Calculation of reinforced concrete structures with a set seismic stability level on an earthquake

O.V. Mkrtichev¹, M.S. Busalova² *

¹Moscow State University of Civil Engineering (National Research University), Yaroslavskoe Shosse, 26, Moscow, 129337, Russia
²RUDN University, Miklukho-Maklaya str., 6, Moscow, 117198, Russia

Abstract

The article discusses a calculation technique for a reinforced concrete building with a braced frame on an earthquake. It allows to produce an adequate assessment of a seismic stability level. A direct simulation of concrete, reinforcement and their binding with the help of volumetric and core finite elements is fulfilled. The paper presents the concrete work chart and considers mathematical models for the material. The authors propose calculation technique of reinforced concrete buildings with the actual reinforcement taking into account. The results of the numerical calculations of structural elements (crossbar) are compared to the field experiments conducted by US Department of Transportation Federal Highway Administration. The paper examines the level of seismic stability of buildings with a braced frame, the actual reinforcement taking into account when calculating on a seismic action.

Keywords: seismic resistance level; criterion of non-collapse; models of materials; concrete and reinforcement binding; nonlinear methods; seismic action

1. Summary

At the heart of the national approach to building and structure calculations on a seismic action, a regulatory document SP 14.13330.2014 "SNiP II-7-81 * "Construction in seismic region" [1] stays and it implements the
response spectrum method of an earthquake calculation. These norms don’t allow design buildings and constructions with a set seismic stability level by non-collapse criterion. Using in calculations a direct dynamic method of integrating motion equations allows you to get more appropriate results, taking into account the non-linear nature of a structure deformation in comparison with a the response spectrum method [2].

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbf{u}$</td>
<td>required vector of nodal displacements</td>
</tr>
<tr>
<td>$\mathbf{u} = \mathbf{v}$</td>
<td>vector of nodal velocities</td>
</tr>
<tr>
<td>$\mathbf{u} = \mathbf{a}$</td>
<td>vector of nodal accelerations</td>
</tr>
<tr>
<td>$\mathbf{M}$</td>
<td>matrix of mass</td>
</tr>
<tr>
<td>$\mathbf{C}$</td>
<td>matrix of damping</td>
</tr>
<tr>
<td>$\mathbf{K}$</td>
<td>matrix of rigidity</td>
</tr>
<tr>
<td>$\mathbf{f}^e$</td>
<td>vector of applied loads</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>integration parameter</td>
</tr>
</tbody>
</table>

For the specified level of seismic resistance following items are required.

1. To use appropriate computational methods and models (nonlinear dynamic calculation methods, seismic action probability models, model of a nonlinear deformation of materials, volumetric finite elements with concrete and reinforcement binding take into account properly the structure and base interaction [3,4], to apply seismic systems, etc.).

2. To apply methods of probability theory and building structures reliability theory.

3. To carry out relevant research work, including those on the verification of design models, and development of practical application techniques.

4. To develop a system of new generation of regulatory documents in the area of earthquake engineering.

Following these recommendations allows more adequately perform calculations to determine the level of seismic resistance of buildings and structures, designed for seismic areas. Some of the proposed clauses are in more detail considered below.

According to the response spectrum method, possible occurrence of nonlinearities in design operating is taken into account by only one coefficient according to table 4 in [1], that is actually in calculations linear schemes are considered only. Thus, the linear-spectral approach to intensive seismic actions calculation does not allow adequately takes into account the design behavior beyond the elastic limit. Another major issue is the need to take into account construction – soil base collaborative work. In Construction Regulations SP 14.13330.2014 "SNiP II-7-81**"Construction in seismic areas" this interaction is indirectly taken into account in determining the dynamic coefficient [1].

In real conditions in an intensive earthquake soil behaves nonlinearly, changes its properties, and there is a probability of such dangerous effects as the soil liquefaction and loss of strength [5, 6, 7] Such soil behavior has a direct impact on the reaction of the located above structure. These factors neglecting can lead to significant errors in the calculation results.

When calculating buildings and structures in view of the non-linear nature of the deformation one may apply a direct dynamic method, which is based on the direct integration of the equation of motion (1) using the implicit (2) or explicit (3) integration schemes.

$$
\mathbf{M}\mathbf{u} + \mathbf{C}\mathbf{u} + \mathbf{K}\mathbf{u} = \mathbf{f}^e \\
(1)
$$

$$
\mathbf{u}_{t+\Delta t} = \mathbf{u}_t + \mathbf{u}_t \Delta t + \left[ \frac{1}{2} - \alpha \right] \mathbf{u}_t + \alpha \mathbf{u}_{t+\Delta t} \Delta t^2 \\
(2)
$$
\[ \mathbf{u}_{t+\Delta t} = \mathbf{u}_t + \mathbf{v}_{t+\Delta t/2} \frac{\Delta t + \Delta t_{t+\Delta t}}{2} \] (3)

With this method, all calculations are performed in the time domain, it becomes possible to consider non-linearity of various types, and the use of explicit methods reduces the time of calculation.

