

Evaluating the Performance of Irregular Low-Rise RC Building Through Static Non-Linear Pushover Analysis

Dayang Afiqah

Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia,
dayangafiqah@siswa.unimas.my

Abstract

In this research, the performance of irregular low-rise RC building was evaluated through Static Non-linear Pushover Analysis (POA) and by using SAP 2000. Moreover, the effects the seismic capacity of irregular low-rise reinforced concrete building in Sabah were also conducted through vulnerability and fragility assessments. There are four models to analyse. The first model, which is Model 1 is the actual design of the building, while the rest of the models are designs that have been proposed to analyse the irregular plan can affect the seismic performance of the building. Models 2 and 3 designed with irregular shapes, while Model 4 is design with the open slab. Then, the model will be categorised in its three (3) vulnerability assessment parameters, which are different type of concrete strength, soil structure interaction, and plan irregularity. From the analysis, Model 4 has a better performance level of building than other models in similar concrete strength of 30MPa because the building has large and different eccentricity due to the design. Among soil structure interaction models, Model 3 was the strongest since it has a better performance level than other models. It has the smallest plan area among other models that might minimise the eccentricity and the irregular lateral displacement. For a different concrete strength comparison, the higher the concrete strength, the better the performance of the building.

Keywords: Earthquake, RC Building, SAP2000, Pushover Analysis, Vulnerability

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I. INTRODUCTION

Earthquakes are a series of motions induced by a rapid release of energy caused by fault displacement [1]. They are one of the natural disasters that can cause destruction and death [2]. This is mainly caused by structures that were not seismic-resistant. Structures must be built to sustain the seismic load and avoid unnecessary damage. Every country experiences many types and stages of earthquakes, from high to low intensity [3].

Malaysia is also one of the countries that is not excluded from experiencing seismic activities. Malaysia's Eastern and Western parts have medium and low seismicity zones, respectively [4]. Although Malaysia is far beyond the main plate border faults, Sabah in eastern Malaysia has seen medium-sized earthquakes from neighbouring active fault lines [5]. Sabah is located at the meeting point of three significant tectonic plates: the Pacific-Philippine Sea Plate to the east, the Pacific-Australian Plate to the west, and the Eurasian Plate to the north [6]. Sabah is also experiencing vibrations from strong earthquakes centred across the Southern Philippines and Northern Sulawesi, in addition to the three local seismic zones [7]. Therefore, Sabah has the highest seismicity area in Malaysia

and the most attractive seismic activity since it has the foremost active fault lines [8].

In June 2015, a 6.0 magnitude earthquake shook Ranau and Sabah and killed several people. The earthquake destroyed some infrastructure, including 23 schools and a mosque [9]. Severe damage was also done to the hostels and rest homes near Mount Kinabalu's base. Later, in March 2018, a 5.2 magnitude earthquake near Mount Kinabalu prompted more than 100 climbers to rush to the nearby Laban Rata safety point [10]. Luckily, there were no reports of injuries or property damage due to the occurrence. Nevertheless, the tremors were reported within 200 kilometres of the centre [7]. It shows that the Ranau, Sabah earthquake impacted society, buildings, the economy, and the environment in Sabah [11].

In this research, the low-rise reinforced concrete (RC) building is modelled using SAP 2000 software to study the risk of building in Sabah under seismic loading. The structures are modelled and tested using two analyses, which are Static Non-linear Pushover Analysis (POA). These design analyses and clarifications can show the engineers and architects which part of the irregular design of the structure would fail when subjected to seismic load [12]. Lastly, the structure is built based on the actual design of the building and the other three irregularly

designed buildings to compare the vulnerability and fragility of the structure during the earthquake.

II. LITERATURE REVIEW

The choices made by the designer significantly influence the seismic structural performances of buildings in seismic zones. A building's seismic vulnerabilities depend on its morphological, structural, and architectural characteristics. The three leading causes of the morphological irregularity that initiates structural irregularity are economical, practical, and formal in terms of aesthetics. There are two types of building irregularities: vertical and plan irregularity. Vertical irregularity is defined by discontinuities in mass and stiffness along a building's height, whereas plan irregularity is defined by an unequal dissemination of earthquake-resistant structures [13].

The dissemination of seismic-resistant vertical buildings or masses in an unequal or non-symmetrical plan indicates irregularity in the plan [14]. Its findings are a dangerous action of torsion consisting of large floor rotations. A typical relationship between the dissemination of mass and rigidity plan decreases eccentricity between the mass centre (CM) and the rigidity centre (CR), causing the building to be primarily a translational behaviour [13]. Figure 1 shows the torsional behaviour due to the eccentricity of the mass centre and the rigidity centre.

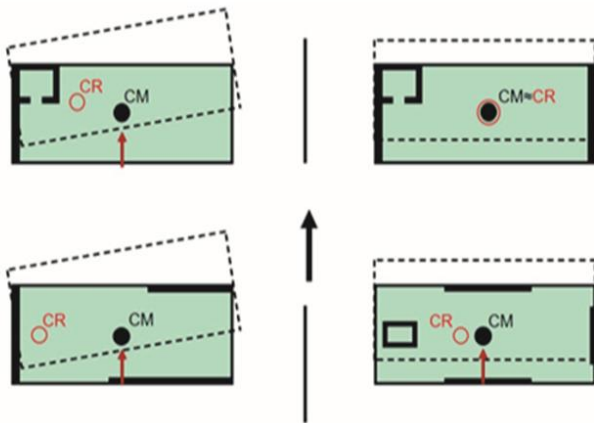


Fig. 1. Irregularity on the plan (on the left) and regularity on the plan (on the right) [13]

Plan irregularity results from asymmetrical design, which results from a specific functional allocation of the areas [15]. As a result, the stiff side of the building plan has a concentration of stiffness and strength relative to the flexible side. The flexible side of the building may also be the result of a concentration of mass on one side of the structure. When a seismic event occurs, a building's reaction is characterised by floor rotations, which is torsional behaviour. The torsional behaviour places more demands on structural components' ductility and frequently leads to catastrophic damage or collapse [13].

