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Modern methods for calculating transport infrastructure objects for progressive collapse

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ABSTRACT Modern Russian methods for calculating transport infrastructure objects for progressive collapse have been analysed and classified. An overview of the methods implemented in the SCAD and LIRA computer systems has been made. The transport infrastructure objects of the frame scheme have been calculated for progressive collapse with the removal of the supporting element. The results of the calculation of the frame scheme, taking into account additional parameters: damping of elements; joint work of the floor and steel structure elements; physical and geometric nonlinearity have been analysed.

Analytical, statistical and mathematical methods were applied.

It has been established that the existing software systems have sufficient functionality for calculating transport infrastructure objects in a static, dynamic, linear and non-linear problem setting. The results of calculations performed in different computer systems show different results in dynamic and quasi-static methods.

The necessity of adjusting the existing Russian building codes, taking into account the calculation procedures in modern computer systems, is revealed.

KEYWORDS: transport; construction; design; progressive collapse; buildings; structures; wireframe; element; initiating occurrence; calculation method; LIRA; computer complex

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Научная статья

Современные методы расчета объектов транспортной инфраструктуры на прогрессирующее обрушение

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АННОТАЦИЯ Проведены анализ и классификация современных российских методов расчета объектов транспортной инфраструктуры (ОТИ) на прогрессирующее обрушение. Осуществлен обзор методов, реализованных в вычислительных комплексах SCAD и ЛИРА. Рассчитаны на прогрессирующее обрушение ОТИ каркасной схемы с удалением несущего элемента. Проанализированы результаты расчета каркасной схемы с учетом дополнительных параметров: демпфирование элементов, совместная работа перекрытия и элементов стальной конструкции, физическая и геометрическая нелинейность.

Применены аналитический, статистический и математический методы.

Установлено, что существующие программные комплексы обладают достаточными функциональными возможностями для расчета ОТИ в статической, динамической, линейной и нелинейной постановке задач. Проведенные результаты расчетов в разных вычислительных комплексах показали различные результаты в динамическом и квазистатическом методах.

Выявлена необходимость корректировки существующих российских строительных норм с учетом расчетных процедур в современных вычислительных комплексах.

КЛЮЧЕВЫЕ СЛОВА: транспорт; строительство; проектирование; прогрессирующее обрушение; здания; сооружения; каркасная схема; элемент; инициирующее воздействие; метод расчета; ЛИРА; вычислительный комплекс

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INTRODUCTION

Modern Russian regulatory documents provide[1, 2, 3, 4, 5, 6] provide no complete information on the calculation methods and no examples of calculations developed in strict compliance with the standards. The documents lack a description of calculation procedures for the dynamics of progressive collapse of transport infrastructure objects, assuming that the designer has the knowledge to perform an analysis that involves a research component. Russian designers are helped by the manuals of the Federal Centre for Norming, Standardization and Conformity Assessment in Construction (FCS) [1, 2], which disclose part of the calculation method. The main problems concerning the existing normative methods is to describe them in generalized words, leaving to the designer their exact interpretation. Scientific studies by Russian [3–9] and foreign [10] authors indicate the relevance of calculations of transport infrastructure objects for progressive collapse and necessity to take into account new, previously unknown or not taken into account factors. This study analyses the regulatory framework for progressive collapse, reviews the computational complexes for progressive collapse calculations and the results of calculations using the selected methods.

RUSSIAN METHODS OF CALCULATING TRANSPORT INFRASTRUCTURE OBJECTS OF FRAME SCHEME FOR PROGRESSIVE COLLAPSE

According to SP 385.1325800.2018 “Protection of Buildings and Structures against Progressive Collapse”[1] and FAE FCS for the design of measures for the protection of buildings and structures against progressive collapse [1, 2], introduced in 2019, two calculation methods are given.

The first method. Calculation in static or dynamic formulation. The essence of the method is to perform the following steps.

1. Form the design scheme of a transport infrastructure object satisfying normal operation (*Fig. 1*, *a*).

2. Remove one of the elements and build a secondary design scheme with the adoption of strength and deformation characteristics in accordance with clause 5.1, loads and impacts in accordance with clause 5.2 [1] (*Fig. 1*, *b*).

3. Calculate the secondary circuit with the removed element. 4.

4. Determine the stress-strain state (SSS) in the elements in the secondary scheme and the criterion test of bearing capacity, as well as stability of the form.

[1] SP 385.1325800.2018. Protection of buildings and structures against progressive collapse. Design rules. Basic provisions (introduced on 06.01.2019). Moscow: TSPP, JSC, 2018. 19 p.

