

The Evaluation of Seismic Fragility Curves for High-rise RC Frames

Cho Wai Phyto Kyaw*, Khin Aye Mon

Abstract—In Yangon City's downtown area, Latha Township is a congested area with a high population density. Most of the buildings in the downtown area are RC residential buildings. Yangon is regarded as a medium seismicity region and is about 40 km west of the Sagaing Fault, which is a major active fault in Myanmar. For disaster seismic risk reduction on human lives and infrastructure, this study evaluates the seismic performance of high-rise reinforced concrete buildings under Service Level Earthquake (SLE), Design Basis Earthquake (DBE), and Maximum Considered Earthquake (MCE) hazard levels. The first objective is to evaluate the seismic performance of such buildings with varying length-to-width ratios under possible future earthquakes by using the mean values of maximum %ISDR, following FEMA 356 criteria. The second objective is to develop fragility curves based on results obtained from Incremental Dynamic Analysis (IDA) using SAP 2000. Hypothetical building models represent structures in Latha Township with material properties aligned with current construction practices, as informed by the Yangon City Development Committee (YCDC). Nonlinear Time History Analysis (NTHA) evaluates seismic performance, correlating inter-story drift ratios (%ISDR) with ground motion intensities, specifically peak ground acceleration (PGA). Nonlinear properties are modeled in compliance with ASCE 41-13 guidelines. This analysis aims to provide a risk transfer measure for those vulnerable high-rise structures in order to protect the properties of residents under possible future earthquakes.

Keywords—dynamic analysis, fragility curves, high-rise buildings, incremental non-linear time history analysis, inter-story drift ratios, peak ground acceleration

I. INTRODUCTION

THE buildings in seismically active regions experience the risk of earthquakes, which can significantly impact their structural integrity and can lead to extensive structural damage. Evaluating the damage caused by these events mitigate risks to life and property by understanding building response and fragility. A rapidly urbanizing city near the active seismic faults faces significant earthquake risk due to its geographic location and increasing number of residential buildings. The city's dense population and the prevalence of high-rise buildings, evaluating potential damage scenarios is critical for improving life safety and informing disaster mitigation strategies. By evaluating the fragility curves, this research provides valuable insights into the vulnerability of residential reinforced concrete building stock and contributes to the broader understanding of urban earthquake resilience in seismically active regions.

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According to the probabilistic seismic hazard analysis for Myanmar, the Yangon region can be regarded as a low-to medium-seismicity region. Some of the large earthquakes caused considerable damage to some buildings and some casualties in and around the Yangon region according to the previous pass records. Following a major earthquake, structural engineers must assess the feasibility of building occupancy. Therefore, seismic risk assessment should be conducted for the purpose of disaster mitigation to prevent casualties and losses. In Yangon, the downtown area is a highly populated and congested region, and the majority of the buildings in the downtown area are reinforced concrete buildings. Due to the advancements in computation techniques, deterministic evaluation methods are no longer adequate for characterizing seismic behavior under various earthquake events. The probabilistic methodology, as per FEMA guidelines, enhances the accuracy and reliability of seismic assessments in rehabilitation decisions.

To evaluate the seismic effects on RC structures, many researchers (Fatimah & Wong, 2021; Leti & Bilgin, n.d.; Massumi et al., n.d., 2021; Mwafy et al., 2006; Qu & Pan, 2022; Singh, 2021) have been performed many studies on the seismic effects on the single-degree-of-freedom and multi-degree-of-freedom structures by using non-linear static and dynamic analysis. Bazzurro et al. have developed guidelines for tagging that involve non-linear structural analyses performed prior to a mainshock to determine the residual capacity of a building in several different states of potential damage. Luco et al., proposed a methodology to compute the residual capacity of a mainshock-damaged building to develop a fragility for a mainshock-damaged building through incremental dynamic analysis.

In this study, the probability of damages for probabilistic seismic damage assessment in terms of fragility assessment is examined by the level of damages as an engineering demand parameter (EDP), which is usually the mean value of the maximum percent inter-story drift ratio (%ISDR) correlating them with ground motion intensity and peak ground acceleration (PGA). The representative 12th-story residential reinforced concrete buildings with length-to-width ratios of 1.23, 1.67, and 2 are selected as hypothetical buildings in Latha Township, Yangon. Nonlinear time history analysis (NTHA) is utilized to evaluate global building performance as per FEMA guidelines, and then the new development of fragility curves by using incremental dynamic analysis considers five performance limit states: Operational Level (OP), Immediate Occupancy Level (IO), Damage Control Level (DC), Life Safety (LS) and Collapse Prevention (CP). Figure 1 describes and summarizes the methodology framework for this study. The findings offer valuable insights into the seismic vulnerabilities of RC frames,

guiding the enhancement of the resilience of urban residential buildings.

