A Study on Necessity for Checking Elastic-Plastic Deformation of RC Frame Structure in Seismic Appraiser

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ABSTRACT

A seven-story RC frame structure is appraised according to Standard for Seismic Appraiser of Building (GB50023-95) and the elastic-plastic response of this structure under the action of an earthquake of fortification intensity is analyzed by using static nonlinear analysis method and time-history analysis method respectively. It is indicated in results that the elastic-plastic deformation of the structure doesn’t satisfy the displacement requirement of preventing collapse of structure under the action of an earthquake of fortification intensity. So it is necessary to check the elastic-plastic deformation under the action of earthquake of fortification intensity in seismic appraiser.

Keywords: RC frame structure, Seismic appraiser, Nonlinear dynamic analysis, Seismic performance, Elastic-plastic deformation

INTRODUCTION

At present, seismic appraiser for RC frame structures are mostly based on ‘Standard for seismic appraiser of building’¹⁄² (GB50023-95, called Appraiser Standard for short hereinafter) in P.R.China. Two level steps are adopted in Appraiser Standard and it is considered that the structure needs not to take the second level step when it satisfies every requirement of Appraiser Standard at first level step. If requirement of Appraiser Standard at first level step is not met, the second level step should be taken except the instance specified by Appraiser Standard. In the existing actual constructional engineering, the result of two level steps Appraiser is the only criterion to judge the security of structure in China. Appraiser Standard points out that the structure, satisfying the requirement of the Standard, should not collapse or break important machine when subjected to frequent earthquake and can continue to use after repair. But this object is not checked. So it is important to discuss whether the fortification object can be satisfied when the structure satisfies the two level step appraiser. In the text, a seven-story RC frame structure is appraised according to Appraiser Standard. And its elastic-plastic response under the action of frequent earthquake is analyzed using static nonlinear analysis method and time-history analysis method respectively. Then whether elastic-plastic deformation of the structure can satisfy fortification object is discussed. So this paper could be the reference for the revision of Appraiser Standard.

STEPS OF SEISMIC APPRAISER FOR RC FRAME STRUCTURES

Two level steps are adopted in current Appraiser Standard. The checking of macro-parameter and constructional appraiser is the principal content in the first level step appraiser. The second level step

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appraiser need not to be taken if every requirement of Appraiser Standard at first level step is met. The second level step appraiser mostly includes seismic checking in addition to considering the constructional factor. At first level step, according to the different seismic fortification levels, the diversity site and the type of building, the current material strength, structural system, the dimension and reinforcing bar of component section, constructional requirement for juncture between filler wall and main structure, etc. are evaluated. In the case of site III and IV when seven degree intensity earthquake and in the case of eight degree and nine degree intensity earthquake, the regularity of layout and the minimum constructional bar should be checked. It is considered that the RC structure meets requirement of synthetical seismic performance when it satisfies every requirement of Appraiser Standard at first level step. When the situations as follow are met, the second level step appraise need not to be taken, but reinforcement or other measure should be adopted: ① monodirectional frame; ② concrete strength grade is below C13 when eight degree and nine degree intensity earthquake; ③ the bearing bricking-up structure connected to frame can not satisfy the requirement; the parapet, door screen and other non-structural elements can not satisfy correlated requirements of Appraiser Standard; ④ multiple items at first level step appraiser can not be satisfied.

Synthetical performance parameter is adopted to check the bearing capacity of storey at second level step appraiser. The synthetical performance parameter can be figured out as follow:

\[ \beta = \varphi_1 \varphi_2 \xi_y \]

\[ \xi_y = \frac{V_y}{V_r} \]  

Hereinto

\( \beta \) ——Synthetical seismic performance parameter of plane frame;

\( \varphi_1 \) ——System influence coefficient, which can be determined according to Clause 6.3.2.2 in the Appraiser Standard;

\( \varphi_2 \) ——Partial influence coefficient, which can be determined according to Clause 6.3.2.3 in the Appraiser Standard;

\( \xi_y \) ——Yield strength factor of storey;

