Verification Analysis of the Degradation of Frequency Parameters Under the Action of Seismic Load

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Abstract. The article discusses the results of a numerical study of the effect of local damage to bearing structures on the degradation of frequency parameters during seismic effects. The studies were carried out in the LS-DYNA software package which implemented the nonlinear concrete model — Continuous Surface Cap Model (CSCM). Design models of a building are modelled both with regard to direct reinforcement using volumetric FE (finite elements) and flat FE. The object of modelling is a 3-storey building of cellular framing. The analysis of the results of the conducted studies suggests that the effect of degradation of natural vibration frequencies cannot be estimated in the building modelled by means of bar FE. The degradation is insignificant; the frequency reduction occurs within the limits of errors. At the moment, it is not possible to identify the effect of degradation in the bar model in this formulation. To do this, it is necessary to conduct additional researches, including those with other models of materials. Taking into account certain assumptions, the LS-DYNA software package allows computational studies of the effect of local damage to bearing structures on dynamic characteristics, including those resulting from an earthquake.

1. Introduction
Since the end of the 20th century, dynamic methods for examining the state of buildings and structures have been actively developed. The essence of the methods is to assess the state of building structures by the features of dynamic (frequency) characteristics, including those after seismic impact. Frequencies and forms of modal analysis play the role of the stiffness characteristics of buildings and structures. Methods using frequency analysis allow determining the presence of defects in the bearing structures, degree of hazard for further operation because of those defects. These methods are based on full-scale experimental studies, including the use of FE software systems [1]. For full-scale use of FE analysis, methods that allow carrying out modal analysis at specific points in time, taking into account damages in the bearing structures, are required. At the same time, it is necessary to select adequate deformation diagrams and verify material models. In software packages, such as ANSYS, LS-DYNA, etc., it is possible to use the diagrams shown in [2] and model the joint behaviour of concrete and reinforcing bars with the help of bar (for reinforcement bars) and volumetric (for concrete) finite elements [3].

The paper objective is to conduct numerical studies using different models of concrete behaviour, to study the effect of local damages on the degradation of frequency parameters as a result of seismic effects.
2. Problem statement
The studies will be carried out in the LS-DYNA finite-element software package in which nonlinear, static, and dynamic methods were implemented.

When solving problems in a nonlinear formulation, methods that implement explicit schemes for integrating the system motion equations become more effective. To model the impact of an earthquake on buildings, we use explicit methods for integrating the motion equations. Explicit methods use recurrence relations that express the displacements, velocities, and accelerations at a given step through their values in the previous steps. In LS-DYNA the central difference method is used for explicit integration. To determine the displacement, an expression with time lag is used [4]:

\[ M \ddot{u}_t + C \dot{u}_t + K u_t = f_t^a \]  

To perform a modal analysis, we will use implicit methods for integrating motion equations. The LS-DYNA is able to perform a transient calculation, during which an earthquake is calculated by explicit methods, with periodic calculation of eigenvalues by implicit methods [5]. This takes into account changes affecting eigenvalues: geometry, stresses and forces, contact conditions. This should allow assessing the degradation of frequency parameters during the earthquake and the technical condition of buildings.

We consider design models of a building modelled both on the basis of the direct reinforcement of concrete with reinforcing bars (volumetric FE), and without direct reinforcement (bar and plate FE).

The object of study is a 3-storey building of cellular framing (figure 1). Overall plan dimensions are 6x6x9.9 (h) m. Floors are beam monolithic reinforced concrete. The slab thickness is 20 cm, the beam and column cross-section is 40x40 cm.

Material of the reinforcing bars is steel; in the reinforcing bar modelling, an ideal elastic-plastic Prandt's model was used with the initial modulus of elasticity \( E = 2.1 \times 10^5 \) MPa, the yield strength was assumed equal to \( \sigma_y = 245 \) MPa, and the limiting plastic deformations \( \varepsilon_{plastic} = 0.1 \). A diameter of longitudinal reinforcing bars of beams and columns was taken to be 28 mm, a diameter of longitudinal reinforcing bars of slabs was taken to be 10 mm.

![Figure 1 Design models: a – volumetric FE, b – bar FE](image)

When modelling structures with volumetric FE for concrete, a nonlinear model of the CSCM material is used, the mathematical model of which is represented by a closed surface with presence of
the so-called "cap". When modelling structures with bar and plate FE, an elastic-plastic model is used with a three-line diagram of the state of compressed concrete (figure 2), including a falling branch. Concrete corresponds to class B45 for cube compressive strength, compressive strength $f_{cm} = 43$ MPa [2, 6].

![Trilinear concrete deformation diagram](image)

**Figure 2** Trilinear concrete deformation diagram

The calculation is made on a rigid base taking into account physical, geometrical and constructive nonlinearities. The seismic impact is given in the form of 2 component accelerograms rated to 7 points by the MSK-64 scale [7]. For the subsequent analysis of the degradation of frequency parameters, verification was carried out between the volumetric and bar design models of buildings. The deflections of the floor slab of the 3rd floor and the frequencies of the main (first three) forms of vibration were chosen as verification parameters.

