doi: 10.18720/MCE.81.8

Survivability of structural systems of buildings with special effects

Живучесть конструктивных систем сооружений при особых воздействиях

V.I. Travush,
Russian Academy of Architecture and Building Sciences, Moscow, Russia
N.V. Fedorova*,
National Research Moscow State Civil Engineering University, Moscow, Russia

Д-р техн. наук, вице-президент РААСН В.И. Травуш,
Российская академия архитектуры и строительных наук, г.Москва, Россия
д-р техн. наук, профессор Н.В. Федорова,
Национальный исследовательский Московский государственный строительный университет, г. Москва, Россия

Key words: survivability of structures; survivability parameter; structural system; static and dynamic diagram; added dynamic loading

Ключевые слова: живучесть сооружений; параметр живучести; конструктивная система; статико-динамическая диаграмма; динамическое догружение

Abstract. The technique of calculation analysis of survivability of reinforced concrete statically indeterminate beams and rod structural systems of buildings and structures under emergency influences is given. The statement of the problem of the computational analysis of the survivability of such constructive systems and the algorithm for determining the survivability parameter under special influences in the form of a sudden shutdown of one of the constructions is expounded. The criteria of the bearing capacity for a particular limiting state for the considered constructive systems arising under such influences are proposed, the excess of which can cause a progressive destruction of the constructive system. An example of a computational analysis of the survivability of a statically indeterminate reinforced concrete continuous beam in comparison of the theoretical results obtained with the results of its experimental studies is considered. However, the problem can be used for determining the parameter of the survivability of buildings and structures for the examined impacts.

Аннотация. Приведена методика расчетного анализа живучести железобетонных статически неопределимых балочных и стержневых конструктивных систем зданий и сооружений при аварийных воздействиях. Изложена постановка задачи расчетного анализа живучести таких конструктивных систем и алгоритм определения параметра живучести при особых воздействиях в виде внезапного выключения одной из конструкций. Предложены критерии несущей способности при особом предельном состоянии для рассматриваемых конструктивных систем возникающие при таких воздействиях, превышение которых может вызвать прогрессирующее разрушение конструктивной системы. Рассмотрен пример расчетного анализа живучести статически неопределимой железобетонной неразрезной балки в сопоставлении полученных теоретических результатов с результатами ее экспериментальных исследований. Приведенные расчетные зависимости могут быть использованы для определения параметра живучести зданий и сооружений при рассматриваемых воздействиях.

1. Introduction

The existing methods for structural analysis of survivability [1–4] and progressive collapse [5–9] of reinforced concrete frames of buildings and structures do not take into consideration additional dynamic loading in structural elements in case of abrupt failure of one of the bearing elements or consider it nominally. The impact on this additional loading of the prestress in structural reinforced concrete elements and brittle fracture of the tensile zone of concrete at the moment of cracking is not assessed either. At the same time survivability experimental data analysis of such structures in accidental limit state [10–14] shows that the impact of these factors while assessing survivability of buildings and structures can be rather significant.

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Let us consider a method for survivability analysis for redundant reinforced concrete framed structures with normal and stressed reinforcement considering the mentioned above factors.

The analysis is aimed at the determination of the survivability parameter of structural systems, criteria of reinforced structural elements in such systems in accidental limit state and determination of an additional dynamic loading factor in bearing element sections due to abrupt failure of one of the structures.

Here, the term survivability of a constructive system (λ) will be defined as a factor equal to the load acting on the structure, with the value of which, in case of switching off one of the load-bearing elements in the structural system, structural changes (failures) leading to local or progressive destruction begin.

Accidental limit state is meant as a state occurring under accident impact beyond which a local or progressive collapse of the structure can take place [15, 16]. Survivability parameter enables quantitative assessment of a building structural system load level under which, in case of accident impact, structural changes can occur, and assessment of these changes regarding stability of geometrical shape.

