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SEISMIC PROTECTION OF EXISTING STRUCTURES WITH DISTRIBUTED NEGATIVE STIFFNESS DEVICES

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ABSTRACT: In this research study, the KDamper concept is extended (EKD device) and applied to multiple floors of existing multi-story building structures, aiming to reduce the structure dynamic responses due to earthquake excitations. The KDamper is a novel passive vibration absorption concept, based essentially on the optimal combination of appropriate stiffness elements, one of which has a negative value (NS). The mass requirements of KDamper are reduced, compared to the Tuned Mass Damper (TMD), as the NS element is implemented to the installed mass and the NS force is in phase with the inertia force, artificially amplifying it. Inspired by the concept of distributed TMDs (d-TMDs), multiple EKDs (d-EKDs) are installed and distributed along the height of the structure, for seismic protection. The design and spatial allocation of these EKDs are determined using a Harmony Search (HS) algorithm, which identifies optimal device parameters while adhering to structural constraints and limitations. Artificial accelerograms are generated and introduced as input to the optimization process. 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. In addition, results indicate no significant alteration of the structural properties and eigenfrequencies due to the installation of the proposed EKD devices, despite the addition of masses and NS elements.

Key words: Seismic Protection, Negative Stiffness, Tuned Mass Damper, Damping, KDamper

INTRODUCTION

In recent years, structural damage, and collapse of buildings due to extreme earthquake events, has led to extensive research and alteration of seismic codes, aiming to achieve resilient structures with enhanced seismic performance. Current practice focuses on increasing structural mass, strength, and rigidity as well as ductility of crucial members of such structures, allowing in this way substantial inelastic behavior and increased damping. Seismic isolation is perhaps the best established approach to decouple the superstructure from the foundation level and thus, protect the structure from earthquake excitations (Naeim and Kelly, 1999; Symans et al., 2007; Warn and Ryan, 2012). The main drawback of such an approach is the required large base displacement and complex implementation, rendering the system expensive and inadequate for retrofitting existing structures. In the past few years, research has focused on novel seismic protection devices, such as TMDs, that can be implemented along the height of existing structures as retrofitting strategy (Elias et al., 2017; Radmard Rahmani and Könke, 2019; Sladek and Klingner, 1983). However, the mass requirements of such systems render their implementation unfeasible. The KDamper (Kapasakalis et al., 2020; Mantakas et al., 2022) incorporates a NS element to the added mass of the TMD, achieving an enhanced dynamic behavior.

This paper extends the application of the KDamper to multiple floors of existing multi-story structures. The approach involves the installation and distribution of several EKDs (d-EKDs) throughout the height of the examined building. The purpose is to provide seismic protection by reducing the structural dynamic responses. To overcome the issue of installing large masses, which is a primary drawback of mass-related vibration control methods like TMDs and KDampers, the design of these d-EKDs is structured to incorporate significantly smaller total added masses. The allocation of these distributed devices and the selection of their optimal parameters is achieved through a constrained optimization method utilizing the Harmony Search (HS) algorithm (Zong Woo Geem et al., 2001). This optimization process considers specific constraints ensuring the practical feasibility of the system. To facilitate the optimization process, a database of Eurocode 8 compatible artificial accelerograms is created and used as input motion. Finally, this research work evaluates the performance of the proposed seismic protection strategy with three numerical examples.

MATERIALS AND METHODS

Proposed Seismic Protection Strategy

A multi-story building of N floors with uniform mass (M_F = 360 *tn*) and stiffness (K_F = 650 *MN/m*) for all the stories is considered (Hadi and Arfiadi, 1998). The structure is modeled according to the following assumptions: (i) the structure is considered to remain elastic under the ground motion, (ii) a single horizontal component is selected as the input motion, and (iii) the effects of soil-structure-interaction are not taken into consideration.