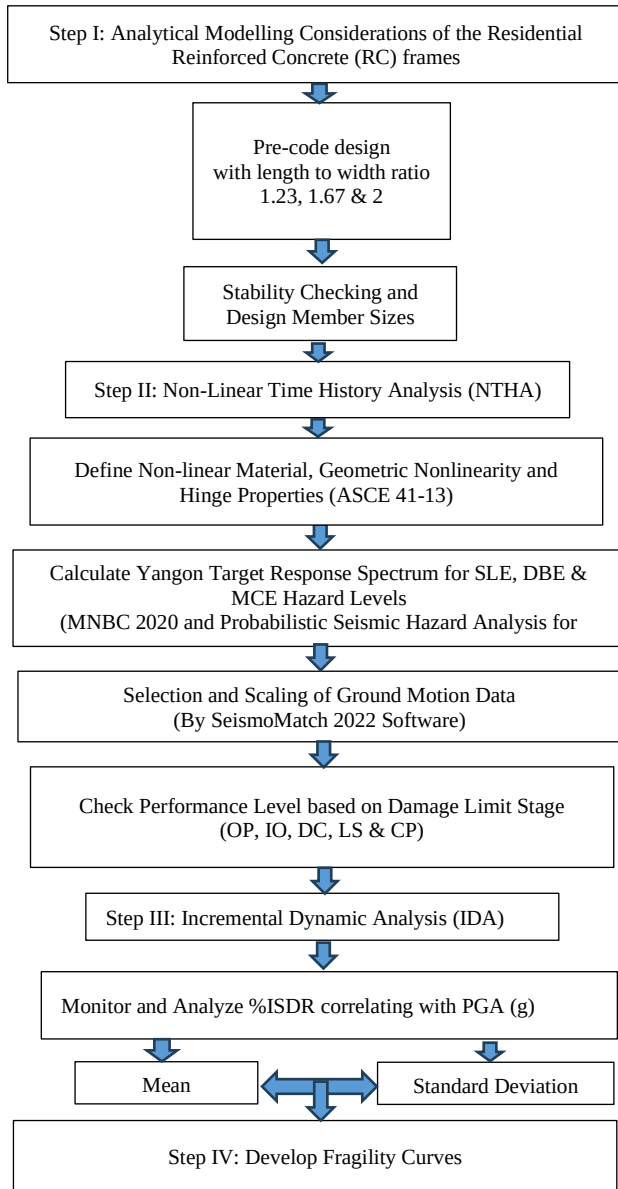


Fig. 1. Methodology framework

II. ANALYTICAL MODELLING

In this study, Latha townships in the downtown area of the Yangon region are selected as a case study because the downtown area is a highly populated and congested region. The plan configuration of the hypothetical building frames is chosen to be similar to the existing residential apartment buildings in Latha township. In this study, high-rise (HR) RC frames are modeled as HR-1 (58 feet length and 47 feet width), HR-2 (42 feet length and 70 feet width), and HR-3 (25 feet length and 49 feet width) with a typical story height of 10 feet and a rectangular shape. In Latha township, nearly 26% of the high-rise RC buildings are designed without considering seismic loadings according to the collected detailed information of the case study area. This study focuses on evaluating and comparing reinforced concrete frames for high-rise (HR) with length-to-width ratios of 1.23, 1.67, and 2, which are designed by pre-code (PC).

According to seismic design levels of HAZUS-MH MR4, RC buildings that are designed without considering

seismic loadings are defined as pre-code buildings, and RC buildings that are designed considering seismic loadings are defined as moderate-code buildings. In this paper, high-rise pre-code buildings are selected as case study RC frames because these buildings can be the more vulnerable type than other moderate-code buildings under possible future earthquakes. Therefore, seismic risk assessment is necessary to conduct in order to evaluate the vulnerability condition of existing buildings and to predict the probability of damages.

