Application of Pushover Analysis for the calculation of Behavior Factor for Reinforced Concrete Moment-Resisting Frames

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ABSTRACT

Modern seismic design codes stipulates a behavior factor (q-factor) to reduce the earthquake loads which the structure is to be designed for. This is in account for the inelastic behavior of the structure when subjected to severe earthquakes. Inelastic dynamic analysis consumes long time in the interpretation of its results. A popular and simple method for studying the nonlinear response of the structure is pushover analysis. Static type of pushover analysis is to be used in this research work where the loads consist of permanent gravity loads and incremental horizontal forces at each storey level. Capacity curves (base shear versus story total drift) obtained from static pushover analysis using a commercially available software called SeismoStruct (SeismoSoft 2014) are used for the calculation of some seismic demand parameters such as behavior factor, q, overstrength factor, Ω, and ductility based reduction factor, R_µ. Four reinforced concrete moment-resisting frames each of 7, 5 and 3 stories are used in the analysis. The research work proved the efficiency of the static pushover analysis in studying the nonlinear behavior of structures and that the suggested behavior factor (q) by the Eurocode 8- Part 1 (Eurocode 8 Committee 2003) for non-dissipative structures presents an acceptable lower limit.

Keywords: Seismic design, Behavior factor (q), Pushover analysis, Inelastic behavior, Capacity curves.

1. Introduction

Nonlinear analysis is an important tool for the seismic design of structures. Among the nonlinear methods of analysis is dynamic analysis. However, this type of analysis is complex, time consuming and requires a careful interpretation of results. An efficient and simple method to assess the nonlinear behavior of structures under seismic loads is the inelastic static pushover analysis which is used here in this research work. This method is suitable for structures featuring dynamic responses that are not significantly affected by the levels of deformation incurred. Most of the modern international seismic design codes stipulates a so called behavior factor or force reduction factor (q) to reduce the earthquake loads considering the fact that the structure will show an inelastic behavior which dissipates the earthquake energy. This inelastic behavior will be associated with large inelastic deformations (ductility capacity) which governs the structural capacity in withstanding the earthquake loads. The structural ductility (µ_s) is calculated as the ratio of maximum displacement to the displacement at yielding. This ductility capacity (µ_s) is to be higher for structures with higher behavior factor (q).
2. The behavior factor (q)

The method of Uang 1991 is adopted in this research for the determination of q factor. The following parameters are defined based on the capacity curves obtained from static pushover analysis where the symbols are as shown in Figure 1.

2.1 Structural Ductility ($\mu_s$)

The structural ductility ratio ($\mu_s$) is defined as the ratio of maximum story drift ($\Delta_{\text{max}}$) to story drift at general yield ($\Delta_y$).

$$\mu_s = \frac{\Delta_{\text{max}}}{\Delta_y} \quad (1.0)$$

2.2 Overstrength Factor ($\Omega$)

This factor measures the reserved strength in the structure from the formation of the first plastic hinge ($V_s$) to the general yield point ($V_y$).

$$\Omega = \frac{V_s}{V_y} \quad (2.0)$$

2.3 Ductility Based Force Reduction Factor ($R_\mu$)

The structural ductility is responsible for dissipating hysteretic energy of earthquake which results in reducing the maximum elastic seismic force (elastic base shear, $V_{eu}$) to general yield point ($V_y$) at failure.

Thus

$$R_\mu = \frac{V_{eu}}{V_y} \quad (3.0)$$
2.4 Allowable Stress Factor ($\gamma$)

The allowable stress factor ($\gamma$) is defined as the ratio of base shear (structural strength) at formation of the first plastic hinge ($V_s$) to the strength at allowable working design shear ($V_w$).

$$\gamma = \frac{V_s}{V_w} \quad (4.0)$$

2.5 Behavior Factor ($q$)

The behavior factor ($q$) used when calculating the seismic forces for building design is used to achieve the balance between resistance and energy dissipation capacity and would be defined as the value of elastic base shear ($V_{eu}$) divided by the allowable working design shear ($V_w$).

$$q = \frac{V_{eu}}{V_w} = \frac{V_{eu}}{V_y \cdot V_s} = R_y \cdot \Omega \cdot \gamma \quad (5.0)$$

3. Examples used in the analysis

Four different reinforced concrete frames each consisting of 7, 5 and 3 stories are utilized in the analysis. These frames are referred to by Build7-2, Build7-3, Build7-4, Build7-5, Build5-2, Build5-3, Build5-4, Build5-5, Build3-2, Build3-3, Build3-4 and Build3-5. The first numeral refers to the number of stories while the second numeral refers to the number of bays. Figure 2 up to Figure 4 show the dimensions of the used frames. The cylinder compressive strength of the concrete of the used frames is 30 MPa and the yield strength of the used reinforcement is 500 MPa. The dimensions of the beams of all the frames are 250*700 mm while the dimensions of the columns are 250*800 mm. Static pushover analysis was performed using a program called SeismoStruct. Both material and geometric nonlinearities are considered when plotting the capacity curves (variation of base shear with lateral displacement) which are shown in Figure 5 up to Figure 7.
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Figure 2: Geometries of the used 7-stories frames.

