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Experimental Study on Structure Model with Shear Wall and Base Isolator Under Dynamic Forces

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Abstract: The dynamic behaviour of structures is influenced by their fundamental frequency and the level of damping exhibited by each mode of vibration. The fundamental frequencies of a building significantly affect its response under dynamic load. Experimental studies can be conducted to predict the actual behavior of real structures, which have the advantage of explaining theoretical concepts and calibrating analytical models. In this study, an experimental investigation was conducted on a 3-story and 4-story aluminum building model with symmetric configurations. The model was subjected to harmonic and seismic excitation using a servo shake table to evaluate the different responses such as displacement of the Shear wall and base isolator. The software was also used to perform time history response analysis and compare the results with those obtained from the shake table. The experimental results showed that the structural responses could be minimized using the Shear wall and base isolator.

Key Words: Experimental Model, Servo Shake Table, Isolators, Displacement

1. INTRODUCTION

Earthquakes can cause significant damage to buildings and infrastructure, making the design of earthquake-resistant structures crucial to ensure safety. In earthquake engineering, experimental studies involve testing physical models of structures under simulated earthquakes of varying intensities, using sensors to measure displacement, velocity, and acceleration. These studies help researchers understand the behavior of structures during seismic activity, assess the effectiveness of design and mitigation strategies, and inform the development of safer and more resilient structures in earthquake-prone regions.

Experimental studies are essential for verifying theoretical models, developing design codes, evaluating building materials, and identifying vulnerabilities in existing structures for seismic-resistant construction. Three types of shake tables are commonly used for experimental studies: horizontal, vertical, and servo shake tables.Michelle et al. (2017) conducted an experimental study on a full-scale reinforced concrete building subjected to seismic base excitations and estimated its effective period and damping coefficient using three system identification methods and found that the effective period varied within a small range, while the effective stiffness of the fixed-base building was reduced significantly [2]. Supradip and Rama (2017) conducted an experiment on multiple-tuned liquid dampers (MTLD) and single-tuned liquid dampers (STLD) attached to a steel-structure model to reduce displacement and acceleration responses and found that MTLD is more effective than STLD in mitigating the response of the structure within a small amplitude range [6]. Trautner et al. (2019) conducted an experimental and numerical study of a miniature steel building to determine the effectiveness of ductile anchored and uplift column base connections under seismic conditions. They found that the ductile anchor uplifting system can significantly reduce total base shear and residual structural drift, as well as extend the natural period [5]. Aleksandra et al. (2019) conducted experimental and numerical investigations of a steel frame with a prestressed viscous damper (PVD) under real-recorded earthquakes, proving that PVDs effectively reduce structural responses. The study was carried out in three phases: experiments on modal and recorded responses, verification of the developed FE model, and optimization of damper placement [1]. Sun et al. (2003) conducted an experiment to evaluate the effectiveness of a magnetorheological (MR) damper in reducing acceleration and displacement during earthquake ground motion on a three-story frame model and found that the MR damper significantly reduced these parameters in

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comparison to a passive system under various ground motions [7]. Zheng et al. (2018) performed a shake table test and numerical simulation on a 1/45 scaled 8.6m high tall building with vibration control effects of the tuned mass damper with different mass ratios, finding that higher mass ratios can improve control effects in common earthquakes, but only slightly damages in rare earthquakes [8]. Zubair et al. (2021) conducted an experimental and numerical study to evaluate the performance of a new response-based control strategy with magnetorheological dampers and compared the response of COC and IDRA strategy, concluding that the IDRA control has better inter-story response alleviation than COC, while both had a similar performance for high-intensity ground motion recordings [3]. Zhang et al. (2018) conducted a Shake-table test on a half-scaled, 4-story reinforced concrete structure with an inertial force-limiting floor anchorage system (IFAS) and found that it reduced seismic demand and improved the performance of the lateral force-resisting system compared to a conventional system, by reducing shear wall base rotation, column inter-story drift, and floor acceleration [4].

While numerous experiments have been conducted to test various types of dampers, including MR dampers, tuned liquid dampers, and viscous dampers, and connections in buildings subjected to random earthquake excitations, relatively few studies have explored the performance of structural models with different framing systems, such as shear walls and soft stories, and base isolators. Moreover, there has been a lack of experimental investigations into structures subjected to near-fault and far-field earthquake excitations.

This paper presents an experimental investigation of 3-story and 4-story aluminium structural models with various framing systems and base isolators under harmonic and seismic excitation. The study aims to (i) examine the performance of buildings with shear walls, and base isolators, (ii) analyze the responses of the structures, including displacement and acceleration, and (iii) compare the experimental results with analytical (software) results.

