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ARCHITECTURE & ENGINEERING

Volume 7
Issue 3
September, 2022

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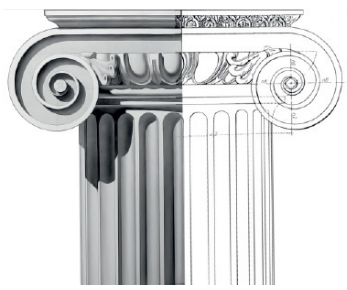
eISSN: 2500-0055
http://aej.spbgasu.ru/

Architecture and Engineering

Volume 7 Issue 3 (2022)

ISSN: 2500–0055



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Architecture and Engineering
peer-reviewed scientific journal
Start date: 2016/03
4 issues per year

Founder, Publisher:
Saint Petersburg State University
of Architecture and Civil Engineering

Indexing:
Scopus, EBSCO, Russian Science Citation Index, Directory of Open Access Journals (DOAJ), Google Scholar, Index Copernicus, Ulrich's Periodicals Directory, WorldCat, Bielefeld Academic Search Engine (BASE), Library of University of Cambridge and CyberLeninka

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St. Petersburg, 190005, Russia

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Email: aejeditorialoffice@gmail.com

Date of issue: 28.09.2022

The Journal was re-registered by the Federal Service for Supervision of Communications, Information Technologies and Mass Communications (Roskomnadzor) on May 31, 2017;
registration certificate of media organization El No. FS77–70026

DOI: 10.23968/2500-0055-2022-7-3-03-12

ADOPTING SMART BUILDING CONCEPT IN HISTORICAL BUILDING: CASE OF ABU JABER MUSEUM, JORDAN

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Abstract

Introduction: Heritage conservation attracts wide attention worldwide. Jordan has many heritage buildings that were preserved, rehabilitated, and adapted to new functions. However, these conservation efforts could not solve the energy consumption problem or maintain the economic and financial balance, thus reducing building efficiency, slowing down the conservation activity, and forcing us to consider new solutions, especially since Jordan has limited energy sources. Integrating smart technologies in historical buildings is widely effective in achieving the sustainability of their historical, symbolic architectural values. **Purpose of the study:** We aimed to explore the potential integration of smart technologies in cultural and heritage buildings. **Methods:** We suggested an alternative solution — adopting the smart building concept in the Abu Jaber Museum in Al-Salt (which recently got on the UNESCO World Heritage List since it has more than 1000 heritage buildings), using an automated lighting control system. **Approach:** We deployed the qualitative method and case study approach to investigate the potential of adopting the smart building concept in the historical building in Al-Salt, Jordan. The study sheds light on the possibilities of utilizing smart technologies in historical buildings in Al-Salt. The findings indicate that smart technologies can offer great opportunity in preserving the architectural heritage and raising the efficiency of heritage buildings. **Novelty:** The study provides a framework based mainly on automated lighting systems in historical buildings. For the first time, the focus was on historical buildings in Jordan and their performance.

Keywords

Historical buildings, lighting, smart building, conservation, Jordan.

Introduction

The world has been going through rapid transformation, especially in the past 20 years. The environment is being damaged significantly, and we are starting to run out of energy sources. Because of that, the main concern worldwide is to protect the environment and save energy as much as possible (Anson, 2014). That is why the concept of sustainability and green cities is being considered in most countries.

Jordan has many heritage buildings with values that cannot be overlooked and must be maintained and integrated with sustainable development plans. Therefore, heritage conservation is a major concern of the government in Jordan in respect to maintaining the value of historical buildings (Akram et al., 2016; Al-Adayleh, 2021). A great number of historical buildings in Jordan have been conserved and adapted to new functions to revitalize the soul of those places. However, like most countries in the world, Jordan is facing a major issue, which is the low efficiency of historical buildings caused by the lack of utilities and energy consumption problem, making it necessary to integrate traditional conservation methods with new approaches in order to solve this crucial issue (Al-Adayleh, 2021).

The study addresses the city of Al-Salt in Jordan, recently put on the UNESCO World Heritage List for its rich history. We chose the Abu Jaber Museum to explore the possibility of installing an automated lighting control system to improve the efficiency of the building. With a new automated lighting control system, we could ensure its continuous maintenance and preserve the memory of the past for the next generations. However, the building is characterized by degrading utilities.

To solve the problem, we will provide an alternative solution to enhance the quality of the Abu Jaber Museum. By applying the smart building concept to the Abu Jaber Museum, it is possible to make it more comfortable and safer for visitors. In addition, this will surely increase the number of visitors to the building. The main problem of the Abu Jaber Museum is the need for lighting (either natural or artificial) and air conditioning.

Our objective was to select a suitable lighting control system to minimize energy consumption and, as a result, enhance the accessibility of historical buildings for future generations.

Literature Review

Studies addressing the use of smart building technologies in heritage buildings, aimed to increase their efficiency and solve the energy consumption issue, are quite limited. There is still a great deal of effort to be done in this area.

Angelidou et al. (2017) investigated how to enhance the historical and cultural heritage of cities using smart city tools, solutions, and applications. They explored the incorporation of the historical and cultural heritage within three smart city strategies, and concluded that cultural heritage should be systematically exploited and formally incorporated in smart city initiatives. According to Pierucci et al. (2018), smart building-integrated adaptive technologies show benefits in terms of comfort and operational energy when compared to traditional ones.

Studies and practices have shown that it is possible to improve efficiency and energy consumption in historical buildings by integrating the smart building concept into such buildings. Several successful attempts in implementing smart technologies in historical buildings have proven their positive impact on the historical value and uniqueness of such buildings. One of those successful examples is the Renwick Gallery of the Smithsonian American Art Museum (Washington DC, United States). It was built by the architect James Renwick Jr. in 1859 (Figure 1).

It was restored for the first time in the 1960s as an art gallery. During the 2011 Washington D.C. earthquake, the building was damaged. As a result, in 2013, it was closed for renovation and re-opened only in 2015. Figure 2 below shows the floor plans of the Renwick Gallery of the Smithsonian American Art Museum with zoning using color legends.

As shown in Figure 2, the building has three floors. Recently, smart technologies were integrated in the building to improve its efficiency. The focus was on the integration of electrical and mechanical systems, namely, the installation of LED lighting, phone, and information systems, the introduction of climate control and relevant infrastructure. As a result of smart technologies adoption, the museum got a rating of 9.74% using the smart building guide. All these measures significantly reduced the environmental footprint of the building. Besides, energy consumption decreased by ±50% although the number of visitors increased.

Another great example of smart technologies use in heritage buildings can be found in Águeda, Portugal. In 1834, this historical city built on a foundation of successive Celt, Turduli, and Greek inhabitants since 370 BC, became a municipality. The city is considered the first smart heritage city in Portugal. It was the first to adopt energy-saving, lighting, and air conditioning systems in its heritage buildings and public spaces. The municipality focused on the participation of the population, providing them with interactive mechanisms so as to create a connection to the town. According to the latest records, Águeda achieved a reduction of 20% in greenhouse gas emissions and aiming to reach 33% in 2022.

The results of various attempts show that the implementation of smart technologies in historical buildings is an efficient approach that helps enhance their historical value and reduce energy consumption

Figure 1. Renwick Gallery of the Smithsonian American Art Museum before and after rehabilitation. Source: WBDG (2017)

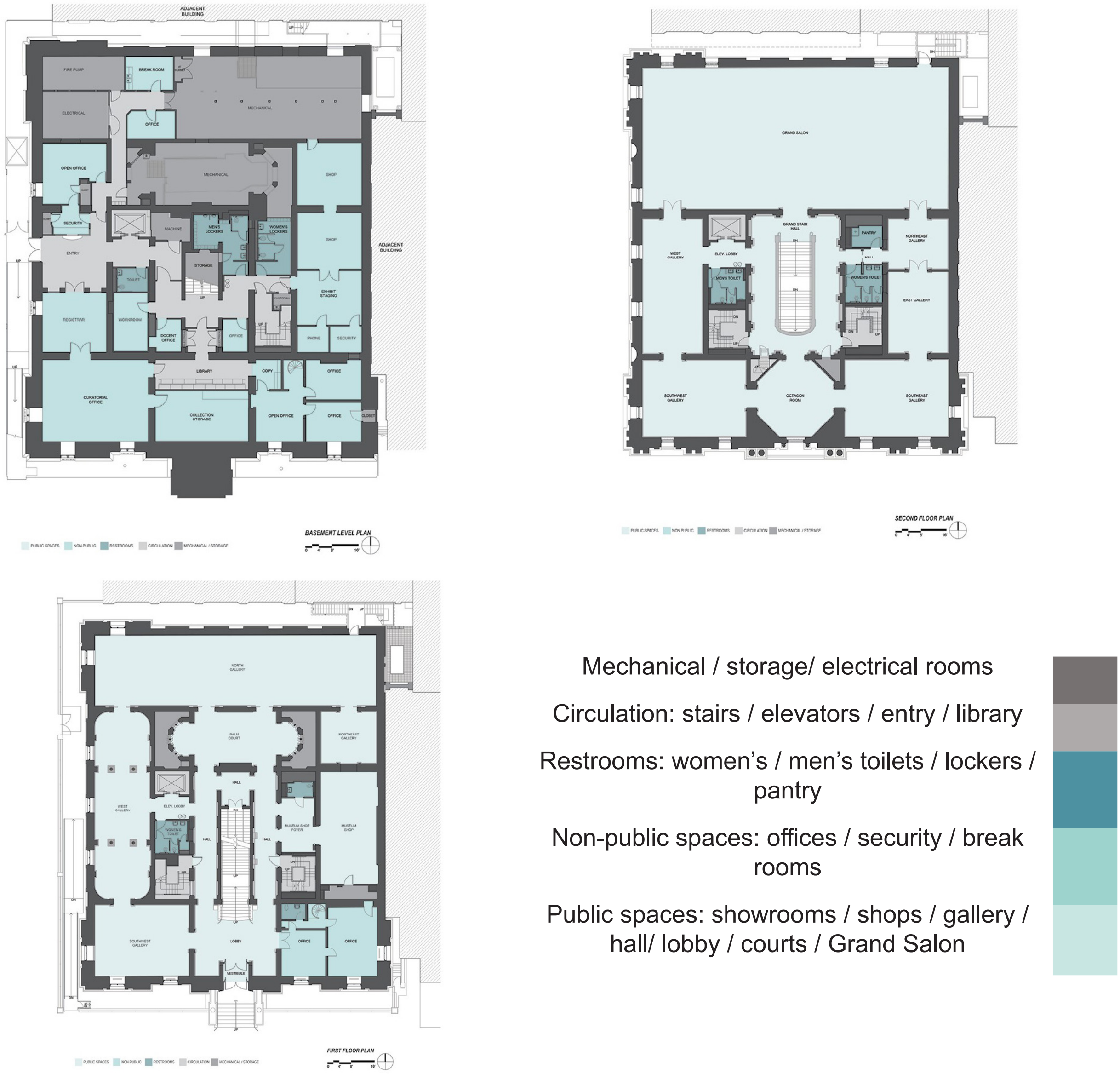


Figure 2. Floor plans of the Renwick Gallery (basement, first floor, and second floor). Source: WBDG (2017)

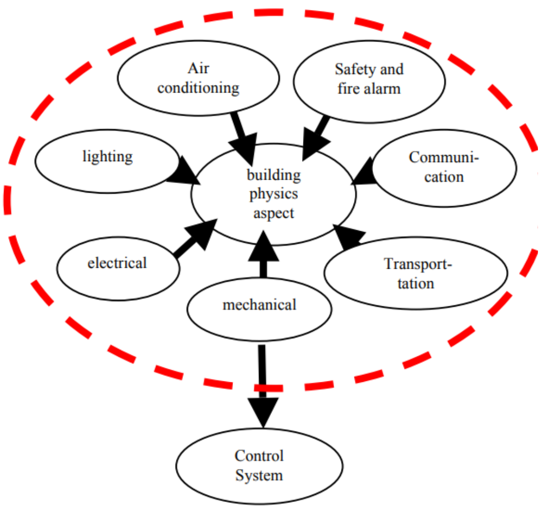


Figure 3. Smart building concept aspects. Source: Purwantiasning and Bahri (2017)

costs, while preserving the architectural heritage. As the smart heritage literature continues to grow and further applications are developed, it seems likely that it will dominate the innovative discussions of the heritage discipline and formalize alongside smart mobility and smart infrastructure.

Methodology

Our qualitative study was based on two methods: descriptive and analytical. Among other things, we also needed to gain a deep understanding of the “smart building” and its physical characteristics with a focus on the lighting system. For a qualitative analysis, we considered several previous attempts of adopting smart technologies in historical buildings. The goal was to suggest a solution or framework for integrating an automated lighting control system, using Bait Abu Jaber in Al-Salt, Jordan, as a case study. In the course of our work, we analyzed some previous studies and used the inductive approach. We performed a pilot survey to choose an appropriate building based on observations over heritage conservation projects in Al-Salt.

The criteria for choosing a building were as follows:

1. Age: 80–100 years old.
2. Landmark: not abandoned, occupied by local community, contributing to social-economic development.
3. Architecture: a distinctive architectural style.

Materials and Methods

1. Smart Building Concept

The “smart building” term has several definitions proposed. According to one of the definitions (Al-Omari, 2007; Brusaporci and Maiezza, 2021), a smart building is any structure that uses automated processes to automatically control the building’s operations, including heating, ventilation, air conditioning, lighting, security, and other systems. This definition is close to another one (Gunatilaka et al., 2021; Khoshelham, 2018): a smart building is a building, which is equipped with fully automated building service control systems. According to Omar (2018), a smart building is a building that has the ability to learn and take into account its users’ interactions with the space.

In conclusion, we can say that a smart building is a building that uses technology to enable efficient and economical use of resources, while creating a safe and comfortable environment for its occupants. Smart buildings utilize a wide range of existing technologies and are designed or retrofitted in a way that allows for the integration of future technological developments. Internet of Things (IoT) sensors, building management systems, artificial intelligence (AI), and augmented reality are a few of the mechanisms and robotics that may be used in a smart building to control and optimize its performance.

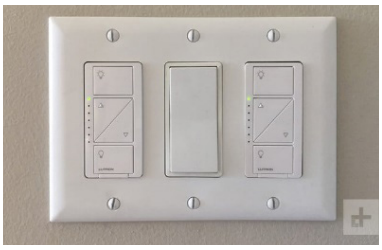
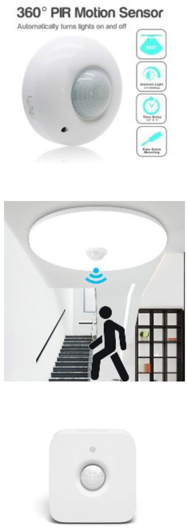
2. Smart Heritage Building Concept

Over the past 15 years, a great number of academic literature records highlighted smart heritage. As we can see, researchers (Batchelor et al., 2021; Purwantiasning and Bahri, 2017) referred to smart heritage as “the use of technology to optimize decision making on the use and management of heritage buildings”. Researchers also mentioned that “smart heritage focuses on adopting more participatory and collaborative approaches, making cultural data freely available (open), and consequently increasing the opportunities for interpretation, digital curation, and innovation” (Batchelor et al., 2021; Purwantiasning and Bahri, 2017). The majority of literature sources identify smart heritage as “offering an innovative new frontier in the convergence of smart technology and heritage disciplines”. When it comes to applying the smart building concept, several aspects should be taken into consideration (Khoshelham, 2018; Purwantiasning and Bahri, 2017). Those aspects are lighting, air conditioning, safety and fire alarm systems, communication, transportation, mechanical (plumbing, etc.), and electrical.

By lighting we mean an automated lighting system to reduce energy costs and improve sustainability. Any lighting system should include several main components: a switch, a dimmer, sensors, and programmers (Latifah, 2015). Each of them are described in detail in the table below.

Table 1. Components of a lighting system (compiled by the authors, 2022)

Name	Description	Image
Switch	A Wi-Fi enabled device that allows you to control the light.	 Figure 4. Wi-Fi switch. Source: LoraTap (2022)

Dimmer	A device used to adjust the brightness of the light.	 Figure 5. Light control dimmer. Source: Digital Trends (2022)
Sensor	A device used to detect and convert light energy into electronic signal depending on a user's motion. Provides self-identification, smart calibration.	 (a) (b) (c) Figure 6. Light sensors: (a) a PIR sensor, (b) a motion sensor, (c) a lux sensor. Source: Walnut Innovations (2022)
Programmer	A device used to control lights in particular conditions.	

3. Sensor Types

1. PIR: (passive infrared sensor) an electronic sensor that measures infrared (IR) light radiating from objects. It can detect movements of objects and radiant heat emitted from them. The sensor ensures auto-switching of lights or other fixtures based on human occupancy in residential and commercial buildings.

2. Lux sensor: concerned with the amount of light falling on a surface (light intensity).

3. Motion sensor: detects movement in and around your home and triggers an action in response. Motion sensors are recommended to be placed at least 6–8 feet off the ground.

Case study of the Abu Jaber Museum (Bait Abu Jaber), Al-Salt

Since the study addressed historical buildings in Jordan, we decided to shed new light on Al-Salt, which was recently (in 2021) inscribed on the World Heritage List by UNESCO. The city has a high potential value, which is due to dense heritage buildings (the number of which exceeds 1000): churches, mosques, and residential buildings aged more than 100 years (Khirfan, 2013). They all were built from yellow stone, and that distinguishes the city from the others. We chose the Al-Salt historical museum (Bait Abu Jaber) as a case study to apply the smart building concept to. According to Khirfan (2013), this historical museum was initially supposed to highlight "the Golden Age of Salt".

Bait Abu Jaber was built in the late 1800s as a residential house for the Abu Jaber family. It is one of the oldest buildings in Al-Salt, which was constructed in two phases: the first phase was completed in 1896, and the second phase was completed in 1902 with a new floor added. The building has a thick wall of 60–100 cm and a cross vault roof (Figures 7–8).

In 2010, the building was rehabilitated and transformed into a museum (Figures 9–10). Its location in the center of Al-Salt has a vital and strategic role since the museum is expected to attract visitors, while preserving the historical value of the building.

Results and Discussion

The Abu-Jaber residence is a significant residential compound in the city of Salt, the former capital of Jordan. It is where Prince Abdullah resided upon the founding of Jordan as a state in 1923. Besides, it is one of the finest examples of a merchant house of the 19th century, incorporating architectural detailing from the greater Syria region in addition to Europe. Its architecture represents the golden age of Salt, when the city was the hub of commercial, political, social, and artistic activity. It was built in stages incorporating the courtyard house and the three-bay houses on its floors (Malhis and Al-Nammari, 2015).

When analyzing the building, we found out that despite great conservation efforts applied to the building, its efficiency is low, and the museum lacks utility services since the maintenance is too expensive. Besides, more than 38% of its income are spent on energy, which is quite high percentage. Therefore, we intended to provide an alternative solution to this issue, which would help increase the efficiency of historical buildings. The approach we used can be seen as a two-stage process: documenting and assessing the current state of the building in terms of lighting; preparing a plan for the installation of an automated control system in the building. Figure 11 shows that the south elevation of the museum has small, narrow openings. Figure 12 shows that the east and west sides of the museum are not that wide to let inside some significant amount of natural light. In other words, the light intensity in the building is low.

Information on light intensity standards for various spaces can be found in the IES Lighting Handbook (KUPDF.NET, 2018). The recommended level of light intensity for museums is 300–500 lux. However, the level of light intensity in Bait Abu Jaber corresponds to that suitable for residential buildings. In other words, it does not meet the requirements of the standards and is not enough for a museum. Figure 13 shows that the level of light intensity in the museum rooms is low.

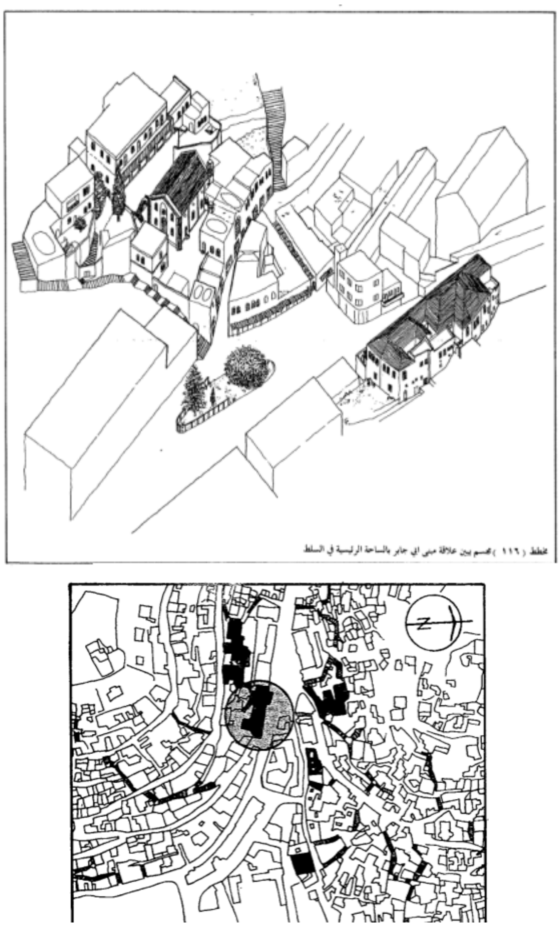
With that in view, to meet the requirements of the standards for lighting in a museum, we suggest using a smart lighting system that includes the following three components:

People’s movement through the museum shows that some rooms/spaces require a different level of lighting because of their nature. Thus, it is required to enhance lighting in the museum to make the area more comfortable for visitors. That is why we decided to suggest installing a motion sensor to ease the detection of visitors’ movement.

To ensure maximum performance, such sensors should be placed in the following locations:

Figure 7. Exterior of the Abu Jaber Museum. Source: Turath office. Documents on the Abu Jaber Museum. 2021

Figure 8. Exterior of the Abu Jaber Museum. Source: Turath office. Documents on the Abu Jaber Museum. 2021



Figures 9–10. Location of the Abu Jaber Museum in Al-Salt. Source: Turath office. Documents on the Abu Jaber Museum. 2021

Figure 11. South elevation of the Abu Jaber Museum with small, narrow openings. Source: Malhis and Al-Nammari (2015)

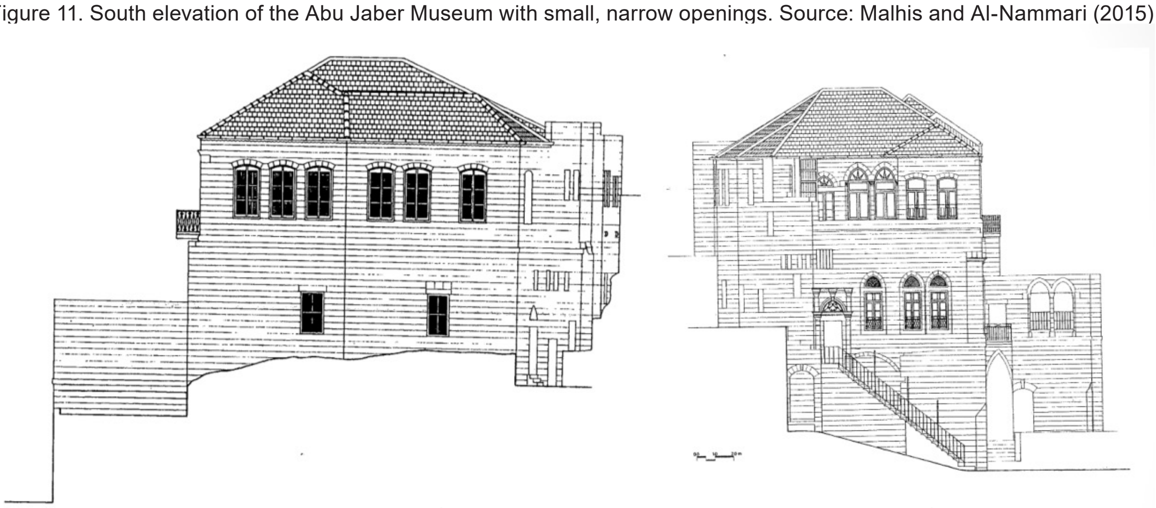


Figure 12. East and west elevations of the Abu Jaber Museum. Source: Malhis and Al-Nammari (2015)

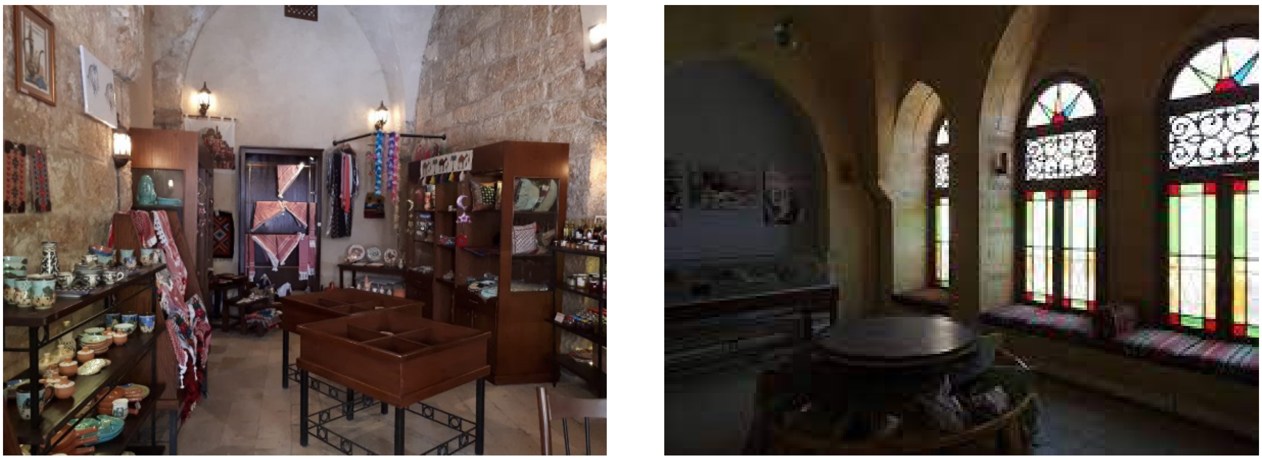


Figure 13. Photos of the Bait Abu Jaber interior, showing the actual state of affairs in terms of light intensity. Source: Turath office. Documents on the Abu Jaber Museum. 2021

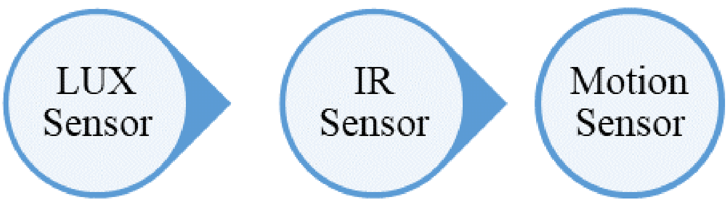


Figure 14. Smart lighting system suggested by the authors (2021)

Corners: these locations ensure the widest possible view of the space below (provided that they are directed at the doorway).

