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Experimental Investigation of Preventing Collision in Adjacent Structures Using Interconnecting Elements

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Highlights

- This paper focuses on preventing collisions in adjacent structures by using rigid interconnection elements.
- Examining the dynamic behavior of adjacent structures with out of phase under resonant harmonic loading.
- Rigid interconnect elements reduced the storey acceleration and displacement of adjacent structures.
- Rigid interconnect elements were successful in preventing collision.

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Abstract

Today, the increasing density of urban construction has led to a rise in the number of adjacent buildings, primarily due to the scarcity of available land. This scenario necessitates measures to prevent collisions between adjacent structures and mitigate potential property damage and loss of life. This study investigates the dynamic behavior of adjacent buildings with distinct dynamic properties under harmonic ground motion, which closely approximates the effects of seismic activity. Harmonic ground motion with an amplitude of 5 mm and 5 cycles was applied to two adjacent building models with resonance frequencies of 2.15 Hz and 2.75 Hz, respectively. Shaking table experiments were conducted for two scenarios: free-standing models and models interconnected with a rigid element on the top floor. Storey acceleration and relative displacement data were collected for both configurations and analyzed. The experimental results indicated that the rigid interconnection element significantly reduced storey acceleration at all levels and decreased relative displacement between the models. Notably, the reductions were more pronounced in the resonant model due to the effects of the interconnection element. These findings demonstrate that the implementation of a rigid interconnection element is an effective strategy to mitigate the risk of collisions between adjacent buildings, thereby enhancing structural resilience and safety in densely built urban areas.

1. INTRODUCTION

In the last century, especially due to the high value of lands in city centers and the prevalence of commercial areas, contiguous buildings are frequently preferred. There are currently many contiguous buildings that have been constructed and are in use. Many such structures have been built without incorporating structural connections to prevent collisions. Due to varying characteristics such as height, stiffness, mass, and damping, adjacent buildings exhibit different dynamic and out of phase behaviors during strong seismic events or winds, often leading to collision or hammering effects. This phenomenon is not only complex but also represents a significant challenge in civil engineering. The collision of large mass adjacent buildings during earthquakes results in high impact effects that are difficult to predict. These impacts can cause extensive structural damage, ranging from partial failure to total collapse. Recent earthquakes in Turkey and globally have demonstrated the destructive potential of such collisions, which have resulted in severe material losses and fatalities. Buildings that would typically withstand seismic loads have failed due to hammering effects, emphasizing the need for earthquake resistant designs that prevent adjacent structural collisions. Numerical and experimental studies on this issue remain limited. Aydın and Güney [1] highlighted how the absence of sufficient joint gaps between neighboring structures can lead to significant damage from collision and hammering effects during earthquakes. They noted that differing dynamic

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characteristics between adjacent buildings often lead to relative displacements, increasing the likelihood of collisions. A simple and effective solution is to construct buildings with sufficient separation. This requires precise analysis and design to ensure adequate spacing based on the relative displacement of adjacent structures during seismic activity. Doğan and Günaydın [2] similarly observed that neighboring buildings with differing dynamic properties experience varying displacements during earthquakes. Given the impracticality of designing buildings with identical dynamic characteristics in modern construction, insufficient separation inevitably results in collision or hammering. Stavroulakis and Abdalla [3] proposed an energy-based method to calculate the required spacing, particularly for out of phase vibrations during severe seismic events. Chau et al. [4] studied collisions between two steel towers with differing natural frequencies and damping ratios through numerical modeling and shaking table experiments under harmonic and actual earthquake ground motions. These studies collectively underscore the critical importance of accounting for the dynamic interactions between adjacent structures in seismic design, emphasizing the need for adequate separation and advanced modeling to prevent faithful outcomes.