2. DETAIL OF STRUCTURE MODEL

A. Details of a structural model:

The experimental study involved testing two aluminum structural models referred to as the three-story and four-story models. The models were constructed in two phases: first as a bare structure and then with shear walls and base isolators. The columns in the three-story model were 25 mm x 3 mm in size, with a height of 404 mm on each floor, while the columns in the four-story model were 25 mm x 6 mm in size and had a floor height of 400 mm. Both models had a slab size of 300 x 150 mm, with the three-story model having a thickness of 12 mm and the four-story model having a thickness of 13 mm.

To determine the damping ratio of the model, a free vibration test was conducted on a single-story model, and the data were analyzed using the logarithmic equation.

$$\zeta = \frac{1}{2\pi j} ln\left(\frac{a_i}{a_{i+1}}\right)$$

The calculated damping ratio of the model was found to be 1.78%. Two tests were conducted to determine the elastic modulus(E): a tension test and a flexural test. The model's calculated modulus of elasticity (E) is obtained 5.238×10^9 N/mm^2.

B. Detail of Structural model with base isolator:

Figure 2 (a) displays a structural model with a base isolator. The properties and dimensions of the model were identical to those of the three-story bare structural model. The only difference in this model was the addition of a sliding base isolator at the base of the model, as shown. The prototype of an experimental base isolator is also depicted in Figure 1.

Figure 1 Base isolator

C. Detail of Structural model with a shear wall:

The structural model shown in Figure 2 (b) was constructed with the addition of shear walls, which were placed in both the X and Y directions on every floor. All the elements in the model had the same dimensions and properties as the 4-story bare model, except for the shear walls, which had different dimensions in the two directions. The shear wall size was 300 mm x 160 mm in the X-direction and 150 mm x 160 mm in the Y-direction, with a thickness of 2.2 mm in both directions.

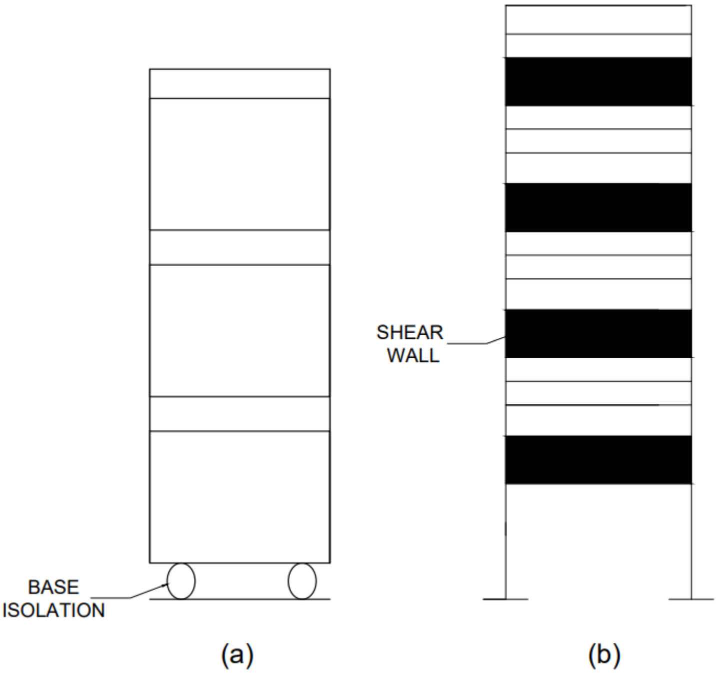


Figure 2(a) 3-Story Bare Structure with the provision of base isolator
Figure 2(b) 4-Story structure with Shear wall

3. DIFFERENT DEVICES AND APPATURAS

A. Servo Shake Table:

The shake table used in the study consisted of a vibration table, connecting rod, linear guideways, and a computer-controlled Servo Actuator. The table could move in a linear motion using linear guideways and could generate adjustable amplitude harmonic motions with varying frequency content. Figure 3 depicts the top view of the Servo Shake Table used in the study, which could produce different seismic excitations, including near fault and far field, as well as various amplitudes and frequencies of harmonic excitation.

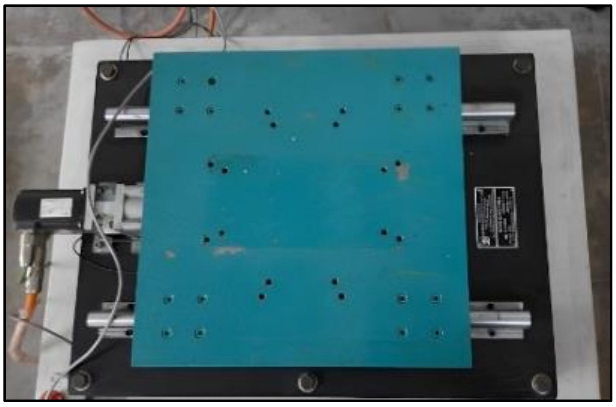


Figure 3 Servo Shake Table

B. Accelerometer:

In earthquake engineering experiments, accelerometers are essential tools for measuring the acceleration, velocity, and displacement of a structure during seismic activity. These measurements provide valuable data for analyzing the structure's behavior, including its natural frequencies, damping ratios, and modes of vibration. This information is crucial in the earthquake-resistant design and the development of building codes and standards. Additionally, accelerometers are useful in evaluating the performance of seismic protection devices such as base isolators and dampers. The accelerometer utilized in the study is shown in Figure 3.2. To measure displacement, accelerometers were installed on all floors of the model in this experimental configuration.