For calculation analysis and determination of the survivability parameter of a reinforced concrete statically indeterminate constructive system, a calculation algorithm including the following steps is proposed.

For a given structural system a primary design diagram for a given design load specified according to the regulatory requirements is built (Figure 1,a, b).

2. Methods

On the basis of a mixed-mode method for redundant systems, a system of fundamental equations as proposed in [1,2] is formed. Load coefficients of equations are presented in the form of two summands:

$$\left.\begin{aligned}\vec{A}\mathrm{M}+\vec{B}Z+\overrightarrow{\Delta_p}+\lambda\overrightarrow{\delta_p}=0\\ \vec{C}\mathrm{M}+0+\overrightarrow{R_p}+\lambda\overrightarrow{r_p}=0\end{aligned}\right\}, \tag{1}$$

where $\vec{A}$, $\vec{B},\overrightarrow{\Delta_p},\vec{C},\overrightarrow{R_p}$ are the matrices of coefficients of the unknowns of the mixed-mode method; $\overrightarrow{\delta_p}$ are the matrices of displacements in the direction of the removed elements from the external parametric loads *P* at $\lambda=1$: $\overrightarrow{r_p}$ are the matrices of the responses in the constraints of the main system from the external parametric load at $\lambda=1$ (Fig.1, b).

Considering fundamental equation features of the mixed-mode method C=-BT (where "T" means operation of transposition), the system (1) is written as follows

$$\begin{Vmatrix}A & B\\ -B^T & 0\end{Vmatrix}\cdot\begin{Vmatrix}\vec{M}\\ \vec{Z}\end{Vmatrix}+\begin{Vmatrix}\overrightarrow{\Delta_p}\\ \overrightarrow{R_p}\end{Vmatrix}+\lambda\begin{Vmatrix}\overrightarrow{\delta_p}\\ \overrightarrow{r_p}\end{Vmatrix}=0. \tag{2}$$

The equation system solution (2) is as follows:

$$\begin{Vmatrix}\vec{M}\\ \vec{Z}\end{Vmatrix}=\begin{Vmatrix}\overrightarrow{M_p}\\ \overrightarrow{Z_p}\end{Vmatrix}+\lambda\begin{Vmatrix}\overrightarrow{m_p}\\ \overrightarrow{r_p}\end{Vmatrix}, \tag{3}$$

where

$$\begin{Vmatrix}\overrightarrow{M_p}\\ \overrightarrow{Z_p}\end{Vmatrix}=-\begin{Vmatrix}A & B\\ -B^T & 0\end{Vmatrix}^{-1}\cdot\begin{Vmatrix}\overrightarrow{\Delta_p}\\ \overrightarrow{R_p}\end{Vmatrix}, \tag{4}$$

$$\begin{Vmatrix}\overrightarrow{m_p}\\ \overrightarrow{r_p}\end{Vmatrix}=-\begin{Vmatrix}A & B\\ -B^T & 0\end{Vmatrix}\cdot\begin{Vmatrix}\overrightarrow{\delta_p}\\ \overrightarrow{r_p}\end{Vmatrix}, \tag{5}$$

A combined stresses (forces, moments) diagram in a set *n*- times redundant structural system due to the design load and prestressing force is built (diagram M_n^c in Figure 1 c, d).

In the given structural system loaded with a design load, accident impact in the form of abrupt failure of one of vertical structural elements, for instance, support 2, is applied. The so called *secondary design diagram* with an excluded vertical element is built (Figure 1, e). Due to the instantaneous character of the accident impact, vertical reaction of support R_2 obtained on the basis of the design load is applied in the secondary design diagram with the opposite sign, supposing that on the first semi-oscillation of the

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beginning of beam vibrations after support removal this reaction and accordingly the moment from this reaction (Figure 1, f) reaches its maximum value. Calculation according to the secondary design diagram is made and new stresses diagrams of all loads and prestress are built (diagram $M^{d}_{n-1,\Sigma,}$ in Figure 1, g).

