Justification of the special limit state characteristics for monolithic reinforced concrete bearing systems in the progressive collapse mode

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Abstract. The paper studies the problem of criteria selection for limit states of monolithic reinforced concrete bearing systems in the progressive collapse mode. Based on the design assumptions and theoretical studies outcome, structural elements and structural units of the monolithic reinforced concrete buildings are defined; the destruction of them occurs primarily in the event of failure of the vertical supporting structure and leads to the evolution of progressive collapse. A computational and theoretical analysis has been performed to determine the ultimate deformation effects or load values according to those criteria that determine the bearing capacity of the core units of monolithic reinforced concrete systems of different spans. It is proved that as a basic criterion to estimate the stress-strain state of the monolithic reinforced concrete structures in view of the failure of a vertical bearing system there can be adopted relative deformation value corresponding to the formation of a 'fracture' zone of the near-support slab section under the action of transverse forces.

1. Introduction and task statement

Stability evaluation of the load-bearing system in the event of individual load-bearing structure failure or when a local defect is created in the structural system is one of the most important tasks in the process of the safety level assessing of the building bearing system in its entirety. In some cases, this task is stated as an estimate of the structure survivability [1, 2, 3] which seems to be a justified approach. The legislative document in force [4] outlines requirements to ensure mechanical safety of buildings and structures in the event of an emergency design situation. 'In a process of designing an increased criticality rating facility, an emergency design situation must also be taken into account ... which is important because of the reaching limit states consequences that can be generated in this situation (including the limit states arising in connection with explosion, collision, emergency situation, fire, and also right after the failure of one of the supporting structures)'. Following further requirements description [4], the government standard [5] introduces a new kind of limit state: 'special limit states, namely the states arising from particular impacts and situations exceeding, which leads to the failure of structures with disastrous consequences'.

The definition of special effects is studied in detail by Code of Regulations [6] which defines that 'the impact caused by particular emergency effects needs to be taken into account in the calculation to determine the structures progressive collapse. ... Calculation for the structures progressive collapse may be considered not compulsory if special measures are ensured which exclude progressive collapse

of a structure or part thereof'. At that, the wording of the standard [5] contains certain criteria only for previously known and used in practice limit states of the first and second groups. The new term 'special limit state' is not given any regulatory definitions or characteristics.
Consequently, the compliance with the requirements of the Russian Federation legislation in force and regulatory documents covering the stability of the load-bearing system analysis in the event of individual load-bearing structure failure (i.e. in response to a special limit state) is not fully grounded by the regulatory criteria. This leads to ambiguity in approaches to assess the stability of load-bearing systems with progressive collapse and to evaluate the efficiency of 'special measures which exclude the progressive collapse of a structure or part thereof'.
In order to justify the approaches to the special limit states criteria evaluation, it is required to determine the operational aspects of the supporting system of the building structure when one of the supporting elements fails. One of the initial guidelines and regulations dealing with the problems of progressive collapse [7] outlines that 'stability of a building against progressive collapse will be ensured if the following condition is met for any element:

$$F \leq S \tag{1}$$

where F and S are force in the element taken from the elastic analysis and its design load-bearing capacity respectively calculated taken into account the guidance of Item 3 [7]'. Pursuant to [7], it can be admitted that the structures are operated under the conditions of plastic deformations development; still the degree of plastic deformations is determined implicitly, namely through the reliability coefficients to the strength characteristics of the materials.

The structure operational principle in the mode of inelastic (plastic) deformation under special conditions of the operational period is widely used: in the context of seismic and explosive effects, in the work sites conditions. Thus, there is a method proposed to take into account the inelastic deformation of the building structures under seismic effect based on the parameter in [8] 'building state in the aftermath of an earthquake which is defined as the maximum tolerated value of 'residual deformations'. The author of [8] shows that 'residual deformations' are the result of the structures operational condition outside the elastic phase.

