The influence of open cracks in compressed area of concrete on behaviour of bending elements of frame buildings under special alternating loads

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Abstract. In design of seismic resistant reinforced concrete constructions it is necessary to take into account the influence of plastic strains on stress-strain state and on possibility of appearance of open cracks in compressed area of concrete while the sign change of the load. In order to evaluate the influence of this factor the design of reinforced concrete beams models with regard to elastoplastic diagrams of materials has been carried out. The dependences of residual cracks height, of bearing capacity and of limit value of coefficient of plasticity in the second half-cycle on the maximum coefficient of plasticity in the first half-cycle have been built. The conclusion has been made about the decrease of bearing capacity of bending elements, caused by the development of plastic strains and due to them the presence of open cracks in compressed area of concrete. The limit state criterion has been offered, preventing brittle fracture on following cycles of loading.

1. Introduction
A significant part of buildings in the Russian Federation is situated in seismically dangerous regions. Under seismic loads local destructions occur and plastic deformations develop in elements of framed buildings, what is taken into account by current standards for earthquake-resistant construction [1]. A large number of investigations are devoted to the study of destruction mechanisms of bending elements, of framed buildings and to the account of plastic deformations in seismic calculations [2], [3], [4], [5], [6], [7], [8], [9].

Usually in design of earthquake-resistant reinforced concrete buildings the possibility of appearance of plastic strains is considered only in determining seismic loads. In the spectral method of design of buildings the presence of plastic deformations and of local damage of constructions is accounted by the introduction of a reducing factor K1. The design of reinforced concrete constructions in this case is carried out by traditional methods without regard of influence of plastic strains of reinforcement on their strength.

However it is obvious, that the development of plastic strains in reinforcement leads to presence of residual cracks in stretched area, which don’t close when changing the sign of internal forces. This fact affects the stress-strain state of reinforced concrete element on subsequent loading cycles and in turn crack pattern and the bearing capacity [2], [5], [6], [10].

2. Objectives and main prerequisites
In order to evaluate the influence of plastic strains on the behavior of bending elements it is necessary
to conduct calculations of reinforced concrete bending elements models with regard to the physical nonlinearity of materials.

The design and the experimental tests of reinforced concrete beams under few repeated alternating loads with the coefficient of asymmetry of cycle equal to -1 have shown, that the accumulation of plastic strains from cycle to cycle take place [2].

But as the design of reinforced concrete frames for seismic effects taking into account elastoplastic deformations of materials has shown, the maximum displacements were observed during the two half-cycles of loading [3], [4] and then decreased. This makes it possible restrict the consideration by two first half-cycles of loading while exploring the stress-strain state of beams and determining the limit state criteria of constructions.

As an example the dependence of horizontal movements of units of a three-storey two-span reinforced concrete frame on time is presented in fig.1. The size of the spans is 4.8 m, the floors height is 3.4 m. The pillars and the beams with the height of the cross section 0.4 m and width 0.4 m are made of Б25 concrete and of A500C reinforcement. The reinforcement of elements is symmetric; the reinforcement ratio is $\mu=0.01$. The ground acceleration has been modelled by the harmonic function. Different variants of amplitude and frequency were considered.

Besides the results of tests of reinforced concrete beams on a small number of repeated loading show, that the bearing capacity of specimens in dynamic tests is higher, than in repeating quasi-static tests. In this regard the limit state criteria, obtained in repeating quasi-static tests can be considered as the lower limit of bearing capacity of constructions [2]. As the object of research is the bearing capacity and the stress-strain state of beams under alternating loads the problem has been simplified solved in in a quasi-static setting and the dynamic effects have been taken into account through the coefficients of dynamic hardening of concrete and reinforcement.

The design in Abaqus of hinged reinforced concrete beams made of Б25 concrete and of A500C reinforcement loaded by two concentrated forces has been carried out. The beam model is presented in fig. 2 and the parameters of beams are presented in table 1.
Concrete and reinforcement bars have been modelled by volumetric finite elements. In order to describe the behavior of concrete the «concrete damaged plasticity» model has been used. This model considers the cracks formation and the theory of strength of concrete. In order to provide the continuity of the finite element mesh the «smeared cracking» method has been used.

