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3D NUMERICAL INVESTIGATION OF AN EXTENDED KDAMPER ABSORBER FOR SEISMIC RETROFITTING OF LOW-RISE BUILDINGS

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Abstract

Research in the field of seismic protection has progressed significantly, starting from the use of simple elastomeric bearings that require a reduction of the system's fundamental frequency to control the dynamic response of the superstructure, to more advanced vibration control devices that incorporate the use of additional oscillating masses and negative stiffness elements. Examples of these devices are the Tuned Mass Damper (TMD), the Quasi-Zero oscillators (QZSs) as well as the KDamper concept that is based essentially on a combination of appropriate stiffness, damping and mass elements, including a negative stiffness element. In this study, a passive KDamper-based vibration absorber is implemented at the base level of a typical existing building, between the foundation and the superstructure, as a means of seismic retrofitting. A mathematical model is formulated, and an optimization procedure is undertaken using both EC8 compatible artificial accelerograms as well as real earthquake records. Geometrical and manufacturing limitations are accounted for, regarding the realization of the negative stiffness mechanics and the rest vibration control components. A sophisticated 3D finite element model is subsequently generated aiming to take into account soil-structure interaction, material non-linearities and effect of geometry and location of the device in a realistic manner. Results indicate the beneficial effect of the system in the dynamic behavior of the structure and highlight the applicability of the system as well as limitations that should be considered in future research.

Keywords: Base Absorber; Retrofitting; Negative Stiffness; Damping

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1 INTRODUCTION

In recent years, seismic codes have undergone significant changes aimed at producing more resilient structures that can better withstand seismic loads. Various types of seismic isolation devices have been created, primarily for use in important structures and bridges. These devices range from simple elastomeric bearings, with or without a lead core, to more advanced roller bearings and viscous dampers. However, while base isolation can control and limit accelerations, it is not a universal solution and may not be appropriate for all structural applications. This is because while large base displacements are necessary in some cases, they can negatively impact the overall performance of the structure. Additionally, flexible utility connections, such as waterworks and power supplies, that can handle significant deformations are necessary at the base level. It is also important to ensure there is enough distance between adjacent structures to prevent collisions during earthquakes. Retrofitting existing structures with base isolation is challenging, expensive, and risky, and as a result, it is rarely considered as a viable option.

To this end, seismic protection research has focused on devices that incorporate additional masses and negative stiffness elements such as Negative Stiffness (NS) Devices [1,2], and Tuned Mass Dampers (TMDs). The use of additional oscillating masses (TMDs) has been applied in various systems, including skyscrapers and structural bases, to shield them from the dynamic effects of environmental loads such as wind, waves, and seismic activity [3–7]. However, the primary drawback of this approach is the requirement for large additional masses compared to the structure's mass itself, as well as the detuning of the TMD parameters that can impact the structure's performance over time.

Antoniadis et al. [8,9] were inspired by these existing vibration control systems and introduced the KDamper, a promising class of absorbers based on increasing the damping by the appropriate introduction of negative stiffness elements. The KDamper combines the favourable properties of both the NS and traditional TMD, providing exceptional damping characteristics to the structure. By incorporating the additional NS element, the damper's inertial forces are increased, and the need for large mass is significantly reduced [10,11]. The stiffness-mass elements can be allocated appropriately to create a system that is statically and dynamically stable, maintaining the structure's initial/static stiffness and avoiding potential instabilities. The KDamper has been examined in protecting bridges, wind turbines, and other structural systems, resulting in reduced displacement demand at the base level [12–16].

In this study, a passive KDamper-based vibration absorber is implemented at the base level of a typical existing building, between the foundation and the superstructure, as a means of seismic retrofitting. For the first time, a detailed 3D finite element model is created to accurately incorporate soil-structure interaction, material non-linearities, and the impact of device geometry and location. The outcomes demonstrate the favourable impact of the system on the structure's dynamic behaviour and underscore the potential uses of the system along with limitations that should be considered for future research.