Theoretical studies to determine 'permissible damage-behavior ratio' are normally based on plasticity characteristics of the structure (plasticity coefficient μ), or on the structural damage parameter ('damage index of the structure' D); for details see further [9, 10, 11, 12, 13, 14] in which various approaches to determine these parameters are proposed: a) by curvature (for reinforced concrete elements); b) by plastic range of turning angle (for reinforced concrete elements); c) by limit state of deflection; d) by accumulation of damage (for reinforced concrete elements); e) by stiffness reduction when loading reinforced concrete elements (criteria parameter is the section curvature); f) based on fatigue assessment; g) based on absorption of energy by the structure, and by a number of other ones.

In [15] the method of estimating the permissible level of damage is described based on the plasticity coefficient μ determined by deformation characteristics; therein the method is further justified for the most frequently implemented reinforced concrete bearing structures of various types:

$$\mu = \frac{\varepsilon_{tot}}{\varepsilon_{el}} \tag{2}$$

where ε_{tot} and ε_{el} are total and elastic relative strains of the structure respectively.

In this regard, there should be set reasonable restrictions for the value of total relative strain. For instance, the following value is deemed reasonable for the basic structural anisotropic materials:

$$\varepsilon_{\max} = 0.85\varepsilon_{tot} \tag{3}$$

It should be noted that, according to the described above method, the plasticity coefficient μ is determined on the basis of deformation parameters subject to thorough control and that provides for an acceptable accuracy level.

In order to protect the load-bearing systems against progressive collapse, various approaches are proposed, i.e. the method of the load-bearing capacity increase for the structural elements beyond the required results generated by elastic calculation. For the most common types of load-bearing systems, namely multi-storey and high-rise buildings with the load-bearing structures of monolithic reinforced concrete, the method of protection against progressive collapse based on the arrangement of the increased stiffness floors (outrigger floors) is proposed and justified (ref. [16]). The method ensures a change in operational pattern of the vertical support structure in the failure event of the underlying element; such structure is 'suspended' to the outrigger floor. The operating principle of the outrigger floor as a structural unit ensuring 'suspension' of vertical bearing structures is fully consistent with the definition of a 'special measure excluding progressive collapse of the structure or part thereof, which contributes to its wide implementation in high-rise reinforced concrete construction projects.

Nonetheless, the absence of sufficient characteristics of the limit states of the load-bearing structures for a special limit state in the event of bearing element failure with allowance for the tolerated level of structures plastic deformation does not permit to fully and reasonably take into account the operation plastic phase of the outrigger floors structures which seems completely admissible.

Apparently, the value of the plastic phase degree for the structure operation should have reasonable limitations. Such limitations are determined not only by the outrigger floors layout, but also by the condition of all other elements of monolithic reinforced concrete bearing system. Thus, the most sensitive elements of the main load-bearing system of a reinforced concrete building are monolithic reinforced concrete floors [17]. It is proved in light of the analysis outcome [17] that localized fractures are formed primarily in the near-supporting zones. The extent of such localized fracture zones and their characteristics are mainly determined by the structural rigidity of the outrigger floor. It is evident to build an outrigger floor of high rigidity massive structures that will solely operate in the elastic stage and ensure minimal deformation values of the suspended ceiling. Nevertheless, such methods to ensure protection against progressive collapse conflict with the reasoning of economic feasibility.

2. Models of monolithic reinforced concrete structures to proceed with the analysis of the fractures formation under the conditions of failure of the carrier system element

In order to determine the utmost tolerated deformations in the structures of outrigger floors, it is compulsory to analyze the processes of the fractures formation in the bearing system core elements (monolithic reinforced concrete slabs), as well as the mechanisms leading to the formation of such fractures. Within the scope of this study, such analysis is performed by numerical methods based on finite element models of typical floors of spans different dimensions and structures stepping: from 3.0 to 7.2 m (the general view of the model is shown in Figure 1).

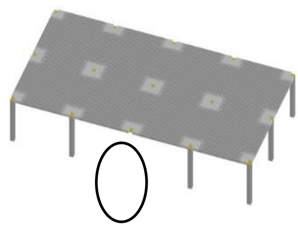


Figure 1. General view of the typical floor model with spans of 6.0 m. Circled in the centre is the zone where a column in the last row is missing ("failure" of the structure).