\( V_y \) ——The existing bearing capacity of storey, which can be determined according to Appendix B in the Appraiser Standard;

\( V_r \) ——Elastic inter-storey shear force under the action of frequent earthquake, which can be determined according to Clause 6.3.2.4 in the Appraiser Standard;

Based on the existing achievement of seismic appraiser and the engineering experience, the current RC frame needs appraiser and reinforcement because of the reasons as follow:

① Due to the earthquake, the frame damage results in shortage of bearing capacity;

② Structural seismic performance degrades because of the change of building function and the circumstance

③ The design load and the design earthquake intensity increase after the revision of Standard.

The reasons above may lead to the collapse of weak storey because of large displacement, so the fortification object of Appraiser Standard can not be satisfied. It is necessary to check the elastic-plastic deformation under the action of frequent earthquake in seismic appraiser, though every requirement of Appraiser Standard at two level step is satisfied.

**SEISMIC APPRAISER AND INELASTIC DISPLACEMENT CHECK FOR A STRUCTURE**

A representative building is, lateral direction, single span, overhanging passage, seven stories RC frame structure. The planar arrangement plan of the structure is shown in Fig. 1. The seismic fortification intensity is eight degree (the design earthquake acceleration is 0.3g). The ground sort is site II. The design earthquake group is the first group. The leftmost bay between the axis 1~2 is staircase. On the beams of axis1~3, 6, 9, 12~13 from the first storey to sixth storey there are 190mm thickness brick-up filler wall. The height of every storey is 3.6m. The concrete strength grade is original grade 200, corresponding to current C18. The cross section size of column is 400×400mm. The reinforcing bar in the column from bottom to top floor is 8@18. The cross section size of beam is 200×600mm. The reinforcing bar in the upper part of lateral beam is 2@25. The reinforcing bar in the
The result of seismic appraiser

According to the Appraiser Standard, the first level step appraiser is taken. The item and the results of the appraiser are shown in the Table 1. Shown in the table, every item at the first level step appraiser is satisfied, so the structure can satisfy the requirement of synthetic seismic performance and second level step appraiser need not to be taken. But in order to study the storey seismic performance of structure in detail, the synthetical seismic performance parameter of structure will be calculated in the text.

Table 1. The result of the first level step appraiser

<table>
<thead>
<tr>
<th>item</th>
<th>Content of appraiser</th>
<th>Requirement of current appraiser Standard</th>
<th>Existing condition</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single direction or two-direction frame</td>
<td>Two-direction frame properly</td>
<td>Two-direction frame</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>2</td>
<td>Joint</td>
<td>Should not be hinge joint</td>
<td>Integral pouring joint</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>3</td>
<td>Concrete strength grade</td>
<td>Should not be below C18(original grade 200)</td>
<td>C18</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>4</td>
<td>Regularity of structure</td>
<td>Plane and elevation is regular, no brick-up wall connects with frame</td>
<td>Regular and no brick-up wall connects with frame</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>5</td>
<td>Plane length-width ratio</td>
<td>3.0</td>
<td>2.26</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>6</td>
<td>Longitudinal rebar of beam and column, lateral rebar</td>
<td>Anchorage length ≥ 30d</td>
<td>35d</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ratio of reinforcement for corner and other columns ≥ 0.8% and ≥ 0.6% individually</td>
<td>1.27%</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lateral rebar of column ≥ φ6@200</td>
<td>φ6@100</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stirrup spacing of beam ≤ 200</td>
<td>150mm</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>7</td>
<td>Cross section size of column</td>
<td>Width of column ≥ 400mm</td>
<td>400×400mm</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>8</td>
<td>The connect between filler wall and main body structure</td>
<td>The thickness of wall ≥ 180mm</td>
<td>190mm</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grout strength grade ≥ M2.5</td>
<td>M5</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2φ6 anchor into wall every 600mm</td>
<td>2φ6 anchor into wall every 500mm</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The length anchored into wall ≥ 700mm and ≥ 1/5 length of wall</td>
<td>The length anchored into wall ≥ 1000mm</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Firm connect between inner wall and column</td>
<td>Yes</td>
<td>Satisfactory</td>
</tr>
</tbody>
</table>
According to Clause 6.3.1 in the Appraiser Standard, the earthquake action of the leftmost frame (axis 1) is maximal. So this frame is investigated at the second level step appraiser. Modal analytical response spectrum method is used to calculate the elastic earthquake shear force (the twelve modals ahead are chosen). The subentry coefficient of earthquake action is 1.0. The reduction coefficient of structural period is 0.7 considering the effect of filler wall. According to current seismic code, the earthquake action effect of the side frame should be multiplied by the amplification coefficient $1.15^2$ for the regular structure.

