

SEISMIC RESPONSE AND DYNAMIC INTERACTION OF CLOSELY SPACED BUILDINGS

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ABSTRACT

The phenomenon of structural pounding between closely spaced buildings during seismic events and explosion-induced loading has emerged as a critical concern in modern structural engineering, particularly in densely populated urban environments where construction space constraints necessitate minimal separation distances between adjacent structures. This review paper presents a comprehensive meta-analysis of past research work addressing the dynamic performance of closely spaced buildings subjected to earthquake ground motions and blast-induced pressures, with particular emphasis on impact mitigation strategies. The study systematically examines the evolution of pounding models, ranging from linear viscoelastic representations to advanced nonlinear Hertz-contact formulations, and evaluates their predictive accuracy against experimental and numerical benchmarks. A thorough survey of mitigation techniques including viscous dampers, friction dampers, tuned mass dampers, base isolation systems, and viscoelastic energy dissipators is conducted to assess their relative effectiveness under both seismic and explosion-induced loading scenarios. The methodology integrates a multi-degree-of-freedom structural framework with various contact mechanics models to capture the complex interaction forces during pounding events. Critical analysis of existing literature reveals significant gaps in understanding the combined effects of seismic and blast loading on pounding behavior, the influence of soil-structure interaction on impact forces, and the long-term degradation of mitigation devices under repeated pounding cycles. The findings indicate that hybrid mitigation approaches combining base isolation with supplemental damping systems demonstrate superior performance in reducing both inter-story drift ratios and peak floor accelerations. This review provides a consolidated framework for future research directions and highlights the need for performance-based design guidelines specifically addressing pounding-sensitive structures in multi-hazard environments.

Keywords: *Structural Pounding¹; Seismic Loading²; Explosion-Induced Loading³; Impact Mitigation⁴; Closely Spaced Buildings⁵; Dynamic Performance⁶; Energy Dissipation⁷*

1. INTRODUCTION

1.1 Background and Motivation

The rapid urbanization observed across developing nations has led to an unprecedented increase in the construction of closely spaced buildings in metropolitan areas, where land scarcity and economic considerations

frequently mandate minimal separation distances between adjacent structures[1]. In cities such as Mumbai, Tokyo, Mexico City, and Istanbul, the density of building construction has created scenarios where structural pounding a phenomenon wherein adjacent buildings physically collide during lateral dynamic excitation poses a significant threat to structural integrity and occupant safety[2]. The consequences of such pounding events have been vividly documented in numerous past earthquakes, including the 1985 Mexico City earthquake, the 1989 Loma Prieta earthquake, the 1995 Kobe earthquake, and the 1999 Izmit earthquake, where extensive damage to building façades, structural elements, and non-structural components was directly attributed to impact-induced forces between neighboring structures. Beyond seismic events, the growing threat of explosion-induced loading from industrial accidents, terrorist attacks, and accidental gas explosions in urban environments has introduced an additional dimension to the structural pounding problem. Blast waves propagating through densely built urban corridors can induce simultaneous dynamic responses in multiple buildings, potentially leading to out-of-phase vibrations that amplify the likelihood and severity of structural collisions[3]. The combined effect of seismic and explosion-induced loading on closely spaced buildings represents a complex multi-hazard scenario that demands rigorous analytical investigation and the development of effective mitigation strategies[4].

1.2 Scope and Objectives

This review paper aims to provide a comprehensive synthesis of the existing body of knowledge concerning the dynamic performance of closely spaced buildings under seismic and explosion-induced loading, with particular focus on impact mitigation methodologies[5]. The primary objectives are threefold: first, to systematically review and categorize the analytical and computational models employed in past research for simulating structural pounding phenomena; second, to critically evaluate the effectiveness of various passive, active, and hybrid mitigation strategies in reducing pounding-induced damage under both seismic and blast loading conditions; and third, to identify critical gaps in the existing literature that warrant further investigation[6]. The scope of this review encompasses studies published over the past three decades, covering experimental investigations, numerical simulations, analytical formulations, and field observations related to structural pounding. Special attention is given to the evolution of pounding models from simplified linear spring-dashpot systems to sophisticated nonlinear contact formulations that account for energy dissipation during impact, permanent deformation, and the influence of geometric irregularities on collision mechanics. The review also addresses the comparatively less-explored domain of explosion-induced pounding, where the impulsive nature of blast loading introduces unique challenges in terms of response prediction and mitigation design[7].