2 OVERVIEW OF THE KDAMPER CONCEPT AS A BASE ABSORBER – RETROFITING STRATEGY

In this section, the extended KDamper concept (EKD) is presented, and the fundamental principles of its function are provided in detail (Figure 1). A single degree of freedom (SDoF) oscillator is considered in which the KDamper is implemented between its rigid base and the oscillating mass. This novel passive dynamic absorber utilizes the oscillating mass (m_D) and the additional negative stiffness (NS) element K_N which connects the additional mass to the base, to generate damping and energy dissipation within the system [10].

The equations of motion of the EKD are presented below:

$$m\ddot{u}_{REL} + c_R\dot{u}_{REL} + K_R u_{REL} + c_P\left(\dot{u}_{REL} - \dot{u}_{D,REL}\right) + K_P\left(u_{REL} - u_{D,REL}\right) = -m\ddot{u}_G \tag{1}$$

$$m_D\ddot{u}_D - c_P\left(\dot{u}_{REL} - \dot{u}_{D,REL}\right) - K_P\left(u_{REL} - u_{D,REL}\right) + K_N u_{D,REL} = -m_D\ddot{u}_G \tag{2}$$

Where $u_{REL} = u - u_G, u_{KD,REL} = u_{KD} - u_G$. The negative stiffness element (K_N) serves as an indirect method to increase the inertial forces of the damper's mass m_D, as the force of K_N is exactly in phase with the inertial force of m_D [10], without, however, the need to increase the mass itself. The total stiffness of the system with the KDamper can be expressed using the following formula:

$$K_R + \frac{K_P K_N}{K_P + K_N} = K_0 = (2\pi f_0)^2\left(m + m_D\right) \tag{3}$$

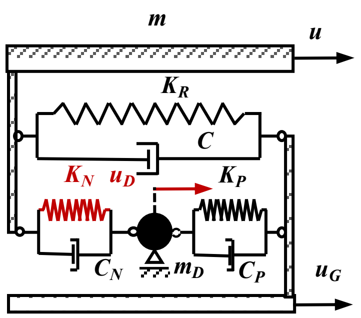

Figure 1: Extended KDamper (EKD) concept.

3 DESIGN AND OPTIMIZATION OF THE EKD-R PARAMETERS

Herein, the application of the Extended KDamper as a method for seismic upgrade of residential buildings, namely the EKD-R, is presented. As reported by Kapasakalis et al. [15], the EKD shares the same fundamental principles as the KDamper, but offers superior performance. The EKD is specifically designed to be installed between the multi-story superstructure and its base, with the objective of controlling the response of the building during earthquakes [14].

To ensure that the retrofitting strategy is designed effectively, it is necessary to obtain the optimal system parameters from a simplified model that reduces computational time. To achieve this, a lumped parameter model (LPM) is utilized for modelling the controlled structure. Contrary to the previous investigations [14,17] that the ground motion excited the structure only in one direction, here a more realistic examination is conducted, assuming that the seismic waves act obliquely to the structure. Hence, two LPMs are required to describe the in plane and out of plane response of the building.

The LPMs are based on certain assumptions, which include: i) concentrating the total mass of the structure at the floor levels, ii) treating the columns as weightless while providing the lateral stiffness of the system, iii) assuming the columns are inextensible, iv) assuming the slabs and girders on the floors are rigid in comparison to the columns, and v) accounting for the effect of soil-structure interaction (SSI) by incorporating nonlinear springs in series with the column stiffnesses of the first floor. The fifth assumption is illustrated schematically in Figure 2.