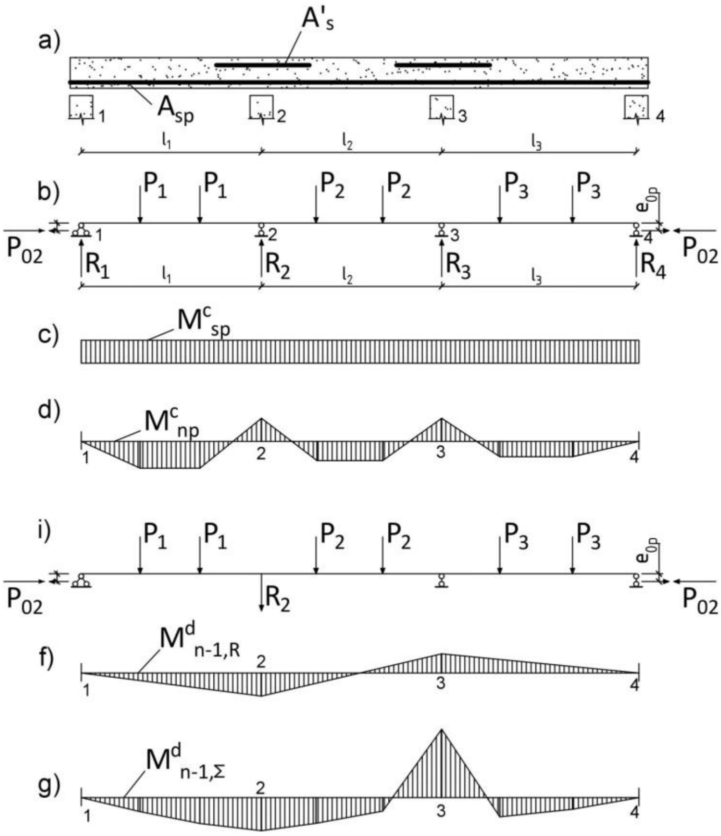

Figure 1. Continuous reinforced concrete beam survivability analysis: a, b – structural and design diagrams respectively; c, d – moment diagrams due to prestressing force and external loading in the primary design diagram; e, f, g – secondary design diagram and moment diagrams in the secondary design diagram

Failure of any section (tie) in a new structure will occur if deformation stress in this element reaches the limit value as per the criteria of accidental limit state (see below). Then, for all forces in failing elements the system of inequalities shall be satisfied:

$$|M_j| = |M_{jq} + \lambda m_{jp}| \leq M_{j,u} \quad (j = 1,2, \dots k) \tag{6}$$

where M_{ju} is the limit value of the force in the failing element taking into account the dynamic strength of the materials. M_{jq}, m_{jp} are the matrix elements of columns M_p and m_p. (In case of ductility of structural system elements, material strength increase under dynamic loads in the secondary design diagram is not taken into consideration).

In the left-hand side of inequality (6), value of the moments M_j is taken in absolute magnitude since the negative sign at M_j indicates that the direction of this force is opposite to accepted in the basic system of the mixed-mode method limit force value.

The minimum value of the survivability parameter $\lambda = \lambda_m$, when in the most loaded *j*- th element the limit value is reached and is found according to the formula

$$\lambda_{(m)} = \min\left(M_{j,u} \pm |M_{jq}|\right) / |m_{jp}| \, , (j = 1,2, \dots k). \tag{7}$$

Sign “minus” in the numerator is applied if M_{jq} and m_{jp} signs are the same, and sign “plus” is applied if these signs are opposite.

