Seismic Response Of Retrofitted Low Rise Structure Under Strong Earthquakes Using Nonlinear Time History Analysis

D R Daniel¹ and A.H Sinaga²

¹ Department of Civil Engineering, University of Sumatera Utara, DR. Mansur Kampus USU Medan 20155, Indonesia
² Department of Civil Engineering, University of Cendrawasih, Kampus Uncen Waena Jayapura, Indonesia
danielteruna@usu.ac.id

Abstract. This paper summarizes the response quantities of existing and retrofitting for three story reinforced concrete (RC) structure under selected seismic excitation. The retrofitting technique addressed in this study include carbon fiber reinforced polymer (CFRP) bar strengthening on beam, steel cage column jacketing, high strength concrete column jacketing, CFRP strengthening of column, and applying the base isolation technique. To evaluate the effect of seismic excitation on the structural responses, three ground motion records, i.e., Newhall, Northridge and Sylmar are selected and scaled to match response spectra design of Indonesian code. Material non-linearity was taken into account and modelled as plastic hinges at the both end of columns and beams element. Nonlinear time history analyses were performed using Newmark’s integration method for existing and all retrofitting models. Finally, the comparisons of the response quantities in term of base shear, roof acceleration, story drift index are presented and discussed.

1. Introduction

Low-rise buildings are generally vulnerable to seismic action which is caused by the use inadequate material specifications, lack of knowledge in detailing, and maybe constructed very poorly. Bothara et al. [1] investigated the causes behind the damage of building after the 7.5 magnitude Padang earthquake which occurred on 30th September 2007 in West Sumatera province. They found that for concrete low-rise structures, most of the damages caused by the lack of understanding and dissemination of concept for earthquake resistant design and construction. The damage mechanism included short column failure due to present of infill wall, sudden changes of stiffness, soft story effect, column shear failure, inadequate of bar splicing, and buckling of column reinforcement due to opening of stirrups. Similar case happened in Banda Aceh in 2004 where it was hit by magnitude 9.3 earthquake followed by Tsunami hit Banda Aceh (located in Sumatera island. Similar mechanism were observed for low- and mid-rise of concrete structures and reported by Saatcioglu et al. [2]. To gain the sustainability structures during seismic events, the retrofitting technique is required for existing buildings with little or no seismic consideration [3]. This paper aims to study seismic response of existing and retrofitted of three story by four bays RC building subjected to the strong earthquake records. Additionally, the paper presents the effect of structural strengthening methods in seismic performance of the structure. Although, the retrofitting method needs consideration in term of
workability, the cost of the implementation, and the interfere with the architecture, however, the discussion is limited on the structural aspect only.

2. The aim and techniques of retrofitting

Different techniques for the repairing and strengthening of RC structures have been reported several authors [4-6]. The techniques are classified as local and global strategy. The global retrofitting methods such as base isolation, steel braces, passive energy dissipation, and shear wall are intended to increase the overall seismic performance of the structure. Meanwhile, the local retrofitting techniques, including concrete jacketing, steel jacketing, CFRP wrapping, steel plate bonded, steel angle prestressed by cross tie, and additional FRP bar, are applied to avoid local failure of the structural component, but can consequently improve the overall performance of the structure. Moreover, Thermou and Elnashai [6] provided detailed outline of the effect of local and global retrofitting methods on the three most important seismic response parameters (stiffness, strength, and ductility).

Various methods of concrete jacketing for RC column in the last two decades was reported by Raza et al. [7]. Concrete jacketing method enhances the seismic performance of the column by increasing the axial and flexural strength capacity as well as its ductility. However, it is costly and time consuming when compared to CFRP jacketing method. Furthermore, the ductility improvement is deemed less significant since concrete material is brittle. It was also noted that it is very difficult to fully restore the initial stiffness of the damaged column.

CFRP Jacketing is one of the most common seismic retrofitting techniques due to its durability, high strength to weight ratio, and ease of implementation [7]. However, CFRP material is relatively costly and exhibits poor properties when it is exposed to high temperature. Rahai and Akbarpour [8] tested eight large rectangular RC columns strengthened with CFRP under axial and bidirectional bending moment. The RC column were wrapped with different CFRP thicknesses and different fiber orientations. It was found that the all columns demonstrated significant improvement on the strength and curvature ductility. Moreover, increasing the number of longitudinal CRFP layer would also improve column stiffness and decrease the curvature.

Experimental investigation on the strength and ductility of retrofitted columns welded rectilinear steel jacket combined with partial stiffeners was conducted by Xiao and Wu [9]. The results revealed that the retrofitted columns exhibited excellent hysteretic curve with drift ratio greater than 8%. Another popular retrofitting technique that can be used to achieve the best seismic performance of structure is base isolation system. Base isolation can be implemented on both existing and new buildings. The system decouples the building from horizontal component of the ground motion by insertion of mechanical devices with low horizontal stiffness in between upper structure and foundation. The performance of base isolated building had been proven during Kobe earthquake [10]. Currently, base isolation system was implemented to specific purpose buildings such as hospital [11], heritage or ancient buildings [12], and nuclear facilities [13] to ensure that these buildings show high level performance in case of unexpected severe earthquakes.

