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Optimization of Seismic Behavior of Adjacent Buildings in Response to Impact Loads

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ABSTRACT

This study explores optimization strategies for the seismic behavior of adjacent buildings under impact and seismic loads. With construction rapidly expanding in densely populated urban environments, accurately analyzing the dynamic response of these structures is crucial. The research begins by identifying key factors that influence seismic behavior, followed by an examination of the dynamic responses of the buildings subjected to various loading conditions. Additionally, this analysis utilizes both analytical models and numerical simulations to assess performance comprehensively. The results reveal that maintaining adequate spacing between buildings, selecting appropriate materials, and implementing effective structural designs can significantly mitigate damage from seismic and impact forces. Notably, a sensitivity analysis indicates that even minor adjustments in design parameters can lead to considerable improvements in structural performance. In conclusion, the study offers practical recommendations aimed at enhancing the design and construction practices of adjacent buildings, thereby improving their safety and stability in the face of natural disasters. These valuable findings provide detailed insights for engineers and architects striving to bolster structural safety and also minimize the risks associated with earthquakes and impact loads. Eventually, By integrating these recommendations, the resilience of urban structures can be significantly improved, ensuring better protection for occupants and communities alike.

Introduction

In recent years, the interaction of adjacent structures during earthquakes has attracted significant attention. Impact oscillations (shaking caused by the collision of two adjacent buildings during an earthquake) occur when structures have different dynamic characteristics, leading to out-of-phase vibrations, where static separation distances are insufficient to accommodate their relative movements. The simplest and most effective way to reduce damage from such impacts is to create a minimum separation distance between buildings. While sufficient separation can prevent collisions between buildings, sometimes establishing adequate separation in urban areas is not feasible due to high land costs, limited access to land, and the need for concentrated facilities. Often, the potential for impact oscillations between adjacent buildings is overlooked during design (Mousavi et.al, 2020). In many cases, the primary factor of impact is the difference in natural vibration periods of neighboring buildings. Variations in mass and stiffness among adjacent structures cause out-of-phase vibrations during an earthquake, increasing the likelihood of structural damage due to collisions (Elwardany et.al, 2022), (Sołtysik et.al, 2013). The main reason for structural impact during an earthquake is the differing dynamic properties and out-of-phase behavior of neighboring buildings. To address this issue, several solutions have been applied in practice and proposed in related research. The connection of buildings with various linking devices is considered the most common method to prevent impacts (Mohamed & Romao, 2021). Xu et.al, (1999) employed viscous dampers between neighboring buildings with different floors. Analyses regarding frequency and time were conducted to demonstrate damper efficiency. Basakararao and Jangid (2006) utilized friction dampers to reduce the seismic responses of adjacent buildings. Rahim (2014) used rubber seismic absorbers to prevent impacts. Research was conducted on the optimal passive control of adjacent structures connected via nonlinear hysteresis devices subjected to a filtered Gaussian, zero-mean multi-frequency seismic excitation (Basili & De Angelis, 2007). Kim and colleagues (2006) analyzed single-degree-of-freedom (SDOF) systems connected by viscoelastic dampers at seismic joints under multi-frequency sound and seismic excitation to observe reductions in structural seismic responses. They also performed dynamic analysis on rigid frames with 5 and 25 stories connected to braced frames. Kandemir-Maznoglu and Maznoglu (2015) have shown that the design and optimization of these buildings can significantly improve their performance under impact loads. They developed a simple optimization method for viscous dampers to determine the capacity and positioning of linear viscous dampers between adjacent buildings, and conducted parametric studies on buildings with equal stories connected by viscous dampers.

Therefore, investigating optimization methods for the seismic behavior of adjacent buildings facing impact loads is crucial not only from a structural engineering perspective but also for reducing casualties and financial losses caused by earthquakes. This paper analyzes and examines various strategies for optimizing the seismic behavior of adjacent buildings and aims to achieve a better understanding of this complex phenomenon through appropriate models and simulations. The main objective of this research is to enhance the safety and stability of buildings against challenges arising from impact and seismic loads.

