Non-linear analysis of seismic performance of low-rise concrete buildings in Indonesia

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Abstract. It is well known that the parts of Indonesia are considered as moderate to high seismicity zones. The Indonesian Standard for seismic design has been developed based on linear analysis which is the most common approach in seismic analysis. This study presents an evaluation of a low-rise reinforced concrete building using non-linear analysis. The main purpose of this study is to investigate the actual safety level of a concrete building seismically designed according to the Indonesian Standard. The results showed that the building satisfies the intended objectives of the seismic design both in terms of global and local response.

Keywords: Non-linear analysis, pushover, earthquake, concrete building, performance-based

1. Introduction

Indonesia is one of the world’s seismic prone regions because of its location on the Pacific Ring of Fire[1]. Recorded experiences showed that earthquake events have caused many fatalities and high levels of damage in the last two decades. For instance, the 2018 Lombok earthquake destroyed approximately 23,000 buildings and caused more than 500 deaths[2]. More recently, the 2018 Palu earthquake followed by a tsunami caused huge damage with more than 2000 deaths.

With substantial damages and losses in the previous occurrences, it becomes necessary to design the building properly against an earthquake. Thus, the Indonesian Standard for seismic design (SNI 1726:2019)[3] has been developed as guidance to ensure occupant safety when an earthquake occurs. In practice, most engineers implement this standard due to its simplicity. This standard is generally based on linear analysis to assess the performance of the structure during seismic event. Thus, the structural behaviour is assumed to be purely elastic. However, this technique does not
reflect the actual performance of the building since the structural material behaviour may exceed the elastic range during an earthquake.

Recent International Codes such as ASCE 41[4] and FEMA 440[5] have provided various approaches including non-linear analysis. Fundamentally, the behaviour of the building can be predicted more accurately using non-linear analysis. Figure 1 shows the main differences between linear analysis and non-linear analysis. It can be seen that the linear analysis is a conservative approach which only considers the capacity in the elastic range. On the other hand, the non-linear analysis examines the behaviour of the building in the plastic range which includes three different performance levels: Immediate occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). These performance levels represent the range from minor to major damage. This study presents the application of non-linear analysis to study seismic performance of building designed in accordance with the Indonesian Standard for seismic design[3]. The main objective is to assess the actual safety level of the concrete building.

![Figure 1: Linear analysis vs non-linear analysis](image)

2. Earthquake analysis

As previously outlined, there are two common approaches to predict the seismic behaviour of the building structures: linear analysis and non-linear analysis. This section discusses a brief review of the design concept of these approaches and associated advantages and disadvantages.

2.1. Linear analysis

The linear analysis is generally the simplest approach which adopts a factor to account for any non-linear behaviour and dynamic effects of the building during an earthquake. This approach has been adopted in the Indonesian Standard for seismic design[3] and is known as a static equivalent method. In this method, the building is subjected to a base shear \( V \) which represents an earthquake load. The base shear \( V \) can be determined by:

\[
V = C_s \times W
\]  

(1)

\( W \) is the effective seismic weight and \( C_s \) is the seismic response coefficient defined by:

\[
C_s = \frac{S_{ds}}{T(1)}
\]  

(2)

The value of \( C_s \) should not exceed the following:

\[
C_s = \frac{S_{ds}}{T(1)}
\]  

(3)
In addition, $C_s$ needs not less than:

$$C_s = 0.044 \ S_{D3} t \geq 0.01$$  \hspace{1cm} (4)$$

where $S_{D3}$ is the design spectral response acceleration parameter at a period of 1.0 s, $S_I$ is the mapped maximum considered earthquake spectral response acceleration parameter and $T$ is the fundamental period of the structure.