3. Calculation results

Figure 3 and 4 show the results of verification of design models. Following table 1 presents the results of verification analysis of design models.
Figure 3. a–d) forms of natural vibrations (on the left-volumetric FE, on the right-bar FE)

Figure 4. Deflections of the floor slab of the 3rd floor (left [mm], right [m])
Table 1. Verification of design models

| Model    | Deflection (mm) | Frequency 1 (Hz) | Frequency 2 (Hz) | Frequency 3 (Hz) |
|----------|-----------------|------------------|------------------|------------------|
| Solid    | 4.72            | 2.19             | 2.19             | 3.6              |
| Beam     | 4.12            | 2.21             | 2.21             | 3.41             |
| Discrepancy | 12.85 %        | 0.9 %            | 0.9 %            | 5.6 %            |

The analysis of the results shows that the differences between the compared parameters are within the limits of errors. Consequently, in these design models it is possible to conduct studies of degradation of frequency parameters.

The results of the bar model calculation show that only when significant plastic deformations are achieved in the element (just before the structure collapse), a weak (within 1%) decrease in the natural vibration frequencies appears (table 2).

Table 2. Change of frequencies in the process of earthquake (bar FE)

| Time t, sec | Frequency 1 (Hz) | Frequency 2 (Hz) | Frequency 3 (Hz) |
|-------------|------------------|------------------|------------------|
| 0.2         | 2.21             | 2.21             | 3.41             |
| 2.5         | 2.21             | 2.21             | 3.41             |
| 5           | 2.21             | 2.21             | 3.41             |
| 7.5         | 2.21             | 2.21             | 3.41             |
| 10          | 2.19             | 2.19             | 3.39             |

Figure 6 shows a graph of the change in plastic deformations in one of the most loaded columns (bar FE).
The analysis of the results of the conducted studies shows that it is impossible to assess the effect of degradation in the building modelled by means of bar FE, as the degradation is insignificant — within the limits of errors. Indeed, the results obtained with bar FE are in good agreement with the results obtained in [8]. At the moment, it is not possible to identify the effect of degradation in the bar model in this formulation. To do this, it is necessary to conduct additional researches, including those with other models of materials.

4. Conclusions

1. With the FE bar, the effect of degradation is insignificant and short-term, only just before the failure of bearing elements and the subsequent progressive collapse.
2. To confirm the phenomenon of degradation in the considered design scheme with bar FE, additional researches are required.
3. The used models of materials should take into account the phenomena of softening and reducing stiffness under cyclic loads.
4. Taking into account certain assumptions, the LS-DYNA software package allows computational studies of the effect of local damage to bearing structures on dynamic characteristics, including those resulting from an earthquake.

Acknowledgement

This study was performed with the financial support of the RF Ministry of Science and Higher Education, grant #7.1524.2017/Project Part.

References

[1] P.I. Andreeva, M.I. Andreev, O.V. Mkrtchyan, O. A. Kovalchuk, and G. E. Shablinsky, Vliyanie geometricheskogo defekta kupol'noj chasti zashchitnoj obolochki atomnogo reaktora VVER-1000 na dinamicheskie harakteristiki s uchetom statisticheskogo analiza, International Journal for Computational Civil and Structural Engineering, vol. 11, Issue 4, pp. 29-35, 2015.

[2] SP 63.13330.2012 Concrete and Reinforced Concrete Structures, Summary, 2012.

[3] M.I. Andreev, S.V. Bulushev, and M.S. Dudareva, Verification of the eccentrically compressed reinforced concrete column calculation model based on the results of a full-scale experimental study, MATEC Web of Conferences, vol. 251, 04013, 2018.

[4] O.V. Mkrtchyan, G.A. Dzhinchvelashvili, and M.S. Busalova, Calculation of a multi-storey monolithic concrete building on the earthquake in nonlinear dynamic formulation , Procedia
Engineering, vol. 111, pp. 545–549, 2015.

[5] Livermore Software Technology Corporation(LSTC), LS-DYNA. Keyword user’s manual, R.11, vol. I, 2018.

[6] O.V. Mkrtchyan, D.S. Sidorov, and S.V. Bulushev, Comparative analysis of results from experimental and numerical studies on concrete strength, MATEC Web of Conferences, vol. 117, 00123, 2017.

[7] O.V. Mkrtchyan, and M.I. Andreeva, Calculation of the Unique High-Rise Building for Earthquakes in Nonlinear Dynamic Formulation, Proceedings of Moscow State University of Civil Engineering, no. 6, pp. 25—33, 2016.

[8] P. I. Andreeva, Metodika rascheta sejsmostojkosti zhelezobetonnyh zdanij i sooruzhenij pri povtornykh zemletryaseniyah s uchetom lokal'nyh povrezhdenij, [Method of calculating the seismic resistance of reinforced concrete buildings and structures under repeated earthquakes with consideration of local damage], Thesis PhD in Engineering sciences, p. 144, 2016.