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PERFORMANCE EVALUATION OF NEGATIVE STIFFNESS-BASED VIBRATION CONTROL DEVICES FOR SEISMIC PROTECTION OF BUILDING STRUCTURES

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Abstract

In this research work, the KDamper concept is extended and applied to multiple floors of an existing midrise storey benchmark building. Inspired by the concept of MTMDs, multiple EKDs (d-EKDs) are installed and distributed along the height of the aforementioned structure, aiming to seismically protect it. The design and spatial allocation of the EKDs is based on a Harmony Search (HS) algorithm that provides optimal parameters of the device based on constraints and limitations imposed by the structure and the installed mechanisms. A number of Eurocode 8 compatible accelerograms are generated and introduced as input to the optimization process of the EKDs installed in the benchmark structure. Based on the numerical results obtained, the d-EKD concept, outperforms the d-TMD in reducing the structural dynamic responses, introducing one order of magnitude smaller added oscillating masses.

Keywords: Seismic Protection, KDamper, Tuned Mass Damper, Negative Stiffness.

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1 INTRODUCTION

In recent years, extensive research has been conducted on the alteration of seismic codes to improve the resilience of structures and buildings against earthquake excitations, which can cause structural damage and collapse. Current practices for mid and high-rise structures with large height-to-base ratios focus on increasing structural mass, strength, and rigidity, as well as ductility, to allow for inelastic behavior and increased damping during seismic activity. However, these structures still suffer from permanent drifts and increased top storey accelerations, which can result in loss of serviceability, material and equipment damage, and potential degradation of the structural members [1]. To this end, seismic isolation has been one of the main approaches to decouple the superstructure from the foundation level and thus, protect the structure from the loads transferred during earthquake excitation [2–5]. The main drawback of such approach is the required large base displacement and complex implementation, rendering the system expensive and inadequate for retrofitting of existing structures.

To address these issues, researchers have developed passive, active, semi-active, and hybrid energy dissipation and vibration control devices. The Tuned Mass Damper (TMD) is a passive mechanism that involves the addition of an oscillating mass, a stiffness element, and a damper to the primary structure. First introduced by Frahm [6] and optimized by Den Hartog [7], the TMD was designed for an undamped single-degree-of-freedom (SDOF) structure, subjected to harmonic excitation. Several researchers have employed the TMD in various structural systems and have reported significant improvements in their dynamic behavior [8–14]. While the TMD has been widely studied and applied in real-life situations, it has two major drawbacks: it is highly dependent on the optimum frequency and selected damping properties of the additional damper elements, and it requires heavy parasitic oscillating masses that generate additional static forces and occupy substantial space.

To overcome these issues, multiple TMDs (MTMDs) have been proposed and studied by researchers. By optimizing the parameters of the MTMDs, located at the top or distributed along different levels of a structure (d-MTMDs), the control frequency bandwidth can be increased, leading to more efficient systems. Studies have shown that the distribution of MTMDs and control of different modal responses based on the excitation frequency and eigenfrequencies of the structure lead to better structural performance compared to controlling only the fundamental modal response [15–20]. However, the introduction of hefty oscillating masses remains an issue, and amplification of the inertia is necessary to achieve enhanced dynamic behavior and applicable damping technologies.

The use of negative stiffness (NS) elements has been proposed as an alternative method to increase the inertia of oscillators and improve the dynamic response of traditional Tuned Mass Dampers (TMDs) for vibration control. The KDamper [21] is a novel passive NS-based absorber that combines stiffness, mass, damping, and a negative stiffness element to achieve enhanced dynamic behavior of the oscillating mass of a TMD. This concept has been applied in various vibration control applications such as seismic mitigation of bridges, buildings, and wind turbines [22–26]. An extended version of the KDamper [27], called the EKD, has been introduced and optimized as a means of seismic retrofitting of existing buildings.