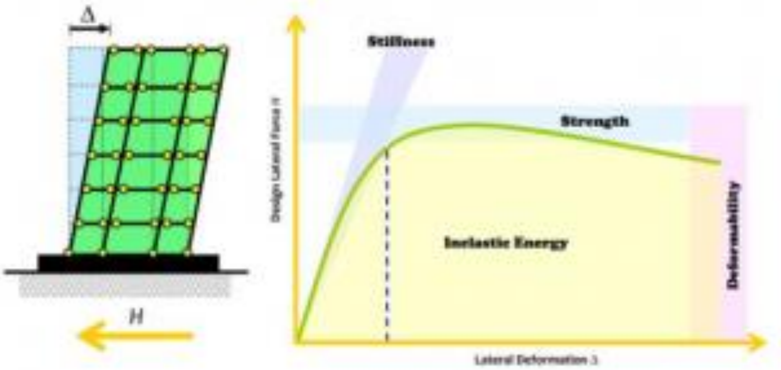
- **Seismic Behavior**

Due to their proximity, adjacent buildings can jointly withstand seismic forces. These loads may lead to severe oscillations in the structures, resulting in significant damage to buildings and their inhabitants. Therefore, the examination of the seismic behavior of these buildings is of particular importance. Research shows that proper design can significantly enhance the seismic performance of buildings (Varum et.al, 2018). For instance, the use of damping systems, specific materials, and innovative designs can reduce the negative impacts of seismic loads. One of the main challenges in designing adjacent buildings is managing their interactive effects. These effects can either amplify or reduce seismic loads, necessitating more precise design. The use of computer simulations and mathematical modeling can greatly aid in this regard. Additionally, there are opportunities for further research and development in new materials and innovative technologies that can improve the seismic behavior of buildings (Kitayama & Constantinou, 2018). The seismic behavior of a building depends on its overall shape, size, geometry, and ultimately how the forces generated by an earthquake are transmitted from the diaphragms to the foundation. In any case, by having an orderly configuration of the structure, a significant portion of the aforementioned problems can be resolved. However, factors such as the economy of increased usable space and the diversity of layouts for optimal space utilization, as well as proportions, all compel the structural engineer to provide various and desirable seismic designs.

- **Important Factors Related to Architectural and Structural Issues**

To construct an earthquake-resistant building, four important factors related to architectural and structural issues must be considered: 1) seismic configuration of the structure, 2) lateral stiffness, 3) lateral resistance, and 4) ductility. Existing seismic codes, by providing regulations and controls, effectively ensure the favorable conditions for the factors of stiffness, resistance, and ductility (Figure 1). However, to ensure optimal conditions regarding seismic configuration, a constructive interaction between architectural goals and the seismic behavior of the structure must be established, in addition to adhering to code requirements (Bertero, 2019). The result of this constructive interaction is to prevent the implementation of undesirable configurations, each of which will be discussed below.

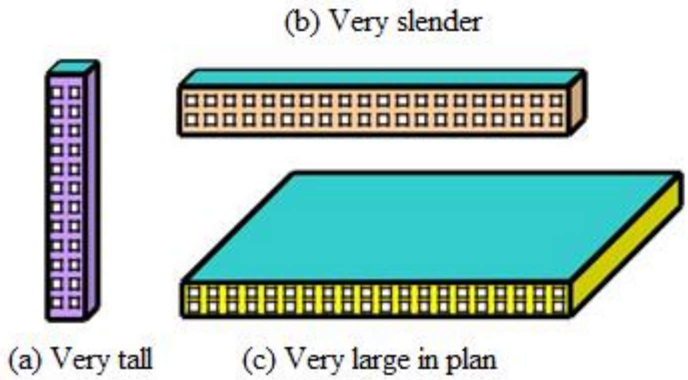
Figure 1: Ensuring seismic conditions for design criteria. a) Resistance, b) Stiffness, c) Ductility.



- **Building Dimensions**

In tall buildings with large aspect ratios (Figure 2-a), the horizontal displacement of floors during an earthquake is significant, while in short and slender buildings (Figure 2-b), due to low torsional resistance, the damage caused by the earthquake is quite high. Finally, in buildings with large plan areas, such as warehouses (Figure 2-c), the horizontal earthquake forces may exceed the load-bearing capacity of the walls and columns.

