Seismic evaluation of reinforced concrete moment resisting frames using pushover analysis

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Abstract. Earthquake events have been demonstrated to be a major threat to building in Indonesia. It was found that many building failures occurred due to design shortage or construction shortcomings. This research is intended to propose the evaluation method for the concrete building against the possible earthquake. Pushover analysis was performed to study the nonlinear behaviour of a concrete building. A total of two types of concrete buildings, designed for seismic and designed for gravity load only, were investigated. The results show that the concrete building designed for seismic has better performance in both local and global response than that of the concrete building designed for gravity.

Keywords: inelastic behaviour, seismic assessment, concrete building, pushover

1. Introduction

It is well known that Indonesia lies within a moderate to high seismic region. A number of recorded experiences indicated that earthquake event caused numerous deaths and fatalities. For instance, the most severe earthquake disaster of the 20th century, the 2004 Aceh earthquake which triggered a tsunami and resulted in 120,000 houses damage and 20,000 deaths[1]. Subsequently, the 2006 Yogyakarta destroyed more than 30,000 houses[1]. More recently, the 2018 Lombok earthquake caused more than 400 deaths, and 300,000 people evacuated[2].

Many buildings collapsed during the earthquake events [1,2]. This is due to the fact that the buildings are not adequate to resist the lateral load due to design shortage or construction shortcomings. Furthermore, it was found that many existing buildings do not meet the national code requirement. Thus, seismic analysis evaluation is required to determine the capacity of the building rehabilitation works.

Majority engineers use the conventional elastic analysis to design the structures because it is very simple and straightforward. A factor is applied in the elastic analysis to accommodate dynamic effect as well as nonlinearity material and geometry. Thus, this approach cannot predict the nonlinear behaviour of the structure accurately. Theoretically, nonlinear dynamic analysis is the most accurate approach yet very complex as it considers all type of nonlinearity. However, it requires time history ground motion data to simulate the dynamic effect.

Nowadays, nonlinear static pushover analysis has been introduced as a new technique to solve the problem expressed above. This method considers both material and geometrical nonlinearities, but it does not need time history records to calculate the dynamic response. In this research, nonlinear pushover analysis is adopted to investigate the seismic behaviour of the reinforced concrete frame.
designed for seismic. For comparison, the reinforced concrete framed designed for gravity load only is also studied.

2. Pushover analysis

In pushover analysis, it is assumed that the building behaviour is associated with the behaviour of an equivalent single-degree-of-freedom (SDOF) system. The building behaviour is determined by single-mode, which remains constant throughout the dynamic response. Although this assumption is incorrect, previous studies\[3–5\] showed that they lead to good predictions of the maximum seismic response of multi-degree-of-freedom (MDOF) structure.

To perform pushover analysis, a lateral load pattern is explicitly subjected to the building, as illustrated in Figure 1. Then, the load magnitude increases continuously until the structure reaches a target displacement or collapse. A target displacement is the top displacement of the structure when subjected to the design earthquake. Pushover analysis produces a pushover curve, which is the relationship between base shear and roof displacement. The pushover analysis, as shown in Figure 1, expresses the global response of the structure against the lateral loads.

![Figure 1: Pushover analysis illustration\[6,7\]](image)

ATC-40\[6\] presents the capacity spectrum methods to determine the target displacement. A step by step of the capacity spectrum method is shown in Figure 2. Initially, the demand response and capacity curve are converted into a capacity spectrum (Sa vs Sd), known as acceleration-displacement response spectrum (ADRS) format \[6\]. The other approaches to determine target displacement are the method of coefficient displacement modification displacement according to FEMA 356\[8\] and FEMA 440\[9\], respectively. However, the previous study by Hakim et al.\[7\] showed that the results obtained from the three methods are closely similar.

![Figure 2: A step-by-step of the capacity spectrum method\[7\]](image)
Once the target displacement is determined, the seismic performance of the building can be evaluated according to the limits in ATC-40[6]. There are two categories, global performance and local performance. The global performance is tied to the inter-storey ratio (IDR). The performance levels are Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). Table 1 shows the limits for each performance level. These limits represent minor to major damage, as shown in Table 2. On the other hand, the local performance can be determined based on the development of plastic hinge in the structural elements, such as beams and columns. The limits on the plastic hinge rotations of beams and column are presented in Table 9-6 and Table 9-7 in ATC-40 [6], respectively.

