Seismic protection of full scale seismically excited steel structures through Targeted Energy Transfers

Concetta Tripepi[1], Francesco Nucera[1,*], Alexander Vakakis[2], Lawrence Bergman[3], D. Michael McFarland[3]

[1] *Department of Mechanics and Materials, Mediterranean University of Reggio Calabria, Italy*
E-mail: *concetta.tripepi@unirc.it, francesco.nucera@unirc.it*

[2] *Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, USA*
E-mail: *avakakis@illinois.edu*

[3] *Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, USA*
E-mail: *lbergman@illinois.edu, dmmcf@illinois.edu*

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SUMMARY. The aim of this work is to show that is possible to apply the Nonlinear Energy Sink (NES) concept to protect full-scale seismically-excited steel structures through Targeted Energy Transfers (TET). We consider, as the primary (linear) system, a multi-storey shear frame with beams sufficiently rigid so that the frame can reasonably be considered as shear-type. To the frame, we connect one NES which is non-smooth and precisely a vibro-impact device (VI-NES). We underline that the NES introduction brings two advantages to seismic design. First, this device, through its fast reaction time during the crucial initial few cycles of the motion, can ensure a reduction of initial peaks of the structural response. Second, it can ensure vibration control of the structural motion during the later stage of the response [1,2].

We show that this nonlinear attachment is capable of engaging in transient resonance with linear modes at arbitrary frequencies. In fact, TET denotes the one-way irreversible (on the average) transfer of the energy of vibration from the primary structure to local attachment. There the energy is confined and locally dissipated without “spreading” back to the main structure because of an instantaneous internal resonance of the attachment with one of the modes of the main structure. As energy decreases due to damping the conditions for Transient Resonance Capture (TRC) fail and escape from resonance capture takes place.

We study the performance and the robustness of the augmented structure excited by a set of Eurocode8 (EC8) spectrum compliant earthquakes. In order to conduct this analysis we employ computational techniques including numerical simulation and post-processing analysis by means of wavelet transforms (WTs). The technique, employed to optimize the parameters of the NES, is a global method called differential evolution [3,4]. This method belongs to the class of evolutionary computations. The set of evaluation criteria that we utilize was introduced in Spencer et al. [5] and provides quantitative measures for the seismic response in terms of maximum response quantities. Through this set, we show that it is possible to drastically reduce the peak structural response in sufficiently fast time scale to effectively control the parameters related to structural damage. Moreover, the criteria are presented in a sufficiently general form, which

permits their application to different types of (single or even combined) earthquakes.

Trough analysis of the relative displacements between floors, we show the occurrence of energy (frequency) scattering towards higher modes. This frequency scattering of the seismic energy to structural modes, other than those mainly excited by the earthquake in the uncontrolled structure, presents a twofold advantage for seismic mitigation. First, for a given input energy, it is common knowledge that the amplitude of vibration decreases with increasing frequency; through the NES, seismic energy is transferred from low-energy, high-amplitude, structural modes to higher-frequency, lower-amplitude, modes. Second, because structural damping dissipation is generally more pronounced at higher modes, the high-frequency scattered seismic energy is more effectively dissipated by the structure itself.

1 INTRODUCTION

1.1 *Linear system*

We consider an idealized six-story building with storey height of 4,5m and one bay for each floor with bay width of 7m. Steel is used to model columns with following sections: HE 240 M for first and second floor, HE 220 M for third and fourth floor, HE 200 M for fifth and sixth floor. We assume beams to be sufficiently rigid, so that the frame can be considered shear -type, and for each floor the total masses are summarized in Table 1.

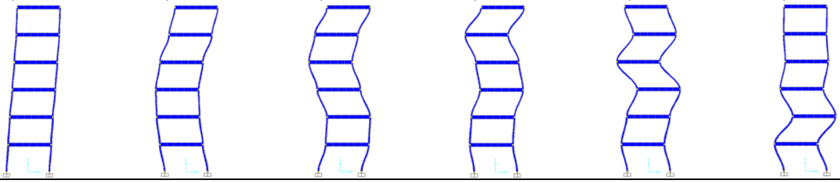
Table 1. Mass for each floor

Floor	Mass, kg
1	16533
2	16353
3	16173
4	16110
5	16047
6	12134

In Table 2 the results of modal analysis are shown in terms of Natural Periods and Modal Shapes.

