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Evaluation of Linear Elastic Dynamic Analysis Behavior on RC Buildings in Sabah Subjected to Moderate PGA

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Abstract: Seismic performance of existing buildings in Southeast Sabah needs further examination, as there has been limited research. It is significant to explore the buildings respond to linear elastic dynamic analysis, especially considering that most reinforced concrete (RC) buildings insufficient earthquake-resistant technology. The current study aims to establish the correlation between peak ground acceleration (PGA) and the performance point of buildings under moderate PGA of 0.12g, 0.14g, and 0.16g, and then to assess the expected performance level of three RC buildings. The selection of three buildings within a 10 km radius from the active faults area. The buildings undergo an analytical method that necessitates the utilization of computational techniques to determine their capacity curve, demand curve, and performance point through the application of pushover analysis under the different of PGA. The performance point of buildings is determined by the intersection between capacity and demand curves, indicating Life Safety (LS) in inelastic range. This study critically evaluates the performance point of buildings that indicates inelastic displacement of the roof according to the intersection between capacity and demand curves under the various PGA.

Keywords: Performance point; RC buildings; Acceleration

1. Introduction

Southeast Sabah is characterised as an area with moderate seismicity region, as determined by Mansor et al. [1] through the macrozonation map. This analysis is based on two-thirds of the values from a 2,475-year average return period that corresponds to ground motions having a 2% probability of exceedance in 50 years. Seismic activities with most of the thrust faults and strike-slip faults have been found in Southeast Sabah, where there are numerous fault scarps, damaged roads, mud volcanoes, and hot springs [2]. Figure 1 shows numerous linear features typically spanning 20 to 40 km in length, in the Lahad Datu and Tawau region. These linear features are mostly linked to earthquakes due to thrust faults indicated by the red line and strike-slip faults in the purple line.

The risk of seismic is a quantification of the potential adverse consequences of an earthquake occurring at a particular site due to ground motion expressed through peak ground acceleration (PGA). It represents the highest ground acceleration recorded during an earthquake, typically expressed as a fraction of Earth's gravitational acceleration (g) and the seismic hazard map for Sabah region has been provided by Minerals and Geoscience Department of Malaysia (JMG) [3]. According to Tongkul [4] and Harith et al. [5], it was determined that the Lahad Datu region of southeast Sabah has the highest PGA value with its maximum value of 0.16g as shown in Figure 2.

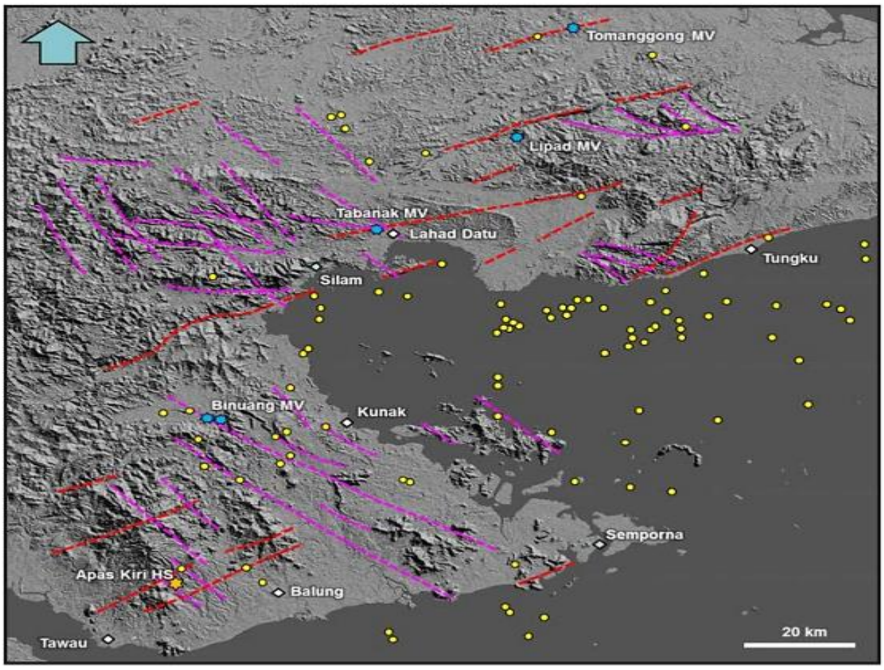

Figure 1. Thrust faults and strike-slip faults in Southeast Sabah [1].

