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Progressive collapse of buildings. International experience and Ukraine application

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***ABSTRACT**: The article discusses regulatory requirements contained in international codes, in regulatory documents of Ukraine and the CIS countries when designing multi-story buildings and structures for progressive collapse. Definitions of the term "progressive collapse" are considered and historical examples of collapsed buildings due to external factors (explosions, earthquakes, fires, etc.), as well as material degradation processes and design errors are given. The types of progressive collapse and general requirements that must be considered when designing are analyzed. Particular attention is paid to the selection of the initial (local) design failure.Examples of local failure according to the codes of the UK, Canada, USA, Russia and Ukraine are given. The design strategy includes redundancy issues, creation of plastic joints, tie interactions, and methods for progressive collapse analysis.*
For analysis the LIRA-CAD software [19] is used, developed in Ukraine, thathas an international certificate and is widely used for various building structures and multi-story buildings analysis.

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I. INTRODUCTION

Among the terms that reveal the process of progressive collapse of buildings, there are similar definitions that are contained in various documents and codes of different countries. The definition is most briefly expressed in the NISTIR 7396 Manual: "Progressive collapse - the propagation of local failure from the initial event, from element to element, which leads to the failure of the entire structure or a disproportionately large part of it; known as disproportionate collapse" [6]. Similar in meaning definitions are contained in other documents of the USA, Great Britain, Russia, Ukraine, [1, 17, 15, 10, 11, 3].

For the first time, the term "progressive collapse" was formulated in 1968 after the crash of the 22-story Ronan Point large-panel residential building in England. The accident was caused by an explosion of domestic gas, which occurred on the 18th floor, and destroyed the outer panel of the building. The upstream structures, having lost support, damaged the lower floors and led to the general collapse of the entire corner of the building. The incident with the Ronan Point building (1968) led to the creation of the UK building regulations (BSI, 1997, 2000), aimed at improving safety, and to changes in the American and Canadian codes (ASCE, 2002; NBCC, 1995).

The recommendations of these documents were preventive in nature and were aimed at observing the principles to ensure the safety of buildings during design. In Ukraine, later Eurocode instructions and requirements of Ukrainian documents apply:

EN 1990:2002, 2.1 (4)P [4]; Eurocode 1. Part 1-7: General Impacts. Special Impacts, 5.3 (1)P [5]; DSTU-N B EN 1990:2008, 2.1 (4)P [14] and DBN B.1.2-14: 2018, Appendix B, which discusses accident scenarios and loss risk assessment [13].

In this article, with reference to international experience, Ukrainian and Russian design standards, recommendations are given regarding the choice of local structural failure and an example of multi-story frame building analysis for progressive collapse is considered

II. PROBLEM DESCRIPTION

The second and third wave of research occurred after the disproportionate collapse of the Alfred P. Murrah Federal Building (Oklahoma City, 1995) and the complete collapse of the World Trade Center Towers (New York, September 11, 2001), which were caused by terrorist attacks (Fig.1 a, b).

During the collapse of the WTC buildings as a result of the terrorist attack, 2752 people died - 200 of them were thrown out of the windows. From the rubble, 20 people were recovered alive.

a

b

Figure 1 - Buildings that were a subject to terrorist attack: a -Murrah Federal Building (Oklahoma City, 1995); b - World Trade Center (WTC, New York, 2011).

III. ANALYSIS REQUIREMENTS

The main requirement for the design of the structure is that "during the construction process and during the design life, it withstands the accidentalactions and maintains the required operational properties" Its load-bearing capacity is related to the design working lifeof the structures defined by EN 1990 [14].

Table 1 –Indicative design working life of buildings and structures (EN 1990)

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures[1)]
2	10 – 15	Replaceable structural parts, e.g. gantry girders,bearings
3	15 – 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental building structures, bridges, andother civil engineering structures
[1)]Structures or parts of structures that can be dismantled with a view to being re-used shouldnot be considered as temporary		

The building's resistance to progressive collapse is verified by calculating a special load and impacts (accidental loads)combinations, as well as an impact of hypothetical local failure of load-bearing structures. When designing structures, the following design situations should be considered [10]:
- established, having a duration close to the design working lifeof the structure;
- transitional, having a short duration compared to the design working lifeof astructure (for example, reconstruction of a structure);
- accidental, corresponding to the exceptional working conditions of the structure, which can lead to significant environmental and economic losses.

As a local (hypothetical) collapse, collapse (removal) of vertical structures of one (any) floor of the house, limited around an area of up to 80 m^2 (or a diameter of 10 m), should be considered:
- collapse (removal) of two walls intersecting in areas from the place of their intersection (for example, from the corner of the house) to the nearest opening in each wall or to the next vertical section with a wall in a different direction;
- collapse (removal) of an individual column (pylon) or column (pylon) with adjacent wall sections located on same floor in the area of local collapse;
- collapse of the overlappart on the same floor in the area of local collapse.