Figure 4 Accelerometer

C. Computer System:

Figure 5 illustrates a computer system that was utilized in the study to control the servo shake tables precisely, record data, and automate the testing processes. The use of these computer systems allowed researchers to simulate various earthquake scenarios and analyze the structures' responses under different conditions accurately.

Figure 5 Computer System

D. Data acquisition system (DAQ):

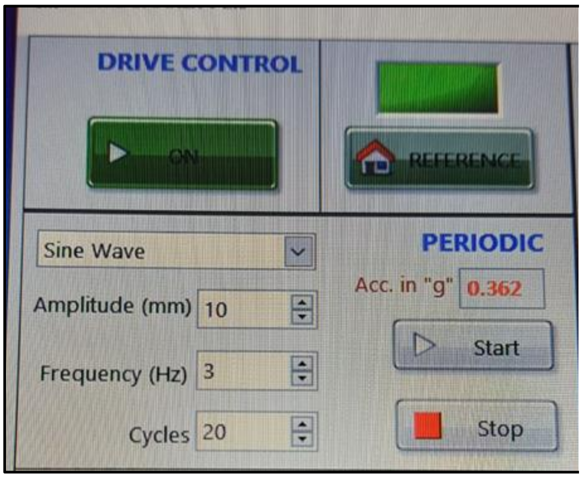
The image presented in Figure 6 depicts the data acquisition system utilized in the study, which is responsible for gathering and storing data from multiple sensors. This system is vital in servo to shake table experiments, as it allows for the assessment of the system's performance, the analysis of the test sample's response, and the validation of the shake table system's effectiveness.

Figure 6 Data acquisition system (DAQ)

4. EXPERIMENTAL STUDY

The study employed two types of excitations: (i) harmonic and (ii) seismic excitation. To generate harmonic excitation, sine waves were utilized with varying amplitudes and frequencies on the shake table system to simulate diverse earthquake scenarios. The amplitude and frequency of the harmonic excitation significantly affect the test model's response and the shake table system's performance. Hence, the researchers applied different combinations of amplitude and frequency to comprehensively evaluate the system's performance and the test specimen's response. The use of harmonic excitation allowed for the study of the structural behavior under well-defined and controlled conditions.

The study utilized sine waves with different amplitudes and frequencies to apply harmonic excitation. The sine wave input was represented by 10sin3t for a frequency of 3 Hz and an amplitude of 10 mm. The input data was incorporated into the servo shake table software, as depicted in Figure 7. Meanwhile, Figure 8 displays the corresponding input graph for the sine wave with the same frequency and amplitude.



Sine Wave
Amplitude (mm) 10
Frequency (Hz) 3
Cycles 20
Acc. in "g" 0.362

Figure 7 Data input in servo shake table software

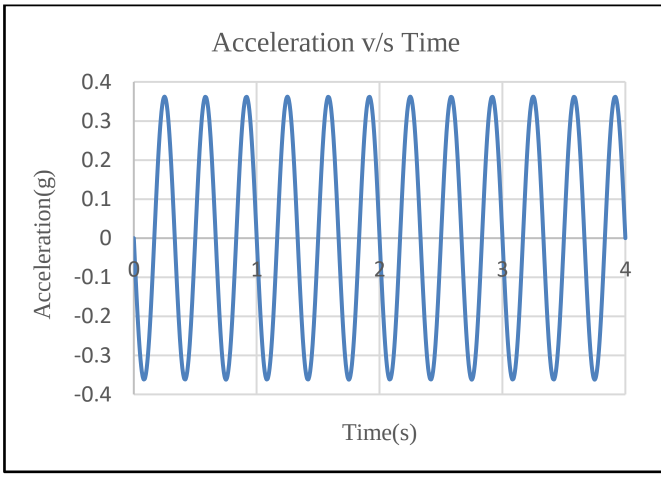


Figure 8 Input graph of 10sin3t

The study employed two types of seismic excitation, namely near-fault and far-field earthquakes, which are crucial in earthquake engineering research. To simulate a range of earthquake scenarios, four different past recorded earthquake time histories were used for each type of excitation. Tables 1 and 2 provide details of the earthquakes used in the study, including their magnitude, station, and other relevant parameters. The use of diverse seismic excitation scenarios enables researchers to evaluate the structural response of buildings and other structures under various earthquake conditions and develop strategies to mitigate earthquake damage.

