Intermodal targeted energy transfer (IMTET) concept in seismically excited model of twenty-story steel structure

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Summary. This study investigates the intermodal targeted energy transfer (IMTET) concept for passive mitigation of a model of large-scale twenty-story steel structure subjected to seismic excitation. This is achieved by introducing strategically placed, local strong nonlinearities, in the form of vibro-impacts of the floors of the building with a relatively light, yet stiff, auxiliary core structure. These impacts rapidly, robustly and irreversibly redistribute the input seismic energy within the modal space of the structure through extremely rapid IMTET from low-to-high frequency structural modes, yielding drastically enhanced mitigation of unprecedented effectiveness, right from the very first cycle of the structural response. Moreover, when optimized, this new concept can be realized fully passively, without the need to adding any mass to the building, and with minimal increase in the resulting floor accelerations and local stresses. Therefore, the IMTET methodology for seismic mitigation has the potential to be truly transformative in the field of hazard mitigation of civil infrastructure.

Introduction

The dynamical responses of structures subjected to extreme loads (such as blast, earthquakes, shock) poses a significant challenge and has attracted great interest among researchers and engineers [1]. One of most important issues here is rather limited suppression achieved for the first few (but most intensive and dangerous) cycles of the structural response to the excitation. Consequently, many new and innovative structural protection fully passive concepts have been proposed, developed, and even implemented, being classified as linear, and nonlinear passive mitigation strategies [1, 2]. Specifically, load mitigation based on irreversible (directed) passive nonlinear vibration energy transfers, known as targeted energy transfers (TETs) has been widely explored for passive vibration control and energy harvesting purposes. This approach is based on transferring energy from a directly excited primary structure to a set of secondary strongly nonlinear structures (referred to as nonlinear energy sinks – NESs), where it is localized and locally dissipated without scattering back to the primary structure [2]. The dynamical mechanisms governing such TET mechanism are isolated or multiple (i.e., cascades of) transient resonance captures. However, such resonant energy transfers to the NESs are achieved through relatively slow modulations of the structural modal amplitudes, which, for some applications involving extreme loads, e.g., blast or seismic excitations, prove not to be fast enough.
Recent studies [3, 4], however, has shown that nonlinear resonance is not the only fundamental mechanism for achieving TET, since it can also be realized through a non-resonant fast scale mechanism involving non-smooth effects. This has been employed to explore the concept of intermodal targeted energy transfer (IMTET) to mitigate the effect of blast loading on a nine-story steel structure [4]. In this study, we explore the implementation of the IMTET strategy for seismic passive protection of tall buildings (in particular, twenty-story) subject to strong earthquakes.

Model description

The primary structure considered here is the benchmark 20-story steel building designed by Brandow & Johnston Associates for the SAC Phase II Steel Project, and its geometrical and physical properties are given in details in [5]. To achieve seismic mitigation using the IMTET concept, a flexible internal core structure is introduced, with distributed clearances with respect to the floors of the primary twenty-story building, as shown in Figure 1.

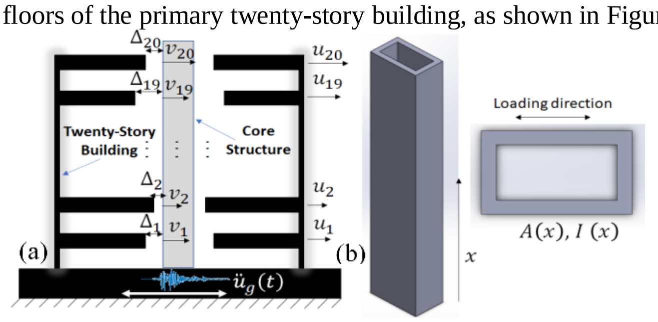

Figure 1: Seismically excited 20-story primary building with internal flexible core structure: Schematic of (a) the integrated building-core, and (b) the flexible core structure

Denoting by $\boldsymbol{M}$, $\boldsymbol{K}$, $\boldsymbol{C}$, and $\boldsymbol{M_{cs}}$, $\boldsymbol{K_{cs}}$ and $\boldsymbol{C_{cs}}$, the mass, stiffness and damping matrices of the primary building and the core structure, respectively, the equations of motion are given by:

$$\begin{aligned}\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{C}\dot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} - \boldsymbol{f}^{NL}(\dot{\boldsymbol{u}}, \boldsymbol{u}, \dot{\boldsymbol{v}}, \boldsymbol{v}, \Delta) = -\boldsymbol{M}\boldsymbol{\Gamma}\ddot{u}_g \\ \boldsymbol{M}_{cs}\ddot{\boldsymbol{v}} + \boldsymbol{C}_{cs}\dot{\boldsymbol{v}} + \boldsymbol{K}_{cs}\boldsymbol{v} + \boldsymbol{f}^{NL}(\dot{\boldsymbol{u}}, \boldsymbol{u}, \dot{\boldsymbol{v}}, \boldsymbol{v}, \Delta) = -\boldsymbol{M}_{cs}\boldsymbol{\Gamma}\ddot{u}_g\end{aligned} \quad (1)$$

