Calculating model allowing to keep the authenticity of transport infrastructure objects

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Abstract. In this work, a calculation model of the building is proposed, which is an object of historical and cultural heritage, which allows, on the one hand, reconstructing the building taking into account the changed operating conditions and regulatory loads according to all the rules of the construction mechanics of the structure, and on the other hand, maintaining the authenticity of the main architectural and decorative elements. The proposed engineering solutions allow for the collaboration of new and historical structural elements, combining the possibility of using modern materials in new structural elements and authentic materials in elements whose historical authenticity is preserved. In the calculation model, it is proposed to use two layers of finite elements, which are responsible for new and historical structural elements, and then ensure the compatibility of their work using special conditions.

1. Introduction

Currently, several tens of thousands of buildings and structures are involved in economic activity, which are historical or architectural monuments or having features of such objects (one of the features is the fact of construction more than a hundred years ago). The issues of operation, repairs and reconstruction of such facilities are regulated by numerous regulatory acts of the federal, regional and local levels, which corresponds to the categorization of such facilities depending on their importance from the point of view of historical and cultural heritage. A separate category is the identified objects of cultural heritage, the measures for the preservation of which have not yet been reflected in the regulatory documentation.

Among all objects of cultural heritage, monuments of federal significance are in the best position, for such objects the most urgent task is their museumification, i.e. bringing the objects into a state that allows for excursions on their territory on an ongoing basis or at a specially designated time.

Cultural heritage objects of regional and especially local significance are often under the economic management or operational management of individual organizations or in private ownership of individuals. Despite the fact that the use of historical objects is regulated by numerous regulatory documents, and in case of failure to comply with certain requirements, procedures are written down to the change of ownership, in reality, recommendations and rules for the use, preservation, registration, protection, town-planning regulation during economic activities or conservation of the object often are not executed, and the object comes to desolation and is destroyed. For objects privately owned by individuals, the urgent problem is when the building is reconstructed or rebuilt by the owner without taking into account its historical and architectural value, which can often be justified by the need for...
normal living conditions at present. The described situations can lead to the loss of a cultural heritage site for posterity.

Often, the loss of historical appearance, architectural authenticity does not occur by malicious intent, but because of a change in the functionality of the object, an increase in the number of visitors, passengers, the use of new technologies, machines and mechanisms in production processes taking place in a particular building, structure that has the features of an object historical and cultural heritage.

The legislative and regulatory acts describe in sufficient detail the actions of the parties involved in the event of a necessary reconstruction or repair, as well as the consequences of failure to comply with all requirements. If the owner of the cultural heritage site included in the register, or of the land within which the archaeological heritage site is located, does not fulfill the requirements for the preservation of the cultural heritage site or performs actions that threaten the safety of this property and entail the loss of its value in relation to cultural heritage sites of federal significance - the federal body for the protection of cultural heritage objects applies to the court with a claim for the seizure of the ownerless contents of the cultural heritage object from the owner's property; in relation to objects of cultural heritage of regional significance, identified objects of cultural heritage - the executive authority of the subject of the Russian Federation authorized in the field of protection of objects of cultural heritage; in relation to objects of cultural heritage of local (municipal) significance - the local government of the municipality.

Problems with the operation and ongoing repair works are most relevant for objects of historical and cultural heritage that are still used for their original purpose: stations, water towers, churches, educational institutions, etc., since the repair and reconstruction of such objects is associated with the direct transfer of certain technological processes to another place, this is especially important for objects of transport infrastructure, since such a transfer is associated not only with the release of the structure from use in established functional chains, but also with a change in logistics schemes.

2. Research methods

The present study is devoted to the development of a model of a building or an object of transport infrastructure, which can allow, on the one hand, the basic characteristics of the structural mechanics of a structure to be calculated, and on the other hand, it will allow to maintain the authenticity of the basic elements and include new structural elements of modern materials in the work of the entire structure, ensuring strength and reliability and the stability of the facility for many years to come [1, 2, 3].

To create such a model, it is proposed to use the finite elements method, which uses linear displacements and rotations of the nodes of the design structure of the facility as the main unknowns, which can describe in sufficient detail both the geometric dimensions of the structure and the mechanical properties of the material of various elements, including, taking into account its aging, changes in elastic characteristics, the development of various defects in the structure, the method allows to duplicate nodes with different fixing conditions [4, 5, 6]. Such a statement of the task and the proposed solution method allow us to separate authentic elements that can be replaced during reconstruction and repair and elements that remain and undergo the decorative restoration only.

As an example of the proposed approach application, we consider the station complex at the Novokhopersk station of the Southeast Railway. The object was erected at the end of the XIX century during the laying of the Liski-Balashov railway. It is formally located outside the city limits of the Novokhoporsky city and belongs to the working village of Novokhoporsky, but since there is no actual border between the settlements, then, according to the List of objects of historical and cultural heritage of the Voronezh region, it refers to the city itself.