The cross-sectional area of all withdrawn vertical elements located on a plot of 80 m^2 should not exceed 0.9 m^2 for reinforced concrete elements, 0.7 m^2 for fiber-reinforced concrete, and 15% for rigid reinforcement;
- collapse of the ceiling of the specified area.

The analysis is required for buildings of consequence class CC-3 and CC-2 with a mass presence of people for most public and residential buildings. The initial failure of one or more vertical load-bearing structural elements leads to an increase in the load on the remaining elements due to the redistribution of forces. The concentration of forces in the supporting elements, which are similar in type and function to adjacent elements. Overloading the remaining, most loaded elements leads to the failure of structures located in the transverse direction. The need of taking into considerationaccidental loads and progressive collapse in the

design of structures should be regulated by building codes and standards. Examples of such European, American, Russian and Ukrainian standards and codes for the design of buildings from progressive collapse are:
- ASCE 7-02. “Minimum design loads for buildings and other structures” [1];
- EN 1990: 2002 Eurocode "Basis of structural design. European standard" [4];
- Eurocode EN 1991-1-7. Part 1-7: General actions - Accidental actions”[5];
- GSA. US leadership. "Progressive collapse analysis and design guidelines", 2003 [3];
- NISTIR 7396. "Best practices to reduce the potentialfor progressive collapse in buildings" (USA, 2007) [6];
- UFC 4-023-03. “Design ofbuildings to resist progressive collapse” (USA, 2009) [9];
- STO-008-02495342-2009. “Prevention of the progressive collapse of reinforced concrete monolithic building structures. Design and analysis”(Russia) [17];
- A guide for the design of residential buildings. Vol. 3.“Constructions of residential buildings (to SNiP 2.08.01-85).” (Russia) [18];
- DSTU-N B EN 1990: 2008 "Eurocode. Basics of the design of structures”(Ukraine) [14];
- DBN V.1.2 - 14: 2018. “General principles for ensuring the reliability and structural safety of buildings and structures” (Ukraine) [13];
- GOST 27751-2014. “Reliability of building structures and foundations” (Russia) [10].

Selection of initial (local) structural failure

The choice of the initial failure is an important design element, which can cause a chain reaction and a general collapse of the structure. Various requirements have been developed to determine the initial failure in the horizontal and vertical directions. Table 2 provides a brief description of some of these criteria according to UK, Canada, and US standards.
Examples of the initial failureselection according to the codes of Russia and Ukraine are shown in Table 3.

Table 2 - Definitions of local collapse according to the codes of Great Britain, Canada and the USA

BS 5950-1:2000 (GB)	**NBCC 1977 Canada**	**NYC 1998, 2003 (USA)**	**DOD UFC 4-023-03 2005 (USA)**	**GSA 2003 (USA)**
Local collapse in horizontal direction				
Less than 15% of the total floor or roof area with an area of 100 m^2 (1000 ft^2)	Truss, beam, narrow tape or floor panel from initial failure plus, the same on both sides; one span; two slabs per span	Less than 20% of the total floor or roof area with an area of 100 m^2(1000 ft^2)	**Outside:** The floor above is collapsed; the destroyed element should be less than 70 m^2 (750 sq. ft.) or 15% of the total floor area; **Inside:** Less than 140 m^2 (1,500 ft^2) or 30% of the total area. Collapse should not go beyond the boundaries of the structure to the destroyed external element or adjacent to the removed (internal) element.	- use of static indeterminacy of elements; - use of shear structures; - designing a floor of free length, columns around the perimeter of an object, between the first and third floors and columns in public areas or uncontrolled parking spaces.
Local collapse in vertical direction				
Initial collapse rate plus one adjacentlevel,orhigher or lower.	Initial collapse rate plus one adjacent level or higher or lower.	less than or equal to 3 floors	The floor directly under the destroyed element should notcollapse.	1800 sq. ft (170 m^2) above the removed outer column or 3600 ft^2 (330 m^2) per floor above the removed inner column.

