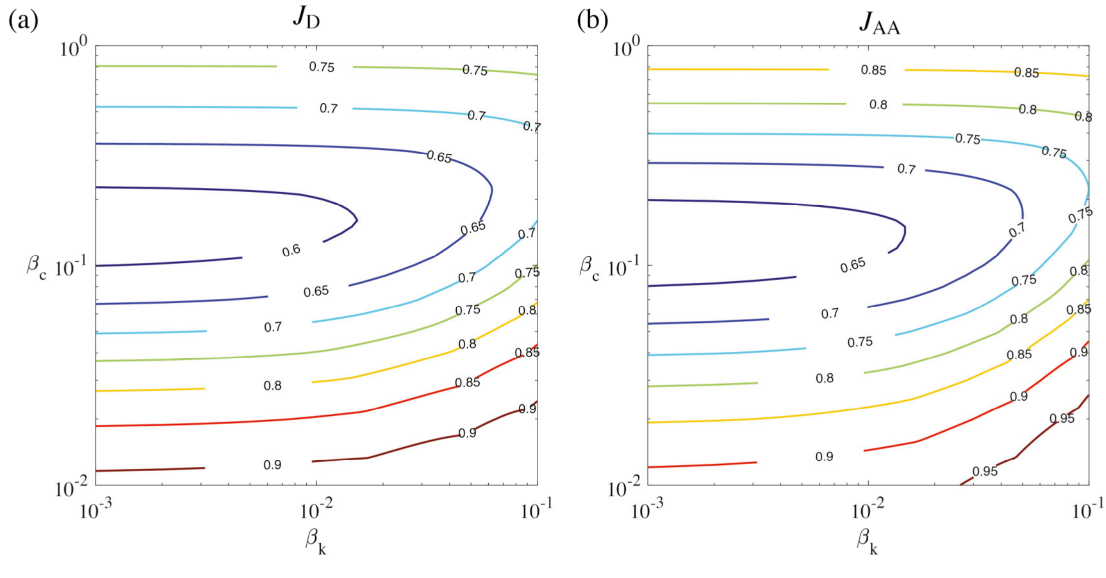

Fig. 4. Performance indices for the primary oscillator in VC configurations with varying parameters of the viscoelastic connection, the stiffness parameter β_K and the damping parameter β_C: (a) J_D for the displacement u_1 relative to ground; (b) J_{AA} for the absolute acceleration $\ddot{u}_{a1}$. It is assumed: $\zeta_1 = 0.05$ and $\zeta_2 = 0.02$.

visco-elastic coupling to the secondary oscillator. Contour plots in Figure 4 show performance indices J_D and J_{AA} versus the parameters of the viscoelastic connection, the stiffness parameter β_K , varying in the range [0.001, 0.1], and the damping parameter β_C, varying in the range [0.01, 1.0]. Mass ratio and frequency ratio are set as $\mu = 0.05$ and $\alpha = 2.0$, respectively, while damping ratios are assumed as $\zeta_1 = 0.05$ and $\zeta_2 = 0.02$. In this case, local minima for J_D and J_{AA} can be found in the spanned parameters range, corresponding to the maximum achievable reductions of the primary oscillator response, allowing for an optimisation of the viscoelastic connection in terms of control performance.

5. Conclusions

A preliminary research work on the dynamic modelling and the performance assessment of exoskeleton structures for seismic protection has been presented. A reduced-order 2-dof model has been introduced to represent the dynamic behaviour of the coupled system and either a rigid connection or a dissipative viscoelastic connection has been considered for the coupling. The equations of motion have been set in non-dimensional form, in order to identify the governing independent parameters, and a parametric study has been carried out with a twofold focus: 1) to highlight the influence of the characteristic parameters on the dynamic properties of the coupled system; 2) to assess the effectiveness of the exoskeleton structure in reducing the earthquake-induced dynamic response. Parametric analyses conducted in the frequency domain have confirmed that exoskeleton structures can be a feasible and effective means for structural vibration control under seismic loading.

Future research will deal with the optimal integrated design of the exoskeleton structures and their connection to the main structure according to a multi-objective optimisation approach, taking into consideration both the control performance and the cost of the retrofitting strategy.

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References

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Von Winterfeldt, D., 2003. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra, 19(4), 733–752.

Gattulli, V., Potenza, F., Lepidi, M., 2013. Damping performance of two simple oscillators coupled by a visco-elastic connection. Journal of Sound and Vibration, 332(26), 6934-6948.

Genta, G., 2009. Vibration Dynamics and Control. Springer, New York.

Housner, G.W., Bergman, L.A., Caughey, T.K., Claus, R.O., Masri, S.F., Skelton, R.E., Soong, T.T., Spencer, B.F., Jao, J.T.P., 1997. Structural control: past, present and future. Journal of Engineering Mechanics, ASCE, 123,897–971.

Impollonia, N., Palmeri, A., 2018. Seismic performance of buildings retrofitted with nonlinear viscous dampers and adjacent reaction towers. Earthquake Engineering and Structural Dynamics, 1–23.

Lavan, O., Abecassis, D., 2015. Seismic Behavior and Design of Wall–EDD–Frame Systems. Frontiers in Built Environment, 1, 1–17.

Luco, J., De Barros, F., 1998. Optimal damping between two adjacent elastic structures. Earthquake Engineering and Structural Dynamics, 27(7), 649-659.

Nakashima, M., Lavan, O., Kurata, M., Luo, Y., 2014. Earthquake engineering research needs in light of lessons learned from the 2011 Tohoku earthquake, 13(1), 141-149.

Parise, G., Martirano, L., Parise, L., De Angelis, M., Reggio, A., Weber, J., 2013. Seismic qualification of electrical equipment in critical facilities. 2013 IEEE Industry Applications Society Annual Meeting, IAS 2013, October 6-11, Lake Buena Vista, FL, USA.

Parise, G., De Angelis. M., Reggio. A., 2014. Criteria for the definition of the equipment seismic levels: Comparisons between USA and European codes. IEEE Transactions on Industry Applications, 50(3), 2135-2141.

Reggio, A., Restuccia, L., Ferro, G.A., 2017. Modellazione dinamica di esoscheletri per la protezione sismica di edifici esistenti. XIV Convegno ANIDIS "L'Ingegneria Sismica in Italia", ANIDIS 2017, September 17-21, Pistoia, Italia, oral presentation.

Saaed, T. E., Nikolakopoulos, G., Jonasson, J.-E., Hedlund, H., 2015. A state-of-the-art review of structural control systems. Journal of Vibration and Control, 21(5), 919–937.

Spencer, B.F., Nagarajaiah, S., 2003. State of the art of structural control. Journal of Structural Engineering, ASCE, 7, 845–856.

Trombetti, T., Silvestri, S., 2007. Novel schemes for inserting seismic dampers in shear-type systems based upon the mass proportional component of the Rayleigh damping matrix. Journal of Sound and Vibration, 302, 486–526.

Tubaldi, E., 2015. Dynamic behavior of adjacent buildings connected by linear viscous/viscoelastic dampers. Structural Control and Health Monitoring, 22, 1086-1102.