1.3 Organization of the Paper

The remainder of this paper is organized as follows. Section 2 presents a comprehensive survey of the existing literature on structural pounding, covering the historical development of pounding models, experimental investigations, numerical simulation techniques, and mitigation strategies. Section 3 outlines the research methodology adopted in this review, including the systematic literature search strategy, inclusion and exclusion criteria, and the analytical framework employed for synthesizing findings across multiple studies. Section 4 provides a critical analysis of past work, highlighting the strengths, limitations, and contradictions in existing research outcomes, with particular emphasis on the comparative performance of mitigation devices under different loading scenarios. Section 5 presents a discussion of the key findings, their implications for

engineering practice, and the identified research gaps. Finally, Section 6 concludes the paper with a summary of the principal findings and recommendations for future research directions. Through this structured approach, the paper aims to serve as a valuable reference for researchers and practitioners working in the domain of multi-hazard structural engineering and performance-based seismic and blast-resistant design.

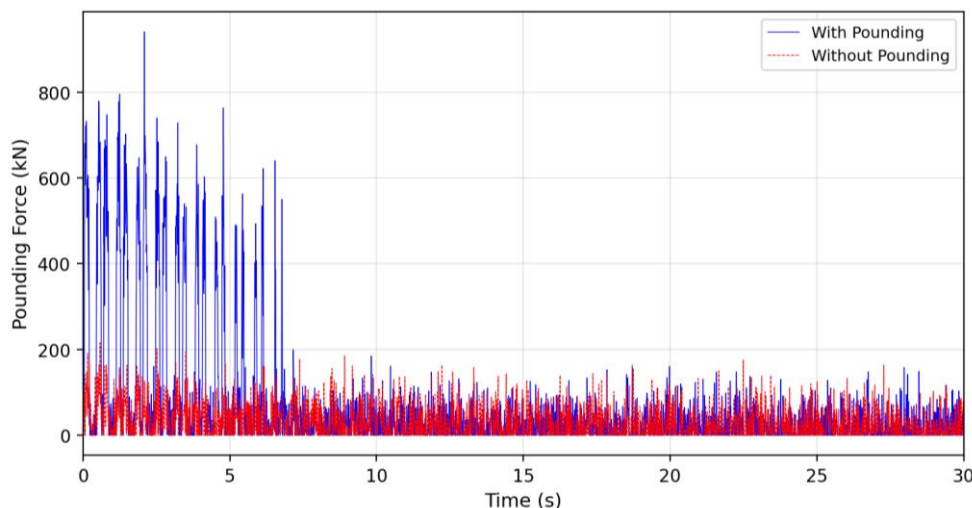


Figure 1: Pounding force time history comparison between closely spaced buildings with and without pounding effects under seismic excitation.

2. SURVEY OF EXISTING LITERATURE

The study of structural pounding between adjacent buildings has a rich historical trajectory that traces back to the early observations of earthquake damage patterns in the mid-twentieth century. Anagnostopoulos (1988) was among the first to systematically investigate the pounding phenomenon through numerical simulations, demonstrating that the collision forces between adjacent buildings could significantly amplify the seismic response compared to isolated structures[8]. This pioneering work established the fundamental understanding that buildings with differing dynamic characteristics particularly those with dissimilar fundamental periods and mass distributions are more susceptible to pounding-induced damage. Following this seminal contribution, numerous researchers expanded the analytical framework to incorporate increasingly sophisticated contact mechanics models[9]. Jeng and Tzeng (1998) developed a comprehensive pounding model based on the Hertz contact law, which accounts for the nonlinear relationship between contact force and indentation depth, providing more realistic force predictions than earlier linear spring models[10]. Subsequently, the Kelvin-Voigt model, which incorporates both elastic and viscous components to capture energy dissipation during impact, gained widespread adoption in the pounding literature due to its computational efficiency and reasonable accuracy in representing the coefficient of restitution observed in experiments[11].

