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Evaluation of RC building strengthened with column jacketing method with consideration of soft-story

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Abstract. The assessment and strengthening method of existing reinforced concrete buildings in terms of seismic responses have been highly important for the past decades especially buildings with soft-story mechanism which are found to be more vulnerable. Several strengthening techniques have been proposed including Fibre Reinforced Polymer and steel jacket of RC column elements. This paper aims to evaluate the effectiveness of two strengthening techniques with variability of soft-story under severe earthquake excitations. Five-story RC building is investigated and non-linear dynamic analysis is performed to capture the inelastic responses of the structure. Four sets of ground motion are selected and matched with target response spectrum for Aceh earthquake. Seismic responses of the considered models and strengthening techniques are compared.

1. Introduction

Recent reported earthquake damage in Indonesia [1] has shown the higher percentage of structural failure associated with soft-story mechanism especially for reinforced concrete building. The soft-story mechanism occurs when the stiffness of one story is much less than the adjacent story stiffness. The structure was designed with inadequate seismic vulnerability assessment. Rajeev [2] reported the effect of soft-story parameters in seismic fragilities of the structure. The structure with higher soft-story level was found to be more vulnerable in moderate to high intensity earthquake. Therefore, strengthening technique to overcome the challenge in soft-story building have been proposed and developed for the past decades. The most common retrofitting techniques are FRP and steel jacketing which have the efficiency in terms of workability and implementation. Evaluation of each strengthening method is critical to obtain the most efficient technique in retrofitting of the building.

The applications of FRP and steel jacketing method and finite element modelling techniques for reinforced concrete column have been reported [3,4]. Recently, Seifi et al. [4] proposed the physical model for FRP confined concrete column calibrated with the experimental data. Moreover, steel jacketed concrete column model was also proposed Campione et al. [5]. Recent Study conducted by Futardo et al. [6] reported the efficiency of strengthening technique in soft-story building. The study shows the method of column jacketing is effective in reducing seismic responses in soft-story building. However, the application of the strengthened column model in building with variability of soft-story
level has yet been evaluated. The premise of this study is to illustrate the efficiency of retrofitting techniques in reinforced concrete building with different soft-story parameters.

2. Building model
Five-story reinforced concrete building is employed to illustrate the effect of strengthening technique in different soft-story effect. Figure 1 depicts the building geometry and main element detailing. The building is designed to resist 20 kN/m gravity load and seismic load based on SNI-1726-2012 for Indonesian Earthquake Code with the location is in Aceh. The concrete has compressive strength of 25 MPa and the yield strength of the reinforcement steel is 420 MPa.

![Building details](image)

Figure 1. Building details.

3. Impact of soft-story
The definition of soft-story is that the stiffness of lateral resisting force in any story is less than 70% of the stiffness of the adjacent story which induces the localized concentration of drift. The soft-story is quantified by story lateral stiffness, therefore the parameter of soft-story used in this paper is the relative height between the first-story column and the adjacent floors column height.

\[ SS = \frac{K_2}{K_1} = \left( \frac{L_2}{L_1} \right)^3 \]  

where \( K_1 \) and \( K_2 \) are the lateral stiffness of first and second story while \( L_1 \) and \( L_2 \) defines the column height of the first and second story respectively. In this study, the parameter \( SS \) (Soft-Story) is chosen as 40%, 60%, 80% and 100% to illustrate the sensitivity of the parameter to the structural responses. The story height for each parameter of \( SS \) is summarized in table 1.

| SS    | %  | First story column height (mm) |
|-------|----|--------------------------------|
| 1     | 100| 3500                           |
| 0.8   | 80 | 3770                           |
| 0.6   | 60 | 4150                           |
| 0.4   | 40 | 4750                           |
4. Element model
The building model is constructed in OpenSees finite element software [7]. Concrete01 material is applied to model the confined and unconfined concrete properties based on Mander et al. [8] respectively. Moreover, Steel02 material based on Giuffre-Menegotto-Pinto is used to model the reinforcement bar. The beam and column elements are constructed with flexibility-based fibre-section element with 5 Gauss-Lobatto integration points. Section aggregator is used to model the shear-axial and flexural response. The method of including shear can be found in [9]. Furthermore, P-Delta effect and Corotational transformation is included to compute the second order effect for columns and beams respectively. Stiffness proportional damping is used and calibrated to be 5% for the first elastic mode. For this study, the base support is assumed to be fixed.

5. Strengthening technique and modelling
In this study, the soft-story column is located at the first-story where the failure is most-likely to occur. Therefore, only the first-floor column is strengthened to observe the effect of the retrofitting method.