Figure 3: Geometries of the used 5-stories frames.
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Figure 4: Geometries of the used 3-stories frames.

Build3-2

Build3-3

Build3-4

Build3-5

Figure 5: Capacity curves of the 7-stories frames.

Build7-2

Build7-3

Build7-4

Build7-5
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Figure 6: Capacity curves of the 5-stories frames.

Figure 7: Capacity curves of the 3-stories frames.
3.1 Ultimate capacity criteria

The ultimate capacity of the structure is said to be arrived to when

1. The structure cannot take any more lateral load due to the formation of mechanism.
2. The interstory drift reaches the limit set by the Eurocode 8- Part 1 (Eurocode 8 Committee 2003) which is as follows for buildings having non-structural elements of brittle material attached to the structure

\[ d_r \nu \leq 0.005h \]  

(6.0)

Where \( d_r \) = the design interstory drift; \( = (d_{s, \text{top}} - d_{s, \text{bottom}}) \)

\( d_s \) = displacement of a point of the structural system induced by the design seismic action (to be taken from the nonlinear analysis made using SeismoStruct software)

\( h \) = the story height

\( \nu \) = the reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirements \( = 0.4 \) for importance classes 3 and 4.

4. Calculation of the behavior factor (q)

The parameters defined in the previous sections are to be derived based on the capacity curves presented in Figure 5 to Figure 7. These curves are obtained from conventional pushover analysis performed using SeismoStruct software (Seismosoft 2014). The locations of the plastic hinges for all the analyzed frames at failure are presented in Figure 8 to Figure 10. The seismic parameters shown in Figure 1 are presented for the analyzed frames in Tables 1 to 3. The overstrength factor \( (\Omega) \) and the structural ductility ratio \( (\mu_s) \) are also shown in the tables.

The \( q \)-factors for all of our frames are calculated assuming a design allowable stress factor \( \gamma \) equals 1.5 and are listed in Tables 1 to 3. For each building, the value of the \( q \) factor varies depending on the number of floors and the number of bays. Generally, for the same number of floors, the behavior factor \( q \) reduces as the number of bays increases. The ASCE/SEI 41-06 code (ASCE Committee for Standard ASCE/SEI 41-06 2007 [1]) recommends the use of the smallest \( q \) factor which leads to a larger design base shear and consequently a safer design. The smallest obtained value of the \( q \) factor equals 3.06 for the 7-story frames, 1.07 for the 5-story frames and 2.3 for the 3-story frames. The Eurocode 8- Part 1 (Eurocode 8 Committee 2003) recommends a value for \( q \) equals to 1.5 for structures classified as non-dissipative. Thus the value for \( q \) factor provided by the Eurocode 8- Part 1 (Eurocode 8 Committee 2003) is a conservative value.
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Figure 8: Locations of plastic hinges at failure for the 7-story frames.
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Figure 9: Locations of plastic hinges at failure for the 5-story frames.

Figure 10: Locations of plastic hinges at failure for the 3-story frames.
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Table 1: Seismic parameters for the 7-story frames

<table>
<thead>
<tr>
<th>Frame</th>
<th>$\Delta_s$ (cm)</th>
<th>$\Delta_y$ (cm)</th>
<th>$\Delta_{max}$ (cm)</th>
<th>$V_s$ (kN)</th>
<th>$V_y$ (kN)</th>
<th>$V_{max}$ (kN)</th>
<th>$\Omega$</th>
<th>$\mu_s$</th>
<th>$V_{eu}$ (kN)</th>
<th>$R_\mu$</th>
<th>$q$</th>
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<tr>
<td>Build7-2</td>
<td>2.2</td>
<td>11</td>
<td>86</td>
<td>160</td>
<td>880</td>
<td>909</td>
<td>5.5</td>
<td>7.8</td>
<td>1380</td>
<td>1.57</td>
<td>13</td>
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<tr>
<td>Build7-3</td>
<td>4</td>
<td>11</td>
<td>57</td>
<td>450</td>
<td>1300</td>
<td>1467</td>
<td>2.9</td>
<td>5.2</td>
<td>1700</td>
<td>1.31</td>
<td>5.7</td>
</tr>
<tr>
<td>Build7-4</td>
<td>5.5</td>
<td>12</td>
<td>26</td>
<td>920</td>
<td>1832</td>
<td>1848</td>
<td>2.0</td>
<td>2.2</td>
<td>2650</td>
<td>1.45</td>
<td>4.4</td>
</tr>
<tr>
<td>Build7-5</td>
<td>8</td>
<td>11</td>
<td>40</td>
<td>1500</td>
<td>2200</td>
<td>2328</td>
<td>1.5</td>
<td>3.6</td>
<td>3000</td>
<td>1.36</td>
<td>3.06</td>
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Table 2: Seismic parameters for the 5-story frames

