

Building constructions calculation models of reinforced concrete using BIM technologies

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ABSTRACT

BIM technology is an information system that digitally describes not only the architectural and spatial features of the building, but also the physical, technical, functional and operational characteristics of the designed object. Automatic recalculation of changed factors is the most important feature of BIM modeling. This article is focused on developing the new methodology for calculating concrete structures using the LIRA-CAD software. It involves taking into account creep deformations in a reinforced concrete structure and deformations under the influence of temperature factors, which corresponds to the Order of the Cabinet of Ministers of Ukraine No. 152-p Kyiv "On approval of the concept for the introduction of building information modeling technologies (BIM technologies) in Ukraine and approval of the action plan for their implementation" of February 17, 2021. The comparison of the suggested calculation with the calculation given in the regulatory documents and the results obtained in the course of the experiment was carried out. Based on the results of the study, the recommendations for calculating structural elements, taking into account the effect of temperature creep were developed.

1. Introduction

The building information modeling (BIM) technology has been used in all stages of the construction project: creating a technical task for design, development of design documentation, construction work, operation, etc. It allows to analyze large amounts of information, accelerating any stage of project implementation. Thus, it is possible to estimate the economic performance of the project at any time, including the cost of the entire construction and the cost of individual types of work. In particular, the implementation of calculation models of building constructions and structures with the help of BIM technologies takes into account the rheological properties of reinforced concrete.

The development of an efficient and competitive national economy in Ukraine requires a systematic comprehensive reform of the construction industry. One of the important components of this reform is its gradual digital transformation. The analysis of the best world experience shows that today the most advanced digital technologies in construction include BIM technologies, which provide a modern approach to the management of digital information used in construction and urban

planning. It is based on a common digital representation of the object to facilitate design, construction and operation processes.

The essence of BIM technologies is the development and joint use of the construction information model of the construction object (BIM model of the object). This model is a set of structured and unstructured information containers (data sets) within the framework of an integral information system. It contains the necessary geometric, physical, functional and other characteristics of the object, on the basis of which design and estimate documentation, operating recommendations are developed [20].

In Ukraine, BIM technologies are mainly determined by two-dimensional design, the storage and transmission of information in paper and/or electronic format. It should also be noted that BIM technologies are given priority by the [32] No. 152-p Kyiv "On approval of the concept for the introduction of building information modeling technologies (BIM technologies) in Ukraine and approval of the action plan for their implementation".

The level of design work complexity has increased significantly. The requirements for the quality of design have increased in the total cost of construction work and the cost of reinforced concrete structures, due to

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Nomenclature		FEM	finite element method
q	strength	E_{cd}	calculated value of concrete modulus of elasticity
τ	moment of time for which deformation is determined	N	axial force
τ'	point of application of elementary stress increase	M_d	bending moment
B_k	constant, $B_0 = 1$	f	strength
γ_k	constant $\gamma_0 = 0$ and $\gamma_k > 0$	$f_{ck}(R_{bn})$	characteristic cylinder compressive strength of concrete at 28 days
C_0	extreme value of creep coefficient	$f_{cd}(R_b)$	calculated value of concrete compressive strength
A_k	concrete characteristics that depend on properties and ageing conditions of concrete	$f_{ctd}(R_{bt})$	calculated value of concrete tensile strength
f_{cd}	calculated value of concrete compressive strength	$f_{yd}(R_s)$	calculated strength of reinforcement at the point of flowability
f_{cd3}	axial compressive structural strength	ε_c	concrete compressive strain
f_{scd}	calculated value of reinforcement compressive strength	ε_{cl}	concrete compressive strain at maximum loads f_c
f_{fd}	calculated value of tensile strength of polymeric reinforcement	ε_{cu}	relative ultimate compressive strain of concrete
d	effective depth of cross section	φ	a spacing between the atoms in the quasicrystalline lattice structure
A_f	cross sectional area reinforced by polymer fiber	m	molarity
h_f	depth of an I-beam (or T-beam) in a compressed area	k	a variable in Hooke's law ($F = -kx$) that indicates stiffness and strength
b_f	breadth of an I-beam (or T-beam) in a compressed area	e	exponent
b	effective breadth of cross section		
FE	finite element		

the growth in the cost of construction materials and iron. Experts often point to the satisfactory quality of project development and the repeatedly inflated project cost during construction [3]: most projects receive a positive conclusion. Among the main systemic reasons that lead to the release of low-quality projects, we can note the low cost of project work, the lack of practice in such projects, and low technical equipment of project teams.

Currently, guidelines and standards in this area refer to past experience, which was a completely different economic situation. These recommendations are based on the number of certain formats working drawings. This assessment is justified because working drawings are the transition from designer to production and construction activity. At the stages of design, production preparation, construction activity and operation of buildings and structures it is necessary to prepare working documentation with a detailed and complete description of all structural elements involving production technology, construction and operation of the structure [6]. The project development class clarifies the level of complexity achieved in its creation: more complex objects force the use of more advanced design automation systems – SAPR. Software and the latest design methods help to get the best result in information assistance at all stages of the project.

The use of SAPR REVIT in the design of metal and reinforced concrete structures and in construction of stadiums, airports, bridges and shopping and entertainment complexes has demonstrated the feasibility of implementing this technology [5]. Tekla's program can also be used to design small facilities. During the implementation of the working project, a conditional structure is created, which includes architects and designers.

BIM software and hardware has the main tools such as Revit, ArchiCAD, ALLplan already has a good pace of development [4]. Accordingly, work on BIM projects in architecture is already becoming quite common. Designers of building structures do not seek to work with the help of BIM programs, justifying their decision by the fact that it is necessary to make calculations on other programs.

In turn, the developers of the program have sharply increased the number of these calculation and design programs that exchange information through formats such as IFC (Industry Foundation Classes) which is directly related to the BIM technology. These include the following programs: Autodesk Robot, Structural Analysis, SOFiSTiK, Bentley STAAD.Pro, Tekla Structure; LIRA-CAD and Advance Steel [8]. In 2024, LIRA-CAD implements BIM technology. It is focused on the

design and calculation of building structures. The implementation of BIM technology is provided by interaction with other architectural, calculation, graphic and documentation systems (SAPFIR-3D, Revit, Tekla, AutoCAD, ArchiCAD, Advance Steel, BoCAD, Allplan, STARK ES, Gmsh) on the basis of DXF, MDB, STP, SLI, MSH, STL, OBJ, IFC.

Accordingly, the developers of payment programs, began to clearly pave the way for BIM technologies. The results showed the efficiency of the process and the acceleration of its implementation time. At this point, the structures are adjacent, i.e., responsible for the engineering equipment of buildings. They do not use BIM programs. The main reason for this is that the projects are carried out in different areas, such as heating, ventilation, air conditioning, plumbing, electricity and some other sections, which are performed by completely different specialists under different rules and regulations. Therefore, it is very difficult to demand from one program sufficiently qualified work at the same time in everything. It is necessary to point out that many designers make the design of working documentation, completely unaware of what will happen next. It happens that according to the requirements for the design of the drawings, they do not know the essence of the project [35].

The use of such software packages as ANSYS, LIRA-CAD, Code Aster allows to take into account all the factors that affect the deformation of the projected object during exploitation. Current standards [22,36,1,23] generally do not consider the processes of weathering, aging, creep, the impact of time, and bearing capacity. The operation of the building is always influenced by a time factor at which the concrete loses its strength and elasticity without proper protection of the concrete in advance. Thus, the deformation stresses and their change should be determined by calculation based on the integral value of rheological influences because the greatest destructions during long-term operation are caused by creep.

At the same time, the developed library of LIRA-CAD (finite elements) allows to create computer models of almost any structures: flat and spatial frames, wall beams, bending plates, shells, massive bodies, as well as combined systems such as plates and shells supported by ribs, plates on a soil basis, frame structures of buildings, systems. Meanwhile, physical nonlinearity accounting modules are based on various nonlinear dependencies $\sigma - \varepsilon$, providing the possibility of computer modeling of the loading process of both mono- and bi-material structures with the trace of crack development and the manifestation of creep and flow deformations. Such modules facilitate obtaining a picture of the structure destruction with the possibility of accounting and

temperature effects.

Accordingly, the aim of the research is to study the calculation models of building constructions and structures, taking into account the rheological properties of reinforced concrete using BIM technologies. The following tasks were set to achieve the aim:

- To investigate the influence of construction temperature changes on the creep factor and its consequences.
- To determine the stress–strain state of reinforced concrete structures, taking into account the physical nonlinearity of concrete.
- To consider the behavior of concrete and rheological properties under the influence of temperature factors in structures modeling.
- To compare the calculated data with the results obtained during the experiment.
- To predict the technical condition of buildings and structures during their operation and determine their service life.