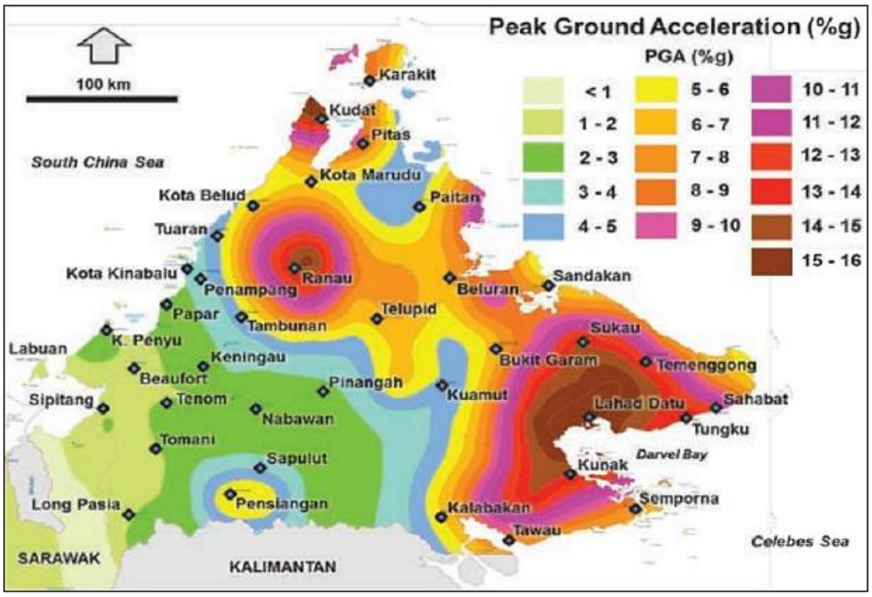

Figure 2. Seismic hazard map [3].

Again Tongkul [6] also stated that most of the earthquakes in this region have a magnitude of less than 5.0 Mw, apart from two earthquakes with a magnitude 6.0 Mw and above, such as the 1976 Lahad Datu earthquake (6.2 Mw) and 1923 Lahad Datu earthquake (6.3 Mw). The Lahad Datu earthquake in July 1976 caused significant property damage to Lahad Datu police complex, low-cost houses, Fire Department flat and Telecom building [6]. The damage that appeared during the event as shown in Figure 3 on the beam and ceiling at Fire Department flat and Telecom buildings. The variances in each building's seismic vulnerability and the observed damage dispersion in earthquake-affected structures are linked to the features of seismic vibrations that are influenced by source characteristics and geological site conditions [7].

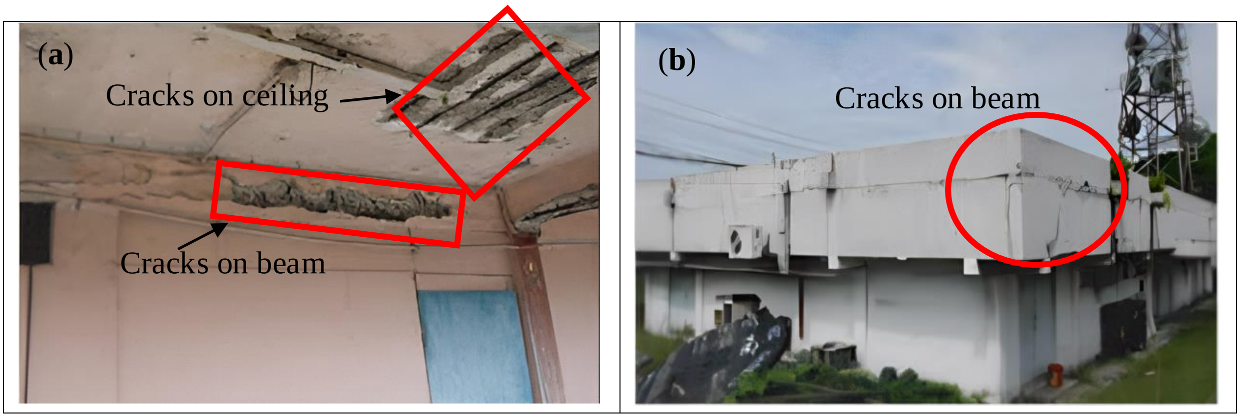

Figure 3. Cracks appeared on RC buildings in Lahad Datu as in (**a**) Fire Department Flat building and (**b**) Telekom building (modified from Tongkul [6]).

For this reason, it is very important to conduct an adequate assessment of this vulnerability, particularly using linear elastic dynamic analysis [8]. Pushover analysis is a straightforward technique for the prediction of non-linear behavior of the structure under seismic loads for the structures [9]. An intersection of the two estimated quantities consisting of seismic demand and seismic capacity, is one of the methods that are used to establish the performance-based analysis. In general, structure in pushover analysis is subjected to a lateral load that monotonically increases and roughly represents the relative inertia forces produced at the centers of masses for each story.

The performance point analysis is the generation of demand and capacity curves, which facilitate performance evaluation based on spectral displacement (Sd) and spectral acceleration (Sa). As defined by Douglas et al. [10], Sd represents the maximum displacement or movement response of a structure to seismic ground motion at a specific frequency. It signifies the expected amount of structural movement, in terms of displacement, at a particular frequency during an earthquake. A higher spectral displacement at a specific frequency suggests that the structure may experience more significant movements and deformations at that frequency. Furthermore, Sa measures the maximum acceleration response of a structure to seismic ground motion at a specific frequency, quantifying how rapidly and forcefully the ground shakes at that frequency during an earthquake.

