Seismic assessment of multi-storey residential building using fragility curve and capacity demand response spectrum

Cite as: AIP Conference Proceedings **2532**, 040008 (2022); https://doi.org/10.1063/5.0110054
Published Online: 28 November 2022

Kay Dora Abd Ghani, Noor Syafeekha Mohamad Sakdun, Rini Kusumawardani, et al.

Seismic Assessment of Multi-Storey Residential Building using Fragility Curve and Capacity Demand Response Spectrum

Kay Dora Abd Ghani[1, a)], Noor Syafeekha Mohamad Sakdun[1], Rini Kusumawardani[2], Abdul Fatah Abdul Hamed[1] and Mohd Amirul Hafiz Roslan[1]

[1]*School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia.*

[2]*Department of Civil Engineering, Universitas Negeri Semarang (UNNES), Kampus Unnes Gd E4, Sekaran, Gunungpati, Semarang 50229, Indonesia.*

[a)] Corresponding author: kaydora@uitm.edu.my

Abstract. Malaysia mostly experiences long-distance tremors caused by earthquake events from nearby countries. The majority of low-rise to medium-rise residential reinforced concrete buildings in Malaysia are designed with inadequate reinforcement detailing to cater for lateral loading. This paper presents findings related to seismic assessment of multi-storey residential buildings using the fragility curve and capacity-demand response spectrum. The main objective of this paper is to evaluate the vulnerability of residential multi-storey buildings with strong beam and weak column designed mechanisms subjected to Design Basis Earthquake and Maximum Considered Earthquake with peak ground acceleration of 0.12g and 0.22g, respectively. Ruaumoko2D programme was used to determine the load and displacement values of the building subjected to the 2015 Ranau earthquake with PGA 0.14g. The ductility of the prototype building was calculated from the load and displacement graph. The value of ductility was used to develop the fragility curve based on damage state characterization in accordance to FEMA273. The findings from the fragility curve show that the building would experience minor to moderate damage and can be repaired or retrofitted after the earthquake events with peak ground acceleration of 0.12g and 0.22g. This study also presents the result of the capacity-demand response spectrum of the building subjected to Design Basis Earthquake and Maximum Considered Earthquake in accordance with Eurocode 8 specifications. The result from the capacity demand response spectrum shows that the building would not survive when subjected to the earthquake excitation with peak ground acceleration 0.22g and exceeds more than 5.5 Richter Scale. This study is important to provide an understanding of the seismic behaviour of the multi-storey non-seismic designed for residential buildings in Malaysia.

INTRODUCTION

Malaysia is located on the Eurasian Plate which was surrounded by Indo-Australian Plate and Philippine's Plate. Furthermore, Malaysia is blessed because it is located quite a distance from the famous tectonic boundaries called the Pacific Ring of Fire. This region is well known as a path along the Pacific Ocean identified as the location of the active volcanoes and earthquakes activities. Therefore, Malaysia often can feel the tremors when Indonesia get hit by the earthquake since Malaysia is the closest country to the mainland of Sumatra, Indonesia. For instance, the long-distance effect of the 2004 Aceh's Tsunami impacted Kuala Muda Kedah and part of the coastal area in Penang which caused severe damage to the buildings affected. On the other hand, Malaysia also experienced series of very low-intensity local earthquakes along Bukit Tinggi fault lines and several moderate intensity earthquakes caused by active fault zones in Ranau and Lahad Datu [1]. The Ranau Earthquake which happened in June 2015 with the magnitude 6.0 Scale Richter and the epicentre was right under Mount Kinabalu has caused severe damages to many reinforced concrete buildings. Figure 1 shows the damages that occurred at the school building of SMK Mat Salleh Ranau, Staff's Quarters SMK Ranau and Staff's Quarters Hospital Ranau after the earthquake. From the figure, most of the damages occurred at the beam-column joints and at the column itself were mostly occurred at the ground level of the building

Proceeding of the International Conference on Advances in Civil Engineering and Science Technology (ICACEST2021)
AIP Conf. Proc. 2532, 040008-1–040008-10; https://doi.org/10.1063/5.0110054
Published by AIP Publishing. 978-0-7354-4274-0/$30.00

[2]. Due to local earthquakes and tremors occurring in neighbouring countries, the local authorities, engineers and designers have started to worry about the seismic vulnerability of public buildings in Malaysia. Most of the common multi-storey buildings in Malaysia are designed as soft-storey mechanisms (or also known as strong beam and weak column design). Soft story buildings are vertically irregular structures that often become weakened or collapsed after a major earthquake [3]. The type of design caused the building weak in lateral load resistance. There is an existing path of plastic hinge propagations which is dominant at the soft-storey columns due to the moments concentrated at the soft storey level [4].