During the study, the creep law is violated, which makes it possible to determine the coefficient at which deformation is possible. It turns out that the destruction (deformation) of the structure occurs at the appropriate load. During the study, it was decided to strengthen the bearing capacity of the model with a supporting a load-bearing formwork. This also reduces transportation and installation costs although it increases material consumption and weight of the structure. In addition, it reduces the technology cost.

During the experiment, the analytical model for reinforcement and strength testing of reinforced structural elements is expanded. As a result, it is concluded that the use of reinforced polymers can significantly increase the bearing capacity of building elements. Thus, the design calculation using BIM technology with partial consideration of rheological properties is shown on the example of a model of a metal curved rack.

These calculation results give the right to assert that concrete demonstrates relaxation. Thus, a part of the additional load that was originally applied redistributes the concrete to the metal elements (reinforcement frame) to avoid destruction. During the experiment, it is found that over time there is an increase in loads on the framework. Therefore, it is recommended to take into account the creep effect when designing bridges since an incorrect assessment of the rheological properties of concrete can lead to the structure instability and emergencies.

The analysis of the temperature effect on concrete structures in the elastic stage shows that as the thickness of the structural element increases, so does the temperature deformation. Therefore, in order to define the creep coefficient of reinforced concrete structures, taking into account temperature changes, ideal conditions for a one-dimensional temperature problem are created.

In addition, in order to ensure the reliability of the developed methodology, a comparative analysis of calculations with a real phenomenon is carried out, namely, calculations of the temperature effect on the reinforced concrete structure. In the course of the study, it is concluded that the analysis of the finite element model according to the author's methodology should be used in the calculation of building structures for fire resistance.

2. Methodology

There are many scientific works that consider the possibilities of strengthening reinforced concrete structures and based on theoretical and empirical values. However, there is still no clear algorithm and methodology for modeling with BIM technologies based on rheological properties [2]. Reinforced concrete structures increase the strength and durability of constructions. Therefore, it is important to use mathematical models that will take into account creep and temperature factors in structures modeling. In composite materials, the main component is called the matrix, and the reinforcing components are called fillers, or

amplifiers. Improving properties is the main function of the filler [22,11].

Composites with a filler of carbon components (fibers, carbon nanotubes) are used in reconstruction and strengthening of buildings, bridges and structures. Leaders in the production of such materials are companies such as BASF and SIKA [22,36,1,23,12,9,10,7,26,31,28,29]. The polymer combination is applied using a special matrix, where the fiber is a material consisting of thin threads with a diameter of 5 to 10 μm , formed mainly by carbon atoms. Carbon atoms are united by microscopic crystals aligned parallel to each other to provide greater tensile strength.

Based on the use of BIM technology, the ability of structures to break and bear the specified loads can be specified. The necessary parameters are met by the software package LIRA-CAD, which provides an opportunity to introduce rheological factors into the structure of mathematical modeling. This software takes into account all new values that may indicate the impact of added loads, changes in structures and elements, offering some variations in the composition of reinforced concrete structures (e.g., several types of reinforcement, or their geometric location). Moreover, it can take into account changes, its geometry, identification of weaknesses and simultaneously conduct statistical processing.

Therefore, it is possible to identify the elements that need to be further strengthened. The fibrous material and its properties that will be selected to reinforce the structure must also be considered. Fig. 1 shows the method of modeling the structure taking into account the rheological properties.

Fig. 2 shows the analytical model for calculations.

During the physically nonlinear analysis, parameters were set to calculate the deformation of the structure, taking into account the concrete creep. The change in creep coefficient over time was determined using the 44th creep law. The creep coefficient was calculated by the following formula:

$$\varphi(\tau) = \varphi(\tau')f(t - t') \quad (1)$$

$$\varphi(\tau') = C + \sum_{k=1}^m \frac{A_k}{(\tau')^k} \quad (2)$$

$$f(t - t') = \sum_{k=0}^m B_k e^{-\gamma_k(t-t')} \quad (3)$$

where, φ is the spacing between the atoms in the quasicrystalline lattice structure; f is strength; τ is a moment of time for which deformation is determined; τ' is a point of application of elementary stress increase; B_k and γ_k are constants, which depend on concrete, while $B_0 = 1$, $\gamma_0 = 0$ and $\gamma_k > 0$; C_0 is extreme value of creep coefficient; m is molarity; k is stiffness and strength; e is an exponent; A_k is concrete characteristics that depend on properties and ageing conditions of concrete.

The load-bearing capacity was calculated after obtaining data for the corresponding construction. The parameters of permissible destruction of concrete and reinforcement deformation are shown in Fig. 3.

After the analysis, numerical values were used, which take into account the rheological properties (creep) to calculate changes in the geometry of the constructive. The broken law of creep allowed to determine the coefficient at which deformation is possible. Fig. 4 shows the plots of the construction and their stress–strain state obtained after the calculation.

It turned out that the destruction (deformation) of the structure occurs at the appropriate load. Fig. 5 shows the internal stresses before and after the destruction (deformation) of the theoretical model.

According to the results, it was decided to strengthen the load-bearing capacity of the model with a load-bearing formwork. This method allows construction to save on installation and dismantling of formwork, decrease the cost of transportation and installation, increase material consumption and the weight of the structure. In addition, it also

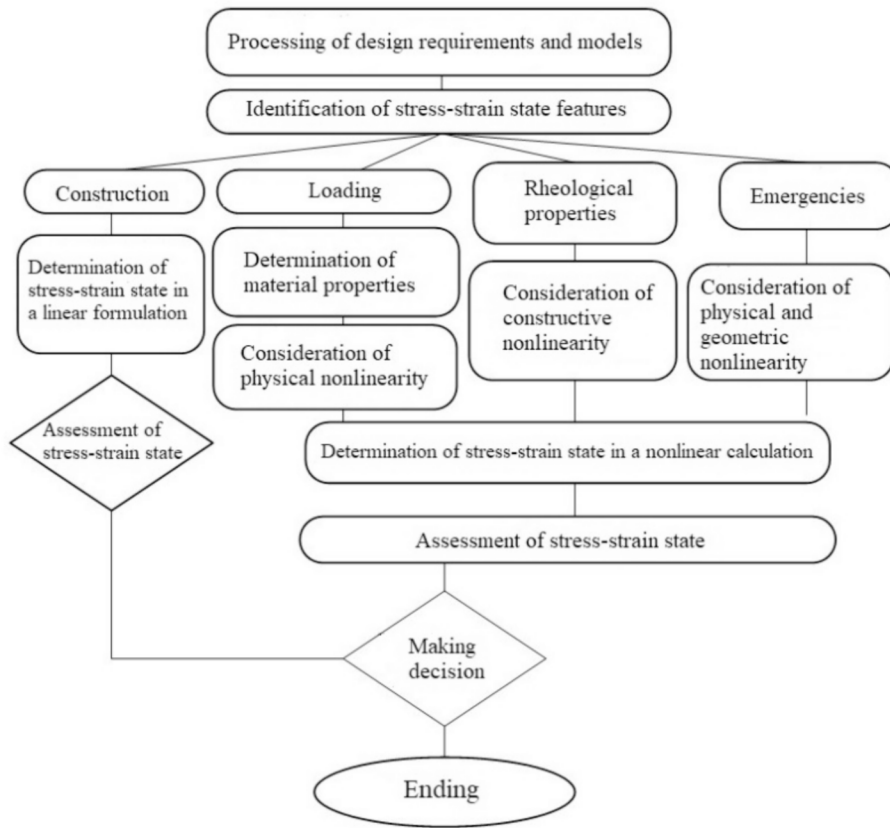


Fig. 1. Technology of modeling the structure in LIRA-CAD.

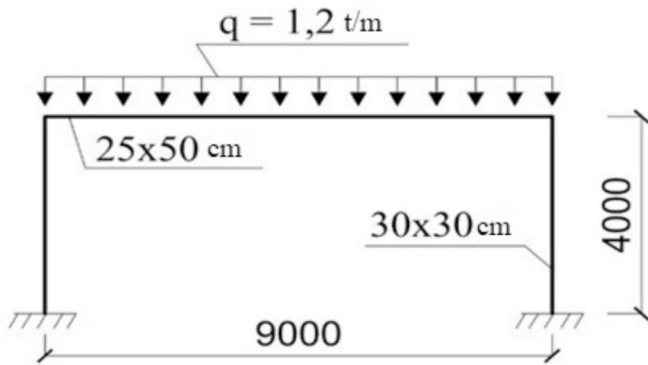


Fig. 2. Load-bearing capacity on the example of the frame model q-strength.