To reduce the probability of progressive collapse, it is recommended:
- calculated values of concrete resistance to axial compression, equal to their standard values, are multiplied by the working conditions factorγ_{b3} = 0.9;
- concrete axial tensile strengths are taken equal to their normative values divided by the reliability factor for concrete γ_C = 1.15;
- values of thecompression resistance of reinforcement are taken equal to the standard values of the tensile strength, with the exception of the reinforcement class A500, for which R_S = 469 MPa (4700 kg / cm^2), and reinforcement class B500, with R_S = 430 MPa (4400 kg / cm^2);
- values of tensile strength of the transverse reinforcement equal to standard values are multiplied by the working conditions factor γ_{S1} = 0.8;
The values of the elastic modulus for reinforcing E_S and the initial elastic modulus for concrete E_b are taken in accordance with SP 52-101-2003 [22] and DBN B.2.6-98: 2009 [12].
Hypothetical effects on the supporting structures of a building in Recommendations [20] take into account aslocal effects:

Karst funnel with a diameter of 6 m, located anywhere under the foundation of the building (for karst-hazardous areas); damage to floors with a total area of up to 40 m^2; uneven precipitation of the base; horizontal load on vertical load-bearing elements equal to 3.5 t for rod and 1 t for lamellar on 1 m^2 of the surface of an element under consideration within one floor (load reliability factor is equal to one).

Frame buildingsstabilityanalysis againstprogressive collapse, with the aboveground part of which is designed with taking into account the seismic impact of 6-7 points (regardless of the category of base soils), can beneglected.

GOST 27751-2014 [10] "reliability of building structures and foundations" proceeds from the provisions that "under special influences, the reliability of building structures should be additionally ensured by one or more special measures, including:

- **the choice of materials and structural solutions** that, in the event of an accidental failure or localfailure to individual load-bearing structural elements, **do not lead to progressive collapse of the structure**;
- preventing or reducing the possibility of the implementation of such effects on the supporting structure;
- usingthe set of special organizational measures to ensure the restriction and control of access by unauthorized personal to the main load-bearing structures of the building.

Recommendations for reducing the risk of progressive collapse

To reduce the risk of collapse in the event of loss of structural elements, in the regulatory documents and design codes of various countries there are various proven methods that should be considered when designing. They are implemented to increase the reliability of structures and limit the spread of failure as a result of the initial event. These include.

Redundancy: the inclusion of redundant schemes for the formation of a system of vertical ties, which provide alternative ways of distributing forces in the structure in case of local failure of primary elements.

Types of ties: loss of the main structural element usually leads to a redistribution of loads and deviations from the equilibrium of the elements. These processes require the transfer of loads throughout the structure (vertically and horizontally) types of ties that are commonly used to ensure the structural integrity of a building are presented in [6].

Plastic deformations: for reinforced concrete and reinforced stone structures, plasticity is achieved through reinforcement, ensuring the continuity of reinforcement by using welds or mechanical constraints that provide overall stability, as well as by creating joints between elements that increase the strength and impact resistance of structures.

Shear strength. The shear bearing capacity must always exceed the bending bearing capacity in order to ensure the plastic work of the structure. Floor should be able to provide resistance to failure in the presence of shear loads and damage at the locations of the columns.

Rotational Resistance: Columns, beams, ceilings and a side load resistance system must be designed to withstand the action of the load in a vulnerable direction.

The procedure of progressive collapse analysis

As can be seen from Tables 2 and 3, the recommendations of regulatory documents on the protection of buildings from progressive collapse are of the same nature. For buildings of various structural systems, the main recommendations are as follows.

1. Preventive protective measures are aimed at preventing progressive collapse. This is due to the fact that:
- it is impossible to completely eliminate local failure to the supporting structures of buildings, since progressive collapse leads to serious consequences;
- with small local failure of structures, the measures that are taken to ensure stability against progressive collapse can prevent severe consequences and protect the building with relatively simple and not expensive technical means.

2. The basic principle of preventing progressive collapse is to increase the continuity of the structural system of the building by applying joints and ties between structural elements.

3. The effectiveness of structural protection depends on the development of plastic deformations in structural elements and their relationships. For ductility of ties, it is required to ensure the strength of anchoring of ties in prefabricated elements, when the anchor tie provides larger bearing capacity than the element itself, or the occurrence of forces causing yielding.

4. When considering protection measures against progressive collapse in comparison with anti-seismic measures, a similarity between them is noticeable [25, 26]. There are examples of earthquake-resistant buildings, the local failure of which did not lead to progressive collapse due to the corresponding seismic protection.

The most vulnerable to local failure are frame buildings, in which the supporting elements are columns. For large-panel buildings, separate wall panels serve as supporting elements, the failure of which should not lead to a complete collapse of the building.