In the research conducted by Hameed et al. [5], the focus was on reducing the impact of collisions between adjacent buildings during earthquakes. They proposed various techniques to minimize these effects including shear walls, cross-bracing systems and friction dampers. Abdel Raheem studied the structural response of adjacent buildings with varying distances between them and suggested measures to alleviate earthquake-induced collisions [6]. Various passive systems can be utilized to enhance the performance of high-rise buildings under seismic effects, with viscoelastic dampers being one of them [7]. Similarly, Tubaldi implemented viscoelastic dampers at the top of the shorter building in a pair of adjacent structures. He examined the dynamic characteristics of two neighboring buildings of different heights [8]. Abdeddaim et al. [9] demonstrated that the installation of MR (magneto-rheological) dampers in two adjacent ten-storey buildings with different dynamic properties could prevent collisions by reducing both acceleration and displacement. Xu et al. investigated the use of MR dampers on a scaled model consisting of a three-storey and a twelve-storey building. Their results showed that MR dampers effectively reduced the seismic impact and the overall seismic response of both buildings. These findings highlight the potential of damping systems in preventing collisions and improving the resilience of adjacent buildings during seismic events [10].

Aydın [11] introduced a straightforward optimization method for determining the optimal placement of dampers in adjacent shear frame buildings. This approach considers the damping coefficients of the additional dampers as design variables. The study explored the effects of various factors, including the upper limit of damper capacities, floor mass and stiffness distributions, damper configurations, cost functions, and additional damping ratios, using six-storey shear frame building models. Numerical results indicated that this method is both practical and effective in identifying optimal damper distributions. In related research, Aydın et al. [12] proposed a method for determining the optimal positioning of viscous dampers between two adjacent structures to prevent collisions. Numerical examples using two four-storey shear frame building models were employed to validate the method. The study identified the appropriate number and placement of linear viscous dampers and assessed their impact on the structural response. Karabörk [13] examined the optimal values of viscous dampers placed between adjacent structures of varying heights to mitigate collisions under different earthquake scenarios. Recognizing that adjacent buildings often possess different dynamic characteristics, the analysis demonstrated that the proposed method enables designers to determine optimal damper values tailored to varying height ratios, thereby reducing collision risks during earthquakes. Karabörk and Aydın [14] developed a novel method for optimizing the placement of viscous dampers between adjacent structures with differing dynamic properties under seismic effects. Three damper configurations classical, staircase and X-diagonal were analyzed for collision prevention in two twelve-storey building models. The study evaluated the influence of damper placement on structural responses, critical period ratios, allowable relative displacements, modal behavior, and damper capacity limits. Results demonstrated the method’s efficacy in optimizing damper placement and eliminating collision risks.

Collisions between adjacent structures, particularly those with out of phase behavior, are a critical issue under wind and earthquake effects. To address this, various systems and interconnection elements have been implemented. This study employed a rigid interconnection bar placed on the top floor of two adjacent structures with differing dynamic parameters. The structural responses of these models to harmonic loads at resonance frequencies were investigated experimentally on the shaking table and compared to those of free models.

2. MATERIAL METHOD

2.1. Establishment of the Experimental Setup

In this section, the creation and realization of the experimental setup is mentioned. In the experiments, two three-storey shear frame models representing real structures were used. In order for the dynamic parameters of these models to be different, the floor masses of the models are designed to be different from each other. As illustrated in Figure 1, the blue model (M10) featured a floor mass of 10 kg per storey, while the red model (M5) had a floor mass of 5 kg per storey. These differences resulted in two models exhibiting out of phase behavior with unique dynamic characteristics.