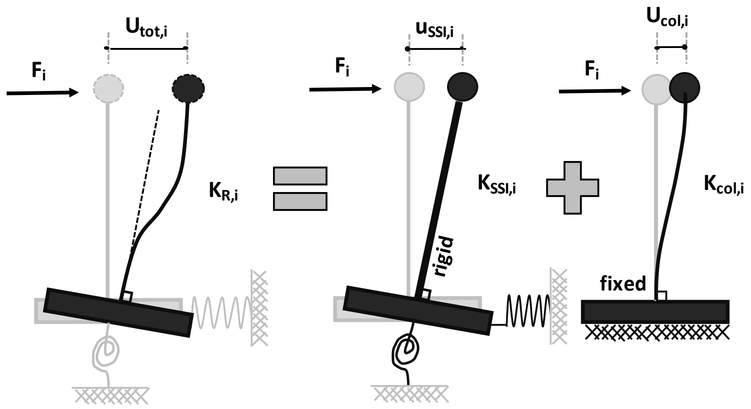

Figure 2: A simplified approach to account for the SSI effects (horizontal and rotational stiffness of the soil) for horizontal displacement at the top of each column [17]

The equivalent first floor stiffness is calculated as:

$$k_1(x_{1,rel}) = \frac{k_{SSI}(x_G) \times k_{col}(x_{1,rel})}{k_{SSI}(x_G) + k_{col}(x_{1,rel})} \tag{4}$$

The controlled structure has now (N+1) dynamic DoFs, where N is the number of the RC building stories. The equations of motion are expressed in matrix form, where the matrices of mass, damping, and stiffness and the vector of displacements have dimensions (N+1)×(N+1) and (N+1)×1, respectively.

$$\mathbf{M}\{\ddot{x}(t)\} + \mathbf{C}\{x(t)\} + \mathbf{K}\{x(t)\} = -\mathbf{M}\{1\}\ddot{x}_G(t) \tag{5}$$

The exact expressions of the matrices involved can be obtained following the procedure presented in [17], and details regarding the parameters of the implemented vibration control strategy (extended KDamper) can be found in [15].

To achieve the best possible design for the EKD-R, the mathematical modelling is accomplished in MATLAB®, and analyzed in the time domain. A set of seismic accelerograms are used as a basis for the design and optimization of the model by adopting an HS algorithm [18,19]. The objective function for this model is the first-floor drift of the structure, while an acceleration filter (AF) is applied to the upper story acceleration, expressed as a percentage of the mean applied PGA. The efficiency of the proposed control strategy for the EKD-R is crucial, and the design values must be chosen realistically. Therefore, appropriate limits are set for the free design variables in the optimization problem, namely K_N, C_N and C_P, as well as for the additional mass m_D and the stability factors ε_N, ε_P and ε_R. These limits are determined based on feasibility and technological constraints.

4 3D NUMERICAL (FE) INVESTIGATION

4.1 Benchmark Building Geometry and Characteristics

In this study, a single bay in the x-direction and two-bay in the z-direction three-story reinforced concrete building is used as a case-study to investigate the feasibility and dynamic performance of the EKD-R application as a seismic retrofitting measure of RC structures. The building has a plan view of 6x12m and consists of columns founded on stiff clay with an undrained shear strength of S_u=200 kPa and a small-strain elastic modulus of E_0/S_u=1000 (where E_0 is the soil's small-strain elastic modulus). The structure is founded on shallow, rectangular 3x3m foundations. The first story of the building has a height of H_1=4m, while the following floors have a height of 3m. The structure is dimensioned and reinforced according to Eurocodes and specifically EC8 for seismic design, using FESPA design software. The building is designed assuming ground type C, with a spectral peak ground acceleration of 0.24 g, behavior factor q=3.5, spectrum type I, and importance class II. The structural properties and geometry of the RC structure are shown in Figure 3. This indicative structure is used as a test case building for the feasibility analysis of the passive seismic control concept, employing nonlinear 3D FE numerical analyses.