Front and back doors: placing motion sensors above doorways keeps them out of sight and makes it nearly impossible for intruders to enter without setting off the alarm.

High-traffic areas: equipping stairways, main hallways and other high-traffic areas with motion sensors ensures that intruders trigger the alarm regardless of where they're trying to go.

Near valuables: putting a motion detector near or behind valuable items will make it so that the alarm is sounded if an intruder attempts to move or steal them.

Besides, light intensity sensors and controls should be installed near the wall openings. Figure 15 shows the floor plans of the Abu Jaber Museum and the level of light intensity in the museum rooms, using color codes.

Low intensity: blue color
Medium intensity: yellow color
High intensity: red color

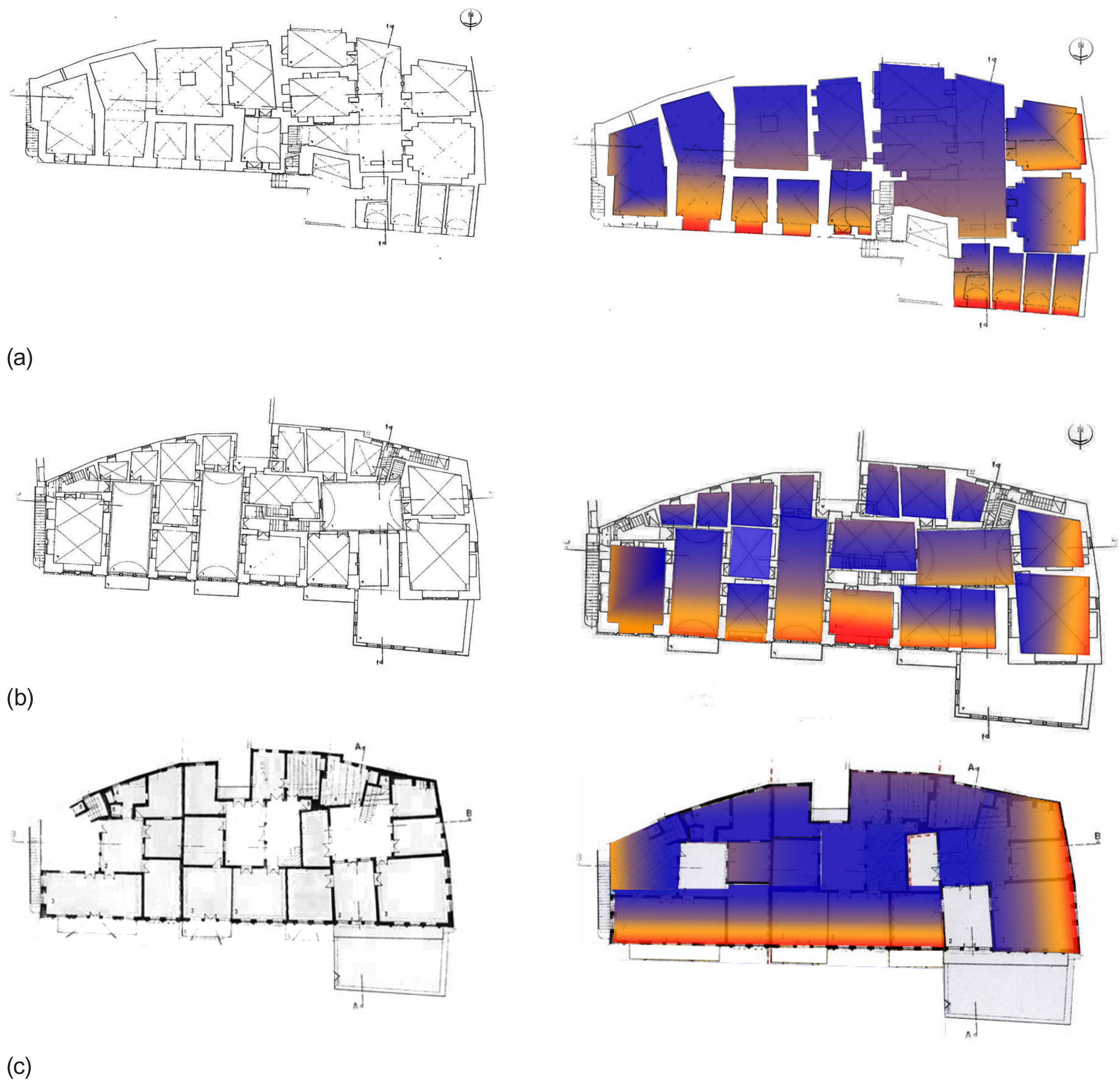


Figure 15. On the left: floor plans of the Abu Jaber Museum (basement, first floor, and second floor). Source: Turath office. Documents on the Abu Jaber Museum. 2021.
On the right: lighting evaluation for the Abu Jaber Museum, which shows light intensity in the museum (drawing by the authors, 2022)

Conclusion

The conservation of historical buildings in Al Salt, Jordan, is the main concern of the local government since the city recently got on the UNESCO World Heritage List. Adopting new solutions in historical buildings to ensure their maintenance and save energy is becoming essential. Therefore, we aimed to introduce the smart building concept into a historical building (Abu Jaber Museum) in Al-Salt, Jordan. For that purpose, we suggested introducing one of the smart building technologies (automated lighting system) in the museum to improve its efficiency and maintain the economic and financial balance.

The results showed that the level of light intensity in the museum does not meet the level recommended in the applicable standards, which has an adverse effect on building efficiency. With that in mind, we suggested a smart lighting system and its simulation model. The simulation results showed that energy consumption might be reduced by 40–43%, potentially lowering maintenance costs for the Abu Jaber Museum in particular and historical buildings in general.

In conclusion, we can say that historical buildings are environmentally friendly. Therefore, smart technologies can offer buildings a great possibility to become smart buildings while keeping their historical value.

This study lays the groundwork for future research on adopting the smart building concept in historical buildings in Jordan. The findings of the study have several important implications for future practices regarding heritage buildings. The study also presented a new approach that can be of interest to users, architects, interior designers, local authorities, and other stakeholders in gaining a better understanding and ensuring heritage building rehabilitation and development.

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DOI: 10.23968/2500-0055-2022-7-3-13-20

HOUSEHOLD BUILDING (LATE 17TH–19TH CENTURY, RYAZAN KREMLIN) RESTORATION AND ADAPTATION TO MODERN USE

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Abstract
Introduction: The issue of preserving historical and cultural heritage is currently highly relevant. The restoration of ancient architectural structures, preservation of their historical appearance, and adaptation to new functions constitute an important step forward towards that goal. Considering the situation with cultural heritage sites in Ryazan, we should note that the city really needs such measures. Many historical, cultural, and architectural monuments have been lost and continue to be destroyed because of incompetent interference with their architectural-and-planning structure (demolition, unauthorized reconstruction, etc.). **Purpose of the study:** We aimed to describe the specifics of the preservation, restoration, and adaptation of cultural and historical heritage sites to modern needs. **Methods:** In the course of the study, we used a systemic approach, analyzed various sources and materials on the restoration and protection of historical and architectural monuments. **Results:** In the paper, we consider a particular example from the architectural practice of adapting a part of an ancient structure to modern use. The paper gives a brief historical background and information on the structures and materials used, discusses methods and technological solutions, analyzes design solutions. Based on the results of the works conducted, we determine issues of adapting a recognized cultural heritage site to modern living conditions and using it in a new capacity in accordance with the applicable regulatory documents. When facing the issue of adapting historical buildings that have lost their original function, it is necessary to perform works without changing their protected features. Within the framework of cultural heritage site preservation, a concept has been developed to serve as the basis for its conversion and operation as a cafe.

Keywords
Cultural heritage site, architectural monument, preservation, restoration, adaptation to modern use, methods and techniques, Ryazan Kremlin, Ryazan.

Introduction

Any ancient city, regardless of its size, has rich cultural and historical heritage that has come to us from past eras. The need to preserve historical heritage is essential for the formation of cultural values. It is a memory of prominent figures and important events of a city, which makes it possible to look into the past, evaluate the present, and get a glimpse of the future (Gerasimova and Karasova, 2020).

Besides, buildings connecting the new generation with the old are increasingly perceived as significant historical sites, which will be in demand for tourism development (Aldohdar, 2020) and can become one of the main sources for the replenishment of the regional budget.

When exploring this issue, it is important to turn attention to relevant studies of modern researchers (both Russian and international). For instance, Khakimov and Trebukhin (2019), Novopashina et al. (2012), Sokolov (2016), and Sakharova (2011) addressed the modern use of cultural heritage objects. Pastukh et al. (2020) discussed the need for the maintenance and repair of historical buildings.

Papers by Solntsev and Petrov (2013) as well as Valegrakhov (2014) are interesting in terms of the economic assessment of cultural heritage sites. Markovich and Luchkova (2011), Romanova (2017), and Zhitlova and Petreneva (2019) explored the adaptability of historical buildings.

In the course of the study, we considered such well-known converted sites of historical-and-cultural, economic, and social significance as the Duisburg-Nord Industrial Landscape Park (Klimova, 2017) and the Zeche Zollverein industrial complex (UNESCO, 2021) in Germany as well as the main house of the Karaul Estate in Tambov Region (Tmbreg.ru, 2015).

Such researchers as Pankratova and Solov'ev (2015), Mokhovikov et al. (2019), Pravdolyubova et al. (2021), and others were engaged in regional studies.

Based on this, it is obvious that the issue of preserving and adapting architectural monuments to modern use is high on the agenda.

Function of the cultural heritage site: historical accounts

The Household Building (late 17th century, 19th century), a recognized cultural heritage site, is located in the south-east of the Kremlin Ensemble (13th–15th centuries, 16th–20th centuries) historical monument of federal significance and was built near the side wall of the Consistory Corps at the end of the 17th century and consisted of three units with different functions: a cooper's shop, a blacksmith's shop, and "sheds for various goods". Initially, the units were not connected, and each had an individual entrance from the courtyard (Kolesnikova, 2012) (Figure 1).

In the course of its operation, the building changed its function and appearance several times. In the 19th and 20th centuries, it was rebuilt to become a residential building. Following the restoration of 1970, the exterior of the architectural monument underwent some changes. The large arched gates were converted into windows. Three new window openings were made in the south blind wall. The building was converted into an office of a historical-and-architectural museum-reserve and then — a boiler room (its latest function) (Figure 2).

Materials and methods

Prior to the development of architecture-and-design solutions to adapt a part of the historical Household Building (late 17th century, 19th century) to modern use, as a cafe, a scientific research was performed. First and foremost, bibliographical and archival sources were studied. Then the

Figure 1. Buildings of the Ryazan Kremlin
1 — the Assumption Cathedral; 2 — the bell tower; 3 — the Bishop's House; 4 — the Cathedral of the Archangel; 5 — the Church of the Holy Spirit; 6 — the Nativity of Christ Cathedral; 7 — the Consistory Corps; 8 — the Singing Corps; 9 — Glebovsky Bridge; 10 — the Cathedral of the Transfiguration of the Savior; 11 — the Church of the Epiphany; 12 — the hotel for monks; 13 — the walls and towers of the Monastery of Our Savior (Spassky Monastery); 14 — the hotel for the nobility; 15 — the household building; 16 — the stables; 17 — the rampart; 18 — the clergy house

Figure 2. Household Building (late 17th century, 19th century), current state. Photo, 2021

visual inspection of the building was performed and its photos and measurements were taken (Figures 3, 4, 5).

Justification of design solutions

It is obvious that since the social structure of society and living conditions changed, the original functions of the historical site turned out to be lost. They do not longer meet the current practical needs. Therefore, to further preserve and use the architectural monument, it is necessary to adapt it to the new reality.

The key in the adaptation of such structures is the right choice of a new function that would take into account the values of the site as well as the present-day social needs and conditions.

Currently, legislative documents define the restoration of cultural heritage sites as a

Figure 3. Facades of the building. Photos, 2010

Figure 4. Condition of the interior walls. Photos, 2010

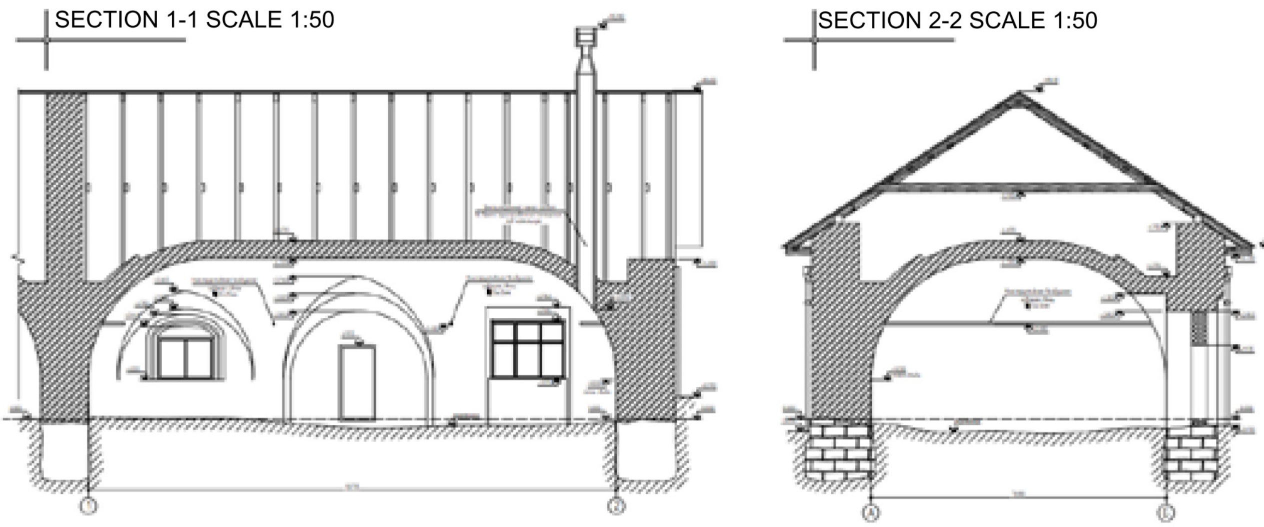

Figure 5. Measurements of the building

comprehensive scientific approach that includes many aspects and tasks pertaining to research, survey, design, and production that shall be considered when conducting operations on their preservation.

In this connection, a specialized organization performed a research and developed a project for the preservation of the cultural heritage site. The project includes activities on restoration and adaptation, i.e., the process of selecting a function that would preserve the appearance, dimensions, and individual characteristics to be protected to the maximum extent, while taking into account the significance of the site as an architectural monument.

The project for the restoration and adaptation of a part of the Household Building (late 17th century, 19th century), a recognized cultural heritage site, to modern use was prepared by OOO Regional Engineering Center (designer, Moscow). The restoration and adaptation of the monument were carried out by OOO Proyektrestavratsiya (contractor, Ryazan).

1. Architectural solutions

The Household Building (late 17th century, 19th century) is a one-story structure, rectangular in plan, with a gable roof, stretching from north-west to south-east. The exterior walls are made of oversize solid clay bricks. The foundations are strip, made of rubble masonry. The window and door openings are wooden.

The ceiling is made of brick, with trough vaults in the outermost rooms, and basket-handle arches in the rooms in the middle (Kolesnikova, 2012).

At the time of design documentation compilation, the walls and ceilings had no interior decoration. The floors are lost. The technical condition of the building was determined as satisfactory.

To increase interest in the architectural monument both among tourists and locals, it was decided to include it in the Monastic Meal tour around the Kremlin. To ensure maximum access to the monument, the project proposed the restoration and adaptation of the outermost room (boiler room) in the building of the architectural monument of the 17th century (Household Building (late 17th century, 19th century)) to a cafe. In today's reality, this function is the best option for the preservation of a historical monument.

Since we are talking about a listed property, the repair and adaptation of cultural and historical heritage structures to modern use shall follow the applicable laws and regulations. These works include the preservation of the original historical appearance as well as structural-and-planning solutions. However, the adaptation of a historical structure to modern standards of safety and essential services inevitably leads to its partial reconstruction and brings particular challenges. In most cases, architectural and planning issues are related to the sanitary-and-hygienic as well as fire safety requirements that have been tightened recently. Since the volume of an architectural monument shall remain the same, they prohibit production in such areas.

The adaptation of the site was carried out with account for the existing planning structure.

The total area of the cafe is only 99.3 sq. m. According to the sanitary-and-hygienic standards, it is impossible to ensure the full-fledged operation of the cafe in such a small area. That is why the project proposed to create a typical diner using semi-finished products almost brought to readiness.

To solve the task, the rectangular room is divided into two functional areas: public and service ones. The public area includes a dining hall for 16 people and a bathroom for visitors. The service area includes a kitchen, a wash room, a storage room, and a staff room with a changing room and a bathroom.

On the northern facade, it is assumed to make an entrance space with two doors and a vestibule. One of the doorways (to be used as the entrance to the cafe by visitors and staff) is formed by the expansion of the existing archway, and the other (to be used to unload products) is made in the late masonry. Such a combination of the entrance for staff and the entrance for visitors is determined by the fact that it is impossible to make an additional opening in the walls of the architectural monument.

Modern fire safety requirements regulating the size and number of escape routes and emergency exits contradict the requirements of regulatory documents applicable to the preservation of cultural heritage sites, in particular in terms of the arrangement of emergency exits. Since, due to the above circumstances, it is impossible to make a second emergency exit, the number of people in the building cannot exceed 20 people: 16 seats for visitors and 4 workplaces.

To ensure equal access to cultural heritage sites and in accordance with the requirements of regulations and state standards (Federal Agency for Technical Regulation and Metrology, 2018; Ministry of Construction, Housing and Utilities of the Russian Federation, 2017), the project provided for some measures for persons with reduced mobility — a paved sidewalk with stairs and a ramp at the approach to the building. Besides, in accordance with the requirements, a semicircular canopy with well-developed forged brackets is proposed above the entrance.

The project also proposed to cover the flooring of the ramp, landing, and vestibule with anti-slip ceramic granite tiles. The one-way ramp has a clear width of 1 m and a slope of 10%.

To ensure the mobility of disabled persons of various categories and account for their number and location in the building, the transport passages and pedestrian routes around the building are separated and just partially combined. Disabled people in wheelchairs can move along the pedestrian sidewalk with a width of more than 1.8 m, the longitudinal slope not exceeding 5%, and the transverse slope not exceeding 1–2%. At the intersections of these pedestrian routes with the roadway, it is planned to reduce the height of the curb by 2–4 cm and make a curb ramp with the slope not exceeding 1:10. One parking space at the parking lot by the Ryazan Kremlin is reserved for persons with reduced mobility. It is marked by signs used internationally. The width of the parking space is 3.5 m.

2. Structural solutions

The high-priority measures aimed at preserving the historical structure included the following successive operations: site clearing, base and foundation strengthening, masonry and brick vault strengthening, restoration of the lost and destroyed sections.

During restoration, the following works were performed:

- preparatory works;
- foundations and foundation/soil contact cementation;
- base soil injection (stabilization);
- masonry injection, brick vault crack injection;
- measures aimed at preventing water from entering the building: foundation damp-proofing, arrangement of a vapor-proof blind area made of discrete materials;
- new walls and partitions laying;
- floor and porch restoration.

To minimize structural deformations, which may occur during the restoration and further use of the architectural monument, the foundation masonry was cemented. Cementation makes it possible to fill the exposed cavities in the foundation body and, thus, improves the bonds between structural elements. In that way, the problem areas are strengthened, the stiffness and load-bearing capacity of the foundation increase. Foundation/soil contact cementation restores the lost bond between masonry and soil and balances pressure along the bottom of the foundation.

To restore the lost bond and ensure masonry grouting, increase the structural strength and load-bearing capacity of the external walls and brick vault, masonry injection was used (Figure 6).

Foundation/soil contact damp-proofing was carried out along the external load-bearing elements of the foundations of the Household Building (late 17th century, 19th century), a recognized cultural heritage site. Boreholes were drilled to the foundation depth, through the joints of the exterior masonry tier, in the direction from the bottom up (wherever possible). Damp-proofing was carried out using a polymer composition to create a damp-proof membrane between the foundation and the soil.

Such measures guarantee the restoration of the exterior walls as load-bearing structures.

As for the internal structure, to adapt the ancient structure to modern standards of safety and essential

Figure 6. Masonry injection

services, it was proposed to install utility (water supply, sewerage, ventilation, electricity, heating) equipment, fire safety and other systems. To create a modern interior, it was proposed to use modern flooring materials characterized by high strength, hardness, and wear resistance.

Therefore, the floors in the cafe were supposed to be tiled as follows, depending on the purpose of the premises: ceramic granite stylized as natural stone (Figure 7a) in the dining room, and standard ceramic granite in the service areas.

Prior to flooring works, the soil inside the building was leveled and thoroughly compacted. In places intended for future internal partitions, holes were made that later were reinforced and concreted.

Since the building does not have a vent line, ventilation was maintained through galvanized air ducts with an outlet to the roof through a hole in the ceiling (Figure 7b).

The porch has a canopy with forged brackets (Figure 7c).

All these measures combined are necessary to preserve the architectural monument and prevent changes in its appearance.

Conclusions

In addition to restoration, the issue of preserving historical-and-architectural heritage shows that it makes sense to search for new approaches and options when it comes to the operation of ancient structures.

Under such an approach, the concept of the restoration and adaptation of the Household Building (late 17th century, 19th century), an architectural monument of the Ryazan Kremlin, to modern use was developed. The key in the restoration process was to preserve the appearance of the building and adapt its layout to new functions with minimal interference with the structure. Despite the new layout, due to modern technologies of damage repair as well as foundation/structure strengthening, the historical load-bearing walls were preserved. This solution made it possible not only to preserve all the valuable characteristics of the site but also to prevent its destruction in the future.

The adaptation of the architectural monument to new functions will enable its preservation. In most cases, being involved in the life of modern society moving at an intense pace, such an adaptation gives ancient structures a certain status, making them more attractive for commercial use.

Due to the wide variety of options used to adapt cultural heritage sites, cities are turning into tourist attractions with a developed economy and unique architectural environments. Each monument contributes to the historical appearance of the city, encouraging people to get to know their culture and history. The site under consideration, located on the Ryazan land, can become another protected place that will attract those who value cultural heritage.

a) b) c)

Figure 7. Household Building (late 17th century, 19th century). Current state. November 19, 2021
a — the interior of the dining room, b — the ventilation duct, c — the canopy

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КОНЦЕПЦИЯ РЕСТАВРАЦИИ И ПРИСПОСОБЛЕНИЯ ПАМЯТНИКА АРХИТЕКТУРЫ РЯЗАНСКОГО КРЕМЛЯ «ХОЗЯЙСТВЕННЫЙ КОРПУС» КОН. XVII В., XIX В.» ПОД СОВРЕМЕННОЕ ИСПОЛЬЗОВАНИЕ

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Аннотация:
Проблема сохранения историко-культурного наследия очень актуальна в настоящее время. Важный шаг к этому – реставрация старинного архитектурного сооружения с сохранением внешнего исторического облика и его приспособление под новое функциональное назначение. Рассматривая сложившееся положение с объектами культурного наследия Рязани, следует отметить, что город нуждается в подобных приемах (мерах). Множество памятников истории, культуры и архитектуры было утеряно и продолжает разрушаться вследствие неграмотного вмешательства в их архитектурно-планировочную структуру (снос, самовольная перестройка и т.п.). **Цель исследования:** Показать особенности сохранения, реставрации и приспособления объектов историко-культурного наследия к новым современным потребностям. **Методы исследования:** В ходе исследования был использован системный подход, изучены различные источники и материалы по реставрации и охране историко-архитектурных памятников. **Результаты:** Авторами рассматривается конкретный пример из архитектурной практики по приспособлению части древнего сооружения под современное использование. В статье дается краткий исторический обзор, приводится информация о конструкциях и используемых материалах, рассмотрены методы и технологические решения, проанализированы проектные решения. На основании результатов проведенных работ раскрываются проблемы приспособления выявленного объекта культурного наследия к современным условиям жизни и его использование в новом качестве в соответствии с существующими нормативными документами. При этом, сталкиваясь с проблемой приспособления исторических зданий, утративших свою первоначальную функцию, необходимо проводить работы не изменяя особенности, являющиеся предметом охраны таких сооружений. Сделан вывод, что в рамках сохранения объекта культурного наследия разработана концепция, на базе которой будет выполнено перепрофилирование, разместив в нём кафе.

Ключевые слова
Объект культурного наследия, памятник архитектуры, сохранение, реставрация, приспособление к современным условиям, методы и технология, Рязанский Кремль, Рязань.

DOI: 10.23968/2500-0055-2022-7-3-21-26

THE ART OF ARCHITECTURE: MEIER'S TIMELESS STYLE

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Abstract
Introduction: An architectural identity is based on lasting architectural designs. Those common features that repeat across the architect's designs determine the architect's style and philosophy. **Purpose of the study:** We aimed to explore the style and philosophy of Richard Meier by studying his building designs developed in different time periods. **Methods:** In the course of the study, we used a mixed-method approach that includes the quantitative and qualitative research methods. By using the quantitative research method, we focused on the five selected cases of Meier's buildings differing in location, typology, and year of construction. The qualitative research method involved the observation method. **Results:** It was established that the main features of Meier's style are the abstract white geometric form, circular structural columns, floor-to-ceiling glass walls, interior double-volume spaces, long circulation axis, and skylights. Richard Meier used the philosophy of combining lightness, placeness, and simplicity to make his vision a reality.

