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COMPARATIVE STUDY OF DYNAMIC BEHAVIOR AND LIFE CYCLE COST BETWEEN FIXED-BASE AND SEISMICALLY ISOLATED IRREGULAR STRUCTURES IN BANGLADESH

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ABSTRACT

In Bangladesh, which is an active seismic region, building irregularities in architectural configurations, mostly driven by limited land resources, have been a prominent problem in terms of seismic safety. Although irregular buildings severely compromise the seismic resilience of structures, seismic isolation has been widely recognized as a response control device for enhancing seismic resilience and structural safety. Irregular buildings with seismic isolation have been realized by investigating a comparative framework of building performance and a sustainable solution for economic effectiveness with a fixed-base structure. Two buildings with torsional and stiffness irregularities, one designed by the old building code and the other designed by the latest building code, were set as target buildings to validate the incorporation of seismic isolation for enhanced performance and reduced life cycle cost, as evidenced by Nonlinear Time History Analysis (NLTHA) and Incremental Dynamic Analysis (IDA).

The NLTHA results indicated significantly improved performance levels for both target buildings with seismic isolation. In contrast, the IDA results provided probabilistic evidence of enhanced seismic resilience with seismic isolation. There is a social cliché that the cost of seismic isolation is too high to adopt this technology. However, the comparative life-cycle cost analysis results indicated that the accumulated repair cost within the design life period of a fixed-base building is approximately 5 times higher than that of a seismically isolated building.

Keywords: Seismic Isolation, Building Irregularities, Fragility Curve, Life Cycle Cost.

1. INTRODUCTION

Bangladesh is prone to significant seismic risk owing to the formation of tectonic plate boundaries around it. Bangladesh has two tectonic plate boundaries. In northern Bangladesh, there is a boundary between the Indian and Eurasian Plates, and in the east, there is a boundary between the Indian and Burmese Plates. The complex interactions between the Indian-Eurasian Plate and Burmese-Indian Plate make the tectonic boundaries in the region a potential source of seismic activity in Bangladesh.

Structural irregularities severely compromise the seismic resilience of buildings. With the rapid urbanization of limited land resources and high population density, many buildings in Bangladesh have been designed with structural irregularities in their architectural configurations. The Bangladesh National Building Code 2020 (BNBC, 2020) describes several types of building irregularities that have significant implications for seismic performance and safety. The most common types of building irregularities in Bangladesh are Plan Irregularity and Stiffness Irregularity or Soft Story. Sadat et al. (2010) observed that over 42% of new residential buildings in Dhaka have soft-story conditions without addressing proper measures to increase the lateral stiffness at the soft-story level.

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Seismic isolation systems are widely recognized as the most effective response control devices. This technology uses flexible elements such as rubber bearings to isolate the superstructure from ground motions. Flexible rubber is often combined with energy-absorbing dampers, such as lead plugs, to dissipate seismic energy and reduce structural response. While seismic isolation systems reduce structural and nonstructural responses and damage, the life cycle cost can also be reduced for seismically isolated buildings compared to fixed-base structures. Bedrinana and Saito (2011) concluded that the life-cycle cost of a seismically isolated structure was reduced by half in 100 years compared to that of a fixed-base structure.

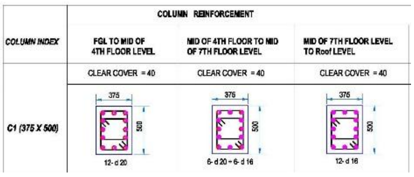
This study intends to frame a comparative assertion of dynamic response, building performance, and life-cycle cost between a fixed base structure with two types of building irregularities and a seismic isolation system for buildings designed by the old and the latest building codes.

2. DATA

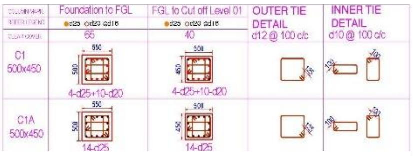
The data used in this study represent detailed architectural and structural drawings, including occupancy category, number of stories, story height, seismic parameters, gravity load information, concrete strength, and rebar yield strength of the selected two target buildings. Both target buildings are medium-rise, irregular residential buildings in different areas with different seismic hazard levels. The Target Building 1 (TB1) is a 10-story residential private building consisting of both plan irregularity and soft story, designed according to the BNBC 1993, the old building code. In contrast, Target Building 2 (TB2), which is a 14-story residential government building, was designed and constructed according to the newly implemented BNBC 2020. TB2 has both plan irregularity and soft story, but both irregularities were addressed by the provisions of BNBC 2020. A summary of both target buildings is presented in Table 1. Plan view and typical column details of both buildings are shown in Figure 1.