During an earthquake event, the acceleration of ground motion is measured as the peak ground acceleration (PGA). PGA has been used as a dominant ground motion parameter in many research related to structural and earthquake engineering, nevertheless, the potential damage of structures in any earthquake events are commonly reflected by the value of PGA. Hence, this study aims to develop the seismic assessment of multi-storey residential buildings using the fragility curve and capacity-demand response spectrum and to evaluate the vulnerability of residential buildings subjected to Design Basis Earthquake (PGA = 0.12g) and Maximum Consider Earthquake (PGA = 0.22g). A six-storey Barat Daya Health Department Staffs' Quarters, Pulau Pinang is chosen as the prototype building in this study.

a) Damaged column in the main block of SMK Mat Salleh Ranau

a) Beam-column joint damaged at Staff Quarters Hospital Ranau

c) Beam-column joint damaged at Staff Quarters SMK Ranau

FIGURE 1. Structural damages at few school and public buildings after the 2015 Ranau Earthquake.

RESEARCH METHODOLOGY

Figure 2 shows the research framework of this study. The non-linear modelling of this prototype building was carried out by [5] to obtain the hysteresis behaviour when subjected to the 2015 Ranau earthquake record with peak ground acceleration, PGA=0.14g. The load and displacement values were used to calculate the ductility of the building. Then, seismic assessment for the prototype building was carried out using the fragility curve and capacity-demand response spectrum. The development of the fragility curves is to identify the damage state level using the guidance described by FEMA273 [9]. The equation developed from [6] was used to obtain the fragility curve under Design Basis Earthquake (DBE) with PGA = 0.12g and Maximum Considered Earthquake (MCE) with PGA = 0.22g for Ranau Earthquake. From the fragility curve analysis, the confidence interval (CI) value can be predicted to understand the damage states of the studied building. The capacity-demand response spectrum for the multi-storey residential building was developed in accordance with Eurocode 8 [7].