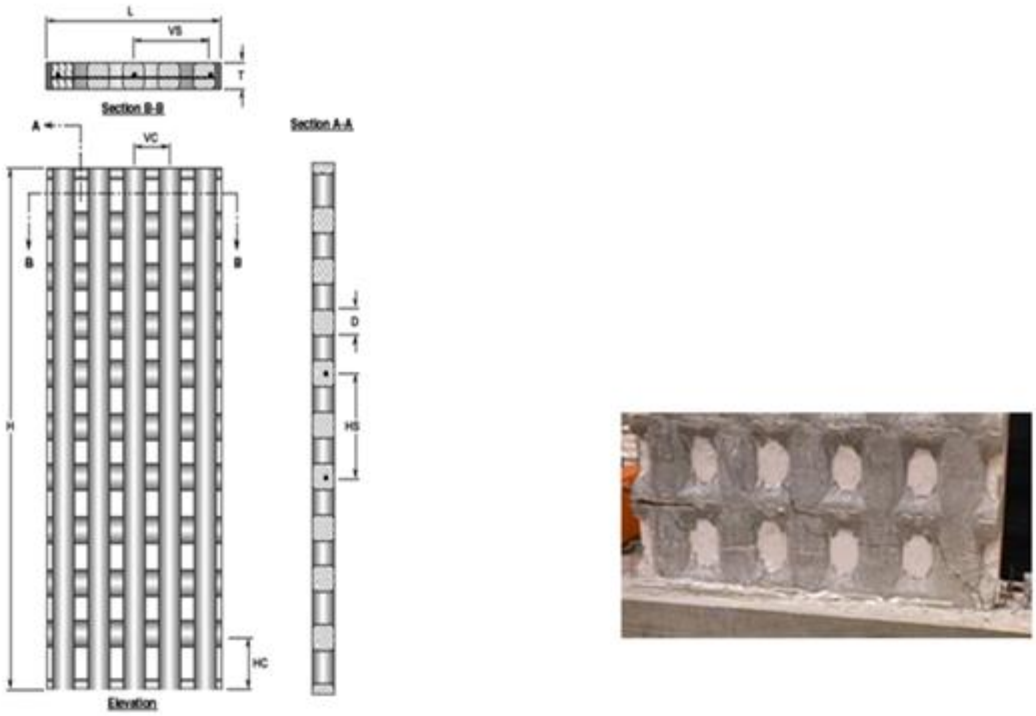
Figure 2: Buildings where one dimension is not proportional to the other two dimensions.



- **Structural Behavior of Materials**
- **ICF Structure**
- **Seismic Behavior of ICF**

The ICF system is one of the systems that currently plays a significant role in the construction of building walls and has received good acceptance. One of the most important aspects that should be considered regarding this system is its seismic behavior, which indicates its capacity to withstand lateral loads (Ghaderi et.al, 2020). The ICF system has a very good ability to counter lateral loads (earthquake and wind), primarily due to the minimal lateral load changes and the appropriate integration of the roof and walls. The main load-bearing elements in buildings using the ICF system have a relatively small thickness, but their high integrity results in suitable seismic behavior for ICF. In fact, in the ICF system, the connection between the roof and the wall is made using bent rebar and cast-in-place concrete, creating a rigid connection for transferring gravitational loads and a shear-accepted connection for transferring in-plane loads caused by the earthquake (Brodsky & Yankelevsky, 2017). Other reasons for the suitable seismic behavior of ICF include its lightweight compared to conventional concrete and steel systems. Although the tunnel system utilizes more concrete compared to the ICF system, the greater use of rebar and metal components in the ICF system results in a lower weight for the tunnel system, leading to better seismic behavior (Pertile et.al, 2021). The greater the number of structural elements participating in load-bearing, the better its seismic performance will be. Improper execution of the beam pocket is one of the main reasons for the inadequate seismic behavior of these systems. When this component is executed with mortar, it compromises the continuity of the wall's concrete and can locally weaken the wall at the base, where the maximum bending moment occurs. Furthermore, if the beam pocket is not executed simultaneously with the wall and lower ceiling, it creates a cold joint, ultimately leading to the weakening of the system and the wall.