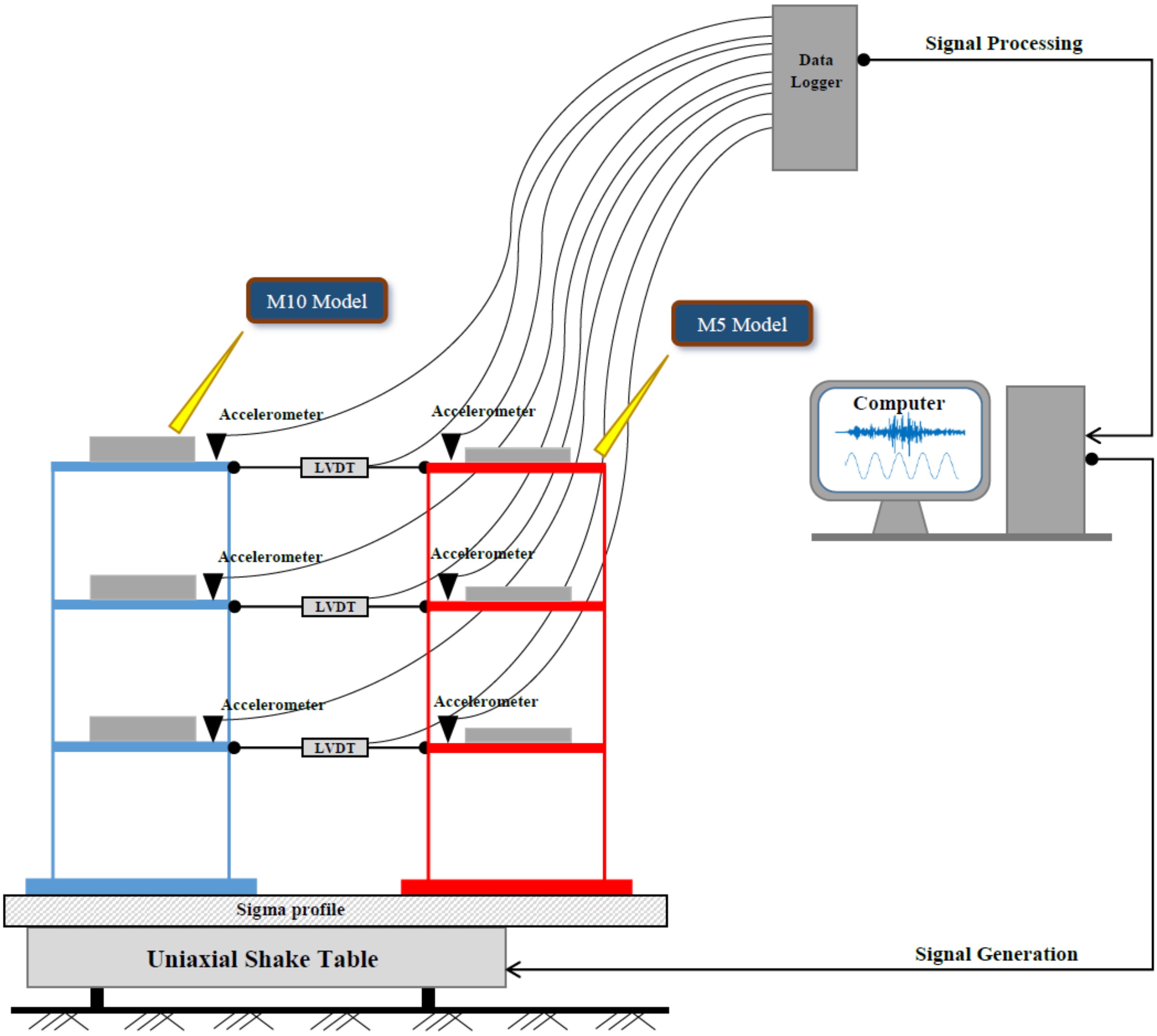


Figure 1. *Schematic representation of the experimental setup used in the laboratory environment*

The experimental setup used is detailed in Figure 1. This setup consists of a uniaxial shake table and program that applies ground motion to the model, a data logger and program, accelerometers and potentiometers with articulated ends for measurement and two small-scale three-storey steel frame models identical to the actual structure mounted on the shaking table, as shown in the figure. The models used in the experiments and with masses placed on their storeys are given in Figure 2. These models have been fixed onto a sigma profile and mounted on the shaking table to enable them to move together.