5.1. FRP jacketing
The base-column is strengthened with 3 layers of MasterBrace FIB 450/50 Carbon Fibre Sheet with fabric thickness of 0.255 mm, fabric width of 500 mm, tensile strength of 4900 MPa and 230 GPa tensile elastic modulus with near surface-mounted (NSM) system of 13 mm diameter reinforcement bar. The ConfinedConcrete01 material available in OpenSees [7] is utilized to assign the effect of FRP confinement in RC column and applied in fibre-section element. The application of this method can be found in [4]. The experimental conducted in [4] showed the failure mode of FRP jacketed column was due to the buckling of the bar. Therefore, the ReinforcingSteel material is assigned to model the reinforcement bar to incorporate the buckling effect based on Dhakal and Maekawa model and rupture behavior.

5.2. Steel jacketing
The steel jacketing technique used in this study is based on the work of Rosario Montouri and Vincenzo Piluso [10]. The column is strengthened with angles and battens to increase the stiffness and confinement. Angle size of 150.150.12 is used with batten width and thickness of 15mm and 3mm respectively with 250 MPa yield strength applied 0.5 m from the column end. Figure 2 shows the strengthened column in this study. The physical model approach used in this study was proposed by Campione et al. [5]. The angles properties were modified from the work of by defining the interface and contact between the steel angles and reinforced concrete column. The maximum load can be resisted by the steel angles is the function of interface stress along the direction of the contact surface as shown in equation (2).

\[ P_a^{*} = 2n_a n_{la} l_0 \left(c_0 + \mu f_{lc,max}\right) \]  \hspace{1cm} (2)

where \( n_a \) is the number of steel angles, \( n_{la} \) is the number of layers, \( l_0 \) is the total length of the angles, \( c_0 \) is the cohesive strength, \( \mu \) is the friction coefficient [5] and \( f_{lc,max} \) is the maximum confinement pressure determined based on [9]. The yield strength of the angles is then defined based on the force over total-area relationship as defined in equation (3).

\[ f_{y(angle)} = \frac{P_a^{*}}{A_{angle}} \]  \hspace{1cm} (3)

\[ E_{(angle)} = \frac{f_{y(angle)}}{e_0(angle)} \]  \hspace{1cm} (4)

The steel-jacketed concrete column is modelled by utilizing fibre-section element with the angles with the angle is modelled with Steel02 material with properties as described previously.
6. Earthquake ground motions
Four 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, Tabas and Managua records. Figure 3 depicts the acceleration spectrum for matched four records and target spectral acceleration.

7. Result and discussion
Inter-story drift of each building models considering different strengthening method and soft-story variability is compared. Inter-story drift represents the structural damage as described in FEMA356 [11] which is 1.0% for Immediate Occupancy, 2.0% for Life-Safety and 4.0% for Collapse Prevention. Figure 4 to 7 show the maximum inter-story drift under four different ground motions as described in previous section.
The result in terms of maximum story drift from four set of ground motions considered is compared. For building with soft-story parameters of 1.0 and 0.8, both FRP and steel jacketing provides better responses than unstrengthened building for Kobe and Loma Petra records. It is noticed that in this case, the strengthening method with FRP and near surface mounted system is ineffective in increasing structural performance due to buckling of NSM bar. For Kobe and Loma Petra earthquake, the result shows that steel jacketing technique is effective in reducing the seismic response for SS1 and SS2. However, the effect of steel jacketing method is found inefficient when the soft-story parameter increases to SS3. Furthermore, to observe the effect of strengthening methods in structure lateral capacity, pushover analysis is performed with inverted triangle lateral force distribution. Figure 8 to 10 depicts the capacity curve of each base column model and soft-story parameter.

**Figure 6.** Maximum drift for Managua.  
**Figure 7.** Maximum drift for Tabas.

**Figure 8.** Capacity curve for SS1.  
**Figure 9.** Capacity curve for SS2.

**Figure 10.** Capacity curve for SS3.  
**Figure 11.** Capacity curve for SS4.
8. Conclusion
Five-story reinforced concrete building with variability of first story column height to represent the soft-story is evaluated under two different jacketing retrofitting technique including FRP jacket with near surface mounted system and steel jacket with angles and battens. Pushover and nonlinear dynamic analysis are performed to assess the nonlinear responses of the structure. Based on the analysis results, several observations are made as follows:

1. The soft-story affect the lateral capacity of the reinforced concrete building. It is observed that the increasing height of the first story results in decreasing peak value of base shear in pushover curve for all building models.
2. Base column strengthened with FRP and near mounted surface system is noticed not efficient in strengthening the structure. More numbers of NSM bars and layers of CFRP may be required for the strengthening method to be applicable. Furthermore, providing the FRP jacket not only at the base column may also be considered.
3. Steel jacketing techniques shows efficiency in increasing structure lateral stiffness and decreasing the nonlinear response under earthquake excitation.
4. Effectiveness of strengthened column varies under different ground motions.

Further study shall be made incorporating more parameters involved in comparing the strengthening method for soft-story building including different location of strengthened elements, concrete jacketing technique, structural vulnerability and different numerical model for strengthened elements.

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