Table 1 Near-fault earthquake data

Sr. No	Name	Magnitude	PGA (g)
1.	Imperial Valley (Array-7)	6.53	0.460
2.	Imperial Valley (Meloland)	6.53	0.127

A near-fault earthquake refers to an earthquake that occurs at or near a boundary where two tectonic plates are rubbing against each other. These earthquakes are typically associated with strong ground motions, which can cause severe damage to structures, especially those with short natural periods or located close to the fault rupture. Moreover, the powerful ground motions from near-fault earthquakes can lead to soil liquefaction, landslides, and other types of ground failures.

Table 2 Far-field earthquake data

Sr. No	Name	Magnitude	PGA (g)
1.	Imperial Valley (Coachella Canal)	6.5	0.115
2.	Landers (Baker Fire Station)	7.3	0.105

A far-field earthquake is an earthquake that occurs at a distance from the location where it is being measured. Typically, it is an earthquake that occurs at a distance greater than a few fault lengths away from the measurement location. Seismic waves from a far-field earthquake propagate through the Earth's crust and can cause ground motion at the measurement location, but the intensity of the waves and their impact is usually weaker than those from a nearby earthquake.

The study involved applying harmonic and seismic excitations to the structural model described in Section 2 and recording the responses, including the displacement of each floor. These responses were then compared with the results obtained from software analysis of similar models created in Staad Pro. The purpose of the comparison was to evaluate the accuracy of the software analysis. Furthermore, the different models were compared experimentally to each other. The results and comparisons of all cases are presented in the following section.

5. TEST PROCEDURE

The procedure you described outlines the process for conducting a shake table test on a frame specimen. Shake table tests are commonly used to simulate earthquakes or other dynamic loads and evaluate the response of structures to these loads. To begin, the framed specimen is prepared according to the required dimensions and properties. The frame specimen is then secured to the platform of a servo shake table. A servo shake table is a device that can generate controlled vibrations and motions, allowing researchers to simulate various types of dynamic loads. The shake table is connected to a computer system, which is used to control and monitor the test. Before the test can begin, the servo shake table and accelerometer need to be calibrated. This involves using specialized software to ensure that the equipment is functioning properly and accurately measuring the vibrations and motions of the framed specimen. Once calibration is complete, the necessary input parameters, such as frequency, amplitude, and cycle, are added into the servo shaker software. These parameters are determined based on the desired test conditions and the characteristics of the structure being tested. The test is then started, and the servo shake table begins to generate controlled vibrations and motions in the frame specimen. Throughout the test, the response of the structural model is recorded using Kampan software, which is designed for data acquisition and analysis. After the test is complete, the collected data can be used to plot graphs of the different responses of the structure to the dynamic load. This information can be used to evaluate the performance of the structure and inform design improvements to ensure it can withstand similar loads in the future.

6. RESULTS AND DISCUSSION

A. Results of structural model with Base isolator:

According to Figures 9, experimental results were obtained for a model subjected to a 5sin2t harmonic excitation at the top floor, which resulted in displacements of 33.96 mm. To validate these findings, the same model was replicated in software using STAAD Pro. The same 5sin2t harmonic excitation was applied to the model in the software simulation, resulting in displacements of 40.5 mm at the top floor, as shown in Figure 10.

