Modelling post-critical deformation processes of flat reinforced concrete elements under biaxial stresses

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Abstract. This paper examines the issue of mathematical modelling of local destruction processes of flat reinforced concrete structures beyond design basis impacts. Analysis of the peculiarities of the local failure mechanisms, which are formed in wall concrete structures, was conducted. The paper shows that the processes of post-critical deformation of flat concrete structures occur through several mechanisms with the relevant strength criteria. The method of post-critical deformation modelling of reinforced concrete structures under biaxial stresses is proposed and justified. The modelling is conducted by the gradual change of the analysis model in the areas of failure using finite elements with stiffness parameters, which corresponds to the conditions of interaction between structure parts separated by a crack.

Keywords: modelling, load-carrying structures, stress-and-strain state, design prediction, calculation technique, calculation model, model of external constraints.

1 Introduction

The prediction of load-carrying building systems stress-strain state within the framework of project impacts is a standard procedure of engineering analysis and has a set of well-developed techniques based on the numerical methods. It is assumed that the load-carrying structure elements have such a level of load-carrying ability that provides the possibility of calculation analysis within straight-line theory. However, in some cases it is necessary to predict the behaviour of building structures and constructions under beyond design basis impacts. For example, in the destruction (failure) of the element of the load-carrying system. Such failure leads to the fact that in other structural elements of the load-carrying system forces (stresses) arise with values exceeding their load-carrying ability, which determines the deformation transition of such structures to the nonlinear stage. Nonlinear deformation occurs with the formation of local damages, the accumulation of their volume

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and the formation of main structural damage zones. Such disruptions can lead to two cases: to an increase in the volume of destruction in the building load-carrying system with the transition to global destruction of the system or to the localization of damages in the destruction zone without the spreading of destruction process in the load-carrying structure system. This kind of problems are considered within the framework of the assessment of the structural survivability and load-carrying system beyond design basis impacts (see papers [1, 2]), and also for the assessment of the load-carrying constructive system ability in the presence of local individual element defects (see, e.g., [3]).

For a reasonable stress-and-strain state prediction of the load-carrying system beyond design basis impacts, a method of modeling inelastic deformation of load-carrying structures is necessary. The correctness of the method of modeling inelastic deformation of load-carrying structures is provided by the reflection of the most important proces regularities that arise when one leaves the linear phase of the structure work.

Thus, the research of the regularities of inelastic deformation of reinforced concrete structures (as the main type of materials of load-carrying building systems), including the phase formed after the occurrence of over-standard crack opening, is an important and urgent problem. Inelastic deformation of reinforced concrete structures in the phase of increasing the volume of cracks and increasing the width of their opening can be defined as the phase of post-critical deformation of reinforced concrete structures. In the phase of post-critical deformation, the conditions for the transition to macro-destruction both separate constructive elements, and the constructive system as a whole are formed. The account of post-critical deformation of the structure allows to consider the decrease in the volume of elastic energy of the building load-carrying system in the formation process of inelastic deformations (local and main destructions). Using of post-critical structure deformation account allows to form a work model of a «softening» constructive system, i.e. a system with a rigidity degrading on certain mechanisms.

The importance of developing of the methods of the reinforced concrete walls failure is determined by the fact that such structures allow the creation of the increased rigidity floors that make it possible to ensure the buildings resistance to a progressive collapse (the general principle is proposed and substantiated in [4], used in a number of other papers [5, 6]]).

2 Analysis of peculiarities of post-critical deformation processes in reinforced concrete elements

For certain types of reinforced concrete structures (for example, for bent beam reinforced concrete elements), the phase of inelastic deformation is well studied. Based on the research results, reasonable approaches to assessing the possibilities of bar reinforced concrete elements to take a certain volume of plastic deformations are formed (see, for example, [7, 8]). For bar reinforced concrete elements, the post-critical deformation modeling methods are proposed and substantiated. For example, the method of modelling local destruction (failure) in bar reinforced concrete elements mainly by reducing the total rigidity of the final element - without detailing by the mechanisms of destruction is used for a finite-element approach (see [9, 10]). This method of modeling can be considered quite acceptable (with an amount of essential refinements - see [6]) to account the failures of bar elements.

However, flat (wall) structures under biaxial stress state have a number of significant differences (in relation to the bar elements) in the realization of post-critical deformation processes: in the forms of failures manifestation, one or another kind of failure criteria formation, in the volumes of local and main destruction possible realization.