As mentioned in section 3, the design values of the EKD-R system are derived from the optimization procedure. More specifically, based on previous work [15,20], realistic values for the generated NS and the viscous dampers implemented are -130 kN/m and 20 kNs/m per tn of total superstructure mass, respectively. The total mass of the benchmark building is 130 tn, and the values of the EKD-R components (for each installed device), obtained from the optimization process, are presented in

Table 1. Finally, the additional oscillating mass of the EKD-R is selected to be equal to 0.1% of the total superstructure mass; this is an assumption that leads to a feasible EKD-R device that does not burden the structure with parasitic masses.

	m_D (tn)	$K_{N\,(uNS=0)}$ (kN/m)	C_N (kNs/m)	C_P (kNs/m)	K_P (kN/m)
Design Values	0.31	-3405.4	230.6	22.5	8262.5

Table 1: Values of the optimized EKD-R components

Since EKD-R devices can operate in parallel, 6 devices are implemented in total; two (2) in x-direction and four (4) in z-direction.

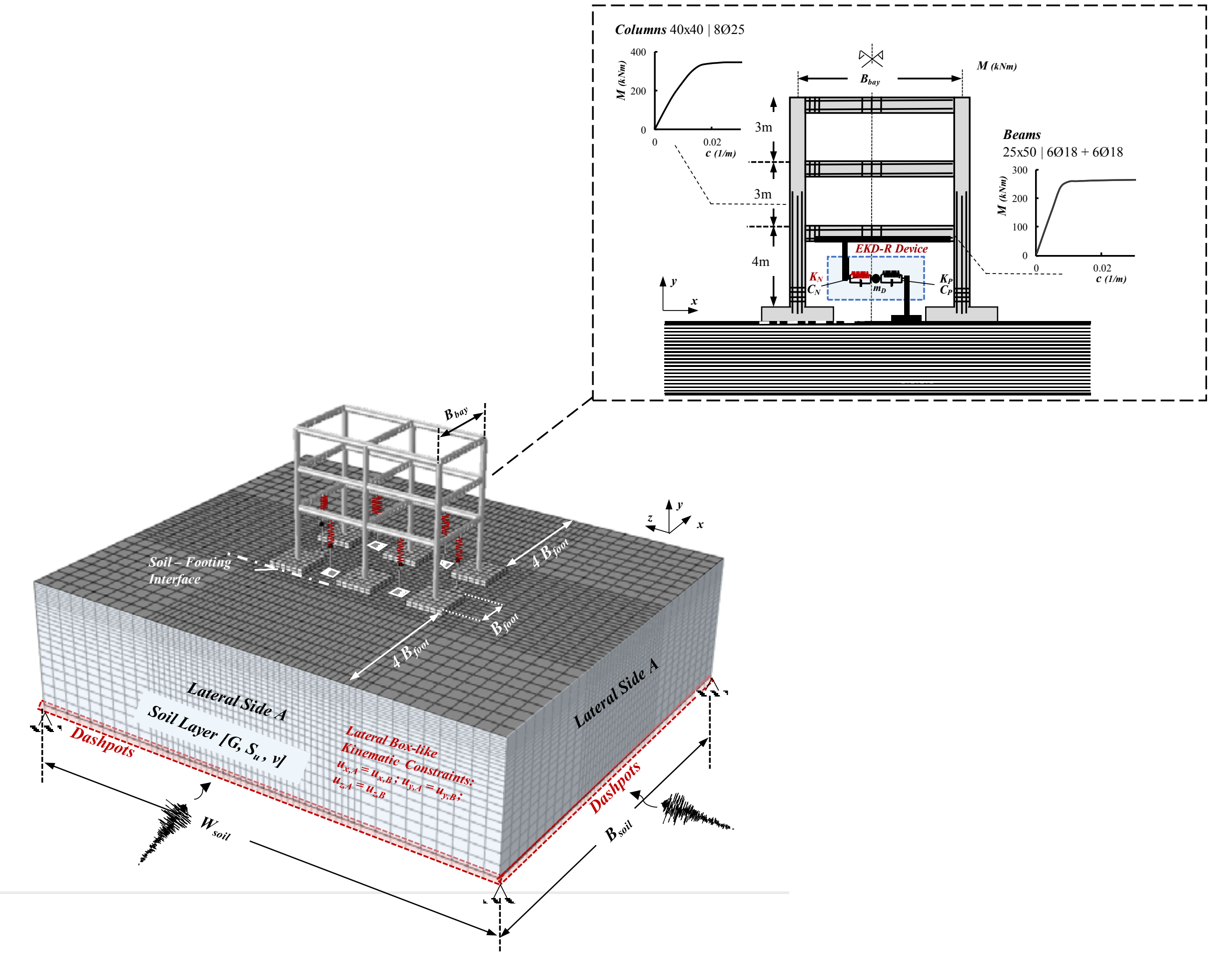

Figure 3: 3D Finite element numerical model and mesh, employed for the dynamic analysis of the benchmark structure. Structural non-linear behavior is also presented.

4.2 Description of the numerical model

The finite element code ABAQUS [21] is employed for a series of non-linear seismic analyses. The main scope of this more advanced simulation is to capture soil and structural non-linearities and damping effects, the soil-structure interaction due to the foundation system of the building, as well as the topology effects of the installed EKD devices. Three-dimensional FE modelling is used to simulate the response of an RC building and hence realistically capture the soil–foundation interaction effects, while accounting for the appropriate geometry (of soil and superstructure), kinematic boundaries, and foundation response. Inelastic behavior of the soil, foundations and structural elements is modelled explicitly.