The shear bearing capacity of storey can be calculated as following (take the first storey for example):

$$N = 1000 \text{kN} \leq \xi_{sa}b_{h} = 0.55 \times 13.3 \times 400 \times 365 \times 0.001 = 1068 \text{kN},$$

therefore the force of column should be calculated according to the formula of the great deflection press.

$$M_{y1} = f_{sk}A_{f}(b_{h} - a_{f}) + 0.5Nb(1 - N/f_{om}b_{h}) = 190 \text{ (kN\cdot m)}$$

$$M_{y2} = f_{sk}A_{f}(b_{h} - a_{f}) + 0.5Nb(1 - N/f_{om}b_{h}) = 176 \text{ (kN\cdot m)}$$

$$V_{y} = 0.7 \times V_{uy} = 0.7 \times \sum \left(M_{y}^{+} + M_{y}^{-}\right)/H_{y} + 0.7 \times f_{ek}A_{m} = 236.3 \text{ (kN\cdot m)}$$

The structure can satisfy every item at the first level step appraiser. So System influence coefficient $\phi_{1} = 1.0$. Partial influence coefficient $\phi_{2} = 1.0$. Synthetical seismic performance parameter of plane frame $\beta$ can be calculated as follow;

$$\beta = \phi_{1}\phi_{2}\xi_{sa} = \phi_{1}\phi_{2}V_{y}/V_{e} = 1.0 \times 1.0 \times 236.3/117.3 = 2.01$$

Shown in the Table 2, synthetical seismic performance parameter of plane frame $\beta$ is all greater than 1.0. So the structure satisfies the requirement of appraiser standard.

<table>
<thead>
<tr>
<th>Floor</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic inter-storey shear force $V_{e}$ (kN)</td>
<td>117.3</td>
<td>102</td>
<td>92</td>
<td>80</td>
<td>65.8</td>
<td>46</td>
<td>24</td>
</tr>
<tr>
<td>The existing bearing capacity of storey $V_{y}$ (kN)</td>
<td>236.3</td>
<td>231.6</td>
<td>223.8</td>
<td>213</td>
<td>199.2</td>
<td>182</td>
<td>162.3</td>
</tr>
<tr>
<td>Synthetical seismic performance parameter $\beta$</td>
<td>2.01</td>
<td>2.27</td>
<td>2.43</td>
<td>2.66</td>
<td>3.03</td>
<td>3.95</td>
<td>6.76</td>
</tr>
</tbody>
</table>

**The checking of the structure elastic-plastic deformation**

In the text, a three-dimensional model structure built by SAP2000 is appraised. Static nonlinear analysis method and time-history analysis method are respectively adopted to check the structure deformation under the action of fortification intensity earthquake. In the model, beam and column are simulated by pole unit with plastic hinge at the two ends. The geometric nonlinear character of the structure ($P$-$\Delta$ effect) is considered. The default plastic hinge M3 is used for beam and the self-defining plastic hinge P-M is used for column (shown in the Fig. 2). The normal value of material strength is adopted and bilinear restoring force model of the element is adopted. The reduction coefficient of the second stiffness adopts 0.02. Numerical integrating method of the program adopts Hiber-Hughes-Taylor.
According to the current seismic Code, three earthquake waves at least should be input in the process of the dynamical time-history analysis. Two natural earthquake waves (USA00170, NZD00205) are chosen by two-band selecting method, and an artificial wave is created by ARMA method. Then its maximum accelerated speed is adjusted according to the Code for seismic design of buildings. Static nonlinear analysis could be done by using two different loading modes. In the first mode, the lateral load is applied to structure according to the distribution of earthquake force which is calculated by modal analytical response spectrum method. In the second mode, the lateral load is applied to structure according to the distribution of quality. Using push-over method to analyze the weaker side (from axis B to A), the capacity-demand spectrum of the structure can be gained (as shown in the Fig. 3). The intersection point between the capacity spectrum and demand spectrum gained in the first mode is (0.111, 0.047), and in the second mode is (0.108, 0.049).

