Structural safety and progressive destruction of operating buildings

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Abstract. The structural safety connection of structures with possible causes of the progressive building destruction is shown. The issues of protecting buildings and structures from progressive destruction are considered.

1. Introduction

One of the main tasks in ensuring the safety of operated buildings and structures is to assess the structural safety of building structures and structural systems that are susceptible to damage. The long term of operation of buildings and structures with the simultaneous manifestation of power and environmental influences leads to the appearance and development of various damage to building structures and junctions. This factor reduces the safety of the structure and is the cause of progressive failure in some cases. At present, experimental and theoretical studies have been carried out aimed at studying the effect of power and environmental damage on the strength and deformation parameters of individual structures and structural systems.

The structural safety of structures and structural systems is determined by the compliance of the parameters of the operated structures with the design values. This approach to assessing structural safety is based on the method of limit states, which is consistent with the regulatory framework for the design of building structures. At the same time, a unified methodology is observed, both in the design of structures and in assessing the structural safety of operated structures. It is necessary to harmonize the methods for assessing the structural safety of operated buildings with the theory of structural safety.

2. Methods

The structural system of a building or structure represents a complex structure from structural materials to the structural system, which is hierarchical in nature. It includes the following levels: materials; structural elements; construction; nodes and interfaces of structures; constructive systems.

The main factor affecting the structural safety of operated buildings and structures are power and corrosion damage [1-3]. An assessment of the structural safety of buildings and structures must be carried out taking into account the corrosion damage of structural materials against the background of the presence of a stress state [4, 5]. The course of corrosion processes in concrete of a reinforced concrete structure depends on the sign of the acting stresses. So, when compressed in concrete samples, the effective diffusion coefficient of carbon dioxide decreases by an order of magnitude, and when stretched, it increases by one or two orders of magnitude. Also, the corrosion resistance of concrete depends on the level of compressive stresses. At compressive stresses not exceeding the lower limit of microcracking of concrete, the porosity of concrete decreases markedly, the structure of concrete is densified. This factor reduces the rate of penetration of chemically aggressive reagents into
the material compared to unloaded concrete. At higher compressive stresses in the concrete structure, the process of formation, accumulation and development of microdamages begins. Then the concrete structure loosens, and the penetration rate of aggressive media into the concrete structure increases. Thus, in this case, the processes of corrosion and power influence are mutually reinforcing.

In reinforced concrete structures, the coefficients of thermal expansion for steel and concrete are almost equal in magnitude. But with corrosive processes of a chemical and physico-chemical nature, concrete expands, and steel reinforcement does not show its own deformations. But under temperature effects on such structures, reinforcement experiences its own deformations, opposite to concrete deformations [5]. In this situation, reinforced concrete structures receive specific damage, and the method for determining the intrinsic stresses in reinforced concrete, based on the equality of forces and the continuity of deformation of concrete and reinforcement, needs to be clarified.

Corrosion damage to elements and structures lead to a decrease in their resource of power resistance. First of all, corrosion reduces the cross-section of the elements, but in addition to such a straightforward consequence, damage caused by aggressive influences manifests itself in more complex schemes. Corrosive changes in the strength and deformation parameters of concrete in a compressed zone, corrosion of the rods of tensile reinforcement with a violation of the adhesion of the rods to concrete lead to a violation of the normative conditions for limiting the height of the compressed zone. This factor makes brittle fracture of bent reinforced concrete statically determinate structures with corrosion damage at design load. Corrosion damage leads to the formation and development of cracks, to a decrease in the rigidity of structures, to the development of significant deformations. In developing the theory of force resistance of building structures with corrosion damage, the prerequisite for the conditionally uniform nature of the impact of an aggressive environment along the span and along the section height of the structure is accepted. With this formulation, the force resistance of a structure with corrosion damage is determined in cross section with the greatest internal forces. However, from the experience of examining the building structures of buildings and structures operated in aggressive environments, it follows that the zones of structures with the greatest corrosion damage do not coincide with the areas of the greatest internal effort. The aforementioned circumstances require the development of the theory of force resistance of structures with the determination of dangerous sections from the point of view of corrosion damage, direction and level of acting forces.