Vertical irregularity is caused by unexpected differences in weight, stiffness, and strength caused by the height of the building, resulting in the creation of a soft story. Thus, a prior collapse may have concentrated the member forces and the ductility requirements [12]. The Figure 2 shows two types of

vertical irregular building designs: soft first storey and soft intermediate storey.

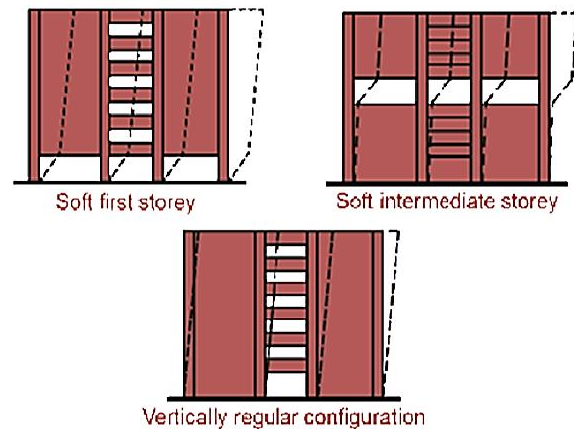


Fig. 2. Above is vertically irregular configurations, and below are regular configurations [13]

Both horizontal and vertical irregularities prevent an equal transmission of damage, making it impossible to manage the system's strength and ductility fully. Therefore, this kind of configuration needs to be avoided. Figure 3 shows how the plane and vertical irregularity are damaged due to the seismic load.



Fig. 3. Damages of the plan and vertical irregularity after the earthquake [13]

A. Performance of RC building after the 2015 Ranau, Sabah earthquake

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In June 2015, an earthquake of 6.0 magnitude occurred at Ranau, Sabah. The central design system used in the earthquake-affected area is a reinforced concrete frame [4], [16]. The damage to the building was caused by; lack of transverse reinforcement, unconfined infill walls, poor construction quality, weak construction materials, consequence of captive column and short column, non-ductile details of the structural components, the form of strong-beam weak-column, the mechanism of soft and weak storey, plan, and elevation irregularity [17].

According to Ramli et al. [18], over 200 households in Ranau and Kota Belud were also impacted by the earthquake, with mudslides destroying their homes, crops, and plantations and disrupting water supplies. Fractures have been recorded in residences, commercial, resort, hotel buildings, and religious assemblies. Even places like the hospital, schools, and police stations that are often utilised for emergencies were not spared. The commonly reported damages included cracked columns and beams, roof collapse, tilting or failing supporting columns, concrete spalling, and broken windows. The table shows the causes of damage to the RC building due to the Sabah Earthquake 2015.

B. Lack of transverse reinforcement

Several of the analysed RC structures showed a lack of transverse reinforcement, particularly in the positions of the plastic hinges. Figure 4 shows the damaged columns of 2-storey RC building in Sabah.



Fig. 4. Large spacing between stirrup in columns [19]

Figure 4a shows the column underwent severe damage to its upper side and concrete spalling, causing it to separate from the supporting beams. Columns should have a minimum dimension of 300 mm or 250 mm, according to seismic code requirements, in order to decrease axial stress and improve ductility. Meanwhile, all the column in this building is 200×200mm which not according to the design codes. In Figure 4b, the gap between stirrups in columns was 250 millimetres, and there was no reduction in distance at the plastic hinge points. From Figure 4c, the bulk of the structures in the impacted region had widely spaced stirrups. The longitudinal reinforcements of columns were measured to be 12 mm in diameter, whereas the transverse reinforcements were measured to be 10 mm shown in Figure 5. It should be noted that seismic design rules require a longitudinal bar diameter of at least 14 mm to prevent buckling.

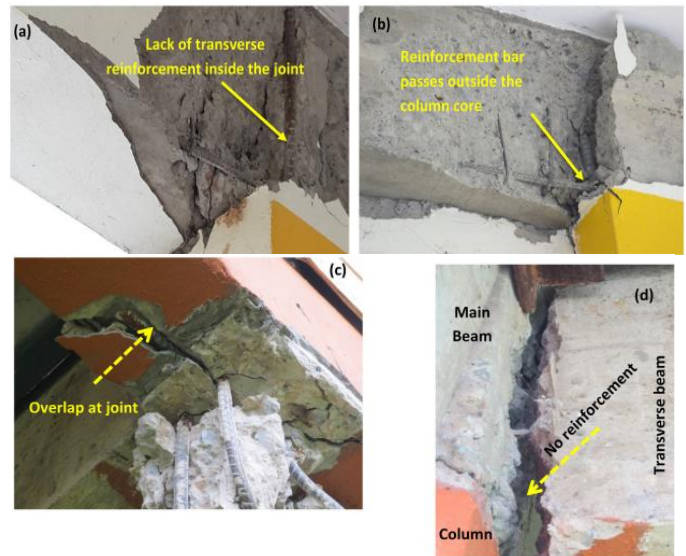


Fig. 5. Inadequately detailed beam to column joints [19]

According to the investigations, several RC constructions had their beam-to-column junctions considerably compromised by the use of inadequate detailing. According to seismic design requirements, lateral ties must be positioned within the joint and spaced not greater than 100 mm apart. Moreover, the reinforcements inside the joints should be given enough anchoring length.

C. Insufficient hooks and anchoring

Figure 6 shows the insufficient hooks and anchoring in beam to column joints. As can be seen from Figure 6(a), there is no hook for longitudinal reinforcement of the beam. Figure 6(b) shows that stress accumulation at the end of the reinforced rebar has caused huge fractures and concrete shattering. Figure 6(c) shows another beam's end side, when the longitudinal reinforcements' anchoring length was insufficient. It should be noted that seismic design rules need appropriate details for reinforcement rebar anchorage. Transverse reinforcements, for example, should feature 135° hooks to provide solid couplings during an earthquake. Nevertheless, the majority of the examined constructions utilised smooth transverse bracing with 90° hooks. [19].