Table 2. Natural Periods Modal Shapes

First	Second	Third	Fourth	Fifth	Sixth
T=1,002sec	T=0,378sec	T=0,242sec	T=0,190sec	T=0,160sec	T=0,128sec



1.2 *Seismic Excitations*

We tested our NES-based seismic mitigation concept by considering the three distinct EC8 spectrum compliant earthquakes shown in Figure 1, obtained by using the software REXELv2.4 beta [6].

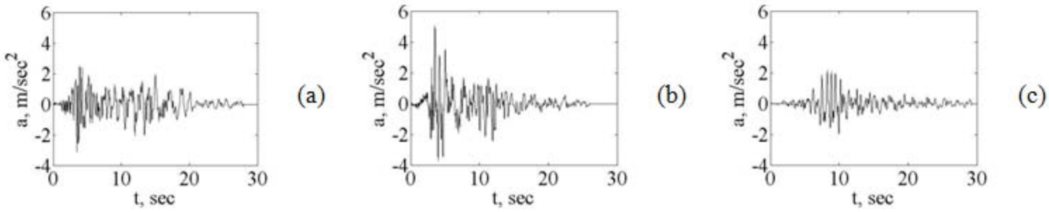


Figure 1: EC8 spectrum compliant accelerograms: (a) earthquake I; (b) earthquake II; (c) earthquake III.

It is inherently impossible to describe a complex phenomenon such as the potential of an earthquake to damage civil infrastructure by a single number. Therefore, we consider two classes of Intensity Measures (IMs), employed in current seismic mitigation practice, with the intention of characterizing the seismic excitations considered [7]. The first class (Class I IMs) contains traditional IMs which describe the earthquake source characteristics and time history record; the considered class I IMs are shown in Table 3. We consider: Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Arias Intensity (I_A), Strong Motion Duration (T_D), Cumulative Absolute Displacement (CAD), Root Mean Square Velocity (V_{rms}) and Medium Period (I).

Table 3. Class I IMs

	PGA (g)	PGV (cm/sec)	I_A (cm/sec)	T_D (sec)	CAD (cm)	V_{rms} (cm/sec)	I (cm/sec^{0,75})
I	0,319	24,55	194,32	15,5	117,22	7,95	48,75
II	0,513	33,45	271,50	11,1	119,35	11,22	61,09
III	0,220	18,21	89,62	13,0	75,00	6,24	34,57

The second (Class II IMs) involves IMs which describe the time history obtained using a single-degree-of-freedom system filter on the original record. These are: Effective Peak Acceleration (EPA), Effective Peak Velocity (EPV), Effective Peak Displacement (EPD) and Displacement Response Intensity (DSI). Their values for each record are shown in Table 4.

Table 4. Class II IMs

	EPA (g)	EPV (cm/sec)	EPD (cm)	DSI (cm)
I	0,330	39,26	12,20	45,77
II	0,394	48,64	17,78	66,68
II	0,207	15,66	9,24	34,73

2 THE MODEL

The six degree-of-freedom damped linear primary system, connected to the VI-NES at sixth floor, is shown in Figure 2.

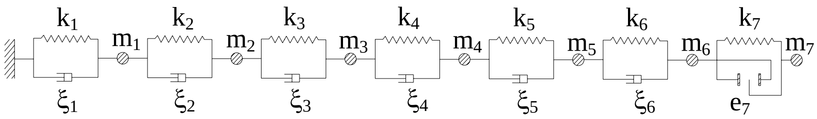


Figure 2: VI-NES attached to a six degree-of-freedom primary structure.

Here k_i is the interstory stiffness; m_i is the mass and ξ_i is the viscous damping ratio of i^{th} floor with i=1,…,6. The VI NES mass (m_7) is connected to the primary linear structure through a weak linear spring (k_7); moreover two rigid stops constrain the relative displacement between the VI NES mass and the mass of the sixth floor to be less than or equal to the clearance (e_7). The energy of colliding masses during impacts is not conserved due to the fact that the coefficient of restitution (rc_7) is smaller than 1, leading to dissipation.