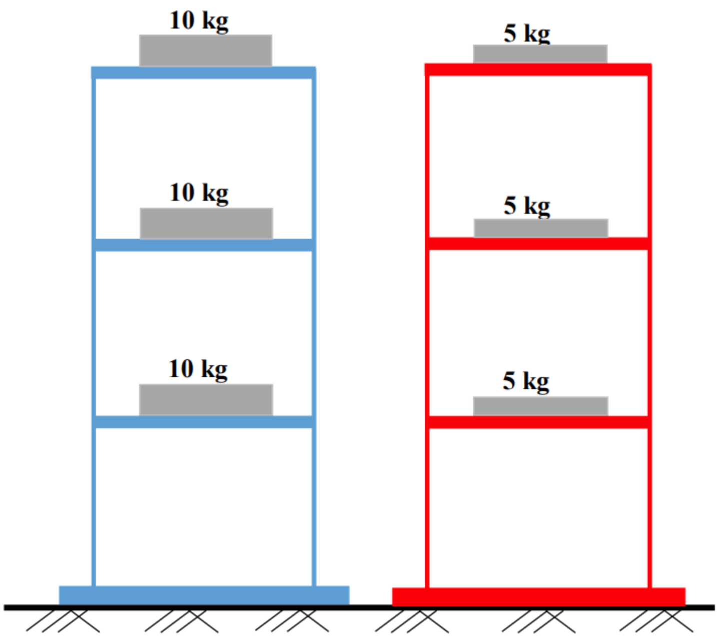


Figure 2. *Models used in experiments*

The shear frame models were designed with a storey height of 300 mm, resulting in a total height of 900 mm each model. They were constructed as uniform structures with an elasticity modulus of $E=2x10^5$ MPa and a Poisson's ratio of $\nu=0.3$. Each storey's rectangular floor measured 300 mm × 300 mm. Detailed information about the models' floor masses is provided in Table 1, while the measurement devices and their quantities are outlined in Table 2.

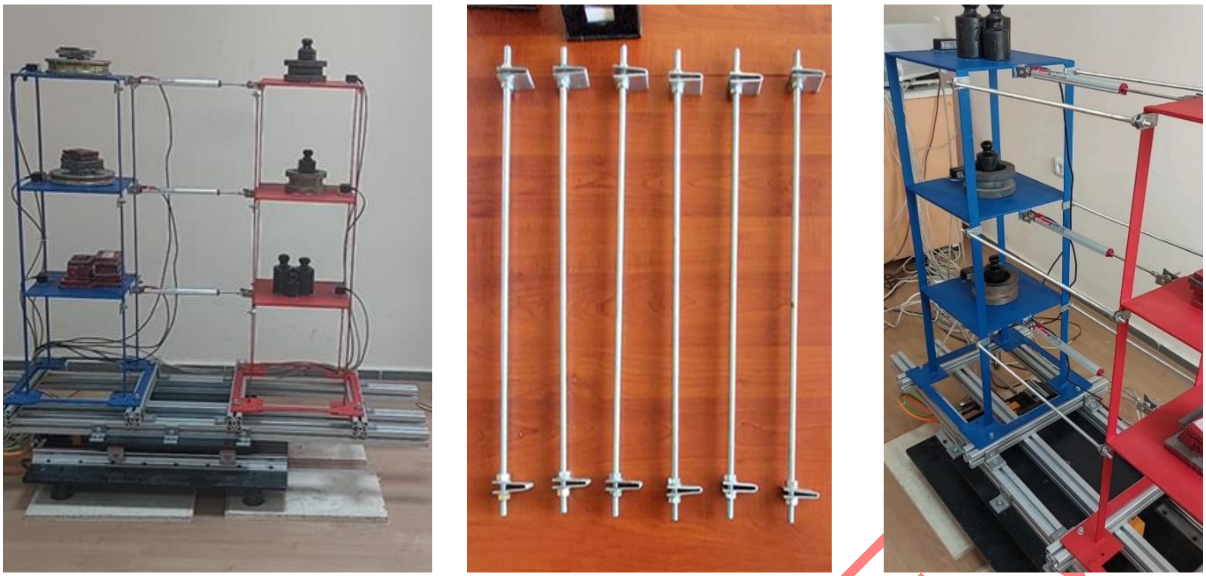
Table 1. *The storey masses of the models*

Model	Storey	Mass from the frame (kg)	Placed mass (kg)	Total mass of storey (kg)
M10	1	5.7	10	15.7
	2	5.7	10	15.7
	3	5.7	10	15.7
M5	1	5.7	5	10.7
	2	5.7	5	10.7
	3	5.7	5	10.7

Table 2. *Measuring devices and numbers used in the experiments*

Devices	Number of devices
Accelerometer	6 pieces
Displacement meter with joints at both ends	3 pieces

In the free-state configuration shown in Figure 3a, the two adjacent structures were separated to accommodate displacement meters, which recorded relative displacements between the floors. To prevent damage to the models and sensors, no physical collisions were allowed during free-state tests. The displacement meters installed on each floor provided data to determine whether a collision occurred. The rigid connection elements are presented in Figure 3b and Figure 3c illustrates the experimental setup with only the 3rd floor connected using a rigid element. The reason for using rigid connection elements only on the 3rd floor is that in adjacent structures, the risk of collision may be highest on the top floor of the structures. This configuration enabled the comparison of the structural responses between free and interconnected models.