A. Loading Considerations and Load Combinations

Loading considerations and load combinations for these models are following MNBC 2020. A total of 15 design load combinations for pre-code design are shown in Table I. The structural system, material properties, and seismic parameters are considered to be consistent with the current practice in the construction industry, according to YCDC. Structural stability for pre-code design is checked in accordance with MNBC 2020. 3D models of high-rise RC frames are shown in Figs. 2 to 4, and design results of member sizes for case study RC frames are shown in Table II. In this study, the material properties and the wind parameters are as follows:

Concrete compressive strength = 2500 psi

Steel yield strength = 40000 psi

Windward coefficients = 0.8

Leeward coefficients = 0.5

Basic wind speed = 100 mph (Yangon wind speed)

Method used = Diaphragm Method

Exposure Type = B

Wind important factor = 1 (Building occupancy = II)

TABLE I
SELECTED LOAD COMBINATIONS

No.	Load Combinations
1	1.4 DL
2	1.2 DL + 1.6 LL
3	1.2 DL + 1 LL
4	0.9 DL ± 1.6 WX
5	0.9 DL ± 1.6 WY
6	1.2 DL ± 1.6 WX + 1 LL
7	1.2 DL ± 1.6 WY + 1 LL
8	1.2 DL ± 0.8 WX
9	1.2 DL ± 0.8 WY

TABLE II
DESIGNED MEMBER SIZES

Case Study	Column	Floor Level	Sizes (in x in)	Beam	Sizes (in x in)
HR - 1	C1	Base to 2F	18 x 18	FB1	9 x 9
	C2	2F to 4F	16 x 16	FB2	10 x 12
	C3	4F to 6F	14 x 14	FB3	10 x 14
	C4	6F to 8F	12 x 12	FB4	12 x 16
	C5	8F to 10F	10 x 10		
	C6	10F to 12F	9 x 9		
HR - 2	C1	Base to 2F	18 x 18	FB1	9 x 9
	C2	2F to 5F	16 x 16	FB2	12 x 12
	C3	5F to 8F	14 x 14	FB3	12 x 14
	C4	8F to 11F	12 x 12	FB4	12 x 18
	C5	11F to 12F	9 x 9		
HR - 3	C1	Base to 2F	18 x 18	FB1	9 x 9
	C2	2F to 5F	16 x 16	FB2	9 x 12
	C3	5F to 8F	14 x 14	FB3	9 x 14
	C4	8F to 11F	12 x 12	FB4	9 x 16
	C5	11F to 12F	9 x 9	FB5	10 x 18

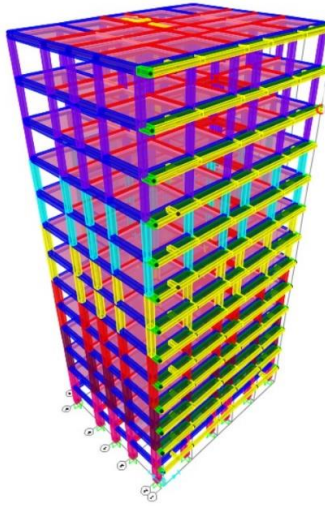


Fig. 2. 3D view of HR - 1

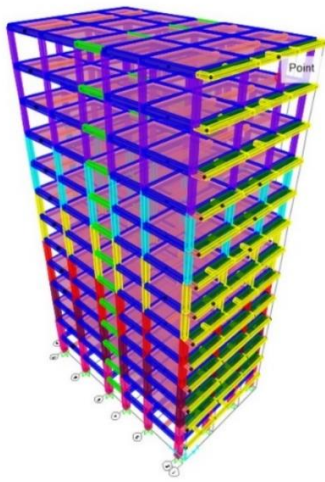


Fig. 3. 3D view of HR - 2

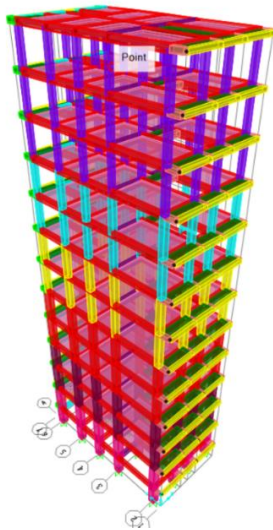


Fig. 4. 3D view of HR - 3

III. EVALUATION OF GLOBAL SEISMIC PERFORMANCE

Non-linear time history analysis (NTHA) is utilized to assess structural response and evaluate building performance after an earthquake. In this study, nonlinear time history analysis (NTHA) is utilized to evaluate building performance by five performance limit states such

as fully operational level (OP, %ISDR = 0.5%), immediate occupancy (IO, %ISDR = 1%), damage control (DC, %ISDR = 1.5%), life safety (LS, %ISDR = 2%) and collapse prevention (CP, %ISDR = 2.5%). The global structural performance level depends on the mean value of maximum structural response (% ISDR) under various earthquake excitations, according to ASCE 41-13.