Figure 3: Geometry of the structure and example of impact failure of the ICF structure



- **Side Impact Structures**
- **Viscous Dampers**

Viscous fluid dampers, or simply viscous dampers, are hydraulic devices used to dissipate kinetic energy resulting from seismic vibrations or to counteract impacts between structures. Viscous dampers are passive speed-dependent devices for energy dissipation that do not have internal stiffness (Zhao et.al, 2023). The control of the response displacement of these devices depends on the damping impact. Within the impact range, the viscous damper has no internal stiffness. The damping force F_d generated, as presented in Equation 1, is dependent on the relative velocity between the two ends of the damper as follows:

$$F_d = cd(\alpha)|\dot{x}|^{\alpha} sgn(\dot{x}) \quad (1)$$

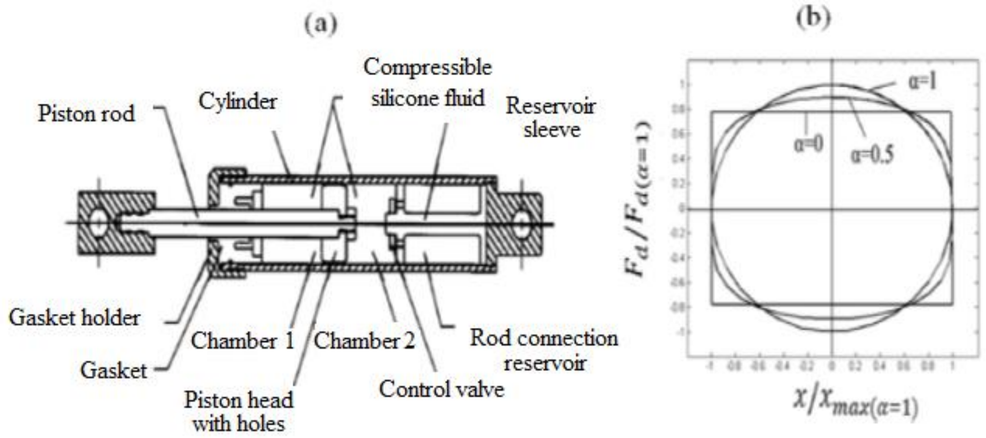
where cd(α) is the damping coefficient dependent on the velocity power α, $\dot{x}$ is the relative velocity at the two ends of the damper, and sgn is the sign function. The power of the velocity takes values between 0 and 1. These coefficient values determine the type of damper: a coefficient of 1 indicates a friction damper, while a coefficient less than 1 indicates a linear viscous damper. If the coefficient is greater than 1, then the viscous damper is non-linear. Figure b1 illustrates the force-displacement characteristics of the three types of dampers. It is important to note that the force of the non-linear viscous damper (NVD) for the same relative velocity (resulting from a velocity power of less than one) is less than that of the linear viscous damper (LVD). This characteristic protects the device from high forces generated at high speeds. Both linear and non-linear viscous dampers have been studied in this paper to assess the impact of parametric variations on reduction capacity. The motion equation of a single-degree-of-freedom system with viscous dampers due to ground motion can be expressed in Equation 2.

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)+cd(\alpha)\dot{x}(t)=-m\ddot{x}_g(t) \quad (2)$$

where m is mass, k is stiffness, c is the inherent damping coefficient, and $\ddot{x}_g$ is the ground acceleration. x(t) is the displacement response at time t, and the points above are derivatives with respect to time. The added damping ratio to the system by LVDs is represented by Equation 3 (Building Seismic Safety Council (US) & Applied Technology Council, 1997), (FEMA 356, F. E., 2000).

$$\xi_d=\frac{T_1\sum_j cd(\alpha)_j \cos^2(\theta_j)(\phi_j-\phi_{j-1})^2}{4\pi\sum_i m_i\phi_i^2} \quad (3)$$

Figure 4: a) Schematic representation (system and components) and b) Force-displacement relationship for friction, linear viscous, and non-linear dampers.



In this equation, T_1 is the fundamental natural period, θ_j is the angle of deviation of the damper, Φ is the first mode horizontal displacement, and m is the mass of one floor. The subscripts are used to indicate the floor number, where j is the floor to which the damper has been added. In this study, viscous dampers are placed between adjacent floors of two buildings. Therefore, Equation 3 is modified as follows:

$$\xi_d=\frac{(\max\{T_{1,1},T_{1,2}\})\sum_j cd(\alpha)_j(\phi_{j,1}-\phi_{j,2})^2}{4\pi\sum_i m_i\phi_i^2} \quad (4)$$

Where max[$T_{1,1}$, $T_{1,2}$] refers to the largest initial natural period of the two buildings, and the subscripts after the comma refer to the building numbers. It is assumed that the dampers are placed horizontally at the same floor level in both buildings, so θ in Equation 4 is equal to zero. $\Phi_{j,1}$-$\Phi_{j,2}$ denotes the relative horizontal displacements between the adjacent floors of the two buildings.

