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A STUDY ON THE COLLAPSE MODELLING CAUSED BY STRONG EARTHQUAKES IN HIGH-RISE REINFORCED CONCRETE STRUCTURES

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Abstract

The increased frequency of powerful earthquakes attacks in recent years has made research on high-rise structure collapse resistance a priority. Beyond standard laboratory simulations and post-earthquake investigations, research advancement has shown that numerical simulation is emerging as one of the most potent methods for collapse analysis. This study proposes a numerical model based on the finite element (FE) approach to predict the collapse mechanism of high-rise buildings impacted by extreme earthquakes. The model includes a fiber-beam element model, a multi-layer shell model, and an elemental deactivation strategy. A detailed discussion is held regarding the effects of various failure criteria that are employed. The research results show that by detecting potentially weak structural elements that could lead to collapse, the suggested numerical model is possible to simulate the collapse process of high-rise buildings that are currently in place. The study's findings will help the optimal design philosophy continue to grow.

Keywords: high-rise buildings, collapse simulation, beam joint element model, elemental deactivation, earthquake

1. Introduction

Base isolation is an earthquake protection method in which the vertical loads of a structure are fully supported while the transfer of horizontal seismic forces is greatly diminished. This approach works by separating the building from the horizontal ground motion components generated during an earthquake. Various technologies have been developed to create isolators, but the laminated rubber bearing remains the simplest and most widely adopted. These bearings consist of alternating layers of rubber and steel plates bonded together, providing the horizontal flexibility needed at the foundation level along with the vertical stiffness required to support structural loads. For buildings utilizing this system, additional base floors beneath the main structure are necessary to allow sufficient clearance between the foundation and base for isolator installation. This is the standard method by which base isolation is incorporated into construction.

Research has shown that the lead plug base isolation system effectively reduces the seismic response of lightweight internal equipment [1]. Another study revealed that when complex modes are applied instead of traditional modal analysis, time-history analysis results in higher response values, while modal analysis of a base-isolated P–S system demonstrated reductions in both superstructure and high-frequency attachment responses [2–3]. Investigations into secondary systems connected to isolated structures reported unpredictable responses when base locations varied. Analysis of the interaction between equipment, structure, and isolation effects on seismic performance indicated that linear LRB systems consistently yielded the lowest peak responses among various isolation methods [4–6]. Further research examined the influence of installing isolation at the connection point of secondary systems, specifically evaluating underwater secondary units fixed to an initially isolated primary structure without modifications to the SS [7–8].

In this method, the superstructure and substructure are decoupled by a base isolator, thereby minimizing lateral seismic forces transmitted to the building [9]. The approach combines flexibility with energy dissipation capabilities; the lateral flexibility lowers the building's fundamental frequency, which in turn reduces seismic loading [10–11]. Literature reviews indicate limited studies on the behavior of plumbing systems installed on three-dimensionally base-isolated buildings subjected to bidirectional earthquakes [12]. In such cases, the pipe attachment points to the main structure experience higher stresses than under unidirectional shaking [13]. Moreover, both the type and magnitude of the earthquake significantly influence the performance of the secondary system [14–15].

2.System Design

2.1Base-Isolated P–S System Evaluation

A nonlinear time-history analysis is performed on the P–S system placed on base isolators, considering bidirectional seismic excitations. From this analysis, a suitable analytical model of

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the system is formulated and implemented using the specialist software SAP2000 for further evaluation.

2.2 Modelling of Isolators

The isolators used are laminated rubber bearings (LRBs) with a circular cross-section. Their hysteretic response is represented using the widely adopted Wen model, which characterizes the force–deformation relationship with a bilinear hysteresis backbone curve, as illustrated in Figure 1.

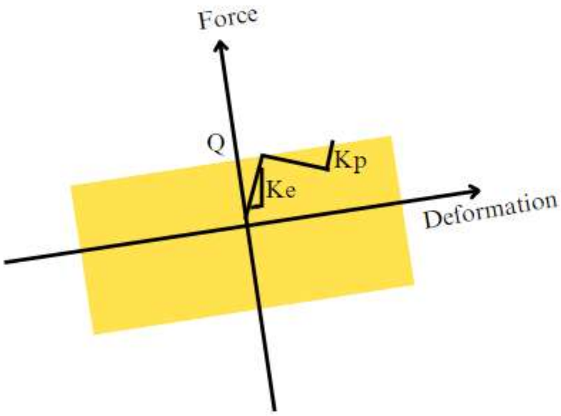

Figure1 Isolator's bilnear behaviour

2.3 Building Properties

Figure 2 shows the structure selected for analysis. It is a three-storey reinforced concrete building with a regular plan and elevation. The floor plan measures 15 m × 15 m, comprising three equal spans along both directions. Each storey has a height of 3 m. The slabs are 200 mm thick, columns measure 450 mm × 450 mm, and beams are 300 mm × 450 mm in cross-section. The concrete used throughout the structure is of grade M25.