[2] SP 16.13330.2017. Steel structures. Actualized edition of SNiP II-23-81* (with Modifications Nos.1, 2, 3, with Amendment) (introduced on 28.08.2017). Moscow: Standardinform, 2022. 148 p.

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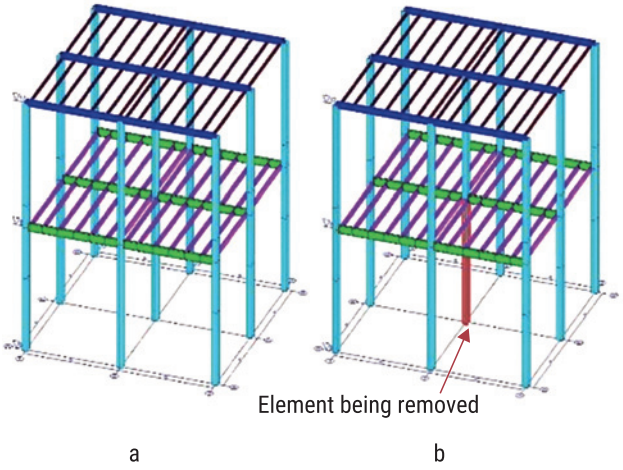

Fig. 1. Transport infrastructure object of the frame scheme:

a — primary calculation scheme; *b* — secondary scheme

5. Modify the primary and secondary design schemes in case of failure to fulfil the criterion check.

The second method. Calculation by the kinematic method of the limit equilibrium theory, the essence thereof is to perform the following steps.

1. Specify the most probable failure mechanisms of transport infrastructure object elements that have lost their support.

2. For each of the selected failure mechanisms determine the ultimate forces that can be absorbed by the cross-sections of all plastically fracturable elements and links Si, including plastic hinges.

3. Find the equidistance G_i of external forces applied to individual links of the mechanism, i.e. to individual non-destructible elements or their parts, and displacements in the direction of their action u_i.

4. Determine the work of internal forces W and external loads U on the possible displacements of the mechanism under consideration.

5. Check the condition of equilibrium $W \geq U$.

6. Change the calculation scheme in case of any failure to fulfil the equilibrium conditions.

7. Check the load-bearing capacity of the load-bearing vertical elements not located above the local failure zone.

REVIEW OF COMPUTATIONAL COMPLEXES FOR CALCULATING TRANSPORT INFRASTRUCTURE OBJECTS FOR PROGRESSIVE COLLAPSE

SCAD++ 21.1.1.1.1 (issued on 24.07.2015) computational complex used in the mode "Progressive collapse" – quasi-static, is based on the paper[1].

In the mode of calculation for progressive collapse of the transport infrastructure object in SCAD++ the instantaneous removal of destroyed elements at the dynamism coefficient equal to 2 is modeled by forces in the nodes with which the removed elements act on the rest of the scheme and applied with the opposite sign, which corresponds to the algorithm of quasi-static calculation at instantaneous removal of an element (Appendix B [1]) (pulldown analysis). If the dynamic coefficient is equal to 1, the forces at the nodes of the removed elements are assumed to be zero, and this corresponds to the gradual removal of elements from the design scheme or is equivalent to the linear static calculation of the system without collapsed elements. Additionally, it is possible to take into account the weight of collapsed structures with a given dynamic coefficient.

The calculation mode automatically takes into account the requirement that the design strength characteristics of materials are equal to their normative values. Also in the program it is possible to realize the *dynamic method* based on the method which is specified in two manuals [1, 2], it consists of three stages:

Stage 1: Obtaining the correct SSS of the structure at the moment of time before the failure of the element. The calculation is performed either in a static formulation or in a dynamic nonlinear formulation with gradual linear loading for a time interval sufficient to level dynamic effects or with increased damping.

Stage 2: Initiation impact. Removal of a structural element in a dynamic nonlinear setting for a time interval equal to 1/10 of the main period of natural oscillations of the removed element, with the appropriate design justification is allowed to adjust these values.

Stage 3: Dynamic calculation of the structure with the removed element in a nonlinear formulation by methods of direct integration of the equations of dynamics in time in explicit or implicit formulations with standard damping parameters.

The calculation of the time of the initiating impact is the key point in the dynamic method and can be performed not only taking into account the requirements [1, 2], but also using the American standards Progressive collapse analysis and design guideline (GSA, 2013) [10] or according to the reference book on dynamic impacts of B.G. Korenev, I.M. Rabinovich from 1972 (p. 95) [3], the impact of choosing one of the calculation methods is shown in the calculation part of this report "Calculation of the Frame Scheme for Progressive Collapse".