For stone structures under biaxial stressed state, the processes of post-critical deformation were investigated in [11, 12].According to the research results, it is established that several mechanisms of local destruction are formed, which have a mutual influence on the development of any of them. The mechanisms are formed according to various strength criteria, which determines the impossibility of using simplified one-parameter methods of the plane-stressed stone structures supercritical deformation processes modeling. Research has shown that the implementation of local destruction mechanisms occurs simultaneously and in different volumes by separate mechanisms, that ensures the stone wall structure workability even when a large volume of local fractures is formed by one of the mechanisms (criteria).

Wall reinforced concrete structures under biaxial stress state also have a number of post-critical deformation features, which, if not taken into account, can lead to a significant decrease in the quality of the stress-and-strain state prediction of such structures in the post-critical deformation phase. The largest volume of deformation and destruction of flat-stressed reinforced concrete walls research was carried out within the framework of seismic impacts on wall structures (the results of the research are presented widely and in detail in the monograph [13]). Within the framework of the research it is established that the destruction of reinforced concrete walls under biaxial stressed state occurs in several stages. At the first stage, a crack is formed in the concrete wall, that can be determined based on general criteria of the plane stress state strength. At the following stages, the local crack development is determined by the work of the reinforcement that crosses the local concrete destruction. Mechanisms of interaction of wall parts, separated by a crack, are schematically represented in Fig. 1. When an expansion occurs in the crack zone, an "open" crack is formed (see Fig. 2), the expansion of which is prevented by the reinforcing bars that crosses the crack (the interaction of the crack sides can be neglected).

In the zone of the "open" crack, due to the shift of the crack sides and the inclusion of reinforcing bars into the work, a dowel action is formed that provides the plane-stressed structural element load-carrying ability level (in some cases - quite large), which is observed right up to the destruction of the reinforcement or crushing of concrete in the zone of its anchorage. The dowel action of the reinforcement work in the crack zone can be taken into account by various methods, for example, proposed in [14].

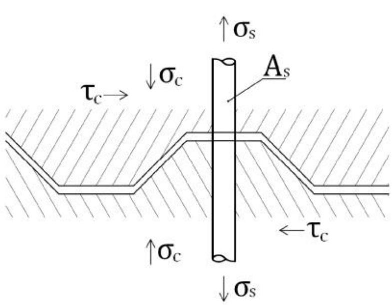

Fig. 1. General scheme of interaction of wall parts, divided by a crack.

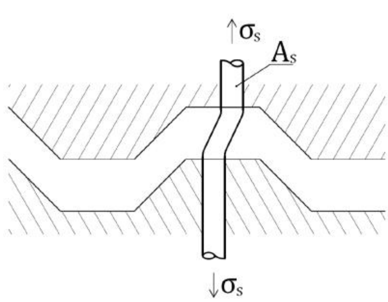

Fig. 2. Scheme of interaction of wall parts, separated by an "open" crack.

The development of reinforced concrete wall destruction is not an irreversible process - with the growth of the crack width in one local zone in other local zones a crack "closure" can occur, which forms the conditions for crack sides interaction in the dry friction regime.

Thus, the physical realization of processes at the post-critical deformation stage of reinforced concrete walls under biaxial stress state has a multi-regime nature, which requires appropriate detailing in the modeling. Obviously, the method of modeling the post-critical flat-stressed walls deformation by reducing the generalized rigidity in some local model region cannot reflect such a complex and multifactor process correctly.

3 Methods of modelling of the post-critical deformation of flat-stressed reinforced concrete elements

The flat-concrete reinforced concrete structures post-critical deformation processes occur within the framework of several local failure mechanisms types, which requires the use of several strength criteria. The using of strength criteria set (system) makes it possible to take into account the various failure mechanisms in evaluating the state of a structure. The critical condition assessment concept of a material based on the durability criteria set is developed and proved in works of A.A. Ilyushin [15] and Ya.B. Friedman [16] and is widely used for a long time.

Based on the research results of A.A. Ilyushin [17] a general approach to the strength criteria set formation is proposed, the essence of which is as follows: let the measures of the damage tensor Mn (Ω), which are the components Ω functions, can be used to formulate the destruction criteria corre-sponding to different failure mechanisms. We define that there exist critical damage constants for the material Ωcrn such that if for any **n**

$$M_n(\Omega) < \Omega_n^{cr} \tag{1}$$

the state of the particle (element) will be durable, and if for some **n=k**

$$M_k(\Omega) < \Omega_k^{cr} \tag{2}$$

k type of destruction will occur.