The general approach using the methods of probability theory of failure can be illustrated as follows. If we accept the probability of a progressive collapse due to event E in the form of P (C), then we can write:

$$P(C) = P(C|LE)\,P(L|E)\,P(E) \quad (1)$$

where

P (E) = probability of occurrence of event E;

P (L|E) = probability of local failure L, provided that event E has occurred;

Table 3 - Appointment of the initial (local) failure according to the codes of Russia and Ukraine

CTO-008-02495342-2009, Russia [17]	**MDS 20-2.2008, FGUP Russia [15]**	**Recommendations for the protection of monolithic residential buildings Russia 2005 [20]**	**Recommendations for the protection of tall buildings. Russia 2006 [21].**	**DBN B.2.2-24:2009 Ukraine [11]**
Failure should be considered within the same floor of a building alternately of one column (pylon) or a section of walls.	**Direct method** **Option 1:** The system should not lose bearing capacity when removing items. **Option 2:** Mandatory standardization of the accidentalactionintensity is required.	Consider the failure (removal) of vertical structures of one (any) floor of a building: - two intersecting walls in areas from the place of their intersection (from the corner of the building) to the nearest opening in each wall with a wall of a different direction (for a length of not more than 7 m); - a separate column (pylon) or with sections of adjacent walls.	Consider removing vertical structures: - one (any) floor, limited by a circle area of 80 m^2 (diameter 10 m) for buildings up to 200 m high and up to 100 m^2 (diameter 11.5 m) for buildings above 200 m: - two intersecting walls (from the corner of the buildingin particular) to the nearest opening in each wall; - columns (pylons) and with adjacent wall sections not exceeding the size of the failure; - overlap on the specified area.	Consider removing vertical structures of one (any) floor, limited to an area of up to 80 m^2 (diameter 10 m): - collapse of two walls, at the areas of their intersection (for example, from the corner of the house) or with a wall of another direction; - removal of a separate column (pylon) or with adjacent wall sections located on the same floor in the area of local collapse; - collapse of the overlapping area of one floor.

Create a system over the destroyed element that can transfer loads to adjacent vertical structures by: - monolithic tie with other structures; - the creation of monolithic belts around the perimeter of the floors; - reinforced concrete walls or beams on the roof that combine the structures with each other.	**Indirect Method:** **Option 1:** Using preventive measures. **Option 2:** Increasing the static indeterminacy of the system by including additional ties, taking into account spatial behavior.	The most dangerous failure schemes should be considered, the possibility of progressive collapse of the structures of typical, technical and underground floors, as well as the attic should be considered.	To assess the stability of the building against progressive collapse, it is allowed to consider only the most dangerous design schemes of collapse.	In all cases, the cross-section of all removed vertical elements located on an area of 80 m^2 should not exceed 0.9 m^2 for reinforced concrete elements, 0.7 m^2 for fiber-reinforced concrete and 15% for rigid reinforcement.

P (C|LE) = probability of collapse taking into account the fact that the occurrence of event L provided that it is caused by event E. The factor P (C|LE) is not presented in existing regulatory documents and the probability of progressive collapse is not considered in such a formulation.

Events E for which P (E) is very small are usually not taken into account in design. However, in the case of an unreliable structure, this simplification becomes unacceptable. The collapse probability should be represented as the logical sum of the failure probabilities of all the constituent elements of the E type, which can lead to a global collapse, the probability of which in this case is quite high.

Loads and their combinations in the progressive collapse analysis

For progressive collapse analysis in Ukraine, certified LIRA and SCAD software systems are used. In other countries, proven software systems are used, on the basis of which three-dimensional finite element models are formed. In the analysis model, it is necessary to take into consideration nonlinear behavior of materialsand the dynamic effect of the initial event.

Load combination. According to UFC-09 [9], for progressive collapse analysis, the following load combinations must be taken into account:

To analyze the floor, which is affected by the local element, the load is considered

$$W_F = 1.2D + 0.5L\,, \tag{2}$$

where W_F = floor load (kN / m^2); D = dead load (kN / m^2); L = live load (kN / m^2).

Consideration for non-uniform load over floor area.

Concentrated loads.

If the concentrated load is in the span or one part of the span is loaded with a load different from the rest of the span, in this case, UFC 4-023 recommends that the load be evenly distributed over the span, as indicated in equation (2).

Load variation.

The amount of load can vary significantly depending over the floor area of particular structure. For example, the production load may be located in one part of the floor and office space in another. In this case, the load is calculated separately for each compartment.

For frame buildings with internal beams or girders, internal ties can cross over load-bearing elements. The internal ties that fall into these areas should be placed on either side of the beam. The required tie strength F_I (kN / m) in the longitudinal or transverse direction is determined from the equation:

$$F_I = 3W_F L_1, \tag{3}$$

where W_F = floor load, determined from (11.2) in (kN / m^2); L_1 = greater of the distances between the centers of columns, frames or walls, in the considered direction in (m).
For a frame with a column pitch in the transverse and with a variable pitch in the longitudinal direction, the definition L_1 is given in [9].