The diagram of concrete under compression and under tension has been modelled by the polyline function. In order to obtain the detailed cracks pattern while the determination of the concrete diagram characteristics after the reaching the ultimate strains the descending branch has been introduced. The bilinear elastoplastic diagram has been used for the reinforcement.

First the beams loaded by the monotonously increasing load until their full destruction were calculated. The loads corresponding to the beginning of the flow in the reinforcement bars and the ultimate values of plastic strains at the moment of the beginning of destruction of compressed concrete were determined. These beams have been used as a standard.

Then in order to estimate the influence of plastic strains of reinforcement in the first loading half cycle on the stress-strain state at a sign change of the load the design of beams with the same characteristics under alternating load has been carried out. In the first loading half cycle each beam was loaded by the monotonously increasing load until the beginning of the flow in stretched reinforcement. After reaching the set value of strains the beam was unloaded and then loaded by the forces of opposite sign. The coefficient of plasticity on the deformation of reinforcement in the first loading half cycle varied from 1.15 to 5.

### Table 1. Geometric characteristic and reinforcement of beams.

| №  | Specimen   | b, mm | h, mm | h0, mm | As, cm² | A’s, cm² |
|----|------------|-------|-------|--------|---------|---------|
| 1  | B0-500-I   | 150   | 200   | 175    | 1.57    | 1.57    |
| 2  | B0-500-II  | 200   | 200   | 175    | 1.57    | 1.57    |
| 3  | B0-500-III | 100   | 200   | 175    | 1.57    | 1.57    |
| 4  | B0-500-IV  | 150   | 250   | 225    | 1.57    | 1.57    |

3. The design results

According to the calculation results the dependences of the destroying external load in the second loading half cycle to the standard destroying load ratio on the maximum coefficient of plasticity in the first loading half cycle have been determined. Such dependence for the specimen B0-500-II is presented in fig. 3.
As one can see from the graph, with the increase in the maximum plastic deformations in the first loading half cycle the bearing capacity of a beam decreases due to the open normal crack formation in compressed area of concrete and as a consequence due to reducing the working height of the section. With significant plastic deformations the decrease of bearing capacity can reach 40%.

Also according to the calculation results the dependences of the ultimate coefficient of plasticity, corresponding to the destruction of compressed area of concrete in the second loading half cycle, on the maximum coefficient of plasticity in the first loading half cycle has been constructed (fig. 4).

One can see from the graph that the increase of plastic strains in the first loading half cycle leads to intensive reduction of the ultimate coefficient of plasticity in the second loading half cycle. This is due to the increase of relative height of residual open crack in stretched area. When loading the reverse sign this crack appears in the compressed zone, reducing the calculated height of the section (fig. 5).
Figure 5. The dependence the residual crack in compressed zone to the beam height ratio on the maximum coefficient of plasticity in the first loading half cycle.

At a certain value of coefficient of plasticity in the first loading half cycle (for the beam B0-500-II it is equal to 4.8) the height of the section in the second loading half cycle reduces so much that the section becomes over reinforced. The compressed zone of concrete begins to destruct before the flow of reinforcement. This value, depending on the reinforcement ratio of the beam (fig.6), can be used as the criterion of the limit state, preventing brittle destruction of beams under alternating loads.

Figure 6. The limit value of coefficient of plasticity in the first loading half cycle per the reinforcement ratio.

4. Conclusion
In the calculation of bent reinforced concrete structures on seismic it is necessary to estimate their strength not only at the moment of reaching the maximum deformations but also on the next half cycle under the influence of seismic force reverse sign. In this case one must regard the influence of plastic strains on reduction of the section height when changing the sign of internal forces and corresponding reduction of the element bearing capacity.

One should introduce the limit state criterion, limiting the maximum value of plastic strains of reinforcement and preventing brittle destruction of beams under alternating loads.
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