Specifically, to model the soil in the analysis, nonlinear solid continuum elements are used, which follow a nonlinear pressure-dependent kinematic hardening model that adheres to the Von Mises failure criterion with associative flow rule [22,23] for clays under undrained conditions. Elastic continuum elements were utilized to model the foundation of both the building and EKD-R mechanism, with tensionless contact elements employed at the soil-foundation interfaces to consider potential uplifting, rocking, and sliding. The interface between the soil and footings was assigned a friction coefficient of μ = 0.7. Appropriate "free-field" boundaries were used at the lateral boundaries of the model (4 x B_{foot}), and dashpots were installed at the base to simulate the half-space below the 20m of soil.

Nonlinear beam elements are utilized to model the columns and beams of the superstructure, with the moment-curvature relationship reflecting the properties of the actual reinforced concrete sections.

Finally, the EKD-R mechanism is modelled using three elements: a point mass element to represent the internal mass m_D, a linear spring element that acts on the x or z-axis with a constant stiffness coefficient K_P and damping coefficient C_P, and a non-linear connector element that acts on the x or z-axis with a variable stiffness coefficient K_N and a constant damping coefficient C_N

4.3 Time-history analysis and discussion

Nonlinear dynamic time-history analyses are performed, by applying the excitation time-histories at the base of the model in x, z directions simultaneously, to simulate the system's dynamic response. The employed accelerograms are recorded in stations installed on top of soil formations with shear-wave velocity ($V_{s,30}$) corresponding to EC8 ground type C (180–360 m/s); this selection ensures that the real records represent realistic earthquake excitations for the assumed benchmark building.

Table 2 presents the key characteristics of the selected strong ground motion records. The records are subsequently scaled to a maximum 0.36 g PGA, aiming to generate acceleration spectra that are above the initial design spectrum of the benchmark structure (EC8–0.24 g) and at the same time corresponding to the adopted realistic regional characteristics, assumed for the test case. The response spectra and time histories of the two selected ground motions are presented in Figure 4.

Earthquake	Year	Station	Ground Motion	M_w	PGA *(g)*	DUR $_{5\text{-}75\%}$ *(s)*
Kocaeli-N	1999	Izmit	Near fault	7.51	0.17	8.2
Landers-N	1992	Joshua tree	Near fault	7.28	0.28	21.7

Table 2: Characteristics of selected ground records.