(a) (b) (c)

Figure 3. *a) Free form of adjacent models, b) Rigid connection elements, c) Rigid connected of adjacent models*

2.2. Conducting Experiments

In this study, the characteristics of sinusoidal harmonic ground motions, simulating earthquake-like loading, were determined for the experimental models. Prior to the primary experiments, free vibration tests were conducted on the M10 and M5 models to identify their natural periods and frequencies during resonance. The resonance frequencies of the M10 and M5 models, obtained from these free vibration tests, are summarized in Table 3. These resonance frequencies were subsequently employed in the harmonic loading applied to the systems.

Table 3. *Natural period and frequency values obtained from free vibration experiments of free-state models*

Model	Natural period, (T_n), s	Natural frequency, (f_n), Hz
M10	0.465	2.15
M5	0.364	2.75

To simulate harmonic ground motion, parameters such as amplitude A, frequency F, and number of cycles C were established. For the M10 and M5 models in resonance, the frequency values were determined as 2.15 Hz and 2.75 Hz, respectively. To prevent excessive acceleration and displacement values that could damage the experimental setup and electronic devices, the harmonic load amplitude was set to A=5 mm, and the number of cycles to C=5. Figure 4 displays the sinusoidal harmonic loads applied to the system, including both free and rigidly connected configurations at the 3rd floor. The blue curve corresponds to the sinusoidal harmonic load at the resonance frequency of the M10 model, while the red curve represents the load at the resonance frequency of the M5 model.