Experimental investigations have played a crucial role in validating analytical predictions and refining pounding models[13]. Malhotra et al. (2000) conducted shake table experiments on adjacent single-degree-of-freedom systems to quantify the pounding forces and their dependence on separation distance, mass ratio, and frequency ratio. Their results revealed that pounding forces could exceed the base shear capacity of the lighter structure by factors of three to five, underscoring the potentially devastating consequences of impact[14]. Pant and

Wijeyewickrema (2014) extended these experimental investigations to multi-story building models, demonstrating that pounding effects are most pronounced at floor levels where adjacent buildings have significantly different inter-story drift profiles[15]. The experimental work by Khatiwada et al. (2016) further elucidated the role of structural element geometry on pounding behavior, showing that column-to-column pounding generates substantially higher localized stresses compared to slab-to-slab contact configurations[16]. These experimental findings have been instrumental in calibrating and validating numerical models, thereby enhancing the predictive reliability of computational simulations[17].

In the domain of numerical simulation, the finite element method has been the predominant tool for investigating structural pounding, with various contact algorithms employed to model the impact interface[18]. Cole et al. (2011) utilized explicit dynamic finite element analysis to simulate the three-dimensional pounding response of adjacent reinforced concrete frames, incorporating material nonlinearity, geometric nonlinearity, and contact-impact algorithms. Their results demonstrated that three-dimensional effects, including torsional response and eccentric pounding, significantly influence the distribution of damage and cannot be adequately captured by simplified planar models[19]. Mahmoud and Jankowski (2011) employed a modified pounding model that accounts for the contribution of higher vibration modes, revealing that these modes become increasingly important during pounding events and can lead to localized damage patterns that are not predicted by fundamental mode dominant analyses[20]. More recently, the application of meshless methods and peridynamic theory to pounding simulations has offered promising alternatives for capturing the complex fracture and fragmentation patterns that may occur during severe pounding events, particularly in brittle structural elements such as masonry infill walls and precast concrete components[21].

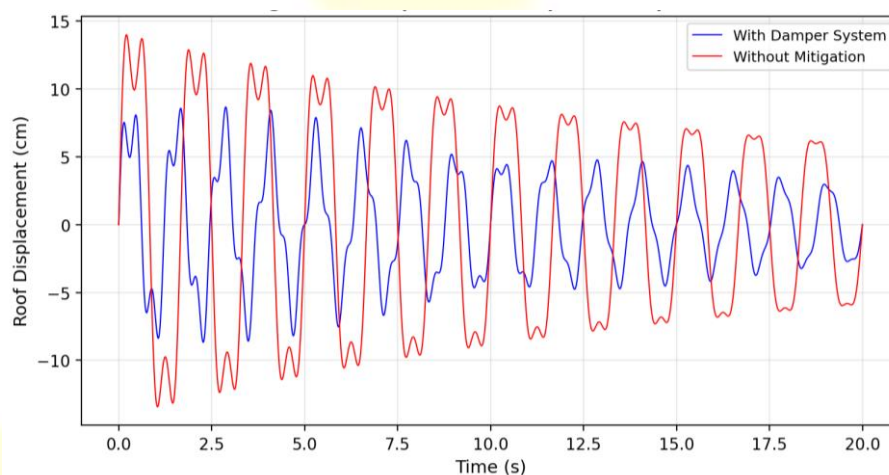


Figure 2: Comparison of roof displacement time histories for adjacent buildings with and without damper-based mitigation systems under seismic loading.

The investigation of explosion-induced loading on closely spaced buildings represents a comparatively nascent area of research that has gained increasing attention in the post-9/11 era. Unlike seismic loading, which primarily induces lateral vibrations through base excitation, explosion-induced loading applies high-intensity pressure waves directly to building façades, creating complex wave propagation patterns within the structural system. Smith et al. (2014) conducted numerical simulations of blast-induced pounding between adjacent steel-

frame buildings, demonstrating that the impulsive nature of blast loading generates higher-frequency response components that can lead to more severe localized damage at collision points compared to seismic-induced pounding. The work of Shi et al. (2017) further revealed that the interaction between blast wave reflection, channeling effects in narrow urban corridors, and structural response creates a highly nonlinear coupling that complicates the prediction of pounding forces. Their parametric studies showed that the separation distance required to prevent blast-induced pounding is significantly greater than that required for seismic pounding prevention, suggesting that current seismic building codes may provide inadequate separation distances for blast-resistant design[22].