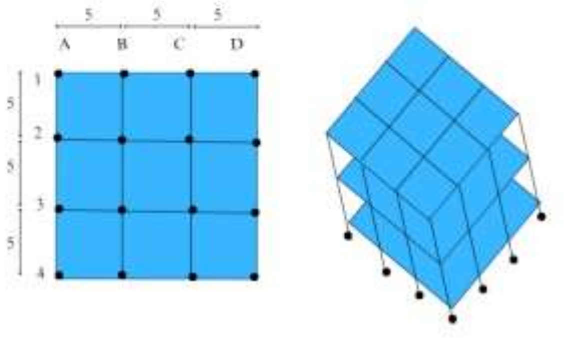

Figure2:Sketch and three-dimensional representation of the model building.

2.4 SimulationModeling

For the fixed-base scenario, the structure is represented as a three-degree-of-freedom (3-DOF) system, whereas in the base-isolated case, it is represented as a four-degree-of-freedom (4-DOF) system. At each storey, a single lateral DOF is used to model the structural response. Rayleigh mass- and stiffness-proportional damping is adopted for the superstructure, with a critical damping ratio of $\xi = 5\%$ applied to all vibration modes. The isolation system in a base-isolated configuration may consist of either a friction pendulum mechanism or an elastomeric bearing, with or without a lead core.

Assumptions

The following modelling assumptions are made for the building:

1. The majority of the building mass is concentrated at the floor levels.
2. Floor slabs and beams are assumed to be infinitely stiff compared to the columns.
3. Lateral stiffness is contributed entirely by weightless, inextensible columns.
4. Soil–structure interaction effects are neglected.

3. Results and Discussion

This study examines how variations in isolator properties influence the seismic performance of base-isolated structures. As illustrated in Figures 3 and 4, the building is idealised as a three-storey shear-type model.