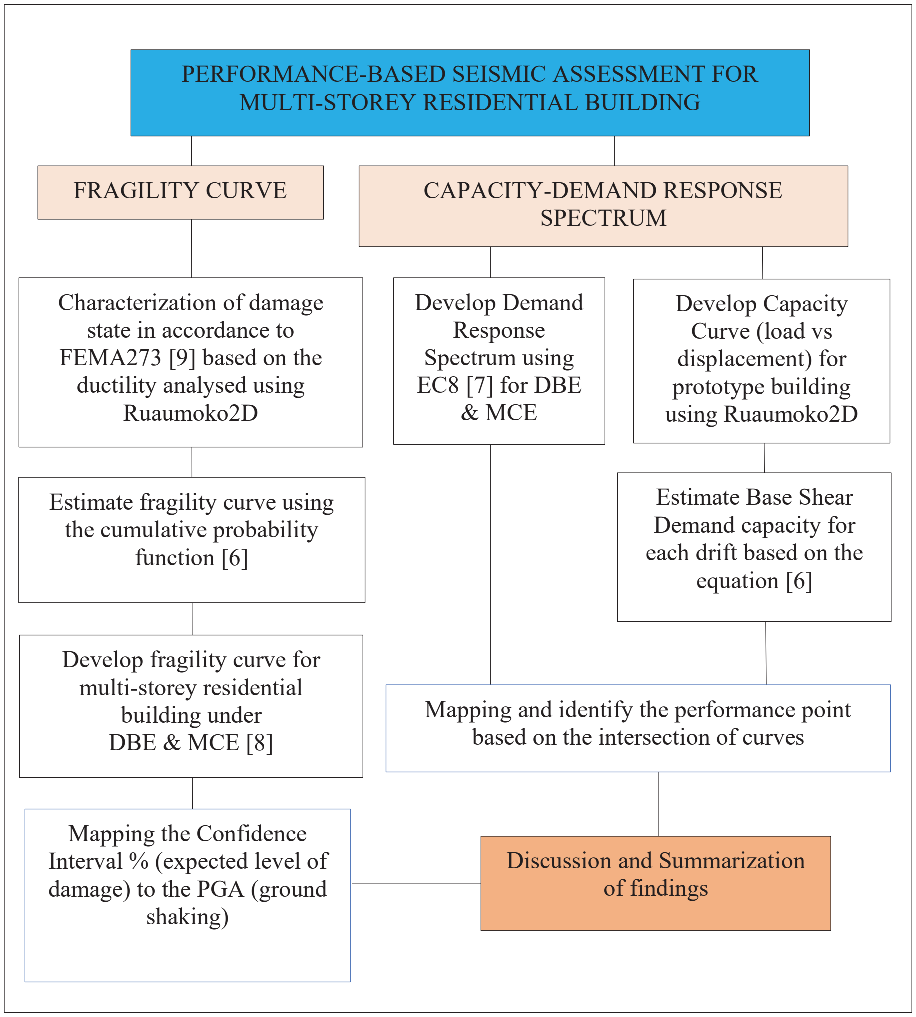

FIGURE 2. Research framework of this study

Selection of Prototype Building

Figure 3 shows the three dimensional of six-storey prototype building namely the Barat Daya Health Department Staff's Quarters, Pulau Pinang, Malaysia [5]. The lateral displacement was obtained by modelling the frame member structure by inserting the nodes and elements number of the multi-storey residential building. The total nodes and elements for this building were 70 nodes and 114 elements as shown in Figure 4. The building was designed in accordance with British Standard (BS8110) and the concrete strength of 35 N/mm^2. Three beam sizes (b x h) were used with various beam lengths which are 250mm x 475mm, 250mm x 750mm and 200mm x 350mm; 2 column sizes of 250mm x 250mm and 350mm x 250mm; the slab thickness was taken as 150mm and the total weight, W is calculated as 10,500 kN.

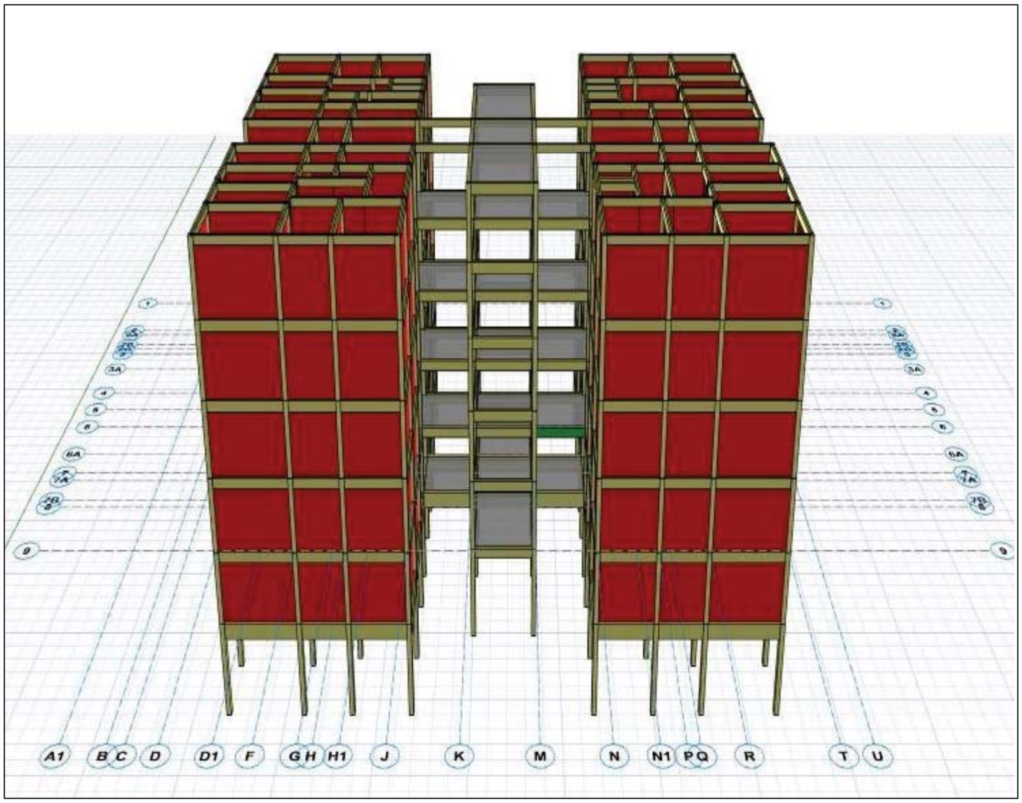

FIGURE 3. Front view of the prototype building using Ruaumoko2D model [5]