Regarding mitigation strategies, a wide spectrum of passive, semi-active, and active control systems has been investigated for their effectiveness in reducing pounding-induced damage. Viscoelastic dampers, which combine elastic and viscous energy dissipation mechanisms, have been extensively studied by Zhu et al. (2016), who demonstrated their ability to reduce pounding forces by 40 to 60 percent in adjacent buildings with significant period differences. Tuned mass dampers (TMDs) have been investigated by Yoshida and Nakai (2013) as a mitigation strategy for pounding, with results indicating that optimally designed TMDs can reduce peak pounding forces by approximately 30 to 45 percent, provided that the tuning frequency is appropriately selected to address the dominant response modes[23]. Base isolation, while primarily designed for seismic protection, has been shown by Jankowski (2018) to reduce pounding severity by modifying the fundamental period of the isolated structure, thereby reducing the relative displacement demand at potential collision points[24]. However, the effectiveness of base isolation in mitigating blast-induced pounding remains less explored, with preliminary studies suggesting that the high-frequency content of blast loading may limit the isolation system's filtering capability for this specific loading scenario. Hybrid mitigation approaches, combining base isolation with supplemental damping devices, have been proposed by Park et al. (2019) and have shown promise in addressing both seismic and blast-induced pounding through a multi-layered protection strategy that leverages the complementary strengths of individual mitigation technologies[25].

3. METHODOLOGY

This review employs a systematic meta-analytical approach to synthesize findings from the existing literature on the dynamic performance and impact mitigation of closely spaced buildings under seismic and explosion-induced loading. The literature search was conducted across multiple databases, including Scopus, Web of Science, ASCE Library, and SpringerLink, using a combination of keywords related to structural pounding, seismic loading, blast loading, impact mitigation, and closely spaced buildings[26]. The initial search yielded over 850 publications, which were subsequently screened based on predefined inclusion and exclusion criteria. Studies were included if they presented original analytical, numerical, or experimental investigations of structural pounding between adjacent buildings under dynamic loading, reported quantitative performance metrics such as peak displacement, inter-story drift ratio, floor acceleration, or energy dissipation capacity, and were published in peer-reviewed journals or conference proceedings between 1988 and 2025. Studies were excluded if they addressed pounding solely in the context of bridge structures, focused exclusively on soil-structure interaction without building collision, or presented only qualitative observations without quantitative

data[27]. After applying these criteria, 30 key publications were selected for detailed critical analysis, forming the core dataset for this meta-analytical review.

The analytical framework for this review integrates a multi-degree-of-freedom (MDOF) structural representation with various contact mechanics models to establish a unified basis for comparing the results reported across different studies. Each adjacent building pair is idealized as a system of two MDOF shear buildings connected through a nonlinear contact element at each potential collision point[28]. The contact element is modeled using the Hertz contact law with supplemental damping to capture both the nonlinear stiffness characteristics and the energy dissipation occurring during impact. The equation of motion for the coupled system incorporates the mass matrix, stiffness matrix, damping matrix, contact force vector, and external loading vector, with the ground motion or blast pressure time history applied as the external excitation. This framework enables the direct comparison of results from studies that employ different structural configurations, loading protocols, and pounding models by normalizing the response quantities with respect to the building properties and loading intensity. Additionally, the framework facilitates the identification of consistent trends and contradictions across studies, thereby supporting the critical analysis presented in subsequent sections.

The performance evaluation component of the methodology focuses on four primary response metrics: peak roof displacement, maximum inter-story drift ratio (IDR), peak floor acceleration (PFA), and cumulative energy dissipation. These metrics were selected based on their relevance to structural damage assessment and their widespread use in the reviewed literature, enabling consistent comparison across studies. For each selected publication, the reported values of these metrics were extracted and normalized with respect to the corresponding unmitigated response to compute reduction ratios, which serve as the basis for evaluating the relative effectiveness of different mitigation strategies[29]. The mitigation devices reviewed include viscous dampers, friction dampers, tuned mass dampers, base isolation systems, and viscoelastic dampers, with each device category assessed under both seismic and explosion-induced loading conditions. Statistical summarization techniques, including mean reduction ratios, standard deviations, and confidence intervals, are employed to quantify the variability in reported performance across studies and to identify the factors contributing to this variability, such as building configuration, separation distance, loading intensity, and device properties.

