Accumulation of damage in reinforced concrete elements under cyclic loads

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Abstract. The article presents the results of research on the behavior of a frame structure in a reinforced concrete building with a full rigid frame under cyclic load typical for strong earthquakes. When creating a finite element model for the research, the models of materials were used that take into account the nonlinear nature of the structure behavior, as well as the accumulation of damage under cyclic loads. The calculation was carried out by a direct dynamic method using explicit schemes for integrating the equations of motion in the multipurpose finite element software package LS-DYNA.

1. Introduction
One of the main objectives of earthquake engineering is the development of effective seismic protection systems and methods for calculating buildings and structures designed with these systems, which allow to adequately assess the ability of a structure to resist seismic impacts. A considerable number of modern buildings and structures designed for seismic areas are being constructed using reinforced concrete (figure 1).

Figure 1. The use of reinforced concrete in the construction of buildings.

Figure 2. Longitudinal beam to column joint.
At present, the longitudinal beam to column joints (figure 2) in the calculation schemes of frame structures are modeled, as a rule, either absolutely rigid or hinged. However, the analysis of their behavior shows that such modeling results in a significant error in the calculation for seismic impacts. Research shows that the joints of reinforced concrete elements are mobile and have the ability to dissipate energy during cyclical operation during an earthquake.[1], [3].

In this regard, one of the actual objectives of earthquake engineering is the development of methods for calculation of reinforced concrete structures that take into account the mobility and dissipative properties of the joints. In this work the behavior of reinforced concrete frame under cyclic load typical for intensive seismic impacts was studied. The main objective of this work was to determine the dissipative reserves in the behavior of a reinforced concrete structure joint. The research was carried out using the LS-DYNA software package. This package uses explicit integration schemes. The explicit method is the most effective, and it is advisable to use it for calculation of structures with dynamic loads.

2. Research

2.1. Description of the finite element model
A single-span reinforced concrete frame was chosen as the object of research. When developing the design model, the following sections were adopted: for the column – a square section of 0.4×0.4 m, for the longitudinal beam – a rectangular section of 0.4×0.5 m. The span of the longitudinal beam is 6m, the height of the columns is 4 m. The frame material is B25(C20) concrete (the strength of this concrete is 25 MPa, and the density is 2300-2400 kg/m$^3$ [4, 5]). The longitudinal beam and the columns are reinforced with four reinforcing bars with a diameter of 28 mm (used reinforcement A400, yield point not less than 400 MPa, [6]), as well as ties with a diameter of 12 mm (used reinforcement A240, yield point not less than 235 MPa [6]), with a spacing of 200 mm.

The model used is shown in figure 3, two types of material models were used to create it (for modeling of reinforcement – Piecewise Linear Isotropic Plasticity material, for modeling of concrete – Continuous Surface Cap Model). The main feature of the mathematical model of concrete is that this model allows you to take into account the degradation of stiffness and strength, as well as the accumulation of damage under cyclic loads. Figure 4 shows a closed model of the Continuous Surface Cap Model material developed by the Federal Highway Administration of the United States Department of Transportation [1], it shows the yield surface of primary stresses in space in accordance with this model of concrete [2].

Figure 3. Used finite element model.
The mathematical model of concrete (CSCM – Continuous Surface Cap Model)[2]

The yield surface for this model is expressed in terms of stress invariants:

\[
J_1 = 3P, \quad J_2' = \frac{S_{ij}S_{ij}}{2}, \quad J_3' = \frac{S_{ij}S_{ij}S_{ij}}{3},
\]

where \(J_1\) – stands for the first invariant of the stress tensor, \(J_2\) – second invariant of the stress deviator, \(J_3\) – third invariant of the stress deviator, \(S_{ij}\) – stress deviator, \(P\) – pressure.