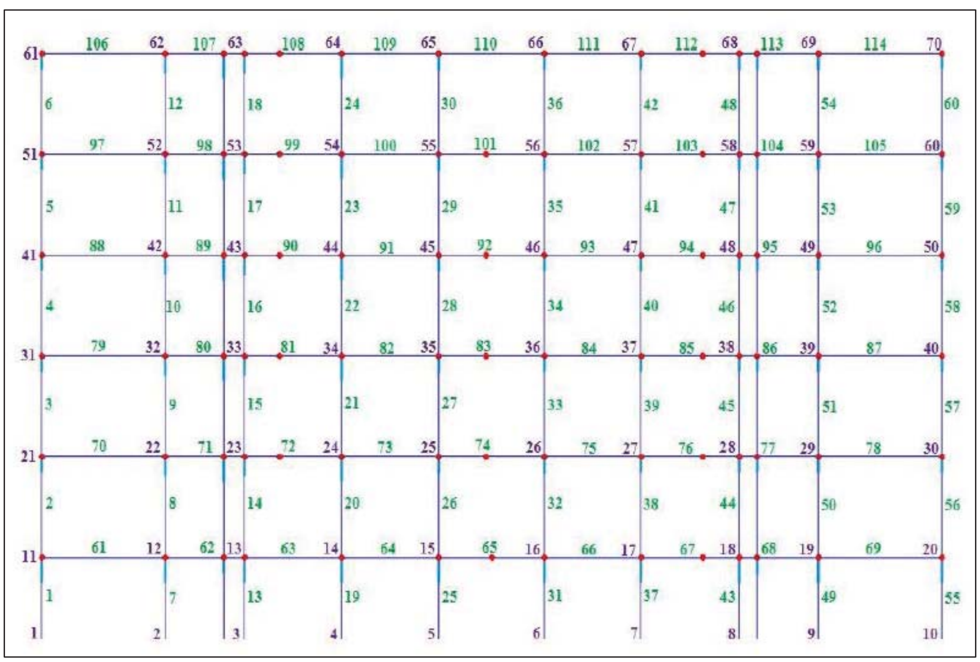

FIGURE 4. Nodes and elements numbering of the building [5]

Theoretical Development of the Fragility Curve

Fragility curves are defined as the probability of the earthquake excitation approaching or exceeding a specific damage state. Fragility curve is also a method of correlating the ground shaking guided with damage level state. The output of the fragility curve depends on the structure damage, the type of structure and the Peak Ground Acceleration (PGA) of the earthquake. The development of the fragility curve was developed by identifying the structural performance and outline the colour code tagging based on the damage state-level using Microsoft Excel, the fragility curve for this building can be plotted using Equation 1.

$$F(SA) = \Phi\left[\frac{1}{\beta_{\frac{C}{D}}} ln\left(\frac{S_a}{A_i}\right)\right] \tag{1}$$

Where, Φ is standard log-normal cumulative distribution function; S_a is the spectral amplitude for a period of T=1 sec; Ai is the median spectral acceleration necessary to cause the i th damage state to occur and $\beta_{C/D}$ is the normalized composite log-normal standard deviation which incorporates aspects of uncertainty and randomness for both capacity and demand [6].

The first step to develop the fragility curve was to identify the damage state of the building structure. There are five damage state levels as stipulated by FEMA273 [9]. Damage state 1 is defined as none or zero effect and it refers to no harm as the ductility displacement 0.08. The damage state 2 refers to slight damage and minor cracking detected by visual observation. The ductility for damage state 2 was 0.38. For damage state 3, the ductility data has been taken out from the previous modelling result and the ductility was 1.18 and categorized as moderate damage. Larger and wider cracks, spalling of concrete cover and wider gap opening at the joint are the types of damage that are expected to occur. The damage state 4 and 5 are unrepairable damage type. Damage state 4 defined that there will be a component failure and reinforcement fracture while damage state 5 defined as partial destruction or complete destruction of the building, either the structure will collapse or some part of the building collapse. The ductility for damage states 4 and 5 are taken as 2.00.

On the other hand, there are four levels of structural performance related to colour-coding as defined by FEMA273 [9]. The first level is the operational level which means no permanent drift and the structure retains considerable original strength and stiffness, also a lower risk to life and this level is tagged with green colour. The second level is marked as immediate occupancy where there is only minor cracking and concrete spalling in a few places in ductile columns and beams. The level is tagged with yellow colour. The third level is marked as life safety level which means there are extensive damages to beams, significant cracking and hinge formation in ductile beams and columns. The building might have lost its original stiffness but still retain the marginal lateral strength against collapse. The structure is not safe to occupy. This level is tagged with orange colour. The final level of structural performance is collapse prevention. At this level, the building has lost most of its original stiffness and strength and has little margin against collapse. The building cannot be entered and the risk to life is high. This level of structural performance is tagged with red colour.

Theoretical Development of the Capacity-Demand Respond Spectrum

The analysis of the capacity-demand response spectrum was carried out using Microsoft Excel spreadsheet to estimate the value of the non-linear spectral acceleration of the multi-storey prototype residential building. For the theoretical development, Equation 2 to Equation 5 were used to develop the demand response spectrum for each floor in compliance with Clause 3.2.2.2 of Eurocode 8 that has outlined the protocols for the horizontal elastic response spectrum (BS EN-Part 1, 2004). The seismic assessment of the building was carried out under DBE=0.12g and MCE=0.22g according to the Malaysian Seismic Hazard Maps [8].

$$0 \leq T \leq T_B : S_e(T) = a_g . S . \left[1 + \frac{T}{T_B} . (\eta . 2{,}5 - 1)\right] \tag{2}$$

$$T_B \leq T \leq T_C : S_e(T) = a_g . S . \eta . 2{,}5 \tag{3}$$

$$T_C \leq T \leq T_D : S_e(T) = a_g . S . \eta . 2{,}5 \left[\frac{T_C}{T}\right] \tag{4}$$

$$T_D \leq T \leq 4s : S_e(T) = a_g.S.\eta.2{,}5\left[\frac{T_C T_D}{T^2}\right] \quad (5)$$

Where, Se(T) is the elastic response spectrum; T is the vibration period of a linear single degree of freedom (SDOF) system; a_g is the design ground acceleration; T_B and T_C are the lower and upper limits of the period of the constant spectral acceleration branch respectively; T_D is the value defining the beginning of the constant displacement response range of the spectrum; S is the soil type factor; and η is the damping correction value (η= 1 for 5% viscous damping ratio of the structure). Ground-type C (dense sand or gravel or stiff clay) is used in the analysis as specified in (BS EN-Part 1, 2004). The capacity response spectrum for the prototype building was developed from Ruaumoko2D programming based on the 2015 Ranau Earthquake record and overlapped with the demand response spectrum from the Ranau earthquake record.

