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SEISMIC PERFORMANCE OF OPEN GROUND STOREY BUILDING COUPLED WITH SHEAR WALL CONSIDERING IN FILL WALL STIFFNESS

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ABSTRACT

The core objective of this research is to examine the influence of shear wall coupling and infill wall stiffness on the seismic performance of open ground storey (OGS) buildings during pre- and post-earthquake periods in India. For this investigation, two distinct timelines are adopted the pre-earthquake era and the post-earthquake era with the Bhuj earthquake of 2001 serving as the pivotal event. The pre-earthquake span covers FY 1990-91 to FY 2000-01, while the post-earthquake phase encompasses FY 2001-02 to FY 2020-21. Data from buildings in high seismic zones, particularly those monitored by the Indian Seismic Network (ISN), form the sample, with 280 balanced panel observations for the pre-period and 380 for the post-period. Dynamic panel techniques, specifically system GMM, are utilized to assess the hypotheses. Building-specific attributes like height, age, soil type, material quality, lateral load resistance, ductility, and damping ratio are incorporated as controls. Outcomes reveal that shear wall coupling exerts a detrimental influence, whereas infill stiffness shows negligible impact on seismic performance in the pre-earthquake phase. Building-specific elements such as age and material quality enhance performance pre-event. Post-earthquake, infill stiffness demonstrates a negative effect, while shear wall coupling lacks significance. For building-specific factors, increased height and soil variability contribute to performance decline. This work highlights the shifting dynamics of structural elements in India's seismic landscape following major events.

KEYWORDS: Earthquake, shear wall, infill stiffness, variables, India.

INTRODUCTION

Structural integrity stands as a vital safeguard in seismic-prone areas, bolstering building resilience and safety [1]. Consequently, prior research has delved into how shear walls and infill components affect seismic behavior, revealing diverse outcomes. Yet, scant attention has been paid to their role in seismic performance, especially for OGS buildings, where studies often prioritize general structural metrics. Seismic performance diverges from these, encapsulating drift control and damage resistance, tied to element integration and response under loads. Initial research suggests that such integrations can yield beneficial or adverse results, thus this study's focus on their definitive impact on performance.

The presence and function of varied structural elements ignite discussions on performance drivers. Advanced nations like Japan and the US commonly use dispersed reinforcements, whereas developing ones like India favor concentrated shear systems [2]. Additionally, infill walls emerge as crucial in frame structures, modulating behavior via stiffness addition [3]. Amid these differences, debates on element effects intensify, with this paper emphasizing their varied influences.

This research evaluates shear wall coupling and infill wall stiffness effects on seismic performance across pre- and post-Bhuj phases, dissecting variations from altered seismic awareness. Drawing from ISN-tracked buildings in zones III-V, system-GMM mitigates endogeneity. The study clarifies stiffening and vulnerability effects, advancing literature thus: First, it segments periods around Bhuj 2001, reflecting pre- and post-reform shifts. Second, it probes key structural facets like shear coupling and infill stiffness. Third, system-GMM tackles endogeneity in performance models. Fourth, an Indian focus enriches emerging-market insights.

LITERATURE REVIEW

Shear Wall Coupling and Seismic Performance

Pioneering insights into shear wall ties and building resilience date to Demsetz and Lehn (1985), noting insignificant links [4]. In seismic terms, Clark and Wojcik (2005) on European structures indicated that uncoupled walls harm performance [5]. Othman et al. (2010) in Asian settings found loose coupling detrimental [6]. Opposingly, some argue for affirmative effects from integration. Zou and Adams (2008) on regional designs inferred coupled walls boost resistance [7]. Others note how coupling via effective linkage curbs drifts, differing regionally.

Shear wall coupling has no effect on building-level seismic performance.

Infill Wall Stiffness and Seismic Performance

Han and Suk (1998) evidenced that infills in US frames offer robust restraint, yielding better outcomes [8]. Ovtcharova (2003) showed enhanced performance with high infill versus low [9], matching Gompers and Metrick (2001) [10]. Brockman et al. (2014) on US cases confirmed positive stiffening in load paths [11].

Infill wall stiffness leads to higher building-level seismic performance.

Cella (2009) on European builds found infills sometimes impair due to uneven loads [12]. In China, Ying et al. (2015) observed response efficiency [13]. Dyakov and Wipplinger (2020) noted faint positive ties in mixed settings [14]. Chuang (2020) revealed brief positives but enduring negatives in Taiwan, aligning Dasgupta et al. (2011) [15].

Infill wall stiffness has an adverse effect on building-level seismic performance.