3. Structural model and ground motion records

A three-story RC building is studied under a combination of gravity load (dead load and live load) and ground motion excitations. Three types of strong near fault ground motion records, namely Newhall, Sylmar and Northridge are used in this study. The selected ground motions were scaled to match design response spectrum of Indonesian code for Padang region with site class C. The elevation view of building is shown in Figure 1, while the corresponding response spectra of considered ground motions is depicted in Figure 2. All concrete material for columns and beams were designed with 25 MPa specified compressive strength, while longitudinal and transverse reinforcements are specified with yield stress of 420 MPa. The dimensions of beams on the first and second floor (B1) are 300x500 mm with 4D-19mm and 2D-19mm for the top and bottom bars, respectively. The roof beams are designed to be 250x400 mm with the top bars of 2D-19mm + 1D-16mm and bottom bars of 2D-19mm. Furthermore, all columns sizes are 400x400mm in which the reinforcement ratio are 2.13% for
columns on the first and second story (C₁) and 1.71% for columns on the third story (C₂). Additionally, The beams of the first and second floor support uniform dead load of 25 kN/m and live load of 15 kN/m. The roof beams carry a dead load of 8 kN/m and live load of 5 kN/m.

**Figure 1.** Elevation view of structure model

**Figure 2.** Target and matched response spectra

4. **Nonlinear time history analysis**

4.1. **Beam column joint and plastic hinge modelling**

Analytical studies of the seismic behaviour RC buildings had revealed that the predicted inelastic behaviours were less accurate if beam-column joint is not taken into consideration. ASCE 41-17 [14] allow beam-column joint to be modelled implicitly by adjusting the centre line model. Figure 3 shows beam column modelling according to ASCE 41-17 in which hatched portions indicate rigid element. The seismic behaviour and performance of a building structure are measured by the stage of damage under a certain ground motions excitation and generally is quantified by roof displacement and deformation of the structural members.

The nonlinear procedures of ASCE 41-17 require definition of the nonlinear load deformation relation. Such a curve is defined in Figure 4. There are five points labelled A, B, C, D, and E are used to define the hinge rotation behaviour of structural members, and three points labelled IO (immediate occupancy), LS (life safety), and CP (collapse prevention) are used to define acceptance criteria for the plastic hinge. In the modelling, plastic hinge is assumed to occur near the beam-column joint.

(b) \( \sum M_{nc} / \sum nb > 1.2 \)  
(c) \( \sum M_{nc} / \sum nb < 0.8 \)  
(d) \( 0.8 < \sum M_{nc} / \sum nb < 1.2 \)  

**Figure 3.** Beam-column joint modeling [14]

Evaluation of the existing structure under selected earthquakes is performed and it is confirmed that the structure experience story drift index greater than 2%. Furthermore, all beams on the first story experienced heavy damage (CP). Moreover, one beam on the second story shows damage state at LS. Overall, all columns base and almost all beams on the roof story indicated damage at the IO level. Figure 5 shows that plastic hinge mechanism under Newhall earthquake. To minimize or to reduce damage of the existing structure, retrofitting is required.
4.2. **Detail of retrofitting used in this study**

The following five methods of retrofitting are evaluated in this article. For the purpose of discussion existing building is referred as type I. Three of retrofitting methods are applied to all columns at the firsts story. The effect of CFRP jacketing on the confined column strength and strain is determined based on ACI 440.2R-17 [15]. In this case, it increases the confined column compressive strength and confined column strain to 30 MPa and 0.0082, respectively (denoted as type II). Concrete jacketing is applied by replacing concrete cover with high strength concrete of 50 MPa compressive strength (denoted as type III). For type IV which is steel cage method, four steel of angles are added to the four corners of each columns The other retrofitting method which include adding two CFRP bars of 10mm diameter in the top side of beams on the first and second is implemented as denoted type V. The purpose of this method is to increase the flexural capacity of all the beams. Figure 6 provide information about retrofitting details of the columns on the first story and retrofitting of beams on the first and second floors. For global retrofitting (type VI), the base isolation system is installed on the existing building. The properties of base isolator used as follows: initial stiffness of 1300 kN/m, yield strength equal to 35 kN, and post yield stiffness ratio is 0.1.

![Figure 4. Force-deformation for plastic hinge](image)

![Figure 5. Hinge formation under Newhall](image)

5. **Results and Discussions**

5.1. **Fundamental periods**

Fundamental periods of existing and retrofitted building is given in Table 1. The Fundamental period of building retrofitted of type II and Type V indicated to remain the same as existing building, while retrofitted buildings using type III and type IV are decreased slightly due to added stiffness. However, retrofitting method of type VI significantly increases the fundamental period.

![Figure 6. Detail of retrofitting for columns and beam](image)
5.2. Diagram interaction of existing and retrofitted columns

Improvement of the column strength corresponds to each retrofitting method is shown in Figure 7. It can be seen that all retrofitted columns have better P-M interaction curve compared to existing column. Retrofitted columns of type III exhibit the highest not only in axial load carrying capacity, but also in flexural capacity.