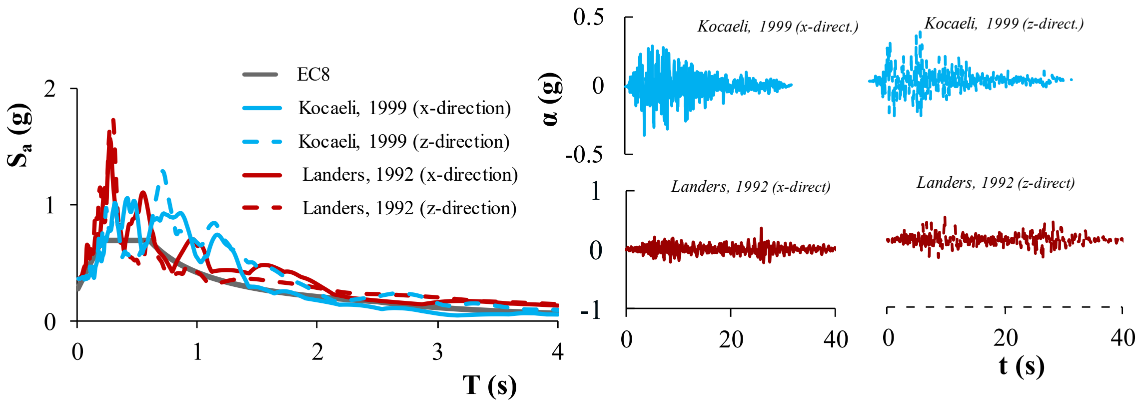

Figure 4: (a) Acceleration response spectra of the two (2) modified ground records along with the EC8 design

response spectrum, and the b) corresponding accelerograms, Kocaeli (1999) and Landers (1992) respectively.

The FE model's response for both the initial and EKD-R retrofitted system is presented in terms of first story drifts (U_1) and upper-story accelerations ($a(g)$). In particular, Figure 5 depicts the building's dynamic response in x, z directions for the Landers (1992) earthquake and Figure 6 for the Kocaeli (1999) earthquake. Results indicate the beneficial effect of the EKD-R in terms of both drifts and accelerations, for both selected records and validate the initial more simplistic 2D FE investigation of Mantakas et al. [14]. Specifically, for the case of the Landers excitation, the maximum acceleration values are reduced to approximately 18% in x-direction and 60% in z-direct, while for the case of Kocaeli, to 28% and 40%, respectively. Considering the maximum first-story drift values, the EKD-R provides 26% decrease in x-direct. and 52% decrease in z-direction, for the Landers earthquake motion. For the case of Kocaeli, drifts are reduced to approximately 29% in x-direction and 43% in z-direction, compared to the initial benchmark structure.