Since its founding in 1710, Novokhoporsky, and then the Khopersky earthen fortress (from the mid-18th century - the Novokhoporsky fortress), has been directly related to transport land and river routes, a waterway passed along the Khoper, Vorona, Savala rivers to the Don river and the Ordobazar road connecting Astrakhan with Ryazan and Moscow (Astrakhan tract). At the time of Peter I, six
ships were laid down and launched for the Azov military flotilla. The second time the fortress gains all-Russian significance in 1768, when a new company for the construction of ships of the navy begins, the main work on equipping the fleet was carried out in Pavlovs, in the Novokhopyorsk fortress and on the Ikorets river. At that time, about 30 ships of various classes were launched, is was Alexei Naumovich Senyavin, the Rear Admiral at that time, who led the revival of the Don and then the Azov Flotilla. The name of another great Russian naval commander and Orthodox saint Ushakov Fyodor Fedorovich, who served in the Don Flotilla since 1769 and received the rank of lieutenant in the same year, is closely connected with these places.

The construction of the Kharkov-Balashov railway line (which runs through Novokhopersk) took place from August 1, 1893 to December 17, 1895, i.e. 657 kilometers of the railway were built in just over two years. During the construction of the railway at the end of the 19th century, it was necessary to create completely the entire transport infrastructure - one of these infrastructure facilities is the railway station near the city of Novokhopersk (at that time it was 4 kilometers from the city). The building of the station itself was repeatedly rebuilt and repaired; at present, it is faced with a plastic siding and has almost completely lost its historical authenticity. The train complex of district towns basically always included the building of the station itself, a hospital, residential buildings and a water tower.

The photograph shown in Figure 1a contains an image of a railway hospital, the building has a one-story volume in plan, located in the form of the letter “L”, the long side of which is oriented from north to south. The main facade of the object, facing the red line of the MPS street, has two pediments in the central and right parts, at that a wing crowned by a triangular pediment on the right has a facade extended for one and a half meters to the roadway of the street. Since the building had a purely functional purpose, not so many decorative elements were used in the design of the facades, of which step pilasters can be noted under the pediment of the central part. Elements of the horizontal division of the facade, namely: a five-row cornice, a row of protruding bricks at the level of the windowsill and the edge of the basement, make the building visually more extended relative to its height. Elements of the horizontal division of the facade, namely: a five-row cornice, a row of protruding bricks at the level of the windowsill and the edge of the socle, make the building more extended relative to its height visually. For year-round heating furnaces with a system of ovens and chimneys, ending on the roofs with brick pipes, were used. Currently, the facility is used almost for its intended purpose - there is a railway clinic.

The railway station complex also includes a residential building (Figure 1b), originally intended for residents of the railway and their families. It has a rectangular shape in plan, two residential floors and a gable roof with an attic. The quality of construction is confirmed by the satisfactory condition of the external supporting and enclosing structures of the building with a century of intensive operation and the possible absence of major repairs (only along the edges of the main facade there are vertical cracks passing through brick arches and overlapping side window openings). The residential building was built in a utilitarian style, among the existing external elements of decoration we can note rows of ashlar bricks in the level of window sills of the window openings of the first and second floors, an interfloor cornice and a small risalit in the center of the building, ending in a triangular attic with a stepped niche. The central part of the building contains a staircase and the main entrance from the side of the red line of the street, staircases are lit through a window that is located at the same level with the window openings of the second floor.

One of the initial stages of creating a calculation model of a structure is the transition from a continuum system, the stress-strain state of which is described by continuous functions, to a system with a finite number of degrees of freedom, depending on a finite number of parameters accepted as degrees of freedom, and it is necessary to present the object in the form of a set of bodies of a standard type attached to nodes [7, 8, 9].

A characteristic feature of creating a calculation model of an object of historical or cultural heritage is that it is necessary not only to describe the geometry of a building or structure accurately, to break it into simple finite elements, to set the mechanical properties of the materials used, but also to take into
account defects that have appeared over many years of operation, and actual state of individual nodes and elements. In this paper, it is proposed to divide the given finite elements into elements responsible for maintaining the authenticity and historical authenticity of the object, and into new structural elements that appear during repair or reconstruction, with significant attention being paid to joint work in the calculation of structures for the first and second group of limiting states [10, 11, 12].

Figure 1. Station complex of the city of Novokhopersk, Southeastern Railway: a) a railway clinic, b) a residential building for the railway workers.