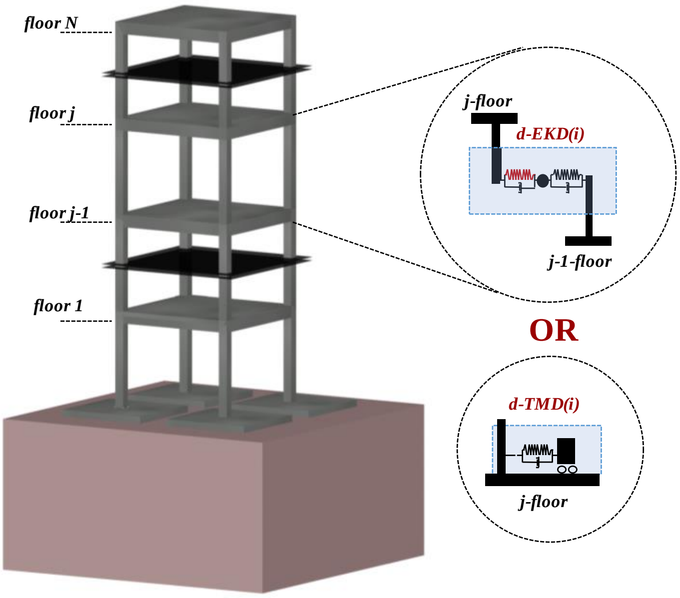


Figure 1. Implementation of a Vibration Control Device (Tuned Mass Damper - d-TMD, or Extended KDamper - d-EKD) Between Consecutive Floors of a Multi-Story Building Structure

The equations of motion of the N-story building equipped with the proposed distributed vibration control devices can be expressed in a matrix form as follows:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=-[M]\{r\}\ddot{X}_G \tag{1}$$

where $[M]$, $[C]$, and $[K]$ are the mass, damping, and stiffness matrices of the controlled structure, respectively, considering the effect of the implemented devices, and can be defined as:

$$[M]=[M_{STR}]+[M_{DVA}],\ \ [C]=[C_{STR}]+[C_{DVA}],\ \ [K]=[K_{STR}]+[K_{DVA}] \tag{2}$$

Indexes *STR* and *DVA* in Eqs. (2) indicate the degrees of freedom of the NC (no-control) building and of the implemented dynamic vibration absorbers, respectively. The implementation of an EKD or a TMD device of number (i) between two consecutive floors (j) and (j-1) is presented in Fig. 1. The additional mass of the EKD with number (i) $M_{D\text{-}i}$ is connected to the floor (j) with a NS element $k_{N\text{-}i}$ and a damper $c_{N\text{-}i}$, as well as to the floor (j-1) with a stiffness element $k_{P\text{-}i}$ and a damper $c_{P\text{-}i}$. The DVA-related matrices of Eqs. (2) are formed as:

$$K_{EKD}(N+i,N+i)=k_{N-i}+k_{P-i},\ \ K_{EKD}(N+i,j)=-k_{N-i},\ \ K_{EKD}(j,N+i)=-k_{N-i},\ \ K_{EKD}(j,j)=k_{N-i} \tag{3.a}$$

$$K_{EKD}(N+i,j-1)=-k_{P-i},\ \ K_{EKD}(j-1,N+i)=-k_{P-i},\ \ K_{EKD}(j-1,j-1)=k_{P-i} \tag{3.b}$$

$$M_{EKD}\left(N+i,N+i\right)=\mu_i M_{TOT},\quad \mu_i=\frac{M_{D-i}}{M_{TOT}},\quad \mu=\sum_1^n \mu_i,\quad M_{TOT}=\sum_1^N M_i \tag{4}$$

$$C_{EKD}\left(N+i,N+i\right)=c_{N-i}+c_{P-i},\quad C_{EKD}\left(N+i,j\right)=-c_{N-i},\quad C_{EKD}\left(j,N+i\right)=-c_{N-i} \tag{5.a}$$

$$C_{EKD}\left(j,j\right)=c_{N-i},\quad C_{EKD}\left(N+i,j-1\right)=-c_{P-i},\quad C_{EKD}\left(j-1,N+i\right)=-c_{P-i},\quad C_{EKD}\left(j-1,j-1\right)=c_{N-i} \tag{5.b}$$