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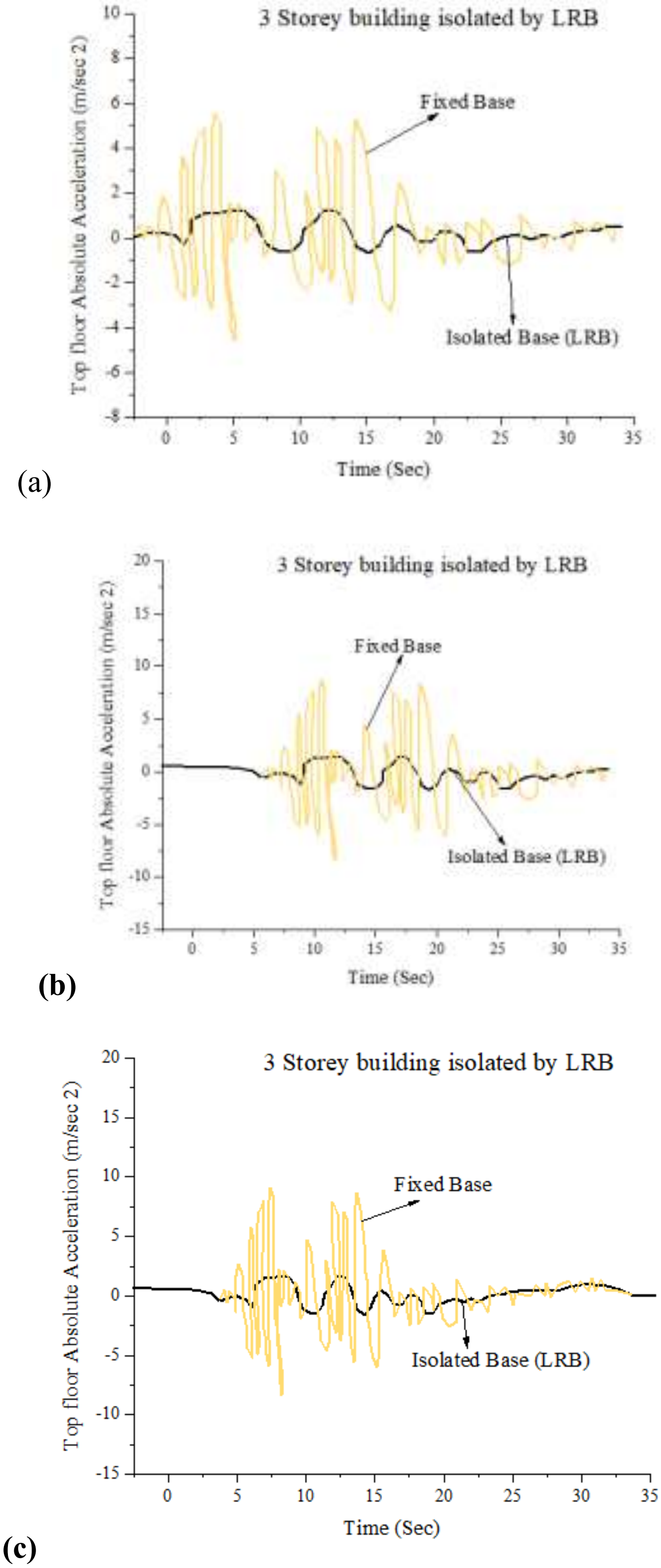
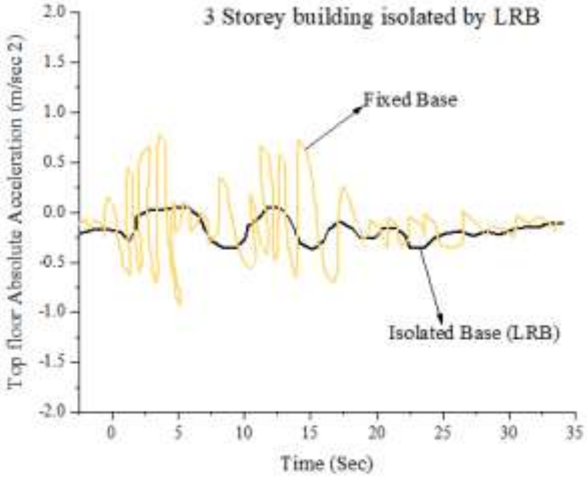
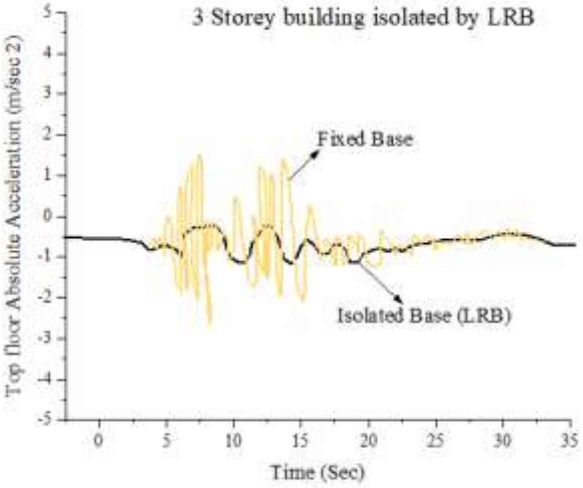


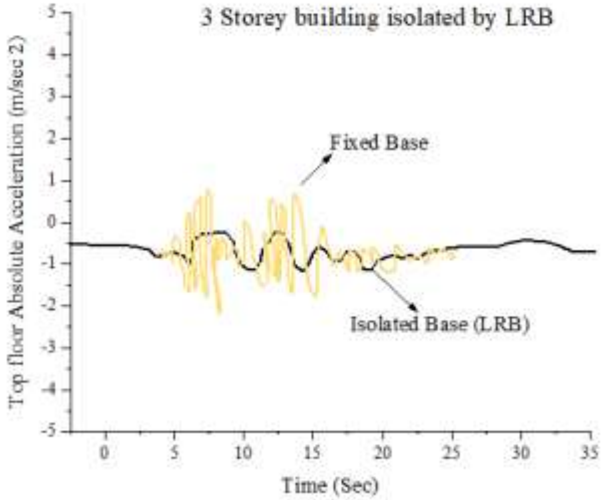
Figure 3: Peak top-storey acceleration for fixed-base and LRB base-isolated buildings