In this study, the EKD concept is applied to multiple floors of an existing 10-storey building to achieve seismic protection without adding significant masses. Multiple EKDs are distributed along the height of the building and optimized using a Harmony Search algorithm. The d-EKD concept introduces negative stiffness elements, so stability conditions are imposed in the optimization procedure to ensure the stability of the structure. The d-EKD concept outperforms an optimally designed d-TMD concept in reducing the structural dynamic responses, introducing one order of magnitude smaller added oscillating masses.

2 METHODOLOGY AND MODELING

This study focuses on analyzing a ten-storey shear frame structure that has uniform mass and stiffness for all its storeys. The structure is representative of a typical medium-sized multi-storey building, with floor weights equivalent to approximately 400 square meters of floor area. The analytical formulation assumes that the structure remains within the elastic limit when subjected to earthquake excitations. Additionally, the building is exposed to a single horizontal (uni-directional) component of ground motion, and the effects of soil-structure-interaction are not considered. The building parameters, which include the mass and stiffness of each floor, have been slightly modified from a previous study [28]. Specifically, the mass of each storey is 360 tn, and the stiffness of each storey is 650 MN/m. A schematic representation of the building structure, including the lumped mass dynamic model, can be found in Figure 1.

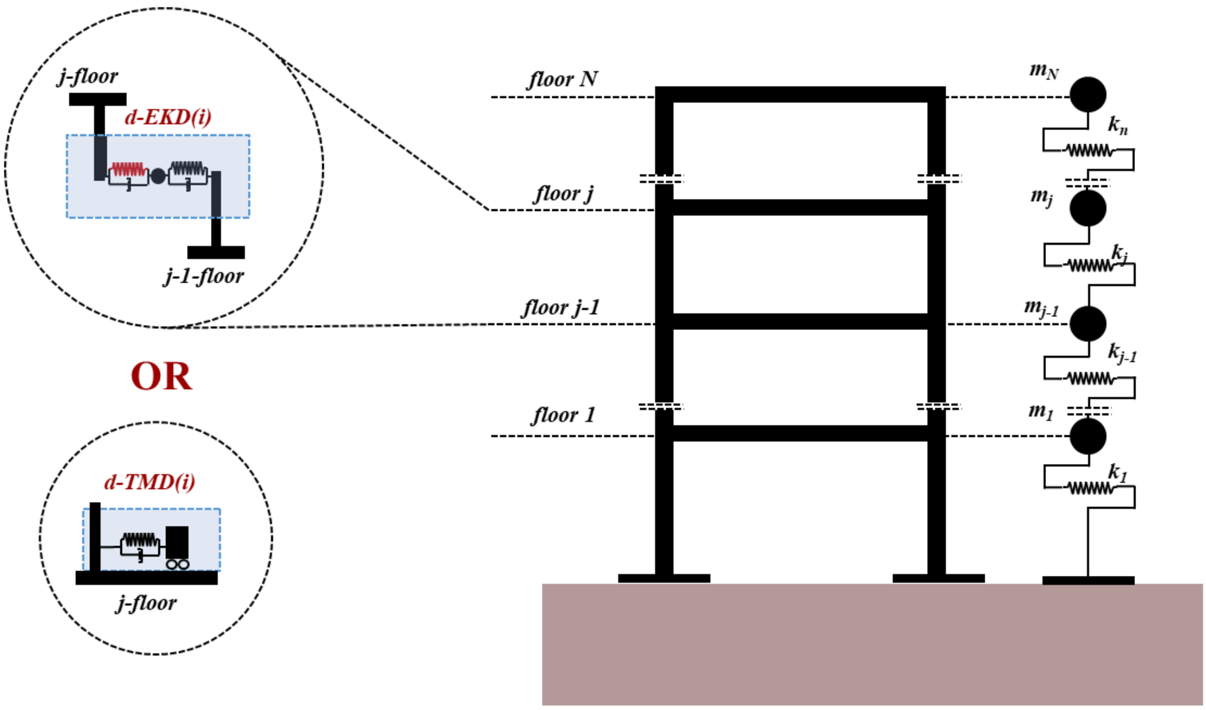

Figure 1: Examined multi-storey building structure along with the lumped mass dynamic model, and the implemented distributed vibration control devices (EKDs, TMDs).