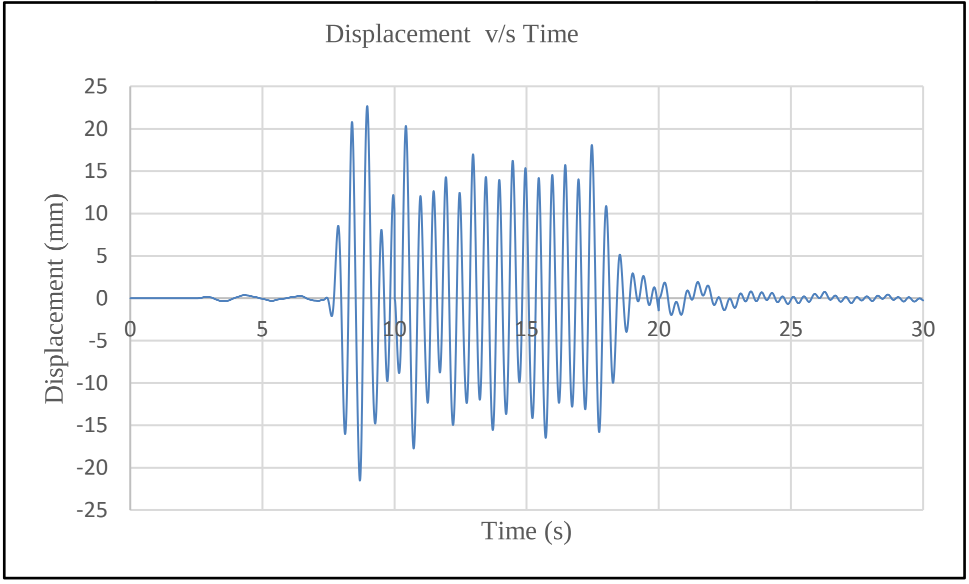


Figure 9 Experimental results of top floor

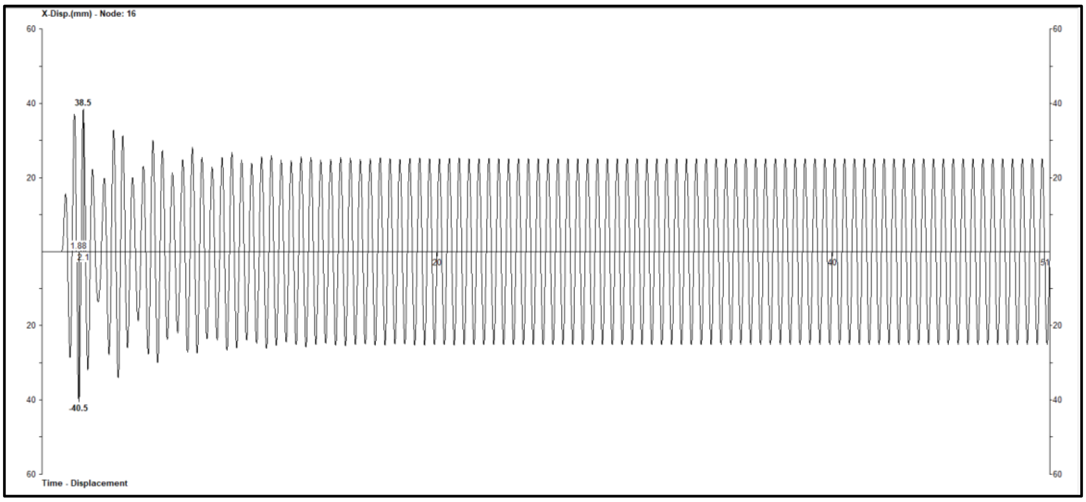


Figure 10 Software results of top floor

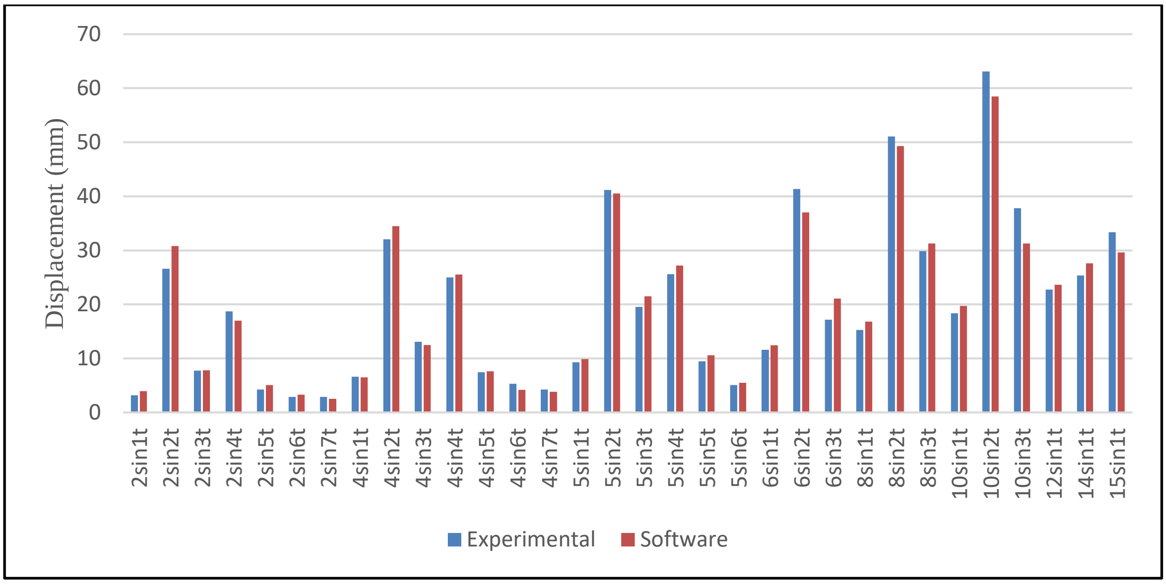


Figure 11 Comparison of experimental and software results

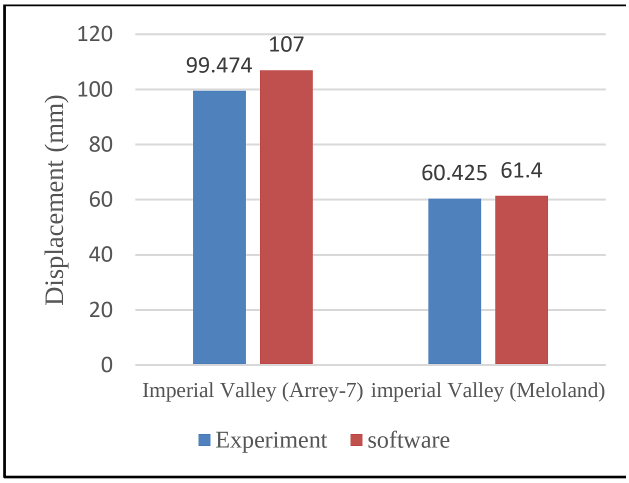


Figure 12 Comparison result of top floor displacement of near-fault earthquake

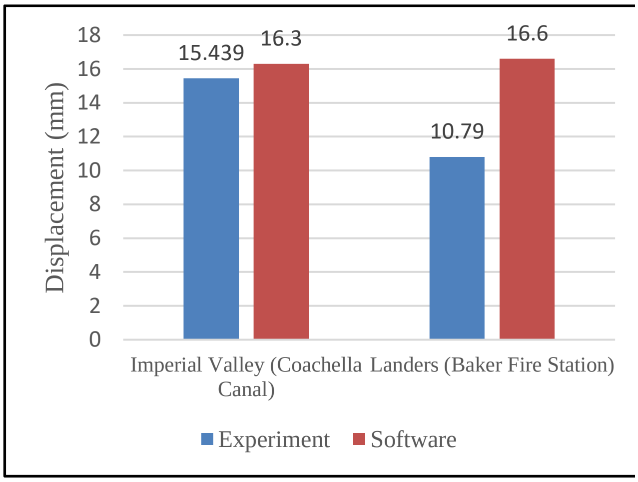


Figure 13 Comparison result of top floor displacement of far-field earthquake

Figure 11 illustrates the displacement of the top story of the base-isolated model under different harmonic excitations applied to the structural model. The figure demonstrates that the experimental and analytical (software) results are highly consistent with each other. Figures 12 and 13 are represented comparison results of top story displacement when different near-fault and far-field earthquake time histories respectively applied to the structural model. The figure clearly shows that near-fault results are more comparatively far field.

B. Results of a structural model with a shear wall:

Figures 14 show the experimental results of a model subjected to a 10sin4t harmonic excitation at the top floor. The experiment resulted in displacements of 16.65 mm. To validate these results, the same model was replicated in software using STAAD Pro, and the same harmonic excitation was applied. The resulting displacements for the top floor in the software simulation were 18.6 mm. This suggests a relatively close agreement between the experimental and analytical results.

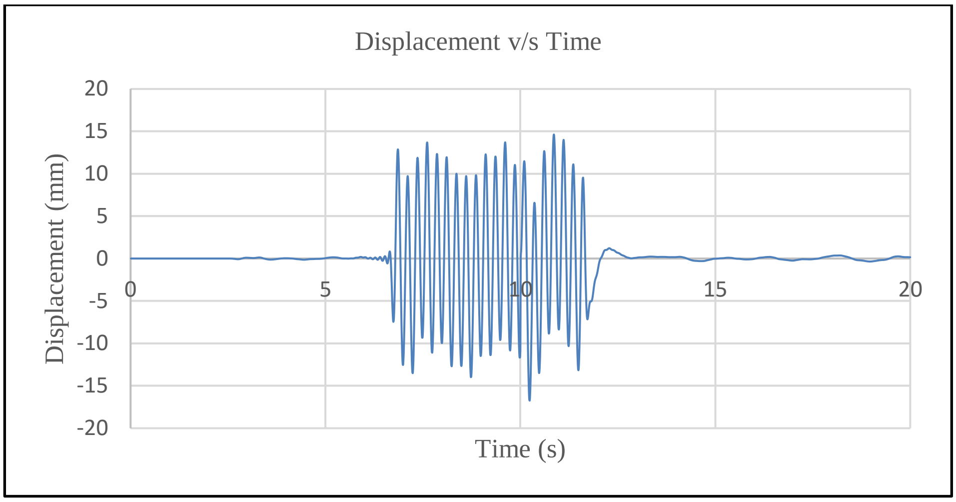


Figure 14 Experimental result of top story

The results of the top story displacement for the 4-story structural model with a shear wall under different harmonic excitations are presented in Figure 15. The figure clearly demonstrates that the software results closely match the experimental results. Also, the same figures 16 and 17 are shown top story displacement of a 4-story structural model with shear wall under different near fault and far-field earthquake time histories respectively. Due to the high ground excitation of near-fault earthquake displacement value will be as compared to a far-field earthquake, which is clearly shown in figure.