The LIRA-SAPR 2020 software package (release date – 16.03.2020) contains the tools "Stages", "Collapse", "Local failure (quasi-statics)", with the help of which the necessary scenario of transport infrastructure object collapse is set. The regulatory documents to be used in the calculation are the same[1, 2, 3, 4, 5, 6] [1, 2].

In the PC the calculation in *quasi-static* formulation is realized as follows:

- a model of a transport infrastructure object is created and design combinations of forces and (or) loads are assigned in accordance with the requirements of regulatory documents;
- to model local failure of elements in the structure the tool "Local failure (quasi-statics)" is used, which allows to assign the dynamics coefficient by selected degrees of freedom to the elements selected by the user as dismantled;
- at the stage of dismantling the structure, to select the dismantled elements to which the dynamic coefficient has been assigned.

The method of calculating the transport infrastructure object in the dynamic formulation provides for taking into account the significant effects of physical, geometric and structural nonlinearities in the destruction/collapse of individual parts of the structure and includes the steps described in the Methodological Manual of FAE FCS on pages 22–25.

In LIRA PC there is a possibility to assign to the elements of the scheme "Time of Failure from Operation" *dT* for modelling of local failure in dynamic formulation. Such assignment can be made either to a single element (e.g. a column) or to a group of elements (e.g. a wall). This will automatically generate impulse loads set in the direction opposite to the reactions of the removed elements. No impulse loads will be applied to the nodes that remained "idle" after the elements were removed (only the removed elements were adjacent to them). It is sufficient to specify only the elements. It is not necessary to specify the nodes, which makes the task less labour-intensive. The program sets the other parameters by itself and performs the calculation: assigns impulse loads (for all degrees of freedom, including rotational ones) and calculates the reactions of the removed elements. In the "Dynamics in Time" menu of the program it is necessary to set the following parameters:

- integration time (probably many times longer than the failure time, so that the system behaviour and oscillation damping can be evaluated in time);
- integration step (to obtain a point with values strictly at the boundary of the momentum growth cessation, and smaller by several times than the failure time);
- number of loading with mass weights (more convenient immediately after the last stage of assembly);
- number of load with damping characteristics;
- number of loading with dynamic loads — any free loading.

In both computational complexes it is possible to perform calculations in the formulation of the problem of local failure by quasi-static and dynamic methods in linear and nonlinear formulation (taking into account geometric, physical, genetic nonlinearity in the process of assembly and disassembly).

MATHEMATICAL EXPERIMENT: CALCULATION OF THE FRAME SCHEME OF THE TRANSPORT INFRASTRUCTURE OBJECT WITH REGARD TO PROGRESSIVE COLLAPSE

Initial data for calculation (*Fig. 2*): a transport infrastructure object of KS-2 structure category; dimensions in plan along the external axes 12 × 12 m, floor height 8 m; column grid 6 × 6 m; number of ground floors — 2; construction area of the city of Saint Petersburg; terrain type A; wind region 2: w_0 = 0,3 kPa; snow region 3: S_g = 1.5 kPa; height of monolithic slab — 90 mm; main beams BG1, BG2 and auxiliary beams BV1, BV2 made of steel C255, I-beam cross-sections on static calculation — 50B2, 40B1 and 30P, 22P respectively (BG1 and BV1 — main and auxiliary beams on the second floor, BG2 and BV2 — on the roof); columns K1 made of steel C255, section according to static calculation — I-beam 35K3 8.5 m long.

1. Quasi-static calculation method (mode "Progressive Collapse").

The results of calculation by the quasi-static method with the collapse of the central column were carried out taking into account the dynamic coefficient 2, according to SP 365 — some elements do not pass the test (*Fig. 3*).

2. Dynamic calculation method.

We choose a method for estimating the time of the initiating action.

Method 1. According to the manual FAU FCS to calculate the time of the initiating effect as 1/10 of the main period of natural oscillations of the removed element is considered scheme, in which the removed element as part of the overall scheme to obtain dynamic

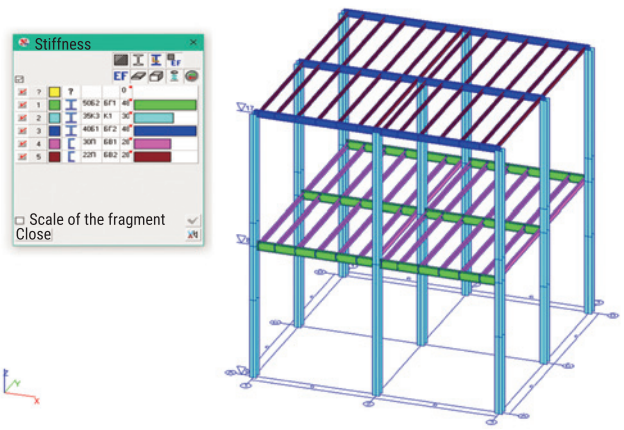

Fig. 2. Primary scheme of the metal frame of the transportation infrastructure object