Table 1. Summary of target buildings.

Description	**Target Building 1**	**Target Building 2**
Occupancy	Residential	Residential
Seismic design code	BNBC 1993 (Old building code)	BNBC 2020 (New building code)
Number of stories	10	14
Story height	3.05 meter	3.05 meter
Maximum PGA of site	0.36 g	0.28 g
Concrete strength	24 MPa	25 MPa
Rebar yield strength	413 Mpa	413 Mpa



(c) typical column detail of TB1



(a) ground floor plan of TB1 (b) ground floor plan of TB2 (d) typical column detail of TB2

Figure 1: Plan view and typical column details of target buildings

3. METHODOLOGY

3.1. Selected ground motions

A total of 15 ground motions were selected based on tectonic diversity, including near-fault crustal inland earthquakes and subduction earthquakes, geographic locations of the epicenters, and magnitude and Peak Ground Acceleration (PGA) range. The selection was done carefully to compensate for realistic seismic demands for Nonlinear Time History Analysis (NLTHA) and to advocate for incremental scaling into different PGA levels for Incremental Dynamic analysis (IDA). These ground motions are obtained from the Pacific Earthquake Engineering Research Center (PEER), Center for Engineering Strong Motion Data (CESMD), and the National Research Institute for Earth Science and Disaster Resilience (NIED).

3.2. Selected damage measures for structural and nonstructural components

In the Japan Structural Consultant Association (JSCA) performance-based design concept, structural performance is categorized into five Damage Measures (DM). In contrast, Chiozzi and Miranda (2017) developed fragility functions for infill masonry, which are categorized into 3 DMs. The categorization of DM is based on the inter-story drift ratio (IDR) of a structure under earthquake loads. The DMs for structural components and masonry walls are shown in Table 2.

Table 2: Damage measures for structural and nonstructural components

DM for structural member	No Damage	Minor Damage	Significant Damage	Severe Damage	Collapse
IDR	IDR≤1/300	1/300<IDR≤1/150	1/150<IDR≤1/100	1/100<IDR≤1/75	IDR>1/75

DM for masonry wall	Few Damage	Distributed Damage	Severe Damage
IDR	1/1000<IDR≤1/500	1/500<IDR≤1/250	IDR>1/250

3.3. Response prediction of isolation layer

Takayama and Morita (1997) developed the method for response prediction of isolation layer in consideration of a balance of input energy and absorbed energy by the isolated structure. The shear coefficient of damper, α_s, shear coefficient of isolation layer, α_1, and maximum displacement of the isolation layer δ_m, are derived from the energy equilibrium as shown in Eqs. (1), (2), and (3). A graphical illustration of response prediction is shown in Figure 2.

$$\alpha_s = \frac{1}{2kg}\left(\frac{V_E^2}{\delta_m} - \frac{4\pi^2\delta_m}{T_f^2}\right) \tag{1}$$

$$\alpha_1 = \frac{4\pi^2\delta_m}{gT_f^2}\left(1 - \frac{1}{2k}\right) + \frac{V_E^2}{2kg\delta_m} \tag{2}$$

$$\delta_m = \frac{kg\alpha_s T_f^2}{4\pi^2}\left[-1 + \sqrt{\left(\frac{2\pi V_E}{kg\alpha_s T_f}\right)^2 + 1}\right] \tag{3}$$

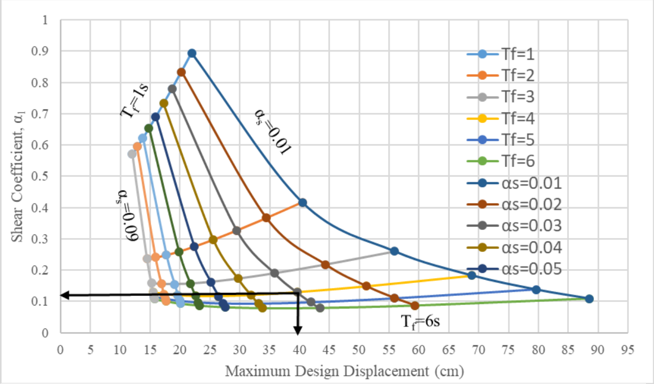


Figure 2: Response prediction of isolation layer

In this study, natural period, T_f and shear coefficient of damper, α_s, are taken to be 4 sec and 0.03, respectively. Using the values in Figure 2, evaluated maximum displacement of the isolation layer, δ_m = 40 cm, and the shear coefficient of isolation layer, α_1= 0.12.