The design model corresponds to a typical floor slab with a set of supporting vertical structures, namely columns. The design analysis is performed in the examination mode of the reinforced concrete section capacity using the SCAD computing complex [18]. The analysis of the load-bearing capacity of the slab model elements carried out in accordance with the provisions of the current norms [19]. The monolithic reinforced concrete slab is approximated by finite shell-type elements as per the Mindlin-Reissner plate theory with the finite elements dimensions of 200×200 mm (main slab surface) and 50×50 mm (in the near-support zone). The contact zone between the column and slab is modeled using an all-solid body.

In view of the impact, the support zones movement of the slab above the "failed" column was considered. The displacement varied from zero to the "tolerated" value (spaced at 0.5 mm) corresponding to the moment of the fracture zone formation (Figure 2).

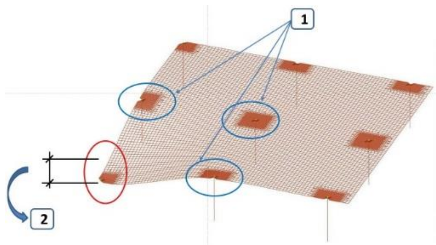
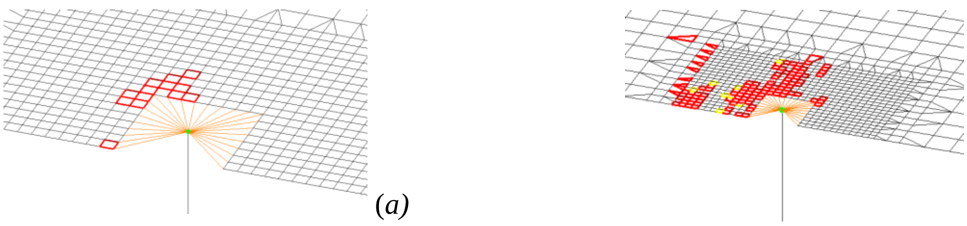


Figure 2. Layout of the design model and deformation load effect created in order to analyze the fracture process of the slabs' near-support zones. 1 – zones under analysis to determine load-bearing capacity; 2 – deformation effect.

In addition to the deformation effect, the values of equivalent applied forces onto the slab in the zone of the 'failed' column were determined, and contributed to the generation of displacement value of the reference support zone equal to the 'tolerated' value. The calculation of the force factor is made to reveal correlation between the deformation and force effects. In accordance with the results of studies [20], by the limiting value of the localized fracture it is adopted a section of the 'destroyed' finite elements within one surface of the column support loop.

3. Numerical studies outcome for the elements limit states in the monolithic reinforced concrete bearing systems in the event of the support structures failure

The process of the fracture formation in the slabs in the near-support zone has a dominant consistent character: the exhaustion of the bearing capacity begins with single finite elements and when the load factor (displacement value) increases; the number of 'destroyed' finite elements increases with the formation of the 'destroyed' finite elements within one surface of the column support loop, and which corresponds to 'destruction' of the near-support zone (Figure 3).



(*a*) (*b*)

Figure 3. Various phases of fracture formation of the near-support slab zone. (*a*) – "destruction" of single finite elements, (*b*) – formation of the "destructed" finite elements area within one surface of the column support loop.

Destruction of the near-support slab zone measured by different criteria (transverse force and bending moment) occurs at quite different displacement values of the section above the failed support element: formation of the destroyed near-support zone occurs at significantly lower transverse forces than if compared with the bending moment criterion (Figure 4).

The values of “marginal” displacements (in absolute values) correlate well with “failures” of the same type of support structures (middle column, edge column, corner column) with increase slab in span (Figure 5).

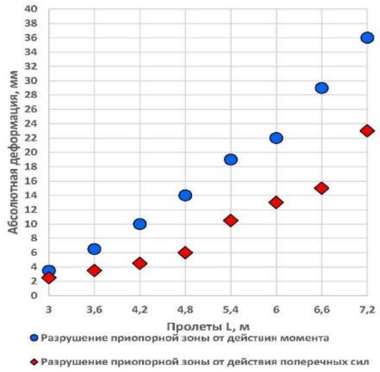


Figure 4. Values of “tolerated” displacements for various criteria of the near-support slab zone formation (middle column).