The N degrees of freedom (DoF) benchmark building (N=10 in our case) is installed with n number of dynamic vibration absorption (DVA) devices (TMDs, KDampers, EKDs, etc.), thereby, the total DoFs of the controlled system with the DVAs becomes (N+n). In general, the governing equations of motion of the structure installed with the DVAs are obtained by considering the equilibrium of forces at the location of each DoF (structural floors and installed devices) as follows:

$$\big[[M_{STR}]+[M_{DVA}]\big]\{\ddot{X}\}+\big[[C_{STR}]+[C_{DVA}]\big]\{\dot{X}\}+\big[[K_{STR}]+[K_{DVA}]\big]\{X\}=-[M]\{r\}\ddot{X}_G \quad (1)$$

Indexes STR and DVA indicate the DoFs of the NC (no-control) building structure and of the implemented DVAs, respectively. The matrices that are related to the NC shear building structure, modelled as a lumped mass system are defined as follows:

$$
\left[M_{STR}\right]=\begin{bmatrix}
M_1 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0\\
0 & M_2 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0\\
0 & 0 & M_3 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0\\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots\\
0 & 0 & 0 & \cdots & M_{i-1} & 0 & 0 & \cdots & 0 & 0\\
0 & 0 & 0 & \cdots & 0 & M_i & 0 & \cdots & 0 & 0\\
0 & 0 & 0 & \cdots & 0 & 0 & M_{i+1} & \cdots & 0 & 0\\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots\\
0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & M_{N-1} & 0\\
0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & M_N
\end{bmatrix} \tag{2.1}
$$

$$
\left[K_{STR}\right]=\begin{bmatrix}
k_1+k_2 & -k_2 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0\\
-k_2 & k_2+k_3 & -k_3 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0\\
0 & -k_3 & k_3+k_4 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0\\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots\\
0 & 0 & 0 & \cdots & k_{i-1}+k_i & -k_i & 0 & \cdots & 0 & 0\\
0 & 0 & 0 & \cdots & -k_i & k_i+k_{i+1} & -k_{i+1} & \cdots & 0 & 0\\
0 & 0 & 0 & \cdots & 0 & -k_{i+1} & k_{i+1}+k_{i+2} & \cdots & 0 & 0\\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots\\
0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & k_{N-1}+k_N & -k_N\\
0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & -k_N & k_N
\end{bmatrix} \tag{2.2}
$$

The damping matrix is defined under the assumption of modal damping. The damping ratio in each mode is assumed to be 3%, and thus the damping matrix of the NC structure is defined as:

$$
\left[C_{STR}\right]=\left[M_{STR}\right]\left[\Phi_{STR}\right]\begin{bmatrix}
2\zeta_1\Omega_1 & 0 & \cdots & 0\\
0 & 2\zeta_2\Omega_2 & \cdots & 0\\
\vdots & \vdots & \ddots & \vdots\\
0 & 0 & \cdots & 2\zeta_N\Omega_N
\end{bmatrix}\left[\Phi_{STR}\right]^T\left[M_{STR}\right] \tag{3}
$$

3 DISTRIBUTED VIBRATION CONTROL DEVICES

3.1 Extended KDampers (d-EKD)

For each EKD number (*i*) installed between the floors (*j*) and (*j-1*), as presented in Figure 1 the additional oscillating mass M_{D-i} is attached to the floor (*j*) with a negative stiffness element k_{N-i} and an artificial damper c_{N-i}, as well as to the floor (*j-1*) with a positive stiffness element k_{P-i} and an artificial damper c_{P-i}. The property matrices that account for such an EKD can be formed as follows:

$$
M_{DVA}\left(N+i,N+i\right)=\mu_i M_{TOT}\ ;\ \mu_i=\frac{M_{D-i}}{M_{TOT}}\ ;\ \mu=\sum_1^n\mu_i \tag{4.1}
$$

$$C_{DVA}(N+i,N+i)=c_{N-i}+c_{P-i}\,;\; C_{DVA}(N+i,j)=-c_{N-i}\,;\; C_{DVA}(j,N+i)=-c_{N-i}\,;$$
$$C_{DVA}(j,j)=c_{N-i}\,;\; C_{DVA}(N+i,j-1)=-c_{P-i}\,;\; C_{DVA}(j-1,N+i)=-c_{P-i}\,; \tag{4.2}$$
$$C_{DVA}(j-1,j-1)=c_{N-i}$$

$$K_{DVA}(N+i,N+i)=k_{N-i}+k_{P-i}\,;\; K_{DVA}(N+i,j)=-k_{N-i}\,;\; K_{DVA}(j,N+i)=-k_{N-i}\,;$$
$$K_{DVA}(j,j)=k_{N-i}\,;\; K_{DVA}(N+i,j-1)=-k_{P-i}\,;\; K_{DVA}(j-1,N+i)=-k_{P-i}\,; \tag{4.3}$$
$$K_{DVA}(j-1,j-1)=k_{P-i}$$

where μ_i is the mass ratio of each EKD number (i), defined in Equation (4.1) and is expressed as a percentage of the total superstructure mass, and μ is the total mass ratio of all the installed EKD devices, as defined in Equation (4.1).

3.2 Tuned Mass Dampers (d-TMD)

To verify the effectiveness of the d-EKD retrofitting strategy, the existing structure is also examined with distributed TMD devices [29–32]. For each TMD number (i) installed on a floor (j), (Figure 1) the added mass of the TMD is attached to the floor (j) with a positive stiffness element $k_{D\text{-}i}$ and an artificial damper $c_{D\text{-}i}$. The property matrices that account for such an TMD can be formed as follows:

$$M_{DVA}(N+i,N+i)=\mu_i M_{TOT}\,;\; \mu_i=\frac{M_{D-i}}{M_{TOT}}\,;\; \mu=\sum_{1}^{n}\mu_i \tag{5.1}$$

$$C_{DVA}(N+i,N+i)=c_{D-i}\,;\; C_{DVA}(N+i,j)=-c_{D-i}\,;\; C_{DVA}(j,N+i)=-c_{D-i}\,;$$
$$C_{DVA}(j,j)=c_{D-i} \tag{5.2}$$

$$K_{DVA}(N+i,N+i)=k_{D-i}\,;\; K_{DVA}(N+i,j)=-k_{D-i}\,;\; K_{DVA}(j,N+i)=-k_{D-i}\,;$$
$$K_{DVA}(j,j)=k_{D-i} \tag{5.3}$$

where μ_i and μ are defined similarly to the d-EKD design as the μ_i is the mass ratio (Equation (5.1) of each TMD number (i), expressed as a percentage of the total superstructure mass, and μ is the total mass ratio of all the installed TMDs, defined in Equation (5.1).

4 OPTIMAL SELECTION OF VIBATION CONTROL PARAMETERS

4.1 Extended KDampers (d-EKD)

Each EKD device number (i) introduces in total five additional elements, the installed mass $M_{D\text{-}i}$, the stiffness elements $k_{N\text{-}i}$ and $k_{P\text{-}i}$, and the artificial dampers $c_{N\text{-}i}$ and $c_{P\text{-}i}$. In order to avoid adding large parasitic masses in the structure, as in the d-TMD concept, the additional mass of each EKD is selected to be equal to 0.1% of the total structural mass. In addition, the nominal frequency of the (j) floor is introduced to better observe the effect of the installed EKD device in the structural system:

$$\omega_{EQ}^{j}=2\pi f_{EQ}^{j}=\sqrt{\frac{k_{EQ,STAT}^{j}}{\left(M_j+M_{D-i}\right)}} \tag{6}$$