Therefore, the seismic performance evaluation of buildings needs to be expanded in Southeast Sabah, as this region has seen limited research compared to Northeast Sabah, where numerous studies have been conducted following the 2015 earthquake in Ranau. This is especially necessary because most of the reinforced concrete (RC) buildings in the study area do not adhere to earthquake-resistant design practices using Eurocode 8 (EC8) Part 1 National Annex (NA) in accordance with MS EN1998-1:2015 [11]. This current study attempts to establish the correlation between PGA and the performance point of buildings under moderate PGA of 0.12g, 0.14g, and 0.16g of RC buildings. These three values are used in this study due to the maximum recorded PGA from the seismic station record is 0.12g (from the 2015 Ranau event). In contrast, the 0.16g is the highest PGA value from the analysis of seismic hazard assessment as studied in MS EN1998-1:2015 [11].

2. Methodology

The study focused on existing buildings, namely Building 1, Building 2, and Building 3 situated in Southeast Sabah. The focus is to study the seismic performance of a multi-story RC building using linear elastic dynamic analysis. The selection of three buildings was selected based on the location that is within a 10 km radius of the active faults. The building is located at the western end of the Lahad Datu Airport, near Kg. Tabanak faults whereas this fault has been identified by the study of Tongkul [2]. The analysis of the anticipated building performance level is conducted under various earthquake loads, specifically PGA of 0.12g, 0.14g, and 0.16g. This approach was motivated by the release of the initial seismic hazard map which identified the Lahad Datu area as a high-hazard zone with PGA values ranging from 0.12g to 0.16g [12]. The analysis procedure in this study contains three distinct phases as illustrated in Figure 4.

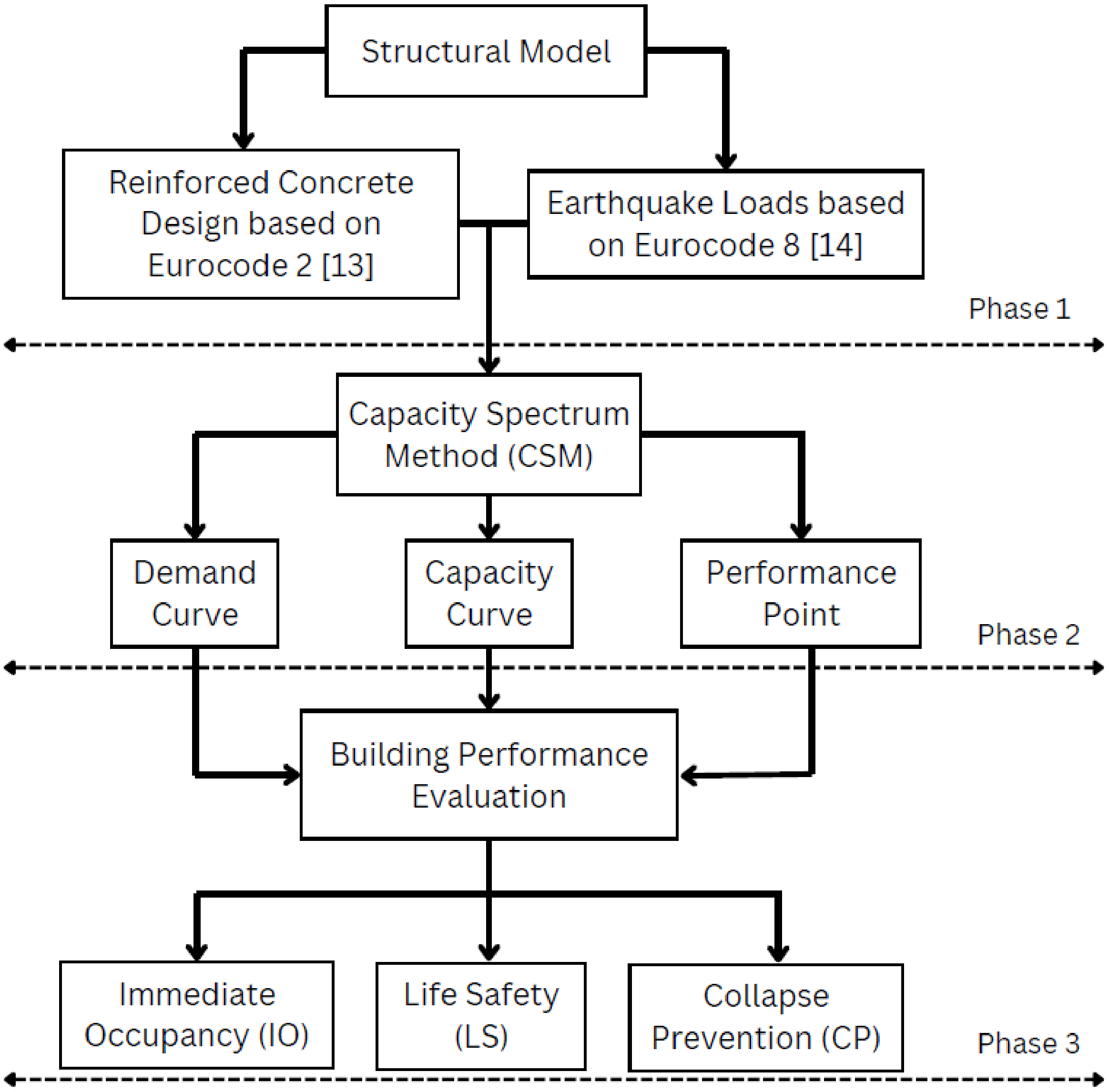

Figure 4. Flowchart of methodology.