### Table 1. Fundamental period

| Retrofitting technique | Fundamental Period (second) |
|------------------------|----------------------------|
| Type I                 | 0.87                       |
| Type II                | 0.87                       |
| Type III               | 0.85                       |
| Type IV                | 0.83                       |
| Type V                 | 0.87                       |
| Type VI                | 1.95                       |

5.3. Time history of base shear demand

The base shear demands occur for existing and retrofitted building under selected ground motion excitations are displayed in Figure 8 to Figure 13. For existing building (type I), the base shear due to Northridge and Sylmar earthquakes are around 10% higher than Newhall earthquake. Similar results was observed for type II where the highest base shear demand occur under Northridge earthquake and the smallest under Newhall earthquake. In addition, the highest base shear demand occurs at the retrofitted building of type IV because it has a lower of fundamental period, and the smallest occurs at the retrofitted building of type VI since it increases its fundamental period out of predominant period of ground motions.

Another phenomenon was found that the maximum of the base shear demand for given ground motion excitations occurred at different times, and also base shear curves versus time exhibit different shape although these ground motion scaled to fit the same response spectrum. However, the maximum of base shear demand for a given earthquake almost occurs at the same time regardless of local retrofitting technique were applied because the fundamental period of existing and local retrofitting buildings almost the same.

![Figure 8. Time history of base shear demand (I)](image1)

![Figure 9. Time history of base shear demand (II)](image2)
5.4. Story drift index demand

Story drift index is one of building response parameter, and generally used as indicator of structural performance. The story drift index of the existing building is depicted in Figure 14, while Figure 15 to Figure 18 depicts the story drift index for building type II to type IV, respectively. Next, the story drift index of structure with base isolation system (type VI) is presented in Figure 19.

Figure 10. Time history of base shear demand (III)  
Figure 11. Time history of base shear demand (IV)  
Figure 12. Time history of base shear demand (V)  
Figure 13. Time history of base shear demand (VI)  
Figure 14. Story drift index along the building height (I)  
Figure 15. Story drift index along the building height (II)
Figure 14 revealed that the maximum story drift index occurs on the second floor under Newhall earthquake. Similar results was observed for all local retrofitting methods (type II to type V). For retrofitting method of type III and type V, the maximum of story drift index takes place at the first floor. Noted that the highest story drift index (almost 2.5%) occurs when the beams are strengthening using CFRP bars (type V). The increase in steel ratio will certainly improve the beam flexural capacity but however, it may also affect the beam ductility and consequently change the behaviour of plastic hinge mechanism as seen from the Figure 20 in which plastic hinges occur on the columns at the second floor.

Figure 16. Story drift index along the building height (III)

Figure 17. Story drift index along the building height (IV)

Furthermore, significant reduction of story drift index can be achieved through global retrofitting (i.e., base isolation system). In this case, the maximum of story drift index is less than 0.7%. Thus, the base isolated building experience excellent structural performance without damage (response elastically). This phenomenon can also be observed from hinge formation and lateral deformation shape as shown in Figure 21. In this case, Sylmar ground motion show more harmful effect compared to Newhall or Northridge ground motions records.

5.5. Top/ Roof floor acceleration demand

The last seismic response parameters considered in this study, namely top floor acceleration for all retrofitting buildings under three selected earthquakes are shown in Figure 22, Figure 24, and Figure 25 for Newhall, Northridge, Sylmar earthquake, respectively. Figure 22 to Figure 24 show that the effect of the local retrofitting techniques increases the top floor acceleration as well as base shear
demand. The floor acceleration for existing building is lower than the retrofitted buildings. Similar results can be observed in the top floor acceleration where the maximum roof floor acceleration always occur under Sylmar earthquake regardless of the type of local retrofitting methods used. In contrast, retrofitting of the building with base isolation system reduces the top floor acceleration significantly as well as in base shear demand. This phenomenon caused by the effect of increasing the fundamental period of base isolated building away from the predominant frequency of ground motion records.

![Figure 22. Top floor acceleration under Newhall earthquake](image)

![Figure 23. Top floor acceleration under Northridge earthquake](image)

![Figure 24. Top floor acceleration under Sylmar earthquake](image)

6. Conclusions

Study on seismic response parameters of existing and retrofitted building was presented. It can be pointed out that seismic response parameters of retrofitted building models such as base shear, floor acceleration, and story drift are influenced by characteristics ground motion excitations and structure dynamic characteristic (fundamental period). Increase of the building lateral stiffness by means of local retrofitting techniques results in higher roof acceleration, base shear, and story drift demand. Improvement of seismic performance was achieved using with base isolation system since the system increases the fundamental period of the building away from the predominant frequency of ground motion records. Thus, the transmitted input energy of ground motion into superstructure decrease significantly and consequently reducing in the seismic response parameters (i.e., acceleration, base shear and story drift index).

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