In terms of displacements with respect to ground, the equations of motion for the system depicted in Figure 2 are given by

$$\underline{\underline{M}}\,\underline{\ddot{u}}+\underline{\underline{C}}\,\underline{\dot{u}}+\underline{\underline{K}}\,\underline{u} = \underline{\underline{M}}\,\underline{\Gamma}\,\ddot{u}_g \tag{1}$$

where $\underline{\underline{M}}$,$\underline{\underline{C}}$ and $\underline{\underline{K}}$ are Mass, Damping and Stiffness matrices of the controlled system, respectively. The Damping Matrix was computed from the Mass and Stiffness matrices of the uncontrolled structure by using the assumption of Rayleigh damping and imposing a viscous damping ratio equal to 0,01 for the first and third mode. $\underline{u}$, $\underline{\dot{u}}$, $\underline{\ddot{u}}$ are displacement, velocity and acceleration vectors of the controlled system, respectively, $\ddot{u}_g$ is the ground acceleration and $\underline{\Gamma}$ is a vector of 1 with six element. The dynamic response of the system with VI-NES is determined using a *Matlab* code which computes exactly the time instants when the impacts occur. The whole system is strongly non-linear; during each impact a significant portion of energy is dissipated due to inelastic collision between the NES mass and the rigid constraints [1].

3 NUMERICAL RESULTS

The VI-NES parameters (mass m_7, stiffness k_7, clearance e_7 and coefficient of restitution rc_7) were optimized through the use of a set of Evaluation Criteria [5]. Each criterion represents the ratio between a controlled and an uncontrolled quantity relative to the response of the structure; J_1, J_2, J_3, J_4 are non-dimensional peak measures in terms of displacements, interstory drifts, absolute accelerations and inertial forces, respectively, whereas J_5, J_6, J_7, J_8 are non-dimensional L_2-normed measures of the same quantities.

The goal of the optimization was to determine the smallest possible output value for each criterion. The technique employed to optimize the NES parameters is a global method called differential evolution [4,8]. This method belongs to the class of evolutionary computations.

Seismic excitation III was employed for the optimization study of the NES. Then, we tested the robustness of the proposed design under the other seismic excitations using the NES parameters found for III.

Having fixed the VI-NES a mass to 3,5% of the total mass of the structure, the optimized values are e_7=0,127068m; rc_7=0,457047; sr_7=0,0007381 (where sr_7 is the ratio between the stiffness of the NES and the mean interstory stiffness).

In Table 5 are shown the Evaluation Criteria computed for all considered cases.

Table 5. Evaluation Criteria

	J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8
I	0,53	0,58	1,04	0,57	0,34	0,38	0,62	0,40
II	0,67	0,71	0,97	0,62	0,43	0,47	0,63	0,46
III	0,56	0,68	0,92	0,70	0,35	0,39	0,62	0,39

In Figure 3, Figure 5 and Figure 7 the controlled and uncontrolled responses of each floor, (under seismic excitations I II and III, respectively) are depicted. It is possible to see how the NES is able to mitigate, in a sufficiently fast time scale, the peaks of the response which occur during the strong ground motion, while allowing good control of the overall response of the system as demonstrated by the small value of the L_2-normed criteria [2].

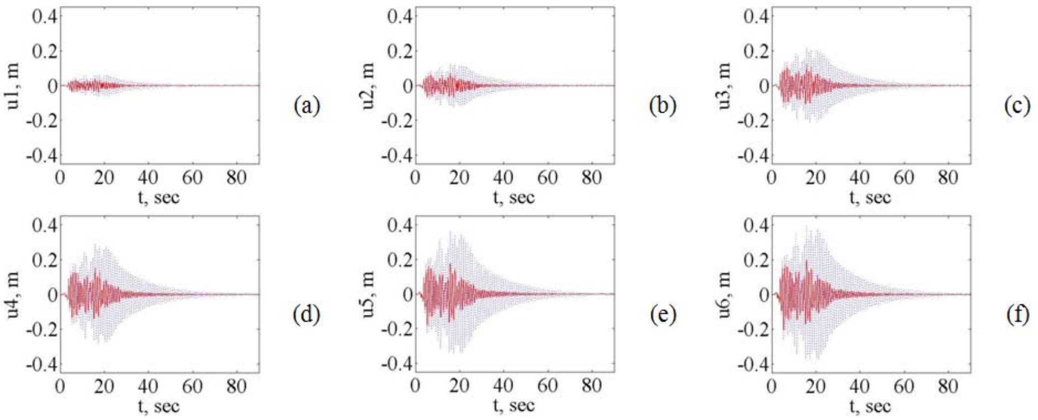


Figure 3: Time history with respect to I seismic excitation of each floor: (a) first floor,(b) second floor, (c) third floor, (d) fourth floor, (e) fifth floor, (f) sixth floor. Blue line without NES; red line with NES.