As a result, the value of the positive stiffness element k_{P-i}, assuming that the value of the NS element k_{N-i} is known, can be obtained from Equation (6). The artificial damper c_{N-i} and c_{P-i} can be expressed with respect to their damping ratios as follows:

$$c_{N-i} = 2\zeta_{N-i}\left(M_j + M_{D-i}\right)\omega_{EQ}^{j} \tag{7.1}$$

$$c_{P-i} = 2\zeta_{P-i}\left(M_j + M_{D-i}\right)\omega_{EQ}^{j} \tag{7.2}$$

Thus, the free (independent) design variables of the d-EKD system are (4×n) in total. These are the following:

1. The value of the NS element k_{N-i}.
2. The value of the equivalent frequency f_{EQ}^{j}.
3. The value of the artificial dampers c_{N-i} and c_{P-i}.

For the design to be efficient and realistic as possible, proper constraints regarding the structural dynamic response, as well as limitations to the design variables must be applied:

1. The controlled structure's maximum drift is set as the objective function.
2. Since the d-EKD concept considers distributed EKD devices along the height of the structure, a small additional mass of 0.1% for each device is selected in order to avoid burdening the structure with parasitic masses [33].
3. The position of the EKD number (i) device varies from 1:N, where N is the number of floors (N=10).
4. The input motion in the optimization procedure is selected from a database of artificial accelerograms [27] (30 in total), designed to be spectrum-compatible with the EC8 acceleration response spectrum.
5. The value of the NS element and the NS stroke are constrained with an upper limit based on Kapasakalis et al. [33]:
6. The damping ratio of the artificial dampers are upper bounded based on previous research work [27] and manufacturing restrictions:
7. The equivalent frequency of the (j) floor is selected to vary in the range:

$$\left(2/3\right)\times\sqrt{\frac{k_F}{M_F}} \le \omega_{EQ}^{j} = 2\pi f_{EQ}^{j} \le \left(4/3\right)\times\sqrt{\frac{k_F}{M_F}}$$

where k_F and M_F are the stiffness and mass of the j^{th} floor, respectively.

4.2 Tuned Mass Dampers (d-TMD)

The effectiveness of installing multiple distributed TMDs in a building depends on the total additional mass. The deciding criterion for the number of the TMDs to be installed, as in Elias et al. [32], requires that the modal mass participation is greater than 90%, resulting in vibration control of the first two modal responses. An additional TMD that controls the 3rd mode is implemented to examine if further devices manage to increase the effectiveness of the d-TMD control strategy. The tuning frequency ratio of each TMD is calculated such that:

$$t_{TMD-i} = \frac{\omega_{TMD-i}}{\Omega_i} \tag{8}$$

where ω_{TMD-i} is the tuning frequency of the TMD number (i), and Ω_i is the eigenfrequency of the i^{th} mode of the NC building structure to be controlled. The tuning frequency of the TMD number (i) is expressed as follows:

$$\omega^2_{D-i} = \left(2\pi f_{D-i}\right)^2 = \frac{k_{D-1}}{M_{D-i}} \tag{9}$$

The optimum tuning frequency ratios are calculated for a base excited building structure based on the formula given by Elias et al. [32]:

$$t^{opt}_{TMD-i} = \frac{1}{1+\mu_i\varphi_i}\left(1-\zeta i\sqrt{\frac{\mu_i\varphi_i}{1+\mu_i\varphi_i}}\right) \tag{10}$$

where μ_i is the mass ratio of the TMD number (i), ζ_i is the damping ratio of the i^{th} mode of the structure, and φ_i is the amplitude of the first mode of vibration for a unit modal participation factor computed at the location of the TMD (i). The damping ratio of the TMD (i) device is obtained from the following equation, as provided by Elias et al. [32]:

$$\zeta^{opt}_{TMD-i} = \varphi_i\left(\frac{\zeta_i}{1+\mu_i}+\sqrt{\frac{\mu_i}{1+\mu_i}}\right) \tag{11}$$