Fig. 6. The insufficiency of anchoring at the end of the reinforcing bar causes column damage [19].

D. Effects of strong beams on weak columns

Columns provide a significant role in maintaining gravity loads in structures. Therefore, the column failure must be prevented to avoid structural collapse damage. Figure 7 shows inadequate column strength in RC building in Sabah.

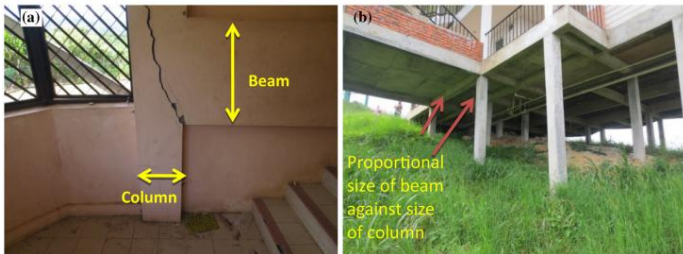


Fig. 7. Inadequate column strength in RC building in Sabah.

Figure 7(a) shows a weak column in a four-story reinforced concrete building. As seen in the illustration, the beam is noticeably bigger by approximately three times than the column. As a result, the beam is undamaged, but a significant fracture developed in the junction during the earthquake and spread to the top section of the column. Strong beams and weak columns are widely used in Malaysian RC-frame construction, and flexible columns are frequently used to sustain deep beams. Figure 7(b) displays following RC structure in the impacted region that had beams that were proportionally sized to its columns. The beam-to-column couplings of the building remained undamaged. The strong-beam weak-column issue may be avoided by giving columns greater proportions than beams, create columns with ductile designating, or employing columns made of concrete with a higher compressive strength than slabs and beams [19].

E. Effects of a captive or short column

Figure 8 and Figure 9 show the effect of captive and short column occurrences. The first scenario shows two columns with comparable proportions constructed adjacent to each other. Column 1 has withstood the earthquake because it is not confined by the brick wall. Column 2 shows major shear fractures on its top part, where a window is installed into the brick infill wall. This figure clearly illustrates that Column 2 was already completely obstructed on its left side by a brick wall. The upper section of the column on the right side is not constrained by the brick wall. Shear load in the column has increased due to the captive column effect [19].



Fig. 8. Captive column occurrence [19]

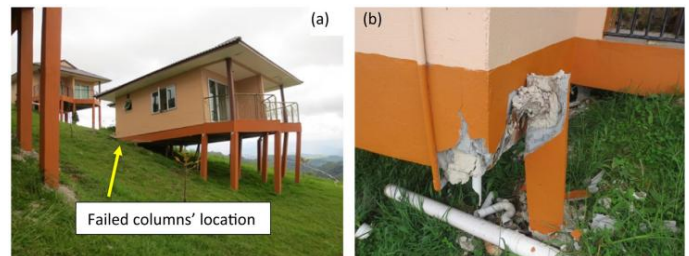


Fig. 9. Short column occurrence of RC building on the slope ground [19]

Figure 9(a) shows a structure on a sloped location that experienced substantial damage as a result of the short column incidence during the tremor. The walls, roof, and ceiling of the building were all built of wood, while the floor structural members were built of reinforced concrete. Based on the information, the smallest column was about 1 m tall. Each column's cross-section was 200 mm by 200 mm. It was strengthened by four bars with a diameter of 12 mm and 250 mm apart of stirrups with a diameter of 10 mm. Figure 9(b) shows that shear stress caused damage to the entire building's columns under 1 m long [19].

F. Poor quality of constructions materials

A number of factors contribute to low compressive strength of concrete in structural components, including uncontrolled quality for on-site concrete mixtures, unevenly sized aggregates,

and the usage of river water to build the mortar [19]. Figure 10 show the low-quality concrete coated by thick layer of plaster.



Fig. 10. A portion of the column that was severely damaged during the earthquake [19].

G. Rehabilitation methods for damaged buildings after 2015 Sabah Earthquake

According to Mansor et al. [20], vertical irregularity (soft story) and plan irregularity were the most common issues discovered after the 2015 Sabah Earthquake. As a result, the rehabilitation methods merely emphasise these difficulties. There are three primary groups of measures done to maintain and rehabilitate a building in the conventional sense of increasing the operation of the current structure, adding elements to make it stronger or more rigid, improving the efficiency of current components by boosting their strength or deformation tolerance and strengthen connections between parts to prevent severance and falling of individual parts. There are five rehabilitation methods proposed: Improve the steel frame bracing (Connected to a Concrete Diaphragm). Adding steel diagonally braced frames to an existing concrete frame structure can strengthen and rigidify the structural system. The addition of the steel braces will not raise the building's weight much. Different brace member section types and various diagonal brace combinations are acceptable [20]. Figure 11 shows several typical arrangements.

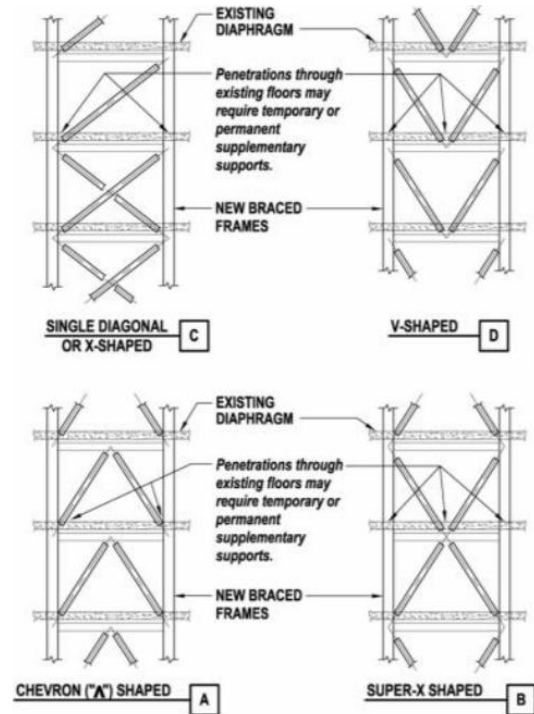


Fig. 11. Common braced frame arrangements [21]