where μ_i is the mass ratio of each EKD. The effectiveness of the d-EKD will be verified by comparing the existing structure seismic performance with distributed TMD devices. The optimal TMD parameters are selected according to (Elias et al., 2017). For a TMD (i) installed on a floor (j), the TMD mass is implemented to the floor (j) with a stiffness element k_{D-i} and a damper c_{D-i}:

$$K_{TMD}\left(N+i,N+i\right)=k_{D-i},\quad K_{TMD}\left(N+i,j\right)=-k_{D-i},\quad K_{TMD}\left(j,N+i\right)=-k_{D-i},\quad K_{TMD}\left(j,j\right)=k_{D-i} \tag{6}$$

$$M_{TMD}\left(N+i,N+i\right)=\mu_i M_{TOT},\quad \mu_i=\frac{M_{D-i}}{M_{TOT}},\quad \mu=\sum_1^n \mu_i \tag{7}$$

$$C_{TMD}\left(N+i,N+i\right)=c_{D-i},\quad C_{TMD}\left(N+i,j\right)=-c_{D-i},\quad C_{TMD}\left(j,N+i\right)=-c_{D-i},\quad C_{TMD}\left(j,j\right)=c_{D-i} \tag{8}$$

Constrained Optimization Methodology

Each EKD (i) introduces in total five parameters, the oscillating mass M_{D-i}, the stiffness elements k_{N-i} and k_{P-i}, and the dampers c_{N-i} and c_{P-i}. The mass ratio of each EKD is selected equal to 0.1%. The equivalent frequency of the (j) floor is introduced to better observe the effect of the implemented EKD device in the building structure:

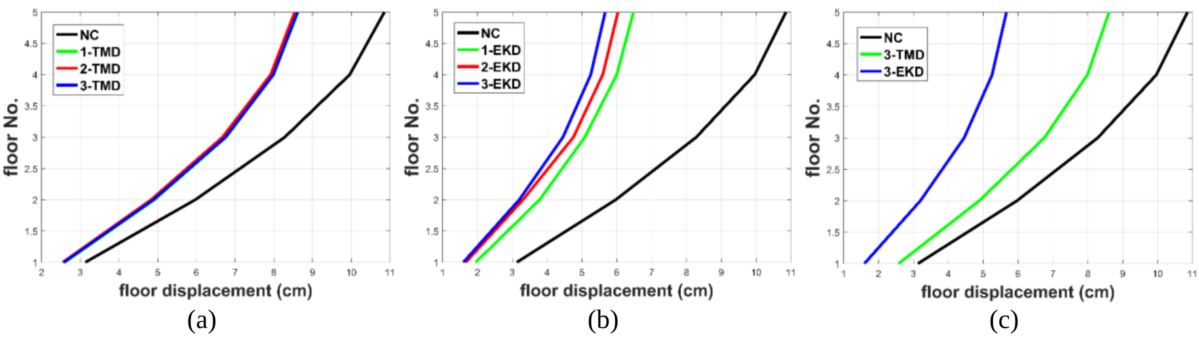
$$f_{EQ}^{j}=\sqrt{(k_{EQ,STAT}^{j})/(M_j+M_{D-i})}/2\pi \tag{9}$$

The k_{P-i} value is obtained from Eq. (9), given that k_{N-i} is known. The free design variables of each EKD are: 1) the NS element k_{N-i}, 2) the equivalent eigenfrequency $f_{EQ,i}$, and 3) the dampers c_{N-i} and c_{P-i}. For the design to be efficient and realistic, proper constraints and limitations to the design variables and to the controlled system's dynamic responses must be applied. The proposed constrained optimization procedure with the HS optimization algorithm follows the steps of (Kapasakalis et al., 2023, 2021), where specific details about the HS algorithm can be found. It is noted that the maximum floor drift is set as the objective function and the equivalent frequency of the controlled floor is set to vary in the range of (2/3) and (4/3) of its original value.