When the survivability parameter changes in the most loaded *j*-th element $\lambda \in [0, \lambda_{(m)j}]$, initial structural system with all included ties works. If $\lambda > \lambda_{(m)j}$, the j-th tie fails and the degree of redundancy of the structure decreases by *1* which is equivalent to the exclusion of constraints (6) from the system of equations (1) and the *j*- th unknown. And the initial matrices shall be transformed as follows:

- in matrix *A* the *j*-th row and *j*-th column are excluded;
- in matrix *B* the *j*-th row is excluded;
- in matrix columns the values of load coefficients $\overrightarrow{\Delta_p}$ and $\overrightarrow{R_p}$ are specified according to the following equations:

$$\Delta_{jp}^{(1)} = \Delta_{iq} + \delta_{ip} \cdot \lambda_{(m)} + \delta'_{ij} \cdot (\pm M_{j,u}), \quad (8)$$

$$R_{jp}^{(1)} = R_{iq} + r_{ip} \cdot \lambda_{(m)} + r'_{ij} \cdot (\pm M_{j,u}), \quad (9)$$

where $\delta_{ip}, \delta'_{ij}, r'_{ij}$ and Δ_{iq}, R_{iq} are the factors at the unknowns (unit deflection and responses) and load coefficients (of displacement and response) of the mixed-mode method of redundant structures analysis. In expression (9) sign at $M_{j,u}$ is taken in line with the sign of $m_{j,p}$.

To find the next failing tie, matrices are changed in the described way and the calculation procedure repeats. After the second failing tie is found the system of equations is transformed taking as initial a system of equations obtained after transformation at the first step of the solution. And at the second and subsequent steps the increment of the survivability parameter $\Delta_{(m)}$ is obtained, i.e. the parameter at which the second and subsequent ties fail. These parameters values are calculated by formulae:

$$\lambda_m^{(2)} = \lambda_m^{(1)} + \Delta\lambda_{(m)}^{1},$$
$$\lambda_m^{(3)} = \lambda_m^{(2)} + \Delta\lambda_{(m)}^{2}, \quad (10)$$
$$\lambda_m^{(k)} = \lambda_m^{(k-1)} + \Delta\lambda_{(m)}^{k-1}.$$

The sign of the solution completion, i.e. exhaustion of the system survivability is the formation of an unstable frame after subsequent tie failure. This sign at each step of the fracture $\Delta\lambda_m$ is found by means of calculation of the determinant of a matrix of coefficients at the unknowns. If the determinant equals to zero, then the structure has exhausted its vitality and turned into unstable system.

Calculating limit forces in the structure sections ($M_{j,u}$) the following constraints for dynamic stresses are taken as criteria of the accidental limit state of a reinforced concrete structure. Fist, constraints for dynamic stresses in the reinforcement (Figure 2, a):

$$\sigma_s^d < R_{s,ser}^d, \quad (11)$$

where σ_s^d are the dynamic loading stresses in the positive reinforcement of the considered design section calculated according to the secondary design diagram, considering additional dynamic loading [17, 18] at the moment of cracking; $R_{s,ser}^d$is the standard value of the reinforcement dynamic strength specified as per the recommendations [1]. Second, constraints for dynamic stresses in compressed concrete (Figure 2, b):

$$\sigma_b^d < R_{b,ser}^d, \quad (12)$$

where σ_b^d are the dynamic stresses in compressed concrete in the considered section, calculated as per the secondary design diagram taking into account additional dynamic loading of compressed concrete at the moment of cracking [18]; $R_{b,ser}^d$ is the standard value of the concrete dynamic strength specified according to the recommendations [1,2].

If both strength criteria for reinforcement (11) and concrete (12) for the most stressed sections of the span of a continuous beam are satisfied (Figure 2 a, b), a deformation criterion of accidental limit state is checked:

$$f \le \frac{1}{\rho} l, \quad (13)$$

where f and ρ are the deflection and the curvature in the beam span l respectively.