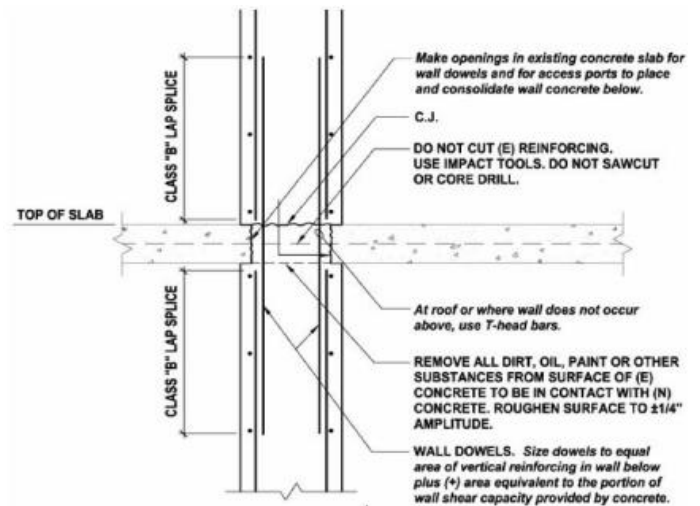


Fig. 12. Connection of a concrete wall to a concrete slab [21]

Add a shear wall made of concrete or masonry that is joined to a concrete diaphragm. The addition of shear walls to an existing concrete frame building is a standard means of increasing the structure's strength and/or stiffness. The replacement walls could be made of cast-in-place concrete, shotcrete, or fully grouted concrete masonry unit [20]. Figure 12 shows a typical concrete wall-to-concrete-slab connection.

H. Fiber-Reinforced Polymer composite overlay to strengthen Column

In the building construction sectors, using a fibre-reinforced polymer (FRP) overlay with columns has proven to be an efficient rehabilitation strategy. Columns are coated with unidirectional fibres in a horizontal position, providing

shear strengthening and confinement akin to hoops and spirals in circular columns and stirrups and ties in rectangular columns. The confinement improves the compression characteristics of the concrete, acts as a clamping action to improve lap splice connections, and offers lateral support for column longitudinal bars [20]. Figure 13 shows an example of a seismic retrofit of columns utilising FRP composites.

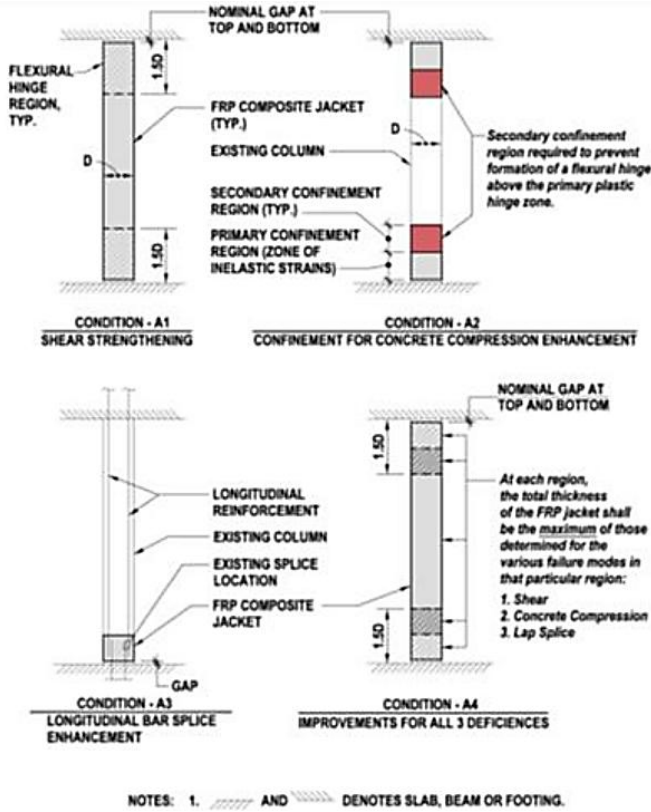


Fig. 13. FRP composite seismic retrofit of columns [21]

I. Improve concrete column with overlay of concrete or steel

A more contemporary method of treating seismic inadequacies involves covering a concrete column with a fibre reinforced polymer (FRP) composite overlay. A more conventional approach to improving a weak concrete column is to add a jacket made of concrete or steel [20]. Examples of concrete and steel jacketing for a rectangular column are shown in Figure 14.

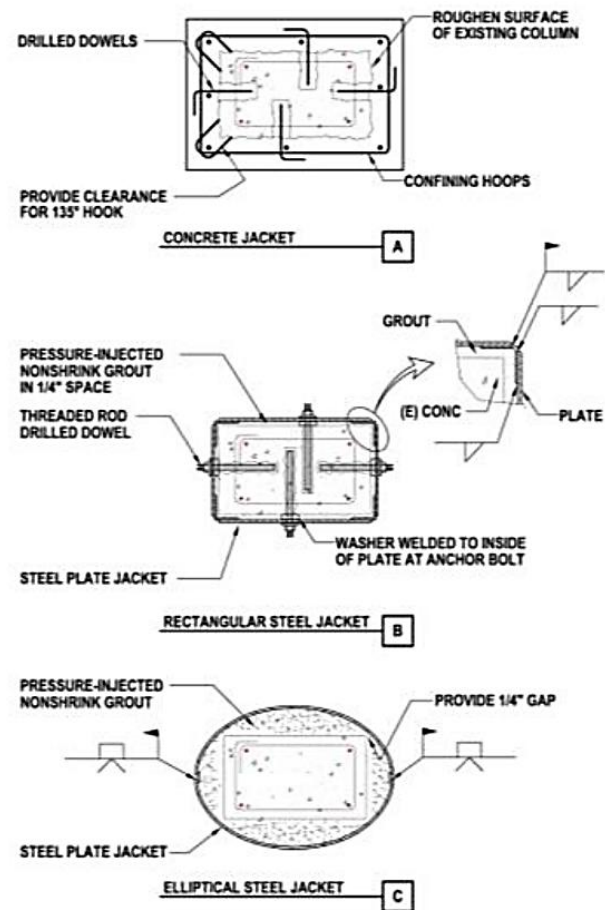


Fig. 14. Overlays for concrete columns made of steel and concrete [21]

J. Improve the concrete moment frame

Direct augmentation or enlarging the columns and beams of the frame with new reinforced concrete, is an alternate technique for improving the strength and stiffness of an existing concrete moment frame or for addressing non-ductile detailed flaws in the frame components. This technique involves wrapping existing columns and beams in reinforced concrete, which is comparable to wrapping them in steel or fibre. Shotcrete or cast-in-place concrete can be used for the new concrete [20].