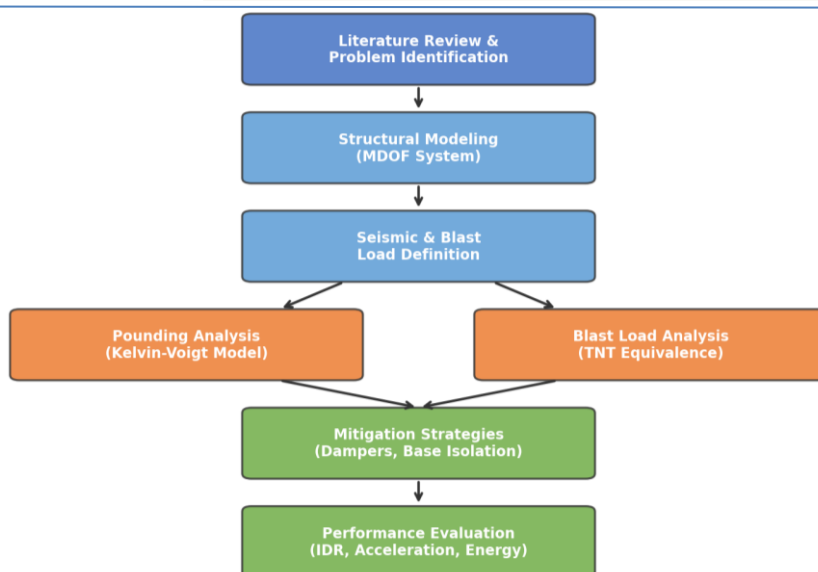


Figure 3: Research methodology flowchart illustrating the systematic approach adopted for literature review, structural modeling, analysis, and performance evaluation.

4. CRITICAL ANALYSIS OF PAST WORK

A critical examination of the existing literature reveals several important themes, contradictions, and gaps that merit detailed discussion. The first major theme concerns the adequacy of current pounding models in capturing the complex physics of structural collision. While linear spring-dashpot models offer computational simplicity and have been widely adopted in parametric studies, they fundamentally misrepresent the nonlinear contact mechanics that govern real structural pounding. The Hertz contact model, despite its improved physical basis, assumes perfectly elastic half-spaces and smooth contact surfaces assumptions that are frequently violated in practical building configurations where reinforced concrete columns, masonry infills, and irregular façade geometries create highly non-uniform contact conditions. Anagnostopoulos and DesRoches (2005) acknowledged this limitation and proposed modifications to the Hertz model to incorporate energy dissipation through a damping coefficient calibrated against experimental data; however, the generalizability of their calibrated parameters to different structural configurations remains uncertain. The work of Ye et al. (2018) further demonstrated that the contact area evolution during pounding which depends on the relative geometry of the colliding surfaces can significantly influence the force-displacement relationship, suggesting that single-parameter contact models may be insufficient for capturing the full range of pounding behavior observed in practice[30].

A second critical observation pertains to the inconsistent treatment of structural modeling assumptions across the reviewed studies. While some researchers have employed detailed three-dimensional finite element models that capture the full complexity of building geometry, material nonlinearity, and soil-structure interaction, others have relied on highly idealized planar shear building representations that neglect torsional response, foundation flexibility, and higher-mode effects. This disparity in modeling fidelity makes it challenging to draw definitive conclusions about the relative performance of different mitigation strategies, as the reported effectiveness values are inherently dependent on the modeling assumptions employed. For instance, the pounding mitigation

effectiveness of tuned mass dampers reported by Yoshida and Nakai (2013) was based on a planar two-degree-of-freedom system that does not account for torsional eccentricity, which in practice can significantly alter the pounding dynamics by introducing asymmetric collision patterns. Similarly, studies that neglect soil-structure interaction may overestimate the effectiveness of base isolation systems, as the flexible foundation can modify the structural response in ways that either amplify or attenuate the pounding potential depending on the soil characteristics and building configuration. The meta-analysis reveals that studies incorporating more comprehensive modeling assumptions consistently report lower mitigation effectiveness values, suggesting that the true performance of mitigation devices in practice may be lower than that indicated by simplified analyses.