A. Non-linear Time History Analysis

Non-linear time history analysis requires the determination of geometric and material nonlinearity. Both are crucial for accurately modeling and analyzing structures and materials that exhibit non-linear behavior. In this study, P-delta effects are considered geometric non-linear. The material non-linear properties of each material, hinge properties, and component in the structure are quantified by strength and deformation capacities, which depend on the modeling assumptions according to FEMA 356 and ASCE 41-13. Moment M3 hinge is assigned at the ends of the beams, and fiber P-M2-M3 hinge is assigned at the ends of columns. Default expected concrete compressive strengths and reinforcing steel are determined by multiplying the lower-bound value by an appropriate factor selected from Table 10-1 (ASCE 41-13). The expected material properties of concrete and reinforcing steel are shown in Table III.

TABLE III
EXPECTED MATERIAL PROPERTIES

Design Code	Expected Material Properties
Pre-code	$f'_c = 2500 \text{ psi} \times 1.5 = 3750 \text{ psi}$ $f_y = 40000 \text{ psi} \times 1.25 = 50000 \text{ psi}$

B. Ground Motion Selection

Secondly, appropriate ground motions shall be selected from events within the same general tectonic regime and having generally consistent magnitudes and fault distances as those controlling the target response spectrum. In this study, seismic hazards for active Sagaing fault southern segment SGSMS-03 are considered to generate ground motion for the study area. The Sagaing Fault (a strike-slip fault), which is located about 40 km east of Yangon. The target spectral response acceleration parameters for expected Yangon SLE, DBE, and MCE hazard levels are calculated and shown in Fig. 5.

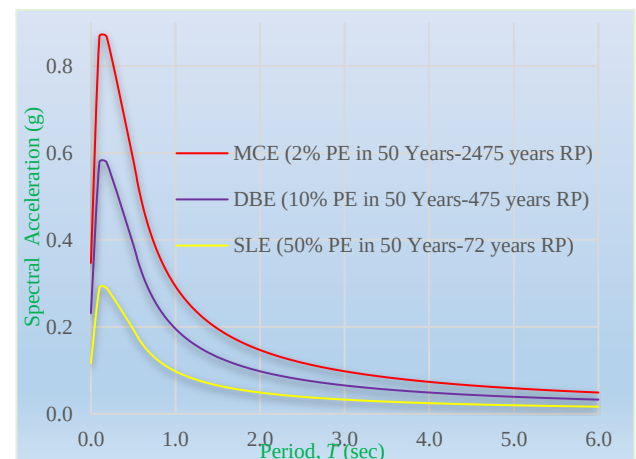


Fig. 5. Estimated Yangon target response spectrum

For this study, a minimum of eleven sets of strong ground motions are selected for each target spectrum that are loaded from the Pacific Earthquake Engineering Research Centre (PEER) NGA website Peer Ground Motion Database by selecting fault type (strike slip), soil type (site class D), source distance, and magnitude that are consistent with the expectation of an earthquake in Yangon. The selected ground motion records are scaled with the expected Yangon target response spectrum by using SeismoMatch software, which is shown in Table IV and Fig. 6, respectively.

TABLE IV
SELECTED EARTHQUAKE GROUND MOTIONS

Event	Magnitude	Duration (sec)	R_{JB} (km)	R_{rup} (km)	$V_{s,30}$ (m/sec)
Morgan hill	6.19	15.3	39.08	39.08	288.6
Chi-Chi Taiwan	6.2	21.5	87.07	87.07	292.61
Victoria, Mexico	6.33	19	18.53	18.53	242.05
Big Bear	6.46	12.1	39.52	39.52	359
Imperial Valley	6.53	10.8	30.33	30.33	316.64
Superstition Hills	6.54	14.3	17.03	17.03	208.71
Kobe-Japan	6.9	19.4	11.34	11.34	256
Hector Mine	7.13	23.1	64.08	64.08	324.62
Duzce, Turkey	7.14	9	12.02	12.02	293.57
Landers	7.28	18.9	23.62	23.62	353.63
Denali, Alaska	7.9	23.1	42.99	42.99	341.56