To compose the defining relations of the finite element method, it is proposed to use node displacements as the main unknowns, which in the calculation scheme of the displacement method are represented as an absolutely rigid body of infinitesimal size. The basic system of the displacement method, which serves as the basis for compiling a system of canonical equations, is selected by superimposing in each node all the connections prohibiting any displacements. The conditions for
equality to zero of the forces in these bonds are the resolving equilibrium equations, and the
displacements of these bonds are the main unknowns of the displacement method [13, 14, 15]. The
conditions for equality to zero of the forces in these bonds are the resolving equilibrium equations, and
the displacements of these bonds are the main unknowns of the displacement method [13, 14, 15].
The equilibrium equations used in problems of structural mechanics are often written in matrix
form, this form of writing is especially relevant, since the systems of defining equations are solved in
computer complexes in which the bulk of the mathematical operations are represented in matrix form
\[ \mathbf{M} \ddot{u} + \mathbf{R} \mathbf{s} = \mathbf{q} \]. \hfill (1)

Relations connecting displacements, forces, and deformations in (1) are represented in the form
\[ \mathbf{e} = \mathbf{F} \mathbf{s} \] or \( \mathbf{s} = \mathbf{C} \mathbf{e} \), \( \mathbf{s} = \mathbf{G} \mathbf{u} \), \hfill (2)

where \( \mathbf{u} \), \( \mathbf{s} \), \( \mathbf{e} \), \( \mathbf{q} \) - vectors of displacements, internal forces, deformations and external load;
\( \mathbf{M} \), \( \mathbf{F} \), \( \mathbf{C} = \mathbf{F}^{-1} \) - matrices of inertia, ductility and stiffness, respectively, \( \mathbf{R} \), \( \mathbf{G} \) - differential
operators.

For the elasticity theory relations used in the calculation, the indicated values take the form as follows:
\( \mathbf{u} = \begin{bmatrix} u_x & u_y & u_z \end{bmatrix} \), \( \mathbf{s} = \begin{bmatrix} \sigma_x & \sigma_y & \sigma_z & \tau_{xy} & \tau_{yz} & \tau_{zx} \end{bmatrix} \), \( \mathbf{q} = \begin{bmatrix} q_x & q_y & q_z \end{bmatrix} \),
\( \mathbf{e} = \begin{bmatrix} \varepsilon_x & \varepsilon_y & \varepsilon_z & \gamma_{xy} & \gamma_{yz} & \gamma_{zx} \end{bmatrix} \), \( \mathbf{M} = \begin{bmatrix} \rho & \rho & \rho \end{bmatrix} \), \( \mathbf{F} = \mathbf{E}^{-1} \begin{bmatrix} 1 & -v & -v & -v & -v & 1 & 1 \ 0 & 1 & -v & -v & -v & 1 & 1 \ 0 & 0 & 2(1+v) & 2(1+v) & 2(1+v) \end{bmatrix} \).

It is proposed to use the following elements of finite elements for the preparation of the finite-element
calculation scheme:
The calculation takes into account the static components of the loads due to their own weight, the weight
of the equipment, vehicles, passengers, wind, as well as the dynamic pulsating component of the wind load,
taking into account the inertial masses of the weight of the structure and the dynamic components of vehicles
moving in various modes, all types of loads are included into the vector of external loads \( \mathbf{q} \). Inertial loads
are taken into account in the nodes of the design scheme in the direction of the degrees of freedom allowed
by the design scheme, they are used to analyze the contribution of each of the considered forms of natural
vibrations for further structural studies. Internal forces and strains are expressed through displacements,
according to the equations of the theory of elasticity. The solution of equations (1) can be performed using
computational systems that quickly calculate a large number of unknown systems of equations and analyze
the resulting values. In this study, the “Mirage” design and computing complex developed by the NIIASS
(Ukraine, Kiev), freely distributed on the Internet and approved for official use in the Russian Federation, is
used as a computing environment. The complex implements finite element modeling of static and dynamic
calculation schemes [16, 17, 18].

Figure 2 shows a design diagram of structural elements and fragments, the historical reliability of
which is maintained during the reconstruction, authentic pilasters, attics of the entrance block and
foundations are clearly visible.
In the process of calculation, it is possible to obtain the full stress-strain state of the structures of the facility and to analyze the forces and stresses arising in the elements of various materials (the old one for authentic elements, the modern one for newly constructed elements) [19, 20, 21], if necessary, power functions can be redistributed, based on the conditions of joint work and the absence of a limit state in the material of different fragments, which can be represented as:

$$\sigma_e = f(\sigma_1, \sigma_2, \sigma_3, k_1, \ldots, k_n) \leq \sigma_0^+$$

where $\sigma_e$ – equivalent stress, $\sigma_0^+$ - simple monobasic stretching limit, $k_1, \ldots, k_n$ – material parameters.

Sometimes it is more convenient to compare the equivalent stress with the limit $\sigma_0'$, corresponding to the resistance of the sample material with simple uniaxial compression.

To verify compliance with the conditions of compatibility of old and new structural elements deformations, it is possible to determine the main displacements in the structural elements of the building and achieve their alignment in the coincident nodes of the design scheme, in which new and historically authentic structural elements (layers) are joined [22, 23].

3. Conclusions

The proposed calculation model based on the division of structural elements into authentic and newly created allows not only presenting the stress-strain state of the structure, calculating all the dynamic, kinematic and geometric characteristics of the structures for the actual load, but also maintaining a high degree of historical reliability during the reconstruction of transport infrastructure objects, which are monuments of history and architecture or having features of such monuments.

The implemented approach will not only extend the life cycle of historical buildings and structures, but also preserve the glorious history of the Fatherland, develop domestic tourism and create new zones of attraction for people in settlements where transport routes are the main source of income.

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