Seismic Strengthening Design and Performance Analysis of an Existing RC Frame

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Abstract. The reinforcement design and seismic performance analysis of the Teaching Building of Jiangyan Experimental Elementary School are investigated in this paper. Firstly, according to the seismic assessment report provided by an inspection company, the seismic strengthening design is conducted by using the methods of enlarging sections and sticking CFRP. Secondly, a three-dimensional model is established by using the structural analysis software OpenSees, and both the dynamic characteristics and seismic responses of the structure under frequent earthquakes are analysed. Lastly, the dynamic elastic-plastic time history analysis of the structure is conducted under rare earthquakes, then seismic performance of the structure with and without strengthening are compared under far-field earthquakes. The results show that the seismic performance of the structure is effectively improved, as the maximum reduction of the storey drifts can reach 35%, when the structure is subjected to rare earthquake.

1. Introduction
China is a country with severe earthquakes which have the characteristics of great frequency, high intensity, shallow seismic focus and wide distribution. Only in 2016, there were 17 earthquakes, which induced 119 people killed, 662 people wounded and a direct economic loss of 6.67 billion RMB. Therefore, earthquake retrofitting plays an important role in the disaster prevention of the urban and rural area in China.

Most buildings in middle and primary schools in China are composed of multi-storey masonry structure and reinforced concrete frame structure, many of which are running the risks of damaging due to the low earthquake resistance level or exceeded design life. During Wenchuan earthquake in 2008, the collapsing of school buildings had led to serious death and injury of teachers and students, which accounts 7% of total deaths. Therefore, many school buildings in China have been assessed and strengthened since 2008. During these projects, several common methods are used in reinforcement concrete structures retrofitting, such as enlarging concrete section, bonded with steel plate or CFRP, and strengthening with hysteretic dampers [1,2] etc. A lot of theoretical and experimental research has been conducted relating to the retrofitting methods for existing RC frame structures by now [3-5]. Xu Cheng-xiang et al. [6] summarized the quasi-static loading simulation method of earthquake damage of concrete structures and the simulation method of that by inputting seismic wave to vibration table and then compared the major reinforcement methods to damaged concrete structures after earthquakes. Wang Su-yan et al. [7,8] studied the seismic performance of damaged high-strength square columns after strengthened with CFRP. The effects of different reinforcement methods on the improvement of displacement ductility coefficient, energy dissipation capacity and stiffness degradation of high-
strength concrete columns were discussed. The study indicated that the seismic performance of repaired earthquake damaged members has been significantly improved. The ductility was far better than that of the comparative members but still slightly lower than that of members directly reinforced without seismic damage. Wang Xin-ling [9] applied a horizontal low-cycle repeated load on a 1/3 scale reinforced concrete frame model to study the effect of the degree of damage on the seismic performance of the strengthened structure. The experimental results showed that with the increase of the damage, the greater the maximum crack width of the frame strengthened by CFRP, the larger the strain hysteresis of CFRP. When the degree of damage became severe, the ductility of the strengthened structure was reduced.

This paper mainly focuses on the seismic strengthening design and performance analysis of a teaching building in the Experimental Primary School of Jiangyan District, Taizhou City, China. The structural characteristics of the RC frame are firstly introduced and then the seismic strengthening design is carried out according to the identification results. A three-dimensional finite element model is established to conduct the dynamic characteristics analysis and the dynamic time history analysis of the structure under the frequent earthquake. Finally, the elastic-plastic seismic behaviour of the structure under rare earthquakes is analysed, and the seismic performance of structure with and without reinforcement under far-field earthquakes is compared.

2. Project Overview and Strengthening Design

2.1 Project overview

The teaching building in Jiangyan Experimental Primary School of Taizhou City (Figure 1) was built in 2007 which is a five-story reinforced concrete frame structure with a total area of 2500m², a height of 14.400m and an independent foundation. The structure is located in Jiangyan District, Taizhou City. The building is in class B of seismic fortification and the structural safety level is 2. The fortified earthquake group is the second group and the seismic fortification intensity is 7th degree. The design basic seismic acceleration is 0.1g, and the site category class is III, with a site characteristic period of 0.55s. It is also assumed that the structural damping ratio is 5%.