Keywords
Architectural style, design philosophy, design thinking, geometric building, Richard Meier.

Introduction

The purpose of design is to provide the most suitable solution addressing true needs and circumstances and determine a solution-focused strategy, which is essential in the formation of an architect's identity and style. Style is considered a form of expression (Chan, 1994). The concept of style has two main aspects: the process (i.e., the way of doing things) and the product (Lawson, 2005). A style is formed by utilizing design constraints (design issues), manipulating mental images (Chan, 1992), and applying design principles and design methods (Chan, 2001). The number of design features, which cover the functional and geometrical relationships between forms, affects style recognition. Any three common features appearing in a design constitute the basic ingredient of a style while four common features ensure strong style recognition (Chan, 2000). Two factors determine how these common design features can be perceived: the size of these features in a design and the significance of perceptibility (Chan, 2000).

Richard Meier is an American architect who is known for his timeless rational postmodernism style (Phibbs, 2015). He viewed architecture as a social art, focusing on improving the quality of living conditions using natural elements (Phibbs, 2015). Meier's buildings refer to Le Corbusier's designs, especially in concrete forms, but he did not manipulate the space as Le Corbusier did (Eisenman et al., 1975).

In this research paper, we study the design thinking methods of Richard Meier, aiming to define his style and philosophy by analyzing specific building designs, focusing on design challenges and solving methods. For that purpose, we selected the following five buildings: the Smith House, the Douglas House, the Neugebauer House, the Luxembourg House, and the Jubilee Church. The paper has six sections: Introduction, Hypothesis, Methods, Data Analysis, Results, and Conclusion.

Hypothesis

The research hypothesis is that all Richard Meier's design projects have repeated common features that identify his style.

Methods

In the course of the study, we used a mixed-method approach that includes the quantitative and qualitative research methods. By using the quantitative research method, we focused on the five selected cases, which were divided into two groups by type: the civic public case involving the Jubilee Church, and the residential cases involving the Smith, Douglas, Neugebauer, and Luxembourg houses. The Smith House was selected since it is the first building design by Richard Meier (Badalge, 2018). The Douglas House has specific site challenges, which were creatively solved through the design process. The Neugebauer House has its own design challenge related to the city regulations in respect of roofing. The Luxembourg House was selected because of its location, design philosophy, and creativity. Besides, all the selected buildings were built in different periods. Such an approach was chosen to see if Richard Meier's design style has changed over time. The qualitative research method was used to study design-solving methods and creativity by observation and define the style and philosophy of the designs. The data were collected from the literature and websites.

Data Analysis

1. Smith House, Connecticut, 1967

The Smith House was Meier's first widely-lauded structure, with an area of 3251 sq. m (Badalge, 2018). The main design challenge was rocky topography. The architect designed three levels of a vertical building instead of a horizontal one to save excavation costs (Badalge, 2018). When designing this house, Meier implemented a basic geometric form, energizing tensions between closure in the front elevation and openness in the back elevation with a view of the water and landscape, which may come as a surprise. The structural system of the Smith House includes circular structural columns supporting the beams and roofing, and timbered walls.

Meier used simplicity, open space, and natural light as the design philosophy for this house. The main design features of the house are the following: an abstract white geometric form, circular structural columns, a chimney, a double volume, an exterior staircase, floor-to-ceiling glass walls, an interior balcony, a ramp bridge, and wooden frame material (Figure 1).

2. Douglas House, Michigan, 1973

The Douglas House is one of the most interesting Meier's house designs in terms of its relationship with the surroundings, with an area of 450 sq. m (Lynch, 2016). The high-sloped site was the main design challenge. A bridge as the main entrance, an exterior staircase connecting the three house levels, and floor-to-ceiling glass walls were the main creative design solutions. The house has an abstract rectangular form with a linear circulation axis, which is similar to the design-solving method used in the Smith House. It has circular structural columns supporting the beams and roofing using reinforced concrete.

The architect used simplicity, open space, and natural light as the design philosophy for this house. The main design features of the house are the following: an abstract white geometric form, a bridge, circular structural columns, a chimney, concrete material, a double volume, an exterior staircase, floor-to-ceiling glass walls, an interior balcony, a long middle corridor separating the public and private zones, and a skylight (Figure 2).

3. Neugebauer House, Naples, 1998

The Neugebauer House is a creative building design of white color with a unique structural roof solution chosen to meet the city regulations, and a skylight. The building is rectangular in form. Its linear organization consists of five parallel layers from front to back: access, service, living, sun terrace, and lap pool (Sveiven, 2011). The structural system includes columns and a roof structure, which consists of modules that control the structural bay. The building geometry design is divided into six equal rectangles with a pool view and glass wall elevations as well as a skylight integrated in a butterfly roof structure.

The main design features of the house are the following: an abstract white geometric form, a butterfly roof structure, concrete and limestone materials, a double volume, floor-to-ceiling glass walls, a long middle corridor

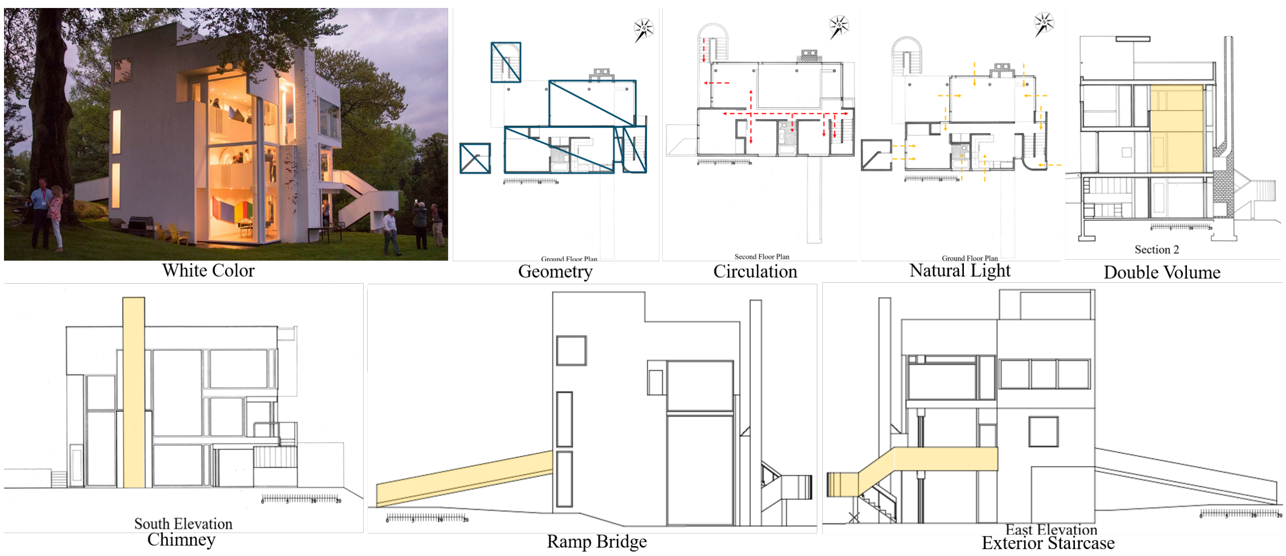

Figure 1. Some of the main design features of the Smith House (Badalge, 2018)

separating the public and private zones, and a skylight. The design philosophy of this house includes simplicity, open space, and natural light (Figure 3).

4. Luxembourg House, Luxembourg, 2012

The Luxembourg House offers both privacy and seclusion as well as panoramic views of the surrounding landscape and has an area of 975 sq. m (Stevens, 2014). The main challenge was sloped topography. In the design of this building, Meier used two rectangular geometric forms with three stories, with a garage on the bottom level. The public spaces including living and dining rooms are on the middle level, and the private spaces are on the upper level. Such a three-story house ensures privacy and does not tower over the neighboring buildings. Besides, the house has a long corridor circulation on each level and a grid structural system with circular columns in a double-volume space. In this design, Meier used the philosophy of placeness, lighting, and simplicity.

The main design features of the house are the following: an abstract white geometric form, aluminum material, circular structural columns, a chimney, a double volume, an exterior staircase, floor-to-ceiling glass walls, an interior balcony, a long middle corridor separating the public and private zones, and a skylight (Figure 4).

5. Jubilee Church, Rome, 2003

The Jubilee Church is a rich case study of the relationship between natural light, geometric forms, and space design. The church has an area of 830 sq. m (ArchDaily, 2009). Among the design challenges, the typology of the building and the shell design can be mentioned. A new concrete mix (TX Millennium) was developed especially for this project, providing a creative solution for the shell design (Cardellicchio, 2018). The design philosophy of the building focuses on lightness, responding to nature, and the quality of the space.

The main design features of the building are the following: an abstract white geometric form, shell structures, a double volume, floor-to-ceiling glass walls, marble and concrete materials, and a skylight

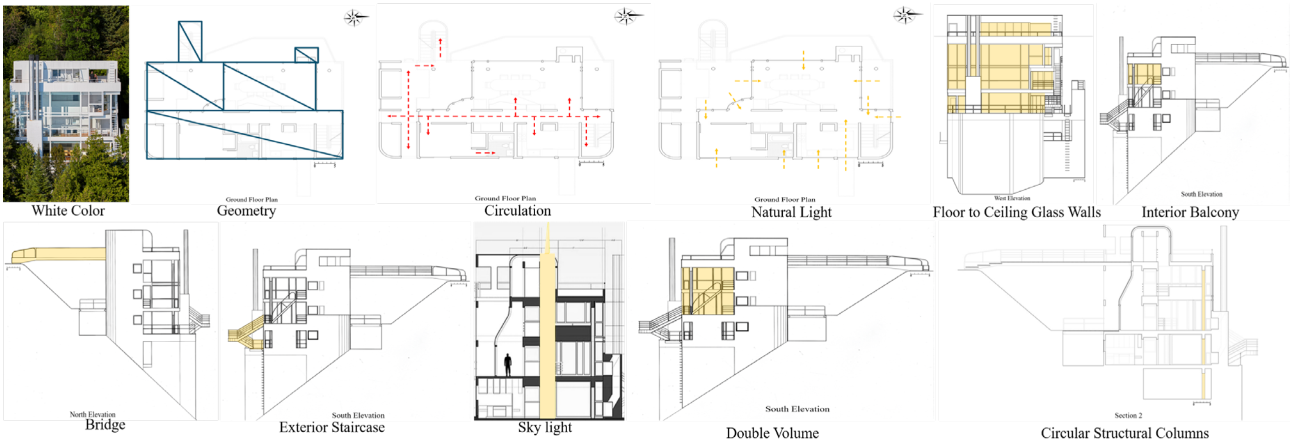

Figure 2. Some of the main design features of the Douglas House (Lynch, 2016)

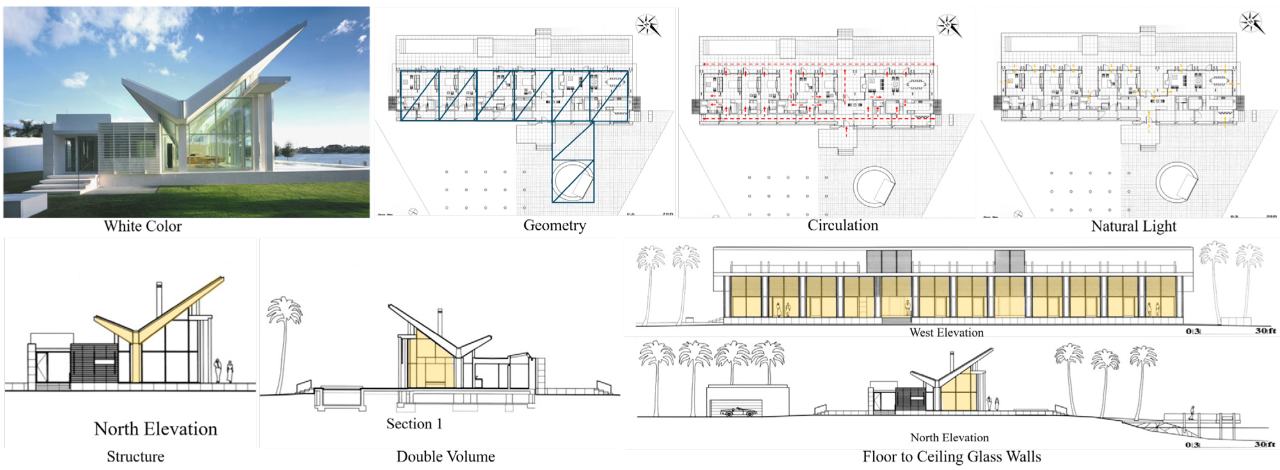

Figure 3. Some of the main design features of the Neugebauer House (Sveiven, 2011)

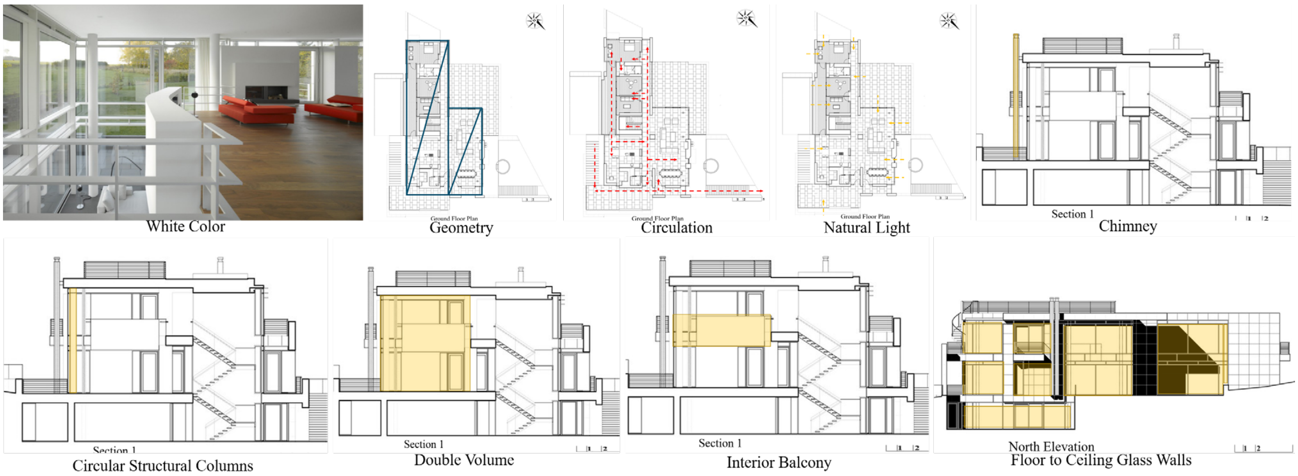

Figure 4. Some of the main design features of the Luxembourg House (ArchDaily, 2014)

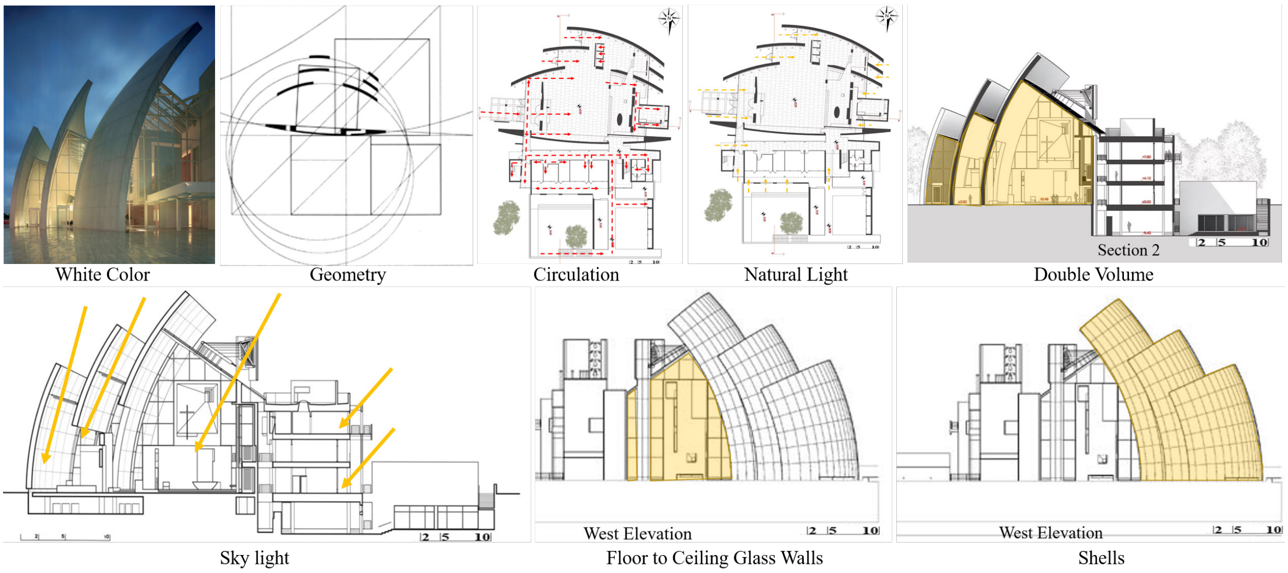

Figure 5. Some of the main design features of the Jubilee Church (ArchDaily, 2009)

(Figure 5).

Results

Based on the analyzed data, we summarized the features characteristic of Meier's style and philosophy in a table below (Table 1). The results show that the repeated design features observed across all the case studies can be classified into three groups, where the strong design features form the design style. The strong features repeat across four case studies or more and include the abstract white geometric forms, circular structural columns, double-volume spaces, floor-to-ceiling glass walls, long corridor circulation, and skylights. The basic ingredient design features repeat in three case studies only and include the chimney, exterior staircase, and interior balcony. The barely perceptible design features repeat only two times across the case studies and include the bridge and ramp bridge. The design philosophy that repeats across all the case studies includes placeness, simplicity, and lightness.

Discussion

This research paper shows that the more common features repeated, the stronger the style became. The features that repeat in Richard Meier's designs the most and define his style are the abstract white geometric forms, circular structural columns, double-volume spaces, floor-to-ceiling glass walls, long corridor circulation, and skylights. These features were the consistent design principles that did not change in 1967–2012, which indicates the timelessness of Richard Meier's designs. That explains his philosophy about using lightness, simplicity, and placeness.

Acknowledgments

The authors would like to thank Chiu-Shui Chan, Professor Emeritus of Architecture at Iowa State University and Guest Professor at Tianjin University, for his support and guidance for this research paper.

Table 1. Summary of the main design features of Meier's style and philosophy

Main Features of Style	Smith House	Douglas House	Neugebauer House	Luxembourg House	Jubilee Church	Strong (S) Style, Basic Ingredient (BI), or Barely Perceptible (BP)
Abstract	●	●	●	●	●	S
Bridge	●	●	-	-	-	BP
Circular Structural Columns	●	●	●	●	-	S
Chimney	●	●	-	●	-	BI
Double volume	●	●	●	●	●	S
Exterior staircase	●	●	-	●	-	BI
Floor to ceiling glass wall	●	●	●	●	●	S
Geometric form	●	●	●	●	●	S
Interior Balcony	●	●	-	●	-	BI
Long Corridor Circulation	●	●	●	●	●	S
Sky light	-	●	●	●	●	S
White Color	●	●	●	●	●	S
Philosophy	Lightness, Simplicity, Placeness					-

●	Feature Exists in the Building
-	Feature Doesn't Exist in the Building

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Urban Planning

DOI: 10.23968/2500-0055-2022-7-3-27-36

FAR EASTERN REGION: SUSTAINABLE DEVELOPMENT OF A LARGE CITY (CASE STUDY OF CHITA)

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Abstract
Introduction: The article considers competitiveness and sustainability concepts and formulates potential mechanisms of their relationship for a large city. In the context of globalization, the sixth wave of innovation, mass digitalization, and achievement of sustainable development goals, large cities are in a state of a constantly structurally changing system. **Methods:** To ensure the realizable complex of their technical indicators, it is necessary to survey a city, which is achieved by the modern method of making a graphical-analytical model (digital twin). In the course of the study, we consider Chita, a city in Far Eastern Region, as an example of a large city. Chita has its own unique features and potential for development. To improve the indicators, some mechanisms of urban framework transformation are proposed, which set in motion all the levers of sustainability, which contributes to sustainable competitive development. **Results:** We elaborate stages of the technology of sustainable development of a large city of Chita in the conditions of Far Eastern Region, and provide recommendations for the development of new software for the actual city survey. **Discussion:** The final goal of applying the transformation technology is to bring all the levers of sustainable development, the functions of a large city, and competitiveness to united balance for the comfort of our and future generations, which corresponds to the main goal of sustainable development.

Keywords
Sustainable development, Far Eastern Region, large city, Chita, competitiveness.

Introduction

It is necessary to establish the framework of such concepts as sustainable development and large city as well as to determine the mechanism of their relationship. Sustainable development is, first of all, a model of moving forward, development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). The strategy for sustainable development aims to promote harmony among human beings and between humanity and nature. Among those numerous researchers who studied sustainable development, it is worth noting *M. V. Shubenkov*. In his articles, the author defined sustainable development as a mechanism for ensuring the integrity of natural and anthropogenic systems (Shubenkov, 2020). A good urban planning system is one where social life is as diverse and intense as possible and the interaction of the urbanized environment with the natural environment is balanced (Shubenkov and Shubenkova, 2018). There are also descriptions of the concept of sustainable development of a small city, in which a model based on a minor intervention in its structure but capable of reviving the uniqueness and viability of a small city, is accepted for consideration (Vavulin and Malaya, 2020). Vaytens and Shubenkov (2020) considered the problems of modern development of urbanized territories in Russia and proposed an urban ecology concept of development, which determines the opportunity of creating forms of urban structure that ensures balanced ecological exchanges of cities and settlements with nature. However, its implementation is hindered by the disinterest of the country’s government at all levels, the almost complete absence of ecological culture in the population, and overall level of the economic development of the country. The problems of sustainable development of border cities were considered in various master’s theses described in the article “Directions for the transformation and development of border cities in Leningrad Region (case studies of Ivangorod and Svetogorsk) in modern conditions” by Vaytens (2020). The goal of sustainable development strategy measures was to transform Ivangorod into a self-sufficient small border town that used various levels of cooperation with its foreign neighbor — Narva. The strategic priorities of Ivangorod included transport, ecology, society, economy, and urban environment. Within each priority, the author formulated long-term development goals conducive to responding to one of the main challenges of the city — decline in population due to its migration.

There is an incomparably small number of studies on the issue of sustainable development of cities in Far Eastern Region, where the authors highlighted the main problems of development and research of the territories, such as fragmentation, narrowly disciplinary orientation, inconsistency, interregional and interdepartmental barriers, violation of the display integrity of the object of study, underdevelopment of a united database, lack of systemic interconnection throughout the "technological chain" from natural sciences to economics, inconsistency and incompatibility of the used parameters of the display of regional objects in their models, which are compiled for each scientific direction in the interests of one or another discipline. All these facts create serious obstacles to the effective scientific support of strategic assessments and forecasts of the rational system formation of the newly emerging region for its further sustainable development (Krasnopolski, 2018). Kalashnikova and Filippova (2019) described the inextricable connection between the sustainable socio-economic development of the Russian Far East regions and environmental situation and proposed decoupling calculated based on the use of the gross regional product, emissions of pollutants, and wastewater discharges as an express method of environmental assessment. The main corrective actions are related to the improvement of the legal framework that ensures the operation of mechanisms to protect against undesirable environmental management; stimulating the introduction of advanced technologies and attracting private investment in the green production.

Any large city that represents a modern competitive system cannot exist productively without a sustainable development strategy. A large city nowadays is a large settlement with a population of 250–500 thousand people (Regulations SP 42.13330-2016). It has a developed complex of commercial units and economy. It is a cluster of architectural and engineering structures that ensure the vital activity of the permanent and temporary population of the city. Kazakov (2014) provided a review of different theoretical views on the concept of a large city and gave his own definition of this concept based on the studied materials: "a large city is a maximally transformed ecological environment with a high concentration of anthropogenic factors".

Two familiar concepts represent a single mechanism where the concepts are connected with each other by common aspects: ecology, social sphere, and economy (Figure 1). In his article, Barsukov (2008) addressed the connection of these concepts: "sustainable development of a large city is ensuring the interests of city residents in the implementation of management activities, the best realization of human potential, achievements in social and economic development, minimizing the negative impact of economic and other activities on the urban system, and ensuring the effective use of all types of resources in the interests of present and future generations".