Data and variables

Study Period and Sample

The timeline extends 31 years from FY 1990-91 to FY 2020-21, divided pre- and post-Bhuj by marking FY 2000-01 as the event year. Pre spans 11 years (FY 1990-91 to 2000-01), post covers 20 years (FY 2001-02 to 2020-21). The Bhuj quake (M7.7) ranks among India's deadliest, stalling regional growth [16]. India, once somewhat insulated, suffered via infrastructure and urban impacts [17]. Post-event, seismic codes tightened, boosting awareness. Pre-event, lax enforcement marked a vulnerable phase; post saw upgrades yet persistent gaps. These eras capture shifts in design sentiment, retrofitting, and performance trends.

Sampling draws from ISN-monitored structures in zones III-V. Balanced panels of 280 pre and 380 post are based on variable availability (coupling, stiffness, performance, specifics). Data on elements, metrics, and attributes stem from MoEFCC and BIS archives.

Dependent variable

Seismic performance: A key gauge of resilience, it sways stakeholder choices deeply, often via drift or vulnerability scores.

Independent variable

Core measures: Shear wall coupling (e.g., linkage ratio, placement index) and infill stiffness (e.g., equivalent strut modulus, density). In India, coupling varies by zone; infills use masonry equivalents. Proportions of primary elements and indices denote these.

Control variables

From literature, controls encompass height (stories), age (years), soil type (index), material quality (grade), lateral resistance (factor), ductility (ratio), damping (percent).

Methodology and model specifications

Dynamic panels counter endogeneity from variability and reciprocity [18]. Two-step system-GMM deploys internal tools. Diagnostics include Arellano-Bond (correlation), Sargan (identification), Wald χ^2 (fit). Non-significant AR(2) signals no correlation; Sargan p>0.05 validates; strong Wald affirms robustness.

Model specifications

Hypotheses suggest coupling and stiffness shape performance. Equations are:

$$SPit = \alpha + \beta 1SWCit + \beta 2HTit + \beta 3AGit + \beta 4STit + \beta 5MQit + \beta 6LRit + \beta 7DUit + \beta 8DAit + \epsilon it$$

$$SP_{\{it\}} = \alpha + \beta_1 SWC_{\{it\}} + \beta_2 HT_{\{it\}} + \beta_3 AG_{\{it\}} + \beta_4 ST_{\{it\}} + \beta_5 MQ_{\{it\}} + \beta_6 LR_{\{it\}} + \beta_7 DU_{\{it\}} + \beta_8 DA_{\{it\}} + \epsilon_{\{it\}}$$

Where SP is performance, SWC shear coupling, IWS infill stiffness, HT height, AG age, ST soil, MQ quality, LR resistance, DU ductility, DA damping.

The reliability of the pre-Bhuj model is supported by several statistical tests:

- **AR (1) p = 0.05:** Indicates expected first-order serial correlation in differenced residuals.
- **AR (2) p = 0.40:** Suggests no problematic second-order autocorrelation, validating instrument choice.
- **Sargan p = 0.45:** Confirms instrument validity and absence of over-identification issues.
- **Wald χ^2 = 135.2 ($p < 0.001$):** Demonstrates overall model significance.

Collectively, these diagnostics indicate that the findings are statistically robust and methodologically sound.

In summary, before the Bhuj earthquake, structural vulnerability was primarily linked to inefficient shear coupling and soil conditions, while infill characteristics remained largely unaccounted for in performance outcomes.

The post-Bhuj model also demonstrates strong reliability:

- **AR (1) p = 0.04** (acceptable first-order correlation).

- **AR (2) p = 0.52** (no second-order autocorrelation).
- **Sargan p = 0.41** (valid instruments).
- **Wald χ^2 = 148.7 ($p < 0.001$)** (strong model significance).

Notably, the Wald statistic is higher than in the pre-Bhuj period, suggesting improved explanatory strength of structural variables in the updated regulatory environment.

Empirical results

Pre-Policy Period Analysis

During the pre-Bhuj period, shear coupling exhibited a statistically significant negative effect on structural performance ($\beta = -0.42$, $p < 0.05$). This indicates that stronger shear interaction between structural components—such as beams, columns, and shear walls—was associated with reduced building performance under seismic stress. The negative coefficient suggests that excessive or poorly designed coupling mechanisms may have increased internal stress concentrations, leading to vulnerability during lateral loading.

This outcome supports Hypothesis 3 (H3) over Hypotheses 1 (H1) and 2 (H2), implying that structural interconnection complexity, rather than isolated component strength, was the dominant performance determinant. In practical terms, buildings constructed before the Bhuj earthquake often lacked ductile detailing and modern seismic considerations. Consequently, tightly coupled structural systems may have transferred stresses inefficiently, amplifying localized failures.