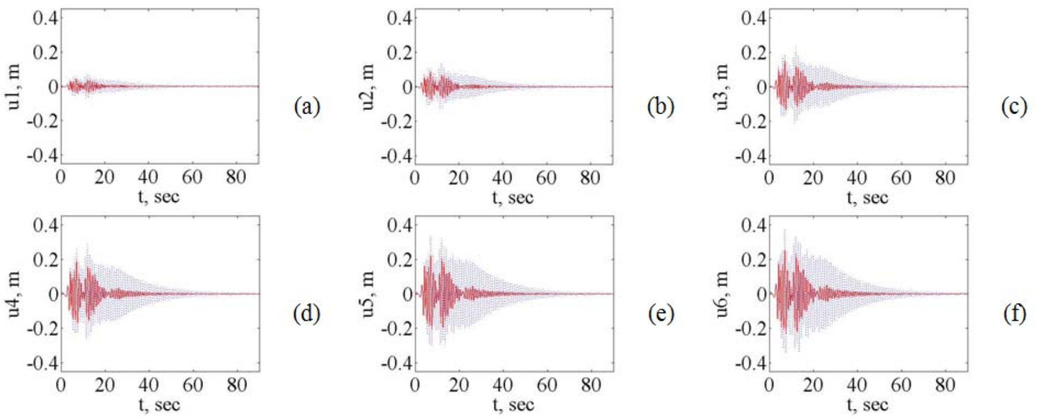


Figure 4: Time history with respect to II seismic excitation of each floor: (a) first floor,(b) second floor, (c) third floor, (d) fourth floor, (e) fifth floor, (f) sixth floor. Blue line without NES; red line with NES.

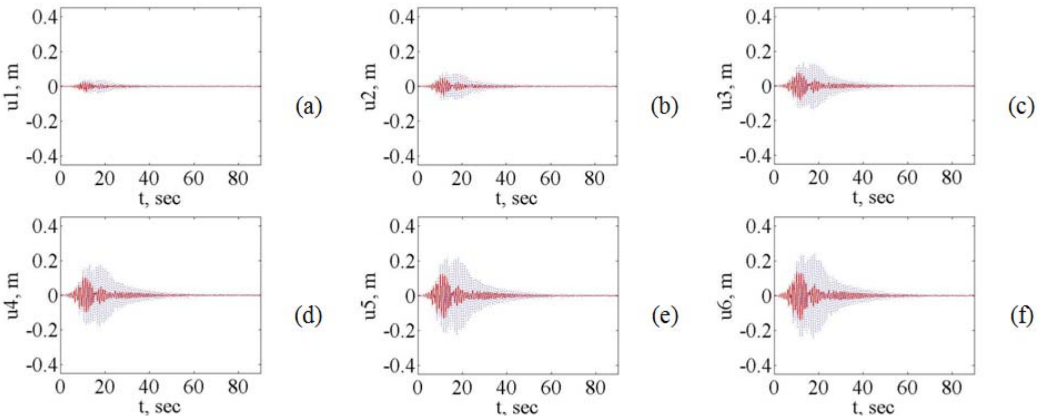


Figure 5: Time history with respect to III seismic excitation of each floor: (a) first floor,(b) second floor, (c) third floor, (d) fourth floor, (e) fifth floor, (f) sixth floor. Blue line without NES; red line with NES.

As shown in Figures 6, 7 and 8 (for excitations I, II and III, respectively), the NES changes significantly the dynamics of the system which, in turn, leads to a reduction of the total Input Energy (IE). Also, the total Dissipated Energy (ED) is a significant portion of the Total Energy (ET).