For isotropic materials, the functions **k** and **q** are invariant measures of the tensor Ω, which in turn express the change of the deformation properties that determine the behavior of materials (elements) under hydrostatic pressure and pure shear, respectively.

It is possible that the element destruction (the local zone of the element) according to one of the criteria adopted within the framework of the criteria system will determine the impossibility of resisting only a certain type of impact, whereas for other types of impacts the particle can work as a part of a general particles ensemble (load-carrying system elements). As shown in [17], formally this can be expressed in an abrupt increase to unity of some damage tensor Mn(Ω) components. The particles work analysis (elements of the calculation model) based of the strength criteria set (system) makes it possible to distinguish the destruction mechanisms and to consider correctly the elements state in the global structure system.

So, for example, when a particle/element is broken according to the shift criteria, this particle can turn out in two state types: in the case of a compressive stress in the zone, the particle will perceive such stresses and participate in the particles ensemble work by the shift criteria within the framework of the friction mechanism; in the case of tensile stresses in the particle zone, this particle disappears from the particles ensemble of the investigated body.

It seems possible to apply the structural local fractures modeling principles, proposed and substantiated in [18], which allow to take into account the performance of the damaged structure zone according to the separate strength criteria types as a general approach to the flat-stressed reinforced concrete constructive element failures.

The flat-stressed rainforced concrete wall destruction multi-mode mechanism modeling can be performed by means of a multi-stage finite element analysis, which takes into account the changing of the calculation model [19]. Numerical investigation of post-critical deformation processes is performed within the framework of the linear problems successive solution process. At each stage, the state of each final calculation model element is evaluated using the strength criteria system.

The finite element model state change in the post-critical deformation phase is modeled by the method of parallel installation of a set of different rigidity plate finite elements in the mutual nodes. At the initial stages of the calculation, the finite element with concrete stiffness parameters. If it is found that the strength criteria for concrete are exceeded in in any finite element of the model, that finite element must be excluded from the model (deactivated). On the deactivated finite element place in the ensemble of the calculation model, one of the finite element from the parallel layer is installed, the characteristics of which correspond to the conditions of operation of concrete in the zone of local destruction, is included.

When acting in the zone of local destruction of tensile stresses, the characteristics of the "new" active finite element must reflect the possibilities of the operation of the reinforcement both in tension and dowel regime, which prevents the shift of the crack sides. When acting in the zone of local destruction of compressive stresses, the characteristics of the active finite element must additionally take into account the interaction of the crack sides in the dry friction regime. In a simplified form, such a scheme (in the form of two parallel finite elements instaled in the mutual nodes) is shown in Fig. 3.

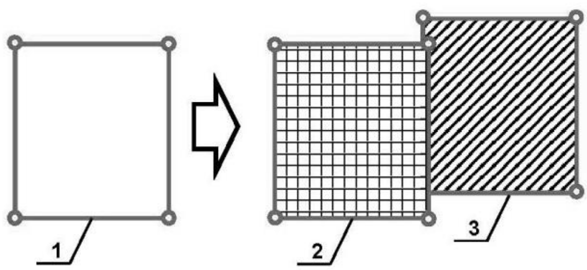

Fig. 3. Scheme of modelling of the post-critical wall deformation process by the method of parallel installed finite elements with different rigidity characteristics.
1 – finite element, approximating the concrete; 2 - finite element, approximating the work of the damaged concrete under the action of tensile stresses; 3 - finite element, approximating the work of damaged concrete under the action of compressive stresses

At the subsequent stages of the calculation, the analysis of the state of the finite elements that are part of the ensemble of the model is performed. If the stress sign changes in the zone of the local crack, it is necessary to replace the finite element with the type corresponding to the new stress sign. It is also necessary to monitor the level of stresses in the finite elements, approximating the work of reinforcing bars, which will allow to determine the moment of the transition of the reinforcement to plastic deformation or destruction. The dowel mode of reinforcing bars also has a definite limit. To track it, it is necessary to control the strength of concrete in the crushing zone, which is a technologically difficult design problem.

Conclusion

The proposed modelling method allows taking into account the key features of the process of post-critical deformation of wall reinforced concrete structures under biaxial stress state. The application of the proposed modeling technology creates conditions for assessment of the evolution of the destruction process of the reinforced concrete wall structure, which is the basis for the prediction of the stability of the load-carrying system beyond design basis impacts.

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