Table 1 shows the values of parameters used for the demand response spectrum for DBE and MCE according to Eurocode 8 [7]. There are four types of spectra that were made by using Equation 2 to Equation 5. These spectra were used to assess the vulnerability of the prototype building by developing the capacity-demand response spectrum analysis. The PGA values were taken based on the maximum peak ground acceleration and M_w is the surface-wave magnitude. The M_w values indicated in the table are the scale richer value differentiate by spectra type 1 and type 2. Spectra Type 1 classifies earthquakes magnitudes of more than 5.5 Scale Richter while spectra type 2 classifies the earthquake magnitude lower than 5.5 Scale Richter.

TABLE 1. Values parameter for demand response spectrum for DBE and MCE

Parameter	DBE		MCE	
PGA (g)	0.12	0.12	0.22	0.22
M_w	<5.5	>5.5	<5.5	>5.5
Type of spectra	2	1	2	1
S	1.5	1.15	1.5	1.15
TB (s)	0.1	0.2	0.1	0.2
TC (s)	0.25	0.6	0.25	0.6
TD (s)	1.2	2.0	1.2	2.0

RESULT AND DISCUSSION

The Fragility Curve of The Prototype Building

Table 2 shows the performance levels and colour coding together with the damage characterization of the prototype building. Since the maximum ductility recorded for this building was 1.20, the building was assumed to fall under damage state 3 (Life Safety performance level) and would have moderate structural damage with cracks in columns and beam-column joints after an earthquake event. The ductility values for Operational, Immediate Occupancy and Collapse Prevention performance levels, were assumed as 0.08, 0.38 and 2.0, respectively, based on previous research by [5].

Figure 5 shows the fragility curve development for the prototype building. The graph is divided into four colours as indicated by the damage state levels. The curvy lines represented the curves of fragility, the dotted vertical lines represented the Maximum Considered Earthquake (MCE) with PGA 0.22g and Design Basis Earthquake (DBE) with PGA 0.12g. The left side of Figure 5 shows the Cumulative Distribution Function (CDF) and the right side shows the percentage of confidence interval (CI) for all performance levels as specified in Table 3 which are operational, immediate occupancy, life protection and prevention of collapse based on structural performance levels and colour-coding by FEMA273 [9].

TABLE 2. Colour coding and performance levels the prototype building

Damage state	Colour code tagging	Performance level	Description of damage level	Displacement Ductility (µΔ)
DS1	Green	Operational	No damage; fine cracks in plaster over frame members; building can be occupied	0.08*
DS2	Yellow	Immediate occupancy	Slight structural damage; small cracks in columns and beams of frames; initial spalling of concrete cover; the building can be entered to remove belongings	0.38*
DS3	Orange	Life safety	Moderate structural damage; cracks in columns and beam-column joints; more spalling of concrete cover; buckling of reinforcement	1.20
DS4, DS5	Red	Collapse prevention	Large cracks in structural elements; fracturing of the longitudinal bars; no stability of structures; the building near collapse and cannot be entered.	2.00*