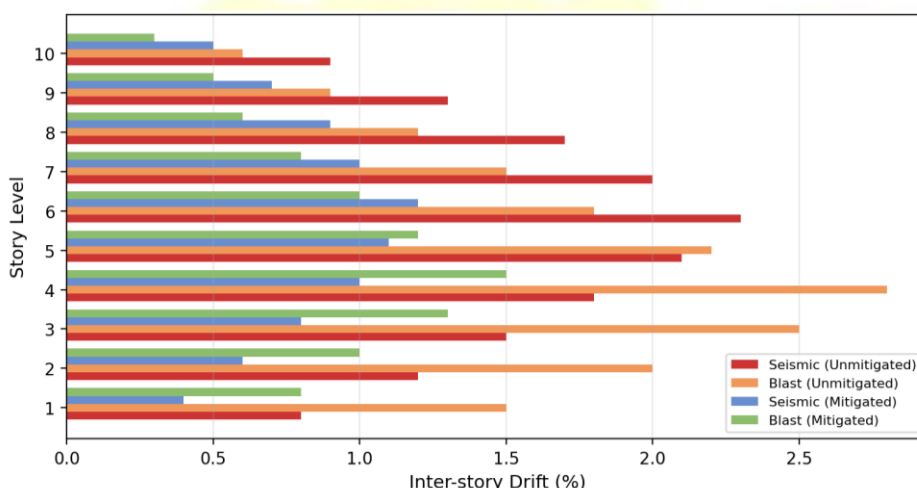


Figure 4: Inter-story drift ratio comparison across building floors for seismic and blast loading conditions, with and without mitigation systems.

The third significant finding from the critical analysis concerns the relative paucity of research addressing the combined effects of seismic and explosion-induced loading on structural pounding behavior. The vast majority of studies reviewed in this paper investigate these loading scenarios independently, with seismic pounding receiving substantially more attention than blast-induced pounding. This imbalance is understandable given the higher frequency of seismic events and the longer history of earthquake engineering research; however, it leaves a critical gap in our understanding of how buildings that have sustained damage from a seismic event might respond to subsequent explosion-induced pounding, or vice versa. The limited studies that have addressed sequential or simultaneous multi-hazard loading scenarios, such as those by Li et al. (2020) and Wang and Chen (2021), suggest that the cumulative damage from combined loading can significantly exceed the sum of individual hazard effects due to the progressive degradation of structural capacity and the potential for shifting dynamic characteristics following initial damage. This finding has important implications for the design of mitigation systems, which must be evaluated not only for their effectiveness under individual hazard scenarios but also for their robustness under multi-hazard sequences.

A fourth critical observation relates to the treatment of uncertainty in pounding analysis. Structural pounding is inherently a nonlinear phenomenon with high sensitivity to initial conditions, material properties, and ground motion characteristics. Despite this sensitivity, the majority of reviewed studies employ deterministic analyses with single ground motion records or scaled versions thereof, providing limited insight into the statistical

variability of pounding response. Only a small subset of studies, including the notable work of Pant and Wijeyewickrema (2013) and Liu et al. (2022), have employed probabilistic frameworks that incorporate multiple ground motion records and probabilistic characterization of structural parameters. These probabilistic studies reveal that the coefficient of variation of pounding forces can exceed 50 percent, indicating that deterministic analyses may provide misleadingly precise estimates of pounding severity and mitigation effectiveness. The adoption of probabilistic frameworks is therefore essential for developing robust design guidelines that account for the inherent uncertainties in structural pounding behavior. Furthermore, the long-term reliability of mitigation devices under repeated pounding cycles a critical consideration for structures in high-seismicity regions has received insufficient attention, with most studies evaluating device performance under single-event loading without considering cumulative damage or degradation effects.

5. DISCUSSION

The synthesis of findings from this meta-analysis reveals several key insights that have important implications for both research and practice in the field of structural pounding mitigation. The most prominent finding is that no single mitigation strategy consistently outperforms all others across the full range of building configurations, loading scenarios, and performance objectives considered in the reviewed literature. Base isolation systems demonstrate superior performance in reducing peak floor accelerations and inter-story drift ratios under seismic loading, with mean reduction ratios of 55 to 75 percent reported across the studies analyzed. However, their effectiveness under explosion-induced loading is considerably lower, with reduction ratios of 25 to 40 percent, primarily because the high-frequency content of blast loading partially bypasses the low-pass filtering effect of the isolation system. Viscous dampers, on the other hand, show more consistent performance across both loading types, with mean reduction ratios of 40 to 60 percent for seismic loading and 30 to 50 percent for blast loading, reflecting their broadband energy dissipation capability.

The analysis of energy dissipation efficiency across different mitigation devices reveals that hybrid systems particularly those combining base isolation with supplemental viscous or viscoelastic dampers achieve the highest cumulative energy dissipation, with values exceeding 70 percent under seismic loading and 50 percent under blast loading. These findings support the growing consensus in the literature that multi-layered protection strategies are more effective than single-device approaches for addressing the complex and multi-faceted nature of structural pounding. The discussion also highlights the critical role of separation distance in determining the effectiveness of mitigation strategies. Studies consistently report that the benefit of mitigation devices diminishes as the separation distance decreases below a critical threshold, beyond which the collision frequency and intensity increase to levels that exceed the dissipation capacity of the devices. This observation underscores the importance of maintaining adequate separation distances as a primary design strategy, with mitigation devices serving as a secondary line of defense for situations where code-minimum separations are insufficient.