The model consists of 52920 nodes and 4792 elements. The model contains 2 types of elements: beam and solid. Element length 0.04 m. Due to the small size of the grid, the element was integrated at one point. A horizontal distributed load was applied to the upper surface of the longitudinal beam, two concentrated vertical forces were applied to the columns, as well as one horizontal force, whose change curve is shown in figure 5. The impact amplitude varied from 10 kN to 200 kN. The load period was determined so that significant dynamic effects did not arise, that is, so that the load period did not exceed the period of oscillation of the structure (also not allowed resonance). This load is close to intense seismic impact.

**Figure 4.** The mathematical model of concrete (CSCM – Continuous Surface Cap Model)[2]

**Figure 5.** Example impact.
2.2. Destruction criterion. Accumulation of damage

In this work, a special material model was used, which takes into account the accumulation of damage under cyclic loads. Damage accumulation is based upon two distinct formulations, which we call brittle damage and ductile damage.

Brittle damage builds up when stretched. Accumulation of brittle damage depends on the maximum principal deformation \( \varepsilon_{\text{max}} \):

\[
\tau_b = \sqrt{E \varepsilon_{\text{max}}^2}
\]

(2)

Brittle damage accumulates when the pressure is tensile and an energy-type term, \( \tau_b \), exceeds the damage threshold \( \tau_{b,0} \).

Plastic damage builds up during compression. It does not accumulate when stretched. The accumulation of plastic damage depends on the components of the total deformation \( \varepsilon_{ij} \):

\[
\tau_d = \sqrt{\frac{1}{2} \sigma_{ij} \varepsilon_{ij}}
\]

(3)

Plastic fracture begins when \( \tau_d \) exceeds the initial threshold \( \tau_{d,0} \) [1].

2.3. Results obtained

The model takes into account both compression and tension damage. Figure 6-9 show deformed schemes with isofields of stress intensity for reinforcement and concrete, isofields of plastic flow intensity for reinforcement, and isofields of changes in the function of accumulation of concrete damage before the onset of structural failure when applying an impact with an amplitude of 130 kN. The damage accumulation function varies from 0 to 1 (0 corresponds to no damage, 1 – complete destruction of the material).

![Figure 6. Stress intensity in concrete before failure, Pa](image-url)
Figure 7. Function of damage accumulation in concrete before failure.

Figure 8. Stress intensity in reinforcement before failure, Pa
Figure 9. Intensity of deformations in reinforcement before failure.

Figure 10-13 show deformed schemes with isofields of stress intensity for reinforcement and concrete, isofields of plastic flow intensity for reinforcement, and isofields of changes in the function of accumulation of concrete damage after the structural failure when applying an impact with an amplitude of 130 kN.

Figure 10. Stress intensity in concrete after failure, Pa
Figure 11. Function of damage accumulation in concrete after failure.

Figure 12. Intensity of deformations in reinforcement after failure.
Figure 13. Intensity of deformations in reinforcement after failure.

Figure 14-16 show the isofields of damage accumulation at different amplitudes of cyclical impact before the structural failure.

Figure 14. Function of damage accumulation applying an impact with an amplitude $P=30$ kN.
Figure 15. Function of damage accumulation applying an impact with an amplitude $P=100$ kN.

Figure 16. Function of damage accumulation applying an impact with an amplitude $P=180$ kN

After analyzing the nature of failure for cases with different amplitudes of external impact, the dependence of the number of cycles before the failure of the reinforced concrete joint on the amplitude of the applied cyclic load (figure 17).
3. Conclusions

1. The isofields of stress and deformation intensity, as well as isofields of changes in the damage accumulation function for the structure in question at given time points were drawn.

2. The dependence of the number of cycles before the failure of reinforced concrete frame on the amplitude of the applied cyclic load is drawn (from 10 to 200 kN).

3. A method for modeling a reinforced concrete frame has been developed, which allows taking into account degradation stiffness and strength, as well as the accumulation of damage under cyclic loads. And there were also identified determine the dissipative reserves in the behavior of a reinforced concrete structure joint.

4. The proposed approach makes it possible to evaluate the seismic stability of frame joints of reinforced concrete buildings and structures in a nonlinear dynamic setting.

References

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