RESULTS AND FINDINGS

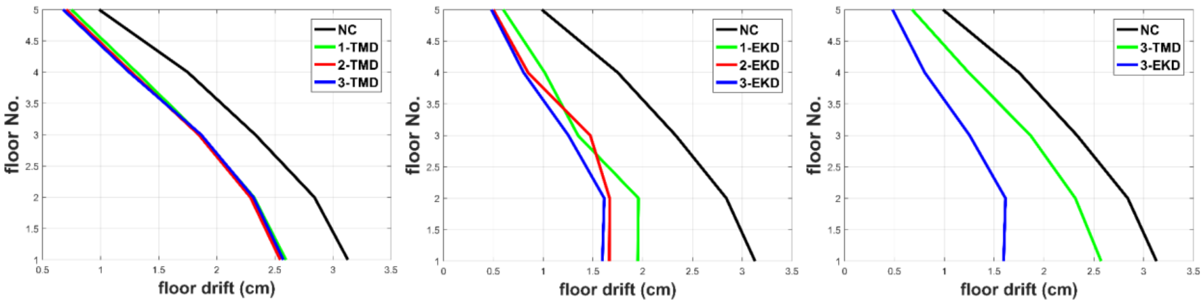
To verify the effectiveness of the d-EKDs, three test cases are examined, a five-story, a ten-story, and a fifteen-story building, where the number of d-EKD devices vary from one to three. The mass ratio of the d-EKDs is 0.1%, while that of the d-TMDs is 1%. Figs. 2-4 present the envelopes of the floor displacements, inter-story drifts, and absolute accelerations of the five-story building. A comparison between the uncontrolled structure (NC) and the response of the upgraded building with d-TMDs and d-EKDs is depicted. Figs. 5-7 and 8-10 present the response envelopes of the ten-story and fifteen-story structure, respectively.

Five-Story Building Structure



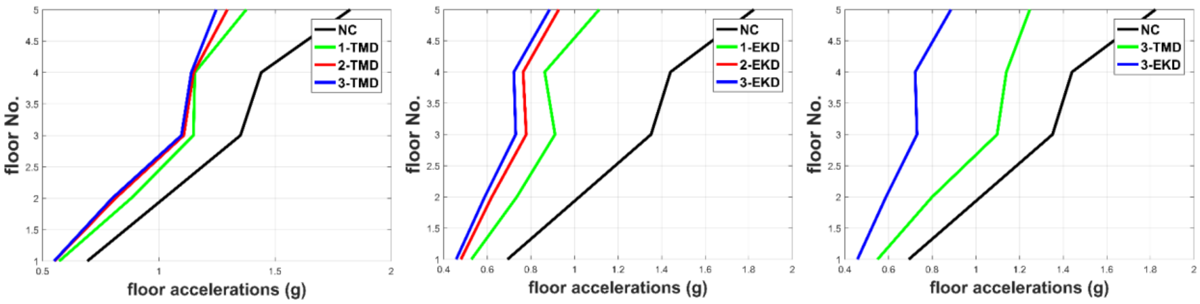
(a) (b) (c)

Figure 2. Floor Displacement Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 5-Story Building



(a) (b) (c)

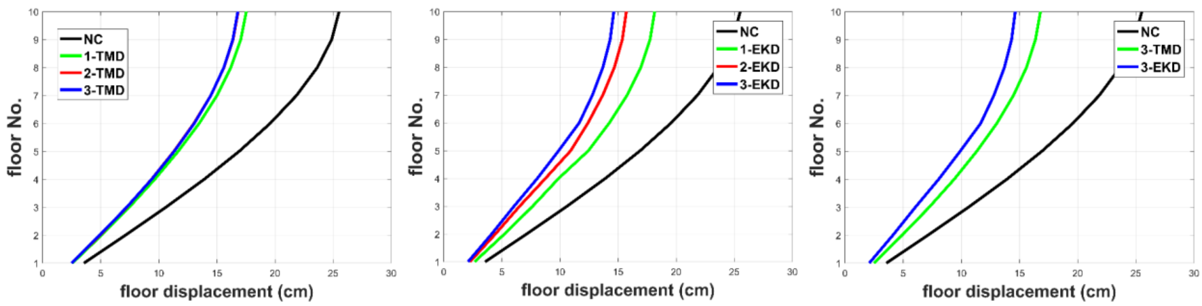
Figure 3. Floor Drift Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 5-Story Building



(a) (b) (c)