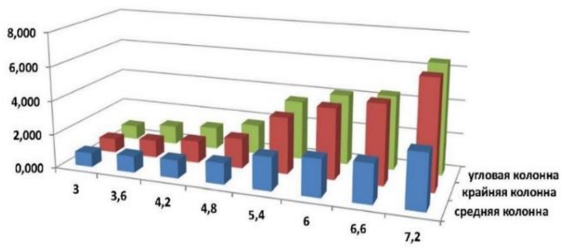


Figure 5. Values of “tolerated” displacements in relative values for various spans/steps of the support slab structures.

The outcome of the applied forces determination equivalent to the values of ‘tolerated’ displacement values in comparison with deformation effects prove that there is no correlation between force and deformation effects (Figure 6). Consequently, the use of the force impact does not provide a correct estimate and cannot be considered as a criteria parameter.

The obtained values of the ‘tolerated’ displacements corresponding to the ‘fracture’ formation in the near-support zone under the failure conditions of the support structure enable to proceed with the calculations of the utmost permissible values of the plasticity coefficients μ (in accordance with (2)) and shift to determining the values of the admissible damages (as per [21]).

Based on the results of the performed numerical studies, the plasticity coefficients corresponding to the maximum permissible deformations for different spans of the bearing system are obtained. For instance, the plasticity coefficients in the event of “failure” of the corner column are given in Figure 7.

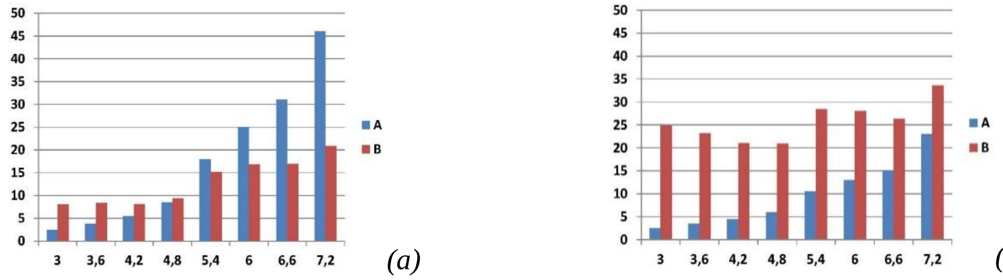


Figure 6. Comparison of the applied load factors for the conditions of ‘destruction’ formation in the near-support slab zone. *(a)* – failure of the edge column, *(b)* – failure of the middle column. The absolute values of displacements (mm) and the values of the tolerated force factor (tons) on the vertical axis are given; A is the deformation and B is the force factors.

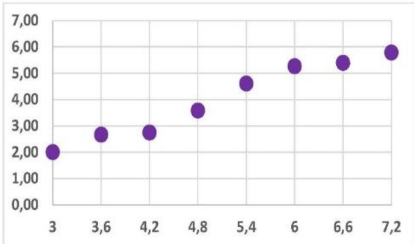


Figure 7. Coefficients of plasticity μ in “failure” event of the corner column.

Reasonable values availability of the core elements tolerated plasticity of monolithic reinforced concrete systems is the basis for further values determination of the permissible damage level, which allows for correct assessment of the outrigger floors operation efficiency as special measure that prevents against progressive collapse of the structure.

4. Conclusion

The undertaken studies justify the possibility to use deformation criteria to estimate the stress-strain state of the monolithic reinforced concrete structures under the failure conditions of the vertical element of the bearing system. The studies prove that as the main criterion to assess the stress-strain state for the monolithic reinforced concrete structures can be considered relative deformation corresponding to the formation of the ‘fracture’ area of the near-support slab zone under the impact of transverse forces.

The force factors modeling the impact in the failure mode of the bearing structure do not reveal acceptable correlation with the bearing capacity exhaustion of the near-support slab zone, which does not allow them to be taken into account while the processes analyzing taking place in the monolithic reinforced concrete bearing systems under the conditions of progressive collapse.

The determined characteristics of ultimate plasticity and corresponding characteristics of the permissible damage level, in fact, prove to be the characteristics of the limit states of monolithic reinforced concrete structures for the progressive collapse mode.

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