(Tb=βT_b = \betaTb=β sec, ξb=10%\xi_b = 10\%ξb=10%) under selected earthquake records



(a)

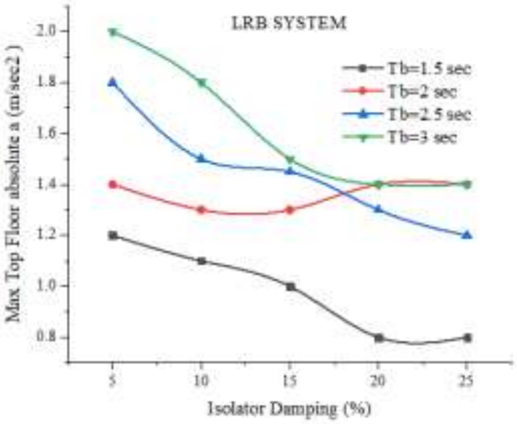




(c)

Figure 4: Upper-storey relative displacement for fixed-base and LRB base-isolated buildings (TbT_bTb sec, ξb=10%\xi_b = 10\%ξb=10%) under selected earthquake excitations

Figure 5 presents the relationship between the isolator damping ratio and two response parameters: absolute acceleration at the top storey and displacement of the isolator. For the LRB configuration, the variations are illustrated for several isolator time period values. The results show that increasing the isolation period leads to greater bearing displacements but lower accelerations in the superstructure. Conversely, raising the isolator damping ratio reduces both bearing displacement and superstructure acceleration. However, the difference in superstructure acceleration becomes negligible when the damping ratio increases from 20% to 25%.



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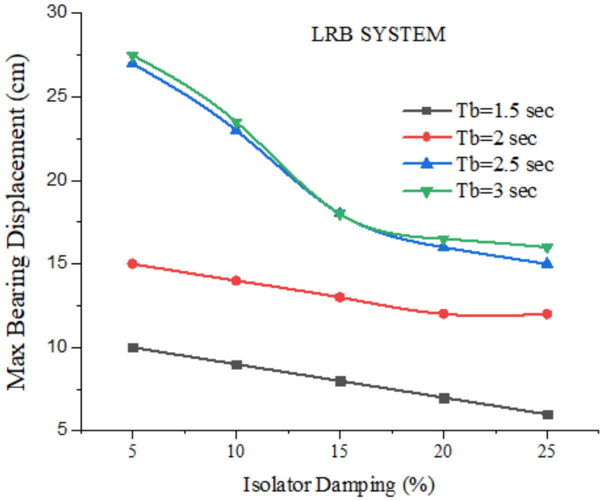
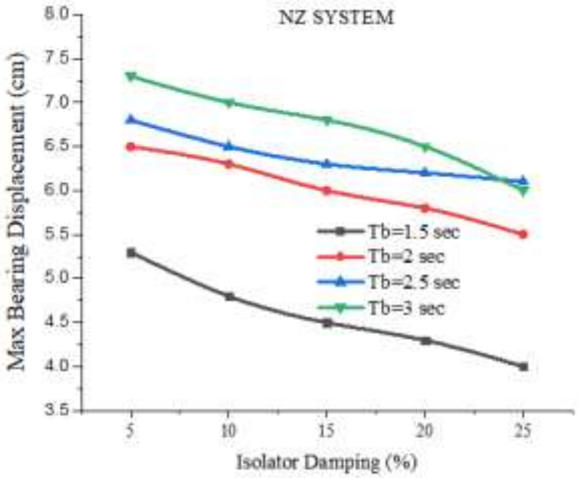


Figure 5:Influence of isolator damping ratio and isolation period on peak bearing displacement and top-storey absolute acceleration

In the N–Z system, the primary parameters include the yield strength F0F_0F0, the bearing damping ratio ξb\xi_bξb, and the base isolation period TbT_bTb. As expressed in Equation (1β), additional characteristics of the N–Z bearing are the yield displacement qqq and the hysteresis loop constants AAA, ω\omegaω, and yyy. When these parameters are fixed, their respective values are q=β0 mmq = \beta_0 \, \text{mm}q=β0mm, A=1A = 1A=1, and β=y=0.5\beta = y = 0.5β=y=0.5.



