Seismic performance of reinforced concrete structures with pushover analysis

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Abstract. A building that looks strong enough might possibly collapse due to the earthquake load. Earthquake resistant design is generally based on an analysis of elastic structures that are given a load factor to simulate ultimate conditions. When an earthquake occurs, the collapse behavior of a building structure is inelastic. Evaluations that can estimate the inelastic condition of buildings during an earthquake are analyzed using pushover analysis. Pushover analysis is the nonlinear static load of the structural collapse behavior of an earthquake, while the performance point is the magnitude of the maximum displacement of the structure during an earthquake. The inelastic structure analysis and evaluation method used computer application SAP 2000. Evaluation results of structural performance levels according to Applied Technology Council 40 (ATC-40) on the X and Y direction structure, the maximum total drift and total inelastic drift maximum values in the X and Y directions included in the Immediate Occupancy (IO) level category (maximum drift value of a building structure 0.00047 < 0.005).

Keywords: seismic performance, pushover analysis, reinforced concrete

1. Introduction

Building structure design is a building plan that goes through various calculation stages by considering various variables, so that the results that are useful can be obtained according to their function. The loading plan is the main data as information for planning structural elements such as dead loads, live loads, and earthquake loads. The latest edition of the 2010 earthquake map and equipped into SNI 1726-2012 was published in the hope of getting more accurate predictions of earthquake loads so that buildings become more reliable when experiencing a planned earthquake. The latest concept contains a period of return, a deterministic approach, building fragility, and coefficients on spectra response [8]. The building structures must be declared capable of accepting earthquake forces at a certain level without causing significant damage to the structure or if the building structure has to collapse (due to earthquake load exceeding the planned earthquake load), the structure is able to provide nonlinear behavior in post-elastic conditions so that buildings against earthquakes and the safety of the inhabitants’ lives are more assured. Thus re-evaluating seismic performance on building structures, is an urgent matter as part of concrete steps in overcoming the impact of the earthquake disaster. The potential for structural collapse will endanger the safety of the occupants or users of the structure. Therefore engineers are required to design structures with earthquake resistance. The design of
earthquake resistant buildings must pay attention to the criteria and details according to the applicable code.

1.1 Pushover Analysis

Pushover analysis is a nonlinear static analysis in which earthquake loads in building structures are considered as static loads. The static load is given to the center of mass on each floor, the value of static load is increased gradually until it exceeds the limit of the first yield on an element of the building structure. So that with an increase in loading will change shape material because it has passed the elastic limit of the material. Then it is followed by yielding at the locations of other elements in the structure [2]. Capacity Spectrum Method (CSM) is one of the analyzes in assessing the performance of building structures. The concept of nonlinear static pushover analysis is to provide additional static load in the lateral direction. Adding a static load is terminated until the structure has reached a certain value or load deviation. From analysis, this static nonlinear pushover obtained a capacity curve which was then further processed by certain methods, one of which was the Capacity Spectrum Method (CSM) [1]. The following is the theory used in this study.

1.2 SAP2000

The SAP2000 application program provides several variations of templates of structure types. In building structure models, users can modify the modeling of structure templates as needed, so that the analysis process becomes faster. SAP2000 has been integrated in the process of analysis and design. After the analysis is completed, the internal forces can be determined, then the design process is carried out to obtain the adequacy of the profile dimensions or the steel reinforcement in the structure. Analysis and redesign can be done easily with the SAP2000 program. Using the SAP2000 program, frame structure elements are modeled as line elements that have linear elastic properties and nonlinear force-displacement characteristics. The frame structural elements are modeled as hinge which is represented by a series of straight line segments.

1.3 Structure Response

The structure of the building will receive earthquake loads, where the load is given in the form of base shear. Base shear for each floor is a function of mass (m) and stiffness (k) on each floor. Base shear causes a shift or displacement on each floor from its initial position structure. For symmetrical structural geometry, deviations will only occur in two dimension, deviations of a mass in only one position so that it can be considered as a single degree of freedom (SDOF) on the roof. When an earthquake load occurs it causes internal forces on the building structure. If the internal forces exceed the building’s capacity, the building will behave in an elastic if the material is still in ductile condition. If the material immediately destroyed, it means that the material loses its ductile properties.

1.4 Capacity Curves

The results of the static non-linear pushover analysis show the relationship between base shear and displacement as shown in Figure 1. The relationship between displacement is proportional to the base shear plotted into a curve called the Curve of Structure Capacity.