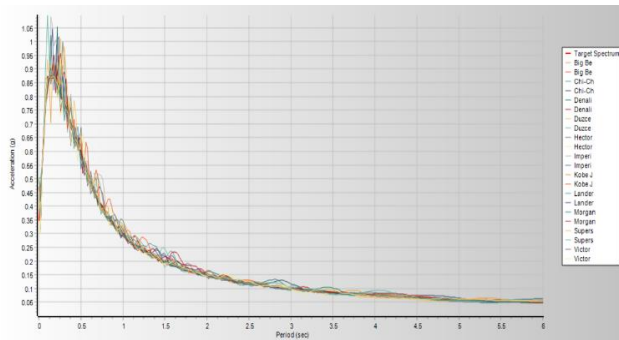


Fig. 6. Scaled spectral response acceleration

C. Evaluated Global Performance Level of Case Studies RC Frames

To fulfill the first aim of this study, the non-linear time history analysis was performed subjected to 11 sets of ground motion acceleration under different hazard levels. Based on each ground motion, the non-linear time history analysis is performed by using SAP 2000 software. After monitoring the analysis results, %ISDR was estimated as crucial engineering demand parameters correlating them with ground motion intensities (PGA) by using an Excel sheet. The global structural performance level of case study RC frames was checked on the average structural response (% ISDR) under 11 sets of earthquake excitations. Thus, the mean value of percent inter-story drift ratios under different hazard levels of high-rise RC frames is shown in the following Figs. 7 to 9. The global

structural performance level of high-rise building frames is shown in Table V, which depends on the mean value of maximum structural response (% ISDR) under 11 sets of earthquake excitations.

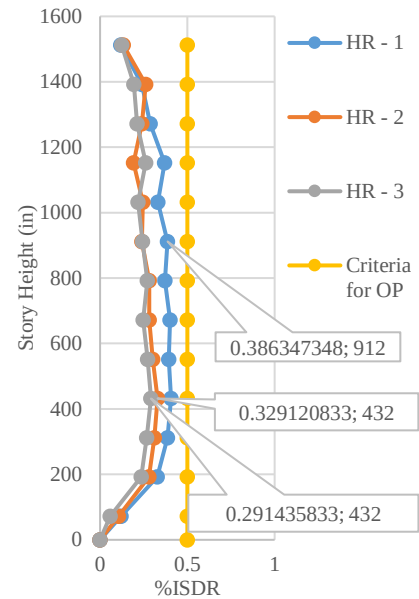


Fig. 7. Mean value of %ISDR under SLE hazard level

TABLE V
EVALUATED GLOBAL PERFORMANCE LEVELS

Case Study	Earthquake Hazard Level	Mean value of max: % ISDR	Performance Level
HR - 1	0.1 g	0.386	Within OP
	0.2 g	0.801	Between OP and IO
	0.3 g	1.628	Between DC and LS
HR - 2	0.1 g	0.329	Within OP
	0.2 g	0.653	Between OP and IO
	0.3 g	1.308	Between IO and DC
HR - 3	0.1 g	0.291	Within OP
	0.2 g	0.576	Between OP and IO
	0.3 g	1.113	Between IO and DC