### Table 1: Inter-storey drift ratio for each level according to ATC-40

| Level                          | Intermediate Occupancy (IO) | Life Safety (LS) | Collapse Prevention (CP) |
|-------------------------------|-----------------------------|------------------|--------------------------|
| Operational (O)               | 0.7%                        | 0.7% - 2.5%      | 2.5% - 5%                |

### Table 2: Performance level of the building

| Level                          | Description                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|
| Operational (O)               | Very little damage, temporary deformation, the structure remains the initial strength and stiffness, all systems are normal |
| Immediate Occupancy (IO)      | Minor damage, temporary deformation, the structure retains original strength and stiffness, the elevator can be restarted, the fire protection still works properly |
| Life Safety (LS)              | Fair damage, some permanent deformation, some residual strength and stiffness remains, damage to partition, building may be beyond economical repair |
| Collapse Prevention (CP)      | Severe damage, large displacement, small residual stiffness and strength but loading bearing column and wall function, the building nearly collapse |

3. **Generic building**

A generic three-storey concrete frame is analysed in this study. The plan and elevation view of the structures are shown in Figure 3. The compressive strength of concrete is taken as 28 MPa, and yield strength of the rebar is 414 MPa. The ultimate design load (1.2 Dead load + 1.6 Live load) is taken as 6 kN/m². The building is designed for moderate seismicity, according to SNI 1726-2012[10] and SNI 2847-2013[11]. Seismic design parameter is shown in Table 3. For comparison, the building is also designed for gravity load only. Reinforced concrete design section details are presented in Figure 4. It should be noticed that structural design for the building is not relatively a single outcome. A different designer may produce different design results. Nevertheless, the reinforced concrete design used in this research is based on common practice.
4. Analysis and results

A commercial finite element software, SAP2000[12] was used to model and analyse the generic building. Steel beams and columns were discretised using nonlinear frame element including lump...
plasticity hinge at both ends of each element where plastic hinge may form during an earthquake, as shown in Figure 5. SAP2000[12] provides defaults hinge, PMM hinges for columns and M3 hinges for beams as described in FEMA.

As discussed in Section 2, two-steps analysis is conducted in pushover analysis. Initially, the building is subjected to gravity load. Subsequently, the pushover analysis is carried out by pushing the building horizontally until the target displacement is reached.

![Figure 5: Plastic hinge assignment](image)

5. Results and discussion

Pushover or capacity curves (lateral load vs top displacement) for the building obtained from pushover analysis are presented in Figure 6. In general, it can be seen that the slope of the pushover curve gradually reduces when the lateral displacement of the building increases. This is because the plastic hinges have been developed in the structural elements. It is worth noting that the building designed for seismic properly have greater performance compared with that of the building designed for gravity load only.

![Figure 6: capacity curves obtained from pushover analysis](image)

For seismic evaluation, two performance limits are considered, as mentioned in Section 2. Figure 7 shows the target displacement of the building using the capacity spectrum method. According to the global limits, the building designed for seismic can be categorised as Intermediate Occupancy (IO) level. On the other hand, the target displacement of the building designed for gravity load is located in Collapse Prevention (CP) level.
Figure 7: Performance point by capacity spectrum method

Figure 8 shows plastic hinge formation for the building at the performance level. For the building designed for seismic, the majority of the structural elements are still within elastic limits (no plastic development). Several plastic hinges develop both in the beams and column. On the other hand, for the building designed for gravity load, many plastic hinges occurred mainly in the column with Collapse Prevention (CP) level.

Figure 8: Plastic hinge formation at performance level.

6. Conclusions

Based on this study, the following conclusions can be made for the structural configuration investigated:

1. Pushover analysis is a relatively simple method to evaluate the behaviour of the building under an earthquake.
2. Pushover analysis is able to predict progressive failure mechanism and identify the weak elements. Thus, proper action can be conducted for rehabilitation work.
3. This analysis shows that the building designed for gravity load only is not adequate to resist lateral load due to an earthquake. This demonstrates that an earthquake load must be considered in the building design.
4. The structure that was designed according to SNI 1726-2012[10] and SNI 2847-2013[11] is adequate.

These conclusions presented in this study are limited due to the fact that only a single symmetry plan is considered. It is worth noting that nonlinear pushover analysis is an approximation method. It may not accurately represent a dynamic phenomenon with large degree accuracy. The load duration due to
long-term effects such as creep is not taken into account. Moreover, dynamic effects are not considered in pushover analysis.

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