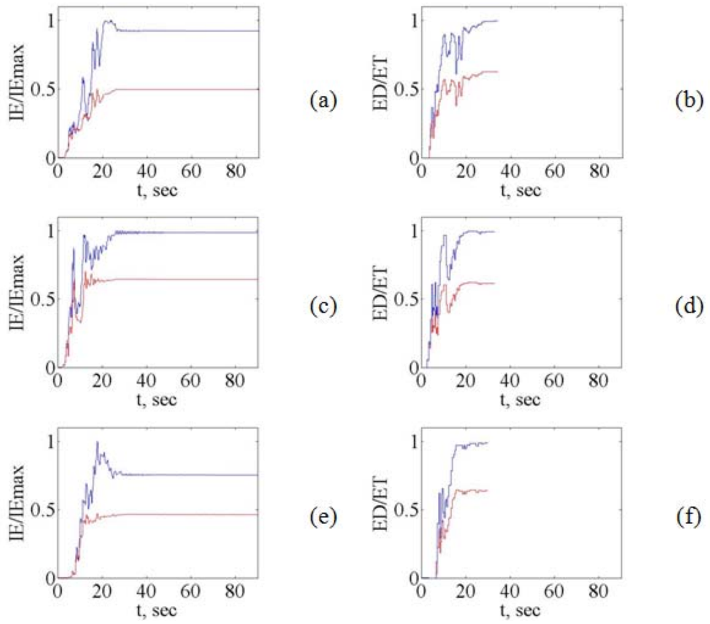


Figure 5: (a), (c) and (e) Normalized Instantaneous Input Energy: blue line without NES; red line with NES, for seismic excitation I, II and III respectively (b), (d) and (f) Normalized Instantaneous Dissipated Energy: blue line energy dissipated by total system; red line dissipated by NES.

The Wavelet spectra of the relative displacements between the floors for each seismic excitation are depicted in Figures 6, 7 and 8. Dotted lines represent the frequencies of the linear system.