5 ASSESSMENT OF THE OPTIMAL EXTENDED KDAMPER DESIGN FOR SEISMIC PROTECTION OF A 10-STOREY BUILDING STRUCTURE

In this paper, three different vibration control systems are investigated: i) a configuration with 1-EKD, ii) 2-EKDs, iii) 3-EKDs. A Harmony Search (HS) algorithm is adopted for the optimization of the parameter values as well as their allocation along the height of the building. The above structural systems are subsequently compared with the corresponding TMD-enhanced buildings, designed according to the analytical solutions provided by Elias et al. [32]: i) a system with 1-TMD, ii) 2-TMDs, iii) 3-TMDs.

A series of time-history analyses are conducted for the set of the 30 artificial earthquakes generated for the optimization process, as described in the previous chapter of this research work. The dynamic behavior of the selected systems is subsequently assessed and a comparison between the response of the original/uncontrolled structure and the building with the d-TMDs and d-EKDs is undertaken. Figure 2 presents the envelopes of the absolute/relative to the ground displacements of each storey, inter-storey drifts, as well as absolute accelerations for the 30 artificial accelerograms, for all the structures under investigation. Results indicate superior performance of the d-EKDs compared to the original structure and the system with the TMDs, showcasing that significant vibration mitigation is achieved by adopting such a vibration control system, with minimal additional masses.

As a following step, an ensemble of eight (8) recorded real earthquake motions is adopted as input seismic excitation to the benchmark structure, aiming to provide further insight regarding the efficiency of the d-EKDs framework. The selected records cover a wide range and variety of key seismic characteristics such as *PGA*, magnitude *(M_w)*, as well as a broad frequency content, duration and number of significant acceleration cycles. Results for two indicative seismic excitations are presented herein.