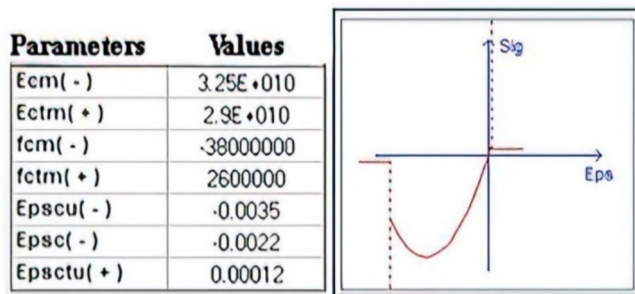


Fig. 3. Destruction of concrete, Pa.

reduces the cost of technology due to the use of shallow vibrators and vibrating metal platforms.

To strengthen the frame elements in which cracks appeared, Aslan fibrous polymers with the following characteristics were selected:

- monolayer thickness: 1,4mm;
- modulus of elasticity: 2400 Pa;
- material strength: 131000 MPa;
- deformation at rupture: 0,0187 %.

The coefficient of operating conditions was taken equal to one.

After selecting the composite material for reinforcement, the load-bearing capacity of the reinforced frame element was checked by ESPRI 2020 Engineer's Electronic Handbook. For reinforced elements that work on compression, the load-bearing capacity check is performed using the following formulas:

- at longitudinal stiffening:

$$Ne \leq f_{cd}bx(d - 0,5x) + f_{scd}A'_s(d - a') + f_{jd}A_fa \quad (4)$$

- at external stiffening:

$$Ne \leq f_{cd3}bx(d - 0,5x) + f_{scd}A'_s(d - a') \quad (5)$$

For elements that work on the bend, the check is performed at the bending moment using the following formula:

- for rectangular cross section:

$$M \leq f_{cd}bx(d - 0,5x) + f_{scd}A'_s(d - a') + f_{jd}A_fa \quad (6)$$

- for T-beams:

$$M \leq f_{cd}bx(d - 0,5x) + f_{cd}(b'_f - b)h'_f(d - 0,5h'_f) + f_{scd}A'_s(d - a') + f_{jd}A_fa \quad (7)$$

where, f_{cd} – calculated value of concrete compressive strength; f_{cd3} – axial compressive structural strength; f_{scd} – calculated value of

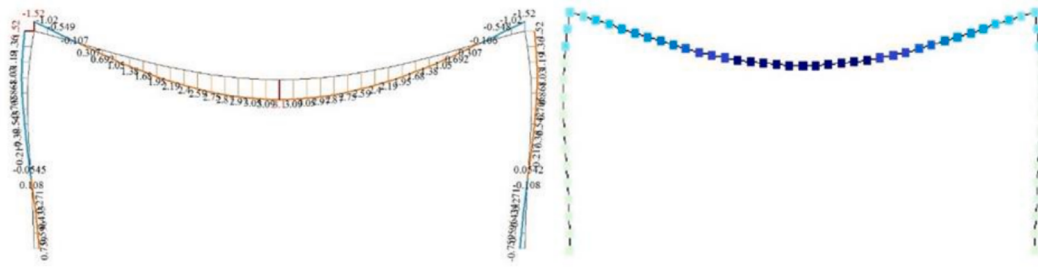


Fig. 4. Constructive diagrams.

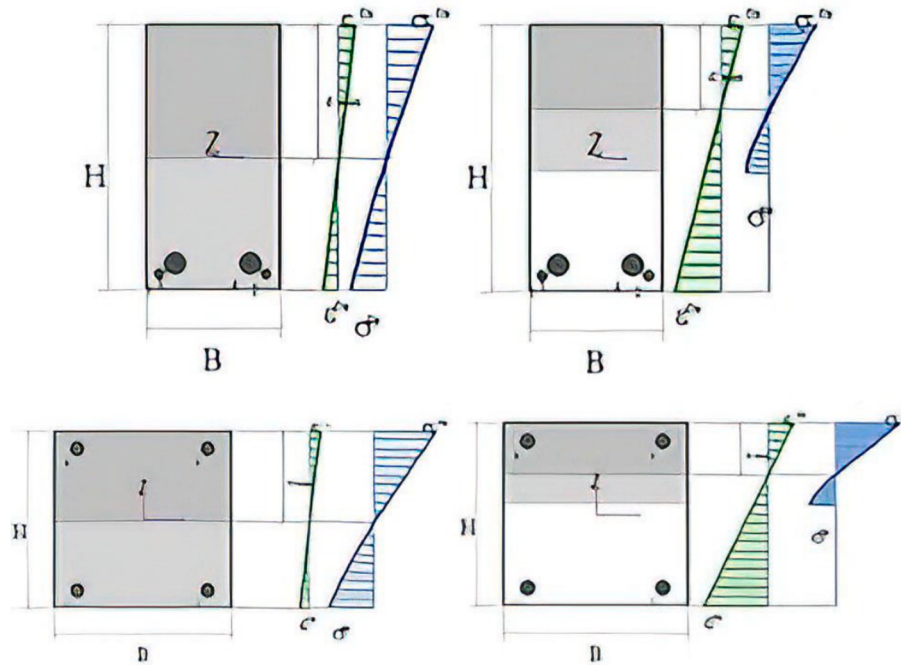


Fig. 5. Stress diagrams before and after deformation.

reinforcement compressive strength; f_{fd} – calculated value of tensile strength of polymeric reinforcement; d – effective depth of cross section; A_f – cross sectional area reinforced by polymer fiber; h_f – depth of an I-beam (or T-beam) in a compressed area; b_f – breadth of an I-beam (or T-beam) in a compressed area; b – effective breadth of cross section.

Having selected the material for reinforcement and strength test of reinforced structural elements, the reduced rigidity of reinforced elements is obtained. To calculate the analytical model, taking into account the new rigidity, the type FE No. 10 was changed to FE No. 210, which gained new reduced rigidity characteristics.

One of the most common classical options for increasing the load-bearing capacity of the structure is to increase its rigidity by installing metal casing. To calculate the reinforcement of the column of the calculated scheme, instead of choosing composite materials, it is necessary to choose the dimensions of metal corners (or plates), which strengthen the structural elements. Verification of the reinforced elements can also be carried out using the ESPRI program “Verification of reinforced concrete cross sections of columns”. To do this, it is necessary to select the verification of concrete sections with metal corners and set the parameters of corner beams in such a way that they modeled the metal casing around the column.

In this case, instead of carbon plates or other composites it is possible to use metal sheets or corners. In one of the subordinate sections of the ESPRI program “Verification of reinforced concrete cross sections of columns”, it is necessary to design a metal clamp around the column so

that it simulates metal casing in order to calculate the composite structure. Fig. 6 shows the deformations of two-line and three-line reinforced concrete cross-sections, which facilitated checking the characteristics.

The movement of deformation loads during reinforcement is shown in Table 1.

Examples of cross-sections of reinforced concrete structures of non-standard modifications that can be used in the program ESPRI are shown in Fig. 7.

The use of reinforced polymers to strengthen structures can significantly increase the load-bearing capacity of building elements. It also allows to extend their service life, prevent or eliminate emergencies, correct design or construction errors. Finally, it facilitates reliable operation and durability of structures.

3. Results

The design of the construction using BIM technology with partial consideration of rheological properties is shown on the example of the iron curved overpass model (Fig. 8) in accordance with acceptable standards [22,24] and taking into account fractures and deformations.

The application of the 15th exponential law allowed to calculate concrete deformation [13]. The functioning of iron elements as reinforcement was modeled on the principle of spatial isoparametric finite elements, while the functioning of concrete was modeled using physical

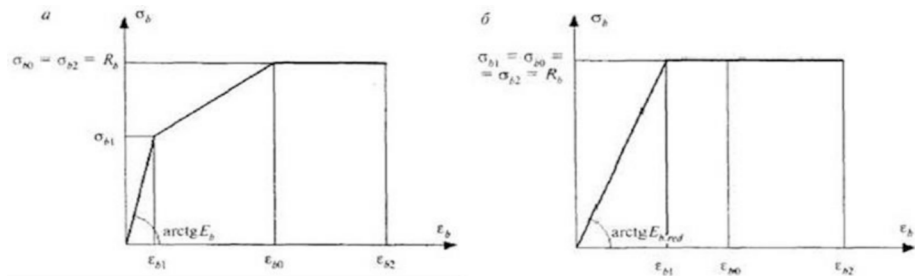


Fig. 6. Three-line and two-line deformation.

Table 1
The movement of deformation loads.