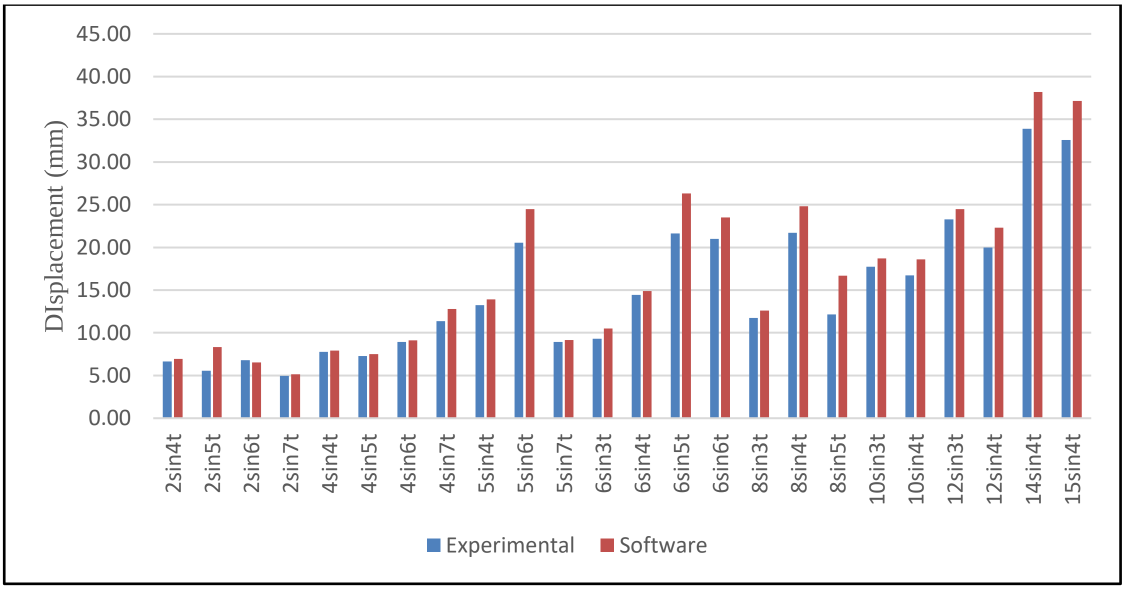


Figure 15 Comparison of experimental and software results

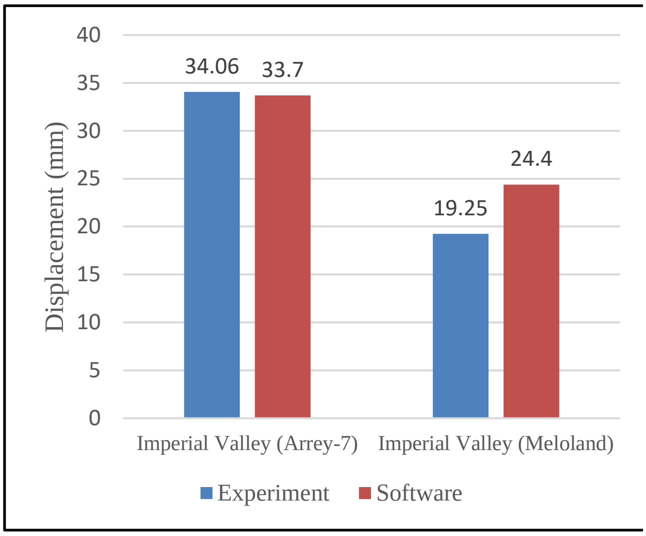


Figure 16 Comparison result of top floor displacement of near-fault earthquake

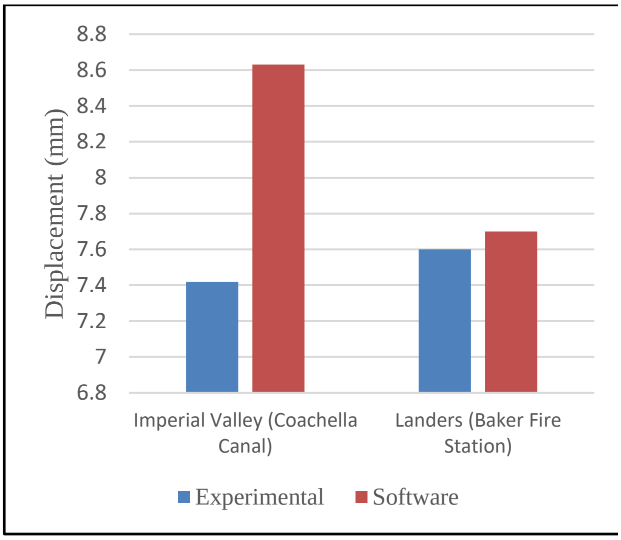


Figure 17 Comparison result of top floor displacement of far- field earthquake

7. COMPARISON OF DIFFERENT FRAME STRUCTURES WITH BARE STRUCTURE

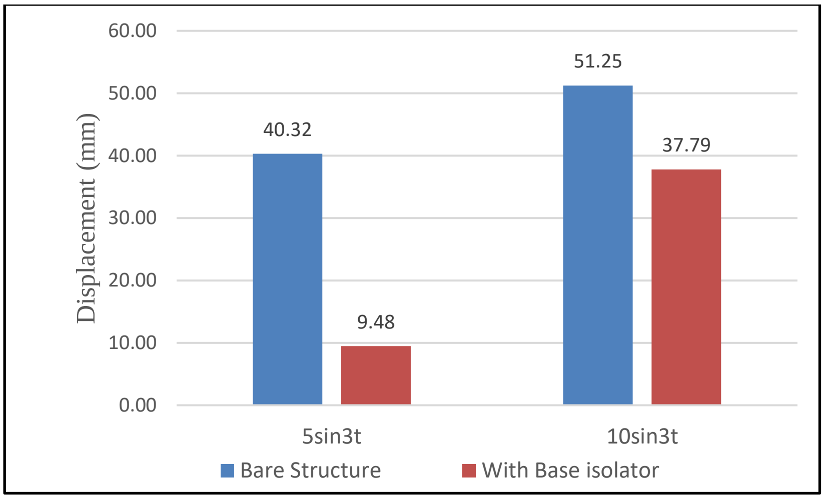


Figure 18 Comparison results of Bare structure and structure with base isolator

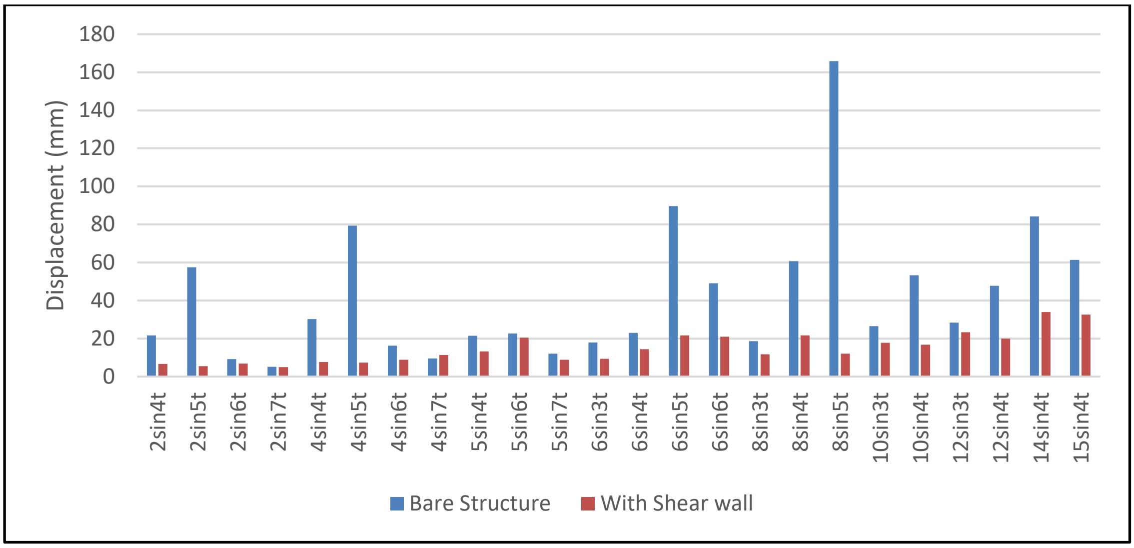


Figure 19 Comparison results of Bare structure and structure with shear wall

Figure 18 presents a comparison between a 3-story bare structure and a 3-story structure with a base isolator. The study examined the displacement of the top story of both models under two different types of harmonic excitation: 5sin3t and 10sin3t. The results demonstrated that the displacement of the structure with the base isolator was significantly lower compared to the bare structure. This finding suggests that incorporating a base isolator in earthquake-resisting building design is a more favorable approach, as it can effectively reduce the amount of displacement and potential damage caused by seismic activity.

The study involved a comparison between a 4-story bare structure model and a 4-story structure model with a shear wall. Figure 19 displays a comparison of the top story displacement results obtained from both models under different harmonic excitations. The results demonstrate that the inclusion of a shear wall in the structure significantly reduces the displacement. Therefore, the use of a shear wall is an effective approach to reducing the displacement and potential damage caused by seismic activity.

8. CONCLUSION

This study involved conducting experiments on various structural models under seismic and harmonic excitations. Additionally, the same models were prepared on software, and the results were compared with the experimental data. The comparison showed a close match between the software and experimental results. Moreover, the study compared the effectiveness of different lateral load-resisting systems and found that incorporating various framing systems significantly reduced the displacement of the structure.

From the study and work carried out herein, the following major conclusion can be drawn.

1) The inclusion of shear walls on each floor resulted in a 47.9% reduction in the maximum displacement observed at the top floor.
2) Incorporating a base isolator into a building design resulted in a noteworthy decrease of 27% in the maximum displacement observed at the top floor.
3) The displacement values were consistently higher for near-fault earthquakes than for far-field earthquakes in all cases.
4) The experimental and analytical results are closely aligned in all cases.

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