Assuming equal energy dissipation from LVD to NVD in one cycle of the force-displacement diagram, the capacity of NVD can be easily calculated. The relationship between the NVD constant and LVD is expressed by the following equation:

$$cd(\alpha)=\frac{cd(1)\left((\min\{\omega_{1,1},\omega_{1,2}\})\cdot x_0\right)^{1-\alpha}}{\beta} \quad (5)$$

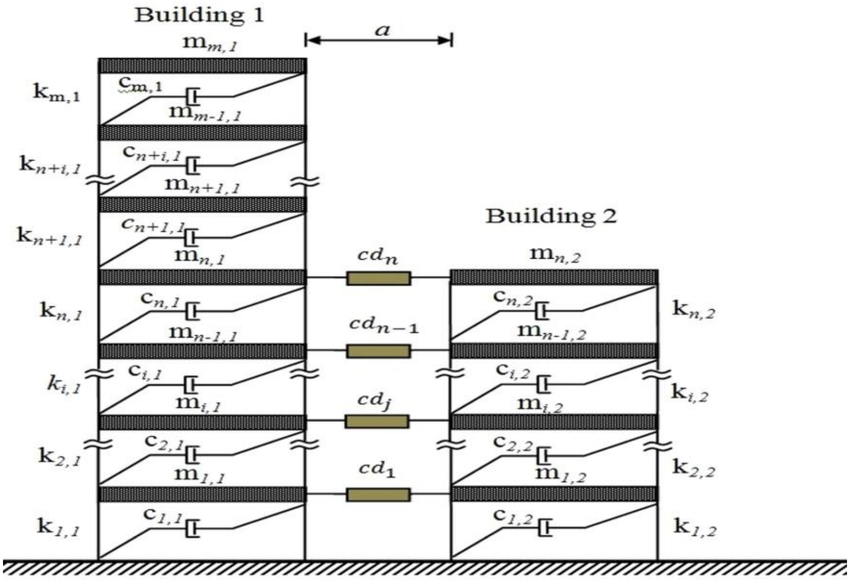
Where cd(1) is the damping constant of LVD, min[$\omega_{1,2}$, $\omega_{1,1}$] is the lowest first natural frequency of the two buildings, x_0 is the maximum displacement between adjacent floors, and the constant β is defined as follows:

$$\beta=\frac{2^{2+\alpha}\Gamma^2(1+\alpha/2)}{\pi\Gamma(2+\alpha)} \quad (6)$$

Where Γ is the gamma function.

- **Equations of motion for connected buildings with viscous dampers**

Figure 5: View of adjacent buildings



Buildings 1 and 2 have m and n floors, respectively. Figure 5 shows these buildings, which are connected at each neighboring floor by viscous dampers. The mass, stiffness, and damping constants of buildings 1 and 2 are denoted as $m_{i,1}$, $k_{i,1}$, $c_{i,1}$ and $m_{i,2}$, $k_{i,2}$, $c_{i,2}$, respectively. The damping constant of the viscous damper at floor j is represented by cd_j.

- **Optimization of the capacity and position of the viscous damper**

The optimization problem has upper and lower bounds to limit the capacity of the damper. The lower bound (lb) is considered to be zero, indicating the absence of a damper between two buildings. For the upper bound or maximum capacity defined (ub), any desired value can be considered. The equilibrium constants are obtained based on the complementary damping ratio relationships in equation 4, from which the constant members of the LVD are derived as follows:

$$A_{eq(j)}=\frac{(max\{T_{1,1}, T_{1,2}\})}{4\pi \sum_{i=1}^{m+n} m_i \phi_i^2}(\phi_{j,1}-\phi_{j,2})^2 \quad (12)$$

$$\{\boldsymbol{A_{eq}}\}=\{A_{eq,1},\ldots,A_{eq,j},\ldots A_{eq,n}\} \quad (13)$$