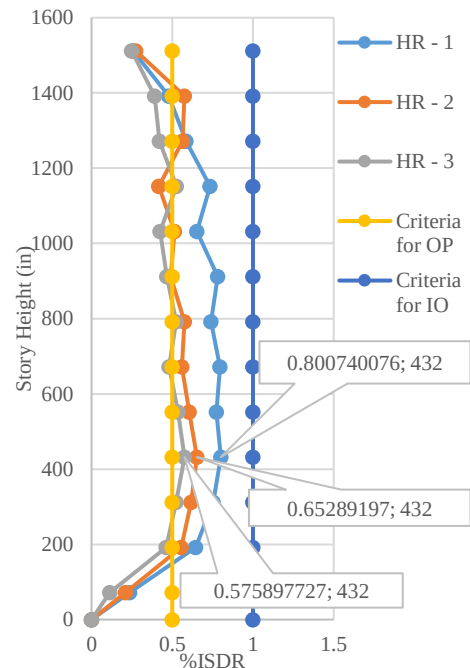


Fig. 8. Mean value of %ISDR under DBE hazard level

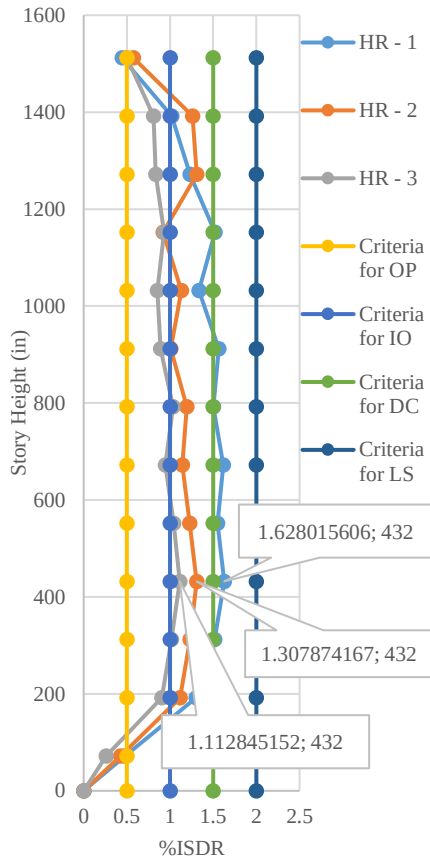


Fig. 9. Mean value of %ISDR under MCE hazard level

After all of the performance analysis results were comprehensively speculated, the mean value of %ISDR for all high-rise models is between 0.3% and 0.4% under the SLE hazard level. So, the seismic performance of all high-rise pre-code buildings remains operational under peak ground acceleration of 0.1 g. Under DBE hazard level (PGA of 0.2 g), all high-rise models are expected to sustain minor damage to structural elements but remain safe to occupy and require minimal repairs. All of the high-rise RC frames are expected to cause moderate damage and are repairable under a PGA of 0.3 g, but the structures remain stable enough to protect building occupants from life-threatening harm. Under strong ground motion beyond PGA of 0.4 g, above RC frames suffer severe damage but avoid collapse, providing a last safety margin. At the collapse prevention (CP) level, if the structural frames are damaged by more than 30% probability of damages, they may be collapsed, and building occupants should evacuate as it could be dangerous.

IV. FRAGILITY CURVES

Fragility curves are used analytically to estimate the risk of the seismic effect on the structural models, which are considered useful tools to predict the probability of damage to any structural systems. In this study, fragility curves are developed by using incremental dynamic analysis (IDA) based on various seismic parameters, such as peak ground acceleration (PGA) and damage measure (%ISDR). These curves are used to predict seismic risk on building frames, using the two main parameters needed to develop the fragility curves: mean and standard deviation. In this study, the equation below has already been used by Y.E. Ibrahim, where Φ is the standard normal cumulative

distribution function, μ and σ are the mean and standard deviation of logarithm PGA, and D is the damage state.

$$P[D/PGA] = \Phi \left[\frac{\ln(PGA) - \mu}{\sigma} \right] \quad (1)$$

A. Incremental Dynamic Analysis and Development of Fragility Curves

Incremental dynamic analysis (IDA) is applied to evaluate structural response under different ground motion intensities, providing more realistic results. IDA is used to analyze the seismic performance of structures subjected to earthquakes until the collapse point. The intensity measure (PGA) scales by 0.1 g until the structural dynamic instability. IDA curves are developed based on the relationship between inter-story drift ratio and PGA intensity. All of the RC frame models were carried out until the point of structural dynamic instability by using incremental dynamic analysis. Equation 1 was used to create the fragility curves for the building frames. Fig. 10 to 12 shows fragility curves for high-rise RC frames with different length-to-width ratios (1.23, 1.67 & 2), which were designed by pre-code.

This study investigated that high-rise RC frames are expected to suffer 100% probability of damages at operational level beyond PGA of 0.3 g. All of the RC frames have nearly a 50% probability of damages under peak ground acceleration (PGA) of nearly 0.5 g when half of the structure has the form of a life-threatening collapse. According to historical earthquake records, if Yangon experienced an earthquake with a PGA of more than 0.3 g, the pre-code buildings would not be able to withstand it. The buildings experience severe damage, providing a last safety margin at PGA 0.4 g. If a strong earthquake with a PGA of nearly 0.7 g were to occur in Yangon, it would be concluded that the types of high-rise buildings that have not been designed to take into account the seismic load in the study area were at high risk of collapse and pose a threat to the lives of the residents.