![Figure 1. Pushover illustration and curve of capacity](image-url)
1.5 Performance Point

The performance point is the point where the curve of capacity intersects the spectrum response curve as used in the capacity spectrum method [1]. The illustrated of the performance point can be seen in Figure 2. At the performance of point, it can be obtained regarding the period of building structure and effective structural stiffness due to changes in the shape of the elements after the plastic joint occur. Based on this information, other structural responses such as the degree of deviation and the position of plastic joint (hinges) points can be identified.

![Figure 2. Performance point curve](image)

Immediate Occupancy (IO) category is a structural condition that is able to withstand, the structure does not suffer structural and non-structural damage during an earthquake. In this category of IO, structures can be re-functional after earthquake. Life Safety (LS) is a condition where the structure is still able to withstand, there is little structural damage, people who live or are inside a building are safe from earthquakes when an earthquake occurs. Collapse Pervention (CP) is a structural condition that suffered very heavy structural damage, but it did not collapse during an earthquake. Structural Stability (SS) is a condition in which a structure experiences partial or total damage, the damage has caused a decrease in strength and stiffness in the lateral force retaining system [1].

| Parameter                  | Performance Level       |
|----------------------------|-------------------------|
|                            | Immediate Occupancy     | Damage Control | Life Safety | Structural Stability |
| Maximum Total Drift        | 0.01                    | 0.01 – 0.02    | 0.02        | 0.33 Vi/Pi           |
| Maximum Inelastic Total Drift | 0.005                | 0.005 – 0.015  | No Limit    | No Limit             |

2. Frame Structure

This study used a reinforced concrete frame structure with eighteen storeys. The function of the building structure is for office activities.

2.1 Concrete material specifications

Concrete weight per unit volume is 2400 kg/m³, with modulus of elasticity \(E\) 23500 MPa, shear modulus \(G\) of 10217.391 MPa, Poisson \(\nu\) of 0.15, with the coefficient of thermal expansion \(\alpha\) of 12 \(\times\) 10^{-6}\(\degree\)C, and the compressive strength of concrete \(f'c\) of 24.924 Mpa [5] [6].
2.2 Steel material specifications

Steel using BJ50 with the weight per unit volume of 7850 kg/m$^3$, joints are connected by welding, with modulus of elasticity ($E$) of 200000 MPa, shear modulus ($G$) of 80000 MPa, poisson ratio ($U$) of 0.25, with the coefficient of thermal expansion ($A$) of $12 \times 10^{-6}$ ºC, minimum tensile stress ($f_u$) of 500 MPa, minimum yield stress ($f_y$) of 290 MPa, minimum strain of 16%. Rebar using BJTP-24, for Ø ≤ 12 mm, $f_y$ of 2400 kg/cm$^2$ and BJTS-50, for Ø ≥ 13 mm, $f_y$ of 5000 kg/cm$^2$ [5] [6].

2.3 Slab Thickness

Floor deck, thickness of 120 mm, parking lot deck, thickness of 200 mm, roof deck, thickness of 0.35 mm, and thickness of concrete cover is 30 mm.

| Type | Dimension (cm) | Cover (cm) | h   | b   | Rebar  |
|------|----------------|------------|-----|-----|--------|
| B1   | 15×30          | 3          | 3D12| 3D8 | Ø8-100 |
| B2   | 30×60          | 3          | 3D12| 3D8 | Ø8-100 |
| B3   | 35×70          | 3          | 3D12| 3D8 | Ø8-100 |
| WF   | 15×10×0.32×0.45|            |     |     |        |

### Table 2. Beam specifications

| Type | Dimension (cm) | Cover (cm) | h   | b   | Rebar  |
|------|----------------|------------|-----|-----|--------|
| K1   | 20×20          | 3          | 3D16| 3D16| Ø8-100 |
| K2   | 25×50          | 3          | 4D16| 3D16| Ø8-100 |
| K3   | 50×50          | 3          | 5D20| 5D20| Ø10-100|
| K4   | 30×60          | 3          | 5D26| 5D26| Ø10-100|
| K5   | 60×60          | 3          | 5D26| 5D26| Ø10-100|
| TS   | 30×30          |            |     |     |        |