$$\{\boldsymbol{A_{eq}}\}[\boldsymbol{cd}]=\xi_d \quad (14)$$

$[A_{eq}]$ is a row vector containing n members, while [cd] is a column vector with the same number of members. Their coefficients represent the complementary damping ratio (ξ_d). In the optimization algorithm, at each step of gradually increasing ξ_d, the values of cd are calculated between the upper and lower bounds. The calculated damper capacity vector is placed in equation b10. The optimization method for the placement of dampers to connect adjacent floors from the top of Building 1 to Building 2, where the maximum impact force occurs, begins here. The capacity of the dampers is entirely dependent on the upper bound values. Initially, the algorithm presents a case where a damper with an upper bound capacity is placed on the top floor of the neighboring building. Then, if the first damper is insufficient to prevent structural impact, a second damper with the required capacity is placed on the lower floor.

- **Creating Sufficient Separation Between Adjacent Buildings to Prevent Collisions**

The most common and simplest solution to prevent collisions between buildings is to create a suitable distance between them. Numerous studies have been conducted to estimate the required seismic separation distance through dynamic response analysis of adjacent buildings. Proper spacing between neighboring buildings is one of the key principles in design and construction, especially in earthquake-prone areas. These distances not only help prevent physical collisions between buildings during an earthquake but also reduce the interactive effects of seismic loads (Kamal & Inel, 2022). During an earthquake, intense vibrations can cause relative movement of buildings. Creating sufficient separation helps reduce the risk of damage to structures and inhabitants. Additionally, proper spacing between buildings facilitates easy access to emergency services and rescue operations during crises. Sufficient distances between buildings also improve natural ventilation and sunlight entry, which can enhance the quality of life for residents (Waheeb & Hemeida, 2022).

- **Factors Influencing Separation Distance**

- **Type of Structure:** The type of materials and design of the buildings significantly affect the separation distance. Taller buildings require more space to mitigate risks associated with vibrations (Taranath, 2016).
- **Geographic Location:** In earthquake-prone areas, the separation distance should be greater than in regions with lower seismic risk.
- **Analytical Models:** Using analytical models and dynamic simulations can aid in determining the appropriate distance. These models can simulate the behavior of buildings under seismic loads.

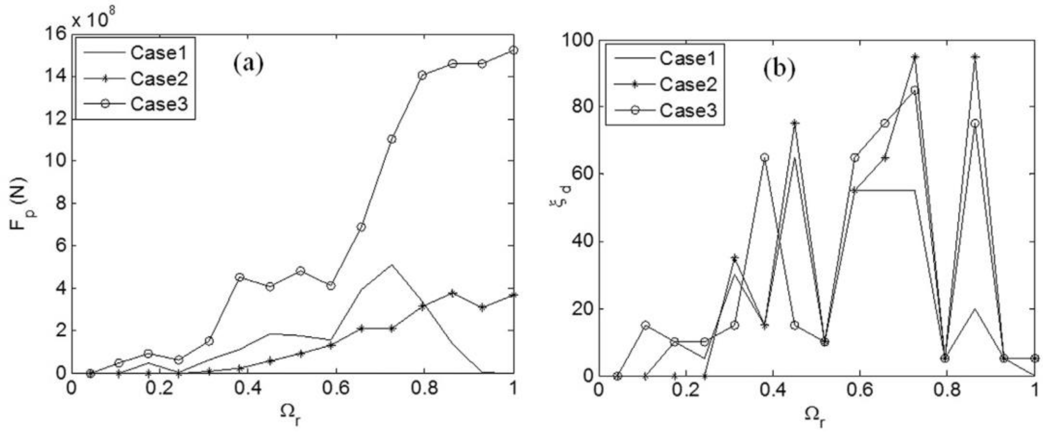
2- Results

Assumptions are required to present the results of parametric studies simply and highlight the efficiency of the optimization algorithm for viscous dampers. It is assumed that two buildings have a symmetrical layout and that ground motion is applied in one direction to the buildings; thus, a two-dimensional shape is sufficient for analyzing the resulting responses. The buildings are multi-degree-of-freedom (MDOF), linear, and shear-type systems. The floors have similar heights and orientations. Mass, stiffness, and inherent damping coefficients are evenly distributed among the floors. Impact forces occur only at the floor levels, and plastic deformations during impact are neglected. Because the impact topic is not the core of this research, the simplest nonlinear model was used to simulate the impact force.
Results are presented for three scenarios:

- **Case 1:** Involves two buildings with similar mass and stiffness at each floor, specifically $m_{i,1}= m_{i,2}= 1\times10^5$ kg and $k_{i,1}= k_{i,2}= 6.8\times10^7$ N/m.
- **Case 2:** The second building is stiffer, with $k_{i,2}= 10\times10^8$ N/m.
- **Case 3:** The second building is more flexible, with $k_{i,2}= 7.2\times10^6$ N/m.