![Figure 1. The teaching building.](image)

2.2 Comprehensive reinforcement design

According to the assessment report for the structure, some of the concrete components can’t meet the anti-seismic requirements of the Chinese Codes. Therefore, in order to improve both the rigidity and bearing capacity of the structure, the section enlargement method was used to strengthen the columns, and the enlarged section and reinforcement were designed according to Chinese Specification JGJ 116-2009. As shown in Figure 2, The cross section of reinforced column JKZ1 is increased from 400mm x 400mm to 550mm x 550mm, that means the four sides are increased by 75mm, 75mm, 0mm, and 100mm respectively. The reinforcements of enlarging-section column section are 4C22+(2C18+2C22) +(2C18+2C22) with stirrups of C8@100/200. The cross section of reinforced column JKZ2 is increased from 350mm x 350mm to 500mm x 450mm, that means the four sides are increased by 75mm, 75mm, 0mm, and 100mm respectively. The reinforcements of enlarging-section
column section are $4C_{22}+(1C_{18}+C_{22}) +2C_{18}$ with stirrups of $C_8@100/200$. The C40 grouting material is adopted to increase column section.

Concrete frame beams are bonded with CFRP to improve their ductility, as shown in Figure 3. The detailed method is to stick one-layer CFRP with the width of 200mm or 300mm along the bottom of the beam, meanwhile, the side of the beam affixes one-layer layering and U-shaped hoops of CFRP, in which, the width of the strip and the U-type hoop are 100mm and 200mm respectively. The spacing of U-shaped hoops of CFRP is 400mm and the specification of all the CFRP is 200g/m$^2$.
3. Finite element model and dynamic characteristics

3.1. Finite element model

The finite software OpenSees is used to establish a three-dimensional finite element model of the teaching building [10]. As shown in Figure 4, the Elastic-Beam-Column element is adopted to simulate beams and columns under the frequent earthquakes. Connections between Beams and columns are rigid and the bottom of columns are fixed.

The original part of the columns adopts C20 concrete and HRB400 steel bars and the enlarged part uses C40 grouting material and HRB400 steel bars. Concrete and reinforcement are modelled using Concrete02 and steel 01 model respectively, and CFRP is simulated by elastic material with elastic modulus of 2.4x10^5 MPa. Where, Concrete02 is based on the Kent-Scott-Park model without considering the restraint effect of steel bars. The main parameters of this constitutive model are shown in Figure 5(a). Where, $E_0$ is the initial elastic modulus of concrete, $f_{c,m}$ and $e_0$ are the peak strain and stress of concrete respectively, $e_u$ and $f_u$ are the ultimate strain and ultimate stress of concrete, $f_t$ is the peak stress of concrete under tension, $E_t$ is the degradation modulus of concrete in tension zone, and $\lambda$ is the reduction coefficient of initial elastic modulus at the ultimate compressive stress of concrete. Steel01 uses the ideal elastic-plastic model as shown in Figure 5(b). Where, $f_y$ is the yield strength, $E_0$ is the modulus of elasticity and $b$ is the coefficient of hardening.

![Figure 3](image3.png)  
**Figure 3.** Reinforcement method of the frame beams.

![Figure 4](image4.png)  
**Figure 4.** Finite element model.

![Figure 5](image5.png)  
**Figure 5.** Stress-strain relationship of the materials’ constitutive model.
3.2. Dynamic characteristics

![Vibration mode shapes](image)

**Figure 6.** Vibration mode shape of the first three modes.

In order to verify the model and analyse the dynamic characteristic of the structure, two structural models are established by using software PKPM and ETABS respectively. The first three natural period of the original structure are shown in Table 1. It can be seen that they are very close to each other. The first natural period of the vibration differs by only 3.3% and the maximum difference between the third natural period is 7.8%, so it can be concluded that the finite element model using OpenSees is reliable. The first three vibration modes of the structure are shown in Figure 6. It can be seen that the first and second modes are the translational mode and the third mode is the torsional vibration mode. Although the structure has some corner planes, it still reveals the vibratory features of regular frameworks.