2.1 Structural Model

The structural model of buildings represents a RC construction with brick infill masonry walls as shown in Figure 5-7. The structure is constructed using M20 concrete grade and designed according to Eurocode 2 [13] for RC and Eurocode 8 [14] for earthquake loads. Meanwhile, the dimensions of the building's structural members are shown in Table 1-3. The buildings were simulated with frame elements for beams and columns, while slabs were represented using shell elements. The pushover analysis of these buildings encompassed three distinct load scenarios which included different type of loads namely gravity loads which encompasses of dead and live loads, as well as lateral loads, including seismic forces, which collectively represent the forces acting on the structure, lateral loads in the X-X direction, and lateral loads in the Y-Y direction.

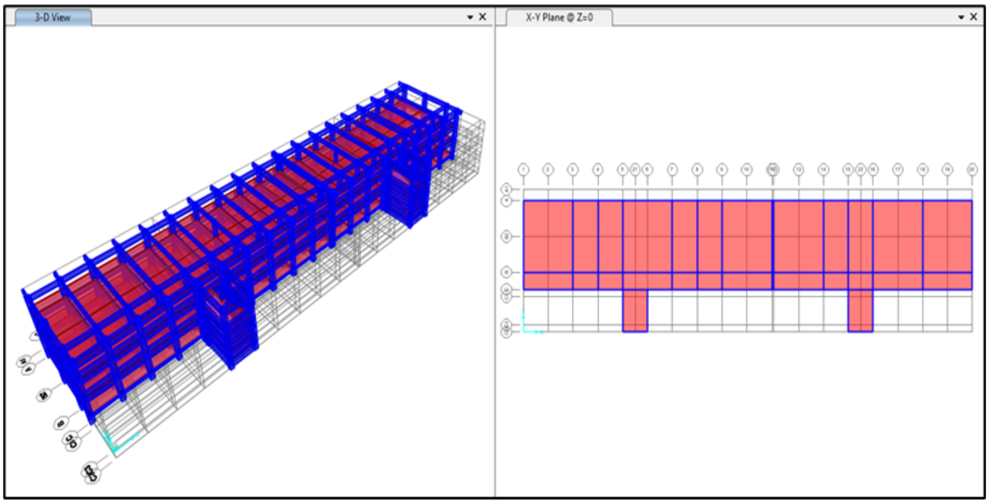

Figure 5. 3D view and typical floor plan of Building 1 (analysis taken from SAP2000 software).

Table 1. Dimension on the structural members of Building 1.

Structural Members	Dimension (mm)		
Beam	200 x 400	100 x 400	200 x 600
	200 x 500	100 x 1000	200 x 300
	100 x 1300	200 x 800	100 x 500
	100 x 300	100 x 600	400 x 600
Column	200 x 200	100 x 200	
Slab	100		

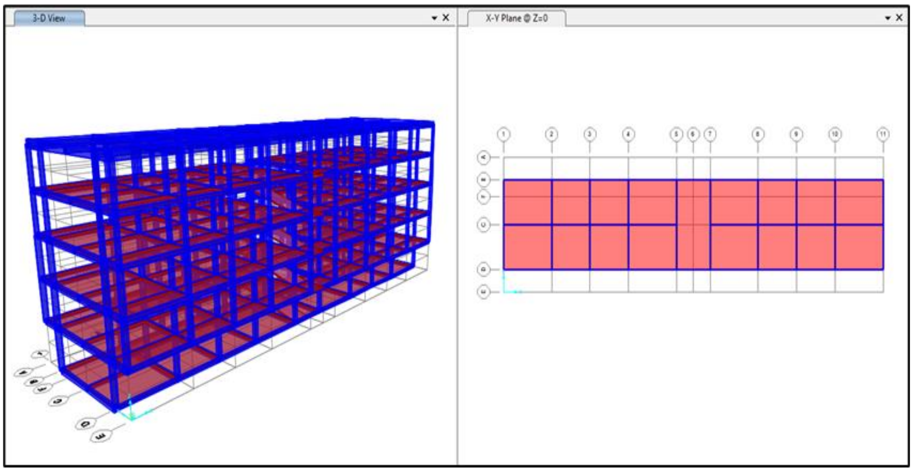

Figure 6. 3D view and typical floor plan of Building 2.

Table 2. Dimension on the structural members of Building 2.

Structural Members	Dimension (mm)		
Beam	200 x 300	200 x 400	200 x 500
	200 x 600		
Column	230 x 300	230 x 400	
Slab	135		

