Seismic responses comparison of RC building in consideration of plastic hinge models and properties

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Abstract. Assessment of reinforced concrete building capacity under seismic excitation has been recognized to be highly important for the past decades especially in Indonesia. Previous studies showed failures of RC building occurred in columns with bad confinement. The confinement in RC column has significant role in providing ductility and shear capacity for seismic loads. For this aim, a five-story RC building having different confinement on column members are investigated under seismic excitation. Three set of ground motions are selected and matched with target response spectrum of Indonesian code. Nonlinear analysis is performed by utilizing OpenSEES finite element software. To account the inelastic behaviour of beam and column elements, two types of plastic hinge are applied for both elements, namely finite length plastic hinges (plastic zone) and distributed hinges along the length of elements. The results show that there is a noticeable difference in seismic responses in correlation with the building model.

1. Introduction

Reinforced concrete has been popular and widely used for most of the building construction in Indonesia. Severe seismic events for the past years have increased the demand of earthquake resistant building system. The earthquake resistant building depends on its capacity to dissipate the seismic energy whilst the structure behaves nonlinearly. Therefore, nonlinear procedures of analysis are developed to assess and evaluate the nonlinear responses of the structural system as described in FEMA 356 [1]. However, the structural nonlinear responses are highly sensitive and require the accuracy of element nonlinear properties to capture the behaviour of the structural system. There are several nonlinear modeling techniques used for simulating structural nonlinear response including distributed plasticity and concentrated plasticity. Inel and Ozmen [2] evaluated the effect of plastic hinges properties in reinforced concrete building. Two proposed plastic hinge length expression were considered. The variation in displacement capacity was observed for different modelling techniques in relation to structural ductility. However, the analysis was carried based on non-linear static procedure and non-linear dynamic response was not evaluated. Botez et al. [3] studied the effect of plastic hinge model and distributed plasticity with non-linear progressive collapse analysis. Variation in analysis result was observed. However, the ductility in terms of column confinement was not considered.

This paper investigates the seismic nonlinear model that had been proposed and evaluate the differences in analysis result. Moreover, the requirement of structural ductility in order to keep its...
stability before collapsing is also considered in this study. The important design specification required for earthquake is the confinement in RC columns for providing ductility. Haraji [4] have studied the effect of confinement enhancement in RC column under seismic loadings. Recent study of Yuen et al. [5] shows the increasing ductility of reinforced concrete column by providing sufficient amount of confinement. Therefore, this study also evaluates the effect of confinement in concrete columns on seismic response. Pushover and time-history analysis are used to investigate the structure’s lateral capacity and response under seismic excitation.

2. Concrete model

Many concrete stress-strain models have been proposed for the past years. Mander et al. [6] proposed the concrete model for both confined and unconfined with consideration of increasing ductility and strength in RC members. The concrete is modeled as unconfined concrete and confined concrete for its cover and core respectively. This study evaluates the confinement variability of concrete column in relation to seismic non-linear responses in RC building. Six-confinement configurations were selected and investigated. The core concrete parameters were developed using proposed equation by Mander et al. [6] The models are described in building model section.

3. Element model

The present design codes and guidelines has required the consideration of structural plastic behaviour in determining structural responses. The popular simplified approach in evaluating structure’s nonlinear capacity is pushover analysis. However, nonlinear model has to be applied which consists of concentrated hinge, distributed plasticity and finite length hinge fibre-based model. This paper evaluates the variability of structural responses for variability of confinement configuration with different nonlinear fibre-based model approaches.

Fibre-based model has been widely used to simulate the nonlinearity of structural member behaviour by using finite fibre elements to capture the responses of the element. Study conducted by Chiara and Rui [7] showed that fibre model managed to simulate the propagation of nonlinearity behaviour along the cross section of the element. The distributed plasticity model predicts the nonlinear behaviour of the element, taken the nonlinear geometry and material into account, with Gauss integration points along the length of the element. The distributed plasticity fibre model is represented in figure 1.

The other modelling approach is finite length hinges approach with the principle that the plastic behavior occurs at the defined region while the rest of the element remain remains elastic. The length of plastic hinges determines the moment-rotation relationship of a particular member. As the length of plastic hinges is defined, the displacement at the tip of the column can be computed by integrating member’s curvatures. Figure 2 represents the definition of plastic hinge length for cantilever member [8].

