Influence of the Structure of the Cross-section of Load-bearing Structures on Their Deformation during Emergency Actions

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Abstract. The paper deals with the issues of destructure modeling for constructive systems of reinforced concrete framing buildings. It is considered the widely using in practice framework of interspecific appliance for multi-storey buildings and structures on the basis of protection against progressive collapse. The results of dynamic additional loading analysis for girders of considering reinforced concrete framework at sudden structural transformation of constructive system are presented. It is obtained that at accidental impact and fragile destruction of tensiled concrete the coefficient of dynamic increasing of internal forces in tensiled reinforcement of reinforced concrete elements depends on the percent of reinforcement in cross section, prestressing level and topology of structure. It is proposed to calculate without of structural dynamic methods on the energetic basis the coefficie nt of dynamic increasing of internal forces in structures at sudden removal of a bearing element and cracking.

1. Introduction
For absolutely majority of buildings safe strength resistance at accidental impacts caused by interruption of technological processes, terroristic acts, mechanical support removal were not taking in account at designing, since it corresponded to emergency situations and economically costly. However, at current moment situations with such impacts occur more often. Therefore, in the new building codes it is envisaged accounting of such accidental impacts [1-3] to buildings and structures safety increasing and saving people's life. At the same time solving of such problems connected with not only determination and rating of impacts but with study of strength resistance and destructure features of structural elements at such impacts. Therefore, studding of stress-strain at ultimate states and developing of strength criteria for bearing elements of loaded reinforced concrete structural systems at considered accidental impacts and caused by it structural transformations and cracking is actual scientific problem.

2. Review of studding and publications
At the last two decades in Russia and abroad it was conducted the row of studding of bearing structures protection against progressive collapse, developed computational models of building and structures at accidental impacts [4-11], as well as ultimate state theory of reinforced concrete (RC) structures is extended to survivability problems [12-14]. In accordance with outlined before building codes the buildings and structures safety is considered in scientific, engineering and juristic aspects.
As it is presented in [13] the problem requires of additional research to develop methods to protect building and structures against progressive collapse. As a variant it is proposed to introduce differential classification, that takes in account social significance and responsibility level [14].

In the papers [8, 15-18] it is determined that sudden failure a bearing element in structural system leads not only to structural changes but also appear of additional dynamic forces in remaining elements and cracking in reinforced concrete elements with dynamic effects [16, 17]. However, as calculation of real structures shows, even for static computation by first (before bearing element removal) or second (after bearing element removal) level computational models [18-20] such calculation is quite laborious, depends on engineer qualification and it results are quite difficult to following analysis. The final result of calculation against progressive collapse for engineer it is evaluation special ultimate state of section or node of each constructive element in accordance with cracks availability and other deformation or destructive features of a structural element.

In relation with presented above discussions studying of stress-strain state features of bearing structural elements at special ultimate states with accounting of cracks or another deformation and destructive features of structural system is one of the actual problem. In particular, one of the such problems is determination of relationships for dynamic increasing of internal forces in reinforcement of reinforced concrete element of statically indeterminate system at cracking and it structural transformation. Since requirement of Russian building codes on protection against progressive collapse [3] are expanded to buildings of normal responsibility level there is practical interest to study reinforced concrete structural system resistance of mass buildings in such formulation.

3. Constructive features of reinforced concrete building frame
Let us consider the deformation and destruction modeling for reinforced concrete framing buildings at special ultimate impacts of the structural system of interspecific appliance which consists of flat frames and bracing beams, such as structural system by 1.020-1/87 series of industrial producing for civil and industrial multi-storey buildings as it is shown in figure 1 (a). reinforced concrete structures are applied in multi-storey buildings operating at different environmental conditions. Wares of this series are not calculated at dynamic, seismic and other special and emergency impacts but in fact it is applied there. Therefore, one of the main problem of research is determining of girder’s bearing capacity at special ultimate states.

Space stability of buildings designed by bracing scheme is provided by system of vertical supports connected with overlap disk. As vertical supports are used bracing panels made of precast concrete rigid diaphragm or steel bracings, connected with nearby columns as it is shown in figure 1 (b). For building’s spans 3, 6, 7.2 m it is proposed to apply girders of 450 mm cross section height. For buildings with 9 m span it is used girders of 600 mm cross section height. Nomenclature of columns not depend on girder cross section height. Since 1.020-1/87 series consist of flat frame and bracing beams the space stability of structural system at construction or operating is provided by overlap disks.