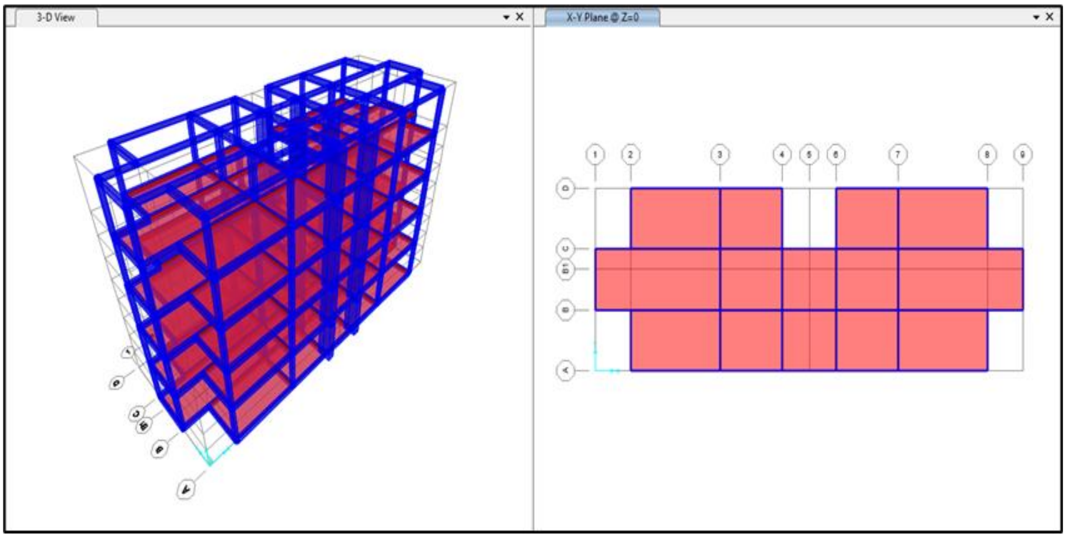

Figure 7. 3D view and typical floor plan of Building 3.

Table 3. Dimension on the structural members of Building 3.

Structural Members	Dimension (mm)		
Beam	200 x 350	200 x 400	150 x 300
	200 x 400		
Column	230 x 300	230 x 400	500 x 1000
Slab	135		

2.2 Capacity Spectrum Method (CSM)

Performance point analysis based on Capacity Spectrum Method (CSM) referring to ATC-40 [15] is a very useful tool in the evaluation design of existing concrete buildings. This method requires the determination of three crucial parameters such as the capacity curve, the demand curve, and the performance point under three different PGA. It provides a graphical representation of the structure's global force-displacement capacity curve and compares it with earthquake demand response spectra representations. CSM is beneficial because of its graphical nature, which allows for the visualization of the connection between demand and capacity when determining the point at which this capacity spectrum intersects with the earthquake demand. The capacity curve represented the ability of the structure to withstand the seismic demand while the demand curve represented the earthquake ground motion.

The demand and capacity curves will be plotted in terms of Acceleration Displacement Response Spectra (ADRS) format. This ADRS is a graph representation of spectral acceleration (Sa) in unit of m/s versus spectral displacement (Sd) in unit m. Demand curve expressed in terms of Sa and period, T based on the response spectrum in Eurocode 8 [14] with the conversion formula using Equation (1) as performed by Leslie and Naveen [9]. The following equation defined as the spectral displacement ordinate (Sd), the corresponding period (T) and spectral acceleration ordinate (Sa).

$$Sd = \frac{T^2}{4\pi^2} Sa \tag{1}$$

2.3 Performance Point Evaluation

Once the capacity and demand curves are established, an evaluation of the expected performance level of the building can be carried out by comparing the estimated target displacement on the demand curve with the actual displacement on the capacity curve under three different PGA of 0.12g, 0.14g, and 0.16g. In this study, the building performance criteria, as suggested by Harith et al. [16], have been adapted to suit the assessment of expected performance levels based on the performance point. The performance point represents the intersection of the demand and capacity curves, indicating the actual displacement demand of a building. The performance level of the building at various stages can be expressed using performance following the guidelines outlined in ATC-40 [15], as shown in Figure 8 described by Abd-Elhamed and Mahmoud [17]. It is important to note that as the displacement of buildings increases, the extent of damage also increases.

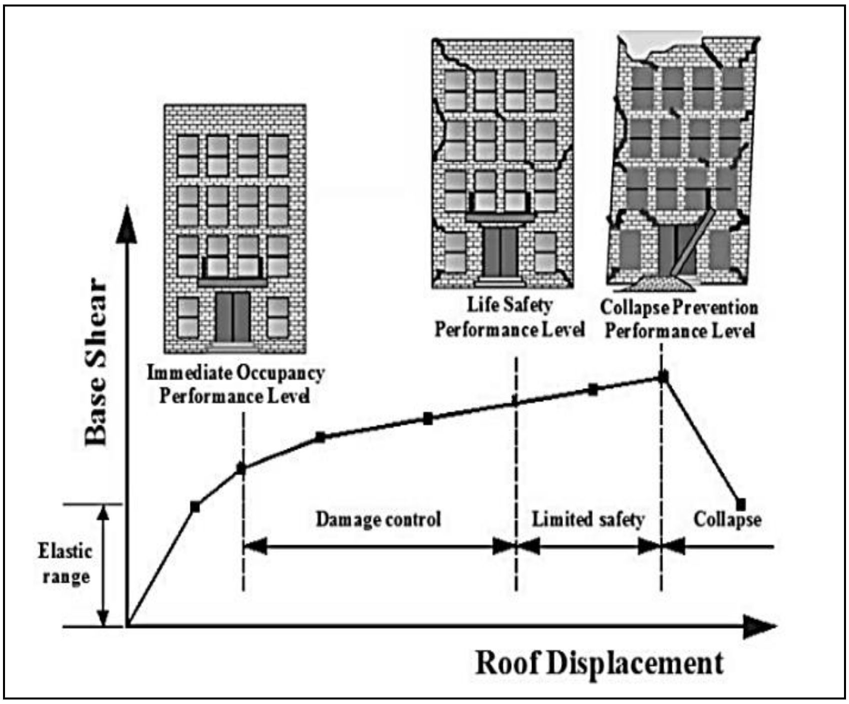

Figure 8. Illustration of building performance levels [15].