For structures with load-bearing external walls and a different ties arrangement, the definition L_1 is considered in Recommendations [9].
It is recommended to remove the external load-bearing walls in the middle of the short side, and at the intersection with the long side in the corner of the building, as shown in Figure 2. If any load-bearing element, such as a column, is at 30% of the floor height H, it should also to be removed.

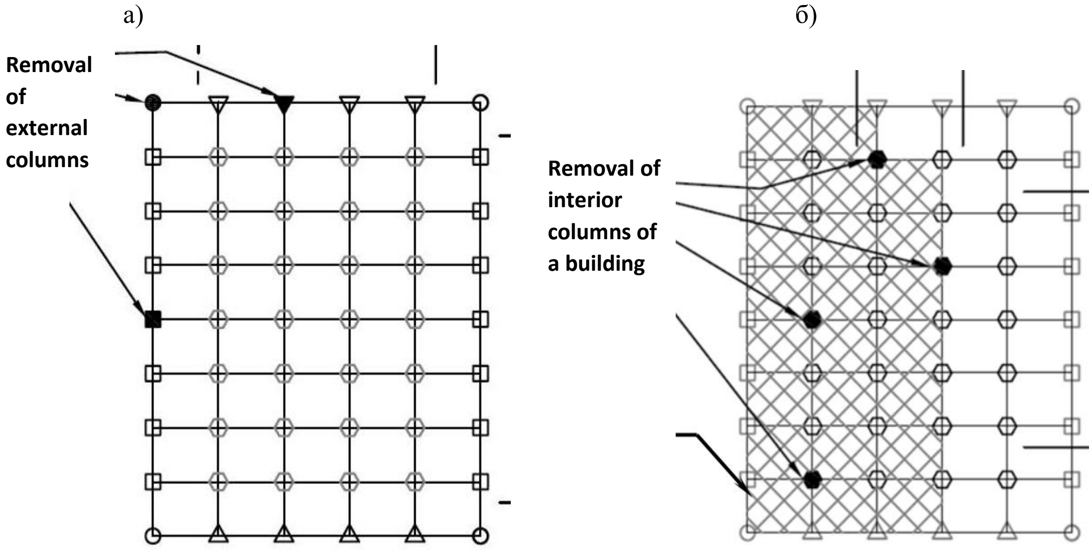

Figure 2 - Local location of the removed columns: a - on the external contour of the building; b - inside the building [9]

Use of damping devices in sections of a building
Another possibility of limiting collapse is to divide the building by structural decomposition. This technique is suitable for horizontal structures.

Horizontal decomposition. Horizontal decomposition of the global system is associated with limiting the transfer of load through hinges and is less suitable for protecting tall buildings. Horizontal decomposition with expansion joints helped to limit damage to the Pentagon building on September 11, 2001.

Vertical decomposition. The height of one segment is considered a certain part of the building, for example, one tenth of the height. Each segment includes the entire floor and is limited to two horizontal boundaries. The boundaries of the segment must be strong and sufficiently rigid. They represent reinforced concrete or prestressed slabs of considerable thickness (about 0.40 m). However, the magnitude of the impact is difficult to establish. These problems are overcome by introducing cushioning zones within the segment (Fig. 3). Shock absorbing devices should be placed around the column or close to the walls (Fig. 3 b). They can consist of steel pipes of a telescoping type of large diameter filled with a material that allows you to absorb compression strains.

In [8], a protection method against disproportionate collapse is proposed:
- creating cushioning zones along the height of the building;
- the use of reinforced floors within vertical segmentation;
- attempt to limit local failure by isolating the collapsing sections and the use of horizontal segmentation, which is effective for buildings of small height.

Design example. The consequence class of structure CC3 is considered in accordance to DSTU-N B B.1.2-16 [16]. The residential building has a basement and 26 residential floors with dimensions of 76.68x28.74 m in plan. The cross-section of the building is shown in Figure 5. The structural scheme of residential building is monolithic frame-link scheme with diaphragms and stiffness cores (staircase and elevator blocks) that accept horizontal and vertical loads. Vertical frame elements (pylons, walls and stiffness diaphragms) with a thickness of 250 and 300 mm are made of concrete class C25/30 and reinforcement class A500C and A240C. Floor slabs with a thickness of 200 and 250 mm made of concrete class C25/30, reinforced with reinforcement A500C and A240C.

The calculation of resistance to progressive collapse is performed by the alternative path method, based on the assumption of static load distribution after the collapse of the local structure [9]. In this case, only dangerous design schemes for local failure are considered. The influence of local structural failure is taken into account by removing structural elements. Load-bearing structures are removed from the structural system to verify the condition that such system is able to maintain stability after removal of the elements [9]. The calculations were performed to remove such load-bearing structures:
- an external column (wall), which is located on the floor plan in the center of the long, short side and/or in the corner of the building;
- an internal column (wall), which is located in an underground parking or other inaccessible room on the ground floor of the building.