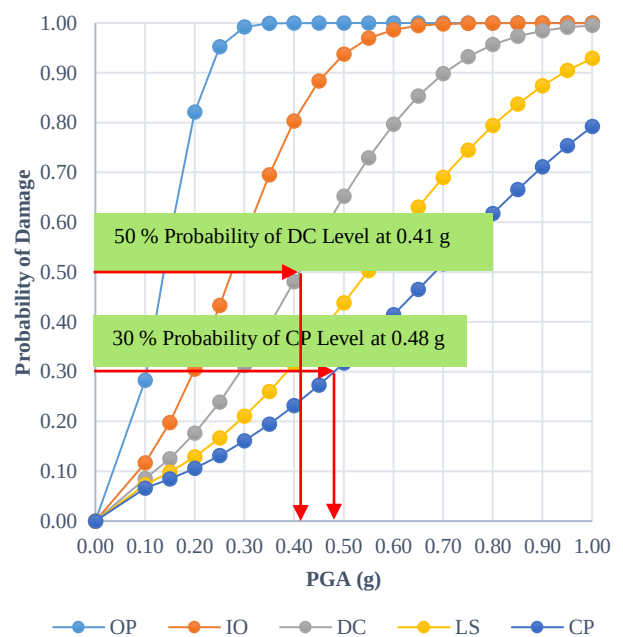


Fig. 10. Fragility curve for HR - 1

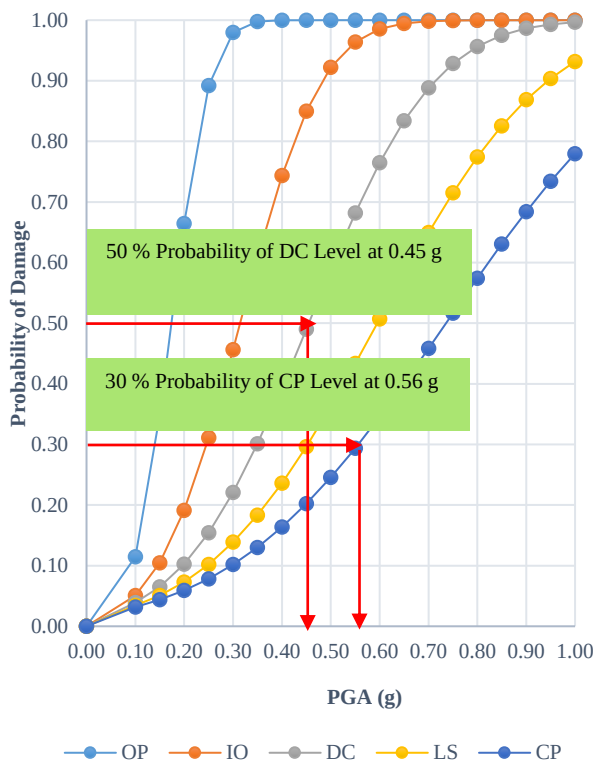


Fig. 11. Fragility curve for HR – 2

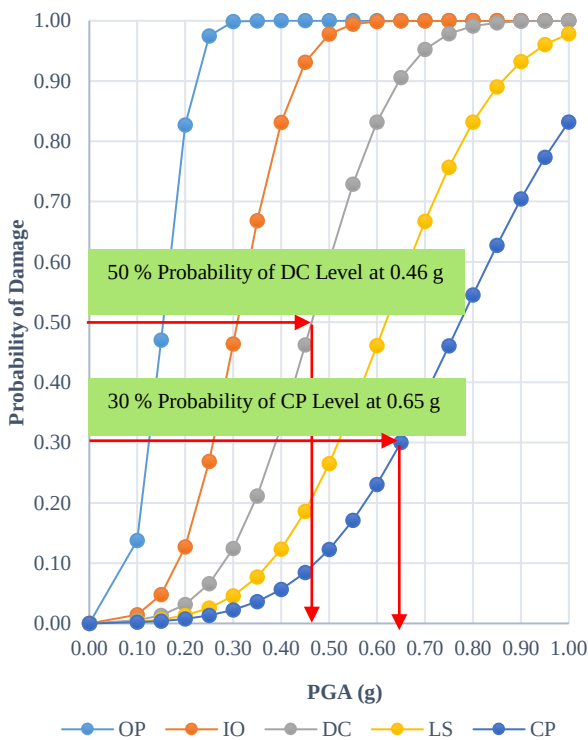


Fig. 12. Fragility curve for HR – 3

B. Comparison of Fragility Curves with different L/B Ratios

Comparison of fragility curves for high-rise pre-code designs with different length to width ratios under damage control (DC) level and collapse prevention (CP) level are shown in Figure 13 and Table VI. After comparing all the fragility curve analysis results, the RC building frames with a length-to-width ratio of 1.23, 1.67, and 2 have 50% probabilities of damages at DC level beyond a PGA of 0.45

g. The RC building frames with length-to-width ratios of 1.23, 1.67, and 2 have 30% probabilities of damages at CP level beyond a PGA of 0.5 g. According to the fragility curve analysis results of this study, it was found that the difference in length to width ratio effects did not make a significant difference in the probabilities of damages.

Observations of the fragility curve and non-linear time history analysis show that high-rise reinforced concrete (RC) frames in Latha Township have significant seismic vulnerabilities. Peak ground acceleration (PGA) of 0.1 g is sufficient for these buildings to function, but 0.2 g causes minimal damage, and earthquakes with PGAs greater than 0.3 g are expected to cause catastrophic collapses. It is evident that older buildings in Latha township experience significant damage under the possible future earthquakes with PGAs larger than 0.3 g.