The previous study in Dya and Oretaa [18] mentioned that the different performance levels used in buildings describe the limiting damage state of a particular building. Immediate Occupancy (IO) represents a building condition in which the structure can withstand an earthquake without experiencing any structural or non-structural damage, but even if the building is affected by the earthquake, it remains recoverable. Life Safety (LS) signifies a condition where a building can endure an earthquake with minimal structural damage, ensuring the safety of people residing or present inside the building during the seismic event. Collapse Prevention (CP) pertains to a structural state in which a building sustains severe structural damage but does not collapse during an earthquake, thereby preventing a complete structural failure. Furthermore, the performance point is the intersection between demand spectrum and capacity curve as illustrated and described in Wooi et al. [19] and Atul and Sekar [20].

3. Results and Discussion

The buildings were subjected to the seismic performance of pushover analysis for two different load cases, termed Push-X and Push-Y in both the x-direction and y-direction, respectively under the various PGA. This capacity-demand curve relationship enables a direct comparison between the capacity and demand curves, indicating the precise intersection point known as the performance point. Figure 9-10 illustrate the performance point for Push-X and Push-Y, respectively, under a Peak Ground Acceleration (PGA) of 0.12g. Similarly, Figure 11-12 represent the performance point for Push-X and Push-Y, respectively, at a PGA of 0.14g. Finally, Figure 13-14 display the performance point for Push-X and Push-Y, respectively, at a PGA of 0.16g. The comparison of performance point, it is evident that each intersection of the demand and capacity curves are between LS and CP signifies the buildings require to be retrofitted specifically at 0.14-0.16g.

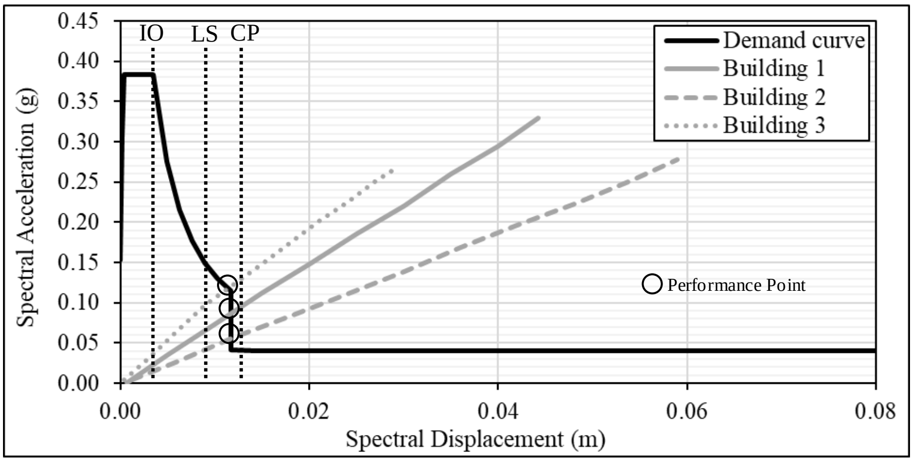

Figure 9. Performance point for Push-X under PGA of 0.12g.

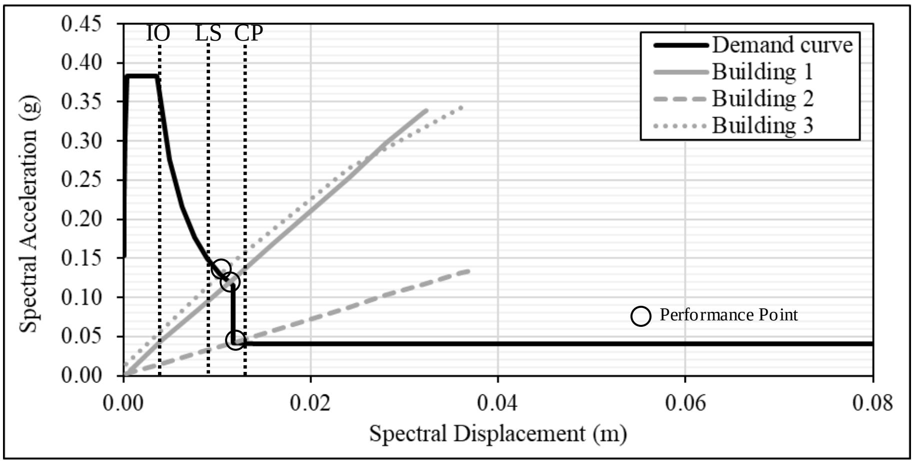

Figure 10. Performance point for Push-Y under PGA of 0.12g.