III. METHODOLOGY

In this study, the chosen vulnerability assessment parameters are beam-column joint connection, type of soil and concrete strength. While for the fragility assessment, using approach of the damage state parameter which is slight, moderate, severe, and major damage. These both assessment analysed by Static Non-linear Pushover Analysis (POA) and Incremental Dynamic Analysis (IDA) using SAP2000 software. Table I, II and III show both vulnerability and fragility assessment parameters used for this study.

TABLE I. VULNERABILITY ASSESSMENT PARAMETERS

Parameter	Description
Plan irregularity	Model 1, 2, 3 and 4
Type of soil	Hard, medium, and soft soil
Concrete strength	16 MPa, 25 MPa, 30MPa, and 50MPa

TABLE II. DETAIL OF SOIL PROPERTIES [22]

Type of soil	Density of Soil (ρ) kN/m3	Modulus of Elasticity (E) MPa	Poisson's Ratio (μ)
Hard	18	65000	0.3
Medium	16	35000	0.4
Soft	16	15000	0.4

TABLE III. FRAGILITY ASSESSMENT PARAMETERS

Parameter	Description
B	Slight damage
IO	Moderate damage
LS	Severe damage
CP	Major damage
C,D,E	Terrible damage

A. Static Non-linear Pushover Analysis (POA)

Pushover analysis (POA) is a static non-linear analysis that increases the structural loading gradually until a certain point to obtain the failure parts of the structure. The load represents the inertial forces that happened during the earthquake. This analysis also can estimate seismic structural deformation. For this research, the pushover analysis is conducted by loading the structure with dead load (Gk) and live load (Qk) based on load combination in EC2, which is $1.35 G_k + 1.5 Q_k$ and lateral load. After the building model and the structural member have been defined, a pushover load is applied at specific joints. The building model is also assigned with the vulnerability and fragility assessment parameters. Then, the pushover analysis will be run to obtain the capacity curve and seismic fragility. Figure 15 shows the flow chart of the Static Nonlinear Pushover Analysis (POA).

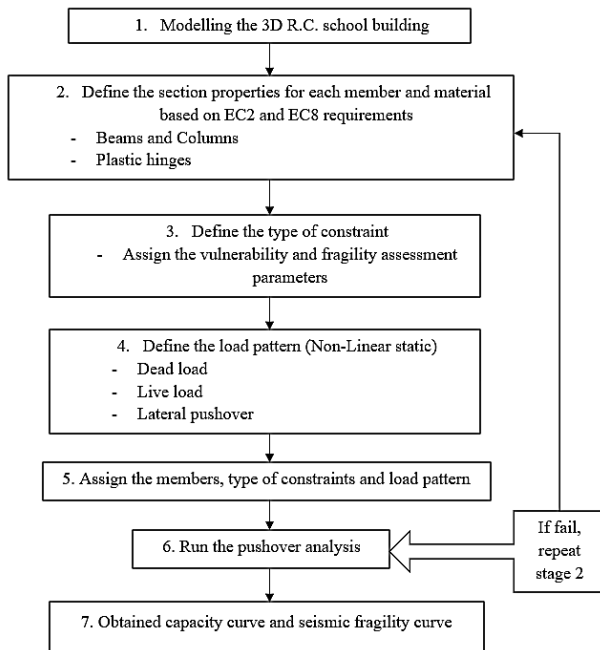


Fig. 15. Flow chart of the Static Nonlinear Pushover Analysis (POA)

This model only consists of R.C. beam and column since the design only checked on the performance of the frame design on the school building. The first model is the is actual design of the building, while the rest of models are design that has been

proposed to analyse vulnerability and fragility assessment of the irregular plan that can affect the seismic performance of the building. The Figure 16, Table IV, Figure 17, and Figure 18 show the model of building and the detail of beam and column in SAP2000. Figure 17 shows the summary of model tested with both vulnerability and fragility assessment and the purpose of the assessment.