Element	Linear calculation		Physical nonlinearity		With reinforcement	
	Variable axis Z, mm	Tension M _y , t*m	Variable axis Z, mm	Tension M _y , t*m	Variable axis Z, mm	Tension M _y , t*m
Column	0	±1,65	−0,1	±1,89	0	±2,06
	−2,8	2,96	−7,6	2,7	−7,3	2,26

nonlinear elements. Taking into account their rheological properties, it is necessary to calculate the structure by the method of nonlinear deformations [9]. The LIRA-CAD software allowed to change parameters of values according to norms [23,22,24] and carry out nonlinear calculations. To do this, simple step-by-step calculations were made with a parameter equal to 30, which in turn presupposed the number of steps. The creep coefficient φ_0 and coefficient β_H were calculated in advance taking into account the relative humidity (RH, %) and conditional cross-sectional geometry (h_0 in mm) and relative humidity (RH, %).

The new additional system Universal Cross-Section Constructor in LIRA-CAD, which appeared in 2018, allows to create multi-material cross-sections with nonlinear properties of materials and calculate the

usual cross-sections of non-stressed reinforced bridge, steel reinforced concrete, and cross-sections reinforced with external reinforcement. In this regard, it is essential to consider the use of polymeric materials in reinforcement. The loads in the existing reinforcement are separately distinguished; the compressed zone of concrete is determined; the stretched concrete is turned off from operation; the stresses in reinforcement structures are analyzed; and the factors of electrocorrosion of concrete are taken into account [37].

Table 2 shows the results of the calculations. According to the spatial overpass model, the classical directions “X”, “Y”, “Z” were used. Thus, the changes of characteristics according to the accepted directions were determined.

Table 2 indicates that the calculated displacements exceed the results, which show the stresses of the reinforced concrete structure in the

Table 2
Extremums of overpass movement points, mm.

Direction	Calculations in the elastic stage	Calculations based on creep				
		28 days	365 days	2 years	10 years	50 years
X	4.73	5.68	6.49	6.69	6.86	7.07
Y	3.27	3.93	4.5	4.65	4.76	4.91
Z	23.1	29	34.1	35.4	36.4	37.7

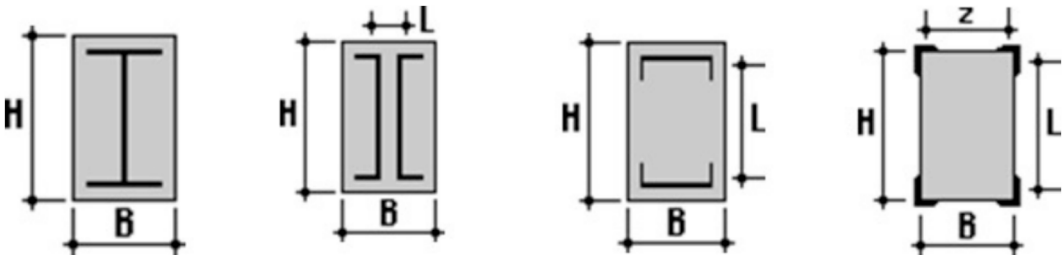


Fig. 7. Cross-sections of reinforced concrete constructions.



Fig. 8. Curved overpass model.

static state. The vertical displacements in the overpass that were simulated with regard to creep also exceed the norm.

Physical and mechanical parameters change due to the influence of rheological properties, while the internal stress increases significantly. At the same time, the value of the modulus of deformation for the simulated overpass model changes over time (Fig. 9).

According to Fig. 9, under the influence of time, the value of the modulus of elasticity $E(\tau)$ decreases, while the greatest decrease is observed in the first trimester. Hence, it is possible to assume that the largest changes in modulus $E(\tau)$ occur at the time of gaining strength of 28 days. The modulus of elasticity becomes non-indicative in 350–400 days. Increasing age of concrete gives it strength and the modulus of elasticity rate decrease slows down. The change in the characteristics over time in the three-dimensional finite concrete elements of the overpass model is shown in Table 3. The LIRA-CAD software takes into account all changes in physical and mechanical properties of concrete and calculates the redistribution of forces between the components of the spatial model.

Considering the results obtained in Table 3, it can be assumed that the concrete shows relaxation. Hence, the part of the extra load that was applied initially redistributes the concrete to the metal elements (reinforcing frame) to avoid destruction. The change in loads is shown in Fig. 10.

According to Fig. 10, the loads are inhomogeneous over time, which indicates that a simple static calculation in the modeling of reinforced concrete structures is unacceptable because there are significant internal changes [6,9,10].

Calculating the creep effect in bridge structures allows to analyze the process of changing their stress–strain state over time. Hence, there is an increase in loads on reinforcement over time. Therefore, it is recommended to take into account the creep effect when designing bridges because an improper assessment of rheological properties of concrete can lead to unsuitability of the structure to normal operation and even to emergencies.

3.1. Design of reinforced concrete structures taking into account temperature changes

In the process of concrete destruction under the influence of high temperatures, water determines the humidity of concrete. Heat energy increasing which transferring externally to the concrete stone increases the rate of the cement hydration. With less water amount in the mixture and a direct decrease in humidity, the hydration of cement stone decreases. Concrete acquires strength not only for 28 days, but also when the hydration of cement stops. When the relative humidity is equal to the value of 0.3, the hydration process is considered sufficient and the

Table 3

Changes in the overpass model, kH.

Loads	Calculation in the elastic stage	Calculation based on creep				
		28 days	365 days	2 years	10 years	50 years
Nx	−3020	−2360	−2100	−2050	−1990	−1980
Ny	−2850	−2200	−1950	−1910	−1850	−1840

concrete acquires necessary strength. The process of hydration in cement stone and concrete directly is considered in many studies. Problems of hydration rate changing were solved both technologically and chemically. In particular, this factor was considered in terms of deformations through rheological influences [7,26,31,28,29,34,38].

Under the influence of external temperature, there is a temperature difference between the concrete and the environment. As a result of exothermia, temperature fields begin to appear in the material. Therefore, there are phase transformations, as a result of which conductive heat transfer and convective transfer begin to interact with each other. Accordingly, part of the heat is transferred due to the thermal conductivity of the elements.

Bazant and Chern [18] were the first to describe a double power law that can be used to calculate the temperature coefficient of creep. This work became the starting point for further research [18,17,14,15,16,19]. Although there is a significant amount of literature based on empirical research, the data of these studies differ. Therefore, in this study it is necessary to represent the average values of the degree of hydration of concrete stone in the form of a graph which would reflect changes in the rate of hydration and water saturation (humidity) over time (Fig. 11).

This graph is relevant for the use of concrete products in heavy production, which maintain a constant high temperature. Thus, in some technological areas, the change in temperature is cyclical, according to technological cycles. Accordingly, this definition of deformation is appropriate [30].

Values obtained by Bazant [14] were used for the calculation. Hence, a prism-shaped beam was selected, which was fixed, and a constant temperature regime was established in the test chamber. Thus, ideal conditions for a one-dimensional temperature problem were created (Table 4).

Fig. 12 shows the difference between experimental and theoretical creep coefficient values when changing the ambient temperature of the samples used.

The release of cohesive and non-cohesive water from cement or concrete stone must be taken into account in advance. First, the rate of water release affects the deformation of its concrete. The amount of

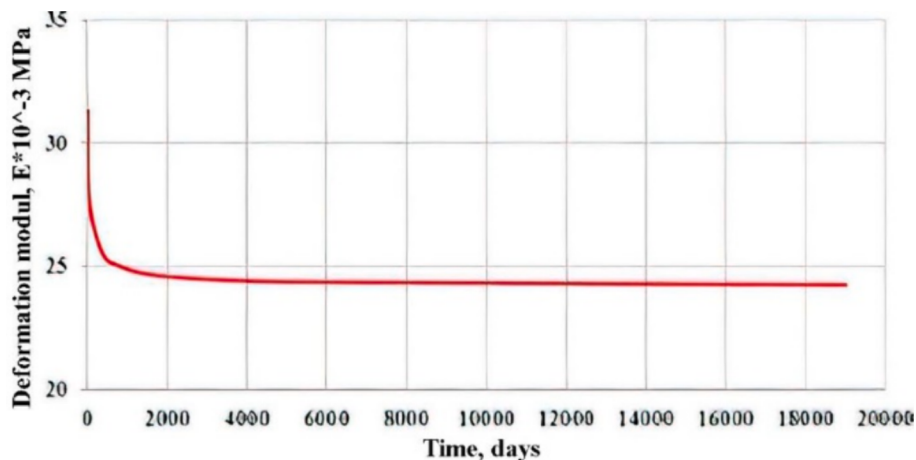


Fig. 9. Changes in deformation module parameters.