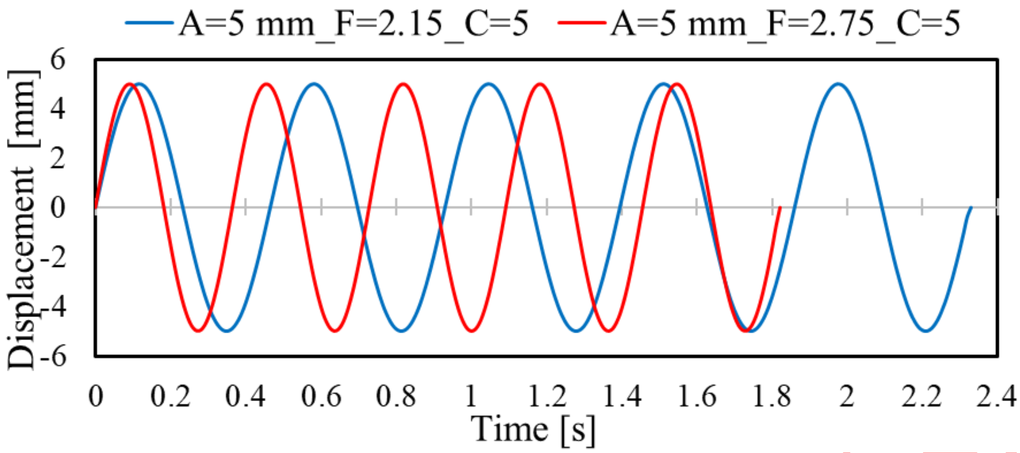


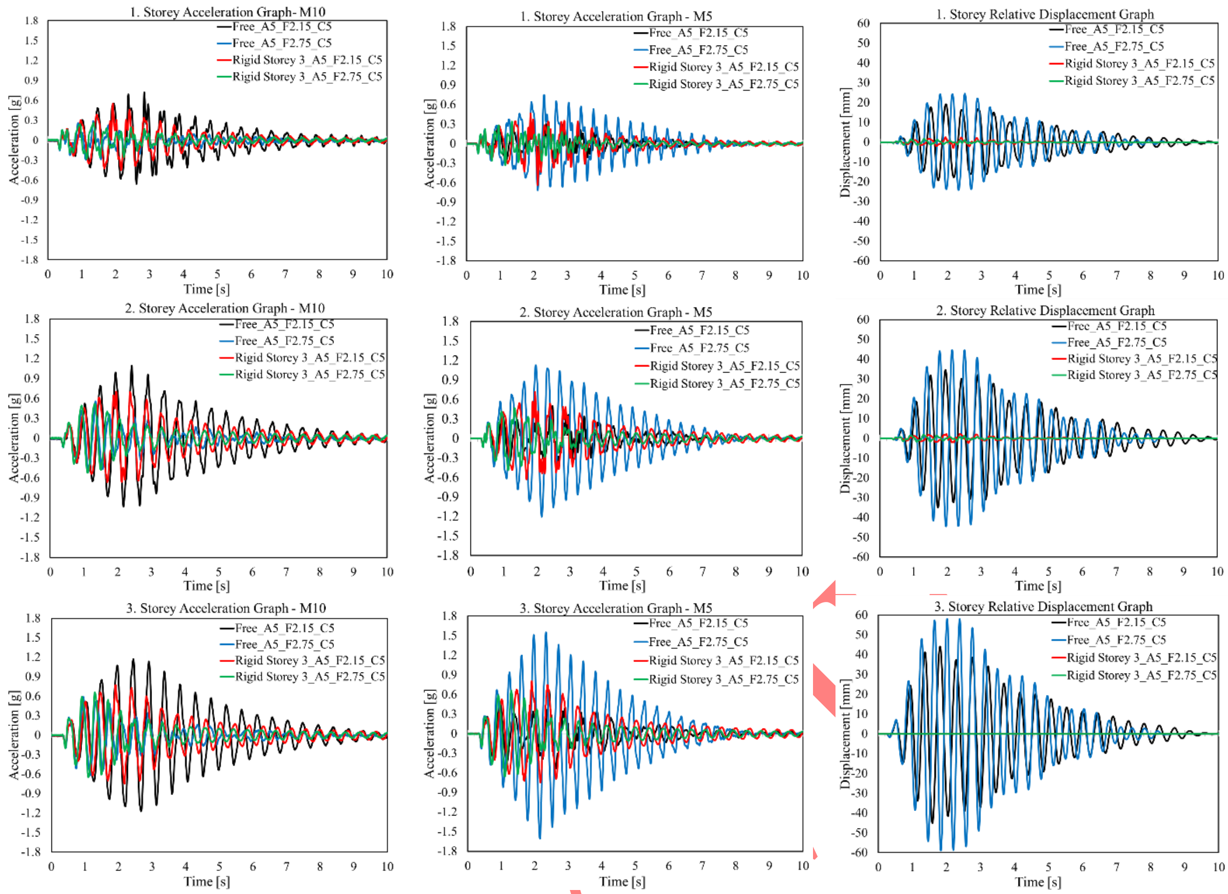
Figure 4. *Graphs of harmonics for models M10 (blue) and M5 (red) at their resonance frequencies*

Forced vibration experiments were conducted at the resonance states of both models configured as adjacent structures. Following the application of forced harmonic ground motion, the models continued their movement under free vibration. The experiment concluded when the system's motion ceased entirely. This approach allowed for a comprehensive analysis of the models' responses under harmonic loading with varying parameters.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental data on mitigating collisions in adjacent structures through rigid interconnection elements were analyzed. Specifically, time-dependent accelerations and relative displacements between the storeys of the adjacent models were evaluated.
The relative displacement is defined as the displacement of the corresponding floors of two models in the experimental setup with respect to each other. A positive value indicates that the adjacent buildings are moving away, whereas a negative value suggests a high likelihood of collision between the two structures. The results are presented time-dependent acceleration graphs for all three-storeys of the M10 model, M5 models and acceleration graphs for all three-storeys of the M5 model and relative displacement graphs between the storeys of the M10 in Figures 5a, 5b and 5c, respectively. These graphs provide insights into the dynamic behavior of the adjacent structures and the effectiveness of the rigid interconnection in reducing collision risk. The abbreviations for the experimental setup models shown in the graphs in Figure 5 are described below.