3.4. Isolator types used for this study

In this study, selection of the isolators was based on the effective stiffness derived from the targeted natural period of the isolation system, and the yield shear force of the damper derived from the preset shear coefficient of the damper. The isolators have been chosen from the Bridgestone 2017 product catalogue. Figure 3 shows the isolation layout plans for both target buildings.

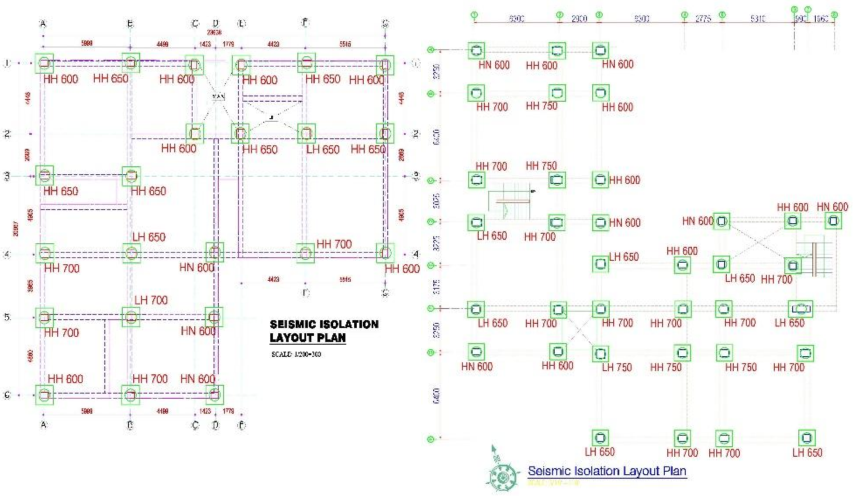


Figure 3: Seismic isolation layout plans, left TB1, right TB2

4. DYNAMIC RESPONSE AND PERFORMANCE COMPARISON FROM NLTHA

NLTHA models the actual behavior of the structural component damage state under a time-varying ground motion. In Bangladesh, artificial ground motions are essential owing to the absence of real, recorded ground motions that match the specific seismic hazard of the sites. The seismic hazard of a site is usually defined by the design response spectrum. To perform NLTHA, a set of 15 artificial ground motions simulated with the design response spectrum, are generated using the phase information of the selected real ground motions.

The NLTHA results frame a comparative statement of the dynamic response and building performances between a fixed-base structure with two types of building irregularities and a seismic isolation system. Figure 4 shows that the performance of TB1 with plan irregularity exhibited significant damage to severe damage. In contrast, performance with the soft story exhibited severe damage to collapse owing to the extreme deformation concentration in the soft story level for stiffness differences. Performance of TB1 with isolation system for both the structural and nonstructural components remained within the no-damage state.