The value of ρ is found by formula

$$\rho = 80 - 2\frac{l}{h}, \quad (14)$$

but is not less than 30,

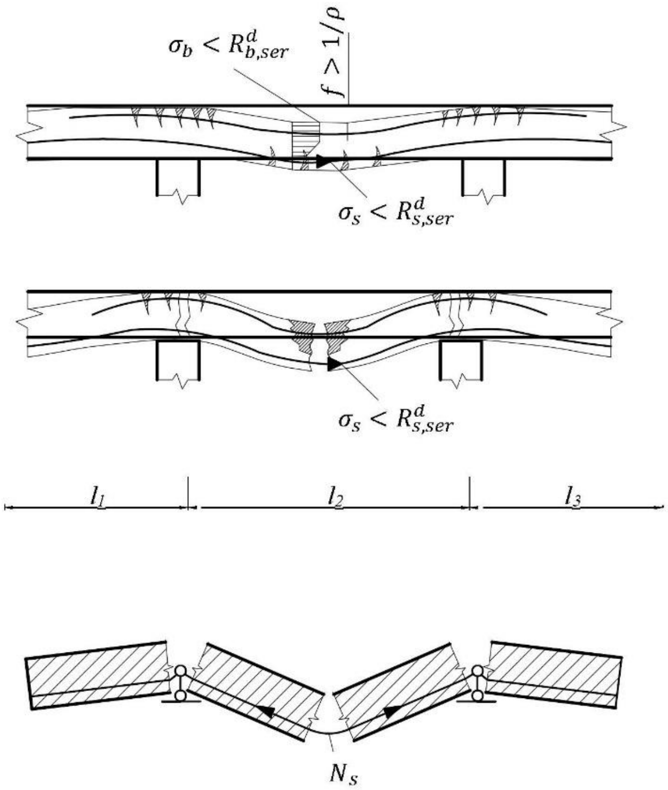

Figure 2. Defining criteria for beam system failure in accidental limit state: a – design diagram for "mild" section failure, b – for compressed concrete brittle fracture, c – for suspended system

where l, h are respectively the span and the depth of section of the structural element.

If compressed concrete fracture (criterion 12) occurs in more than three sections of the beam, then, if thrust bearing is structurally possible, a rigid structure turns into a suspended structure (Figure 2, c). Survivability of such a system for accidental limit state is checked as per condition:

$$N_s < A_s R^d_{s,ser}, \quad (15)$$

where N_s is the force in positive reinforcement of the span l of the continuous beam calculated as for a suspended cable for the design load applied to the continuous beam in the span considering additional dynamic loading in the considered design section. And sections of connection of rigid blocks (disks), the beam span is divided into in case of compressed concrete zone brittle fracture in the most stressed beam sections, are taken as the design ones (Figure 2, c). If condition (15) is not fulfilled, a local fracture of the considered span occurs (element) of the constructive system.

Calculation Example*.* Let us consider the survivability analysis of the reinforced continuous beam which test results are given in [11].

A three-span continuous beam consisted of three prefabricated unstressed reinforced elements of concrete B25, with section of 120x40 mm and length of 1200 mm. Prefabricated element reinforcement involves two-dimensional welded reinforcing mats with main reinforcement of 8 mm diameter, grade A400. Crosswise reinforcement of the prefabricated elements was of wire with diameter 1.5 mm and spacing 60 mm. Assembling of prefabricated elements into a continuous beam was performed as per the inserts, with butt joint grouting between the edges of the prefabricated elements using the same concrete as was used for prefabricated elements.

The structural system was loaded with two concentrated forces P_i (i =1, 2, 3) in each span according to diagram Figure 1b. As an impact beyond design basis a moment tie failure (section fracture) above the first intermediate support 2 was studied.

3. Results and Discussion

The result data of the calculation based on the described algorithm are presented in the diagram “moment- curvature” (Figure 3).