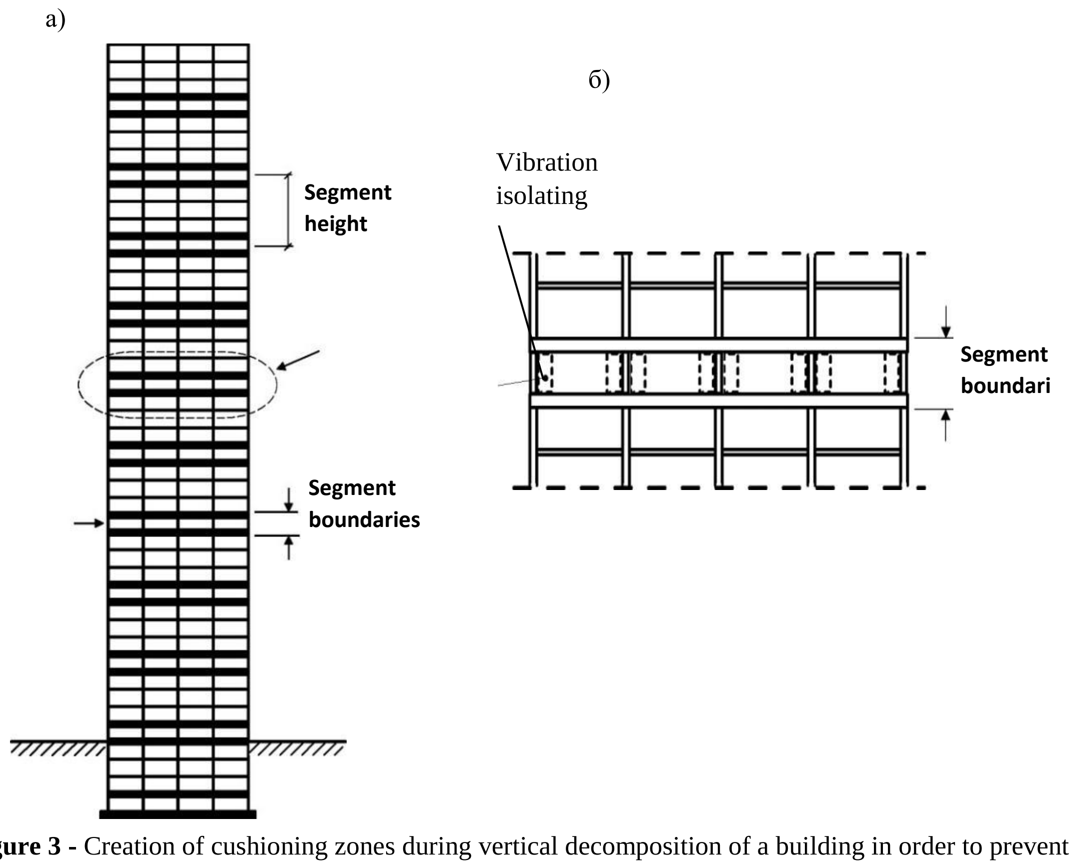

Figure 3 - Creation of cushioning zones during vertical decomposition of a building in order to prevent collapse:a - section of the building; b - insulating segment [7, 8].

Limitations on tie strength.

For models that include joints between horizontal bending elements (beams, plates, girders, etc.) and vertical supporting elements (columns and walls), the strength of the tie should not be greater than the strength of the horizontal element associated with it.

The following gravitational loads combination is used for calculation:
- increased gravitational loads for the area of overlap over the removed column or wall;
- a combination of increased dead weight is applied to the floors located next to the removed element on all floors above the removed element, as shown in Figure 4.