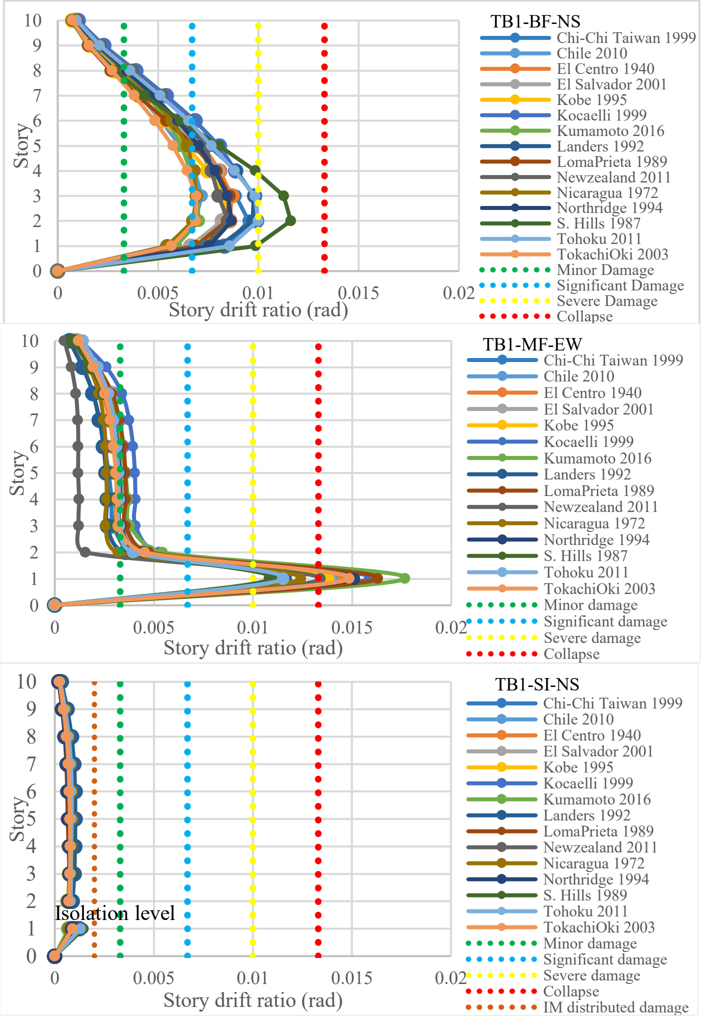


Figure 4: Performance comparison of TB1 from NLTHA

5. SEISMIC FRAGILITY-BASED DAMAGE PROBABILITY COMPARISON

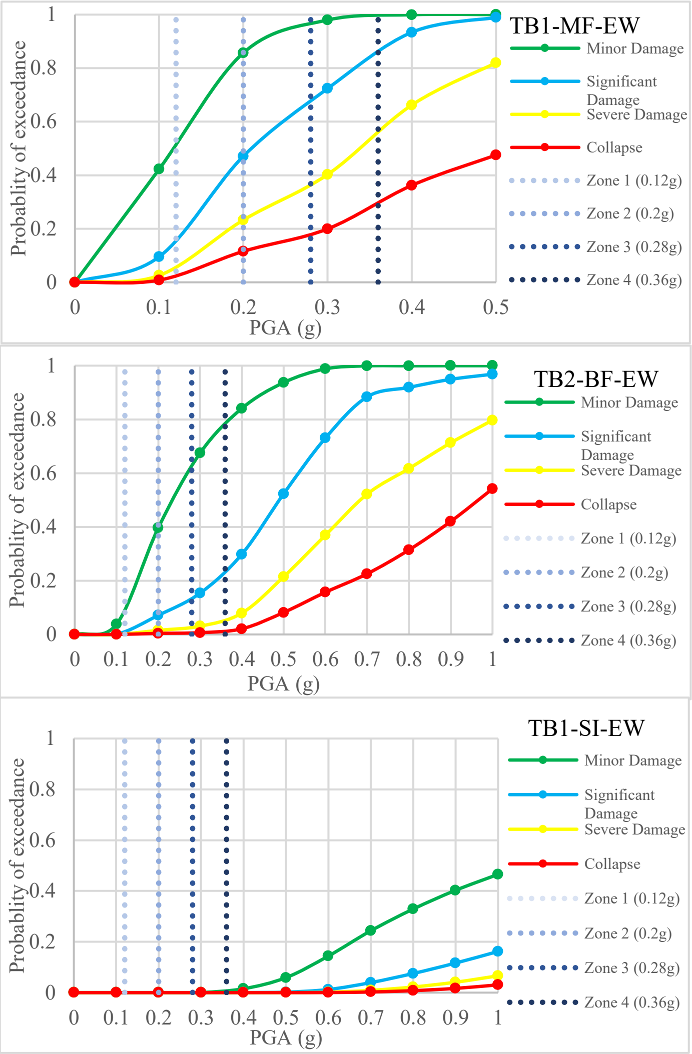


Figure 5: Fragility curves

The IDA principle uses real ground motion data scaled into different PGA levels as intensity measures (IM) to obtain distinct characteristics of different ground motions. The PGA levels used in this study are 0.1 g to 1.0 g based on the expected mean PGA of the site. This study uses the maximum inter-story drift ratio (IDR_{max}) as the DM to evaluate the performance level. The IDR_{max} derived from the IDA for each PGA level across 15 ground motions is assessed as the natural logarithm of the median data at the 50th percentile ($\ln(IDR_{max})^{50\%}$), along with the equivalent dispersion (δ_{eq}), to determine fragility-based damage probabilities. Benjamin and Cornell (1970) derived Eq. (4) to evaluate equivalent dispersion:

$$\delta_{eq}=\frac{\ln(IDR_{max})^{84\%}-\ln(IDR_{max})^{16\%}}{2} \qquad (4)$$

Nagae et al. (2006) evaluated probability of damage at which IDR_{max} exceeds the IDR limit using the following formula:

$$P[IDRmax>IDR]=1-P[IDRmax\leq IDR]$$
$$=1-\phi\left(\frac{\ln(IDR)-\ln(IDRmax)^{50\%}}{\delta_{eq}}\right) \qquad (5)$$

The fragility curves characterize a relationship between damage probability of each performance level in different PGA levels, ranging from 0.1 g to 1.0 g. Figure 5 illustrates the fragility curves for TB1 with soft story, TB2 with plan irregularity, and TB1 with seismic isolation. The key findings of this comparative statement are summarized as follows:

- TB2 with plan irregularities was less likely to be damaged than TB1
- TB1 with soft story had the maximum seismic vulnerability in terms of the seismic performance level, that is, collapse at low PGA intensity levels.
- TB1 with the seismic isolation yielded excellent seismic resilience, as evidenced by the performance level of minor damage to significant damage at extreme PGA levels.