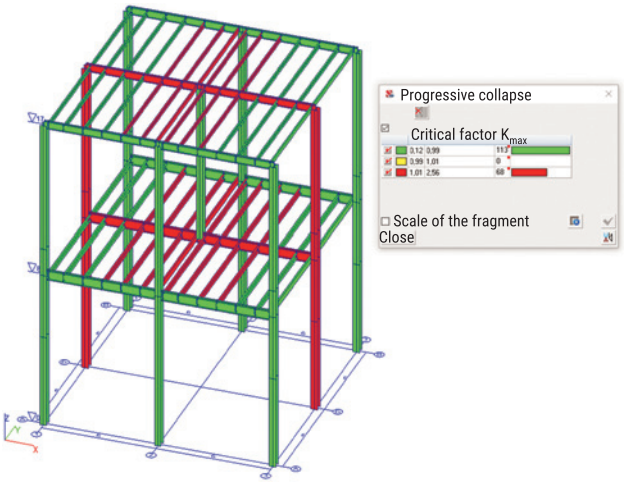

Fig. 3. Results of calculation of the transport infrastructure object by quasi-static method with collapse of the central column (secondary scheme of metal frame). Critical factor K_{max}

degrees of freedom along the length of the element is broken down in sufficient detail (detail breakdown can be recommended order 6 elements) and performed modal analysis. The results of the modal analysis are the period of oscillation of the element (the central column of the first floor T = 0.0461 s and T = 0.0325 s, the time of the initiating influence is equal t_{otk} = 0.0461 s and t_{otk} = 0.0325 s, respectively.

Method 2. According to the recommendation of American standards Progressive collapse analysis and design guideline (GSA, 2013) $t_{otk} \le 0.1T$, where T is the period of oscillation of the structure without the retired element on the form of oscillations resembling static deformation of the system. Results of modal analysis — T = 0.40588 s, time of initiating action — $t_{otk} = 0.1T$ = 0.0406 s.

Method 3. According to the reference book on dynamic impacts by Korenev and Rabinovich of 1972 (p. 95), by analogy with the calculation of impact, if it is impossible to estimate the time of impact by calculation or experience, but there is confidence that it is small enough, it is possible to take t_{otk} = 0.001 s as a reserve of strength and rigidity of the structure.

The results of calculations by different methods showed the discrepancy between the values obtained for the displacement of the node and the maximum value (*Table*).

Based on the calculations obtained, the following conclusions can be drawn:

1. At calculation by the direct dynamic method the displacement values turned out to be 1.05 times greater (by 5 %) than by the quasi-static method.

2. At calculation by direct dynamic method the values of critical factor were 3,52 times more (by 252 %), than by quasi-static method.

3. All three methods of dynamic calculation of transport infrastructure object show close results. The highest values were found in method 1, where the oscillation period of the retired element was determined to find the time of element failure.

4. The results of calculation at different failure times of 0.2 and 0.001 s show that the response of the system and, accordingly, the SSS factors depend significantly on the loading rate, and when the failure time d_T is set in the range from 0 to 0.1T (the period in the scheme without a column), the change in the SSS factors is not so significant.

5. After the collapse of the central column of the transport infrastructure object the whole structure collapses, the system becomes geometrically variable – the object is completely destroyed.

6. The damping of elements, which should be taken 0.2, was not taken into account in the calculations. The used versions of the programs do not allow to set the damping coefficient in the stiffness parameters of the elements.

7. The calculations did not take into account the joint work of the reinforced concrete slab, most likely the values of displacements and the critical factor would have been less, there fore, the number of subsequently retired elements would have been less.

On the basis of the obtained results it is possible to state the necessity to improve software products for carrying out calculations of transport infrastructure objects taking into account the joint work of reinforced concrete slab and steel structure elements.

Table

Summary table of calculation results

Parameter	Dynamic method				Quasi-static method
	Method 1		Metod 2 t_{otk} = 0.0406 s	Method 3 t_{otk} = 0.001 s	
	t_{otk} = 0.00461 s	t_{otk} = 0.00325 s			
Displacement of the unit on Z	–135.04	–135.02	–133.29	–134.95	–128.43
K_{ma}	9	9	8.89	9	2.56
Number of elements with K_{max}: 0–0.99	113	113	113	113	113
Above 0.99	68	68	68	68	68

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