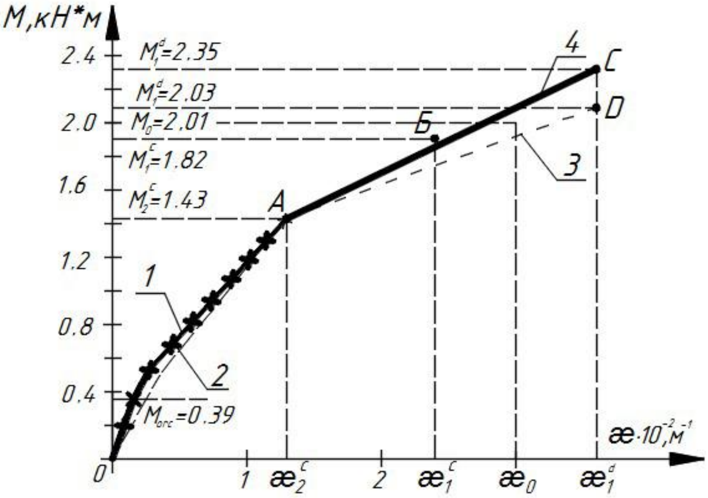

Figure 3. Moment-curvature diagram in the most stressed section of the first span of the beam

Here, curve 1 shows an experiment diagram in the most stressed span section of the first span of the continuous beam when it was loaded with the design load; curve 2 shows the design diagram for static loading of the beam with the set load P_i, up to the impact beyond design basis (point A), and before the bearing capacity exhaustion in the section subject to static deformation of the section after failure of the moment tie (section AB), 3 and 4 are the design and experiment diagrams of the dynamic deformation of the section of the first span after the impact beyond design basis and before the failure of this section due to the working reinforcement fracture (the criterion defined by the formula (11)). In the diagrams “moment-curvature”, parameters $æ_2^c$,$æ_1^c$,$æ_1^d$,M_2^c, M_1^c, M_1^d are the curvatures and moments in the initial redundant to the second degree beam and those in the beam with a failed moment tie above the support 2 in static and dynamic states of the structure. Moment M_{crc} characterized the beginning of cracking in the continuous beam system, moment M_0 corresponded to the design value of the limit beam curvature.

It is pertinent to note that in well-known publications on the problem, determination of dive dynamics in the design of buildings is more often, or through the use of direct methods of structural dynamics, e.g. [19, 20], or the dynamics is taken into account in a simplified way – the introduction of dynamic factor [21, 22]. In the first case, for complex structural systems, the solution is relatively time consuming. In the second case, the result is relatively close. The proposed variant of the quasi-static method for determining the dive dynamics makes it relatively easy to accurately determine the parameter survivability of structures and load dynamics in its structural elements.

The obtained in [11] experiment pattern of the failure of the beam system (Figure 4) after the impact beyond design basis in the form of abrupt failure of the moment tie above the second support of the continuous beam were marked by the fracture of the working reinforcement in the first and third spans and above the second intermediate support, and completely complied with the design value of the survivability parameter and the criterion (11) for accidental limit state.

Figure 4. General view of the secondary structure failure

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4. Conclusion

1. The proposed algorithm for survivability analysis of redundant beam structural systems under accident impact and the accidental limit state criteria for redundant systems make it possible to determine the minimum level of loading of a structural system (survivability parameter λ) at which in a structural system in case of a sudden removal of one of the load-bearing structural elements (a tie) structural changes – failures leading to structural local or progressive collapse begin.

2. Comparison of the calculation data and experimental data of static – dynamic loading of a continuous three-span reinforced concrete beam with a suddenly failed in it moment tie, showed the efficiency of the developed algorithm for quantitative assessment of the survivability parameter of a structural system and suitability of the accepted criteria for accidental limit state under accident impact.

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Vladimir Travush,
+7(495)625-73-16; travush@raasn.ru

Nataliya Fedorova,
+7(960)697-12-30; fenavit@mail.ru

Владимир Ильич Травуш,
+7(495)625-73-16; эл. почта: travush@raasn.ru

Наталия Витальевна Федорова,
+7(960)697-12-30; эл. почта: fenavit@mail.ru