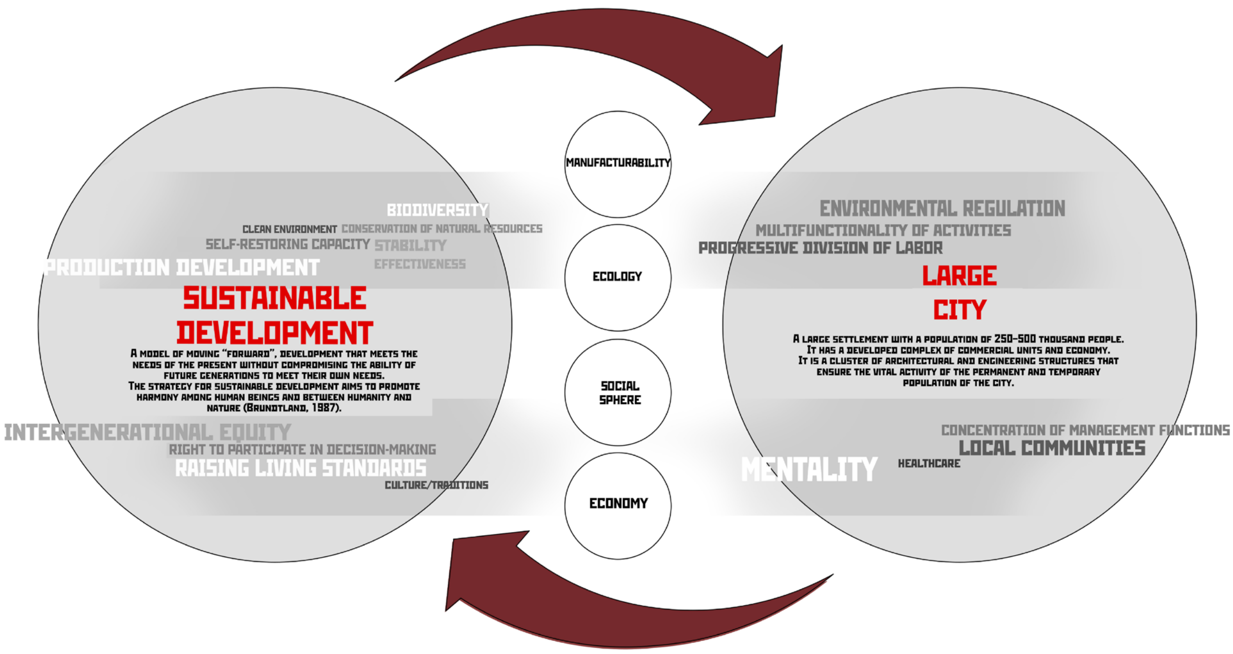

Figure 1. Scheme of the relationship between the concepts of sustainable development and large city

Cities that have a balanced set of these indicators are competitive. Starovojtov (2004) discussed the relevance of introducing competition between cities, leading to the activation of economic, financial, and human resources of cities, and provided directions in which competitiveness can develop. Bogomolova and Mashentsova (2015) presented their own method of classifying cities. This method includes a quantitative indicator — the number, and a qualitative indicator — functional affiliation, which makes it possible to visually systematize cities and identify the closest competitors, which, in turn, will allow to adapt the existing effective development models following the size and functions of the city and to build optimal strategies for sustainable development of territories in the long-term horizon.

The object of the study is Chita. It is a large city in Zabaykalsky Krai with a population of 351 thousand people. It also has its own characteristics: production capacity, environmental situation in the region, as well as the mentality of residents, which is one of the important indicators of the social sphere. Its closedness, due to the large number of military units and percentage of military to the civilian population, is a strong aspect and problem as well. Few studies that were conducted for Chita mainly concerned the environmental aspect and addressed the problems of gardening the city (Martynova, 2020), analysis of atmospheric air (Samoilov, 2021), and ecological solutions to problems of sorting and recycling of wastes (Stremilova, 2015). All studies relate to narrow indicators of the ecological situation, but a comprehensive survey of the state of the ecological environment of the city has not been conducted (Kanga et al., 2022). Chita, as a historical city founded in 1653, has historical value, which implies the potential for development of a tourist cluster (Bolshakov and Gladysheva 2014). It is a huge recreational resource, which, in turn, can also be an object of attraction for rehabilitation. Its use can be expressed in figures as well: which operating resorts are in Chita and which need reconstruction, suitability of beaches, rivers, and lakes for vacationers, number of landscaped areas, to calculate the characteristics of the ecological framework for the spatial organization of settlement in Chita and the surrounding area (Dangi and Petrick, 2021).

Relevance

In the context of particular geopolitical events, the potential of the import substitution strategy for products and some services provided from abroad has become a priority: it is necessary to develop existing industrial capacities, preserve the potential available in all areas and develop new industries, which is possible using the post-industrial heritage of the regions. Currently, the Russian Federation is unevenly developed geographically, the influence of the predominance of the western part over the eastern remains, as a result of which the concentration of high technologies, highly qualified personnel, and maximum comfort of essential services are pertaining to the capitals and nearby cities. A similar situation developed after the era of Fordism in Detroit (Perez, 2012). At the same time, Siberian Federal District and Far Eastern Region are territories lagging behind the western part of the country, therefore, the problem of population outflow naturally arises in the cities of these regions, which negatively affects migration processes in general. However, at the same time, the territories of these regions are rich in recreational and industrial resources, have historical value, therefore, with the use of some methods of leveling the urban environment, the potential of the eastern regions will become more expressed and receive its proper development to ensure a more competitive country with its own knowledge-intensive production. No studies concerning the integrated development of all indicators of sustainable development, as well as no working action plan to bring these indicators and individual characteristics of the city to a single balance, have been conducted for Chita.

Purpose of the study

We aim to elaborate the stages of the technology of sustainable (competitive) development of a large city in the conditions of Far Eastern Federal District (case study of Chita). A technology is a set of methods and tools to achieve the desired result, usually through stages or with a clear sequence of actions. This technology is being developed for cities of the Russian Federation with a population of 300–400 thousand people, for which the problem of population outflow and general situation of stagnation or regression of the city, or the predominance of any industry over the rest is relevant. The main **objectives** of the study are to conduct graphical-analytical analysis using software, elaborate stages of the sustainable development technology, as well as identify tasks for the development of necessary software for the survey of the city.

Methods

What is the concept of competitiveness? Competitiveness is one of environmental factors, and the most important is the requirement for a modern city. The concept can be divided into competitiveness within the country and competitiveness at the global level. In order for competitiveness to reach its maximum, there are some aspects that characterize it and also have some of their own indicators. The most important aspect is essential services, which implies the creation of modern infrastructure for the city's population. This implies maintaining existing production capacities, improving the set and quality of public utilities and public sector services, and reducing prices for them. Responsible and effective urban management has a direct impact on all aspects, its development requires increasing

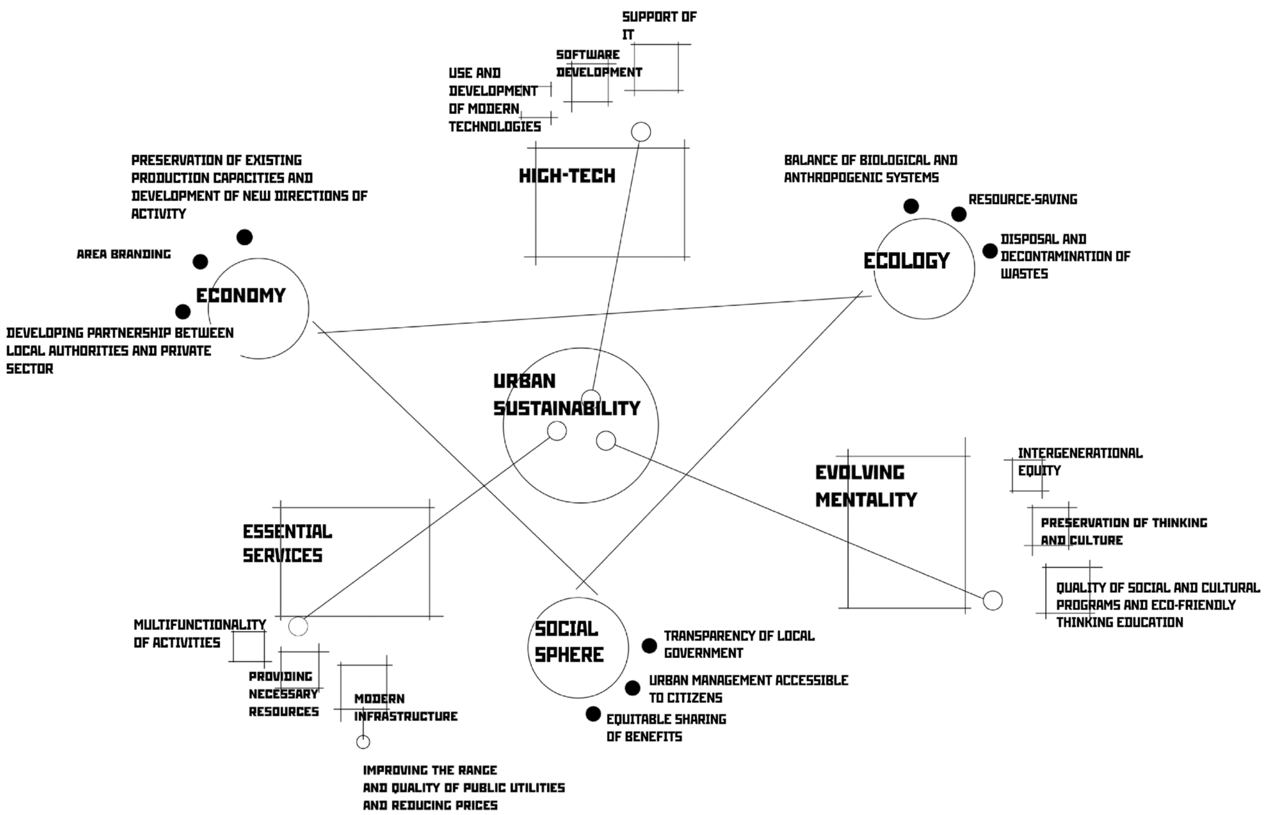

Figure 2. Scheme of competitive indicators of development sustainability

the openness of local authorities, developing partnerships between local authorities and the private sector, and using the best practices of urban management. One of the engines of the city's development is the attraction of domestic and foreign investments, implying public and private partnership. The concept of development sustainability, in turn, is represented by three main indicators: ecology, economy, and social sphere, which are supported by high-tech, preservation of ecological thinking and productive essential services for the system. The combination of these indicators makes it possible to calculate and express in numbers the states of these spheres for the selected object of study. In the conditions of modern reality, in the context of high technologies, this approach has a high relevance, which implies the need to develop software for automated calculation of such indicators (Figure 2).

The indicators will be applied to a large city, which is a whole system consisting of management, economy, ecology, social sphere, and essential services. This system should work as a balance, primarily for the comfortable living of residents and for the benefit of future generations. Hence, a paradigm arises: to achieve a set of technical indicators of sustainability and competitiveness, an in-depth survey of the city is required (Heinrichs, 2021).

What methods can be used to survey the city, in addition to full-scale, photographic, graphical-analytical, and statistical ones? The most relevant method is the construction of graphical-analytical models of cities with the introduction of some of the studied indicators. For this purpose, existing software packages such as QGIS, Grasshopper, and SpaceSyntax are used. With the introduction of indicators of population, production capacities, recreational resources, development of the territory, and their various functional uses, the graphical-analytical model itself changes, and we can clearly see how the indicators affect the development of the city, and find the right balance in percentage terms for uniform sustainable development.

As mentioned earlier, Chita has its own individual characteristics associated with the closedness of some planning structures of the city, prevailing evolving mentality, formed territories of religious and economic purposes, valuable architectural historical environment, and the border position relative to China. Such indicators should be taken into account when surveying the city to obtain an actual comprehensive assessment of the city's state. QGIS software package was used in the graphical-analytical research method. The first layer of the constructed city map is the "building" layer, which shows the functional purpose of buildings and structures. This layer does not work correctly since it does not show all buildings or have up-to-date information. The indicators characterizing the individual characteristics of the city are not taken into account in the subsequent available layers of the simulated digital map. After building a digital model of Chita, it was supposed to study the indicators of the territory using the Openstreetmap service, which became impossible due to the conditions of some geopolitical events. This proves the priority of the development of the strategy for import substitution of products and some services provided from abroad: the necessary development of IT sphere, development of its own modern technologies as well as architectural and urban planning software complexes.

Results and Discussion

The first stage of the urban framework transformation technology is a survey of the city, which includes an in-depth historical and genetic analysis, which makes it possible to identify the discrepancy between the urban environment quality index (an already developed tool with 36 indicators) and the actual state of the set of indicators aimed at implementing the concept of sustainable development. Such indicators include: the number of reference points of sustainable development both in architectural and planning, volumetric and spatial, as well as in social, economic, environmental context; the number of implemented social and cultural programs, their qualitative state and potential of spatial and temporal development; and others (indicators and criteria generally relate to external and internal competitiveness of the urban environment of Chita) (Urban Environment Quality Index, 2021). Based on the totality of the obtained indicators, it is necessary to proceed with the second stage of the transformation technology, which includes the development of an approbation model by means of simulation modeling with subsequent verification. The approbation model is variable and essentially a mechanism for transforming the urban environment. They can be economically regulated mechanisms, as well as planning mechanisms for leveling the urban framework, social, and aimed at regulating the ecological state with the subsequent development of eco-thinking and eco-potential (e.g., by means of eco-tourism), as well as including criteria for the preservation of industrial and historical heritage (Gulotta and Toniolo, 2019). The third stage includes the development of original software complexes, which are the prism of activation of connections and components, which will serve as the basis for innovative technology formation for the real transformation of the urban environment (Borovikova, 2019). It is worth noting that an important stage, from the ecological side, is the screening of communications since the city has a historical core, therefore, it is very important to connect water-soil purification and subsequently replace existing communications with more environmentally friendly methods of water treatment systems.

All three stages of the transformation technology work together, and for each city the technology and the sequence of stages will be unique (Figure 3).

Based on the research results obtained by the method of constructing a graphical-analytical model, it can be concluded that it is necessary to develop software that is both a method of surveying the territory and a mechanism for transforming the urban framework (Cappai et al., 2018). New software will meet modern software requirements (convenience and clarity for users, security, completeness, consistency, satisfaction of all necessary needs, etc.). First of all, the developed software should contain the following functions:

- display of zones of urban planning regulations for construction;
- analysis of the need to build kindergartens, schools, and transport stops following the accessibility for the nearest residential areas;
- display of current routes between locations, construction of the shortest path (for pedestrian,

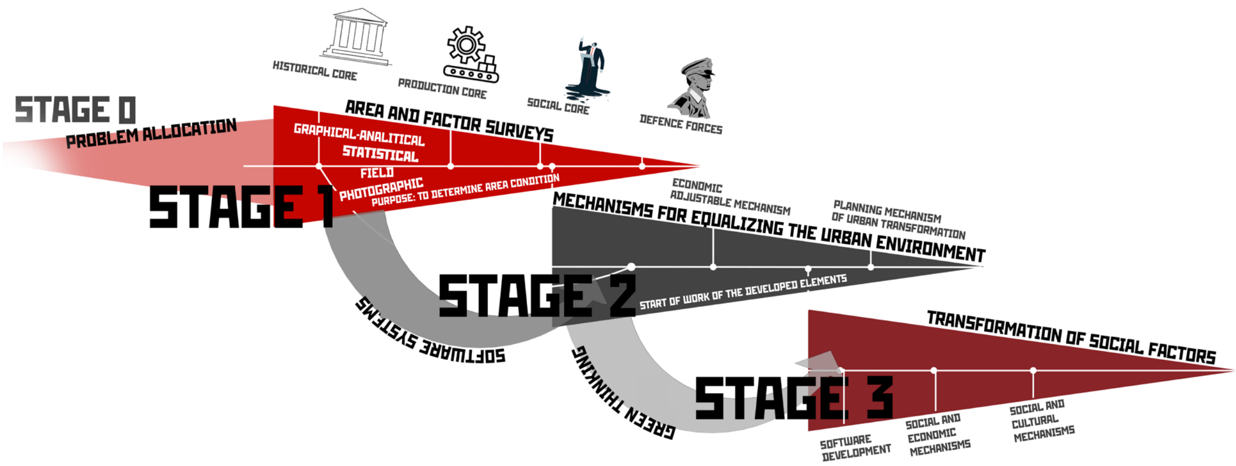

Figure 3. Stages of the urban framework transformation technology

automobile, and public transport);

- analysis of the height and compositional placement of construction facilities, the possibility of voting and making proposals at the concept stage;
- up-to-date, high-quality, and realistic data on the survey of the city's state: buildings, parks, recreation areas, infrastructure (the use of flying drones);
- open general urban plan, developed master plan;
- the state of the transport infrastructure, the quality of roads, current parking places;
- clear disclosure of planning projects for a citizen who is not involved in architectural and urban planning concepts;
- terrain data;
- weather and climate data interactively in real time;
- current population and density data (dynamic map of concentration points);
- data on monitoring the environmental situation and active actions for volunteers to improve the quality of the urban environment;
- the opportunity to edit and add new information for users of different social components, which will provide a constant update of data about the city;
- the opportunity of voluntary replenishment of the city's fund for beautification (charity, creation of a fund to improve the quality of urban infrastructure);
- communication with the main Internet information resources (Chita.Ru, Podslushano Chita, Zab.Ru);
- a tab about social programs and cultural events, the opportunity of creating an event and registration;
- the opportunity of open communication with local authorities;
- feedback in applications and software complexes should be built with the principle of stimulation;
- support Initiatives tab for entrepreneurs (to support small businesses, a user can post the project and request support from both local authorities and users on a voluntary basis);
- a social and cultural program for the education of children through involvement in the game process (virtual walk around the city and search for artifacts that tell the history of the city, sights, opportunities. Communication with social media accounts for accrual of points, votes, OK);
- assistance to retired and disabled people (Services tab, where a user can write about the necessity for support).

The opportunity of using the software should be implemented both on a personal computer and in an application for a smartphone. The application, as well as its interface, should be accessible and understandable to each category of users (Figure 4).

In his article, Barsukov (2008) suggested a similar review mechanism of city management "management for the interests of city residents", which consists in transforming blocks of interests of residents (taking into account the order of their implementation, and within the framework of the provisions of the sustainable development theory about the limitations and necessity of reproduction and conservation of resources) into a system of goals and objectives of city management bodies.

The development of the technology for the transformation of the urban framework is the main and relevant tool for ensuring sustainable competitive development of the country in general. The stages of the technology are a variable mechanism that can change depending on the object (city) of application. The final goal of applying the transformation technology is to bring all the levers of sustainable development, the functions of a large city, and competitiveness to united balance for the comfort of our and future generations, which corresponds to the main goal of sustainable development.

Conclusions

The main conclusions based on the results of the study include the following: 1) it is advisable to conduct a survey of settlements remote from the center on the basis of regional architectural and construction research organizations, which will largely take into account the regional peculiarities of the place and preserve them; 2) the context of digitalization and post-industrial development of the urban environment determines the need to add the key of technology to the three main keys of sustainable development; 3) the totality of existing programs does not always have a positive effect on the real transformation of the urban environment due to the lack of transparency mechanisms and the adjustment of such programs adequate to modern requirements; 4) modern means of simulation modeling (Information System Designed for City Planning, ISOGD) do not fully provide an understanding of the real state of the territory, which leads to the need for the development of applications, software, and software complexes; 5) potential competitiveness, as a rule, will consist of positive indicators of the economic, environmental, and social aspects of an architectural and urban object (in particular, a city), which is one of the key mechanisms for determining the sustainability of the object's development. It follows from this that the development of the stages of the sustainable development technology for a large city should be carried out taking into account its regional peculiarities, as well as in the context of high-tech with the development of software necessary for the survey of the city territory and transformation programs. In the context of the development of the smart city technology, the tightening of the use of the Information System Designed for City Planning (ISOGD), the creation of the National System of Spatial Data (NSPD) (in fact, the registry) as general requirements for software, the following can be

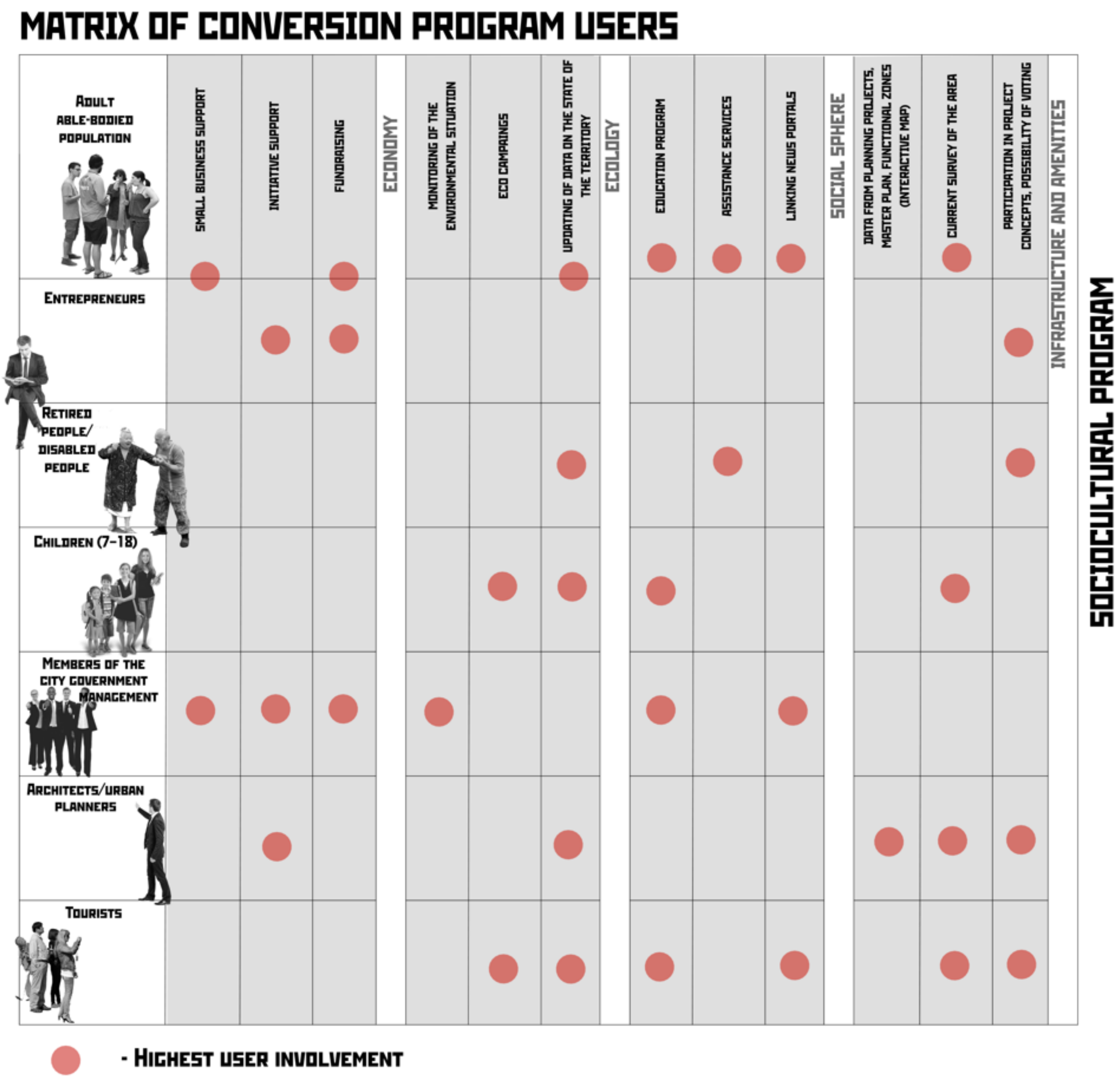

Figure 4. Matrix of conversion program users

designated: 1) maintaining the layering of GIS tools; 2) using Openstreetmaps-type open data; 3) the presence of machine learning or artificial intelligence elements in the software structure, which is primarily associated with a large amount of data processing; 4) using server or cloud data storage technology; 5) using CAD or BIM resources; 6) potential consideration of ISO-standardization of CIM (City Information Model) and PIM (Planet Information Model); 7) use of data processing engines implying the output of information in XML format; 8) development of a shell accessible to both non-professional and professional users; 9) availability of a resource (WEB or Mobile) for organizing feedback (as an example, open master plans, when a citizen can offer the idea or make certain changes).

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ДАЛЬНЕВОСТОЧНЫЙ РЕГИОН: УСТОЙЧИВОЕ РАЗВИТИЕ КРУПНОГО ГОРОДА (НА ПРИМЕРЕ ГОРОДА ЧИТА)

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Аннотация

В статье рассматриваются понятия конкурентоспособности и устойчивости развития, а также формулируются потенциальные механизмы их взаимосвязи для крупного города. В условиях глобализационной политики, шестого технологического уклада, массовой цифровизации и достижения целей устойчивого развития, крупные города пребывают в состоянии постоянно структурно-изменяющейся системы. Для обеспечения реализуемой совокупности их технических показателей необходимо обследование города, которое достигается и современным **методом** построения графоаналитической модели (цифрового двойника). В качестве примера крупного города рассматривается город Чита в Дальневосточном регионе. Город Чита имеет свои уникальные особенности и потенциал к развитию. Для повышения показателей предлагаются некоторые механизмы преобразования городского каркаса, которые приводят в движение все рычаги устойчивости, что способствует устойчивому конкурентоспособному развитию. **Результатом** исследования является разработка этапов технологии устойчивого развития крупного города Чита в условиях Дальневосточного региона, а также приведены рекомендации для разработки нового программного обеспечения по актуальному обследованию города. **Обсуждение**: Окончательной целью применения технологии преобразования является приведение всех рычагов устойчивости развития, функций крупного города и конкурентоспособности к единому балансу, в котором будет комфортно проживать наше и будущие поколения, что соответствует главной цели устойчивого развития.

Ключевые слова

Устойчивое развитие, Дальневосточный регион, крупный город, город Чита, конкурентоспособность.

DOI: 10.23968/2500-0055-2022-7-3-37-43

EVALUATING THE APPLICABILITY OF BERNOULLI'S HYPOTHESIS IN BEAM ANALYSIS

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Abstract
Introduction: In this paper, based on the properties of unit functions, we present accurate solutions to beam bending under various transverse loads and edge restraint conditions, using equations based on Bernoulli's hypothesis and the hypothesis taking into account transverse shears. By comparing the analytical solutions obtained for a rectangular beam, we determined beam length-to height (L/h) ratios for cases when the difference in deflections is less than the permitted value. Thus, criteria for Bernoulli's hypothesis application were obtained. The results of beam bending analysis can be applied when studying rod systems using the force and displacement methods. In this case, Bernoulli's hypothesis is used. All the ratios obtained are simple and clear. However, this hypothesis is applicable for the analysis of thin-walled structures. Meanwhile, the hypothesis taking into account transverse shears can be used for structures of medium cross-section height. To ensure accurate results when studying building structures (beams, plates, shells, rod systems), the criterion of Bernoulli's hypothesis (hypothesis of the straight normal) applicability was needed. **Purpose of the study**: We aimed to build a mathematical deformation model and develop a method for the analysis of bending in elastic Timoshenko beams with account for transverse shears. **Methods:** By applying generalized functions and direct integration of the differential equation for the bending line, we obtained analytical expressions for the deflection function under various boundary conditions. **Results:** Based on the proposed method, we performed beam analysis under various transverse loads and edge restraint conditions. We also evaluated the scope of Bernoulli's hypothesis application for the main types of beams used in the analysis of rod systems by the displacement method.