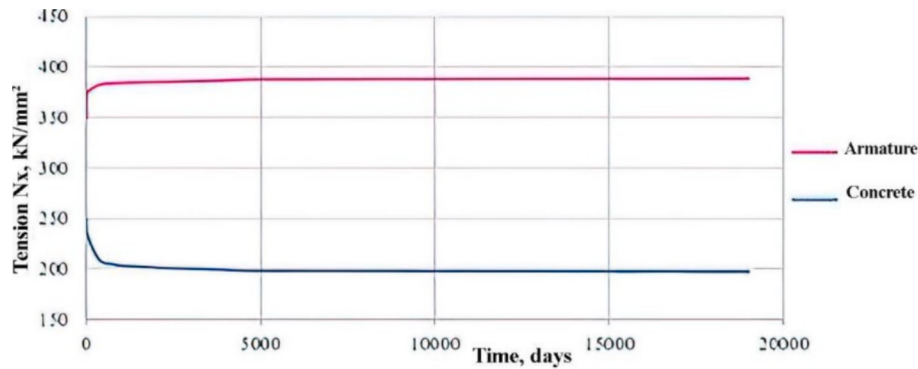


Fig. 10. Loads of the overpass reinforced concrete structure over time.

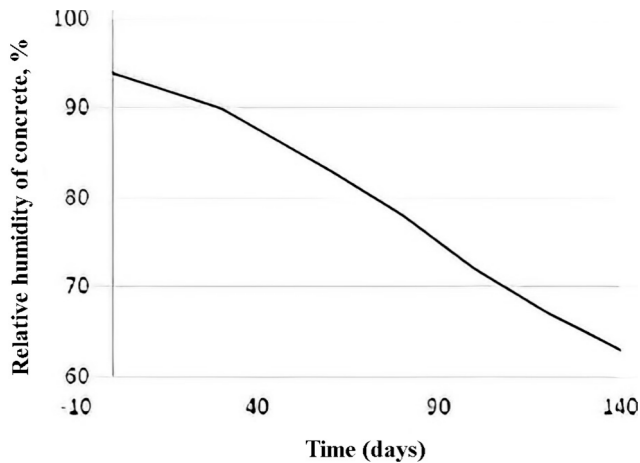


Fig. 11. Dependence of concrete humidity on time [26,31,28].

Table 4

Temperature influence on concrete samples.

No. of block	Age before the start of warming in days	Warming up			Cooling	
		Duration in hours	ΔT in degrees	T_{max} in degrees	Duration in hours	T_{max} in degrees
1	19	49	37.8	57.4	166	34.3
2	21	67.5	42.5	60.5	336	41.8
3	36	48	40	59	204	38

water in the concrete affects the strength characteristics and influences the rheological properties and behavior of concrete during temperature changes. Thus, negative temperatures also have a negative effect on the concrete structure, especially in the period of immature concrete, when it has not yet gained the necessary strength. At critical temperatures, higher values are required. Therefore, when designing concrete structures, it is important to consider temperature values, especially at calculations of fire resistance.

With the help of the LIRA-CAD software the deformations of reinforced concrete slabs were analyzed, which can be used in civil engineering. The calculation parameters are shown in Fig. 13. The problem was solved taking into account the nonlinear materials deformation.

The calculation was divided into three stages:

1. At the first stage, it is necessary to solve the problems of thermal conductivity and in some cases heat capacity at extreme values. Therefore, features that determine the distribution of temperature values in the element of the design and the dependencies that vary

proportionally depending on the time and location of the point of determination of temperature were considered.

2. At the second stage, their dependence on temperature and time was determined via calculations of elastic-moment stresses.
3. At the third stage, the rheological properties (in the case of creep) and the definition of temperature and time-dependent deformations were identified.

The values for modeling and determination of deformations due to internal temperature loads and temperature parameters were uploaded in the LIRA-CAD software, where the calculation was performed to model nonlinearly loaded structure.

Fig. 14 shows the difference in temperature loads that were used on different surfaces of structure modeling. The calculation of the temperature load is shown in Fig. 15, along with the calculation formulas that take into account different parts of the structure.

When implementing the analysis of temperature effects, namely the fire resistance of buildings and structures, the choice of building rules and regulations is fundamental. It depends on the country in which the construction is planned. It is noted that in order to perform a thermo-structural analysis for fire resistance, it is essential to determine how the temperature will be distributed throughout the cross-section of each structural element exposed to fire. To perform this task, it is necessary to conduct an engineering heat-transfer analysis using the finite element method or the finite difference method. Based on the temperature distribution data, it is crucial to take into account the change in material properties and conduct a strength analysis. However, within this approach it is necessary to take into account creep deformations.

The temperature effect and thermal strain are of great importance for concrete structures since these stresses reach the highest values if calculated by conventional methods of structural mechanics. One of the widely known methods for determining deformations of structures under the influence of fire is to take into account the thermal strain in the structure. This can be illustrated by calculating fire exposure of a structure, when determining thermal strain. The room with dimensions shown in Fig. 16 is taken as an example, while the finite element model is shown in Fig. 17.

The analysis of methods for calculating temperature effects on concrete structures in the elastic stage showed that with an increase in the thickness of the structural element, the temperature strain also increases. In other words, it is necessary to enter the limits of permissible loads, deteriorating the conditions of temperature resistance. As a result, the tensile stresses obtained by elastic calculation significantly exceed the permissible ones. Some results of an experimental study that determine the effects of fire on the considered fragment of a reinforced concrete house are shown in Fig. 18.

During the experiment, the fire lasted 6 min it was established that after 6 min of fire, the flame spread throughout the room and was extinguished. Otrosh et al. [33] provide an example of manual

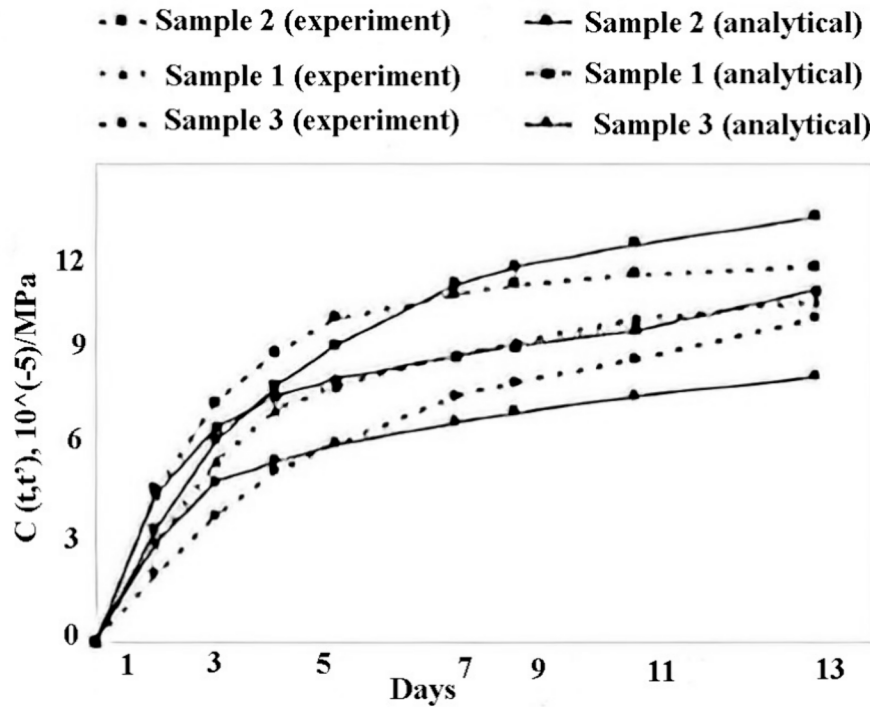


Fig. 12. Comparative graph of creep coefficient.

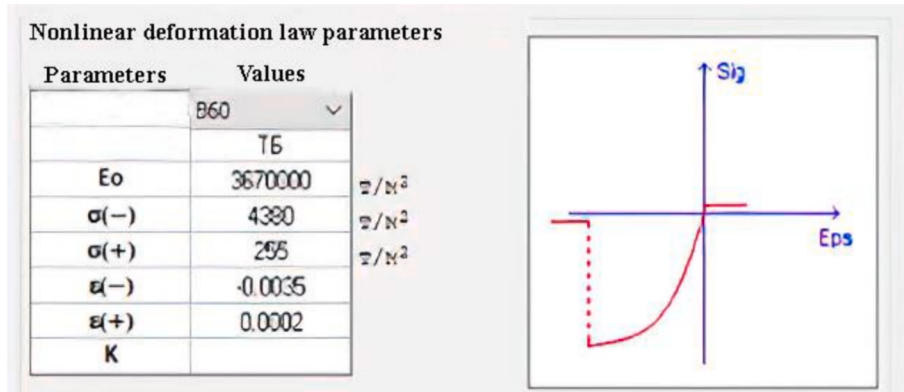


Fig. 13. Parameters of nonlinear materials deformation.