6. COMPARATIVE LIFE-CYCLE COST ANALYSIS

Life-cycle cost analyses were conducted on TB2 only. This study emphasizes the repair cost ratio, R_s,developed by Takahashi and Shiohara (2004) for structural and nonstructural members, which are summarized in Eq. (6) and Table 3. D_c was taken as 0.01.

$$R_s=\begin{cases}0.0 & for\ DI[t]\leq D_c\\ \frac{DI[t]-D_c}{1-D_c} & for\ D_c<DI[t]\leq 1\\ 1.0 & for\ DI[t]>1\end{cases} \qquad (6)$$

Table 3: Repair cost ratio for infill wall

DM of infill wall	Repair cost ratio
Few damage	0.1
Distributed damage	0.16
Severe damage	0.4

From the IDA, the damage index (DI) and average IDR were obtained for each PGA level. An annual probabilistic distribution of each PGA level was evaluated through Probabilistic Seismic Hazard Analysis (PSHA). Figure 6 shows the annual lognormal distribution of each PGA level. The probability of each PGA level in t years, with an annual frequency λ, was evaluated using the Probability Density Function of Poisson Distribution, derived as follows:

$$P(t)[X \geq 1] = 1 - e^{-\lambda t} \quad (7)$$

The expected DI or IDR in t years, DI[t] or IDR[t], was obtained from the DI or IDR for each PGA level and the probability of each PGA level in t years using the following formula:

$$DI[t]\ or\ IDR[t] = \sum_{i=0.1g}^{1.0g} DI\ or\ IDR(PGA_i)\begin{bmatrix} P(PGA_i) - \\ P(PGA_{i+1}) \end{bmatrix} \quad (8)$$

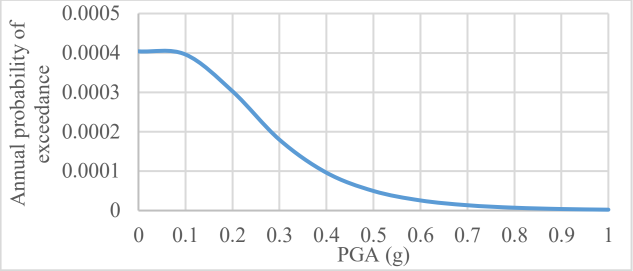


Figure 6: Annual frequency of PGA levels

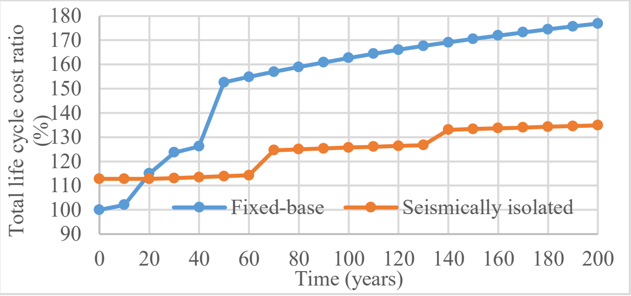


Figure 7: Total life-cycle cost ratio

The total life-cycle costs for fixed-base and isolated buildings were obtained, as shown in Figure 7, which indicates that in less than 20 years, the total life-cycle cost of the fixed-base structure reached the break-even point of the life-cycle cost of the isolated structure, and in 50 years, it is 52.6% higher than that of the isolated structure. Over 100 years, the total life-cycle cost of a fixed-base building was 4.86 times higher than the life-cycle cost of seismically isolated buildings.

7. CONCLUSIONS

This study emphasizes the incorporation of seismic isolation in irregular buildings to identify a comparative framework for the performance level and life-cycle cost-effectiveness. The seismic isolation system exhibited significantly improved performance, as evidenced by NLTHA results. The seismic fragility-based damage probability also indicated the excellent performance of the seismic isolation system. Even TB1, which had the most seismic vulnerabilities in terms of the damage state of collapse at lower PGA levels, exhibited an increased performance in terms of minor damage at extreme PGA levels with seismic isolation. Moreover, the seismic isolation showed a significant reduction in life cycle cost compared to a fixed-base structure.

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