Keywords
Beam, bending, Kirchhoff model, transverse shear, Timoshenko model, unit functions.

Introduction

Latest advances in construction science show that a balanced combination of materials in a structure makes it possible to utilize their benefits to the maximum extent. Due to the widespread use of new structural materials ensuring structural efficiency, it is required to apply analytical models that would fairly represent the stress-strain state of structural elements in buildings and structures (Zveryayev, 2003). Many researchers explored how to build one-dimensional and two-dimensional approximate analytical models based on three-dimensional equations of elasticity theory (Donnell, 1982; Goldenweiser, 1976; Maslennikov, 2009; Nazarov, 2002; Tovstik, 2007; Zveryayev and Makarov, 2008).

To ensure a balanced combination of material properties, we need to make sure that such a combination is appropriate and provides the required load-bearing capacity of the structure while reducing its weight and manufacturing complexity, optimizing the construction period and operating expenses, thereby improving the performance of investment in construction, and justify that with analysis and calculations.

The widespread use of modern software systems for structural analysis in construction necessitates their verification to determine the reasonable level of detail with regard to the analyzed analytical model and the required accuracy of calculations (ANSYS, 2009; Simulia, 2012: SOFiSTiK AG, 2014). Thus, it is required to obtain accurate solutions for typical problems related to the analysis of new building structure types in order to use analytical solutions (Karpov et al., 2021) for verification of various software systems.

S. P. Timoshenko (Timoshenko, 1945; Timoshenko and Woinowsky-Krieger, 1963) is rightfully considered the author of the refined theory considering transverse shear in the analysis of beams, plates, and shells. He proposed an analytical model that takes into account bending and shear deformations and, thus, can be used to describe the behavior of beams of medium thickness as well as sandwich panels, and the high-frequency vibrations of beams when the wavelength becomes comparable to the cross-section height. In this case, the shear coefficient depends on Poisson's ratio. Numerous researchers attempted to obtain an exact expression for it (Cowper, 1966; Hutchinson, 1981; Stephen, 1980).

In engineering practice, the Timoshenko model (Timoshenko and Gere, 1976) is sufficient in most analysis cases. Based on the results of experimental studies conducted later, it was shown that, in the analysis of many building structures, the shear coefficient is underestimated (Franco-Villafañe and Méndez-Sánchez, 2016; Méndez-Sáchez et al., 2005).

Yeliseyeva et al. (2011) studied the application of the Timoshenko model in beam deflection analysis with account for bending and shear deformations. They showed that the resolving equation in the problem of accounting for additional shear in beam bending has terms with different physical meaning, which introduces particular aspects when boundary conditions are considered.

Lalin and Beliaev (2015) solved the problem of bending of a geometrically nonlinear cantilever beam, using the Kirchhoff and Cosserat–Timoshenko theories followed by a comparison of the results obtained. In their opinion, the findings can be used for verification of various software systems.

When classic beam bending problems are considered, Bernoulli's hypothesis is mainly applied. However, this hypothesis is not valid for, e.g., composite beams. The degree of approximation is mainly determined by the ratio between the cross-section height and the length of the beam as well as physical characteristics and structure of the material (Pavlenko and Vereshchaka, 2002). Rossikhin and Shitikova (2010) provided an analytical review of Timoshenko-type theories in respect to thin-walled open-section beams and concluded that currently there are no theories that would describe the beams under consideration and fully meet the requirements of engineering practice (analysis) and experimental data.

By using Bernoulli's hypothesis, Karpov et al. (2021) presented a method to find an accurate solution to the beam bending equation for a beam of uniform cross-section height, subjected to different types of transverse load (distributed along the entire length of the beam, distributed along a part of the beam, concentrated force, or a moment of a couple of forces), with different types of beam end restraint. An analytical solution for a beam can also be obtained by using the hypothesis taking into account transverse shears. By comparing these solutions, it is possible to determine criteria for Bernoulli's hypothesis application in beam analysis.

The equation for the equilibrium of a beam with length *L* and cross-section height *h*, subjected to the load *q*, when Bernoulli's hypothesis is used, is as follows:

$$EJw^{IV} = q, \tag{1}$$

where $J = h^3/12$ — the moment of section inertia, $w(x)$ — the beam deflection, $q(x)$ — the load (MPa).

If we apply the hypothesis taking into account transverse shears (Timoshenko model), then the equations for the equilibrium of such a beam will be as follows:

$$\frac{dQ_x}{dx} + q = 0, \ \frac{dM_x}{dx} - Q_x = 0, \tag{2}$$

where $Q_x = Gh\left(\psi_x + \frac{dw}{dx}\right), \ M_x = EJ\frac{d\psi_x}{dx}$.

Here ψ_x — the function taking into account transverse shears.

The method of solving Eq. (1) described by Karpov et al. (2021) can also be applied to solve system (2).

Direct integration of the differential equation for the bending line

Let us find a general solution of system (2) by direct integration of the differential equation for the bending line under different types of loads and boundary conditions. We will consider a case when the load *q* is uniformly distributed along the entire length of the beam. Let the beam be rigidly fixed at *x* = 0 and unrestrained at *x* = *L*. In this case, the following conditions must be fulfilled:

at *x* = 0, *w* = 0, and $\psi_x = 0$;

(3)

at *x* = *L*, $M_x = 0$ $\left(\frac{d\psi_x}{dx} = 0\right)$ and $Q_x = 0\left(\frac{d^2\psi_x}{dx^2} = 0\right)$.

Based on the second equation of system (2), we obtain the following:

$$Q_x = \frac{dM_x}{dx} = EJ\frac{d^2\psi_x}{dx^2}, \ \frac{dQ_x}{dx} = EJ\frac{d^3\psi_x}{dx^3}.$$

By substituting the obtained expressions into the first equation of system (2), we obtain the following:

$$EJ\frac{d^3\psi_x}{dx^3} = -q \quad \text{or} \quad \frac{d^3\psi_x}{dx^3} = -\frac{q}{EJ}. \tag{4}$$

Differential equation (4) represents an equation with separable variables. By integrating this differential equation successively, we get the following:

$$\frac{d^2\psi_x}{dx^2} = -\frac{q}{EJ}x + C_1, \ \frac{d\psi_x}{dx} = -\frac{q}{EJ}\frac{x^2}{2} + C_1 x + C_2,$$
$$\psi_x = -\frac{q}{EJ}\frac{x^3}{6} + C_1\frac{x^2}{2} + C_2 x + C_3. \quad (5)$$

By using boundary conditions (3), we find the following arbitrary constants:

$$C_3 = 0, \ C_1 = \frac{qL}{EJ}, C_2 = -\frac{qL^2}{2EJ}.$$

To find *w(x)*, let us use the following expression:

$$Q_x = Gh\left(\psi_x + \frac{dw}{dx}\right) = \frac{dM_x}{dx} = EJ\frac{d^2\psi_x}{dx^2};$$

i.e.,

$$Gh\left(\psi_x + \frac{dw}{dx}\right) = EJ\left(-\frac{q}{EJ}x + \frac{qL}{EJ}\right).$$

Hence, given that $G = E/3$, we obtain the following:

$$\frac{dw}{dx} = \frac{Eh^2 3}{12E}\frac{d^2\psi_x}{dx^2} - \psi_x.$$

By integrating this relation, we get the following:

$$w(x) = \frac{q}{EJ}\left(\frac{x^4}{24} - \frac{L}{6}x^3 + \frac{L^2}{4}x^2\right) + \frac{q}{EJ}\frac{h^2}{4}\frac{(L-x)^2}{2} + b_1. \quad (6)$$

By using the boundary conditions at $x = 0$, $w = 0$, we find b_1:

$$b_1 = -\frac{q}{EJ}\frac{L^2h^2}{8}.$$

Thus, the function *w(x)* will take the following form:

$$w(x) = \frac{q}{EJ}\left(\frac{x^4}{24} - \frac{L}{6}x^3 + \frac{L^2}{4}x^2\right) + \frac{q}{EJ}\left[\frac{h^2}{4}\frac{(L-x)^2}{2} - \frac{L^2h^2}{8}\right]. \quad (7)$$

If transverse shears are not considered (Kirchhoff model), then *w(x)* will be as follows:

$$w(x) = \frac{q}{EJ}\left(\frac{x^4}{24} - \frac{L}{6}x^3 + \frac{L^2}{4}x^2\right).$$

Therefore, since in this case transverse shears are considered, deflection (7) changed by Δ:

$$\Delta = \frac{q}{EJ}\left[\frac{h^2}{4}\frac{(L-x)^2}{2} - \frac{L^2h^2}{8}\right].$$

The maximum deflection will be at *x* = *L*, i.e.:

$$\Delta_{max} = -\frac{q}{EJ}\frac{L^2h^2}{8}.$$

To apply Bernoulli's hypothesis in this case, Δ_{max} must be small (NMT 5% of the permitted deflection w_{perm}). Based on this condition, we can find an estimate for the L/h ratio. For instance, for a rectangular concrete beam ($E = 3 \cdot 10^4$MPa, $w_{perm} = 0.0057h$, at $q = 2 \cdot 10^{-2}$MPa, we have $\frac{q}{EJ}\frac{L^2h^2}{8} = 0.05 \cdot 0.0057h$, hence, we can find $L=16h$. Thus, if $h>L/16$, then we need to use the model taking into account transverse shears. Based on the condition $w_{max} \le w_{perm}$, we obtain $L=30h$.

In the example considered, at $L=10m$, the permitted height of the beam *h* (when Bernoulli's hypothesis is applied) shall not exceed 0.625 m, and based on the condition $w_{max} \le w_{perm}$, the beam height turned out to be 0.33 m. If we need to increase the beam height based on the condition of structural integrity, then it can be increased by 0.295 m. In this case, the hypothesis of the straight normal remains valid.

For a rectangular metal beam ($E = 2.1 \cdot 10^5$MPa, $w_{perm} = 0.01h$, at $q = 2 \cdot 10^{-2}$MPa, $L = 60h$. At L = 10 m, $h = \le 0.16$ m, so that the beam bending equation with the use of Bernoulli's hypothesis could be applied in beam analysis.

Let us assume that the ends of the beam subjected to a load that is uniformly distributed along the entire length of the beam have a hinged support. In this case, at $x = 0$ and $x = L$, the following conditions must be fulfilled:

$$w=0, \frac{d\psi_x}{dx} = 0. \quad (8)$$

By using these boundary conditions, we will find arbitrary constants (except for C_3) and obtain the following:

$$\psi_x(x) = -\frac{q}{EJ}\frac{x^3}{6} + \frac{qL}{2EJ}\frac{x^2}{2} + C_3.$$

Based on $Gh\left(\psi_x + \frac{\partial w}{\partial x}\right) = EJ\frac{d^2\psi_x}{dx^2}$,

we will find *w(x)*. In this case:

$$\frac{dw}{dx} = \frac{q}{EJ}\left[\frac{x^3}{6} - \frac{L}{2}\frac{x^2}{2} - \frac{EJ}{q}C_3 - \frac{h^2}{4}\left(x - \frac{L}{2}\right)\right].$$

By integrating this relation, we get the following:

$$w(x)=\frac{q}{EJ}\left[\begin{array}{c}\frac{x^4}{24}-\frac{L}{12}x^3-\frac{EJ}{q}C_3x-\\ \frac{h^2}{4}\frac{\left(x-L/2\right)^2}{2}\end{array}\right]+b_1.$$

By using boundary conditions (8), we will find C_3 and b_1. Thus, $w(x)$ will take the following form:

$$w(x)=\frac{q}{EJ}\left\{\begin{array}{c}\frac{x^4}{24}-\frac{L}{12}x^3+\left(-\frac{L^3}{24}+\frac{L^2h}{32}\right)x-\\ \frac{h^2}{4}\left[\frac{\left(x-L/2\right)^2}{2}-\frac{L^2}{8}\right]\end{array}\right\}.$$

If transverse shears are not considered, then the deflection function will be as follows:

$$w(x)=\frac{q}{EJ}\left(\frac{x^4}{24}-\frac{L}{12}x^3-\frac{L^3}{24}x\right).$$

Therefore, since in this case transverse shears are considered, the deflection changed by Δ:

$$\Delta=\frac{q}{EJ}\frac{h^2}{4}\left[\frac{L}{8}x-\frac{\left(x-L/2\right)^2}{2}+\frac{L^2}{8}\right].$$

Since the maximum deflection will be at $x=L/2$, then $\frac{9qL^2}{16Eh}$ must be small. In case of a concrete beam, we have the following ratio: .

$$\frac{9qL^2}{16Eh}=0.05\cdot 0.0057h.$$

Therefore, to apply Bernoulli's hypothesis in beam analysis, the following condition must be fulfilled: *h<L/27*. If *h>L/27* , then we need to use the model taking into account transverse shears. For a concrete beam, at *L* = 10 m, the cross-section height *h* shall not exceed 0.37 m.

For a metal beam, *L/h* = 95, therefore, if *h>L/95*, then we need to use the model taking into account transverse shears. For instance, at *L* = 10 m, the beam cross-section height *h* shall not exceed 0.105 m.

In the same way, we can analyze Bernoulli's hypothesis applicability for beam analysis in case of other types of loads and beam end restraint.

Let the load be uniformly distributed along a part of the beam span, i.e.:

$$q(x)=q_1\bar{\delta}(x-x_1)=q_1\left[u(x-a_1)-u(x-a_2)\right],$$

where $u(x-a_1)$ and $u(x-a_2)$ are unit functions.

If the beam is rigidly fixed at $x=0$ and unrestrained at $x=L$, then the boundary conditions will take the form corresponding to that in system (3). In this case, Eq. (4) will take the following form:

$$\frac{d^3\psi_x}{dx^3}=-\frac{q_1}{EJ}\left[u(x-a_1)-u(x-a_2)\right]. \quad (9)$$

By using the properties of unit functions

$$\int u(x-a_1)dx=(x-a_1)u(x-a_1);$$

$$\int (x-a_1)u(x-a_1)dx=\frac{(x-a_1)^2}{2}u(x-a_1).$$

and successively integrating Eq. (9), we obtain the following:

$$\frac{d^2\psi_x}{dx^2}=-\frac{q_1}{EJ}\left[\begin{array}{c}(x-a_1)u(x-a_1)-\\ (x-a_2)u(x-a_2)\end{array}\right]+C_1;$$

$$\frac{d\psi_x}{dx}=-\frac{q_1}{EJ}\left[\begin{array}{c}\frac{(x-a_1)^2}{2}u(x-a_1)-\\ \frac{(x-a_2)^2}{2}u(x-a_2)\end{array}\right]+C_1x+C_2;$$

$$\psi_x=-\frac{q_1}{EJ}\left[\begin{array}{c}\frac{(x-a_1)^3}{6}u(x-a_1)-\\ \frac{(x-a_2)^3}{6}u(x-a_2)\end{array}\right]+C_1\frac{x^2}{2}+C_2x+C_3.$$

By using boundary conditions (3), we will find C_1, C_2 and C_3:

$$C_3=0, C_1=\frac{q_1}{EJ}(a_2-a_1),$$

$$C_2=\frac{q_1}{EJ}\left[\frac{(L-a_1)^2}{2}-\frac{(L-a_2)^2}{2}-L(a_2-a_1)\right].$$

Based on the following condition:

$$Gh\left(\psi_x+\frac{\partial w}{\partial x}\right)=EJ\frac{d^2\psi_x}{dx^2}=-q_1\left[\begin{array}{c}(x-a_1)u(x-a_1)-\\ (x-a_2)u(x-a_2)-\\ a_2+a_1\end{array}\right],$$

we will get:

$$\frac{dw}{dx}=\frac{q_1}{EJ}\left[\frac{(x-a_1)^3}{6}u(x-a_1)-\frac{(x-a_2)^3}{6}u(x-a_2)\right]-C_1\frac{x^2}{2}-$$
$$C_2x-\frac{q_1}{Gh}\left[\begin{array}{c}(x-a_1)u(x-a_1)-\\ (x-a_2)u(x-a_2)-a_2+a_1\end{array}\right].$$

By integrating this expression, we will find the beam deflection function:

$$w(x)=\frac{q_1}{EJ}\left[\frac{(x-a_1)^4}{24}u(x-a_1)-\frac{(x-a_2)^4}{24}u(x-a_2)\right]-C_1\frac{x^3}{6}-C_2\frac{x^2}{2}-\frac{q_1}{Gh}\left[\frac{(x-a_1)^2}{2}u(x-a_1)-\frac{(x-a_2)^2}{2}u(x-a_2)-(a_2-a_1)x\right].$$

Based on the condition at x = 0, w = 0, we will get b_1=0.

In order to keep the expression for $w(x)$ as simple as possible, we will not substitute C_1 and C_2 with the values obtained.

If transverse shears are not considered, then:

$$w(x)=\frac{q_1}{EJ}\left[\frac{(x-a_1)^4}{24}u(x-a_1)-\frac{(x-a_2)^4}{24}u(x-a_2)\right]-C_1\frac{x^3}{6}-C_2\frac{x^2}{2}.$$

Therefore, with transverse shears considered, the deflection changed by Δ:

$$\Delta=-\frac{q_1}{Gh}\left[\frac{(x-a_1)^2}{2}u(x-a_1)-\frac{(x-a_2)^2}{2}u(x-a_2)-(a_2-a_1)x\right].$$

The maximum value will be at $x=L$:

$$\Delta_{max}=-\frac{q_1}{Gh}\left[\frac{(L-a_1)^2}{2}-\frac{(L-a_2)^2}{2}-(a_2-a_1)L\right].$$

Based on the condition $\frac{3q_1}{2Eh^2}\left(a_1^2-a_2^2\right)=0.05\cdot 0.0057$, we will estimate the L/h ratio. Let $a_1=\frac{L}{3}, a_2=\frac{2}{3}L$, then $\frac{q_1L^2}{2Eh^2}=0.05\cdot 0.0057$. Hence, $\frac{L}{h}=29$.

Analysis results

The following table presents the analysis results:

Type of beam, with height *h* and span *L*	Type of load, uniformly distributed	Beam material	Recommended *L/h* ratio for beam analysis	
			by Kirchhoff model	by Timoshenko model
Cantilever	$0\le q\le L$	Concrete	≥ 16	<16
		Steel	≥ 60	<60
	$L/3\le q\le 2L/3$	Concrete	≥ 29	<29
Hinged support	$0\le q\le L$	Concrete	≥ 27	<27
		Steel	≥ 95	<95

Conclusion

When Bernoulli's hypothesis (Kirchhoff model) is applied, the relations used to determine the components of the stress-strain state of a beam resisting bending under various types of transverse load and beam end restraint are simple and clear as shown above. The obtained values of deflections and bending moments can be used in the analysis of rod systems, e.g., with the use of the displacement method. However, to ensure that analytical models and solutions are accurate, we need to evaluate the applicability of Bernoulli's hypothesis. This method makes it possible to do that easily. The obtained estimates for beams can be used approximately in the analysis of plates and shells.

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ОЦЕНКА ПРИМЕНИМОСТИ ГИПОТЕЗЫ ПЛОСКИХ СЕЧЕНИЙ ПРИ РАСЧЕТЕ БАЛОК

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Аннотация

Используя свойства единичных функций, в данной статье находятся точные решения изгиба балки при различной поперечной нагрузке и различных условиях закрепления краев, как при использовании уравнений, основанных на гипотезе плоских сечений, так и на гипотезе, учитывающей поперечные сдвиги. Путем сравнения полученных аналитических решений для балки прямоугольного сечения находятся соотношения её длины *L* балки и ее высоты *h*, когда разница в прогибах меньше допустимой величины. Таким образом, получаются критерии использования гипотезы плоских сечений. Результаты расчета изгиба балок используются при исследовании стержневых систем методом сил и методом перемещений. При этом используется гипотеза плоских сечений. Все полученные соотношения имеют простой и наглядный вид. Однако эта гипотеза применима при расчете тонкостенных конструкций. А гипотеза, учитывающая поперечные сдвиги, может быть использована для конструкций средней высоты поперечного сечения. Для получения корректных результатов исследования строительных конструкций (балка, плита, оболочка, стержневая система) был необходим критерий применимости гипотезы плоских сечений (прямой нормали). **Цель исследования:** Построение математической модели деформирования и создание методики расчета на изгиб упругих балок типа Тимошенко с учетом поперечных сдвигов. **Методы:** На основе применения математического аппарата обобщенных функций методом непосредственного интегрирования дифференциального уравнения изогнутой оси балки получены аналитические выражения функции прогибов для различных граничных условий. **Результаты:** По предложенной методике проведены расчеты балок при действии различной поперечной нагрузки и различных видов закрепления концов краев балки. Выполнена оценка области применения гипотезы плоских сечений для основных типов балок, используемых для расчетов стержневых систем методом перемещений.

Ключевые слова

Балка, изгиб, модель Кирхгофа, поперечный сдвиг, модель Тимошенко, единичные функции.

DOI: 10.23968/2500-0055-2022-7-3-44-52

MECHANICAL AND MICROSTRUCTURAL CHANGES IN POST-FIRE RAW WOOD

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Abstract

Introduction: Today, the need for the neutralization of the environmental, economic, social, and other consequences of natural emergencies is becoming more and more urgent. One of such devastating disasters is forest fires, which are currently very widespread in the world. In most cases, after a fire, we are left with a forest that was partially exposed to fire. A burnt tree loses its immunity. As a result, an outbreak of various subcortical insect species, which infect healthy trees as well, occurs in these territories. Such a forest is subjected to sanitary cutting. **Purpose of the study:** We aimed to determine the residual mechanical properties of raw wood to be used as a structural material. **Methods:** In the course of the study, we used destructive and non-destructive testing methods in respect of the mechanical properties of the material. **Results:** It was established that changes in the microstructure of wood correlate with its strength properties. The maximum decrease in the strength properties of wood was observed at the top end of the tree and amounted to 22.7% as compared to the reference wood. The minimum decrease in the strength properties of post-fire wood was observed in the butt end of the tree and amounted up to 15.0%. In the middle part, a decrease in the strength properties of wood was up to 24.0%.

Keywords

Wood, fire, strength, microstructure, building structures.

Introduction

More and more consumers around the globe prefer wood in the design and construction of buildings. Wood is an environmentally friendly, renewable material, which is easy to use. However, wood resources are limited.

Forest fires are one of the most terrible and dangerous widespread natural disasters (Castillo et al., 2021; Interfax, 2021; Puntzukova, 2019; Ria, 2018; Soto et al., 2013; Yang et al., 2022). Every year, Russia witnesses thousands of forest, grass, and peat fires causing significant damage to the environment and economy (Nedkov et al., 2020; Veselkin et al., 2022). After a fire, there remains a burnt forest area, the nature of which depends on the type of forest that was there before the fire, the type of fire, its intensity, area, and duration.

As it is known, a burnt tree loses its immunity. Bark beetles get under the bark of such trees. However, they can also spread to healthy trees. The increasing length and severity of recent forest fire seasons annually cause widespread injury to millions of trees, facilitating the subsequent outbreak of various subcortical insect species infecting trees not affected by the fire (Arefyev, 2018; Kopylov et al., 2022). In burnt pine forest areas, the maximum abundance of insects can be observed in the fourth and fifth years after a fire (Ecologia, 2007; Kitchens et al., 2022). In small areas, the maximum abundance of insects can be observed in the second year after a fire. Forests are thinning due to forest cutting and parasite outbreaks. Burnt forests areas are subjected to sanitary cutting.

Within the implementation of the Ecology national project (National Projects of Russia, 2022) as well as the efficient use and saving of natural resources, the need for the sustainable use of wood shall be addressed.

We aimed to determine the residual strength properties of raw wood to be used as a structural material. Of particular research interest is post-fire raw wood, not older than 4–5 years from the fire, with a loss in the cross-section of up to 20%. The study of the strength properties and microstructure of such wood will make it possible to determine if such a material is suitable for structural use. It will also expand the scope of application for burnt wood (including as a structural material).

Thus, the study of wood with reduced physical and mechanical properties (including post-fire wood) is an important step toward the sustainable and rational use of natural resources.

Methods

Among other things, it is suggested to use post-fire wood in wooden building structures, including as lamellae in glued elements (Ayansola et al., 2022; Koshcheev et al., 2022; Lisyatnikov et al., 2022; Nippon Steel, 2005; Sergeev et al., 2022). Wooden structures are made mainly from coniferous wood (pine, spruce), therefore, the studies were performed with the use of pine wood samples (Chernyh and Moskalyev, 2020; Lisyatnikov, 2022; Noren, 1983; Sergeev, 2022).

Destructive and non-destructive testing methods were adopted to study the physical and mechanical properties of post-fire wood (Berwart et al., 2022; Jaworski et al., 2021; Roshchina et al., 2022).

In many wooden structures, wood resists compression, bearing, shear, bending as well as longitudinal and transverse tension (Lukina et al., 2022; Sergeev et al., 2021). In many cases, a complex stress-strain state is observed (compression with bending in arches, shear and bearing stresses in the supporting elements of structures, tension at an angle to the fibers and shear at the truss chord splices, etc.).

Earlier, we tested wood for compression and tension along the fibers as well as static bending. As a result, we established a decrease in the strength of the samples taken from the top end of the tree trunk. For instance, under static bending, the strength of the post-fire wood samples taken from the top end decreased by more than 20%, under compression along the fibers — by 28.8%, under tension — by 30.6%. The minimum decrease in strength in all three types of tests was observed in the samples taken from the butt end: under static bending, the decrease was almost 6.0%, under compression along the fibers — 15.0%, and under tension along the fibers — 8.4%.