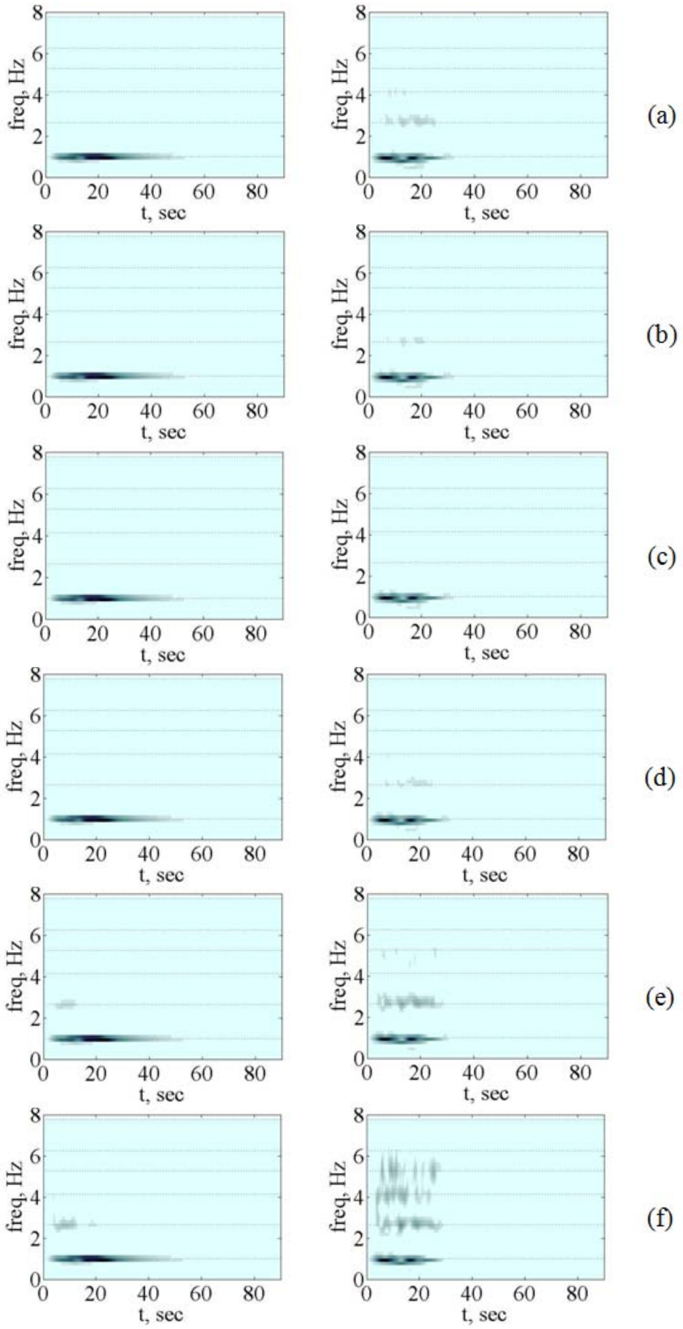


Figure 6: I seismic excitation: comparison between the wavelet spectra of uncontrolled (left column) and controlled (right column) relative displacement for the primary system with optimized VI-NES attached at sixth floor: (a) u_6-u_5, (b) u_5-u_4, (c) u_4-u_3, (d) u_3-u_2, (e) u_2-u_1,(f) u_1 w.r.g.m

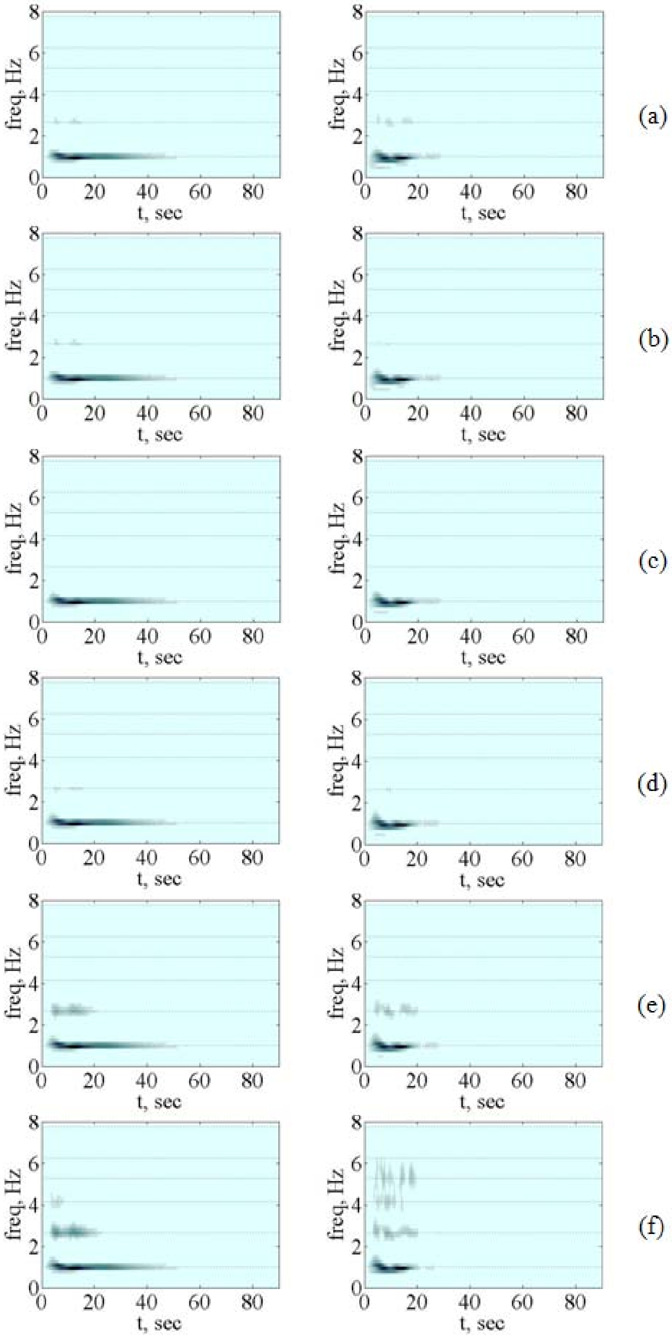


Figure 7: II seismic excitation: comparison between the wavelet spectra of uncontrolled (left column) and controlled (right column) relative displacement for the primary system with optimized VI-NES attached at sixth floor: (a) u_6-u_5, (b) u_5-u_4, (c) u_4-u_3, (d) u_3-u_2, (e) u_2-u_1, (f) u_1 w.r.g.m