Under strong earthquake action, the elastic-plastic deformation of structure and element should be checked. The elastic-plastic deformation of the reinforced concrete frame structure mainly consists of bending and shearing deformation in the bearing area of the element and the slipping drift of the longitudinal rebar among the joints. The story displacement angle is the sum of the three parts. A great deal of experimentation indicates that the limited value 1/50 for storey displacement angle of the frame structure can assure the structure should not collapse.

Figure 4. Story displacement angle under strong earthquake action

Figure 5. The time history curve of the bottom story displacement

Figs. 4 illustrates the maximal story drift at every storey in the structure. In the graph, it is clearly shown that the maximal story displacement appears at the bottom story, i.e. the bottom story is the
weak story of the structure. The time history curve of the bottom story displacement is shown in Figs. 5. In Table 3 the maximal story displacement angle of the bottom story is shown. In the Table 3 and Figs. 5, it is indicated that the maximal story displacement angle of the bottom story exceeds the value 1/50, which is specified for the RC frame structure to prevent collapse.

<table>
<thead>
<tr>
<th>Consult position</th>
<th>time-history analysis method</th>
<th>capacity-spectrum method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>artifical wave</td>
<td>USA00170</td>
</tr>
<tr>
<td>First (①Axis)</td>
<td>1/43</td>
<td>1/42</td>
</tr>
<tr>
<td>Second (②Axis)</td>
<td>1/45</td>
<td>1/44</td>
</tr>
<tr>
<td>Third (③Axis)</td>
<td>1/47</td>
<td>1/47</td>
</tr>
</tbody>
</table>

Analyzing the non-linearity of the local element, the plastic hinge diagram of structure can be gained by dynamical time-history analysis and pushover analysis (as shown in the Fig. 6). It can be concluded that, plastic hinges appear both on beams and columns. But nonlinear development of the plastic hinge on columns is deeper than on beams. The building is “strong beam and weak column” structure. Especially for the plastic hinges on the columns at axis B, their deformation ductility ratios exceed 6. For the bending deformation of the beams, their deformation ductility ratios is mostly between 1 and 2, and the maximum does not exceed 2~4. According to the statistic of experimentation, the ductility of beam can reach 8 or more. For column which is distributed steel symmetrically, ductility ratio can reach 6 or more when the axial force ratio is small. But in this structure, axial force ratio of the bottom columns approaches to 0.9, so ductility ratio of columns can not reach 6. Bottom story columns of axis 1 have been destroyed by the earthquake action, resulting in collapse of the structure probably.

From the analysis above, it is indicated that the structure can satisfy the two level step appraiser, but the maximum elastic-plastic storey displacement of structure subjected to frequent earthquakes exceeds the value limited in the current seismic code. So the object, that is, the structure does not collapse when subjected to frequent earthquakes, can not be assured.

CONCLUSIONS

Following the Appraiser Standard strictly, the RC frame structure is appraised in the text. Although the structure can satisfy the two level step appraisers, the maximum elastic-plastic storey displacement of structure subjected to frequent earthquakes exceeds the limited value 1/50. The object in the Appraiser Standard, which is that the structure will not collapse when subjected to frequent earthquakes, can not be satisfied. So it is suggested that the necessity of the deformation checking, the confine and the method of checking should be specified in the Appraiser Standard. The study in the text may be reference for the next revision of the Appraiser Standard.
REFERENCES