**Table 1.** First three modes of the structure.

| Number of stages | PKPM model | ETABS model | OpenSees model |
|------------------|------------|-------------|---------------|
| 1                | 1.094      | 1.0577      | 1.0590        |
| 2                | 1.016      | 1.0385      | 1.0326        |
| 3                | 0.942      | 0.997       | 1.0154        |

4. Elastic seismic behaviour of structures subjected to earthquakes

4.1. Seismic waves

Three seismic ground motions are selected for dynamic time history analysis. The response spectrum curves of these three seismic waves are shown in Figure 7 (a). By comparing with the normalized Chinese Code response spectrum curves, the selected seismic waves meet the code’s requirements of statistical significance in the frequency spectrum energy. The acceleration time history curve of Kern County ground motion is shown in Figure 7 (b). By using these earthquake waves, the structural responses under both frequent earthquake and rare earthquake are analysed respectively. Here, frequent earthquake is defined as the earthquake with a 50 years exceedance probability of 63%, while rare earthquake is the earthquake with 50 years exceedance probability of 2-3%.
Figure 7. Seismic wave for time history analysis.

4.2. Structural response under frequent earthquakes

4.2.1. Base shear force

Table 2. Base shear force under frequent earthquakes.

| Direction                  | Horizontal | Longitudinal |
|----------------------------|------------|--------------|
| Response spectrum of PKPM  | 1588.10kN  | 1622.20kN    |
| Response spectrum of ETABS | 1573.09kN  | 1488.53kN    |
| Kern County                | 1191.28kN  | 1242.91kN    |
| Mohawk Val Portola         | 1135.19kN  | 1258.38kN    |
| Friuli Italy-02            | 1294.70kN  | 1320.97kN    |

Response spectrum analysis is proceeded by using PKPM and ETABS, in which the accidental eccentricity and 15 modes of vibration are taking into account. The three seismic waves are amplitude-modulated to 35gal and the elastic time-history analysis is conducted by using OpenSees. As shown in Table 2, under the same conditions, the values of the base shear force in the longitudinal and transverse directions of the structure are close to each other. Combined with the results in Table 1, it shows that due to the square cross-section of the frame columns, the stiffness in both directions and the mass source of each storey of the structure are equal, which leads to the relatively close dynamic characteristics of the two directions in the elastic state.

Figure 8. Lateral displacement responses of the structure under frequent earthquakes.
4.2.2. Structural displacement response

Figure 8 shows the displacement responses of the structure under frequent horizontal earthquakes. It can be seen that: (1) In Figure 8 (a), the drift of the first storey is the largest before retrofitting, and decreases obviously after retrofitting. However, the weak storey is transferred from the first one to the second one. (2) As shown in Figure 8 (b), the degradation of interlayer stiffness of first storey is not obvious under frequent earthquakes. So the bottom storey with the largest structural deformation is still in elastic state, and its residual deformation is very small.

5. Structural elastic-plastic seismic behaviour under earthquakes

5.1. Structural displacement response

The seismic waves are exemplified to a peak acceleration of 220gal for rare earthquakes, and then structural elastic-plastic time-history analysis under rare earthquakes is carried out. Figure 9 shows the displacement responses of the structure under rare earthquake. By comparing Figure 9 (a) and (b), it can be seen that: (1) the average of maximum storey drifts of rare earthquakes before strengthening is only 45.8% of the code’s limit value; (2) After the strengthening, the storey drift of the bottom floor of the structure has a large attenuation; (3) After strengthening, the storey drifts of the 1st, 2nd and 3rd storeys of the structure tend to be close, and the structural weak storey under earthquakes transforms to the 2nd storey which is similar to that of elastic time history analysis.

![Figure 9](image-url)

Figure 9. Lateral displacement responses of the structure under rare earthquakes.