The base shear is then distributed vertically at every level or storey. The lateral load at every level can be defined by:

$$F_x = C_x V$$ \hspace{1cm} (5)$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}$$ \hspace{1cm} (6)$$

where $C_{vx}$ is the vertical distribution factor, $w_i$ and $w_x$ is the portion of the effective seismic weight of the structure ($W$) located at level $i$ or $x$, $h_i$ and $h_x$ is the height from the base to level $i$ or $x$, and $k$ is an exponent associated with the structure period ($k = 1$ for structures having a period of 0.5 s or less and $k = 2$ for structures having a period of 2.5 s or more).

2.2. Non-linear analysis

Non-linear analysis can be categorized as static and dynamic. Non-linear dynamic analysis known as non-linear time history analysis is the best approach theoretically to simulate the behaviour of the building against an earthquake. However, it is very complicated and not practical since all non-linearities and time history records of the earthquake event are taken into account. To overcome these drawbacks, non-linear static analysis, referred to as pushover analysis, has been developed. Pushover analysis considers both material and geometrical non-linearity but does not require a set of time history records to simulate the dynamic response.

Figure 2 presents an illustration of pushover analysis[6–8]. It can be seen that the building is initially loaded with a particular lateral force. Then, the lateral force is gradually increased up to collapse occurs, or the target displacement is reached. Pushover analysis results a pushover curve or capacity curve which is a relationship between the total base shear and the lateral deflection at the top of the building. This curve expresses the global behaviour of the structure against the horizontal loads.

![Figure 2: Structural behaviour](image)

It worth noting that the target displacement is the expected building displacement due to a seismic load. There are three common approaches to establish the target displacement: capacity spectrum[6], displacement coefficient[9] and displacement modification[5]. Hakim et al.[7] presented an overview of these approaches. The study also showed that the displacement modification is the most conservative approach although the results are nearly similar. Thus, the present study adopts the displacement modification approach in the target displacement determination.
3. Selected building

A two-storey reinforced concrete building is examined in this study. The building is seismically designed according to the Indonesian Standard[3,10] corresponding to a structure designed as a control building for a power plant. Figure 3 presents the plan of the building plan which has a column section of 50 x 50 cm with 16-D19 and the concrete slab thickness of 12 cm. The beam schedule is presented in Table 1. The compressive strength of concrete is taken as 28 MPa, and the yield strength of the rebar is 400 MPa. Steel sections of WF 300x500x6.5x9 and C 150x50x20x2.3 are adopted for the roof frame and purlin, respectively.

![Figure 3: The selected building plan](image)

| Beam | Dimension  | B1    | B2    | B3    |
|------|------------|-------|-------|-------|
|      | 400x700    | 400x700| 400x550|
| **Flexural Reinf.** | | | | |
| **Top** | End | Mid | End | Mid | End | Mid |
| | 8-D22 | 4-D22 | 6-D19 | 4-D19 | 7-D16 | 4D-16 |
| **Bottom** | 4-D22 | 6-D22 | 4-D19 | 6-D19 | 4D-16 | 5D-16 |
| **Shear reinf.** | D10-150 | D10-200 | D10-125 | D10-200 | D10-150 | D10-250 |

| Beam | Dimension  | B4    | B5    | B6    |
|------|------------|-------|-------|-------|
|      | 400x550    | 400x700| 400x550|
| **Flexural Reinf.** | | | | |
| **Top** | End | Mid | End | Mid | End | Mid |
| | 3-D16 | 3-D16 | 4-D16 | 4-D16 | 3-D16 | 3D-16 |
| **Bottom** | 3-D16 | 3-D16 | 4-D16 | 4-D16 | 3D-16 | 3D-16 |
| **Shear reinf.** | D10-150 | D10-250 | D10-150 | D10-250 | D10-150 | D10-250 |

The seismic parameters can be defined based on the building location as follows: $S_s = 0.581 \, g$, $S_1 = 0.249 \, g$ and $PGA = 0.289 \, g$. According to the Indonesian Standard, the building is classified as category IV with Importance factor $I$ of 1.5. The building can be categorised as seismic design category D. According to ASCE 41-17, the basic performance objectives of the building with risk category IV are as follows:
1. Immediate Occupancy structural performance objective for seismic hazard taken as two-thirds of the ground shaking based on the Risk-Targeted Maximum Considered Earthquake at a site (BSE-1N).