2. Development of calculation methods

To account physical nonlinearity you can use concrete deformation diagrams, which are given in [8] (Figure 1).

The authors have conducted their research on concrete mathematical model verification (Figures 2, 3), developed by U.S. Department of Transportation. Federal Highway Administration [9, 10, 11], with the experiment results. This mathematical model of concrete was implemented in the LS-DYNA software package.

---

**Fig. 1.** Curvilinear concrete stress-strain diagram.

**Fig. 2.** Mathematical model of concrete (CSCM – Continuous Surface Cap Model).
The main advantage of the application of this model is the ability to use at simulating three-dimensional finite elements with concrete - reinforcement binding, non-linear work of the concrete taking into account. Figure 4 shows the finite element models of bearing elements with reinforcement.

Figure 5 shows the results of field tests conducted by a group of scientists (Yvonne D. Murray, Akram Abu-Odeh, Roger Bligh) US Department of Transportation [9,11]. For comparison, Figures 6-7 show the results obtained by a numerical simulation and calculation in LS-DYNA software package by the authors.
The results obtained during the experiments agree well with the results, received by the authors in LS-DYNA software package. Thus, the possibility of simulating of load bearing construction elements with actual reinforcement taking into account allows accurately display the behavior of the structure as a whole during the seismic action [12, 13, 14].

3. Problem Statement

As an example of the developed technique we perform the calculation of a multistory reinforced concrete building with a braced frame on a seismic action. We used three-dimensional elements to simulate concrete, stem - to valve, with the corresponding algorithm of reinforcement - concrete binding being used.

The calculation scheme of a braced frame building is shown in figure 8a, figure 8b shows the reinforcement frames. The calculation was carried out on a 3-component seismic impact rated to 9 points.

Fig. 5. a) Estimated beam scheme; b) - c) results of the experiment, d) results of numerical simulating.

Fig. 6. The results obtained by the authors in LS-DYNA software package.

Stresses

<table>
<thead>
<tr>
<th>Time = 0.09999</th>
<th>Time = 0.20999</th>
<th>Time = 0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Stress (σ)</td>
<td>Effective Stress (σ)</td>
<td>Effective Stress (σ)</td>
</tr>
<tr>
<td>2.930e+01</td>
<td>2.930e+01</td>
<td>2.930e+01</td>
</tr>
<tr>
<td>1.760e+01</td>
<td>1.760e+01</td>
<td>1.760e+01</td>
</tr>
<tr>
<td>0.000e+00</td>
<td>0.000e+00</td>
<td>0.000e+00</td>
</tr>
</tbody>
</table>

Plastic deformations

<table>
<thead>
<tr>
<th>Time = 0.09999</th>
<th>Time = 0.20999</th>
<th>Time = 0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Plastic Strain</td>
<td>Effective Plastic Strain</td>
<td>Effective Plastic Strain</td>
</tr>
<tr>
<td>8.000e-01</td>
<td>8.000e-01</td>
<td>8.000e-01</td>
</tr>
<tr>
<td>7.000e-01</td>
<td>7.000e-01</td>
<td>7.000e-01</td>
</tr>
<tr>
<td>6.000e-01</td>
<td>6.000e-01</td>
<td>6.000e-01</td>
</tr>
</tbody>
</table>

Fig. 6. The results obtained by the authors in LS-DYNA software package.
4. The calculation results

Figure 9 shows the plastic deformations which occur in the building structure at different times. Figure 10 shows a detailed view at the start of a cascade progressive collapse of the building structures.
5. Conclusion

For a given level of seismic stability on the criterion of non-collapse in designing buildings in seismic areas, nonlinear dynamic methods, appropriate material models for simulating reinforcement and concrete with regard to their joint work and the non-linear nature of the deformation should be used. This approach allows us to estimate and analyze the actual response of the construction to a seismic action.

Fig. 9. The development of plastic deformations in the structure.

Fig. 10. Progressive collapse of the building.
Acknowledgements

This study was performed with the support of RF Ministry of Education and Science, grant No. 7.2122.2014/K. All tests were carried out using research equipment of Head Regional Collective Research Centre of Moscow State University of Civil Engineering.

References