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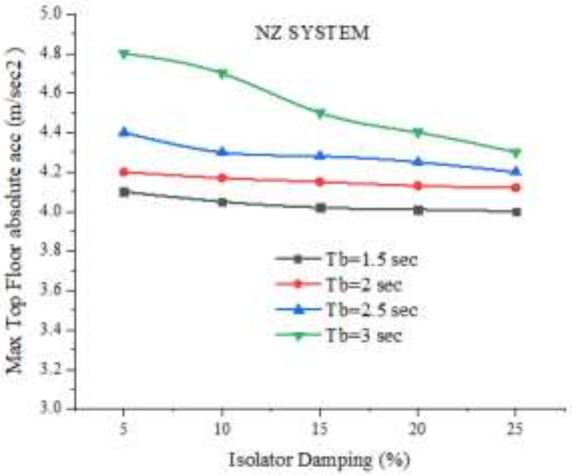

Figure 6: Effect of isolator damping ratio and isolation period on peak bearing displacement and top-storey absolute acceleration (F0=0.05F_0 = 0.05F0=0.05) under the El Centro (1940) earthquake

Figure 6 illustrates how the isolator displacement and the absolute acceleration at the top storey vary with changes in the isolator damping ratio. For several isolation period configurations of the N–Z system (Tb=1.5,2,2.5,T_b = 1.5, 2, 2.5,Tb=1.5,2,2.5, and 333 seconds), the plotted results show that a longer isolation period increases bearing displacement while reducing the acceleration experienced by the superstructure.

An increase in isolator damping results in a reduction of both bearing displacement and superstructure acceleration. Figure 7 illustrates how the absolute velocity at the top storey and the isolator displacement vary with the isolator's normalised yield strength (F0F_0F0). The plotted trends are shown for different isolator time period settings (e.g., Tb=1.5T_b = 1.5Tb=1.5 and β\betaβ seconds). The results indicate that as the normalised yield strength (F0F_0F0) of the bearing increases, the bearing displacement decreases, whereas the superstructure acceleration shows an upward trend.

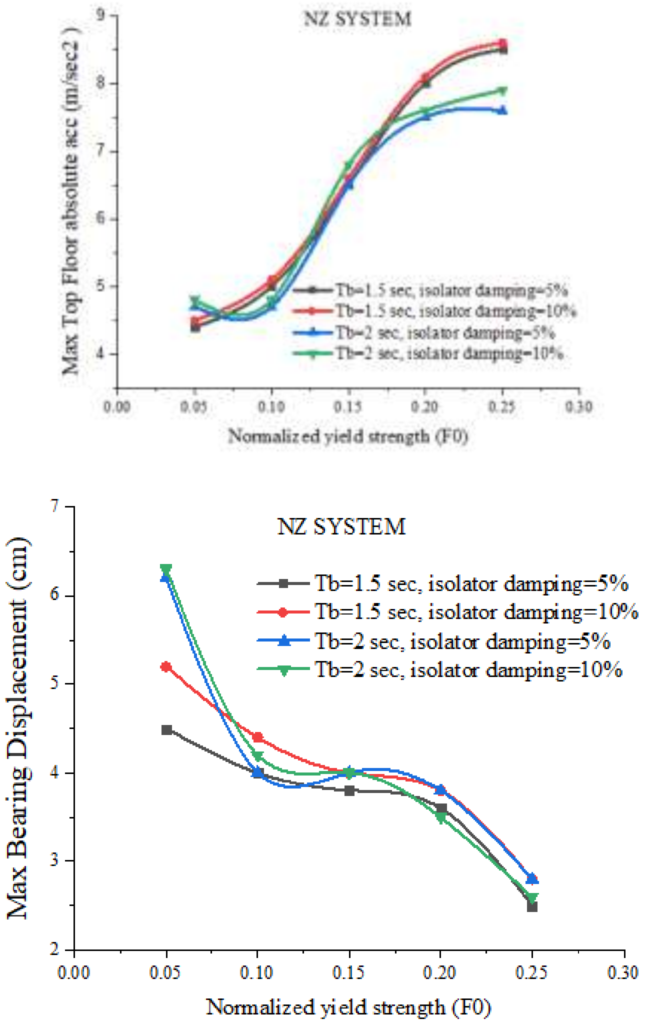

Figure 7: Effect of normalised yield strength on peak bearing displacement and top-storey absolute velocity

Figure 8 presents the relationship between isolator displacement, top-storey absolute acceleration, and the friction coefficient (μ\muμ) for the FPS. The plots are provided for multiple isolation period values (Tb=1.5,β,β.5,ηT_b = 1.5, \beta, \beta.5, \etaTb=1.5,β,β.5,η seconds). The results indicate that increasing the isolation period reduces the superstructure's acceleration while increasing the displacement of the bearing. Conversely, as the friction coefficient (μ\muμ) rises, the acceleration of the superstructure increases. A comparison of the three isolation system types shows that the LRB configuration achieves the largest reduction in superstructure acceleration, but its bearing displacement is greater than that observed in the N–Z and FPS systems. In contrast, both the N–Z and FPS systems require relatively smaller bearing displacements.