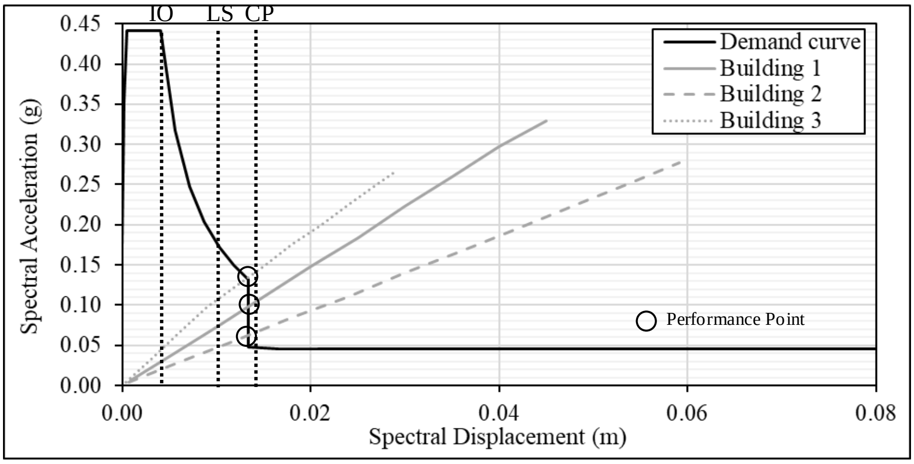

Figure 11. Performance point for Push-X under PGA of 0.14g.

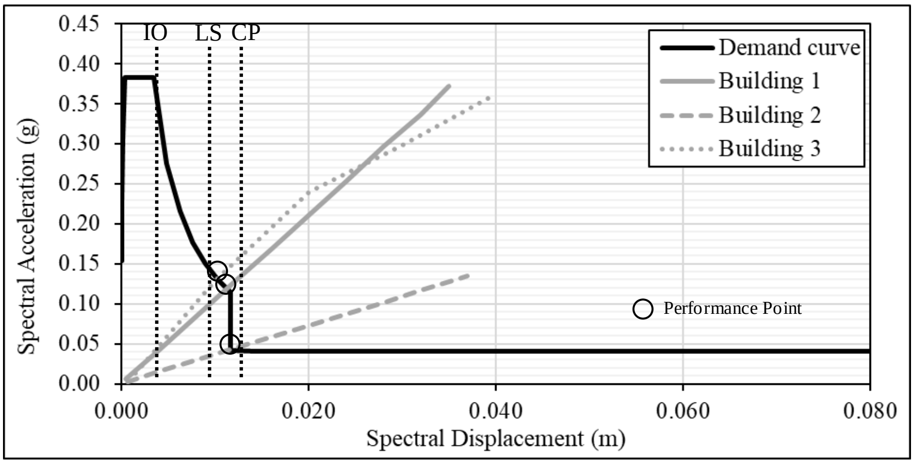

Figure 12. Performance point for Push-Y under PGA of 0.14g.

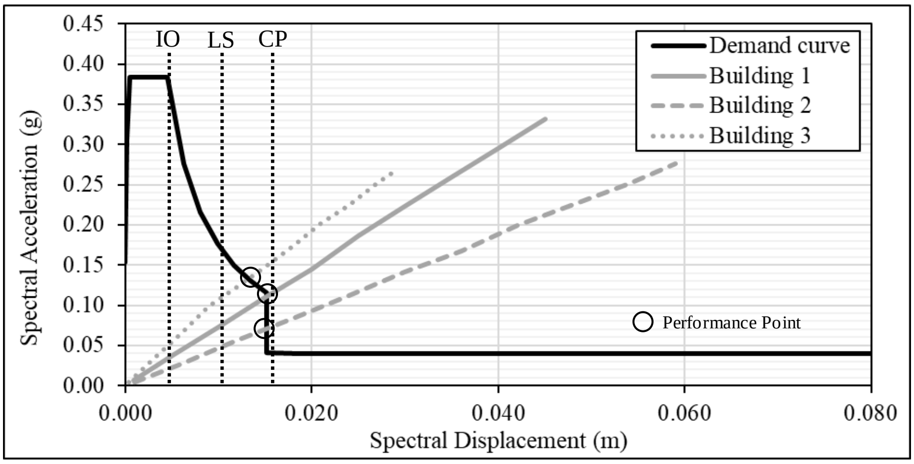

Figure 13. Performance point for Push-X under PGA of 0.16g.

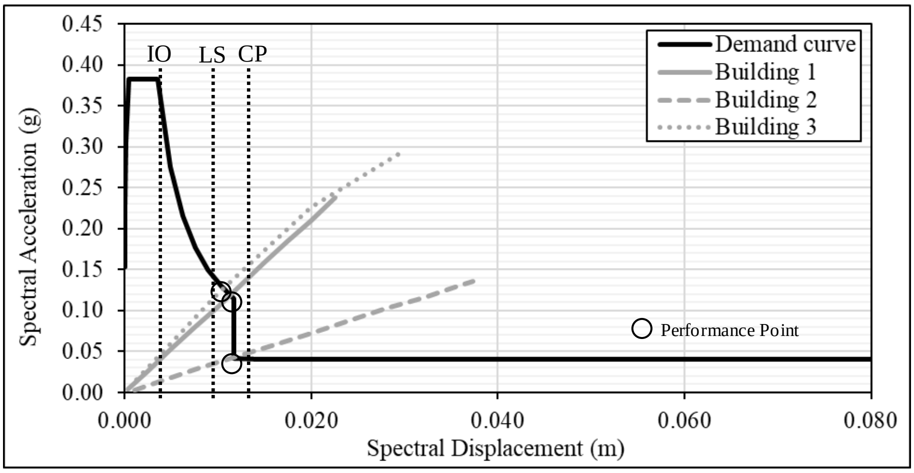

Figure 14. Performance point for Push-Y under PGA of 0.16g.