The structural safety of buildings and structures is largely ensured by the integrity of the interfaces and links of the structurally statically unchanged system. During designing buildings and structures, structural solutions should preferably be laid that increase the degree of static indeterminacy of the building system. Another condition for ensuring the structural safety of buildings and structures is the design of connection nodes of structures not susceptible to brittle fracture [6]. Corrosion damage to the structural interfaces within the structural system leads to changes in the boundary conditions of the structures, to the redistribution of forces between the elements of the structural system. In the first case, for example, for a frame reinforced concrete building with corrosion damage to the rigid junctions of the crossbar with columns, the design of the crossbar changes from rigidly clamped at the ends to the scheme of the articulated beam, which leads to a decrease in the power resistance of the crossbar by half. In the second case, as a result of the redistribution of internal forces between structures, cases of occurrence of forces in individual structures that exceed design ones are possible, and as a result, deformations of unacceptable magnitude develop in these structures.

Regarding the structural systems of buildings and structures, structural safety is determined by the ability to maintain the necessary degree of static indeterminacy by the system, which ensures the perception of design loads during power and corrosion damage of individual structures, interfaces and couplings.

The proposed hierarchical approach in assessing the structural safety of building materials, structural elements, structures, units and structures, structural systems requires a systematic approach to creating physical, computational and mathematical models for the processes under consideration [7]. The task of developing a physical model of corrosion damage to reinforced concrete, taking into
account loading modes, stress state variability, the need to convert physical models based on the adoption of motivated hypotheses and assumptions, the development of calculation models remains relevant. Hence, there is a need to develop a methodology and to conduct experimental studies of building structures and structural systems to study the laws of joint power and corrosion effects, as well as the mechanisms of transformation of structural systems due to their structural changes (changing boundary conditions, changing the rigidity of nodes and others).

The theory of structural safety of buildings and structures should from a single point of view describe the stress-strain state and evaluate reserves according to the first and second groups of limit states at all stages of the life cycle of a building and structure. It should be based on the principles of force, environment and time factors, technological impacts, structural transformation and other factors. The theory of structural safety is the basis for developing effective methods of renovation, reconstruction of buildings and structures, strengthening building structures, for developing a theory of survivability of buildings and structures.

The studies performed to date are mainly aimed at assessing the structural safety of operated buildings and structures and at strengthening individual structures, if necessary. Moreover, the stress-strain state of the structure is taken into account at a particular stage of operation of the facility. It should be noted that corrosion damage to the elements and interfaces in structural systems are of a long-term nature, accompanied by a redistribution of forces and a change in the static circuit. With corrosion damage in structural systems, there are practically no cases of sudden shutdown of system elements [8]. In structural systems, in parallel with corrosion damage, as already noted, the process of redistribution of internal forces between the elements of efforts proceeds, the system adapts to changed operating conditions with self-regulation of stiffness and internal forces in the system elements. In modern construction science, the mechanisms of self-regulation of structural systems under the influence of changing operating parameters, when corrosion damage occurs, and also when changing boundary conditions during operation and reconstruction have not been studied. At the same time, the creation of a theory and based on it practical methods that allow controlling the structural safety of structural systems of buildings and structures taking into account the genesis of structural systems, quasi-stationary operation, reconstruction and renovation of objects, will ensure reliable and at the same time optimal design of buildings and structures as at the stage designing facilities, and at the design stage of reconstruction and renovation.

Further development of the theory of structural safety of buildings and structures, taking into account the concept of hierarchical construction should be considered in the following areas:
- study of the mechanisms of damage to reinforced concrete from power and corrosive effects, taking into account the sign and level of stress;
- carrying out experimental and theoretical studies of the bearing capacity, deformability and crack resistance of individual structures and structural systems under the conditions of manifestation of corrosion damage to concrete and reinforcement, damage to structural interfaces, changes in the system when it is strengthened;
- development of the theory of management of structural safety of buildings and structures, reflecting the genesis of structural systems, quasi-stationary operation, reconstruction and renovation of objects;
- development of a model of adaptive evolution of adequate quasistationary structures and structural systems.