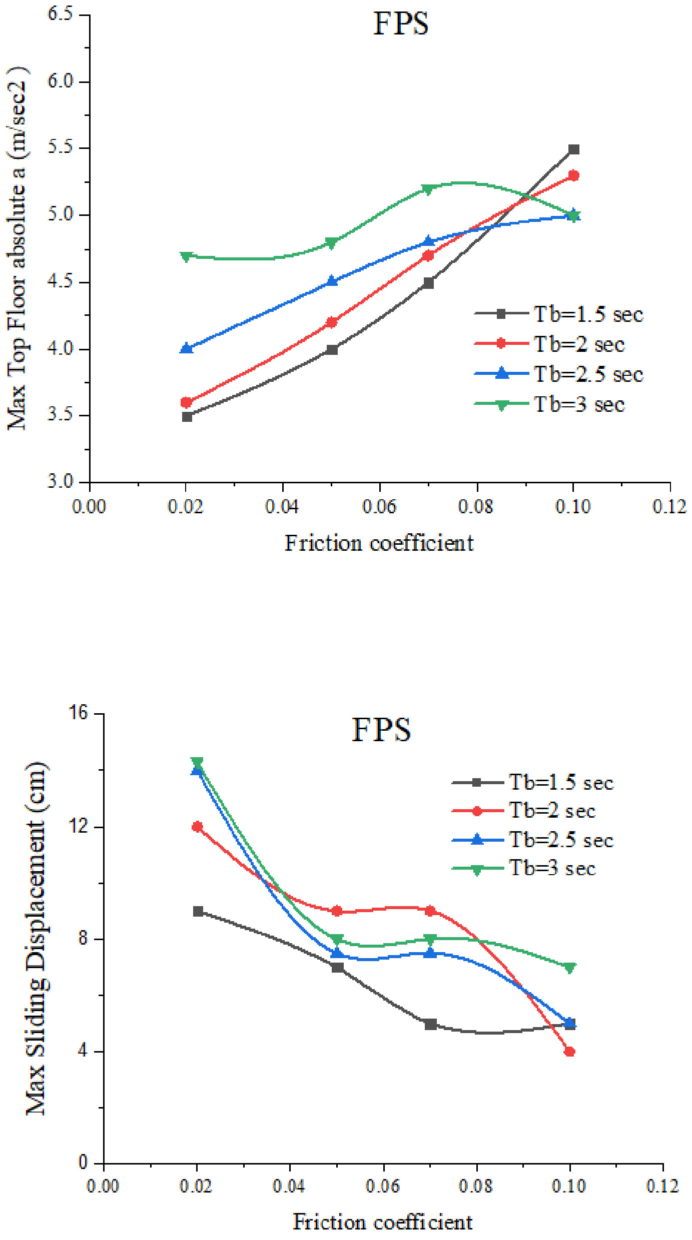

Figure 8:Effect of friction coefficient (μ\muμ) and isolation period (TbT_bTb) on peak bearing displacement and top-storey absolute acceleration for an FPS-isolated building under the El Centro (1940) earthquake

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5. Conclusions

This study enhances the understanding of collapse behaviour in high-rise building structures subjected to severe seismic events. Under selected ground motion scenarios, the possible failure modes, collapse progression, and vulnerable zones of two existing RC frame–core tube tall buildings, along with a simplified 10-storey RC frame, were modelled. The outcomes offer practical insights that can be applied in engineering practice for designing similar structures with improved collapse resistance. Importantly, the research contributes to the conceptual framework for preventing collapse during major earthquakes, supporting the future development of structural health monitoring strategies and optimized design methods. Furthermore, this work proposes an innovative approach to modelling progressive collapse. It is important to note, however, that validation of the full-scale collapse simulations presented remains challenging, as few large-scale collapse experiments are available in existing literature. Consequently, further studies and experimental verification are necessary to refine collapse modelling for large-scale structural components and complete building systems.

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