### Table 3. Column specifications

2.4 Structural loading

The structure will carry out dead load such as reinforced concrete 2400 kg/m$^3$, sand (dry air to moist) 1800 kg/m$^3$, cement mix/species 21 kg/m$^3$, plasterboard/ceiling 11 kg/m$^3$, ceiling hangers 7 kg/m$^2$, partition wall (glass) 10 kg/m$^3$, floor coverings (ceramics) 24 kg/m$^2$, roof cover (tiles) 50 kg m$^2$, brick pair 1700 kg/m$^3$, and dead load reduction coefficient of 0.9. In the other hand, the structure will also carry out live load for office function is 250 kg/m$^2$ in each floor, while for the basement floor the live load is 800 kg/m$^2$. Rainwater load calculated with (40 - $0.8\alpha$) kg/m$^2$: (40 - (0.8×16)) = 27.2 kg/m$^2$, for rainwater loads taken 20 kg/m$^2$, where $\alpha$ = roof slope in degrees, provided that the load does not need to be taken if it is greater than 20 kg/m$^2$, [5] [6] and does not need to be reviewed if the slope of the roof is greater than 50°. So 20 kg/m$^2$ are taken to the calculation. Earthquake load is an equivalent static load that works on a building or part of the building that imitate the effect of ground motion due to the earthquake. The earthquake load planned is based on seismic parameters according to the type of land on which the building was built. The design of earthquake loads uses a spectral response plan [4].

2.5 Response spectrum design

First, determining $S_s$ and $S_1$, where $S_s$ is the parameter for spectral response acceleration, MCE (maximum credible earthquake) in the short period = 0.2 seconds with 5% attenuation and $S_1$ is the parameter for spectral response acceleration, MCE (maximum credible earthquake) in the period of 1
second with 5% attenuation [4]. Both parameters are obtained by the quake map of Indonesia. Then determine the building risk categories and priority factors. Determining the spectral response in the building is not only adjusted to the risk categories, but ground level amplification is also categorized into several classes of sites, namely A, B, C, D, E and F. In this site class the land is divided into classes according to the structure the land is like rock, hard rock, hard soil, medium soil, soft soil and also land that requires special investigation. Then determining Site, $F_a$ and $F_i$ Coefficients. In addition to determining earthquake maps, determining the acceleration spectrum of the MCER earthquake response on the ground surface requires a seismic amplification factor for the period of 0.2 seconds and a period of 1 second, in which factors cover vibration factors related to acceleration in the short period ($F_a$) and vibration factors related to period of 1 second ($F_i$). This factor is used as a multiplier for the acceleration of bedrock on earthquake maps to obtain acceleration parameters for spectral responses in short periods ($S_{MS}$) and periods of 1 second ($S_{MI}$) or can be formulated as follows [4]:

For short periods:

$$S_{MS} = F_a \times S_s$$  \hspace{1cm} (1)

As for the 1 second period with the formula:

$$S_{MI} = F_i \times S_i$$  \hspace{1cm} (2)

Where $S_{MS}$ is the parameters for accelerating the spectral response, MCE (Maximum Credible Earthquake) in the short period is 0.2 seconds with 5% attenuation and $S_{MI}$ is the parameter for accelerating the spectral response, MCE (Maximum Credible Earthquake) in the period of 1 second with 5% attenuation. After obtaining the $S_{MS}$ and $S_{MI}$ values through equations (3) and (4), then to design spectrum responses we need design spectral acceleration parameters for short periods ($S_{DS}$) and for 1 second period ($S_{DI}$), which can be determined by the following equation [4]:

$$S_{DS} = \frac{2}{3} S_{MS}$$  \hspace{1cm} (3)

$$S_{DI} = \frac{2}{3} S_{MI}$$  \hspace{1cm} (4)

Where $S_{DS}$ is the parameters for accelerating the spectral response, MCE (Maximum Credible Earthquake) in the short period is 0.2 seconds with 5% attenuation and $S_{DI}$ is the parameter for accelerating the spectral response, MCE (Maximum Credible Earthquake) in the period of 1 second with 5% attenuation. If the design response spectrum is required by this procedure and site-specific ground motion procedures are not used, then the design response spectrum curve must be developed by referring to Figure 3 and following the terms as follows [4]:

- For periods smaller than $T_0$, the spectrum of the design acceleration response, $S_o$, must be taken from the equation below

$$S_o = S_{DS} \left(0.4+0.6 \frac{T}{T_0}\right)$$  \hspace{1cm} (5)

- For periods greater than or equal to $T_0$ and smaller than or equal to $T_s$, the equation will become

$$S_o = S_{DS}$$  \hspace{1cm} (6)

- For periods greater than $T_s$, the design response acceleration spectrum, $S_a$, is taken according to the equation below

$$S_a = \frac{S_{DI}}{T}$$  \hspace{1cm} (7)

Where $T$ is the fundamental vibration period of the structure, $T_0$ is 0.2 seconds, $T_s$ is $S_{DI}$, and $T_i$ is $S_{DI}$. By using the equations above, the response spectrum will form a curve as shown in figure 3.
2.6 Modeling approach

The general finite element package SAP 2000 has been used for the analyses. A three-dimensional model of each structure has been created to undertake the non-linear analysis. The Existing model and loading structure shown in figure 4. Beams and columns are modeled as nonlinear frame elements with lumped plasticity at the start and the end of each element. SAP 2000 provides default-hinge.