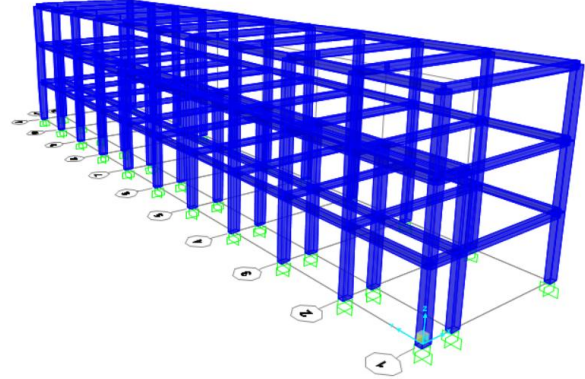


Fig. 16. Three dimensional of Model 1 in SAP2000

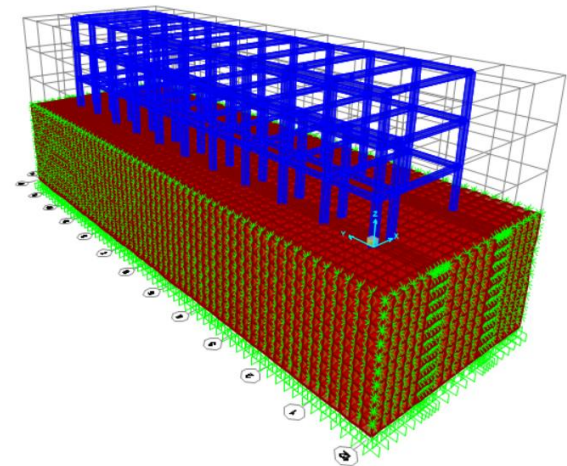


Fig. 17. Three dimensional of Model 1 for soil interaction structure in SAP2000

TABLE IV. SUMMARY OF MODEL INVOLVED IN THE ASSESSMENTS

Vulnerability and fragility assessment	Type of model tested	Analysis involved	Purpose of study
Model in different concrete strength	Model 1, 2,3, and 4	Static Non-linear Pushover Analysis and Incremental Dynamic Analysis	To identify the performance of the building under different type of concrete strength.
Model in different type of soil			To identify the performance between fixed base and soil interaction structure model.
Model in different type of plan irregularity			To identify the effect of the configuration on the structure.

TABLE V. TYPE OF BUILDING MODEL IN SAP2000

Type of model	Plan view
Model 1 (Actual design)	
Model 2	
Model 3	
Model 4	

IV. RESULTS AND DISCUSSION

The first model which is Model 1 is the actual design of the building, while the rest of models are design that has been proposed to analyse the irregular plan can affect the seismic performance of the building. The models are tested on two analyses, which are Static Non-linear Pushover Analysis (POA) and Incremental Dynamic Analysis (IDA) to obtain seismic performance and behaviour of the building by using seismic vulnerability and fragility assessment approach.

A. Static Nonlinear Pushover Analysis (POA)

The first method to analyse the building's seismic response is Pushover Analysis. The parameter used to define the shape of horizontal elastic response spectra for Sabah was adapted from MS-EN-1998-1:2015. In this analysis, the five different types of concrete strength models used ground type B, while the soil structure interaction model used three different types of soil, as mentioned in the methodology.

TABLE VI. PARAMETER FOR DEFINING HORIZONTAL ELASTIC RESPONSE SPECTRA IN SABAH

Ground type	S	TS (s)	TC (s)	TD (s)
A	1	0.1	0.4	2
B	1.4	0.15	0.4	2
C	1.15	0.15	0.6	2
D	1.35	0.2	0.8	2
E	1.4	0.15	0.5	2

Figures below show the comparison of each models in base shear vs displacement and static pushover curve demand capacity obtained from pushover analysis.

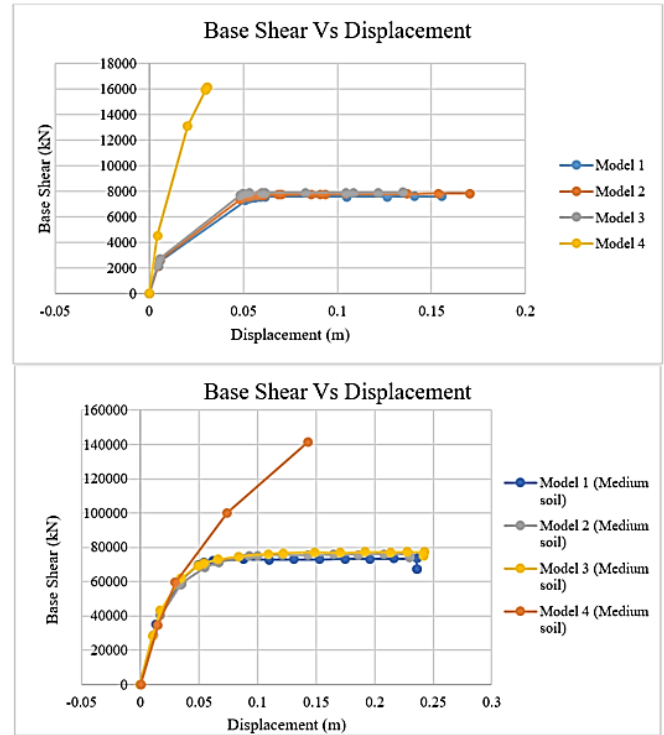


Fig. 18. Pushover capacity curve for different type of model in similar concrete strength (30MPa) based on plan irregularity and Pushover capacity curve for different type of model in medium soil

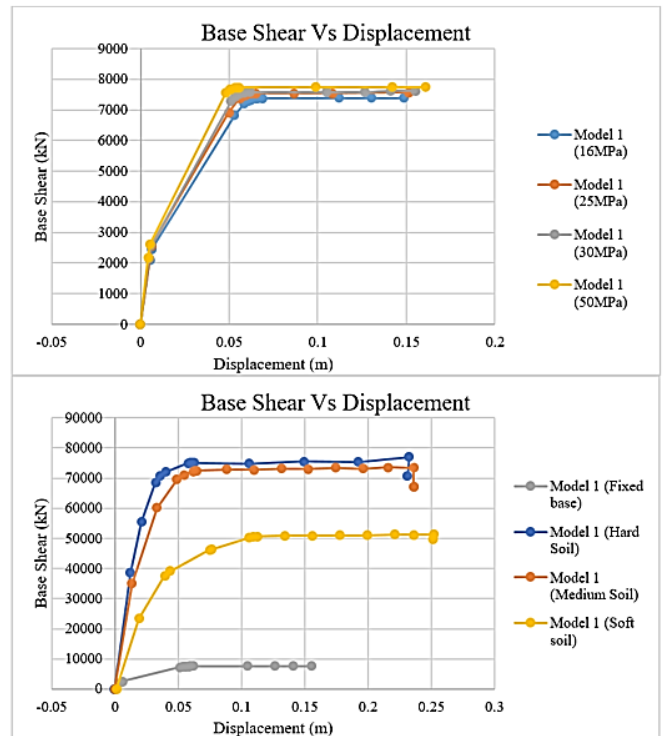


Fig. 19. Pushover capacity curve for different type of concrete strength of Model 1 and Pushover capacity curve for different type of soil of Model 1