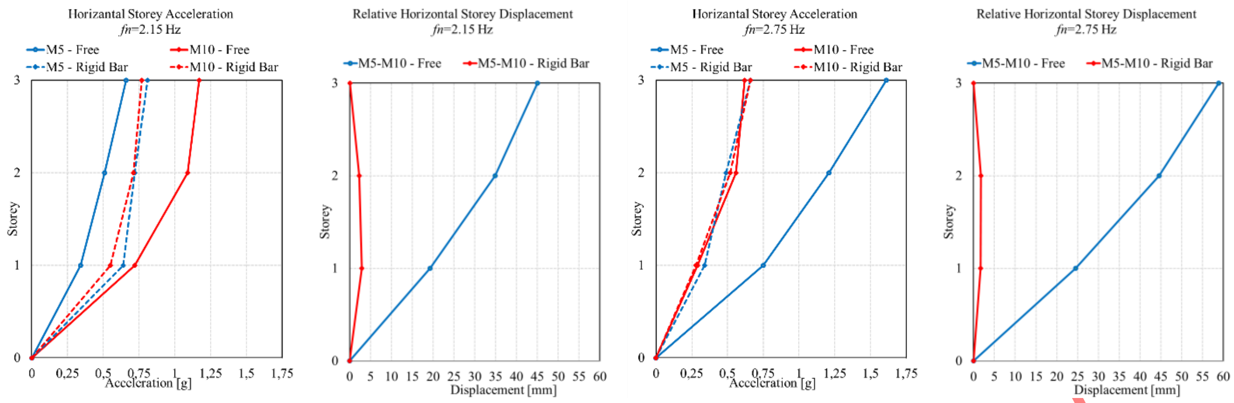
Free_A=5_F=2.15_C=5:	This model applies sinusoidal harmonic ground motion with a 5 mm amplitude, a 2.15 Hz frequency, and 5 cycles to a freely adjacent setup without any interconnecting elements.
Free_A=5_F=2.75_C=5:	This model applies sinusoidal harmonic ground motion with a 5 mm amplitude, a 2.15 Hz frequency, and 5 cycles to a freely adjacent setup without any interconnecting elements.
Rigid Storey 3_A=5_F=2.15_C=5:	This model applies sinusoidal harmonic ground motion with a 5 mm amplitude, a 2.15 Hz frequency, and 5 cycles to an adjacent setup where rigid interconnect elements are used only on the 3rd floor.
Rigid Storey 3_A=5_F=2.75_C=5:	This model applies sinusoidal harmonic ground motion with a 5 mm amplitude, a 2.75 Hz frequency, and 5 cycles to an adjacent setup where rigid interconnect elements are used only on the 3rd floor.



(a) (b) (c)

Figure 5. *In the experiments performed: a) Accelerations in each storey of the M10 model, b) Accelerations in each storey of the M5 model, c) Relative displacements between the storeys of the M10-M5 models*

As illustrated in the graphs in Figure 5, a total of four shaking table experiments were conducted using sinusoidal harmonic loads at frequencies of 2.15 Hz and 2.75 Hz. These experiments utilized two setups: one with free adjacency and the other with a rigid connection element on the 3rd floor. The frequency of 2.15 Hz corresponds to the resonance frequency of the M10 model, while 2.75 Hz is the resonance frequency of the M5 model. The results showed that the maximum acceleration values measured from the storeys of the M10 model occurred during harmonic loading at its resonance frequency at 2.15 Hz in the free configuration in Figure 5a. Similarly, the highest acceleration values for the M5 model were observed during loading at its resonance frequency at 2.75 Hz Figure 5b. Analysis of relative displacements between the floors revealed that the most severe collisions occurred at the loading frequency of 2.75 Hz Figure 5c. Furthermore, the rigid bar placed as a connection element at the top storey (3rd floor) had a displacement value of zero, effectively reducing displacement values on the 1st and 2nd storeys. This finding confirms that the rigid connection element on the top floor is highly effective in preventing collisions.



(a) (b) (c) (d)

Figure 6. *a-b) Peak storey acceleration and inter-storey peak relative floor displacements of the models shaken with 2.15 Hz (resonance for M10), c-d) 2.75 Hz (resonance for M5)*

The peak floor acceleration and relative displacement values of the models subjected to harmonic loads at 2.15 Hz and 2.75 Hz are shown in Figure 6. At both frequencies, the addition of a rigid bar between the top floors significantly decreased the displacement values of all floors Figures 6b and 6d, demonstrating that collisions between adjacent structures can be effectively prevented.