2.7 Pushover Analysis

Pushover analysis aims to control structural displacement. This analysis is done after modeling the geometry of the structure, material data, dimensions of structural elements. Pushover load are imposed to the structural geometry model until the first yielding occurs in the elements. The displacement is analyzed at each step to determine the maximum displacement of the upper elements (roof), where the maximum displacement allowed is 4% of the building height. A pushover curve is a curve that compares the value of shear forces and displacement on the roof. The maximum point of the curve represents the capacity of the material structure that can resist maximum lateral loads. The initial stiffness of the structure is obtained from the tangent on the pushover curve with a zero load level. The assumption of collapse is when the structure experiences a stress loss of 75%, where there has been a maximum displacement on the roof called the maximum roof displacement. This value is reflected in the shear force curve compared to the displacement on the roof. Performance points and locations hinges in various stages can be obtained from the pushover curve as shown in Figure 5. The AB line is the elastic range, B to IO is the immediate occupancy range, IO to LS is the life safety range, and LS to CP is the collapse prevention range. When the hinges is reached at point C, the force versus
displacement curve begins to decrease. The load is then derived from the condition of the plastic joints that have been reached at point C until the condition of the forces on the plastic joints is consistent with the forces at point D. Once the yielded hinge reaches the Point D, the pushover force is increased and the displacement begins to increase. After the resulting plastic joint reaches the force level at point D, the pushover force is increased which causes an increase in the displacement value. If all hinges are below the CP limit then the structure is said to be safe. However this also depends on the level of importance of the structure after the range of IO may also need to be retrofitted [1].

**Figure 5.** Performance points showing different stages of plastic hinge result [3]

### 3. Results and discussion

The resulting pushover curve for the building is shown in Figure 6. The graph shows when the displacement ($D$) reaches 0.0031 m the condition of the structure is still elastic which then behaves elastically until the displacement reaches 0.0642 m. Furthermore, the structure begins to collapse with a marked decrease in curve.

**Figure 6.** Pushover curve
From the figure 7 it is obvious that the demand curve tend to intersect the capacity curve near the event point B, which means an elastic response and the security margin is greatly enhanced. Therefore, it can be concluded that the margin safety against collapse is high and there are sufficient strength and displacement reserves.

The figure 7 resulting the performance point variable and value that shown by the table 4.

| Variable          | Value      |
|-------------------|------------|
| $V$ (Ton), $D$ (m) | 82,206 ; 0.034 |
| $S_a$ (g), $S_d$ (m) | 0.012 ; 0.029 |
| $T_{ef}$ (second), $\beta_{ef}$ | 3.066 ; 0.185 |

Displacement Limit according to SNI 1726-2012 is determined at 2% of the building height. From the result the displacement $D = 1.52$ m $(0.02*76 \text{ m}) > D = 0.034$ m then the building’s displacement performance is good. The value of the effective basic shear force obtained in a linear state is smaller than the value of the shear force plan $V = 82,206$ tons $< V_r = 206.88$ tons. Maximum drift value of a building structure using the formula $D/V = 0.034/76 = 0.00047$. As for the maximum value of inelastic drift using formula $(D_i - D_i)/H = (0.034 - 0.00)/76 = 0.00047$. Evaluation results of structural performance levels according to Applied Technology Council 40 on the X and Y direction structure, for the maximum total drift and total inelastic drift maximum values in the X and Y directions included in the Immediate Occupancy (IO) level category as shown in the figure, the risk of fatal accident from structural failure is not too significant, the building does not suffer significant damage, and can be immediately functioned/re-operated.

3.1 Plastic hinges mechanisms

The plastic hinges formation for the building mechanisms has been obtained at different displacement levels. The hinging patterns are plotted at different levels in figures 8 to 12. Plastic hinges formation
starts with beam ends and base columns of lower stories, then propagates to upper stories and continues with yielding of interior intermediate columns in the upper stories. But since yielding occurred at B, IO and LS respectively, the amount of damage in the building will be limited.

Figure 8. Deformed shape at step-0

Figure 9. Deformed shape at step-1

Figure 10. Deformed shape at step-3

Figure 11. Deformed shape at step-4
4. Conclusions

Based on the results of research conducted several conclusions can be drawn that the building is included in the performance level of Immediate Occupancy, namely the discovery of damage to structures where the strength and stiffness are almost the same as the conditions before the earthquake and the building can be reused. This is indicated by the formation of plastic joints starting from the beam element which then when it reaches the performance point the majority of the beam elements are formed plastic joints then in some elements the beam reaches inelastic boundary conditions.

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