![Confined concrete fibres](image1)

**Figure 1.** Fibre model for reinforced concrete member.

![Moment, M](image2)

**Figure 2.** Plastic hinge length definition.
In this study, three proposed evaluation for determining the length of plastic hinges in concrete structure is investigated. Proposed equation by Park et al. [9] and Paulay and Priestley [10] are evaluated and expressed below:

\[ L_p = 0.5H \]  \hspace{1cm} (1)
\[ L_p = 0.08L + 6d_b \]  \hspace{1cm} (2)
\[ L_p = 0.08L + 0.022d_b f_y \]  \hspace{1cm} (3)

where \( L_p \) is Length of plastic hinge, \( H \) is the height of member cross section, \( d_b \) is the diameter of longitudinal reinforcement, and \( f_y \) defines the yield strength of steel reinforcement.

The OpenSEES [11] finite element software is used for distributed plasticity model in this study and finite length hinge with different length of plastic hinges considered. Furthermore, the shear response in concrete column was modelled by a uniaxial hysteretic law. The section aggregator was used in OpenSEES to construct the coupling of axial/bending interaction with shear. The adopted shear-deformation law was degrading hysteretic with two hysteretic law (one degrading with ductility parameter of 0.03 and one non-degrading) in parallel. Figure 3 illustrates the adopted law with characteristic point at cracking, peak and residual strength. The shear strength, as proposed by Sezen and Mohele [12], it is expressed as follows:

\[ V_{peak} = V_c(N) + V_s \]  \hspace{1cm} (4)

where \( V_c(N) \) is the concrete shear strength with contribution of axial load and \( V_s \) is the shear strength provided by ligatures. In this study, the cracking strain is computed with elastic uncracked behaviour properties. The degradation starts after the peak strength in this adopted model.

\[ \gamma_{crack} = \frac{V_{crack}}{GA^*} \]  \hspace{1cm} (5)

Following the study by Sezen [13], estimated the shear displacement where axial collapse occurred. The peak strain is calculated as the function of steel yield stress \( f_s \), normalised axial force \( \nu \), longitudinal reinforcement ratio \( \rho \), and shear span \( L_v \) over section height \( H \).

\[ \gamma_{peak} = \frac{f_s \rho}{5000 \sqrt{vL_v / H}} - 0.0004 \]  \hspace{1cm} (6)

Finally, the ultimate strain for the model is expressed as the ductility factor from the peak strain and shown in equation (7).

\[ \gamma_{res} = \left[ 4 - 12V_{peak} / (A_c f_c) \right] \gamma_{peak} \]  \hspace{1cm} (7)

4. **Earthquake ground motions**

Three set of ground motion records are selected and matched with target response spectrum of Banda Aceh earthquake with site class D. The records include Kobe, Loma Petra, and Managua records. Figure 4 depicts the acceleration spectrum for matched four records and target spectral acceleration.

5. **Building description**

Five-story reinforced concrete building is evaluated in this study. The building frame considered is interior frame and subjected to 24 kN/m dead load and 10 kN/m live load for floor and 5 kN/m on the roof designed to resist gravity load and earthquake load based on SNI-1726-2012 for Indonesian Earthquake Code with the location is in Aceh. The base support is assumed to have fixed connection for the purpose of this study. The geometry of the building is shown in figure 5.
V\textsubscript{crack} = V\textsubscript{c}(N)
V\textsubscript{peak} = V\textsubscript{c}(N) + V\textsubscript{c}
V\textsubscript{res} = V\textsubscript{c}

Figure 3. Monotonic shear envelope model of RC member.

Figure 4. Response spectrum of matched records.

The dimension of column member is 500x500 mm for interior and exterior column along the height of the building and all beams are designed with 300x500 mm cross-section in addition with D10-150 shear reinforcement. The first to third story columns have 12 numbers of 22 diameter longitudinal reinforcement while for the fourth and fifth story, 8D22 is assigned. The beam reinforcement for the first and third story is typical with 5D19 and 3D19 for top and bottom reinforcement respectively. The second story beam has 6D19 for the top reinforcement instead, while for the fourth and fifth story beam, 4D19 is used for top reinforcement.