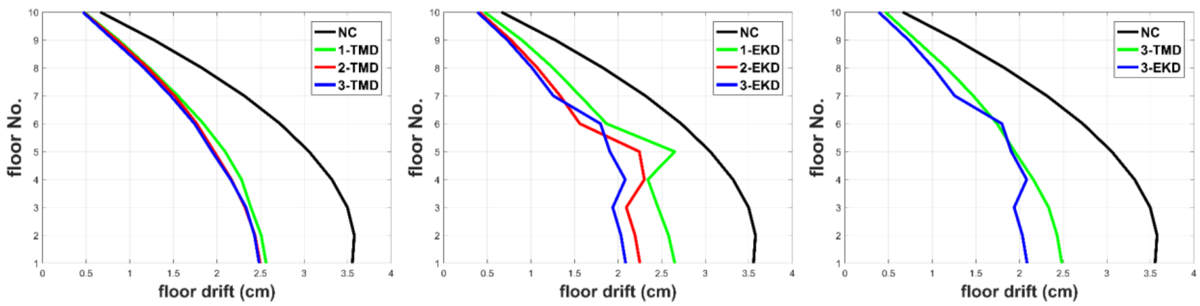
Figure 4. Floor Absolute Acceleration Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 5-Story Building

Ten-Story Building Structure



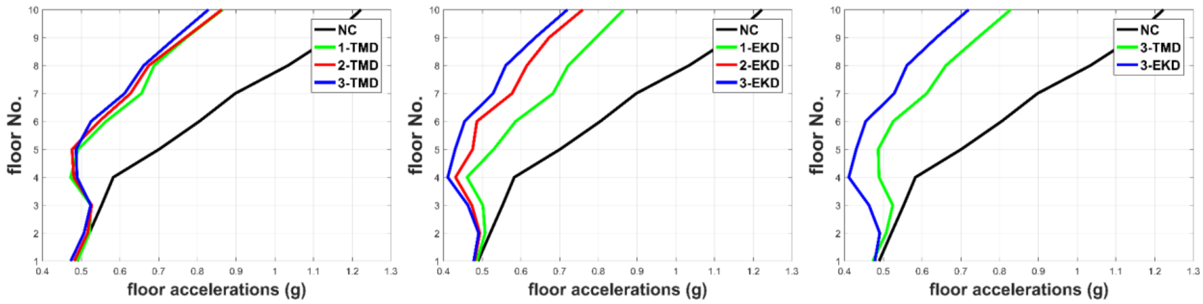
(a) (b) (c)

Figure 5. Floor Displacement Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 10-Story Building



(a) (b) (c)

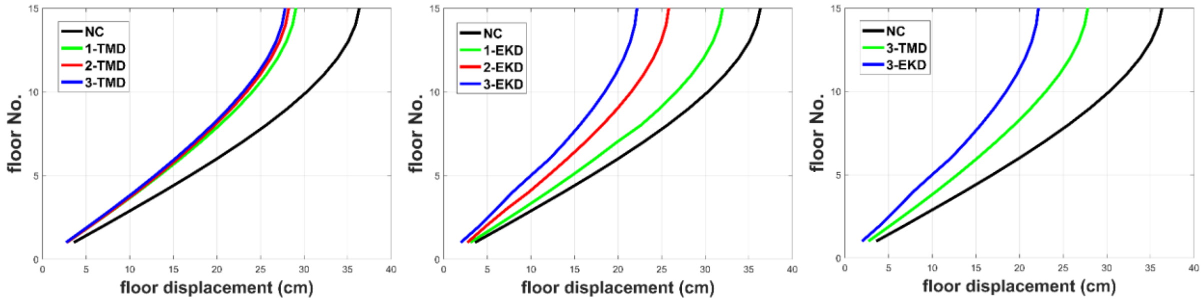
Figure 6. Floor Drift Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 10-Story Building



(a) (b) (c)