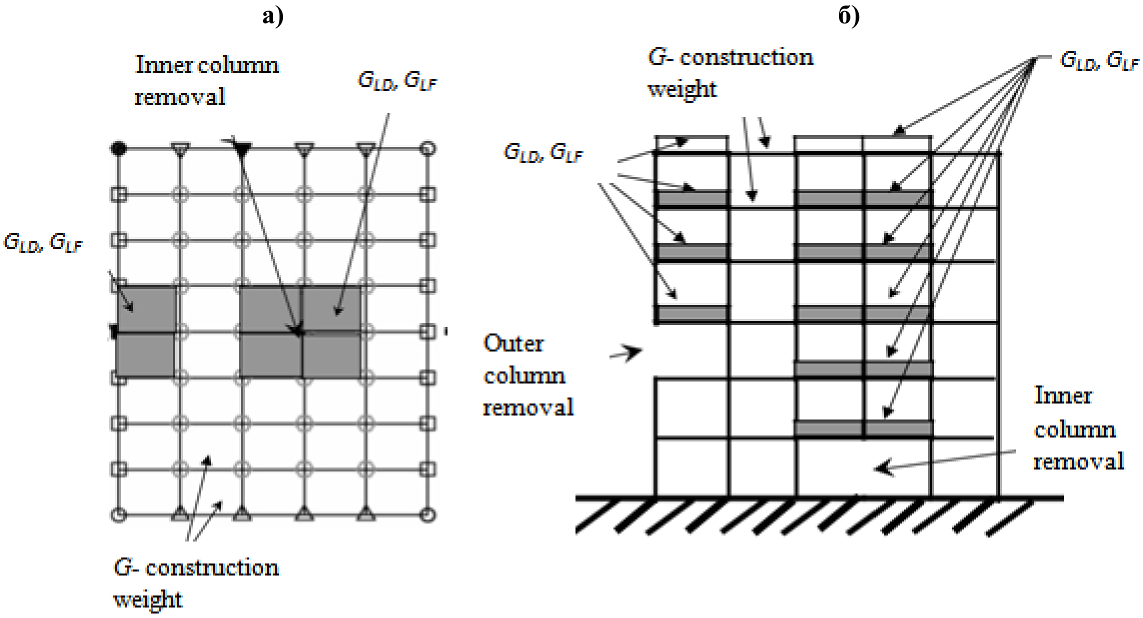

Figure 4 - Recommended loads when removing the inner and outer columns: a - plan; b –cross-section; G is the gravity loads; G_{LD} - increased gravity loads for deformation effects in linear static analysis; G_{LF} - increased gravity loads for force actions in linear static analysis.

Modeling the accidental action on one of the supporting structures of the building made it possible to evaluate the behavior of the building due to the accidental impact [23].

The calculated spatial finite element model of the building was developed in the LIRA-SAPR 2017 R4 software complex [19]. Frame pylons and floor slabs were approximated by rectangular finite elements. The total number of nodes of the calculation model was 78823, elements - 98460.

The characteristics of the model were adopted as follows: floor slabs - plates H = 200 and 250 mm, pylons - plates H = 250 and 300 mm, initial modulus of elasticity of concrete E = 30000 MPa, Poisson's ratio ν = 0.2, density R_0 = 2 5 t / m^3. Concrete class C25/30 and reinforcement class A500C.

Nonlinear calculation of the building in case of local failure of supporting structures was performed according to the limiting states of the first group [20, 21, 18]. The criterion for the onset of the ultimate state of reinforced concrete structures was one of the following conditions [12]:

- loss of balance between internal and external forces in the cross section (maximum on the "moment-curvature" graph);
- destruction of concrete in the compressed zone of the section or rupture of the tensile reinforcement due to their ultimate deformations.

The movement of the structures and the width of the crack opening were not limited. The arrangement of vertical elements is shown in Figure 6. The parameters of the stress-strain state of the building structures after local failure of the pylon located in the middle of the long side of the basement floor, presented in the form of internal forces in the elements and movements in the structural nodes, are shown in Figures 3 and 4.

Figure 5 - Cross section of a building

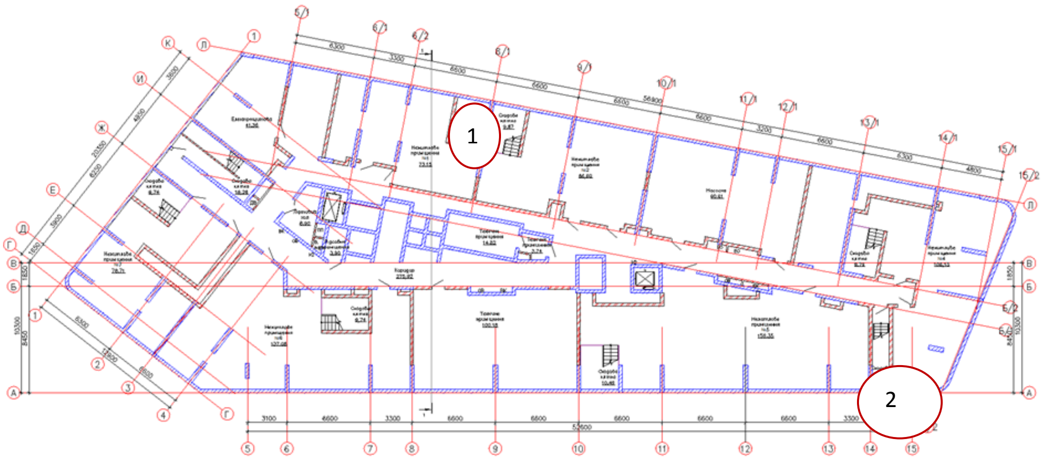

Figure 6– Arrangement of vertical load-bearing elements in the basement of the building at elev. -3.00
1, 2 - places of a possible local failure of pylons

a)

b)