All cases were analyzed for Building 2 with 1 to 15 floors, while the number of floors in Building 1 remained constant at 15 floors. The inherent damping ratio ξ was set to 5% for both buildings, and Rayleigh damping was used to form the damping matrix. A seismic gap of 0.16 m was considered, calculated based on the regulations (2-10-3-2) of the Turkish Earthquake Code (Code, T. E., 2007). The spring constant in the Hertz model for the impact force was considered to be 80 $kN/mm^{3/2}$. In this paper, in addition to nonlinear viscous dampers, nonlinear viscous dampers with a velocity power of 0.5 were also used to observe the reduction in capacity.

Figure 6. Relationship between the dimensionless frequency ratio parameter Ω_r and a) impact force b) complementary damping ratio ξ_d.



- **Natural Variations of Impact Force in Adjacent Buildings**

The different vibration characteristics of adjacent buildings during ground motion cause out-of-phase behavior, which is the main reason for the impact on buildings during an earthquake. In this section, three scenarios were examined to observe the effect of differences in the natural frequencies of the buildings on the impact force. These scenarios were compared in a dimensionless scale of this study instead of the dimensionless frequency ratio $\omega_{1,1}/\omega_{1,2}$, according to the varying properties of each building. The dimensionless frequency parameter Ω_r is defined as follows:

$$\Omega=\omega_1 s^2\sqrt{\frac{m}{k}} \quad (15)$$

where ω_1 is the natural frequency of the buildings, S is the number of floors, and m and k are the mass and stiffness constant of a floor, respectively. The effects of the ratio of the dimensionless natural frequencies

$\Omega_r = \Omega_2 - \Omega_1$ of the adjacent buildings on the impact force are illustrated in Figure a4. The impact force increases if one of the buildings is more flexible, and it becomes larger with an increasing dimensionless frequency ratio (except in Case 1). This phenomenon occurs because of the out-of-phase behavior immediately observed in Case 1, when the number of floors in the buildings is equal. As a result, in Case 3, Building 2 deforms more than in other cases, producing a greater impact force for each dimensionless frequency ratio. In Case 2, since Building 2 is stiffer, a lower impact force is observed. Figure b6 presents the dimensionless natural frequency ratio against the necessary complementary damping ratios required to eliminate the impact force. The required damping ratios are provided relative to the inherent damping ratio by the viscous dampers. From the shape of a6 and b6, it is clear that the required damping ratios are independent of the impact force values; however, interestingly similar behavior was observed in all three cases.

3- Conclusion

The present study investigates the optimization of the seismic behavior of adjacent buildings in the face of impact loads and has achieved significant results in this regard. The findings indicate that an appropriate distance between buildings, along with the selection and design of optimal structures, can have a considerable impact on reducing damage from seismic and impact loads. The analyses conducted showed that increasing the distance between buildings improves their dynamic response to impact loads and decreases the likelihood of serious damage. Additionally, selecting materials with energy-absorbing properties and suitable design can help reduce the transmission of seismic forces between adjacent buildings. Furthermore, the sensitivity analysis conducted on various design parameters revealed that small changes in structural dimensions and characteristics can have significant effects on the overall performance of the buildings. This underscores the importance of precision in design and material selection. Ultimately, this research recommends that engineers and structural designers adopt innovative and scientific approaches in the design of adjacent buildings, maximizing their safety and stability against natural disasters. In this paper, the existing design relationships for structures with supplemental viscous dampers for two interconnected buildings have been modified. The results indicate that the optimal selection of damper properties effectively reduces displacement response and prevents impact. The relationship between the upper bound of damper capacity, total damper capacity, and the number of dampers was obtained through a damper installation optimization algorithm. As the upper bound increases, the total capacity and the number of dampers decrease, and vice versa.

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