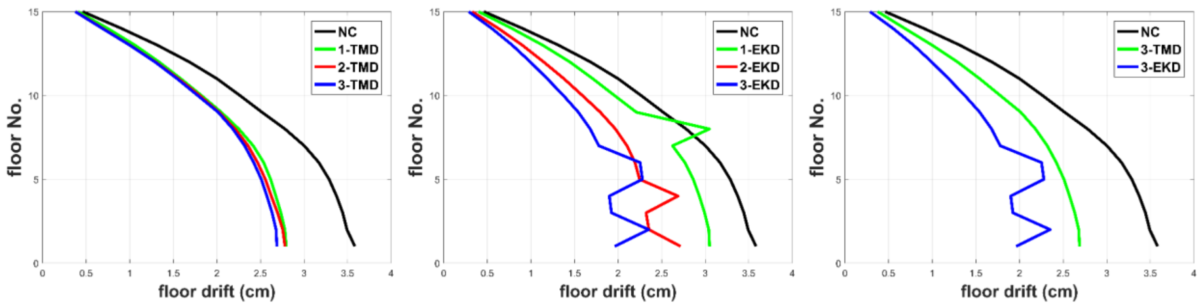
Figure 7. Floor Absolute Acceleration Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 10-Story Building

Fifteen-Story Building Structure



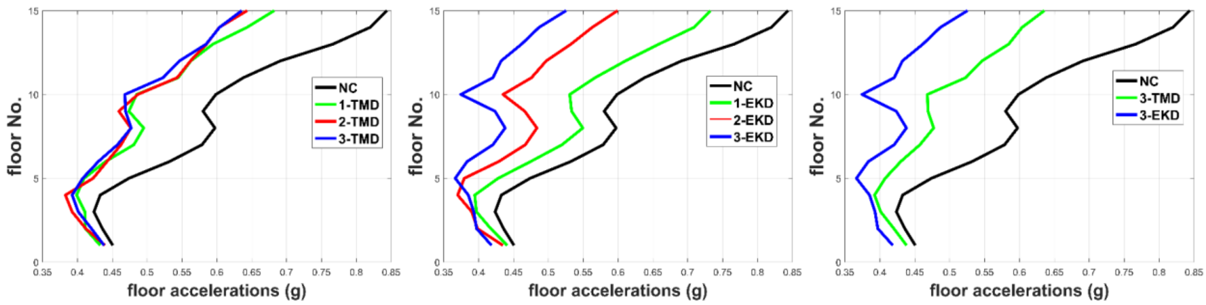
(a) (b) (c)

Figure 8. Floor Displacement Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 15-Story Building



(a) (b) (c)

Figure 9. Floor Drift Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 15-Story Building



(a) (b) (c)

Figure 10. Floor Absolute Acceleration Envelopes for the (a) d-TMD (one up to three devices), (b) d-EKD (one up to three devices), and (c) 3-TMDs and 3-EKDs, for the 15-Story Building

CONCLUSION

This research examined a framework towards the seismic protection of existing multi-story building structures with distributed extended KDamper (d-EKD) devices. The d-EKD concept for vibration control involves the incorporation of minimally sized additional oscillating masses, strategically designed to prevent overburdening the structure. This study employs a constrained optimization approach to select the system parameters, ensuring the reduction of the structural dynamic responses while adhering to specific design variable values and constraints. To demonstrate the effectiveness of the seismic protection approach proposed, a comparison with distributed Tuned Mass Dampers (d-TMDs) is conducted. Based on the numerical results obtained, the following conclusive remarks can be made:

1) The design of the d-EKD is realistic, as it uses small masses and imposes constraints and limitations on the free design variables and the system's dynamic responses. In addition, results depict minimal effect of the seismic protection strategy on the modes of the structure, rendering d-EKD feasible retrofitting strategy.
2) The superstructure dynamic behavior is superior with the d-EKDs as compared to the d-TMD concept, introducing ten times smaller oscillating masses.
3) The performance of the d-EKDs is enhanced as the number of installed devices increases, while for the d-TMD concept, the improvement is slightly affected.
4) The d-EKD offers a broadband response compared to the d-TMD, as its performance is not directly affected by the device tuning but rather by the optimal combination of stiffness and damping elements.
5) The d-EKD performance decreases as the number of floor increases, as high-rise structures are not sensitive to ground motions as compared to mid-rise structures.

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