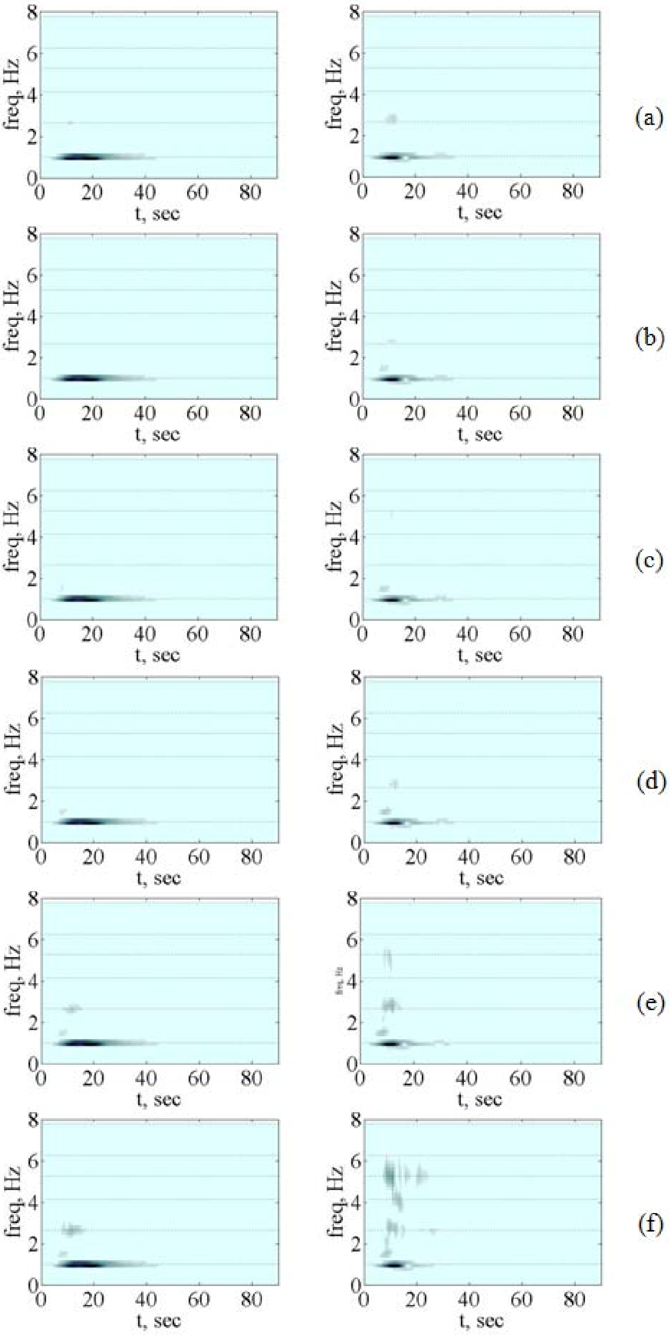


Figure 8: III seismic excitation: comparison between the wavelet spectra of uncontrolled (left column) and controlled (right column) relative displacement for the primary system with optimized VI-NES attached at sixth floor: (a) u_6-u_5, (b) u_5-u_4, (c) u_4-u_3, (d) u_3-u_2, (e) u_2-u_1, (f) u_1 w.r.g.m

1 CONCLUSIONS

We applied the concepts of targeted energy transfer (TET) and of the nonlinear energy sink (NES) to seismic mitigation of a six-story full-scale steel structure subjected to EC8 compliant earthquakes. The advantages of applying the VI-NES are twofold. First, it is possible to significantly and rapidly reduce the level of seismic structural response, especially in the initial stage of seismic response when the energy of the system is at its highest and the potential for structural damage is greatest. Second, vibro-impacts at the NES redistribute the seismic energy over a wide frequency ranges, to lower and higher structural modes; as a result, the response of the primary structure is significantly reduced, because higher structural modes generally exhibit lower amplitudes of vibration and dissipate energy more efficiently. Moreover, despite the fact that we added the NES mass to the structure, there is no increase in the total inut energy because the NES is able to change significantly the dynamics of the uncontrolled structure. It turns out that this seismic mitigation strategy is robust. In fact, keeping fixed the NES parameters optimized for earthquake III, the performance was even better for the other analyzed cases and, in particular for I, resulting in a reduction of 57% and 52% for the maximum displacement and the maximum interstory drift,(J_1 and J_2), respectively. The wavelet spectra show the significant spreading of the energy towards higher modes for relative displacements.

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