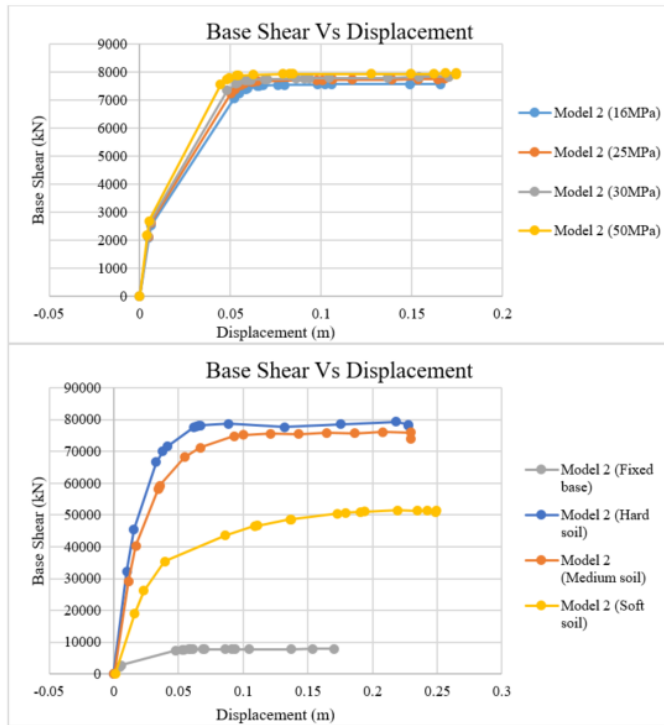


Fig. 20. Pushover capacity curve for different type of concrete strength of Model 2 and Pushover capacity curve for different type of soil of Model 2

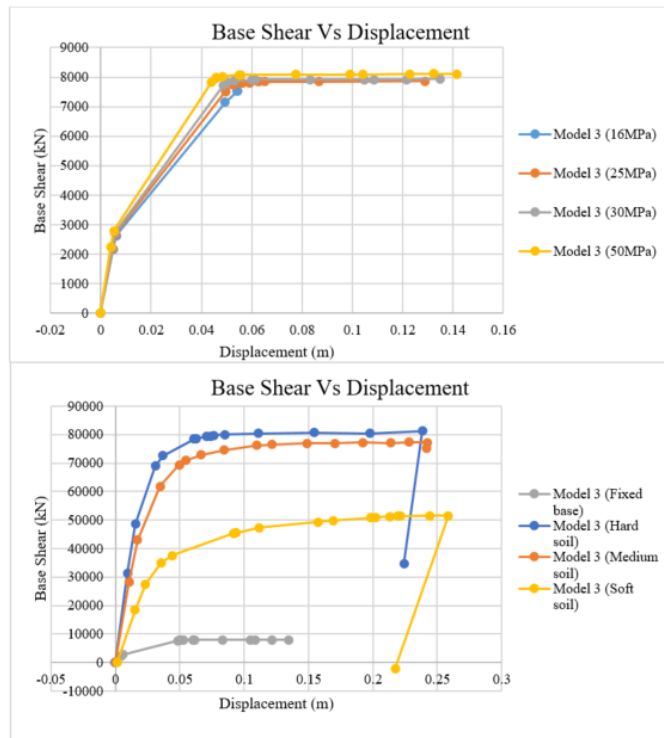


Fig. 21. Pushover capacity curve for different type of concrete strength of Model 3 and Pushover capacity curve for different type of soil of Model 3

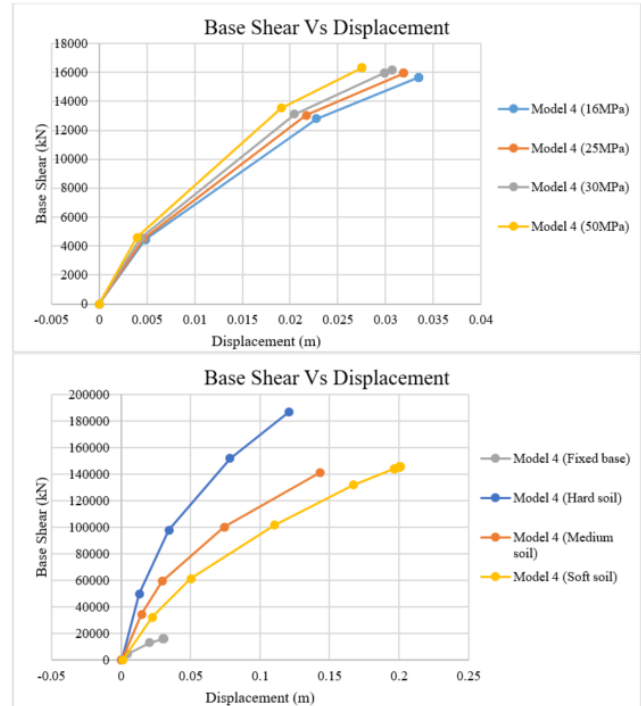


Fig. 22. Pushover capacity curve for different type of concrete strength of Model 4 and Pushover capacity curve for different type of soil of Model 4

Figure 18 shows that model 4 has the highest base shear which is 16161.8kN with the lowest displacement, 0.03m but model 2 has the highest displacement, 0.17m among all model in similar concrete strength of 30MPa. Figure 18 shows Model 4 in soil structure interaction model behave the same with fixed base model, where model 4 has the highest base shear of 141471.78kN with lowest displacement of 0.14m but model 3 has the highest displacement of 0.24m among all model in medium soil.

Figure 19, 20 and 21 shows that the models with the highest concrete strength which is 50MPa have the highest base shear and displacement. Figure 19, 20, 21 shows the models with soft soil has the highest displacement while models with hard soil has the highest base shear. It also shows that soil structure interaction model has higher base shear and displacement than fixed based model. In figure 22 and 23, model 4 for different type of concrete strength and soil has different behaviour than other models. The model 4 with highest concrete strength (50MPa) has highest base shear and lowest displacement shear while model 4 of 16 MPa has highest displacement and lowest base shear. The model 4 with hard soil structure interaction has highest base shear and lowest displacement but model 4 with soft soil structure interaction show the highest displacement and lower base shear than hard soil.