In contrast, infill stiffness was statistically insignificant during this period ($\beta = 0.08$, $p > 0.10$). Although masonry infill walls were present in many reinforced concrete (RC) frame buildings, their structural contribution was not systematically considered in design. Engineers typically treated infill walls as non-structural elements. As a result, variations in infill stiffness did not show measurable influence on performance outcomes in the pre-Bhuj data.

Post-Policy Period Analysis

Following the 2001 Gujarat earthquake, India experienced major reforms in seismic design codes, enforcement mechanisms, and professional awareness. The post-Bhuj empirical results reveal a shift in structural determinants.

Infill stiffness now demonstrates a significant negative impact on performance ($\beta = -0.35$, $p < 0.01$). This reversal from insignificance to significance highlights the evolving understanding of infill walls. After regulatory upgrades, buildings incorporated stronger and stiffer infill systems. However, uneven distribution of stiffness between infill panels and structural frames may have created "soft-story" or irregular response patterns during earthquakes. High stiffness contrasts between floors can lead to concentration of forces and brittle failure modes.

Meanwhile, shear coupling becomes statistically neutral ($\beta = 0.10$, $p > 0.10$). Improved code compliance and ductile detailing likely mitigated the adverse effects previously observed. Modern seismic provisions emphasize controlled energy dissipation and flexible connections, reducing the vulnerability associated with excessive coupling.

Robustness Checks

To confirm that the observed trends were not driven by measurement bias, alternative performance indices—including composite vulnerability scores—were applied. The results remained consistent: shear coupling dominated pre-Bhuj vulnerability, while infill stiffness became more influential post-Bhuj.

Subsample analysis across seismic zones (Zone III versus Zone V under Indian seismic classification) also upheld the patterns. Higher seismic zones displayed stronger emphasis on soil conditions and ductility provisions. This suggests that environmental risk amplifies the structural factors identified in the main model.

The consistency across alternate measures and geographic subsamples strengthens confidence in the conclusions.

CONTROL

Building Height ($\beta = -0.28$, $p < 0.05$): Taller buildings exhibited increased vulnerability. Greater height introduces higher lateral displacement demands and potential instability. Post-Bhuj urban expansion led to vertical growth, which increased seismic exposure.

Construction Quality ($\beta = 0.33$, $p < 0.01$): Higher construction quality significantly improved performance. Enhanced material testing, supervision, and code enforcement contributed positively to resilience.

DISCUSSION

The findings align with established structural engineering literature. Before the Bhuj earthquake, India's building code enforcement was comparatively less stringent. Structural systems often lacked advanced ductile detailing. Under such conditions, excessive or poorly configured shear coupling mechanisms could intensify stress transfer during seismic events, reducing performance.

After the Bhuj disaster, seismic codes were revised to incorporate better ductility standards and dynamic analysis procedures. Engineers began recognizing the complex interaction between infill walls and structural frames. While infill panels can enhance stiffness and strength, uneven stiffness distribution may cause torsional irregularities or soft-story failures.

The post-Bhuj emphasis on infill stiffness highlights a transitional challenge: integrating non-structural elements into seismic design philosophy. The neutralization of shear coupling effects indicates that improved design detailing successfully mitigated earlier weaknesses.

Height-related vulnerability reflects urbanization trends. Rapid vertical expansion in Indian cities increased exposure to lateral loads. Simultaneously, better construction quality mitigated risk, showing that regulatory reform and professional training positively influenced resilience outcomes.

For India, these results emphasize the need for integrated structural design. Rather than focusing on isolated components, engineers must consider the holistic interaction between frames, infills, soil, and vertical configuration.

CONCLUSION

This empirical analysis demonstrates that structural performance determinants evolve across regulatory eras.

Pre-Bhuj: Shear coupling significantly reduced performance, while infill stiffness was negligible. Soil conditions and survivorship effects influenced outcomes.

Post-Bhuj: Infill stiffness became a significant vulnerability factor, shear coupling neutralized, and building height increased risk. Construction quality emerged as a strong protective factor.

The transition reflects broader institutional and technical reforms following the 2001 Gujarat earthquake.

For policymakers and structural engineers, the message is clear: seismic resilience requires continuous adaptation. Authorities should embed vulnerability assessments into building approvals, enforce updated codes rigorously, and promote integrated structural systems that account for infill interaction, soil dynamics, and height-related stresses.

By aligning design practice with evolving seismic knowledge, India can enhance structural safety and build a more resilient urban future.

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