Analyzing presented constructive designs shows that it is not adapted for considering special impacts. Therefore, it is necessary to develop computational methods accounting accidental impacts to providing of protection of such buildings against progressive collapse.

4. Computational schemes to reinforced concrete deformation and destruction modeling
Solution to problem of reinforced concrete structural system of building and structure modeling at special impacts in general case deals with deformation and destructure analysis by space computational model in dynamic formulation in accordance of physical, geometrical and constructive nonlinearity [8, 16]. Obtaining of such computational model with required detalisation for whole building is labor intensive, bad to evaluating and not always effective. Therefore, one of the variants of computational analysis algorithm for structural system destructure modeling at accidental impacts may be algorithm based on multi-level computational models in quasi static formulation with differentiated requirements for computational results at each stage of calculation. At the first stage it is carried out calculation of space structural system under loading and determined stress-strain state of
each element by the first-level computational model, which is shown in figure 1 (c), with using PC, for example LIRA-SAPR program. Calculation is provided for general combination of operating loadings at force reliability coefficient equal 1.

Figure 1. Reinforced concrete framing system fragment with bracing elements (a), structural (b) and computational (c) models: 1 – column, 2 – girder, 3 – overlap slab, 4 – rigid diaphragm, 5 – steel braces.

The result of stress-strain analysis of structural system at design loadings is formulation of proposals to create so called second level computational models for resistance against progressive collapse evaluation. Calculation of structural system against progressive collapse is carried out for each secondary computational model independently each other.

5. Calculation of structural system on stability against progressive collapse
Algorithmization of calculation against progressive collapse is carried out for reinforced concrete frame of civil building made of by 1.020-1/87 series of industrial producing. Since the considered structural system is not adapted to apply in construction at considered special impacts, the protection against progressive collapse provided by rigid connection columns with beams.

The calculation is carried out by first and second level computational models at removal corner column 1 or outermost column 2 of first storey, as it is shown in figure 1 (c). In secondary computational model forces from removal column, which are obtained for first level computational model, are attached in opposite direction.

Physical nonlinearity is accounted by partially linear deformation model.

For considered special ultimate state of reinforced concrete structures of building frame it is applied the following criteria:
- limitation of the compressed concrete deformation by ultimate value $\varepsilon_{b2} = 0.0035$, that is determined by bilinear diagram for it static and dynamic deforming at stress values equal to $\varphi R_{b,ser}$, where $\varphi$ is concrete dynamic strengthening coefficient.

- limitation of the tensiled reinforcement deformation by ultimate value $\varepsilon_{s2} = 0.025$.

Displacement mosaic and crack's width in reinforced concrete elements at calculation by secondary computational model with removal outermost column 1 are presented in figure 2.

![Figure 2](image_url)

**Figure 2.** Displacement mosaic for overlap disk in mm (a) and beams (b), width of cracking in mm (c) in structures of building at sudden removal of corner column at hinged connection of beam with column of second storey.

Analysis of these data shows that traditional constructive design of frame-bracing structural system by 1.020-1/87 series exclude progressive collapse of entire building at considered accidental impact. At the same time, it is possible local destruction in the building, the sizes of which in accordance with [21] are limited by area 28 square meters or circle of 6 m diameter with center at removal column.

It is accepted rigid connection of beams and columns of first and second storey to exclude local destruction in zone of the removal column. The calculation of such structural system presents that progressive collapse or local destruction not occur at accepted deformation criteria as it is shown in figure 3. It is should be noted that it is possible another technique to protect building frames of considered series against progressive collapse, for example, it may be installation of additional cross or triangular steel bracings as it is shown in figure 1 (b).

6. **Evaluation dynamic force increments in tensiled zone of reinforced concrete elements at cracking caused by accidental impact**

The technique of dynamic coefficient introducing for each element of structural system that is used in some scientific papers and in programs for PC, is not corresponded to physical meaning of considered problem. In this case it is necessary to use instead the dynamic coefficient the coefficient of dynamic force increment for remaining elements of statically indeterminate system caused by sudden removal of a bearing element or section at cracking that leads to change order of static indetermination.

As physical model of strength resistance for cross section it is used deformation model by V.M. Bondarenko and V.I. Kolchunov [22] to evaluate increments of dynamical internal forces in tensiled zone of bending RC elements at cracks formation. Such model allows more fully account stress-strain state in crack zone on the basis of constant of fracture mechanics and RC mechanics. Meaning of this method is using of so called two cantilever element as computational model of cross section, that allows to link potential energy of deformed RC element with flexibility constant $\xi$ of crack 'coasts' at it formation and traditional parameters of RC deforming such as $E$, $G$, $\varepsilon$. In accordance with this model
the internal force distribution scheme for RC cross section after crack formation is presented in figure 4 (a).