*assumption values based on the calculation of ductility

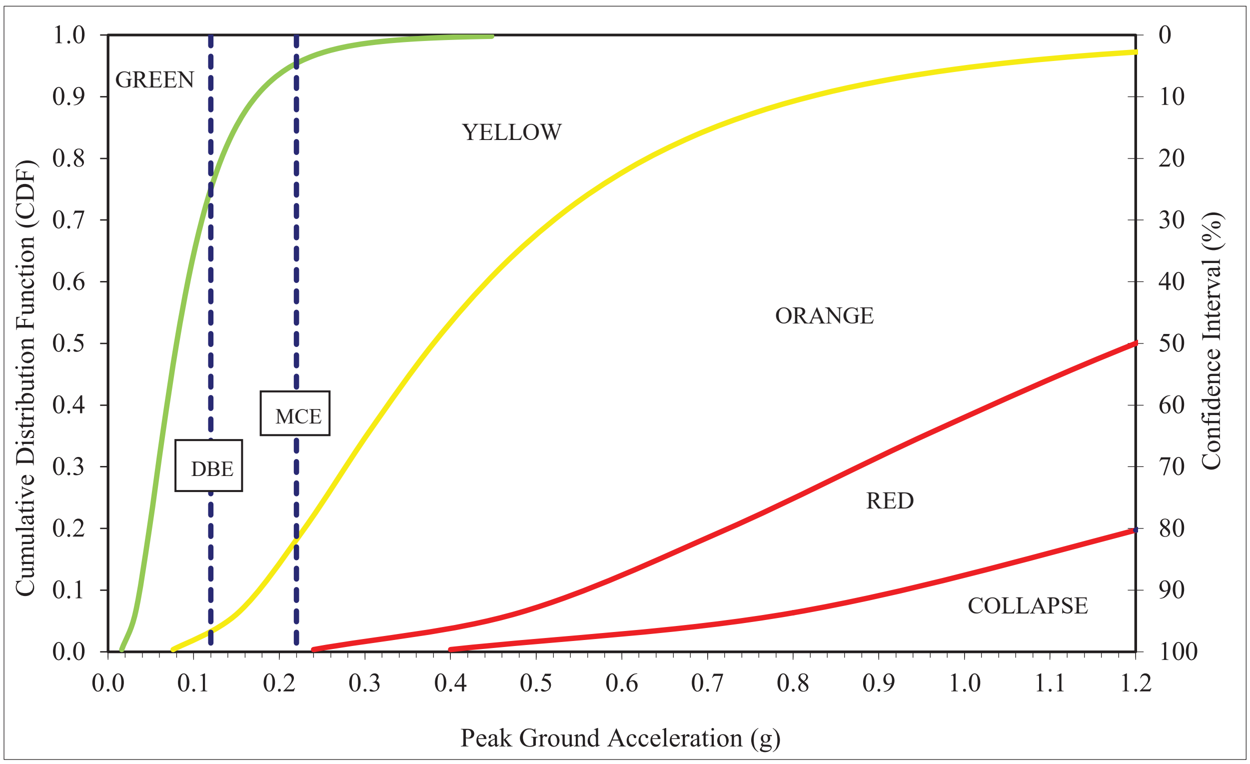

FIGURE 5. Fragility curve of the prototype building

From Figure 5, the fragility curve is divided into two earthquake limit states. For DBE with PGA of 0.12g, the percentage of CI was 23% under the green colour-coding tag which means that the prototype building has 23% confidence that this floor has no damage and only having minor crack (Damage State 1); CI was 74% under the yellow colour-coding tag and there is probably have 74% of slight structural damage, small cracks in columns and beams of frames and initial spalling of concrete cover (Damage State 2). The remaining 3% of CI was presented under the orange colour-coding tag which means around 3% of the prototype building would fall under Damage State 3 and experience moderate structural damage and buckling of reinforcement cracks in column, beam and frames. However, the building still can be entered for inspections and reoccupied after rehabilitation works have been made.

Next, under MCE with PGA of 0.22g, only 5% of CI was recorded under the green zone colour-coding tag (Damage State 1) and about 76% confidence was recorded under the yellow colour-coding tag zone (Damage State 2). This means, the prototype building would probably experience small cracks in columns and beams of frames and initial spalling of concrete cover. Another 19% of CI was recorded in the orange colour-coding tag zone (Damage State 3). This means there is 19% probability of the prototype building to experience moderate damage of the structure, buckling of the reinforcement beam or column and spalling of concrete cover which can harm the occupants. Table 3 shows the summary of the CI for the second floor of the prototype building.

TABLE 3. Summary of confidence intervals (CI) for each earthquake limit state according to the colour code tagging

Earthquake limit state	Confidence Intervals (CI) for the second floor according to the colour code tagging (%)			
	Green	Yellow	Orange	Red
DBE (0.12g)	23	74	3	-
MCE (0.22g)	5	76	19	-

Analysis of the Capacity Demand Response Spectrum for the Prototype Building

Table 4 shows the values of spectral displacement (S_d) and spectral acceleration (S_a) for the prototype building. The spectral accelerations for each floor were calculated by using Equation 6.

$$(SA)_i = 2\pi B_L \sqrt{\frac{C_C \theta H}{g}} \tag{6}$$

TABLE 4. Spectral displacement and spectral acceleration for each floor

Floor	Spectral displacement, S_d (m)	Spectral Acceleration, S_a (g)
First floor	0.02838	0.019358872
Second Floor	0.05764	0.036648085
Third floor	0.08814	0.05222168
Fourth Floor	0.12032	0.074743129
Roof	0.15484	0.087306137

Figure 6 shows the capacity-demand response spectrum of the prototype building. The capacity curve was developed from the values of spectral accelerations over spectral displacements as shown in Table 4. The seismic performance of the building was referred to as the point of intersection of the capacity curve and the demand response spectrums. From Figure 6, it is clearly shown that the capacity curve intersects with three demand response curves, except for MCE Type 1. It means, the prototype building is expected to have severe damages or collapse if there is an earthquake with PGA 0.22g and more than 5.5 Scale Richter strikes. It is proved that the soft-storey designed of the building can be considered not safe for moderate to strong earthquakes and even the building would have minor structural damages under low to moderate earthquake excitations.