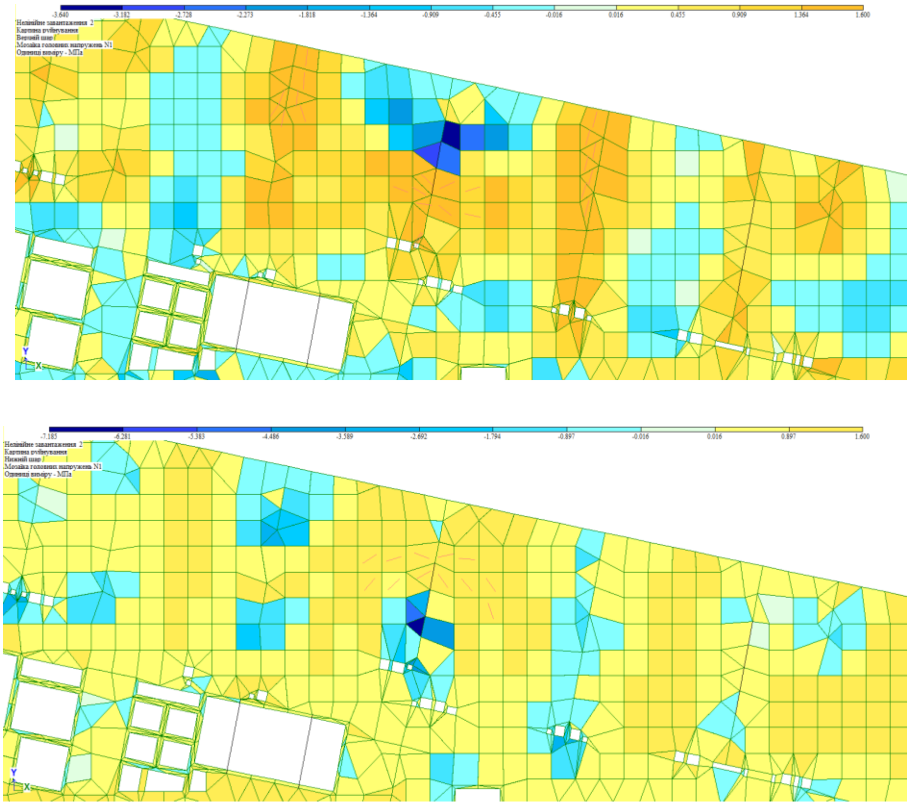

Figure 7 - Patterns of cracking in the slab above the basement after removal of the pylon: a) on the upper edge of the plate; b) on the bottom of the plate

IV. CONCLUSIONS

1. An article is of a reviewing nature, which addresses the issues of progressive collapse, and gives comparative requirements for ensuring safety in the case of a hypothetical collapse of structures. Examples of the collapse of buildings are considered, starting with the accident of the 22-story Ronan Point large-panel residential building in England in 1968. The incident in England led to building regulations aimed at improving security and to changes in the US and Canadian codes. In Ukraine, Eurocode instructions and requirements of Ukrainian documents apply: EN 1990; DSTU-N B EN 1990 and DBN. Particular attention is paid to the failureduring the explosions and terrorist attacks.

2. The definitions of local failure according to the codes of Great Britain, Canada, USA, Russia and Ukraine are considered. Recommendations for calculating progressive collapse in different countries have similar requirements. To reduce the risk of collapse during the design process, the following should be provided: the use of additional ties; the possibility of the formation of plastic elements; the use of shear structures, as well as their ability to withstand bends.

3. An example of designing a multi-story building is given. According to the calculation results of a multi-story residential building with monolithic reinforced concrete frame, changes in the stress-strain state of the building structures due to the removal of the frame pylons were recorded:

- when the pylon is removed in the basement of the building, the values of the displacement of the floor over localfailure increase by 1.5-2.0 times in comparison with the values of the displacement of the nodes of the floor under normal conditions;
- bending moments in the elements of the floor are redistributed from the span of the floor to its supports, and the values of bending moments on the supports increase compared to the values of bending moments on the supports under normal conditions;
- longitude forces in the frame elements are redistributed from the removed pylon to adjacent frame elements of the same floor and to elements located above the local failure site; cracks in concrete appear on the floor sites and plastic joints form along the upper face of the floor slabs.

4. In general, the stability of a multi-story reinforced concrete building against the progressive collapse of the entire structural system for the considered schemes is ensured. Local failure of building structures (pylons, floor slabs) did not cause chain failure of structures and the building as a whole. The onset of geometric variability of building structural system was not recorded.

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