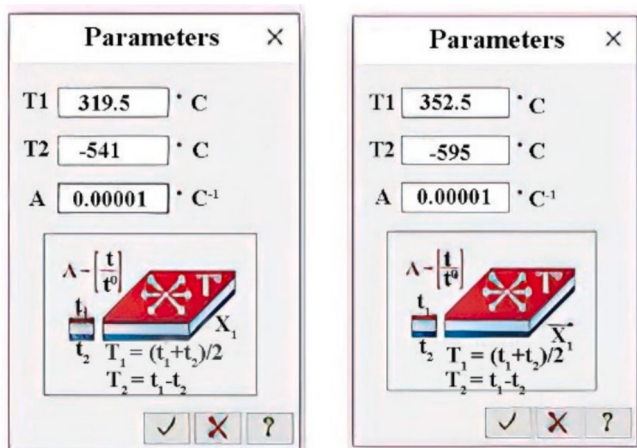


Fig. 14. Temperature loads.

calculation of the deflections of the floor slab of the room when taking into account the fire temperature. The calculation results are shown in Figs. 19 and 20.

Numerical calculation results are given in Figs 21 and 22.

The asymmetry is explained by the fact that the design scheme is not symmetrical, that is, it has the window on the one side of the wall and the door on the other side of this wall. Therefore, there is an asymmetry of movements. Figs. 23 and 24 present the results of calculating the deflections of the walls and floor slab of the construction, which were compared with the analytical calculation.

The statistics show that the following construction deflections [33]:

- when calculating the standard temperature curve $f_1 = 7$ mm;
- when calculating the average temperature by volume $f_2 = 23$ mm.

The calculation made by the LIRA-CAD software is equal to $f_3 = 21.4$ mm.

Statistics for wall deflection is as follows:

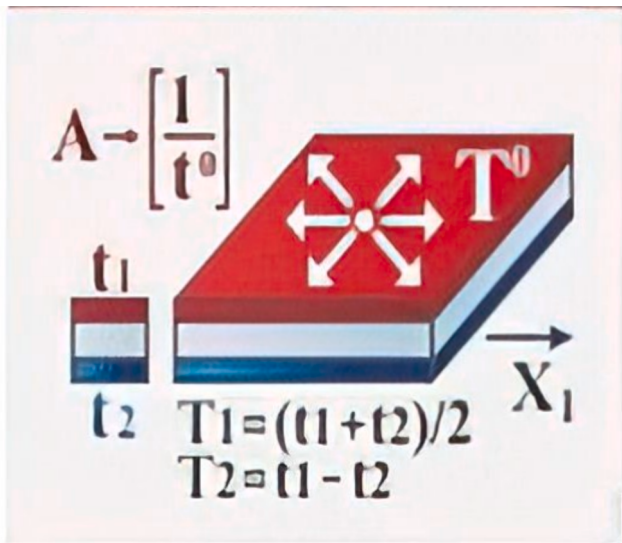


Fig. 15. Temperature loads calculation.

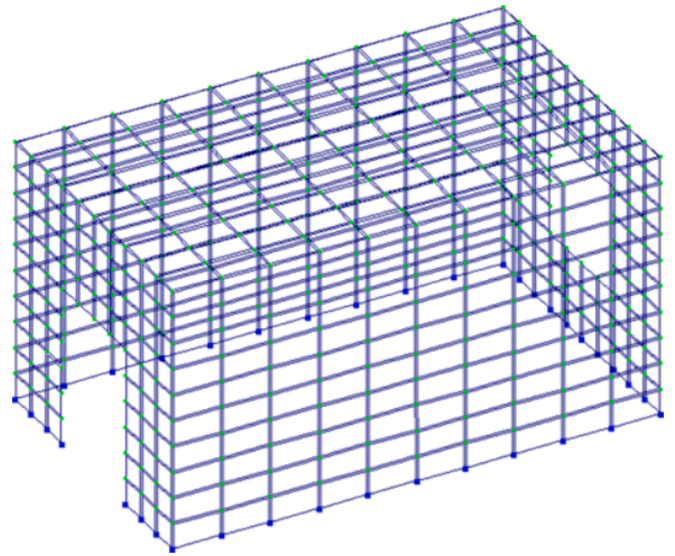


Fig. 17. Finite element model.

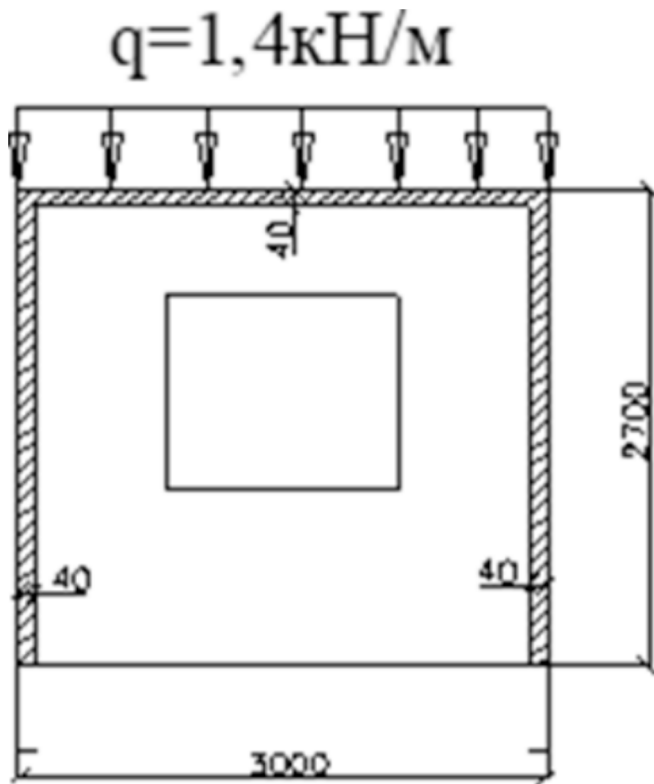


Fig. 16. Geometry of the analyzed room.

- when calculating the standard temperature curve $f1 = 50$ mm;
- when calculating the average temperature by volume $f2 = 57$ mm.

The calculation of the LIRA-CAD software is equal to $f3 = 57.9$ mm.

4. Discussion

To obtain a good concrete structure it is necessary to make the static concrete mixture that has sufficient shear resistance and sufficient viscosity to prevent its delamination during the laying of the concrete mixture. These values should be reduced to a minimum, while structural

properties should be thixotropic. The viscosity of the solution at constant water content is determined by the content of sand and cement: the less water in the cement solution, the more sand is needed. Therefore, when modeling concrete and reinforced concrete structures, rheological properties must be taken into account to ensure long-term operation of buildings and structures. Hence, variable loads, such as creep, constantly affect concrete structures [22,36,1,23,11,9].

When studying the phenomenon of creep, the usual tensor is used, which shows the deformations and how fast they occur. Under ideal conditions or when deformations do not occur, the movement of body points does not occur. To obtain empirical values, necessary conditions that must be met. In some cases, the creep deformations exceed other deformations. The comparison of empirical studies with calculations performed by the classical way and the spatial modeling shows that the classical method takes into account only the initial stresses and does not consider a sufficient degree of deformation that occur with time. This result confirms that the physical and mechanical changes occur not only as a result of classical stresses, but also due to the rheological properties.

Hence, the improvement of calculations through mathematical modeling should take into account not only the classical types of loads. The more factors will be taken into account, the more accurate the calculation will be. The development of programs should link a variety of parameters that would also show the systems and laws of mutual change and could be tested using physical methods. Taking into account rheological properties is more complex than the introduction of constant values or positions because constants do not change as a phenomenon of creep.

According to the theory of creep is complex because it involves changes and time. Thus, the equations should take into account these changes. The system should consist of various simplified equations that would display a range of phenomena and properties. The composition of the materials for which the equations are developed should also be considered for a more complete modeling of spatial structures. Such systems are complex, so the Newton's law in its pure form cannot be used. In these systems, liquids have elasticity and shear forces. To make correct mathematical modeling of their properties, it is necessary to combine the equations which are inherent in hydrodynamics and mechanical equations, which describe the theory of elasticity.

Furthermore, temperature changes should be included in a separate equation that in turn should be related to other parameters. In this way, it is possible to describe deformations depending not only on time but also temperature and rate in order to prevent the destruction of structures due to these deformations [21]. Although there are studies on the



Fig. 18. Stages of arson and fire development of the room.