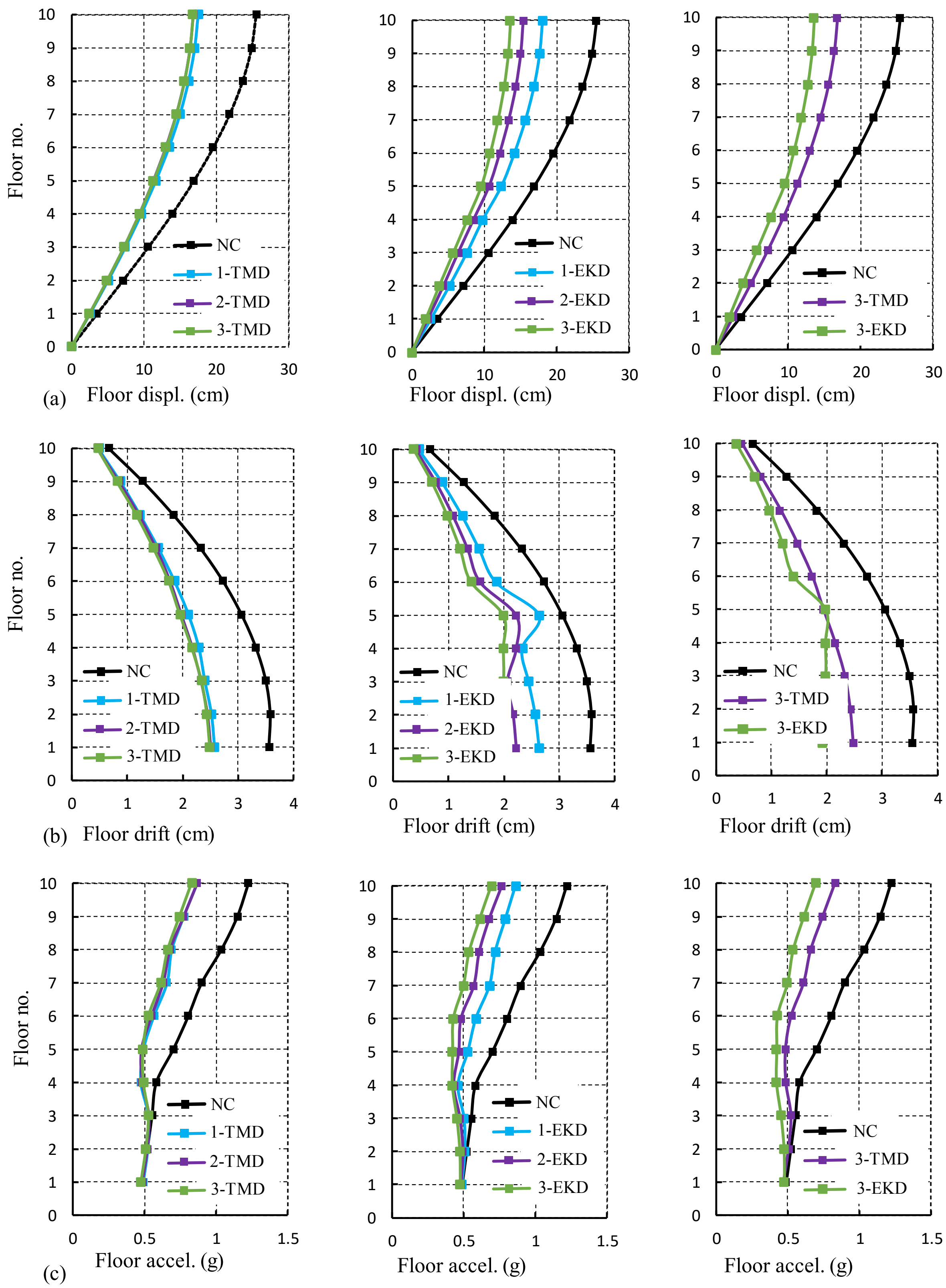

Figure 2: (a) Relative to the ground floor displacement envelopes, (b) floor drift envelopes, and (c) absolute floor acceleration envelopes, for the (a) d-TMDs, (b) d-EKDs, and (c) 3-TMDs and 3-EKDs, against the NC structure.

Figure 3 illustrates indicative time-history analyses results for the case of Northridge (1994) and Kobe (1995) earthquake records. The plots present a comparison between the uncontrolled structure and the building with 3-TMDs and 3-EKDs respectively. By all means, for both cases the d-EKD system outperforms the traditional d-TMDs, highlighting the efficiency of the system.