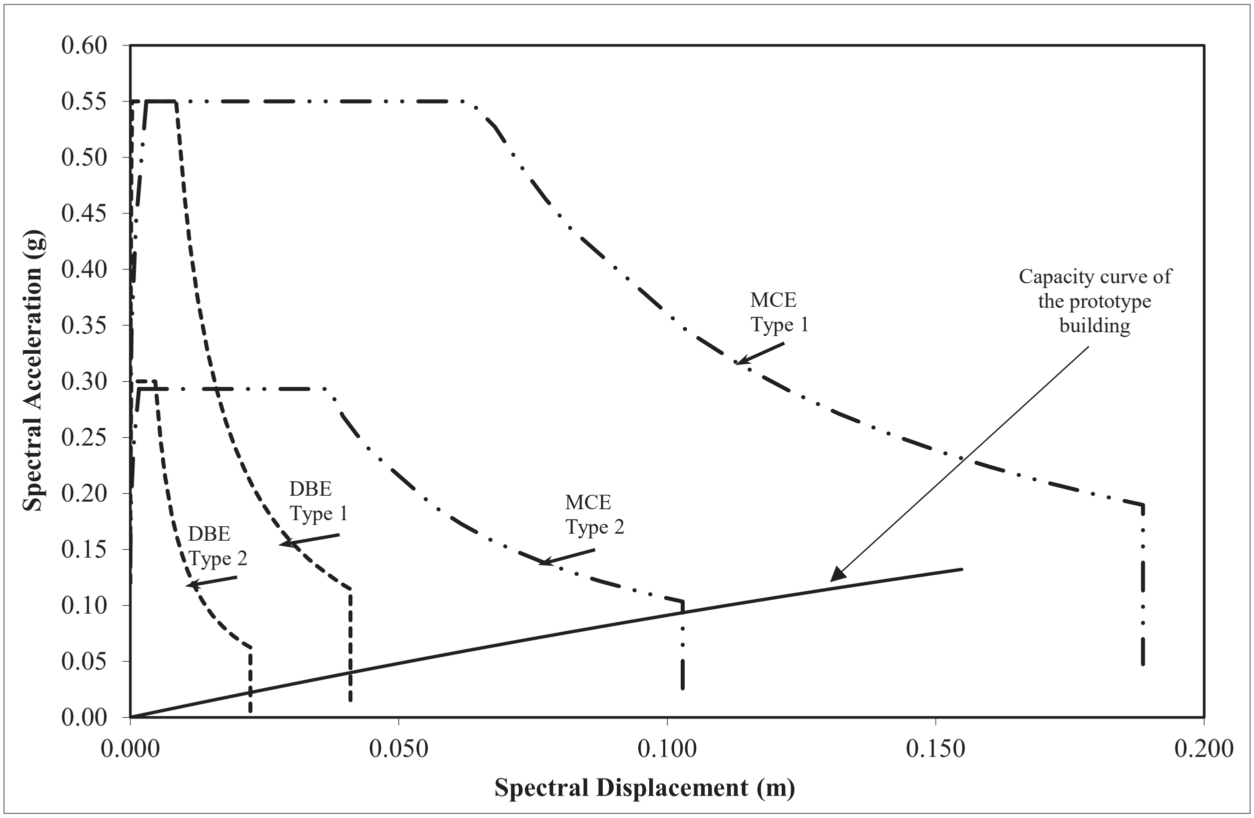

FIGURE 6: The capacity-demand response for the prototype building

CONCLUSIONS

In conclusion, the fragility curve and the capacity-demand response spectrum has been developed is to evaluate the vulnerability of a six-storey residential building with a soft-storey designed mechanism subjected to Design Basis Earthquake and Maximum Considered Earthquake with peak ground acceleration of 0.12g and 0.22g, respectively.

Overall findings from the fragility curve show that this building would experience Damage State 2 (immediate occupancy performance level) with yellow colour-code tagging as specified by FEMA273 [9]. The building would probably have a confidence interval (CI) of 74% to 76% for DBE and MCE, respectively, with light structural damage, small cracks in columns and beams of frames and initial spalling of concrete cover. The occupants still can enter the building to remove belongings and the building can be occupied after structural rehabilitation has been made.