Table 4-5 present a tabulation of the roof displacements based on the performance point for each building, considering both Push-X and Push-Y directions across three distinct PGA values of 0.12g, 0.14g, and 0.14g, respectively. The correlation between displacement and PGA is a fundamental aspect when assessing the expected seismic performance level of buildings. Notably, as the PGA escalates, the displacement of buildings tends to escalate as well. This implies that more intense ground shaking or higher PGA levels can result in increased deformation and movement within the structure. A previous study conducted by Abd-Elhamed and Mahmoud [17] aligns with this notion, indicating that heightened seismic activity leads to greater building displacement. Their research concentrated on building evaluations subjected to 0.15g and 0.30g intensities, revealing that the building's performance point varies with the application of seismic forces in both the x-direction and y-direction.

Table 4. Expected displacement of buildings for Push-X under various PGA.

Building Name	**Peak Ground Acceleration (PGA)**			**Performance point**
	0.12 g	**0.14 g**	**0.16 g**	
Building 1	0.012 m	0.014 m	0.015 m	LS
Building 2	0.012 m	0.014 m	0.015 m	LS
Building 3	0.011 m	0.013 m	0.014 m	LS

Table 5. Expected displacement of buildings for Push-Y under various PGA.

Building Name	**Peak Ground Acceleration (PGA)**			**Performance point**
	0.12 g	**0.14 g**	**0.16 g**	
Building 1	0.011 m	0.011 m	0.012 m	LS
Building 2	0.012 m	0.012 m	0.012 m	LS
Building 3	0.010 m	0.010 m	0.011 m	LS

The performance point is linked to the inelastic roof displacement to assess how all buildings are expected to perform under varying PGA levels for both Push-X and Push-Y. It is evidence that the performance point in the elastic zone shows a good performance point. However, the performance point of buildings in the inelastic zones shows a poor performance point [21]. The inelastic zone is when buildings are subjected to dynamic loadings that exceed their elastic range and which damage will be permitted. A previous study conducted in Estêvão and Carvalho [7] proved that the performance point determined for RC buildings in the elastic zone is linked to no damage obtained grouped as the best-case scenario. Conversely, the performance point determined for RC buildings in the inelastic zone is categorized as the worst-case scenario. The overall buildings in Southeast Sabah show that they are prone to damage due to their performance point being associated to the inelastic roof displacement that occurs beyond the elastic range of deformation and is typically associated with the inelastic range.

In accordance with Maske et al. [22], if the performance point occurs with a minimal margin for strength and deformation capacity, it can be inferred that the buildings exhibited inadequate performance under the seismic forces applied and must undergo retrofitting to prevent significant future damage or structural failure. A level of damage that is considered tolerable for a particular building and a specific level of ground motion intensity is denoted as a performance level, particularly the state of Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). In Yadav et al. [23], the study concluded that the performance point considers both structural and non-structural performance criteria, incorporating aspects such as significant building damage, potential safety hazards, and the post-earthquake functionality of buildings. They identified the structural performance level which signifies a post-earthquake state where the building has undergone minimal structural damage.

A prior study by Ismaeil [24] found that buildings with performance levels that fell below a certain threshold after reaching the IO state were recommended to undergo retrofitting measures. The overall performance level of buildings in Southeast Sabah is categorized as LS state, thus the buildings may need to be retrofitted. In Mansor et al. [1], the authors recommended retrofitting existing buildings by incorporating steel diagonal braced frames with concrete frames as a highly effective technique for reinforcing the strength and stiffness of the structural system. This method allows for the enhancement of structural performance without significantly increasing the total weight of the building. There is considerable flexibility in the design process, with a multitude of configurations available for the diagonal braces, as well as the option to choose from various types of brace member sections. This adaptability in retrofit design ensures that the chosen approach can be tailored to the specific needs and requirements of the building, making it a versatile and efficient method for structural enhancement.

4. Conclusions

The seismic performance of three existing RC buildings was examined using pushover analysis as a relatively simple way to explore the non-linear behavior of buildings. This pushover analysis was employed to compare the performance levels of the buildings with the criteria outlined in ATC-40 [15], aiming to assess the extent of seismic damage experienced by the structure. The relationship between PGA and the performance point related to the inelastic roof displacement of buildings shows that as PGA increases, the displacement experienced by the building tends to increase. The expected performance level evaluation exposes overall buildings in the LS state due to their performance point in the inelastic zone that needs retrofitting the addition of steel diagonal braced frames into an existing building.

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Conflicts of Interest

The authors declare no potential conflict of interest with respect to the research and publication of this article.

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