Such close attention to power and corrosion damage is explained by the fact that such damage to individual elements of the building structural systems can be the causes of progressive destruction of operating buildings [9]. During assessing the condition of objects with damaged structures, the calculation of possible progressive destruction is not performed, it is necessary to reliably assess the impact of such damage, ensure the structural safety of the structure and, ultimately, prevent possible progressive destruction [10, 11]. Currently, research is being carried out aimed at protecting against progressive collapse during the design of buildings and structures [12-14].
A number of techniques evaluate situations with limited areas of local destruction, from the point of view of their possible development according to the scheme of progressive destruction [15-18]. The general methodology for reducing the risks of progressive destruction of buildings has been adopted:

- a warning or a complete exclusion by organizational methods of the possibility of an accidental impact, for example, explosions as a result of a terrorist attack, namely, such a design situation is considered in which one or more elements are instantly removed from the structural system;

- reduction of the volume of destruction of an object by constructive methods: the creation of a general structural continuity of carcasses, the introduction of additional connections into the structural scheme, the continuous reinforcement of elements of monolithic reinforced concrete floors, the exclusion of brittle destruction of individual elements and their interface nodes, and others;

- prevention of progressive collapse: on the basis of the analysis, structural elements are revealed, the destruction of which inevitably leads to progressive collapse and causing the greatest damage to the facility, personnel and equipment. During designing, the “absolute” strength of this element on the effect of emergency loads is ensured.

The most common method of protection against progressive destruction of designed buildings is to reduce the amount of progressive destruction due to its localization. The frame of the building is “divided” into separate volumes, the exit of the source of destruction beyond which it is excluded, for which the building is divided in horizontal direction by expansion joints, in the vertical direction are connected floors or powerful crossbars of floor floors. Another way to reduce the amount of destruction is the introduction of additional connections into the design scheme, so it recommends that the supporting frames carry out connections along external columns, vertical connections, contour connections, internal connections. The safety of the designed building can be ensured if, in order to prevent progressive destruction, the load-bearing capacity of all elements of the system will be sufficient to absorb the initial emergency impacts. Such a solution significantly increases the material consumption of the constructive solution. As shown in [6], the reinforcement required for the perception of accidental impact and applied loads exceeds the number of reinforcement 3–3.5 times that is necessary from the calculation to ensure the load-bearing capacity of structures at design loads. Thus, when considering various options for possible progressive destruction, all possible options for local damage are analyzed. But at the same time, it is necessary in parallel to solve the problem of the economy of the obtained technical solution.

Implementation options for the progressive destruction of structural systems:

1) Local destruction of a damaged structure at design loads, leading to a redistribution of efforts in the elements of the system with possible subsequent progressive destruction of the structural system.

2) Local destruction of an individual element during an emergency action, leading to an avalanche-like destruction of the structural system.

3) The loss of stability of the structural element, leading to an avalanche-like destruction of the structural system.

4) The combination of factors leading to the progressive destruction of the structural system.

Local structural failure under design loads, leading to a redistribution of forces in the system elements with possible subsequent progressive structural failure, possibly due to degradation processes such as aging, corrosion and others. In this case, we are talking about the destruction of structures operating for a long time in conditions that reduce the design bearing capacity of structures.

The reasons for this reduction in bearing capacity are power damage, as well as environmental damage (corrosion, temperature and others). The most difficult is the task of accounting for operational damage to prevent the progressive destruction of structural systems of buildings and structures with reinforced concrete elements. Progressive destruction of the reinforced concrete frame with operational structural damage is possible at design loads or even at smaller loads. The structural system of a building or structure is a complex structure that has a hierarchical nature from structural materials to the structural system: materials; structural elements; construction; nodes and interfaces of structures; constructive systems. In identifying the possible progressive destruction of the structural system, a hierarchical approach is also necessary in assessing the significance of operational damage.
During assessing the structural safety of buildings and structures, it is first necessary to take into account corrosion damage to structural materials against the background of the presence of a stress state. The course of corrosion processes in concrete depends on the sign of the existing stresses. So, when compressed in concrete samples, the effective diffusion coefficient of carbon dioxide decreases by an order of magnitude, and when stretched, it increases by one or two orders of magnitude. Also, the corrosion resistance of concrete depends on the level of compressive stresses. At compressive stresses not exceeding the lower limit of microcracking of concrete, the porosity of concrete decreases markedly, the structure of concrete is densified, which reduces the rate of penetration of chemically aggressive reagents into the material compared to unloaded concrete. At higher compressive stresses in the concrete structure, the process of formation, accumulation and development of microdamages begins, the concrete structure loosens, and the penetration rate of aggressive media into the concrete structure increases. Thus, in this case, the processes of corrosion and power influence are mutually reinforcing.