![Figure 3](image.png)

**Figure 3.** Displacement mosaic for overlap disk in mm (a) and beams (b), width of cracking in mm (c) in structures of building at sudden removal of corner column at rigid connection of beam with columns of first and second storey.

Distribution of longitudinal stresses \( R_{bt} \) in tensiled concrete at the distance from crack is accepted as evenly through the height of tensiled zone and alternating nearby of crack. In the reinforcement zone of \( t_0 \) height nearby crack the tensile stresses changes its direction due to discontinuity effect [22].

For accepted scheme of stresses distribution in tensiled concrete of bending element in accordance with papers [8, 16] let us write the analytical equation for dynamic internal force in reinforcement in the form:

\[
N_{d}^d = N_s + 2N_{bt},
\]

(1)

where \( N_s \) is internal force in reinforcement, caused by external load \( P \); \( N_{bt} \) is internal force in tensiled concrete.

The resultant force in tensiled concrete \( N_{bt} \) in zone nearby crack is determined on the basis of two-cantilever model of element [22]. For considered reinforced concrete bending element it takes the form, as it is shown in figure 4 (b):

\[
N_{bt} = -\Delta T + 0.5 \sigma_{bt} b t R_{bt} b (h_{rcr} t - m) - \frac{2}{3} \sigma_{bt} R_{bt} b m,
\]

(2)

where \( b \) is width of RC element cross section; \( t = 1.5 d \) is parameter characterizing sizes of concrete compressed zone nearby crack, \( d \) is diameter of reinforcement bar; \( h_{rcr} \) is length of crack; \( x_{rcr} \) is height of concrete compressed zone at crack formation moment; \( \Delta T \) is shear force acting by contact zone between reinforcement and concrete; \( m \) is zone where may be destruction in the next moment.

Tangential and normal stresses in reinforcement \( \tau_{bt}(z) \) and \( \sigma_p \) presented in figure 4 (b) on the two-cantilever element model are not included in equilibrium equation since it projection on the x axis equal zero and it leverage are small. It is not accounted nail effect for reinforcement.
Proposed analytical relations to determination of dynamic force increment in reinforcement of bending element at crack formation are verified by calculation of RC girder RPD 4.56-50 by the considered 1.020-1/87 series. The girder has 5.56 m length, two symmetrical cantilevers for supporting of hollow-core overlap slabs of 450 mm height. Loading is 50 kN/m. Reinforcement made of steel bars A500 class. Concrete is C30 class. Reinforcement includes space frame, connectors, steel nets reinforcing down surface of beam, cantilever steel nets and corner steel nets. The main longitudinal reinforcement in down zone of beam is 4 bars of A500 class of 24 mm diameter ($A_s=19.64*10^{-4} m^2$).

As result of calculation by formula (2) it is obtained $N_{ot}=38.9$ kN internal force value for tensiled concrete of beam in zone nearby of crack. Calculation is provided at moment of crack formation $M_{rc}=36.98$ kN*m.

Internal force in tensiled reinforcement of reinforced concrete beam before crack formation equals to $N_s=86.54$ kN.

Dynamic force in reinforcement of the beam at crack formation moment equals $N_{sd}=86.54+2*38.9=164.34$ kN.

Respectively the coefficient of dynamic force increment in reinforcement at crack formation moment equals $\theta = N_{sd}/N_s = 1.89$.

7. Conclusions
Reinforced concrete framing structural system of considered building, which designed by bracing constructive scheme, does not provide requirements of protection against progressive collapse that presented in new building codes. It is necessary to apply additional constructive solutions providing protection against progressive collapse to using such framing system in buildings of high and normal level of responsibility.

At designing of protection for reinforced concrete structural system of buildings and structures it is necessary to account coefficient of dynamic force increment for secondary computational model, obtained after a bearing element removal. It is proposed to take in account stress-strain state in crack zone at its formation to more fully accounting of additional dynamic forces in RC structures.

Acknowledgments
The Reported study was Funded by Government Program of the Russian Federation “Development of science and technology” (2013-2020) within Program of Fundamental Researches of Ministry of
Construction, Housing and Utilities of the Russian Federation and Russian Academy of Architecture and Construction Sciences, the Research Project 7.4.8.

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