To ensure a comprehensive study of the strength properties of post-fire raw wood, it is necessary to perform tests for shear along the fibers.

The samples were taken from post-fire trees (pine). Forest growing area: Yakutia, Russia. Intended use of the forest: commercial forest. Type of fire: creeping, independent, medium-scale. Damage to the forest stand from the fire: 10–15% by the cross-section. The bark of the trees is charred.

The samples were taken from the butt and top ends as well as the middle part. The samples were made from each slice, at different depths to the core part: in the center, at a depth of 0.5 radius (in the middle), and on the periphery (near the bark). Therefore, sap wood, the most commonly used wood in building structures, was studied. As a reference, samples of intact pine wood were taken.

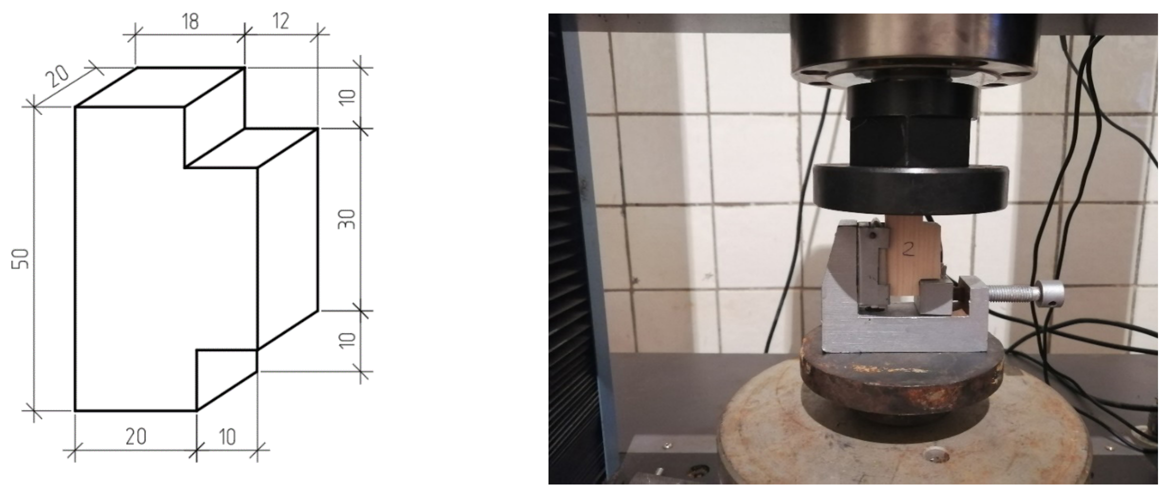
Strength depends on moisture. Before the tests, the samples were brought to a moisture close to the normalized one, followed by conversion to 12% moisture (Korolkov et al., 2021; Ye et al., 2022).

Before the tests, the samples were weighed, and the density of wood was determined. The density of the samples taken from the butt end was 454.3 kg/m^3, from the middle part — 403.6 kg/m^3, from the top end — 346.7 kg/m^3.

Determining the strength of wood weakened by fire under shear along the fibers

The samples were tested for shear along the fibers (Figure 1).

The studies were carried out using an REM-100-A-1 testing machine. The universal REM-100-A-1 testing machine meets the applicable requirements and is intended for mechanical tests



a) b)

Figure 1. Testing of wood weakened by fire for shear along the fibers:
a) test sample shape; b) sample testing

involving the tension, compression, and bending of samples and items made of materials with a breaking strength not exceeding 100 kN.

The sample was loaded uniformly at a constant speed of the loading head. The speed of the loading head was 4 mm/min.

The obtained experimental data on the samples of wood weakened by fire were compared with those on the reference samples (Figure 2). Based on the test results, the statistical processing of the experimental data was performed.

Analysis of the post-fire raw wood microstructure

The strength properties of wood depend on the microstructure of the material. To clarify and confirm the results of the mechanical tests, the scanning electron microscopy and optical microscopy of the samples were carried out.

The scanning electron microscopy of the samples was performed using a Quanta 200 3D microscope (USA). With scanning electron microscopy, it is possible to study the micromorphology and fine structure of the sample surface using a focused electron beam scanning the sample surface (Cao et al., 2022; Labudin et al., 2022; Grünewald et al., 2012). Optical microscopy was performed using a Raztek MRX9-D digital optical microscope (Russia), which allows for the visual observation of the microstructure of opaque objects.

The studies involved the samples that were selected for mechanical tests prior to the tests for shear along the fibers.

Results and discussion

Figure 2 shows the results of the mechanical tests of the samples for shear along the fibers. Under static load, the shear resistance of wood at first increases in proportion to the increase in the length / projection of the sample (Figure 2); then, as soon as the length of the projection reaches a value equal to 9*h,* shear resistance becomes constant — shear occurs.

The ultimate strength of wood under shear along the fibers is determined as follows:

$$\tau_w = \frac{P_{\max}}{b \cdot l}, \quad (1)$$

where P_{max} is the maximum load, kN; b is the sample thickness, mm; l is the shear length, mm.

The ultimate strength of wood under static bending is determined as follows:

$$\sigma_w = \frac{3F_{max}l}{2bh^2}, \quad (2)$$

where F_{max} is the maximum load, kN; l is the distance between the centers of the supports, mm; b is the actual width of the samples, mm; h is the actual height of the samples, mm.

The ultimate strength under compression along the fibers is determined as follows:

$$\sigma_w = \frac{P_{max}}{ab}, \quad (3)$$

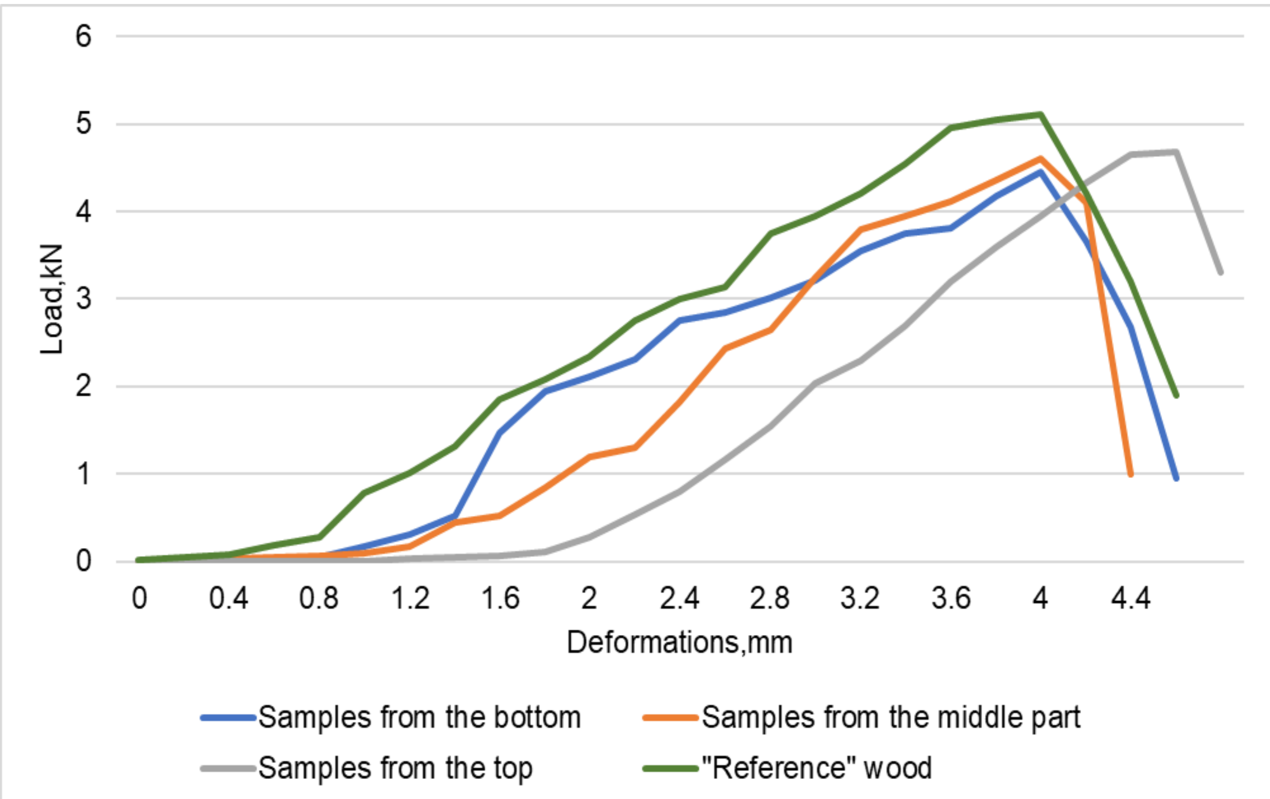


Figure 2. A load vs. deformations diagram for pine wood weakened by fire under shear along the fibers

where P_{max} is the maximum load, kN; *a, b* are the cross-sectional dimensions of the sample, mm.

Based on the test results, the statistical processing of the experimental data was performed.

The accuracy figure *P* (%) is determined using the following equation:

$$P = \pm \frac{m}{V} \cdot 100\%, \quad (4)$$

where m is the standard error of the mean; V is the coefficient of variation.

Based on the results of the tests, Table 1 was compiled in addition to the tests performed earlier.

Table 1. Comparative data on the mechanical properties of post-fire wood throughout the trunk height in comparison with reference wood

Type of test	Breaking load P_{max}, kN / Accuracy figure P, %				Stress σ, MPa / Strength decrease, %			
	Butt end	Medium part	Top end	Reference wood	Butt end	Medium end	Top end	Reference wood
Shear along the fibers	4.45 / ±1.41	4.61 / ±1.46	3.95 / ±1.25	5.11 / ±1.62	7.42 / 12.92	7.68 / 9.78	6.58 / 22.70	8.52
Static bending	1.12 / ±0.36	1.05 / ±0.33	0.95 / ±0.32	1.19 / ±0.38	32.26 / −5.84	30,24 / −11,76	27.36 / −20.16	34.27
Compression along the fibers	10.34 / ±3.27	9.88 / ±3.12	8.68 / ±2.75	12.12 / ±3.83	25.86 / −14,99	24,76 / −18,31	21.67 / −28.81	30.43
Tension along the fibers	6.57 / ±2.08	5.81 / ±1.84	4.91 / ±1,55	7.84 / ±2.47	82.17 / −8.39	72.63 / −23.58	61.51 / −30.61	98.11

The microstructure of pine was determined using scanning electron microscopy in the cross-section of the samples since this method is considered suitable for studying the structure of wood at the molecular level. The results of this study contribute to a better understanding of changes in the microstructure of wood throughout the trunk height and the mechanism of changes in the strength properties of post-fire wood.

The microscopic analysis of pine wood was performed to determine the number and diameter of tracheids, the thickness of their walls, and some other changes in the structure of wood. The study of tracheids was carried out both for post-fire and intact wood samples.

Figure 3 shows a significant post-fire increase in the number of tracheids as a result of fire in comparison with the reference samples. The largest increase in the number of tracheids is characteristic of the butt end.

Signs of a post-fire increase in the average diameter of tracheids were observed. Using a microscope, the resin channels in the reference and post-fire wood samples were calculated.

Changes in the density of the resin channels (the number of the resin channels per 1 cm^2) are characterized by the following pattern: in the top end, it decreases, and in the butt end, it increases, taking on a more rounded shape. This observation is confirmed by a number of studies (Kuroda et al., 2022; Park et al., 2022). Resin from the top layers runs down to the butt end of the trunk, which explains a sharp increase in the density of this area right after the fire, before wood is affected by a fungal disease (Kiseleva et al., 2020).

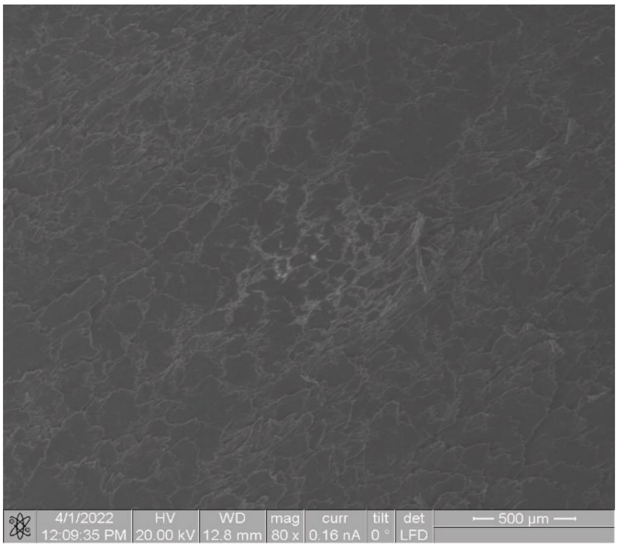
The microscopic analysis of post-fire wood showed that the wood cells are "empty" and the samples are quite light as compared to the reference ones. The analysis of density demonstrated the following: a decrease in density in the butt end as compared to reference wood was 10%, in the middle part — 24%, and in the top end — 44%.

Figure 4 shows the results of the analysis of the wood samples in the longitudinal section using optical microscopy.

Optical microscopy shows partial breaks and cracks along the fibers. The development of such cracks is associated with internal stresses that occur as a result of sudden temperature and moisture fluctuations. Wood begins to shrink. Its outer layers become drier than its inner layers.

High temperature during a fire has a destructive effect on the structure of wood. This type of cell wall destruction can be explained by the fact that under the influence of high temperatures, free moisture in the tube cavities boiled off, and that, in turn, led to an increase in the excess pressure of the vapor-air mixture, which contributed to the destruction of

a)



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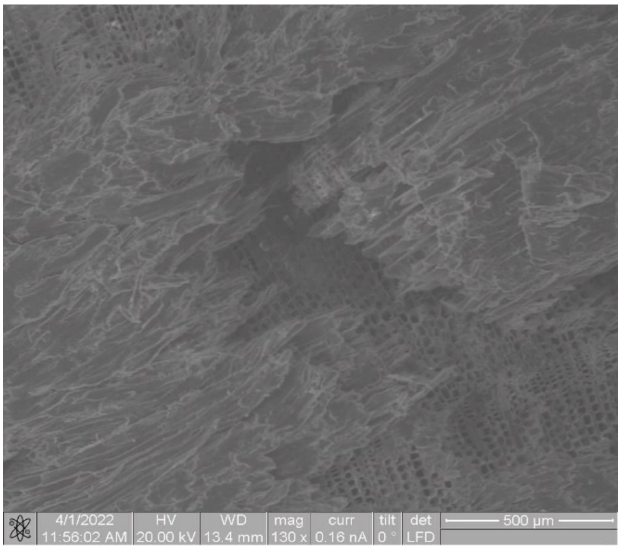

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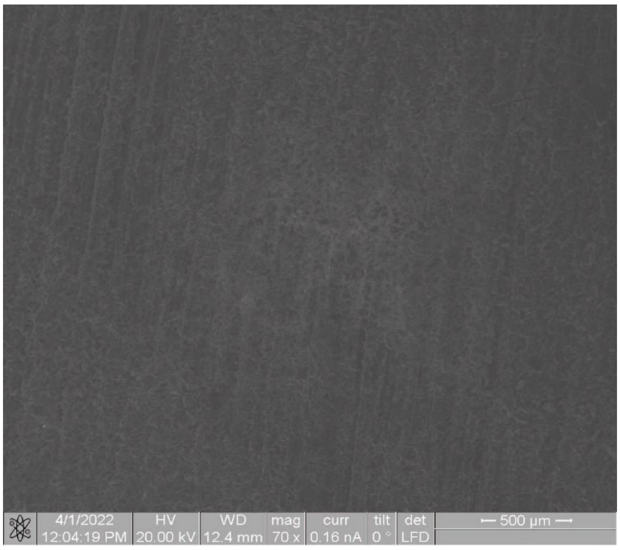

d)

Figure 3. Analysis of the wood samples in the cross-section using scanning electron microscopy:
a) the butt end weakened by fire; b) the middle part weakened by fire;
c) the top end weakened by fire; d) the reference samples

the cell walls in the groups of tubes (Kantieva et al., 2021; Scandelli et al., 2021).

The study of the wood samples using scanning electron microscopy showed that in the case of creeping fires, up the trunk, fire damage is less.

Therefore, as a result of high temperatures, the mechanical properties of wood change: wood becomes brittle, thus, its shock resistance decreases. Qualitative changes in the microstructure of wood are also represented by changes in strength properties. The following pattern can be observed: post-fire wood is characterized by reduced strength properties. The maximum decrease in strength properties is observed in the top end and amounts to 22.7%; in the middle part and butt end, a decrease in strength under shear is 10–12%.

Conclusions

Thus, we can draw the following conclusions in respect of changes in the microstructure of raw wood under the influence of forest fires:

1. Fires cause changes in the anatomical structure of tubes and fiber tracheids. Anatomical changes in raw wood occur throughout the entire height of the trunk. The following pattern is observed: the shape and number of tracheids in the annual ring change. The butt end is characterized by a higher density of resin channels.

2. Fires cause changes in the number of tracheids. Quantitative changes are accompanied by qualitative changes represented by changes in strength properties. Anatomical changes correlate with changes in the strength properties of wood. The maximum decrease in strength properties is observed at the top end and amounts to 22.7% as compared to the reference wood. The minimum decrease in the strength properties of post-fire wood

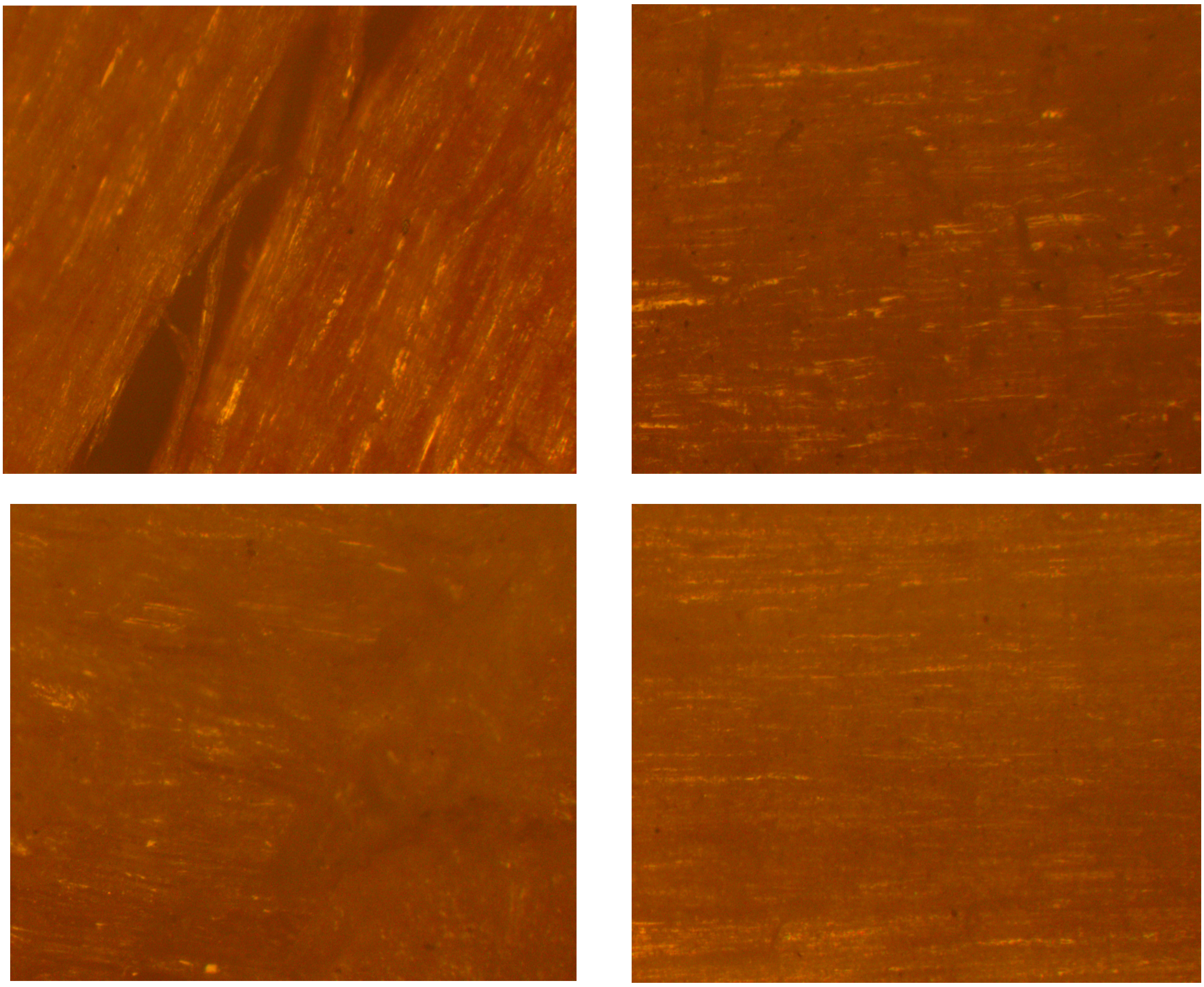

Figure 4. Analysis of the wood samples in the longitudinal section using optical microscopy:
a) the butt end weakened by fire; b) the middle part weakened by fire;
c) the top end weakened by fire; d) the reference samples

is observed in the butt end.

3. Post-fire wood is characterized by high resinosis in the butt end, higher density, and, therefore, higher strength properties. The peformed mechanical tests for static bending, compression along the fibers, tension along the fibers, and shear along the fibers show that the total strength decrease amounts to 6.0–15.0%.

4. Taking into account the strength properties of post-fire raw wood can help in solving a practical problem: is it always necessary to urgently cut down burnt trees that are still alive?

Funding

The research was supported by grant of the Russian Science Foundation No. 22-29-01579 (https://rscf.ru/project/22-29-01579/). The studies were carried out with the use of the equipment of the interregional multidisciplinary and interdisciplinary center for the shared use of advanced and competitive technologies in the areas for the development of domestic advances in the field of nanotechnology and their application in industry/mechanical engineering (Agreement No. 075-15-2021-692 dd ugust 5, 2021).

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МЕХАНИЧЕСКИЕ И МИКРОСТРУКТУРНЫЕ ИЗМЕНЕНИЯ СЫРЬЕВОЙ ДРЕВЕСИНЫ, ПОДВЕРЖЕННОЙ ОГНЕВОМУ ВОЗДЕЙСТВИЮ

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Аннотация
Нивелирование экологических, экономических, социальных и других последствий чрезвычайных ситуаций природного характера становятся сегодня все более актуальным. Одним из разрушительных бедствий являются лесные пожары, которые широко распространены в мире. На местах после пожара остается лес, который зачастую частично подвергается огневому воздействию. Обожженное дерево теряет иммунитет, поэтому на этих территориях происходит вспышка различных подкорковых видов насекомых-вредителей, которые заражают в том числе и здоровые деревья. Такой лес подвергается санитарной вырубке. **Целью работы** является определение остаточных механических свойств сырьевой древесины для использования в качестве конструкционного материала. Использованы **методы:** разрушающего и неразрушающего методов контроля механических характеристик материала. В **результате** установлено, что изменение микроструктуры древесины коррелируется с прочностными свойствами. Максимальное снижение прочностных свойств наблюдается в вершинной части дерева и составляет 22.7% по сравнению с эталонной древесиной. Минимальное снижение прочностных свойств древесины, подведённой огневому воздействию, наблюдается в комлевой части – до 15.0%. В срединной части снижение прочности составляет до 24.0%.

Ключевые слова
Древесина, пожар, прочность, микроструктура, строительные конструкции.

DOI: 10.23968/2500-0055-2022-7-3-53-64

MODERN MATERIALS AND STRUCTURES USED IN HOUSING CONSTRUCTION: INTERNATIONAL EXPERIENCE

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Abstract
Introduction: The article addresses the possibility of using universal energy-efficient engineering and technological solutions in mass housing construction, regardless of the climatic region of construction, with account for modern development in Saint Petersburg (Russian Federation) and Münster (Germany). The article not only considers improvements in building technologies used in modern housing construction but also offers an overview of the latest energy-efficient materials and structures. **Purpose of the study:** We aimed to introduce energy-efficient solutions in housing construction using innovative technologies and materials. In addition to theoretical materials, practical calculations will be presented, clearly showing the advantages and disadvantages of various engineering and technical solutions. **Methods:** In the course of the study, we used **a)** a comparative analysis of physical and thermal properties as well as strength characteristics of building materials used in mass housing construction; **b)** a problem-logical method to analyze possible typical space-planning and structural solutions for the design and construction of buildings, with account for climatic conditions and geographical features of the construction region, in compliance with the basic principles of modern sustainable construction, energy and environmental standards, economic efficiency of the solutions used, in accordance with international European LEED and BREEAM and Russian GREEN ZOOM standards. **Results:** We propose to introduce, along with the already well-known and time-tested ones, innovative patented solutions in materials and construction technologies both in private and mass housing construction in the countries under consideration: Russian Federation and Germany. **Discussion:** The discussion of field tests and implementation of the latest building materials in housing construction clearly demonstrates the importance of international cooperation in this field at various levels. As a consequence of the growing volume of housing construction and energy consumption, there emerge new stricter requirements and standards for the quality of materials produced and their technical characteristics, as well as a variety of decorative solutions enabling the construction market to be competitive and meet the over-demand requirements of the rapidly developing industrial society, while necessarily taking environmental protection measures, including those on conservation and mindful use of natural resources.

Keywords
Energy efficiency, housing construction, modern building materials, reinforced concrete structures.

Introduction

Currently, innovative technologies and engineering advances are actively introduced into all spheres of everyday life of society. In this respect, the field of design and construction is by no means an exception.

The development of energy saving and energy efficiency in construction as well as housing and utility sector can be seen as one of the priorities in every country. In the construction industry of the Russian Federation and leading European countries, the efficient and rational use of energy and more active utilization of renewable energy sources, reducing greenhouse gas emissions, are considered important measures. A smart state policy in this area will undoubtedly improve the quality of life in general (Elistratov et al., 2019; Kiseleva and Pastukh, 2017).