The rigid connection element also caused substantial reductions in storey acceleration values for both models at their respective resonance frequencies. In the case of 2.15 Hz harmonic loading Figure 6a, the M10 model exhibited high acceleration values in the free configuration due to its resonance frequency. However, with the addition of the rigid connection element, the acceleration in the M10 model decreased, while the storey acceleration values of the M5 model increased as the two models began to move together. This increase in acceleration for the M5 model is a disadvantage for its structural response.

For the 2.75 Hz resonance frequency of the M5 model Figure 6c, storey accelerations of the M5 model decreased significantly. Unlike the 2.15 Hz case, there was a more pronounced reduction in the storey accelerations of the M5 model, while the acceleration values for the M10 model remained largely unchanged. This difference can be attributed to the larger mass of the M10 model compared to the M5 model, which resists changes in acceleration more effectively. Detailed explanations of these findings are provided in Tables 4 and 5 below.

Table 4. *Storey acceleration values and percentage changes of models with different harmonic loads*

Frequency	Storey acceleration at 2.15 Hz			Storey acceleration at 2.75 Hz		
Models \ Storey	1	2	3	1	2	3
M5 - Free	0.34	0.51	0.66	0.75	1.21	1.61
M5 - Rigid bar	0.64	0.72	0.81	0.34	0.49	0.66
Percentage change	88%	41%	23%	-55%	-60%	-59%
M10 - Free	0.72	1.09	1.17	0.29	0.56	0.62
M10 - Rigid bar	0.55	0.71	0.77	0.28	0.52	0.66
Percentage change	-24%	-35%	-34%	-3%	-7%	6%

***Table 5.** Storey relative displacement values and percentage changes of models with different harmonic loads*

Frequency	Storey acceleration at 2.15 Hz			Storey acceleration at 2.75 Hz		
Storey / Models	1	2	3	1	2	3
M5 - Free	19.27	34.86	44.99	24.53	44.61	58.87
M5 - Rigid bar	2.91	2.32	0.04	1.72	1.78	0.02
Percentage change	-85%	-93%	-100%	-93%	-96%	-100%

4. CONCLUSIONS

This study examined the effects of employing rigid interconnection elements to prevent collisions between adjacent structures with differing dynamic properties under harmonic ground motion. The findings from the shaking table experiments are summarized as follows:

- When the models with distinct dynamic parameters acted out of phase and were subjected to the same ground motions in their free state, the floor acceleration values were higher for the model resonating at its natural frequency. Specifically, the M10 model experienced higher accelerations at 2.15 Hz, while the M5 model exhibited higher accelerations at 2.75 Hz.
- The rigid interconnection bar placed between the top floors of the adjacent structures effectively prevented collisions between models with differing dynamic properties when subjected to ground motion. The interconnection significantly reduced both the relative displacement values and the storey acceleration values, as shown in Tables 4 and 5.
- Under harmonic loading at 2.15 Hz, the addition of a rigid connection reduced the storey acceleration values of the M10 model. However, it increased the acceleration values of the M5 model, resulting in the storey acceleration values of both models converging. This indicates a load-sharing behavior, which is beneficial for the M10 model but disadvantageous for the M5 model.
- For harmonic loading at 2.75 Hz, the storey acceleration values of the M5 model significantly decreased with the rigid connection, while the M10 model's floor accelerations remained largely unchanged. This convergence in acceleration values was advantageous for the M5 model, though it had no noticeable effect on the M10 model.
- The most severe collision scenario occurred in the free-state models subjected to harmonic loading at 2.75 Hz. This was due to the peak relative storey displacements recorded during ground motion at this frequency.
- Rigid interconnection significantly reduced relative displacements between the models during resonance at both frequency values. The relative displacements were also observed to be comparable at the two frequency values when the rigid connection was in place.

The results demonstrate that rigid interconnection elements placed on the top floor of adjacent structures can reduce storey accelerations and relative displacements, effectively preventing collisions. Due to its practicality, low cost and effective results, this system can be adopted for real-world applications, making it a preferred choice. Further research on this topic will be conducted, focusing on both numerical simulations and experimental investigations.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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