<table>
<thead>
<tr>
<th>Frame</th>
<th>$\Delta_s$ (cm)</th>
<th>$\Delta_y$ (cm)</th>
<th>$\Delta_{max}$ (cm)</th>
<th>$V_s$ (kN)</th>
<th>$V_y$ (kN)</th>
<th>$V_{max}$ (kN)</th>
<th>$\Omega$</th>
<th>$\mu_s$</th>
<th>$V_{eu}$ (kN)</th>
<th>$R_\mu$</th>
<th>$q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build5-2</td>
<td>1.8</td>
<td>7.5</td>
<td>64.4</td>
<td>200</td>
<td>950</td>
<td>1015</td>
<td>4.8</td>
<td>8.6</td>
<td>1700</td>
<td>1.79</td>
<td>12.9</td>
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<td>Build5-3</td>
<td>4.0</td>
<td>5.0</td>
<td>25.5</td>
<td>875</td>
<td>970</td>
<td>1068</td>
<td>1.1</td>
<td>5.1</td>
<td>970</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Build5-4</td>
<td>1.7</td>
<td>5.8</td>
<td>55.1</td>
<td>420</td>
<td>1550</td>
<td>2083</td>
<td>3.7</td>
<td>9.5</td>
<td>1700</td>
<td>1.1</td>
<td>6.1</td>
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<td>6.5</td>
<td>38.9</td>
<td>700</td>
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<td>2665</td>
<td>3.2</td>
<td>6.0</td>
<td>2800</td>
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<td>6.0</td>
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Table 3: Seismic parameters for the 3-story frames

<table>
<thead>
<tr>
<th>Frame</th>
<th>$\Delta_s$ (cm)</th>
<th>$\Delta_y$ (cm)</th>
<th>$\Delta_{max}$ (cm)</th>
<th>$V_s$ (kN)</th>
<th>$V_y$ (kN)</th>
<th>$V_{max}$ (kN)</th>
<th>$\Omega$</th>
<th>$\mu_s$</th>
<th>$V_{eu}$ (kN)</th>
<th>$R_\mu$</th>
<th>$q$</th>
</tr>
</thead>
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<tr>
<td>Build3-2</td>
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<td>4.5</td>
<td>51.1</td>
<td>125</td>
<td>1000</td>
<td>1138</td>
<td>8</td>
<td>11.4</td>
<td>1500</td>
<td>1.5</td>
<td>18</td>
</tr>
<tr>
<td>Build3-3</td>
<td>1.4</td>
<td>4.5</td>
<td>32</td>
<td>550</td>
<td>1600</td>
<td>1705</td>
<td>2.9</td>
<td>7.1</td>
<td>2500</td>
<td>1.56</td>
<td>6.8</td>
</tr>
<tr>
<td>Build3-4</td>
<td>0.9</td>
<td>4.6</td>
<td>20.2</td>
<td>430</td>
<td>2270</td>
<td>2292</td>
<td>5.3</td>
<td>4.4</td>
<td>5000</td>
<td>2.2</td>
<td>17.5</td>
</tr>
<tr>
<td>Build3-5</td>
<td>3.4</td>
<td>4.5</td>
<td>25.6</td>
<td>2140</td>
<td>2600</td>
<td>2653</td>
<td>1.2</td>
<td>5.7</td>
<td>3300</td>
<td>1.27</td>
<td>2.3</td>
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</table>

5. Conclusions

1. The inelastic behavior of the structure when subjected to severe earthquakes can be accounted for by reducing the earthquake loads using the behavior factor ($q$-factor).

2. Static pushover analysis is an efficient and quick method to study the nonlinear behavior of structures under seismic loads compared to the inelastic dynamic analysis which is complex and time consuming.

3. Static pushover analysis produces capacity curves (base shear versus story total drift) which can be used to calculate the seismic demand parameters.
4. The method of Uang 1991 is suitable for the calculation of the force reduction factor (q).

5. The smallest value obtained for the behavior factor (q) is 2.3. This value is on the conservative side when compared with the more safe value of 1.5 suggested by the Eurocode 8- Part 1 (Eurocode 8 Committee 2003) for non-dissipative structures.

6. References