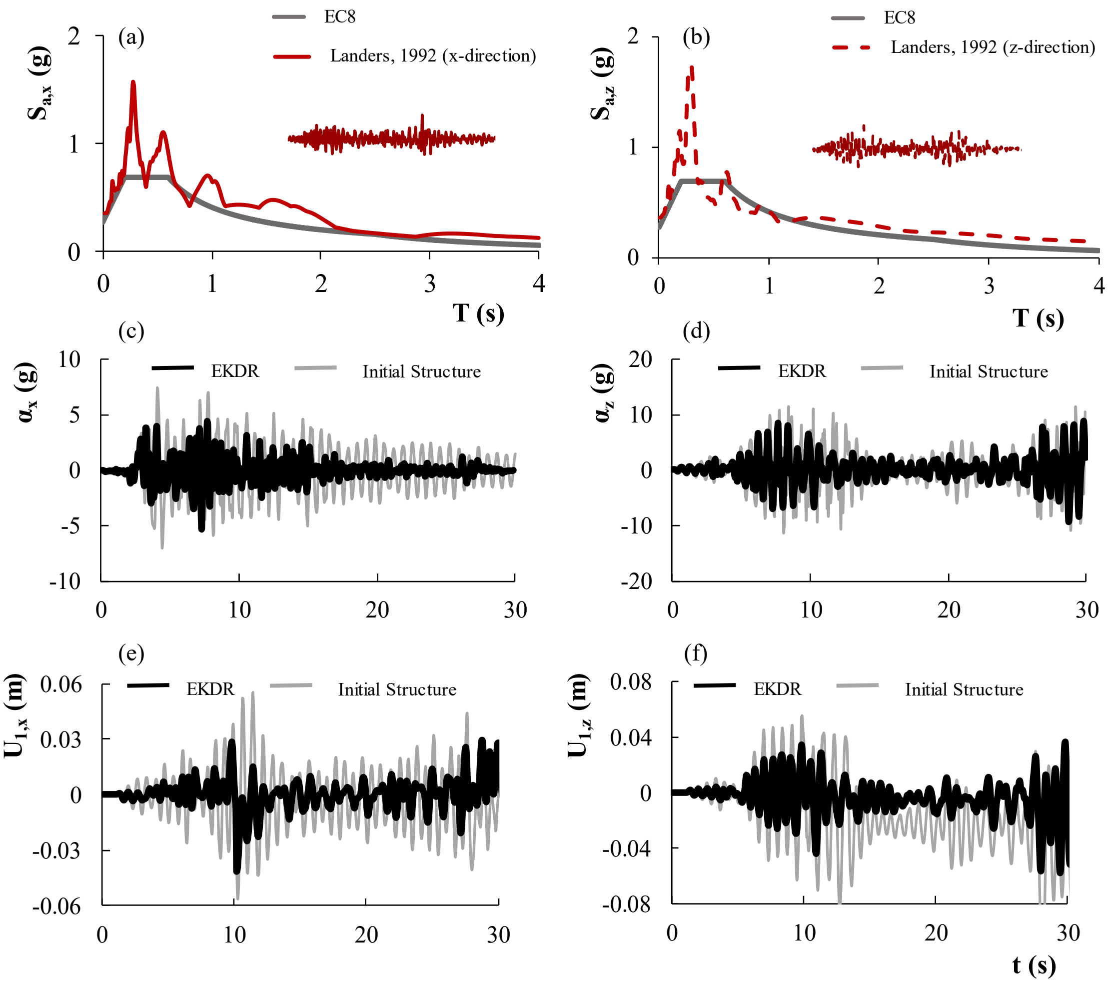

Figure 5: Comparative dynamic response results between the initial system and the system with the EKD-R device for the Landers (1992) earthquake for x, z directions, using the FE model: (a)-(b) Acceleration response spectra of the two records, (c)-(d) upper story acceleration and (e)-(f) first story drift time histories.