In reinforced concrete structures, the coefficients of thermal expansion for steel and concrete are almost equal in magnitude. But with corrosive processes of a chemical and physico-chemical nature, concrete expands, and steel reinforcement does not show its own deformations. But with temperature effects on such structures, reinforcement experiences its own deformations, opposite to concrete deformations. In this situation, reinforced concrete structures receive specific damage, and the method for determining the intrinsic stresses in reinforced concrete, based on the equality of forces and continuity of deformation of concrete and reinforcement, needs to be clarified.

The structural safety of buildings and structures is largely ensured by the integrity of the interfaces and links of the structurally statically unchanged system. During designing buildings and structures, structural solutions should preferably be laid that increase the degree of static indeterminacy of the building system. Another condition for ensuring the structural safety of buildings and structures is the design of connection nodes for structures not susceptible to brittle fracture. Corrosion damage to the structural interfaces within the structural system leads to changes in the boundary conditions of the structures, to the redistribution of forces between the elements of the structural system. In the first case, for example, for a frame reinforced concrete building with corrosion damage to the rigid junctions of the crossbar with columns, the design of the crossbar changes from rigidly clamped at the ends to the scheme of the articulated beam, which leads to a decrease in the power resistance of the crossbar by half. In the second case, as a result of the redistribution of internal forces between structures, it is possible that forces arise in individual structures that exceed the forces from the design load, and as a consequence, the development of deformations in these structures is not permissible values.

Regarding the structural systems of buildings and structures, structural safety is determined by the ability to maintain the necessary degree of static indeterminacy by the system, which ensures the perception of design loads during power and corrosion damage to individual structures, interfaces and couplings.

In the case of corrosion damage to the elements of the structural system or the nodes of the interfaces of the elements, progressive structural failure schemes are implemented:
- local destruction of the damaged structure and, leading to the redistribution of forces in the elements of the system to values exceeding the calculated values;
- loss of stability of the structural element due to damage to the element or interface, leading to an avalanche-like destruction of the structural system.

3. Results
Existing documents containing provisions for the protection of buildings and structures from progressive destruction are aimed at designing objects, and not at solving a similar problem for operated buildings and structures and do not take into account operational damage to individual elements and components of the structural system.
The theory of structural safety will allow to reliably assess operational damage to reinforced concrete elements of structural systems. This allows, from a single point of view, to describe the stress-strain state and evaluate structural reserves at all stages of the life cycle and construction of a building based on the consideration of capacity, environmental and time factors, technological impacts and structural transformations and other factors [13].

Further studies of the structural safety of buildings and structures from the standpoint of the development of the theory of progressive destruction should be considered in the following areas:

- study of the mechanisms of damage to reinforced concrete from power and corrosive effects, taking into account the sign and level of stress from the standpoint of the possibility of a local separate structure, as the cause of the progressive destruction of the structural system;
- development of the theory of structural safety management of buildings and structures, reflecting the genesis of structural systems, quasi-stationary operation;
- determination of the criterion of structural safety of systems taking into account compositional and power control of structures and structural systems of buildings and structures;
- development of a model of adaptive evolution of adequate quasistationary structures and structural systems.

The implementation of the formulated lines of research and development of the theory of structural safety of buildings and structures will allow us to obtain solutions that open up the possibility of managing the structural safety of objects and solve the problem of confronting the progressive destruction of structural systems of operated buildings and structures.