![Figure 10](image-url)

Figure 10. Lateral top displacement time history curves of the structure under rare earthquakes.

Figure 10 shows the time history curves of the structural top displacement under rare earthquakes. It can be seen that under the same seismic ground motions, both the top displacements of the structure...
are small before and after strengthening, and the time history curve is flat under far-field earthquakes. After strengthening, the top displacement of the structure at the pulse time decreases by 23.6% compared with that before strengthening. So, the reinforcement scheme greatly reduces the damage probability of the structure at this moment and improves the aseismic performance of the structure.

5.2. **Overall structural deformation**

![Image of structural deformation before and after strengthening]

(a) Before strengthening  (b) After strengthening

**Figure 11.** Structural damage under rare earthquakes.

Further analysis is carried out on the overall damage distribution of the structure under rare earthquakes. As shown in Figure 11, the structural damages of all structural members are small and the changes before and after strengthening are significant. In general, the comprehensive reinforcement scheme in this paper improves the seismic performance of the reinforcement concrete frame structure obviously.

**6. Conclusions**

In this paper, the seismic strengthening design and the seismic performance analysis of a teaching building in Jiangyan Experimental Primary School are presented. The main conclusions are as follows:

1) The method of enlarging section effectively increases the stiffness of the bottom columns, so that the displacement angle of the bottom storey of the structure decreases obviously comparing with that of the other storeys. The method of bonding CFRP can effectively improve the bearing capacity and ductility of the frame beams.

2) After strengthening, the structural performance parameters, such as the storey drifts, the top displacement and the base shear of the structure, have been attenuated in different degree, and the maximum attenuation of storey drifts can reach 35%.

**7. References**

[1] Benavent-Climent A., Mota-Páez S. Earthquake retrofitting of R/C frames with soft first story using hysteretic dampers: Energy-based design method and evaluation[J]. Engineering Structures, 2017, 137: 19-32.

[2] Khampaenit A., Leelataviwat S., Kochanin J., et al. Energy-based seismic strengthening design of non-ductile reinforced concrete frames using buckling-restrained braces[J]. Engineering Structures, 2014, 81: 110-122.

[3] Merczel D. B., Aribert J. M., Somja H., et al. Plastic analysis-based seismic design method to control the weak storey behaviour of concentrically braced steel frames[J]. Journal of Constructional Steel Research, 2016, 125: 142-163.

[4] Qu Z., Kishiki S., Maida Y., et al. Seismic responses of reinforced concrete frames with buckling restrained braces in zigzag configuration[J]. Engineering Structures, 2015, 105: 12-21.

[5] Stefani L D, Scotta R, Lazzari M. Optimal design of seismic retrofitting of RC frames with eccentric steel bracing[J]. Bulletin of Earthquake Engineering, 2015, 13(2):613-633.

[6] Xu Cheng-xiang, Peng Wei, Xu Kai-long. Research status and prospect of the reinforcement of seismic damaged concrete frame structure [J]. Journal of Yangtze University(Natural Science Edition), 2014, 11(2): 68-71(in Chinese).

[7] Wang Su-yun, Cao Huai-chao, Liu Yi. Experimental investigation on seismic behavior of damaged high strength concrete columns repaired with CFRP sheets[J]. Journal of Railway Science & Engineering, 2012, 9(3): (in Chinese).
[8] Wang Su-yan, Yu Wen-hua. Experimental research on ductility behavior of square high concrete columns retrofitted with FRP hybridized methods[J]. China Civil Engineering Journal, 2010, (S1): 429-435 (in Chinese).

[9] Wang Xin-ling, Fan Jian-wei, Yao Zhang-tang, et al. Damaged degree effect on seismic behavior of RC frames strengthened by CFRP sheets[J]. Building Structure, 2011, 41(6): 94-97 (in Chinese).

[10] Qi Hu, Sun Jing-jiang, Lin Lin. Research on fiber model of OPENSEES[J]. World Earthquake Engineering, 2007, (04): 48-54 (in Chinese).

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