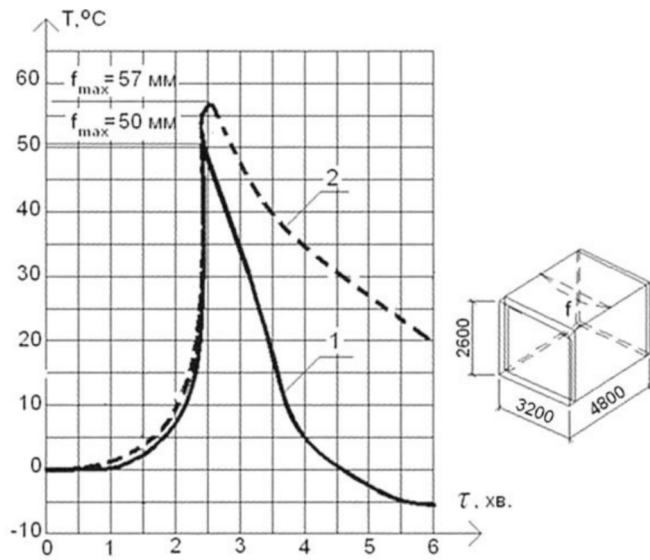


Fig. 19. Floor slab deflections (1 – determined by the average temperature by volume; 2 – defined by standard temperature curve).

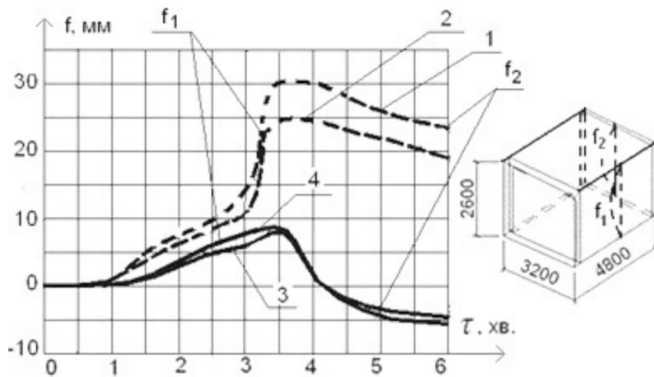


Fig. 20. Wall deflections (1, 2 – determined by the average temperature by volume; 3, 4 – defined by standard temperature curve).

destruction of concrete and reinforced concrete due to temperature, but the mathematical relationships are insufficiently described [25].

For the reliability of the developed methodology, the comparative analysis of calculations with a real phenomenon were conducted, namely the calculations of the temperature effect on the reinforced concrete structure. Fig. 25 shows a diagram of the deformed floor slab at the 240th minute of fire exposure.

During the static physical linear calculation, the maximum

movement of the structure along the Z axis was 19.4 mm. The comparison of vertical movements of the structure during physical nonlinearity calculation is given in Table 5.

As can be seen from Table 5, the values obtained taking into account the physically nonlinear operation of the structure and the reduced characteristics of concrete differ significantly from the linear static calculation, depending on the increase in temperature. At the same time, the creep calculation further increases the vertical movements of the structure. Different regulations describe different methods for determining creep deformations. Fig. 26 shows a comparison of the deflections of the structure using different methods for determining creep deformations, namely: the methods described in STO [36], Eurocode [22,23], and the author's method.

According to calculations made with reference to regulatory documents, this design scheme must withstand fire load for 240 min. Although the degree of fire resistance of the structure is -R240, the calculations by the author's method showed that the stability of the structure was not ensured. The comparison of the number of destroyed finite elements of floor slabs over time is demonstrated in Fig. 27.

According to Fig. 27, as a result of the fire, the lower layer of the concrete is completely destroyed after 180 min of the fire and loses its integrity. Therefore, it can be argued that the lower reinforcement layer will be heated to a temperature exceeding its conditional limit value (600 °C) and will begin to melt. Meanwhile, the upper layer of the floor slab still can bear the loads and can avoid destruction. If the requirements to the slab design are met, the floor slab with a thickness of 300 mm should withstand fire exposure during 240 min. However, Fig. 27 shows that the considered design loses its integrity at the 180th minute of fire exposure. Moreover, at the 160th minute of fire exposure, the deflections exceed the maximum permissible values. The calculation was made for the plate of the Auchan building of the Sky-Mall shopping center (Kyiv). The comparison was carried out after the fire. A photograph of a real object which corresponds to the design scheme of the slab is shown in Fig. 28.

Fig. 28 shows that the lower protective layer of concrete was completely damaged during the fire. Due to the fact that it was designed incorrectly, the temperature of the reinforcing rods reached a critical value. As a result, the reinforcement melted. It is this pattern of destruction that was obtained when calculating the floor slab according to the proposed method, taking into account the thermal refractory coefficient.

So, it is possible to conclude that the analysis of finite-element model by the author's method taking into account creep and changes in ambient temperature coincides with the results of the fire that occurred in reality. Hence, this method should be used in the calculations of buildings designs for fire resistance. Taking into account the impact of creep, it is possible to determine the time of the complete deformation of the structure and to develop an updated method of calculating building design.

The destruction occurs with the line dependence: the higher the temperature, the less load must be applied to cause the destruction. The

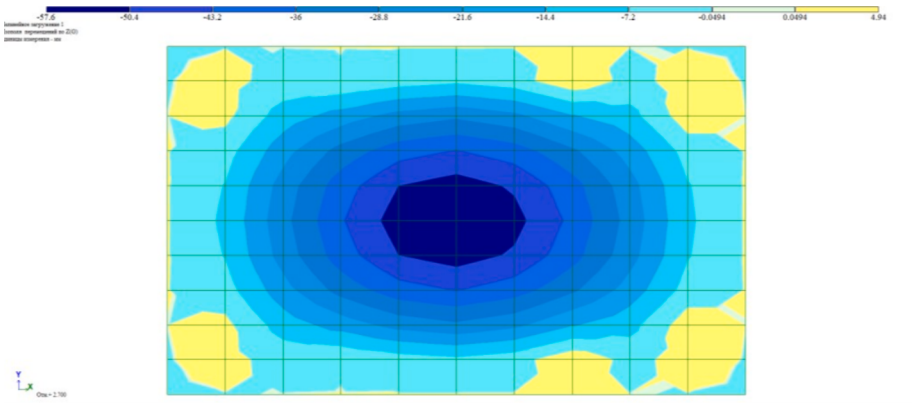


Fig. 21. Vertical movements of floor slab, mm.

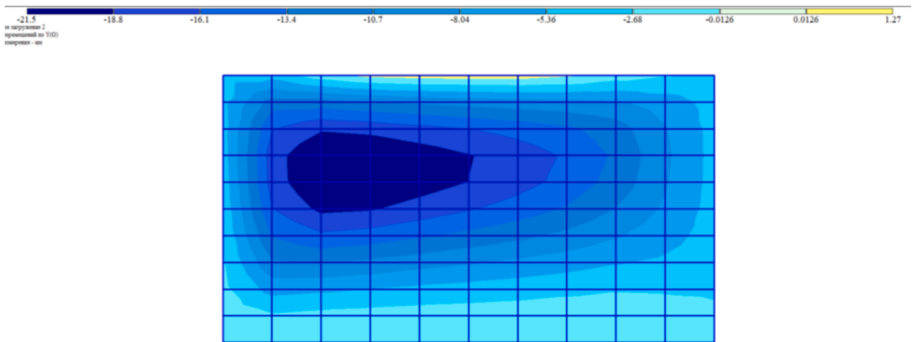


Fig. 22. Epure of displacements from the wall plane, mm.

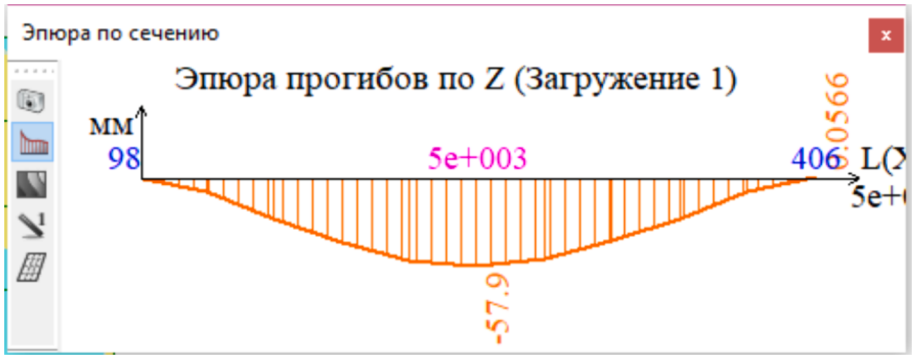


Fig. 23. Epure of plate deflections, mm.