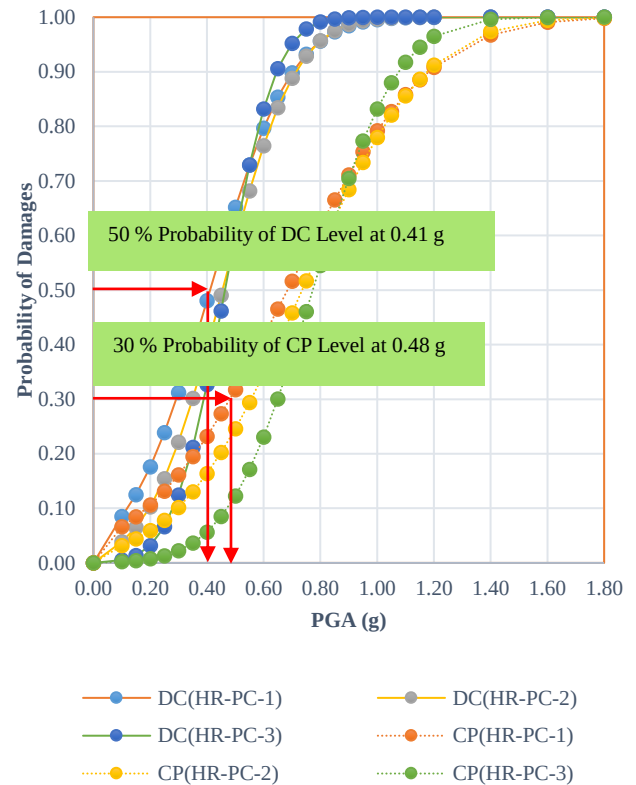


Fig. 13. Comparison of fragility curve with different L/B ratios

TABLE VI
COMPARISON OF PROBABILITY OF DAMAGES

Case Study	50% Probability of Damages at DC Level	30 % Probability of Damages at CP Level
HR-1	0.41 g	0.48 g
HR-2	0.45 g	0.56 g
HR-3	0.46 g	0.65 g

IV. DISCUSSIONS AND CONCLUSIONS

Based on the non-linear time history analysis results carried out, high-rise RC frames in Latha township have been selected as a case study. This study found that high-rise RC frames perform well under peak ground acceleration of 0.1 g but suffer minor damage under peak ground acceleration of 0.2 g. The existing structural system is adequate to resist gravity and wind loadings assigned to the building; however, it is foreseen unable to resist any

strong earthquake that could hit Yangon in the future. Yangon may have experienced an earthquake with a PGA of more than 0.3 g; the pre-code buildings would not be able to withstand it. Therefore, those buildings need to be retrofitted and strengthened.

From the observation of fragility curves, results revealed that high-rise RC buildings in Latha Township with a length-to-width ratio of 1.23, 1.67, and 2 suffer a 50% probability of damages beyond PGA of nearly 0.4 g, 0.5 g, and 0.6 g, respectively. Therefore, it would be concluded that the difference in length to width ratio effects did not make a significant difference in the probabilities of damages. To mitigate the probability of damages, these building frames need to be updated with design practices to a performance-based seismic design code and need to be strengthened under a possible future strong earthquake.

From the above observations, it is recommended that the particular retrofitting techniques such as shear walls, steel bracings, base isolators, dampers etc; that focus on enhancing the seismic resilience of high-rise residential RC buildings in Latha Township. From the political point of view, the local authorities should prepare the investigation of performance-based seismic design codes for all new constructions and investigate a well-suited retrofitting technique for existing old buildings in high seismic zones that could improve the structural stability, lateral load resistance and seismic performance. During the future seismic events, for protecting the catastrophic damage of infrastructure and life property, the previous results highlight the critical need for strong policy frameworks and focused retrofitting measures. Through the use of these suggestions, the city can greatly improve its earthquake resistance.

The above findings from the high-rise residential RC frames in Latha Township, Yangon region provide valuable insights into seismic risk assessment and mitigation strategies. The transferability to other regions depends on several factors, including seismic hazard levels, target response spectral acceleration at the project site, site soil profiles, building typologies, building structural system, building types, local building construction practices, and local building codes.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

CONTRIBUTIONS

This study mainly focuses on the seismic fragility curves for high-rise reinforced concrete building frames. The theoretical analysis of analytical modelling for high-rise RC frames plays an important role in enhancing the performance during an earthquake. This study could be provided to evaluate building performance level after an

earthquake to reduce potential impact on human life and infrastructure.

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