Modern building materials allow architects and designers to put a lot of creative out-of-the-box ideas into practice in cooperation with civil engineers competent in the operation and technology of assembly in respect of any building design, required for project implementation.

The technology of housing construction with the use of prefabricated reinforced concrete panels ensures the maximum speed of assembly of residential buildings, which gives it an advantage over traditional construction technologies (Krikun and Tzay, 2020). Various countries of the European Union and the Russian Federation have accumulated experience in using this technology. As it is well known, in the 1950s, several European countries adopted state policies intended to resolve the housing problem quickly. First in Denmark and France and later in other countries, prefabricated housing construction, i.e., the in-plant manufacturing of reinforced concrete building elements and the subsequent structure assembly at a construction site, served as the technological basis for housing construction. This technology implies the use of prefabricated reinforced concrete panels as walls and floor slabs, including room-size slabs.

The prefabricated housing construction technology ensured the maximum speed of assembly, which gave it an advantage over traditional construction technologies.

In the Soviet Union, this technology gained widespread use. The preferences given to this type of construction by the state in terms of obtaining land plots and loans made it possible to meet acute social housing needs (Ivanov and Golovina, 2015). Due to the administrative-command system of economic management, up to 90% of housing in cities were built with the use of reinforced concrete prefabrication technologies. However, despite the high manufacturability of prefab panels, the architectural appearance of such buildings and the urban environment could hardly be considered aesthetically pleasing.

In Western Europe, they started addressing the issue of providing adequate housing conditions for urban residents at the end of the 20th century. When the acute housing availability problem was resolved, in particular, in the 1980s, the demolition and reconstruction of buildings constructed industrially with the use of reinforced concrete prefabrication technologies started. However, it was not physical depreciation but obsolescence that caused the reconstruction of urban areas in Europe in the 1960s. In this regard, the following accompanying circumstances can be considered: stricter requirements for energy saving in the operation of residential buildings, the emergence of a mass effective demand for a higher-quality urban environment, prevailing studies on life in high-rise, high-density housing, which established damage to health and social relations in case particular design parameters and operating conditions are exceeded (Deilmann et al., 1977).

Depending on the economic situation in a specific country or city, two approaches to reconstruction were used. The first approach constitutes total or partial demolition of prefab buildings and subsequent construction of new buildings at the cleared sites. The second approach constitues total or partial preservation of load-bearing structures in buildings erected in the 1960s but with the transformation of the appearance of a building.

Materials and Methods

To retrofit the housing stock, save energy and rationally use natural resources, the authorities of various countries have developed state programs for the renovation of dilapidated housing. These programs are intended for long-term implementation. They establish measures aimed not only at improving housing conditions but also at increasing social cohesion among residents of districts (Elistratov et al., 2019).

The study addressed the experience in the construction of residential buildings in the cities under consideration, located in different climatic zones but having similar needs in terms of the energy efficiency of building structures and construction quality (Mähner et al., 2016).

The use of modern building materials in the construction of residential buildings (prefabricated, cast-in-situ, or mixed) will not only significantly improve the technical characteristics of load-bearing and enclosing structures but also take care of the environment, in compliance with the European (LEED and BREEAM) and Russian Federation (GREEN ZOOM) standards (Pastukh et al., 2021a).

It is possible to increase the area utilization efficiency by adding new residential space to existing buildings with a height of 2−5 floors and new construction facilities, e.g., a section inserted between existing buildings or attached end sections.

An increase in the housing stock due to additions and inserted sections should not exceed 25%. On the one hand, this ensures a sufficient number of new apartments allocated for sale, and on the other hand, such additions and inserted sections do not significantly affect the existing social and engineering infrastructure. The balance of income and expenditure serves as a criterion of success (Linov and Ivanov, 2018).

In addition to new construction, reconstruction and repair activities performed in mid-rise residential buildings should include the following:

- provision of elevators and entrances adjacent to staircases;
- addition of recessed balconies on metal supports to attach to existing buildings, which is not usually provided for in the typical series of residential buildings;
- conversion of the first floors with the arrangement of apartments with separate entrances for people with reduced mobility;
- arrangement of one-story covered parking lots adjacent to the first floors, with rooftop playgrounds for children, sports grounds and recreational areas for adults;
- allocation of storage areas for residents on the converted first floors;
- facade insulation and finishing;
- replacement of the thermal insulation of external building apertures;
- replacement and repair of in-house utilities and equipment.

Utilities and design features can be upgraded with the use of modern energy-efficient materials and technologies: air conditioning, thermal insulation, energy- and water-saving equipment. In countries with cold climate, the modernization of residential buildings involves increasing the energy efficiency, i.e., using modern engineering technologies aimed at reducing energy consumption for heating, water and power supply by ensuring microclimate control.

A good example is the installation of solar panels on parapets, serving as decorative elements of the facade and providing the residential building with additional energy. The installation of radiators with individual energy meters in a multi-apartment building provides a convenient system that enables accurate cost allocation and increase the energy efficiency of the building. As for excess heat, the problem can be solved by the arrangement of sun protection structures, such as recessed balconies, canopies, etc. and ventilation equipment installation. Waste heat from apartments and passive solar rays can be passed through a controlled ventilation system and integrated into an element of the technological system. According to the European documents on the National Strategy for the Reconstruction of Buildings to Improve Energy Efficiency, it is required to install ventilation systems with heat recovery in buildings of certain energy efficiency classes.

In the current situation in the construction industry, which occurred as a result of the intensive transformation of the living environment in major Russian Federation (e.g., Saint Petersburg) and European (e.g., some urban settlements in Germany) cities, the technological aspect of construction and renovation of buildings is gaining particular importance in terms of the effective use of house-building technology.

We aimed to investigate the scope of rational use of house-building as well as repair-and-construction technologies and compare the stages of modern development of the architectural-and-planning structure in Russian Federation and European cities using Saint Petersburg (Russian Federation) and Münster (Germany) as case studies.

In this regard, of great interest are large-panel, cast-in-situ, and masonry construction technologies used for the assembly of residential buildings. These technologies were formed following the development of load-carrying devices for construction mechanization and emergence of new building materials, which can be clearly seen in the development of house-building technologies in Saint Petersburg (Figure 1).

Results

1. Housing construction in Russian Federation

The study of housing construction in Saint Petersburg revealed a widespread use of global advanced technologies and materials: precast and cast-in-situ reinforced concrete, steel and wooden structures, brick, effective insulation materials, etc.

Reinforced concrete elements, which are load-bearing, as well as enclosing structures are also widely used in the construction of industrial and civil buildings and structures. They include load-bearing columns, walls, structural floors and cladding, as well as other constructions of buildings and structures of various purposes.

The further development of the house-building industry in Saint Petersburg led to the application of the cast-in-situ and precast construction technology. A distinctive feature of this technology is the use of prefabricated vertical (except for vertical stiffening diaphragms, which are cast-in-situ) and cast-in-situ horizontal structures — rigid slabs, which ensure the spatial rigidity of the building (Figure 2). In this case, wall panels can be single-layer or multi-layer.

Typically, external walls are built of precast reinforced-concrete three-layer (sandwich) panels supported by internal load-bearing walls or floors. The inner load-bearing layer of a panel is made of heavy concrete (at least 100 mm thick), while the outside layer is made of light or heavy concrete (at least 50 mm thick), with the surface matching the architectural design of the facade. In the middle of the panel, there is a layer of effective insulation material (approximetely 150-180 mm thick), which meets the requirements of thermal conductivity analysis for Saint Petersburg (Figure 3). Based on this technology, several residential complexes were built in Saint Petersburg and Leningrad Region: IQ Gatchina, Yutteri, Jaanila Drive, Novaya Dubrovka, etc.

The flexibility of modular systems combined with the variety of changes introduced into the morphogenetic building volume enables creating an individual architectural appearance for each project with aesthetically distinguished structural solutions.

In Saint Petersburg, in addition to precast reinforced concrete panels, the ventilated facade technology is applied (Kovalenko and Pastukh, 2017) in the design of load-bearing and enclosing structures. In accordance with this technology, aluminum plates, ceramic granite slabs, and other materials are used as the external cladding layer (Figure 4).

The technological capabilities of computer-aided design as well as modern additive construction technologies prompted the authors of the article to review the use of modern materials and technologies in the construction of residential buildings in Russian Federation (using Saint Petersburg as a case study) and Europe (using Münster, Germany, as a case study) (Figure 5) (Kiseleva and Pastukh, 2017; Pastukh, 2018).

Construction works in the historical urban environment, which includes many central districts

Figure 1. Construction of a multi-apartment residential building with integrated premises with the use of the cast-in-situ and precast technology. Saint Petersburg, 2022. Photo by O. A. Pastukh

a. b.

Figure 2. Cast-in-situ floor slabs with precast walls: a — a general view of the floor slab assembly; b — a formwork with a reinforcement grid, 2021. Photos by O. A. Pastukh (a) and V. N. Elistratov (b)

of Saint Petersburg, result from the requirement to expand infrastructure and preserve existing residential and public facilities, protecting them against settlement during the construction of new buildings in their proximity. The above explains why modern architects and builders tend to apply the brick / cast-in-situ concrete construction technology, which implies the use of such technologies as slurry walls, bottom-up underground construction, bored cast-in-situ piles, cast-in-situ construction of underground and above-ground structures. These technologies ensure foundation stability upon deep pit excavation and underground space development and are implemented at small construction sites


a. b.

Figure 3. Three-layer reinforced-concrete panels: a — by K-33 Group of Companies; b — by Gatchina House-Building Plant, 2017−2018. Photo by V. N. Elistratov


a. b.

Figure 4. A ventilated facade made of ceramic granite slabs on the walls of residential buildings with structural solutions in ceramic granite slabs: a, b — Europe City residential complex, 4 Medikov Prospekt (developer: Vozrozhdenie Saint Petersburg construction company, contractor: LSR Group, architect: S. Tchoban, architectural bureau: Rech). Saint Petersburg, 2015. Photo by V. N. Elistratov

with a minimum stock of building materials.

When converting of buildings located in the historical city center to another use, specialists often choose to cover courtyard spaces with dome structures. It is quite acceptable to use light supporting geodesic domes made of wooden rods connected with fiberglass joints (Zhivotov and Pastukh, 2020).

2. Housing construction in Germany

In Germany, the requirements for thermal insulation are regulated by technical specifications (DIN 4108 (Beuth Verlag, 2013)) and energy saving regulations (ENEV 2016).

The requirements for winter thermal insulation can be met with single-shell masonry walls in combination with bricks that have a very low thermal conductivity.

Earlier, joints between bricks were 1–1.2 cm thick. Currently, thin bed joints of 1–3 mm in thickness are being used more and more frequently for load-bearing inner shells. Such a joint design has a number of advantages: a higher load-bearing capacity of the wall, resistance to moisture penetration into the building structure, and better thermal insulation properties (Sielicki and Łodygowski, 2019).

In double-shell constructions, the distance between the inner and outer shells is about 15–20 cm. The space in between is filled with thermal insulation. In many cases, an air layer of at least 4 cm thick is also incorporated, which allows air to circulate within the construction and, thus, minimizes possible moisture damage. Along the air layer, dewatering or drainage of possible moisture ingress due to driving rain can also be ensured.

Usually, mineral or rock wool is used as the material for thermal insulation (Yörükoğlu et al., 2020). This material is often laid in two layers, which are staggered to avoid possible thermal bridges. If no air layer is planned, the thickness of thermal insulation can be up to 20 cm according to current technical constraints. The two masonry shells are joined by stainless wire anchors (5–7 anchors/m²) with a thickness of 4–6 mm.

Recently, efforts in the use of renewable raw materials for thermal insulation have increased. Various reserches are currently underway to this end, and the long-term durability of the material should also be studied. Among the examples of alternative materials for thermal insulation, the following can be mentioned: cellulose, hemp, flax, and wood chips. Figure 6 shows a double-shell outer wall at the base. Here, it is especially important to provide a moisture barrier against the effects of rain, spray water, and moisture penetration into the construction.

Due to recent fires involving such external wall constructions, some issues have become apparent when flammable thermal insulation is used. In most cases, the applied plaster can prevent fire spread. To prevent such incidents, fire barriers made of mineral or rock wool should be installed at regular intervals or the entire thermal insulation should be non-combustible.

Furthermore, such external wall constructions it can be problematic to recycle. It is quite difficult to separate individual materials because of the bond between them. At present, Germany lacks suitable disposal concepts. This issue is currently addressed in several research projects.

Such a design solution for external walls is often used in Saint Petersburg for the construction of multi-storey cast-in-situ buildings (Figure 6) (Mähner et al., 2013).

In Germany and Russian Federation, ceiling constructions are usually made of reinforced concrete. They are characterized by good fireproof and sound insulation properties. Wooden beam ceilings are rarely used. This kind of application is mainly limited to small single-family houses. Constructions with steel beams to transfer the load are used very rarely in residential construction.

In-situ concrete solutions can be used for concrete ceilings. In this case, bottom and top

Figure 5. Construction of a multi-story residential building in Saint Petersburg (Legenda na Institutskom residential complex), 16 Institutsky Prospekt, (Legenda Intelligent Development, construction of the above-ground structures), 2020. Photo by A. N. Panin

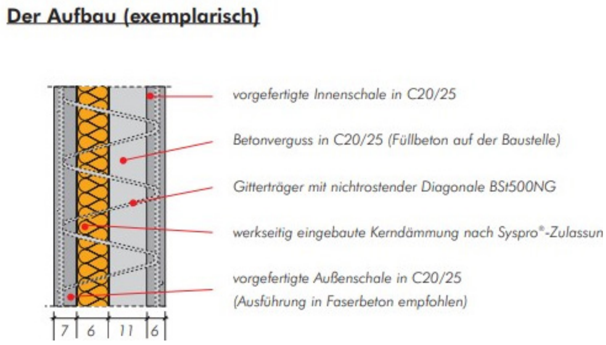

Figure 6. Double-shell outer wall at the base

Figure 7. Precast reinforced-concrete ceiling with in-situ concrete added. Photo by D. Mähner

Figure 8. Precast reinforced-concrete ceiling with in-situ concrete added. Photo by D. Mähner

Figure 9. Non-ventilated flat roof. Photo by D. Mähner

reinforcement (for continuous slabs) is laid on a prepared continuous flat formwork at a construction site. Then in-situ concrete is placed (López-Mesa et al., 2009).

For reasons of streamlining and economic efficiency, slabs are often designed as prefabricated reinforced-concrete slabs with in-situ concrete added. In this case, a precast slab with bottom reinforcement (with a thickness of approximetely 5–7 cm) is manufactured at a precast factory. The surface of those slabs is roughened or profiled to ensure adhesion. At a construction site, slabs do not require continuous formwork. They require only wooden supports (Figure 7). Top support reinforcement is laid on ceiling slabs and then in-situ concrete is placed as the top layer (Mähner and Pitscheider, 2001).

This system can also be combined with larger main and secondary beams of reinforced concrete (Figure 8). In this case, beams are completely formworked and reinforced, and a precast reinforced-concrete slab is constructed as described above.

Flat and pitched roofs can be used for residential buildings. As for flat roofing, non-ventilated roofs ("warm roofs" (Figure 9)) are commonly used (Triano-Juárez et al., 2020). A non-ventilated flat roof has a vapor barrier on the outside of the ceiling (usually of reinforced concrete) to prevent moisture from the building from entering the insulation. Then thermal insulation is glued on. A vapor pressure equalization layer and final sealing are installed on top. Surface protection usually applied to the insulation layer (concrete slabs, gravel pack, top layer of polymer-bitumen membranes, etc.) dampens temperature fluctuations, provides additional protection against mechanical damage or UV radiation, and increases the service life of roof waterproofing. In recent years, there has also been a trend toward green roofs integrating more nature in urban areas.

Discussion

In this article, we highlighted a range of engineering and technological issues making it possible to solve a number of important tasks regarding the preservation and development of the architectural-and-planning structure in cities due to the proper application of basic manufacturing and assembly technologies of residential building construction, modern energy-efficient materials, as well as innovative structural solutions. Particular attention was paid to methods and technologies based on the widespread use of local building materials, light-weight structures, and new domestic technologies.

In recent years, the construction industry in Russian Federation and Germany has been applying widely used technologies of precast as well as cast-in-situ and precast construction (with a partial use of prefabricated structures).

The use of distribution booms installed on tower columns to feed a concrete mix in confined conditions is an innovative trend in cast-in-situ and precast construction. A concrete mix is pumped by concrete pumps to the distribution booms through a pipeline. The issue of automation and, in the future, robotic automation of concrete mix feeding and distribution in the construction of cast-in-situ buildings using the sliding formwork method is highly relevant.

When erecting buildings in the existing urban environment, it is very important to correctly select and apply various housing construction technologies, which can have a direct positive impact on the preservation and development of the architectural-and-planning structure of the city.

In order to renovate the housing stock, save energy, and rationally use natural resources, authorities of all the capital cities of the World Green Building Council member nations (the USA, Australia, Spain, the UK, Japan, the UAE, Russian Federation, and Canada) launched an urban development program. This program is designed for the long term abd aimed at not only renovating the old housing stock and preserving historical monuments but also improving living conditions and promoting a greater sense of community among citizens (Pastukh et al., 2021a).

Green standards are aimed at regulating a sustainable approach to construction, assessing the extent to which buildings meet the basic principles, and accelerating the transition from traditional building design and construction technologies to sustainable practices. The basic principles of sustainable construction are the following:

- providing conditions ensuring health and wellbeing of residents;
- reducing or eliminating the negative impact on the environment;
- keeping in mind possible interests of future generations.

The environmental situation in the world has not changed significantly for the better over the past decades. Continuous breakouts of natural disasters are forcing mankind to think about the need to reduce CO_2 emissions and develop technical solutions aimed at the use of natural materials with minimal waste in the production process. Sustainably harvested wood and wood-based materials are considered such natural building materials. It is a constantly renewable resource, it is easy to handle, and it does not leave any inorganic waste after having been used (Pastukh et al., 2020).

Polymer materials are of interest as well for their technical and physical-mechanical properties. The wide range of properties of these materials, modified by various production methods, opens up many possibilities for scientific and technical solutions in the future.

Solutions for designing geodesic domes from metal and reinforced concrete structures are widely used in modern practice. We believe that the combination of wood and polymer materials in the construction of geodesic domes is highly advantageous in all areas: engineering, financial, economic, energy, and even environmental ones (Pastukh et al., 2021b).

Conclusions

Our main goal was to perform a comparative analysis of the materials and technologies used in housing construction in Russian Federation and Germany, using specific construction sites as examples.

The considered examples of residential buildings constructed with the use of energy-efficient materials, modern structures and technologies of housing construction, allowed us to conclude that, in most cases, identical universal engineering solutions can be used at various construction sites in Germany and Russian Federation, despite different climatic zones.

Therefore, we consider that it is reasonable to continue cooperation between the two countries

a.

b.

Figure 10. Examples of certified design and construction of buildings in Russian Federation and Germany in accordance with international quality and energy efficiency standards: a — the patented “warm wall” technology by Mähner and colleagues (Mähner and Pitscheider, 2001); b — a residential building project in Saint Petersburg, built in 2020, with a LEED quality certificate; the complete list of projects is available at https://arhmc.ru/projects/zelenoe-stroitelstvo/

in the research and implementation of modern innovative solutions for the construction of buildings and structures based on the development of standard design and technical solutions for a large number of different types of building structures that meet the requirements of current regulations and climatic characteristics of the construction region. Particular attention should be paid to compliance with the requirements of sustainable construction, environmental and energy efficiency standards, which will make it possible to take care of the environment in accordance with European LEED and BREEAM standards, as well as Russian Federation GREEN ZOOM standards. Figure 10 shows the title page of the information booklet describing the "warm wall" technology patented in Germany, authored by Dietmar Mähner and colleagues.

In the course of the study, the purpose of cooperation was to share modern rational methods and technologies of erecting residential buildings, ensuring the preservation and progressive development of the architectural-and-planning structure of cities with the use of modern innovations in construction, with specialists at various levels.

The article is published based on the results of the research performed under the grant for research to be performed by academic staff of the Saint Petersburg State University of Architecture and Civil Engineering in 2022.

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СОВРЕМЕННЫЕ МАТЕРИАЛЫ И КОНСТРУКЦИИ, ИСПОЛЬЗУЕМЫЕ В ЖИЛИЩНОМ СТРОИТЕЛЬСТВЕ: МЕЖДУНАРОДНЫЙ ОПЫТ

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Аннотация

Предметом данного исследования является возможность применения универсальных энергоэффективных инженерно-технологических решений в массовом жилищном строительстве вне зависимости от климатического региона строительства на примере современной застройки Санкт-Петербурга (Российская Федерация) и Мюнстер (Германия). Помимо совершенствования строительных технологий, применяемых в современном жилищном строительстве, в настоящем документе основное внимание будет уделено обзору новейших энергоэффективных материалов и конструкций. **Целью исследования** является внедрение энергоэффективных решений в жилищное строительство с помощью инновационных технологий и материалов. В дополнении к теоретическим материалам будут приведены практические расчеты, наглядно показывающие преимущества и недостатки тех или иных инженерно-технических решений. **Были использованы следующие методы: а)** метод сравнительного анализа физических, теплотехнических свойств и прочностных характеристик используемых строительных материалов в области массового жилищного строительства; **б)** проблемно-логический метод анализа возможных типовых объемно-планировочные и конструктивные решения проектирования и строительства зданий с учетом климатических условий и географических особенностей региона строительства, с соблюдением основных принципов современного устойчивого строительства, энергетических стандартов, экономической эффективности применяемых решений и экологичности с учетом международных (европейских и российских) стандартов LEED, BREEAM. GREEN ZOOM. **В результате** авторы предлагают внедрять, наряду с уже известными и проверенными временем, инновационные запатентованные решения в материалах и технологиях возведения как в частном домостроении, так и в массовом жилищном строительстве рассматриваемых стран: Российской Федерации и Германии. **Обсуждение** опыта практических испытаний и процесса внедрения новейших строительных материалов в жилищное строительство наглядно показывает важность международного взаимодействия в данной области на различных уровнях. Растущий объем жилищного строительства и энергопотребления устанавливает новые требования и стандарты к качеству производимых материалов, их техническим характеристикам и разнообразию декоративных решений, позволяющих строительному рынку быть конкурентноспособным и соответствовать завышенным требованиям быстроразвивающегося индустриального общества, не забывая заботиться об экологии окружающей среды, сохранении и бережном использовании природных ресурсов.

Ключевые слова

Энергоэффективность, жилищное строительство, современные строительные материалы, железобетонные конструкции.

DOI: 10.23968/2500-0055-2022-7-3-65-75

STABILITY AND RELIABILITY OF LONG-SPAN BRIDGE STRUCTURES

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Abstract
Introduction: Despite the fact that, in recent years, the construction of long-span bridges has been extensively developed, cases of bridge structures buckling in wind still occur, but the issue of their interaction with wind has not been sufficiently studied. **Purpose of the study:** We aimed to improve the structural integrity and operational safety of long-span bridge structures by conducting a computational and experimental study on the effect of various designs of aerodynamic dampers on the aerodynamic stability of such structures. **Methods:** The study was performed in two stages. At the first stage, preliminary two-dimensional numerical modeling was conducted to study the effect of various designs of aerodynamic dampers on the wind flow over selected bridge spans. Based on the results of the preliminary two-dimensional numerical modeling, we chose the most effective designs of aerodynamic dampers and made their models to conduct experimental studies on aerodynamic stability on a special test bench**. Results:** Based on the obtained computational and experimental results, we analyzed the effectiveness of various designs of aerodynamic deflectors and fairings used to improve the aerodynamic stability of the standard bridge structure under consideration. **Discussion:** For a span with one main girder, we determined the deflector design that reduces the vibration amplitude at high wind velocities.

Keywords
Bridge structures, aerodynamics, aerodynamic stability, experimental studies, numerical modeling, damping, deflector, fairing.

Introduction

The stability of elastic structures in wind is one of the most knowledge-intensive and insufficiently studied aspects of structural aerodynamics. Aeroelasticity — a branch of structural aerodynamics covering this aspect — deals with solving nonlinear problems of the dynamics of building structures in wind, and, as a consequence, assessing the likelihood of aeroelastic instability phenomena. In general, the tasks, goals, research methods, and even the terms pertaining to the aeroelasticity of building structures are very similar to those pertaining to the classic aerodynamics of aircraft. The aerodynamics of aircraft brought us terms that determine aerodynamic instability phenomena: vortex excitation, galloping, flutter, etc. Their occurrence during the construction and operation of buildings and structures gave rise to the development of aerodynamics as a separate branch of construction science.

Below we list some well-known cases of elastic structures buckling in wind. However, it should be noted that aerodynamic instability phenomena are becoming more common in metal girder spans (Tozaki Viaduct, Trans-Tokyo Bay Highway Bridge, the bridge crossing to Kansai Airport, the spans and approaches to Oshima Bridge, the spans and approaches to Great Belt Bridge (East Bridge), etc.), although it was historically believed that cable-stayed and suspension structures with longer spans were the most sensitive to dynamic wind action (Ovchinnikov et al., 2015).

Ensuring the stability and safety of bridge structures around the world is regulated by relevant regulatory documents. In the Russian Federation, such regulatory documents include Regulations SP 35.13330.2011 “Bridges and culverts” and State Standard GOST 33390-2015 “Automobile roads of the general use. Bridges. Load models and actions”, in Europe — Eurocode 1: Basis of design and actions on structures - Part 2-4: Actions on structures - Wind actions (with national applications), in the USA — ANSI/ASCE 7-95, etc. The experimental studies of elastic structures in wind tunnels are an integral part of design. In international regulatory documents, the corresponding experimental techniques are represented more widely and in more detail.

The scientific and technical literature distinguishes three basic ways to improve the aerodynamic stability of bridge structures (Kazakevich, 2015; Kazakevich and Zakora, 1983; Kazakevitch, 2020):

- aerodynamic damping (installation of fairings and deflectors);
- installation of man-made mechanisms for vibration energy dissipation (various dampers, shock absorbers, shock transmitters, etc.);
- changes in the design model of a structure.