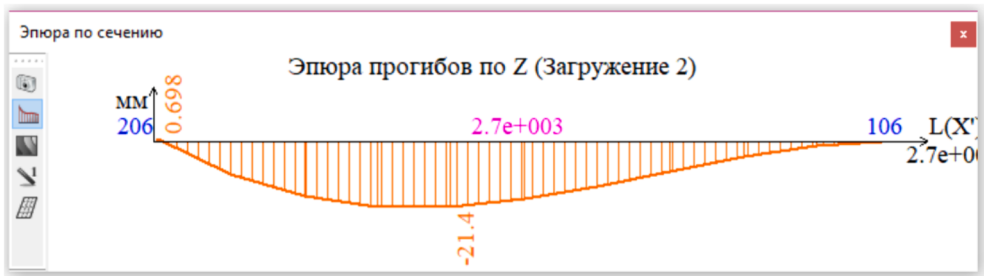


Fig. 24. Epure of wall deflections, mm.

same dependence is applied to time: given the temperature–time loads, the time of destruction by creep increases when the load decreases [27]. Given that concrete made from different manufacturers have different

composition, the deformations caused by rheological phenomena may differ. Accordingly, the formulas should be modified taking into account these differences [13].

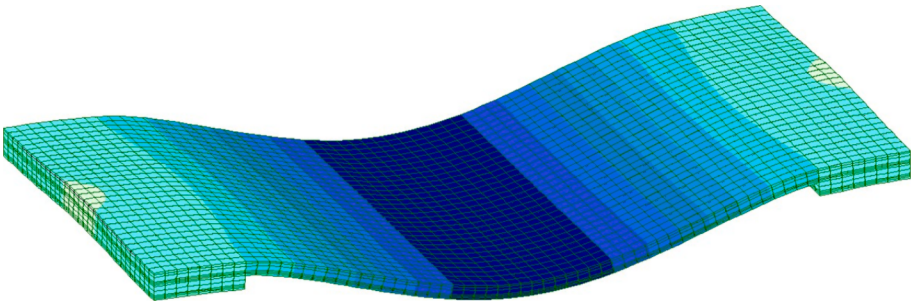


Fig. 25. Diagram of the deformed floor slab.

Table 5
Maximum movements of the structure along the Z axis, mm.

Task	Time of calculating deformations			
	60 min	120 min	180 min	240 min
Physical nonlinearity	16	22	28	28.9
Physical nonlinearity and creep	36.1	82.4	156	233

The analysis of the finite element model taking into account rheological phenomena, temperature effects, and time made it possible to describe and model the deformations that may occur in the fire. Therefore, the LIRA-CAD software can be used not only in spatial structures modeling, but also in calculations of buildings and structures for fire resistance and high temperatures under natural operating conditions.

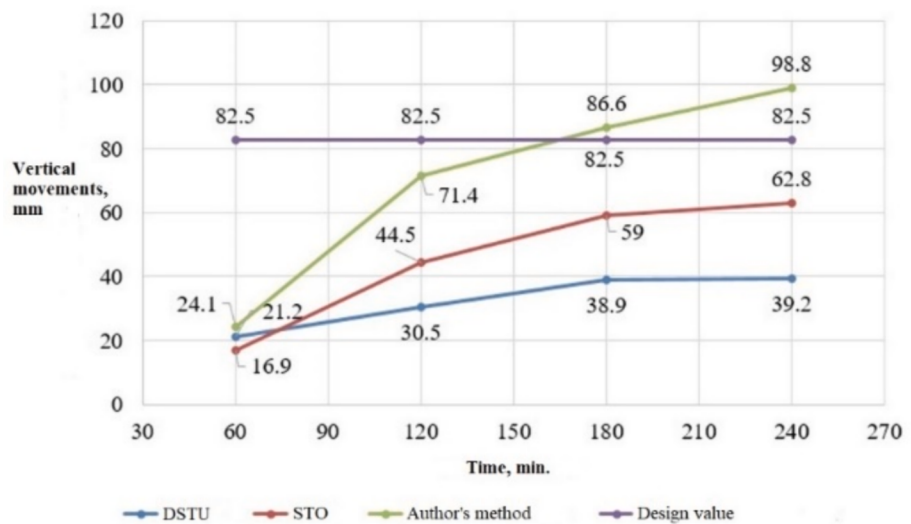


Fig. 26. Comparison of the structure deflections using different methods for determining creep deformations.

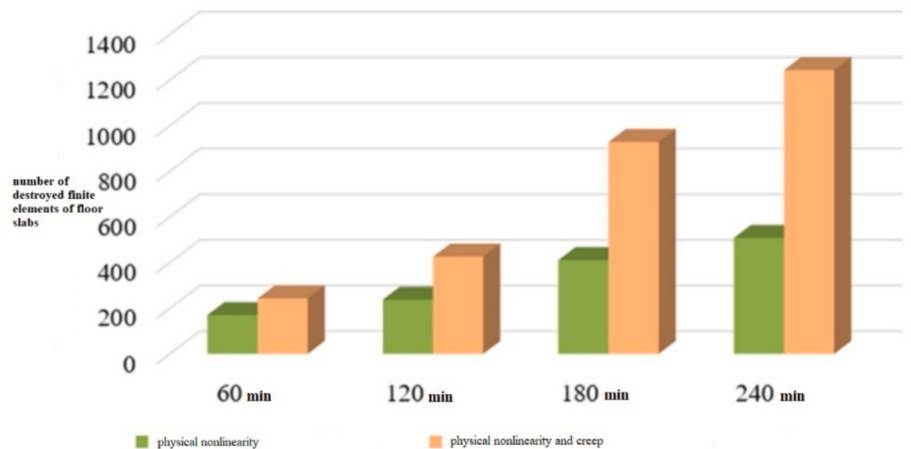


Fig. 27. Destruction of finite elements of floor slabs.



Fig. 28. The consequences of the fire in the Auchan store, the Sky-Mall shopping center.

5. Conclusion

In the course of the study, a number of dependencies were analyzed, taking into account rheological properties and phenomena that can ensure the equilibrium of the elastic-creeping medium. Thus, on the example of the reinforced concrete structure of the overpass, the modeling tasks were considered, taking into account creep and excluding ultimate forms of deformation. At the same time, the dependencies of static and kinematic data were explored and illustrated by graphs.

Using the ESPRI program and the LIRA-CAD software, the modeling of deformations and changes in the concrete environment was carried out. In addition, an increase in stresses in the reinforcement structures over time was investigated. Therefore, it was concluded that the creep phenomenon should be taken into account when designing reinforced concrete structures.

As a result, it was confirmed by an equalizing analysis that the lack of consideration of the impact of concrete creep on modeling reinforced concrete structures of overpasses can lead to destruction and the increased cost of structure repair. Apart from that, if there is the lack of proper maintenance, it can cause emergencies or forced construction reinforcement. Furthermore, theoretical and empirical data of creep coefficients were considered and compared with the experimental dependencies. Thus, the analytical calculation showed an increase in destructive forces and, accordingly, the need to use additional structural reinforcements.

Having considered analytical models of stress epures before and after deformation, it was established that the load-bearing capacity of the models was increased due to the use of metal casing as a reinforcing factor. Thus, the introduction of reinforced polymer materials as reinforcement was considered. Consequently, values of stress-strain state of frame structure element within the analytical model were calculated. Therefore, it was decided to use ASLAN fiber as a fibrous polymer.

Furthermore, the methodology for analyzing reinforced structures was developed using BIM technologies. The ESPRI calculator and the LIRA-CAD software were used to analyze the reinforcement of given structures. Moreover, with the help of these tools, the stress-strain state of the structure was evaluated when modeling its reinforcement by a reinforced polymer fiber through a physically nonlinear statement of the problem.

In addition, the analysis of the finite element model was carried out with the calculation of structures taking into account rheological properties, temperature effects, and time. Accordingly, it was possible to describe and simulate deformations that may occur during a fire. For this purpose, the non-standard problem of calculating thermal conductivity was used. The dependence of deformations on the influence of creep-temperature-time was also calculated, showing different effects over time.

Finally, the technique was developed that allowed to consider rheological properties, electrocorrosion at different stages of time, temperature changes in a numerical form. Thus, the experiment was carried out, which proved the relevance of using BIM technologies in modeling concrete and reinforced concrete structures, taking into account rheological properties and temperature changes.

6. Ethica approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

7. Authrs contributions

Authors' contributions are equal.

8. Availability of data and materials

Data will be available on request.

9. Consent to participate

Informed consent was obtained from all individual participants included in the study.

10. Consent for publication

All individual participants agreed to be included in the study.

11. Fundig

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CRedit authorship contribution statement

Meiyu Shao: Visualization, Project administration, Funding acquisition, Conceptualization. **Maria Barabash:** Validation, Software, Project administration, Conceptualization. **Olha Bashynska:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Yaroslav Bashynskyi:** Validation, Resources, Investigation, Formal analysis. **Andrii Bieliatynskyi:** Validation, Resources, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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