where $\ddot{u}_g$ is ground acceleration, $\boldsymbol{u}$ and $\boldsymbol{v}$ the displacement vectors of the building floors and core contact points, respectively, $\boldsymbol{\Gamma}$ the influence vector for base motion, and Δ the vector of clearance gaps. Uniaxial seismic excitation is assumed, along the weak direction of the primary building (Figure 1(a)). The vector $\boldsymbol{f}^{NL}(\dot{\boldsymbol{u}}, \boldsymbol{u}, \dot{\boldsymbol{v}}, \boldsymbol{v}, \Delta)$ contains the inelastic Hertzian contact interactions, and its jth element is given by:

$$\boldsymbol{f}_j^{NL}(\dot{\boldsymbol{u}}, \boldsymbol{u}, \dot{\boldsymbol{v}}, \boldsymbol{v}, \Delta) = k_c \left[\left[v_j - u_j - \Delta_j \right]_+^{\frac{3}{2}} - \left[u_j - v_j - \Delta_j \right]_+^{\frac{3}{2}} \right] \left(1 + \frac{3(1-r)}{2\left(\dot{u}_j^- - \dot{v}_j^-\right)} \left(\dot{u}_j - \dot{v}_j \right) \right) \quad (2)$$

where $k_c = \frac{2E\sqrt{R}}{3(1-\nu^2)}$ is a stiffness coefficient (Hunt and Crossley, 1975), assuming that the impact is between a semi-sphere of radius R on the core structure and a contact point on a flat plane on the primary building, with the contacting bodies having the same Young's modulus E and Poisson’s ratio ν. Also, $\dot{u}_j^-$ and $\dot{v}_j^-$ are the contact velocities of the jth floor just before the impact, and r is a restitution coefficient. The subscript $(+)$ indicates that only non-negative values of the arguments in the brackets should be taken into account, with zero values being assigned otherwise.

Preliminary results

The computational results provide a preliminary demonstration of the effectiveness of IMTET for rapid seismic mitigation of the primary building response subjected to Kobe (1995) ground motion. Figure 2(left) shows an extremely rapid attenuation of the overall structural response, compared to the linear case of no core (i.e., infinite gaps). The governing nonlinear mechanism responsible for the drastic enhancement in seismic mitigation is shown in Figure 2(right), where the percentage of input seismic energy eventually dissipated by the inherent (modal) dissipation of each of the ten leading structural modes of the primary building (with no core) is depicted. Indeed, compared to the linear case of no core – where the energy dissipation is dominated by the fundamental structural mode in the case of optimized clearance gaps the seven leading modes participate in energy dissipation. Hence, there is a noteworthy, rapid, and irreversible nonlinear targeted energy transfer (or IMTET) from the low structural modes to the higher ones, causing rapid reduction of the structural response.

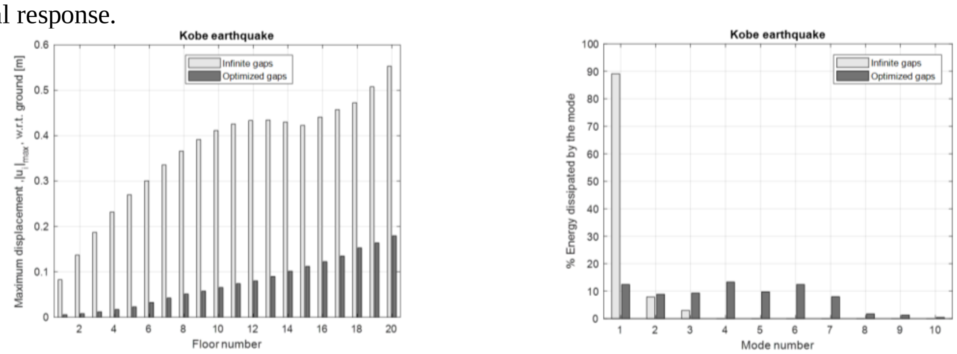

Figure 2: Primary building with optimized core and no core subject to the Kobe earthquake: Maximum floor displacement (left); Input seismic energy (%) dissipated by the inherent damping of the leading modes of the primary building (right)

Conclusions

In this work, a radically new concept for seismic mitigation of civil infrastructure is discussed, based on extremely rapid nonlinear scattering of seismic energy from low-to-high frequency modes of a building through strong local nonlinearities, which is referred to as intermodal targeted energy transfer (IMTET). The results show that the overall level of system vibration is reduced not by adding extra dissipative elements but rather by redistributing energy from lower to higher frequencies where the vibration amplitudes decrease. Moreover, the dissipative capacity of the system itself is radically enhanced since a much larger set of vibration modes (especially high-frequency ones) participate in the response, which can greatly enhance the rate of energy dissipation. Hence, IMTET provides a new approach to passive energy management.

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