Further assessment on the prediction of the survivability of the prototype building has been made through the capacity-demand response spectrum analysis. From the analysis, the capacity curve of the prototype building does not intersect with MCE Type 1 demand response curve. This finding has come to the prediction that the prototype building is vulnerable and predicted to experience severe damages or collapse if there is an earthquake with PGA 0.22g and more than 5.5 Scale Richter strikes. Nonetheless, it is also proved that the soft-storey designed of the building can be considered not safe for moderate to strong earthquakes and even the building would have significant structural damages under low to moderate earthquake excitations. This is because the plastic hinge propagations would be larger at the soft-storey columns when the building is design as the weak column-strong beam. In overcoming this issue, the reinforced concrete building must be designed in accordance with the relevant design code of practice such as Eurocode 8 as the guidance for future safety measures so the building could survive under the various intensity of earthquake excitations.

ACKNOWLEDGMENT

The authors would like to acknowledge The Ministry of Education Malaysia for their financial and support for the publication processes via research grant FRGS/1/2018/TK01/UiTM/02/26. Special thanks to School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Malaysia for providing the research materials and expertise for data analysis.

REFERENCES

1. F. Tongkul, Active Tectonics in Sabah – Seismicity and Active Faults, *Bulletin of the Geological Society of Malaysia*, Volume 64, (Geological Society of Malaysia, Kuala Lumpur, December 2017), pp. 27 – 36.
2. A.G. Kay Dora, M.A Tukiar and M.S. Zulhaimi, Structural Deformation of Staff's Quarters SMK Ranau subjected to the 2015 Ranau Earthquake using Ruaumoko2D, *Advances in Civil Engineering and Science Technology*, Issue 1, (AIP Publishing, Melville, NY, 2020a), pp. 020038-1- 020038-6.
3. J.M. Jara, E.J. Hernández, B.A. Olmos & G. Martinez, Building damages during the September 19, 2017 earthquake in Mexico City and seismic retrofitting of existing first soft-story buildings, *Engineering Structures,* Volume 209, (Elsevier, Amsterdam, 2020), pp. 109977.
4. C.G. Tan, W.T. Chia, A.M. Taksiah, F.M. Nazri, and M.I. Adiyanto, Soft Storey Effects on Plastic Hinge Propagation of Moment Resisting Reinforced Concrete Building Subjected to Ranau Earthquake, (AIP Publishing, Melville, NY, 2017), doi: https//doi.org/10.1063/1.5005748.
5. A.G. Kay Dora, J.M. Safwan, J. Nurjuhanah and R.N. Mohamed, Seismic Performance of Reinforced Concrete Residential Building Modeled Using Ruaumoko2D Program. In: Mohamed Nazri F. (eds) *Proceedings of AICCE'19. AICCE 2019*. Lecture Notes in Civil Engineering, vol 53. (Springer, Cham, New York City, 2020b), doi: https://doi.org/10.1007/978-3-030-32816-0_53.
6. N.H. Hamid, Seismic Damage Avoidance Design of Warehouse Buildings Constructed Using Precast Hollow Core Panel, Doctoral Thesis, University of Canterbury, 2006.
7. BS EN. Eurocode 8: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization (2004).
8. A. Adnan, A.M. Hendriyawan, P.N. Selvanayagam and A. Marto, Development Hazard Maps of East Malaysia. *Advances in Earthquake Engineering Application* (Universiti Teknologi Malaysia, Johor, 2008), pp. 1-18.
9. FEMA 273, NEHRP Guidelines for the Seismic Rehabilitation of Buildings. Emergency Management Agency, Washington, D.C. (1997).
10. T. Choudhury and H.B. Kaushik, Seismic Fragility of Open Ground Storey RC Frames with Wall Openings for Vulnerability Assessment. *Engineering Structures*, Volume 155, (Elsevier, Amsterdam, 15 January 2018), pp 345-357.
11. P. Haoran, K. Koichi and Y. Hattori, Capacity-Curve-Based Damage Evaluation Approach For Reinforced Concrete Buildings Using Seismic Response Data, *Engineering Structures*, Volume 197, (Elsevier, Amsterdam, 15 October 2019), pp. 109386.
12. A. Marto, A. Adnan, H. Hendriyawan and M. Irsyam, Microzonation Maps for Kuala Lumpur And Putrajaya. *Malaysian Journal of Civil Engineering*, 23(1) (Universiti Teknologi Malaysia, Johor, 2018), doi: https://doi.org/10.11113/mjce.v23.15811
13. R. Jena, B. Pradhan, G. Beydoun, Nizamuddin, Ardiansyah, H. Sofyan and M. Affan, Integrated Model for Earthquake Risk Assessment Using Neural Network and Analytic Hierarchy Process: Aceh Province, Indonesia. *Geoscience Frontiers*, Volume 11, Issue 2, (Elsevier, Amsterdam, 2020), pp. 613-634. doi: https://doi.org/10.1016/j.gsf.2019.07.006.
14. P. Haora and K. Kusunoki, Aftershock Damage Prediction of Reinforced Concrete Buildings Using Capacity Spectrum Assessments. *Soil Dynamics and Earthquake Engineering*, (Elsevier, Amsterdam, 2020), 1-7. doi: https://doi.org/10.1016/j.soildyn.2019.105952