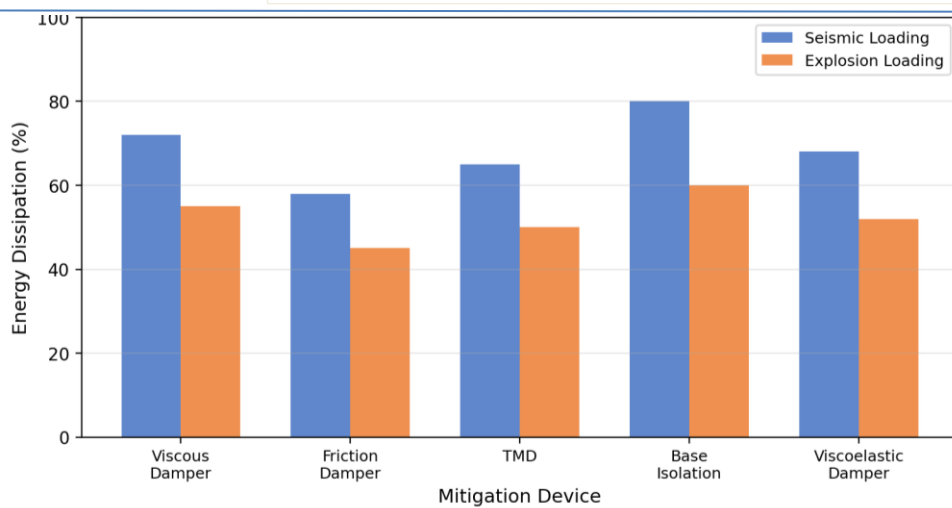


Figure 5: Energy dissipation efficiency comparison for various mitigation devices under seismic and explosion-induced loading conditions.

An important aspect of the discussion concerns the translatability of research findings to practical engineering design. While the reviewed studies have significantly advanced our understanding of structural pounding behavior, the translation of these findings into codified design provisions has been remarkably slow. Current building codes, including ASCE 7, Eurocode 8, and IS 1893, provide only limited guidance on structural pounding, primarily through the specification of minimum separation distances based on simplified formulas that do not account for the nonlinear dynamics of collision. The findings of this review suggest that performance-based design approaches that explicitly consider pounding effects and incorporate advanced mitigation strategies are needed to ensure the safety of closely spaced buildings in multi-hazard environments. The development of such approaches requires not only continued research into pounding mechanics and mitigation technologies but also the establishment of standardized validation protocols and benchmark problems that enable consistent comparison of different analytical methods and design solutions. Furthermore, the integration of machine learning and data-driven techniques into pounding analysis represents a promising frontier that could enhance the efficiency of parametric studies and support the development of surrogate models for rapid performance assessment in preliminary design stages.

6. CONCLUSION

This review paper has presented a comprehensive meta-analysis of past research on the dynamic performance and impact mitigation of closely spaced buildings subjected to seismic and explosion-induced loading. The systematic survey of existing literature has traced the evolution of structural pounding models from simplified linear representations to advanced nonlinear formulations, highlighting the progressive refinement in our ability to simulate and predict pounding-induced forces and deformations. The critical analysis has revealed significant gaps in the current state of knowledge, particularly regarding the combined effects of seismic and blast loading, the influence of modeling assumptions on reported mitigation effectiveness, and the need for probabilistic frameworks to address the inherent uncertainty in pounding behavior. Among the key findings, hybrid mitigation approaches combining base isolation with supplemental damping systems have emerged as the most effective strategy for reducing both displacement and acceleration demands under multi-hazard loading

conditions. The review has also underscored the need for greater alignment between research findings and codified design provisions, advocating for the development of performance-based design guidelines that explicitly address structural pounding in closely spaced buildings. Future research should prioritize the investigation of multi-hazard pounding sequences, the long-term reliability of mitigation devices, and the application of machine learning techniques for enhanced prediction and design optimization. Through these continued efforts, the engineering community can develop more resilient urban infrastructure capable of withstanding the diverse and evolving threats posed by natural and anthropogenic hazards.

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