6. Analytical model
The building with 2 dimensional model is established in OpenSEES finite element software [11]. The material properties for concrete chosen is Kent-Scott-Park with degrading stiffness properties and no tensile strength. Reinforcement bar material was modelled with bilinear uniaxial material with kinematic strain hardening which is available as Steel01 in OpenSEES. The concrete material has compressive strength of 20 MPa and the steel material has yield strength of 400 MPa. Fibre model is applied for both distributed plasticity and concentrated hinges non-linear model.

The concrete fibre model comprises of concrete cover, concrete core, and reinforcement steel. The concrete cover is constructed using unconfined concrete material properties while concrete core is assigned with confined concrete properties. Flexibility based-element with 5 Gauss-Lobatto integration points is assigned for both beam and column in distributed plasticity model. Moreover, nonlinear geometry P-Δ and corotational is activated for column and beam section respectively. Furthermore, Beam and column with hinges element is assigned for finite length hinges building model. Figure 6 depicts the types of column confinement considered in this study. Core concrete uniaxial material model is computed for each confinement type and presented as follows.
Figure 6. Column confinement model.

The building model with finite length hinges following expression as described in previous section for determining its length of plastic hinges is expressed as CH1, CH2, and CH3 respectively while distributed plasticity model is labelled as DP. The building is subjected to deadload and liveload in a factor of 1.0 and 0.3 respectively before non-linear static pushover and time-history analysis is conducted. The floor mass is computed from the gravity load applied on the structure.

7. Result and discussion

7.1. Capacity curve

Pushover analysis was performed for each building model with inverted triangle lateral load distribution corresponding to first mode period of the structure. The results of analysis for considered building models in terms of base shear versus roof displacement are presented in figure 7. The variability of confinement shows insignificant contribution in terms of structure lateral capacity. However, the increase in ductility has been noticed from observation of the capacity curves. The confinements with 3 legs has better ductility performance with less degradation in stiffness after peak lateral strength. Furthermore, the effect of hinge model in structure capacity curve is also compared and shown in figure 8.

Figure 7. Capacity curve comparison for different confinement.

Figure 8. Capacity curve for different hinge length parameter.

7.2. Nonlinear time-history analysis

In order to study the structural behaviour considering different types of confinement and analysis model, nonlinear time-history analysis is conducted under three different excitations matched with target spectrum design as described in previous section. Figure 9 to 11 illustrated the inter-story drift profile of the building under considered ground motions and confinements.
From three ground motions considered in this study, CH1 model shows different trend of drift profile with the other model. Moreover, model CH3 has better correlation profile with DP model. The confinement variability shows no different in terms of drift profile however, slight less drift is observed in DP model by providing more confinement to the column. It may caused by higher dissipated energy as providing more confinement increases the degradation or hardening behaviour of the concrete elements. The structure has performance level between IO (Immediate-Occupancy) and LS (Life-Safety) with maximum drift in between 1% to 2%. The highest response occurs in Managua earthquake.

8. Summary and conclusion
Five-story RC building with variability of column confinement is investigated through severe nonlinear analysis model including distributed plasticity and finite length hinges with fibre model. Pushover analysis is performed to assess the structure’s lateral capacity and ductility. Moreover, nonlinear time-history analysis is also conducted to simulate the building nonlinear behaviour under four ground motions which are matched with Aceh earthquake response spectrum. Based on analysis result and observation, several conclusion can be drawn as follows:

1. Ground motions matched with target response spectrum provides different responses of the structural system. As observed from the drift profile, the building is considered Immediate-Occupancy for Kobe and Loma Petra earthquake while it is life-safety for Managua earthquake.

2. The confinement spacing determines the ductility of the structure based on pushover analysis. Less degradation after peak strength is observed by providing more confinement in the column.
3. The seismic nonlinear models of finite length hinges CH2 and CH3 show good correlation with distributed plasticity model while CH1 gives inaccurate result for simulation of building nonlinear responses.

4. The inter-story drift profile for nonlinear seismic model CH2,CH3 and DP shows similar trend under three ground motions considered.

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