4. Discussion

An analysis of experimental and theoretical studies found that the instantaneous destruction of an element or a connection of a structural system under the action of an operational load leads to a dynamic loading of all other elements of the system and, as a result, to a possible progressive collapse. In design methods we call this phenomenon the “dynamic effect”. Currently, directions have been formed for calculating structural systems in the event of the destruction of an element and the occurrence of a danger of progressive collapse. The first direction: high-precision nonlinear dynamic calculation; second direction: approximate dynamic calculation in an elastic-linear formulation; third direction: a simplified calculation based on the use of equivalent static loads with the introduction of a dynamic coefficient. Recently, simplified calculation methods have been developed in which a linear static procedure requires the application of an increasing coefficient for loads, taking into account both non-linear and dynamic effects. To assess the dynamic effect in practical calculations, a dynamic coefficient of load is used. In many methods, the dynamic coefficient of the load is assumed to be 2.0 during the elastic calculation of the structural system, the coefficient decreases if the system is calculated taking into account plastic deformations. The introduction of the dynamic coefficient made it possible to simplify the accounting of the dynamic effect during the instantaneous destruction of one of the elements of the structural scheme, namely, the dynamic calculation to lead to the static calculation. The main task for the effective application of this method is to establish differentiated dynamic coefficients that take into account the operation of the structural system under dynamic emergency actions, the nonlinear nature of the deformation of materials, the geometrically nonlinear deformation of the structural system as a whole. The methods developed to date to prevent progressive destruction can be conditionally divided into three groups.

The first group consists of the methods of “possible damage”. In accordance with these methods, when designing buildings and structures for calculation of design loads, they perform dynamic calculation for special loads. This takes into account changes in the strength and deformation characteristics of materials in the conditions of short-term dynamic loading. In the design situation, the exclusion of one or more load-bearing structural elements in the zone of local destruction is not performed.

The second group consists of methods in which “key elements” are designed to perceive special influences, which eliminate the occurrence of local destruction, or assess the redistribution of internal
forces in the system when an element (or several elements) is removed. In both cases, the calculated values of the forces and movements should not exceed the permissible value. These methods are based on a probabilistic approach to constructing a scenario of progressive destruction of a structural system at the design stage, according to which a “key element” or a group of “key elements” are responsible for confronting progressive destruction. That is, the problem is solved only within the framework of the proposed scenario. The manifestation of an emergency that causes local destruction of a separate structure and, as a consequence, progressive destruction, is random in nature, both in terms of the application and the magnitude of the emergency load. These methods are limited in application, for example, it is almost impossible to determine the progressive destruction of a high-rise frame building of a communication system in the event of the destruction of one of the columns. The “key element” method is effective when the place of application and the magnitude of the external special load are unambiguously known at the design stage. For example, in the case of designing an object in a separate room which, under technological conditions, an explosion of a gas-air environment is possible. The method of the "key elements" of the structural system leads to an increase in the material consumption of the design solution.

The third group of methods limits the zone of local destruction due to the removal of an element (or several elements) by constructive methods: setting up a system of horizontal and vertical connections. These methods are implemented by the device in the structural system of high-rise buildings of connected floors, the use of powerful lower beams in the structural scheme, the use of vertical and horizontal ties in the supporting frames with countersinking in the ties in adjacent structures.

Also known is the method of separating structural systems, when the statically indeterminate structural systems of a frame building are divided into independent blocks by hinged inserts. In this case, when one element is destroyed, the dynamic effect is localized within one block.

5. Conclusions
The implementation of the formulated directions of research and development of the theory of structural safety of buildings and structures will allow to obtain solutions that open the possibility of managing the structural safety of objects. It reflects the genesis of structural systems, quasi-stationary operation, reconstruction and renovation of objects, based on the criteria of structural safety of systems, taking into account compositional and power control of structures and constructive systems of buildings and structures.

The above methods of counteracting progressive destruction are especially dangerous, technically complex and unique objects. However, taking into account the risk of emergency situations, it is justifiable to protect against possible progressive destruction and buildings of mass development. In residential buildings, the most likely case of progressive destruction is the collapse of floor slabs. During designing the unit supporting the plates at the joints, it is necessary to ensure the safety of the unit under the action of possible emergency loads.

The presented analysis showed that the protection of structural systems from progressive collapse is implemented in three main areas: reduction to an acceptable level of risk of accidental impacts; ensuring the absolute bearing ability of the "key element" on the perception of special effects; limiting the extent of progressive collapse with the removal of an individual element by a local zone. These methods do not solve the problem of progressive destruction of structural systems of operated buildings and structures in the presence of damage. Given the specifics of the issues under consideration, the provisions of the calculation methods require appropriate adjustment.

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