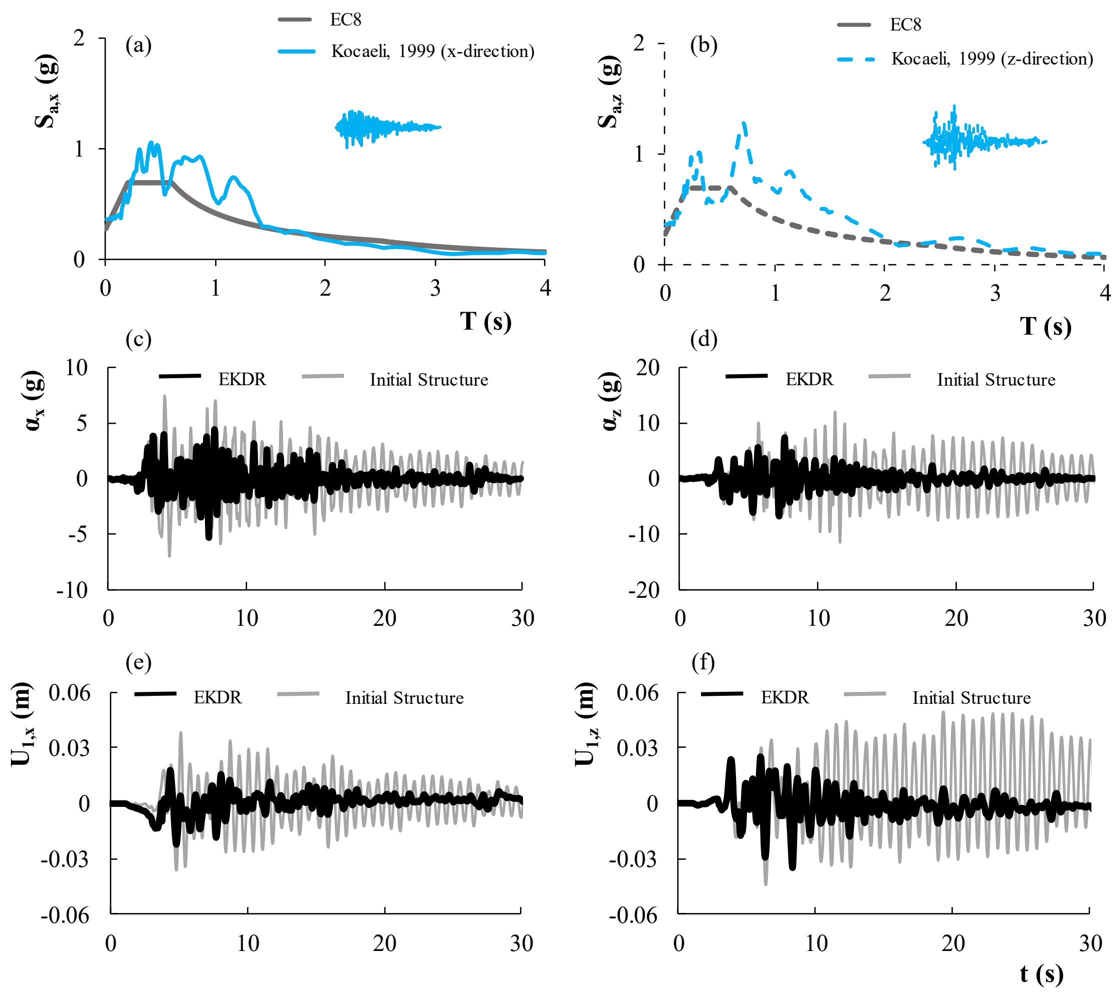

Figure 6: Comparative dynamic response results between the initial system and the system with the EKD-R device for the Kocaeli (1999) earthquake for x, z directions, using the FE model: (a)-(b) Acceleration response spectra of the two records, (c)-(d) upper story acceleration and (e)-(f) first story drift time histories.

5 SUMMARY & CONCLUSIONS

This paper numerically explores the performance of a conventionally designed structure with a novel NS-based vibration absorber (EKD-R) added as a seismic retrofitting measure. The proposed device comprises an optimal combination of additional mass, positive and negative stiffness elements, and damping components. The benchmark structure is a three-story, one-bay in the x-direction and two-bay in the z-direction, building designed according to the latest European seismic codes (EC8). The study examines the implementation of EKD-R devices at the base of this benchmark residential building, between the foundation and the first story, taking into account oblique to the building seismic excitations. The 3D FE analysis showed that the optimized EKD-R mechanism significantly reduces the accelerations and drifts, of the building, revealing the importance of fine-tuned, optimally located KDampers. The EKD-R retrofitted building's performance is investigated under real earthquake records, and the system appears promising as aseismic mitigation measure, as both floor accelerations and inter-story drifts were significantly reduced. The study concludes that the EKD-R vibration absorber is a successful seismic retrofitting measure that accounts for structural non-linearities and SSI effects, and it has been demonstrated to be a compelling seismic mitigation technology.

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