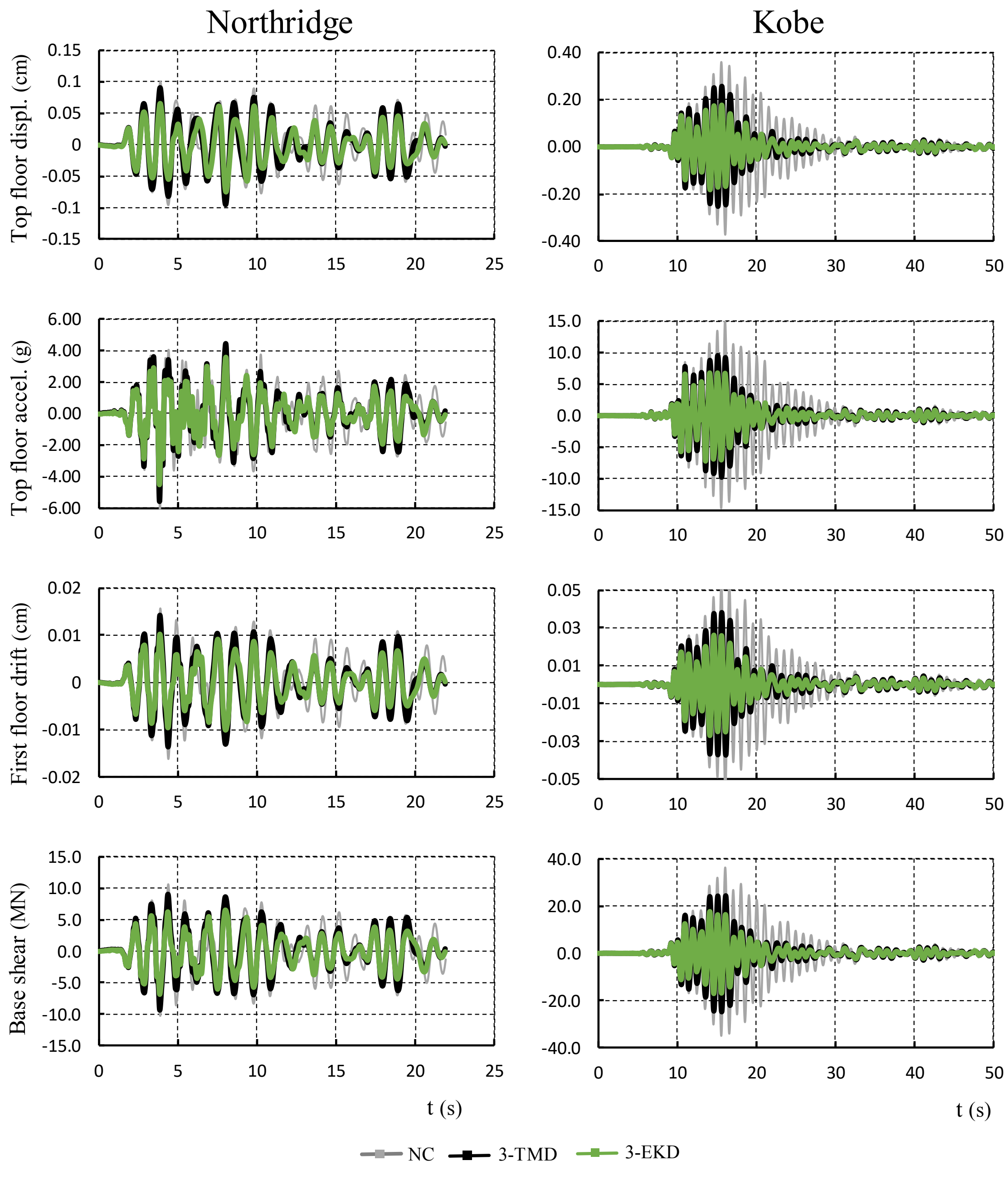

Figure 3: Comparative time history results between the NC system and the system with the d-TMDs and the d-EKDs in terms of top floor displacements, accelerations, first floor drifts, and base shear for the Northridge, and Kobe earthquakes respectively.

6 CONCLUSIONS

This research investigates the seismic protection of a mid-rise building using distributed extended KDamper (d-EKD) devices. The d-EKD concept involves adding small oscillating masses to the structure to control its vibrations without overburdening it. The study employs a constrained optimization approach to select the system parameters, which restricts the dynamic response of the structure and the values of the design variables. The performance of the controlled structure is evaluated by subjecting it to real ground motions and assessing it against various commonly used performance criteria. A comparison with distributed Tuned Mass Dampers (d-TMDs) is also conducted to demonstrate the efficiency of the proposed seismic protection approach. Based on the results of the dynamic analysis, the study highlights several major concluding remarks:

1. The d-EKD design is considered practical as it involves minimal additional oscillating masses, and sets limitations on the design variables, making it feasible within reasonable technological capacities.
2. The d-EKD controlled superstructure displays superior dynamic behavior compared to d-TMD, even when the installed devices involve significantly smaller additional masses (one order of magnitude).
3. By increasing the number of the implemented devices the d-EKD vibration control strategy is enhanced, whereas the mitigation of the dynamic responses is only slightly impacted by the d-TMD approach.
4. In comparison to the d-TMD, the d-EKD provides a broadband response, as its effectiveness is determined by the ideal combination of positive and negative stiffness elements rather than the tuning frequency of the device.

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