The performance point (S_a , S_d) of a building for each model can be showed by plotting the capacity curve together structural demand curve which represents the performance point that is formed and calculated based on Eurocode 8, for Sabah with 0.16g PGA (Ranau). From Figure 18-24, the performance of each of the models are almost the same respectively. This can conclude that all of the models have the same performance under response spectrum of Sabah.

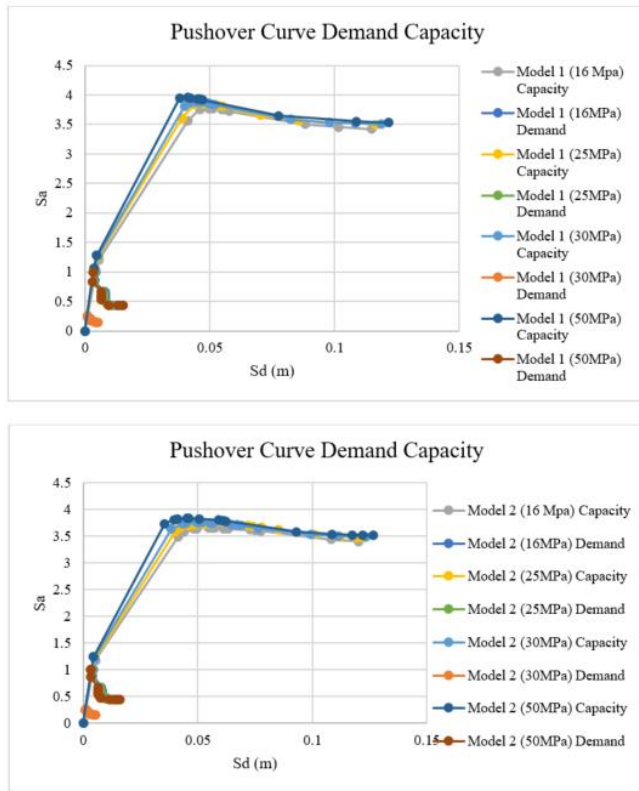


Fig. 23. Pushover curve demand capacity for different type of concrete strength of Model 1 and Pushover curve demand capacity for different type of concrete strength of Model 2

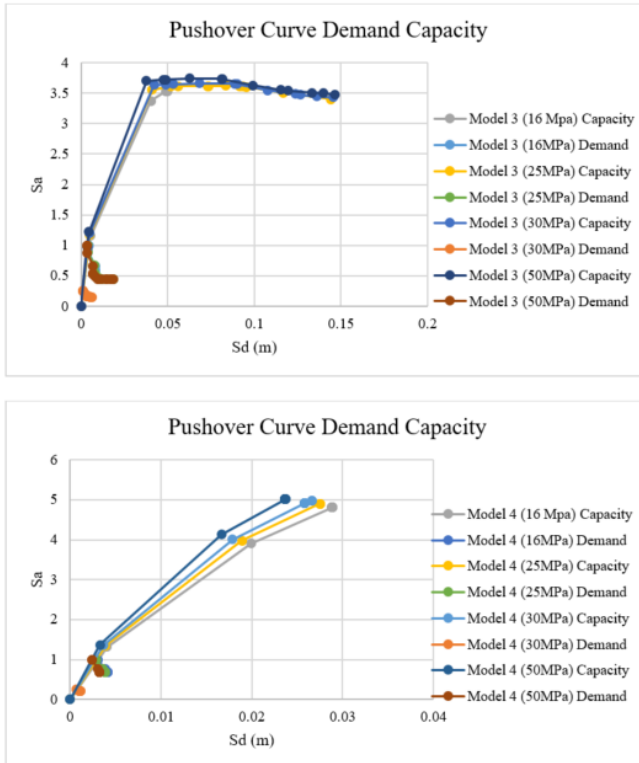


Fig. 24. Pushover curve demand capacity for different type of concrete strength of Model 3 and Pushover curve demand capacity for different type of concrete strength of Model 4

V. CONCLUSION

The results of this study show the performance of four different plan designs of school buildings under Sabah's seismic condition at various PGA ranges from 0.1g, 0.2g, 0.3g and 0.4g. The buildings were analysed based on two methods: the Non-linear Static Push over Analysis (POA) for each model. The models also assign different types of vulnerability parameters to assess the seismic vulnerability and fragility of the buildings. The IDA was analysed using three different time histories, which are Big Bear, Coalinga and Upland, that scaled to Sabah's seismic condition to obtain the average performance index with PGA of 0.1g, 0.2g, 0.3g and 0.5g. Both analyses provide the seismic performance of the four models, which show the relative change in the performance level to assess the influence of configuration factors on the seismic resistance of low-rise buildings by seismic vulnerability and fragility assessment approach, which is the main objective of this research. Based on the results obtained from the investigation, a sequence of conclusions can be made:

Based on POA, Model 4 has the highest base shear with the lowest displacement, while Model 2 has the highest displacement among all models in similar concrete strength of 30MPa. Model 4 has the highest base shear with the lowest displacement, but Model 3 has the highest displacement among all models in medium soil. Therefore, Model 4 is the strongest building among all models since it can uphold the highest base shear than another model with the lowest displacement. The model in different types of concrete strength shows that the higher the concrete strength, the higher the base shear and displacement. The model in different soil types shows that the soft soil structure interaction has a higher base shear and displacement than that of medium and hard soil [23]. It also shows that the soil structure interaction model has higher base shear and displacement than the fixed-based model.

Based on IDA, Model 1 has the highest inter-story drift among all models in similar concrete strength of 30MPa, while Model 4 has the highest inter-storey drift among all models in medium soil structure interaction. Then, a model with the lowest concrete strength, which is 16MPa, has the highest inter-storey drift. Therefore, the lower the concrete strength, the higher the interstory drift. The model in soft soil has the highest inter-story drift and also shows that the model with soil-structure interaction has higher inter-story drift than fixed base conditions.

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