2. Life Safety structural performance objective for the seismic hazard taken as ground shaking based on the Risk-Targeted Maximum Considered Earthquake at a site (BSE-2N).

Based on the data above, the response spectrum curve can be established as shown in Figure 4.

![Response spectrum](image1.png)

Figure 4: Response spectrum

4. Numerical analysis

A commercially available finite element software ETABS is utilised to analyse the selected building. Columns, beams and roof frame are discretized using beam elements and the concrete slab is modelled using shell elements. Figure 5 shows the three-dimensional finite element model. To consider non-linearity, ETABS provides a non-linear hinge element that can be defined automatically.

The non-linear hinge element is assigned at ends of columns and beams where the location of plastic hinges occurs during an earthquake event. The plastic hinge definition is determined according to ASCE 41-17[4] as shown in Figure 6. It can be seen that each performance criteria is defined in the plastic hinge. The building evaluation is mainly based on the plastic hinge development in the structural elements. Pushover analysis is performed using a displacement control approach.

![ETABS 3D model](image2.png)

Figure 5: ETABS 3D model
5. Results

5.1. Global behaviour

Figure 7 shows the pushover curves obtained from the pushover analysis. It can be seen that the maximum total base shear from pushover analysis is 4108 kN and 3387 kN in the X and Y direction, respectively. This shows that the pushover in the Y direction is more critical since the building has a lower lateral resistance in this direction compared to that of X direction.

As discussed previously, the target displacement can be obtained using the displacement modification approach which is available in ETABS. Table 2 shows the target displacement of the building against BSE-1N and BSE-2N. The global performance of the building can be examined in accordance with ACI 384.2R-13 criteria. The performance level is Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) when the inter-storey drift ratio is less than 1%, 1-2%, and 2-4%, respectively. It is noted that the building height is 9 m. Thus, the allowable displacement of the
building is 90 mm and 180 mm for BSE-1N and BSE-2N, respectively. It can be seen in Table 2 that the global performance of the building is still within the limit.

Table 2: Target displacements

| Direction | BSE-1N | | BSE-2N | |
|-----------|--------|---|--------|---|
|           | Lateral Displacement (mm) | Base shear (kN) | Lateral Displacement (mm) | Base shear (kN) |
| X         | 43     | 2519 | 73     | 3530 |
| Y         | 56     | 2501 | 91     | 3364 |

5.2. Local/element behaviour

In the pushover analysis, plastic hinge rotation can be captured at every step. The behaviour of structural elements can be examined based on the plastic hinges that occur at the performance level.

Figure 8 shows the hinge response at the base of the column from the beginning until the failure of the column. It can be seen that the column is still within the limit of Immediate Occupancy (IO) level under BSE-1N as the deformation is in the elastic region. On the other hand, the plastic hinge develops at the bottom of the column under BSE-2N. However, the deformation of the plastic hinge is still within the limit of Life Safety (LS) level.

Figure 8: Plastic hinge development

6. Conclusions

This study provides an investigation of the seismic performance of a low-rise concrete building designed according to the Indonesian Standard using non-linear pushover analysis. The analysis is performed using a displacement modification approach. According to ASCE 41-17, the building should meet Immediate Occupancy (IO) and Life Safety (LS) criteria under BSE-1N and BSE-2N, respectively. Based on the global response, the maximum drift ratio of the building is 0.62% and 1.01% for BSE-1N and BSE-2N, respectively. Based on the local response, the most critical hinge developed within IO and LS level for BSE-1N and BSE-2N, respectively. Therefore, it can be concluded that the building has complied with the intended objective of the seismic design.
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