In terms of ensuring the stability of a structure in wind, it is rational to use aerodynamic damping. Most studies assessing the effectiveness of various aerodynamic dampers addressed particular bridge structures at the stage of design. Besides, most of the structures studied are suspension and cable-stayed long-span bridges. As for girder bridge structures, they have been studied less. Meanwhile, in recent years, the construction of long-span girder bridges has been extensively developed.

Methods

To conduct studies, we chose a typical span of a long-span girder bridge with one main stiffening girder, commonly used in modern construction (Figure 1).

To study the designs of aerodynamic dampers, we chose fairings of the most common shapes: a fairing of a beak shape (Figure 2a), a fairing with a smooth contour (Figure 2b), a fairing with a sharp edge (Figure 2c), which have proved their effectiveness in the assessment of the aerodynamic stability of suspension and cable-stayed bridge spans, as well as two types of deflectors (Figures 2d, 2e) ensuring favorable flow over a span.

To pre-select the optimal aerodynamic damping model, it is advisable to use numerical modeling in special flow dynamics software. This method makes it possible to choose the most effective shape of a deflector, based on the analysis of a qualitative pattern of wind flow over the bridge cross-section.

These studies are sufficiently reliable for choosing the shape and design of a fairing. Moreover, experimental studies in wind tunnels are a necessary condition to ensure the aerodynamic stability of a bridge structure.

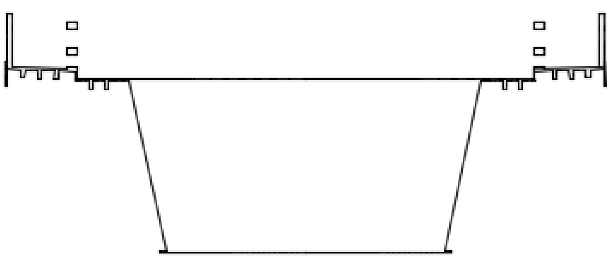

Figure 1. A span with one main stiffening girder

To conduct preliminary numerical modeling, we used recommendations based on the experience of using computational fluid dynamics (CFD) packages in the aerodynamics of buildings and structures, accumulated expertise, and ANSYS user manual.

The inlet of the computational domain was represented by surfaces through which the flow entered the computational domain. On the bridge surfaces, the so-called no-slip wall condition was set, and the flow velocity was zero. At the outlet, an average relative static pressure of 0 Pa was set. In the case of zero angle of attack at the upper and lower boundaries of the computational domain, the boundary conditions of impermeability were set. Hybrid initialization was used. Pressure-Velocity coupling was specified according to the SIMPLE algorithm.

At the first stage, we analyzed the flow over the selected types of spans with no account for the design of fairings. The modeling was conducted for the following three angles of attack of the incoming flow: –3° (downward flow), 0°, and +3° (upward flow). It was established that the upward flow (angle of attack: +3°) is the most unfavorable in terms of aerodynamic stability. Below we present the results of preliminary modeling with various designs of deflectors and fairings for this angle of attack (Figures 3–8).

Based on the analysis of the results obtained (flow pattern), the following preliminary conclusions can be drawn: as for the selected span with one girder, it is deflector of type 2 that has the most favorable effect. It deflects the wind flow from the lower edge of the main girder, thus changing the flow pattern for the better. The studied designs of fairings did not have any significant impact on the flow pattern, which is most likely due to their small dimensions.

It should be noted that in all cases under consideration, vortices still periodically separate from the span, which indicates the need for experimental studies to obtain complete information on the aerodynamic stability of a structure in wind.

At the second stage, we conducted experimental studies on the aerodynamic stability of a span with the selected deflector design, by using a special test bench as part of a unique research setup — the Large Gradient Wind Tunnel, — and analyzed the results obtained.

Considering the scale of the available sectional models, we determined the scale and basic characteristics of the deflector for their manufacturing. The deflector model was made of 1.5 mm thick sheet aluminum (Figure 9).

The method of conducting experimental studies with the use of sectional models (Figure 10) of spans on special test benches for static and dynamic tests is described in detail in the scientific and technical

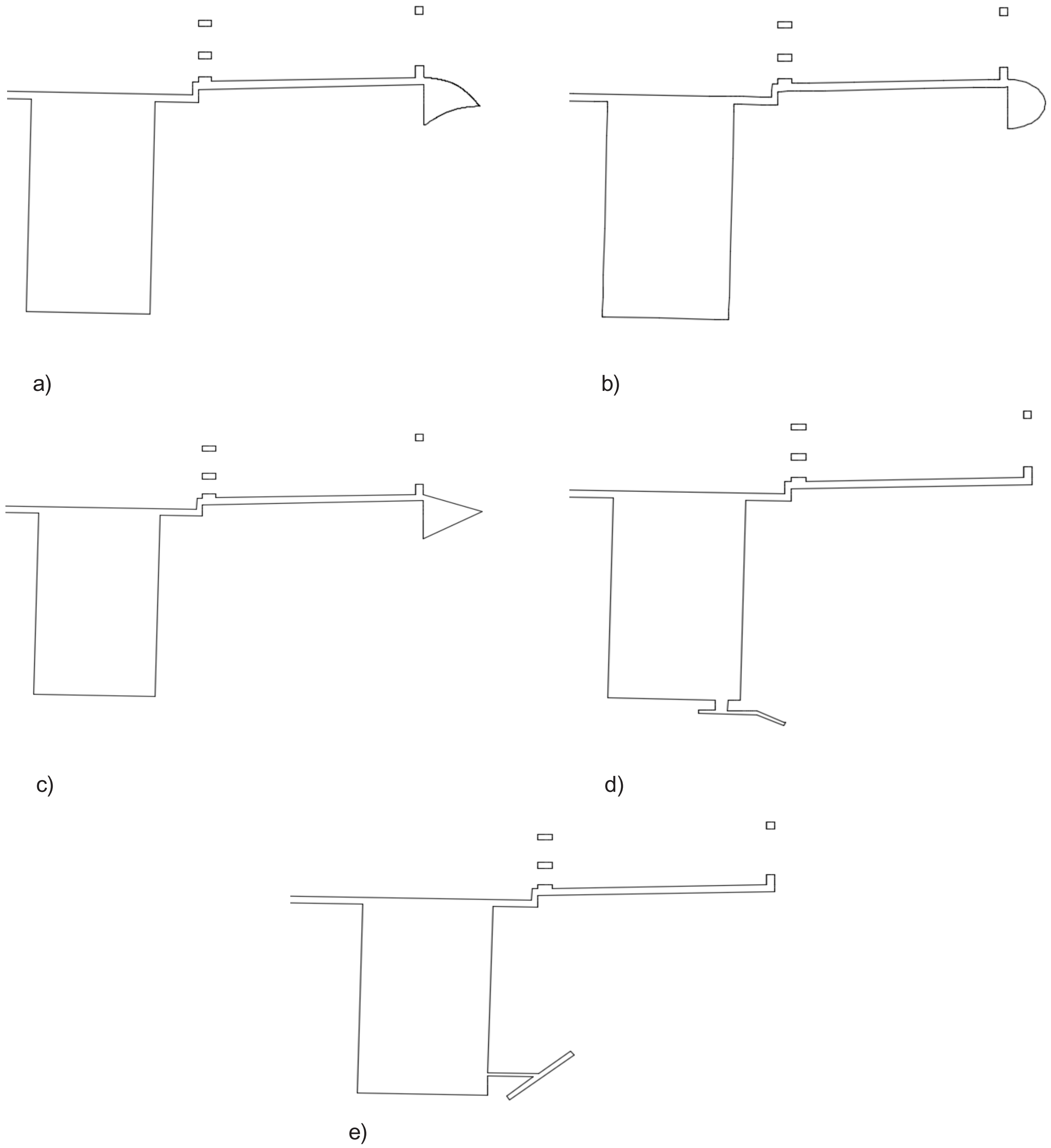

Figure 2. Diagrams of aerodynamic fairings and deflectors

literature (Highways Agency, 2001; Kazakevich and Zakora, 1983; National Research Council of Italy. Advisory Committee on Technical Recommendations for Construction, 2010; Poddaeva et al., 2018; Salenko, 2005).

In the course of dynamic testing of a span, the following parameters of the forced vibrations of a model induced by wind are determined: vibration amplitudes, vibration frequencies, vibration modes, and vibration spectrum.

The experimental studies were performed at a yaw angle of 0° — the flow was perpendicular to the axis of the span, which is the most unfavorable direction in terms of aerodynamics.

During dynamic testing, the model was fixed with spring suspensions on the special test bench. The characteristics of the spring suspensions and the corresponding flow velocity scale were determined at the stage of model design. The damping level of the model was as follows: $\delta = 0.02$, which meets the requirements of the regulatory documents. The low damping level is ensured by the rigid metal structure of the model and its low dissipative properties.

Results

The results of the experimental studies are presented as a graph that shows the span vibration

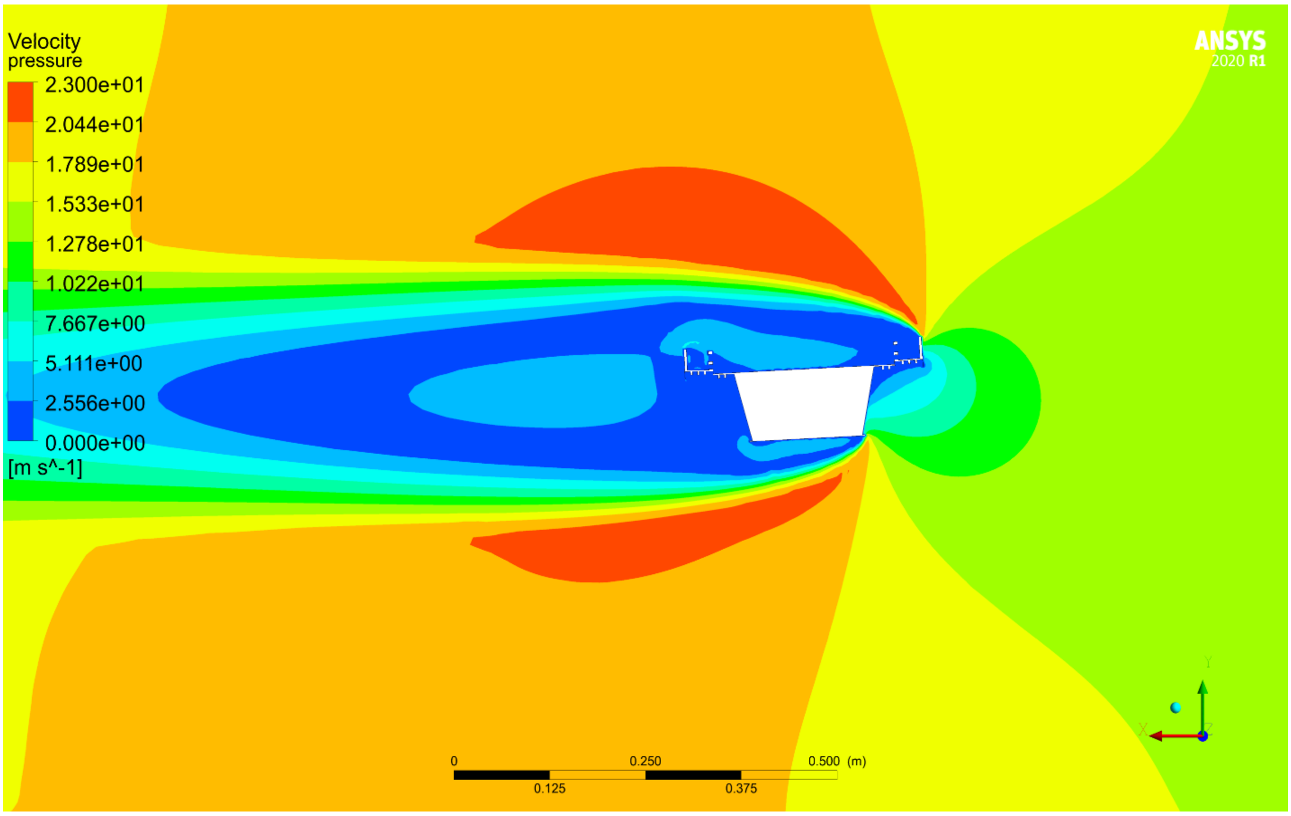

Figure 3. Flow velocity distribution at $\alpha = +3°$ (without fairings)

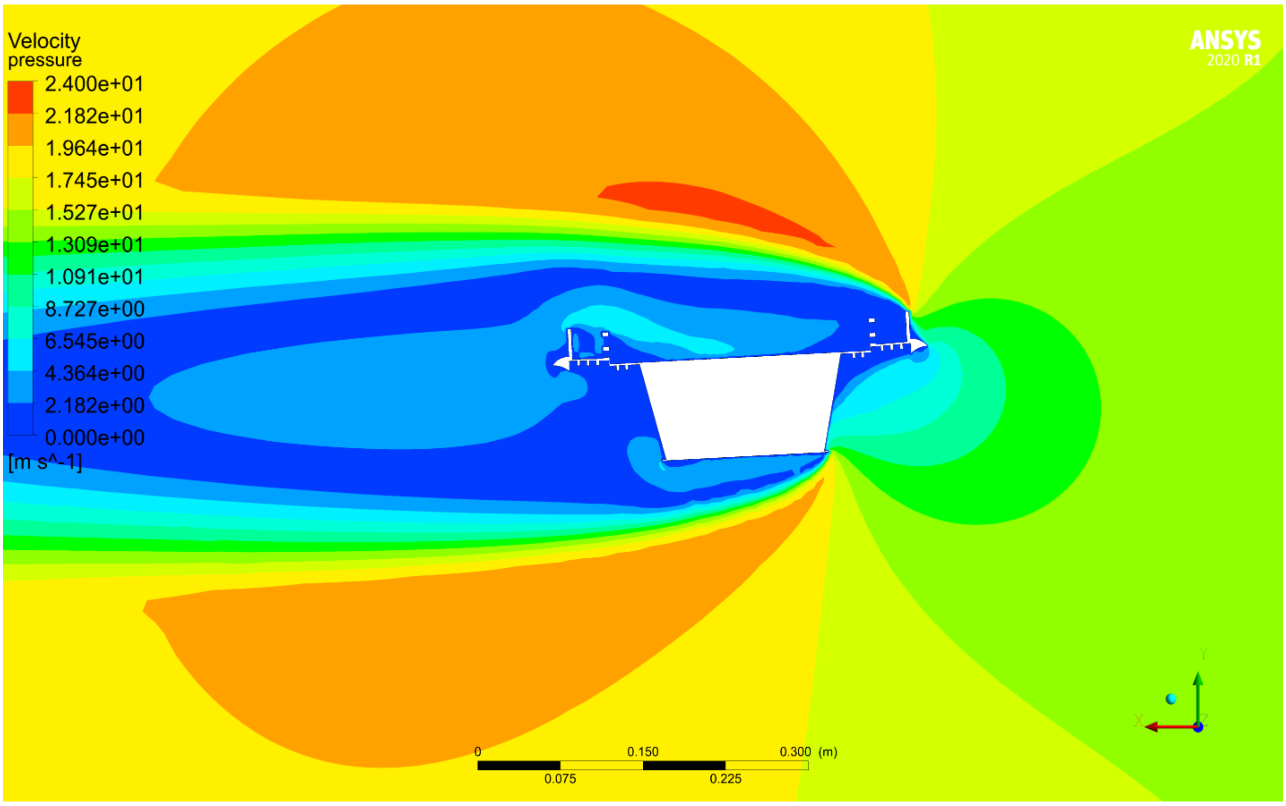

Figure 4. Flow velocity distribution at $\alpha = +3°$ (fairing of a beak shape)

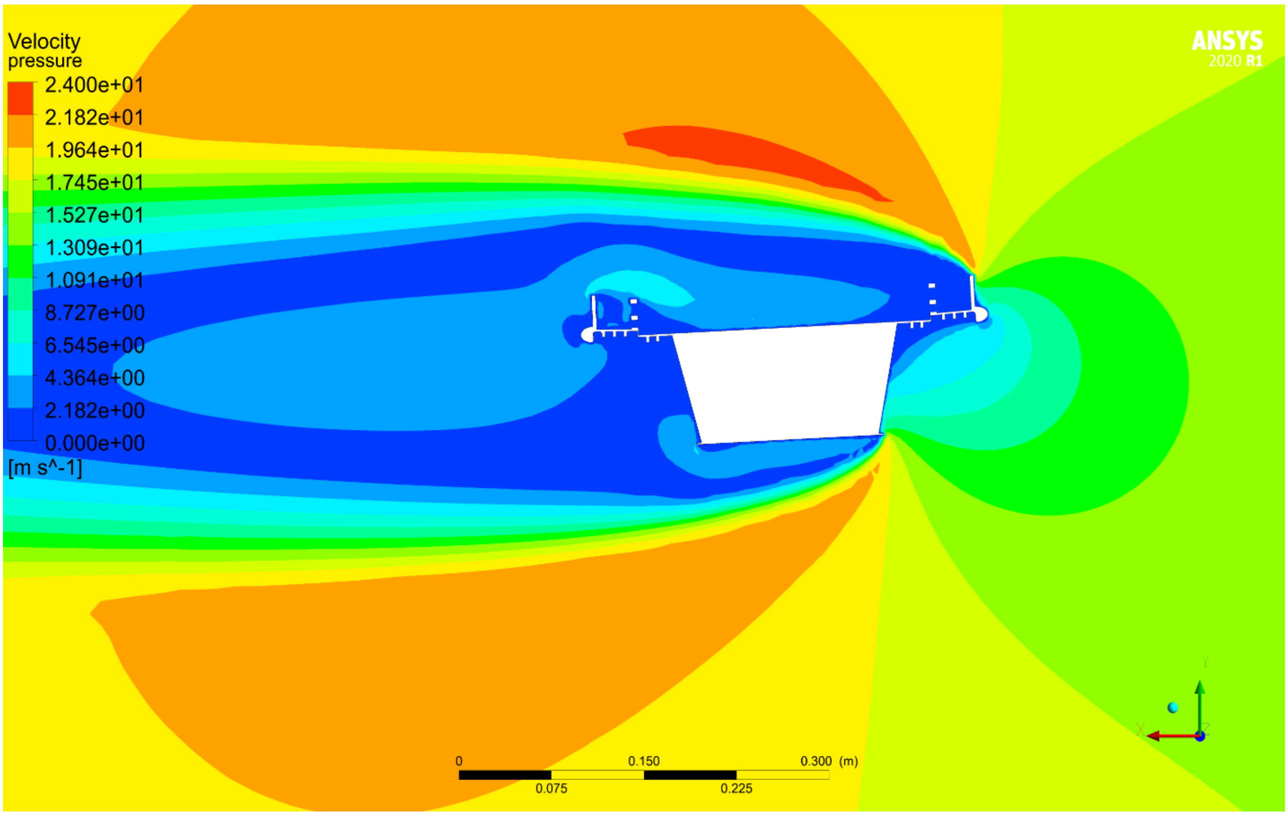

Figure 5. Flow velocity distribution at $\alpha = +3°$ (fairing with a smooth contour)

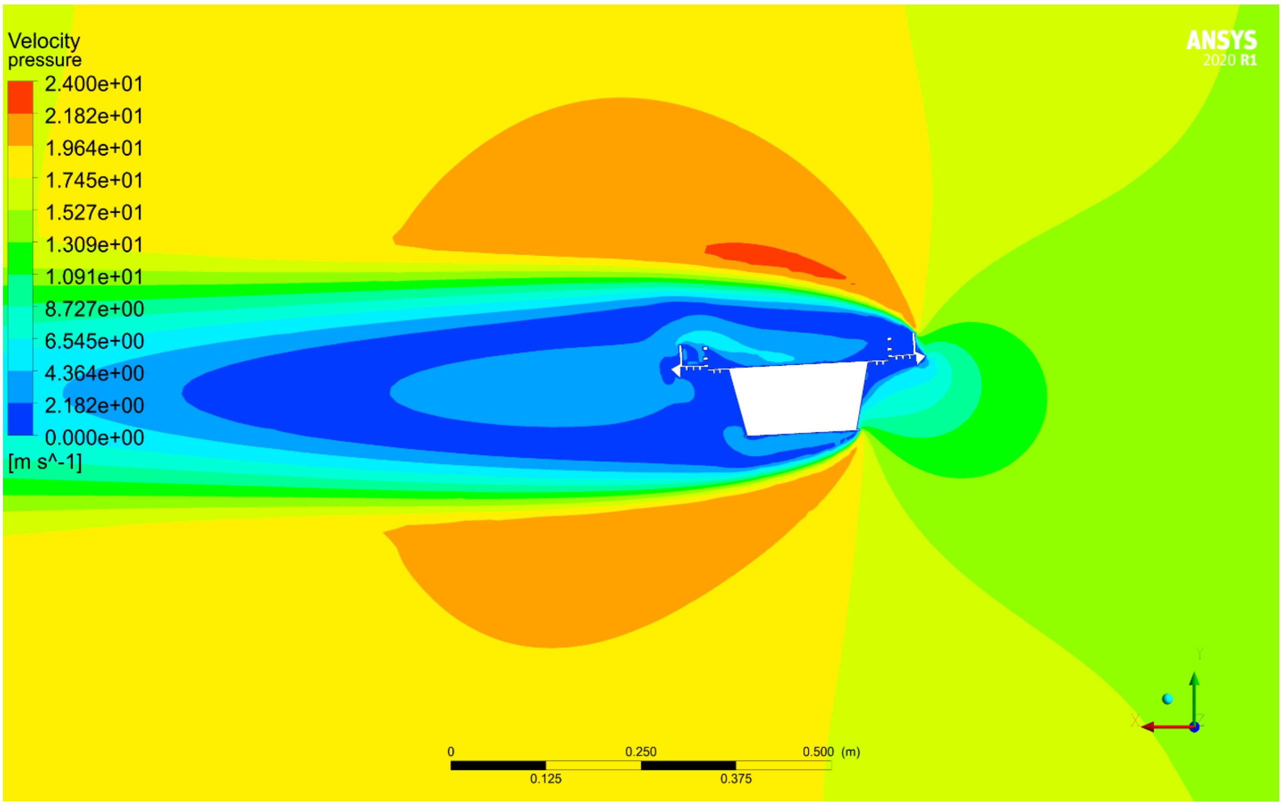

Figure 6. Flow velocity distribution at $\alpha = +3°$ (fairing with a sharp edge)

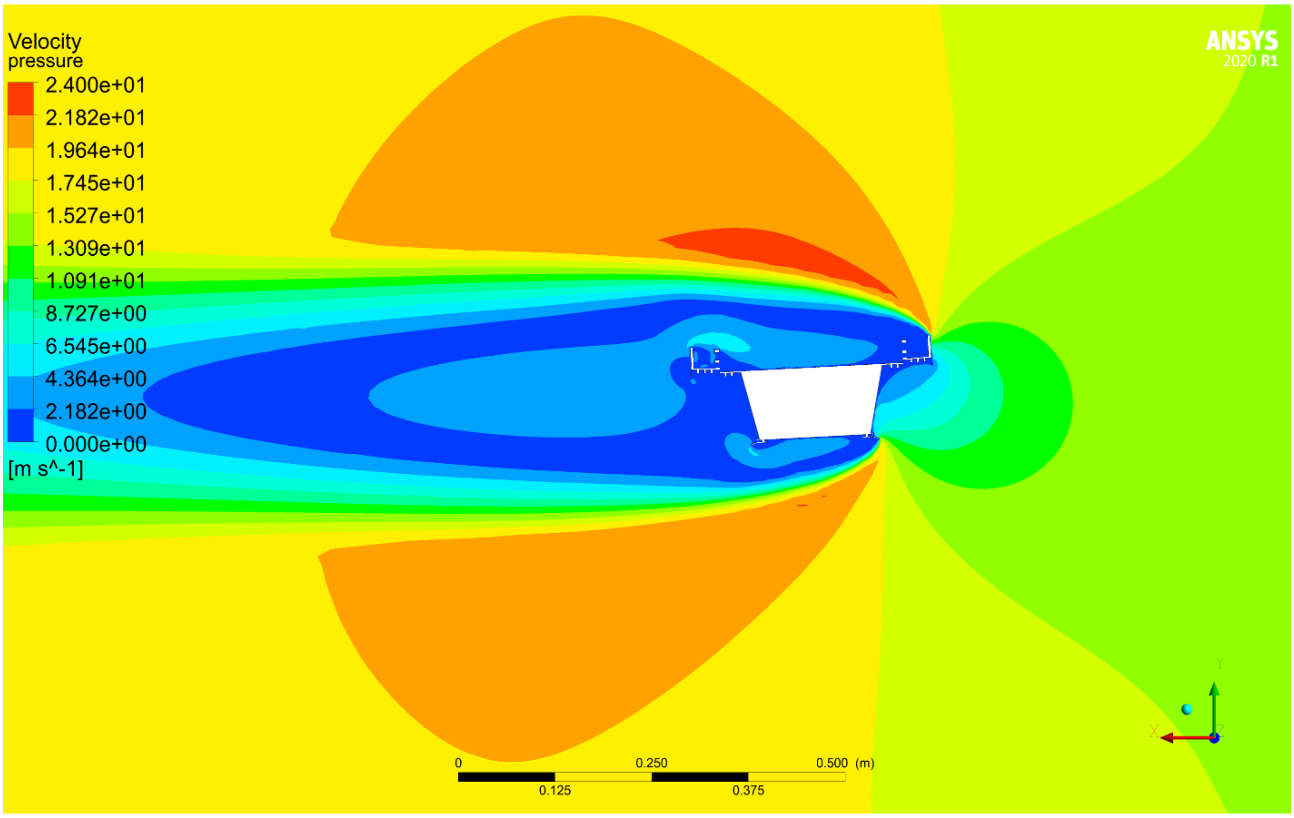

Figure 7. Flow velocity distribution at α = +3° (deflector of type 1)

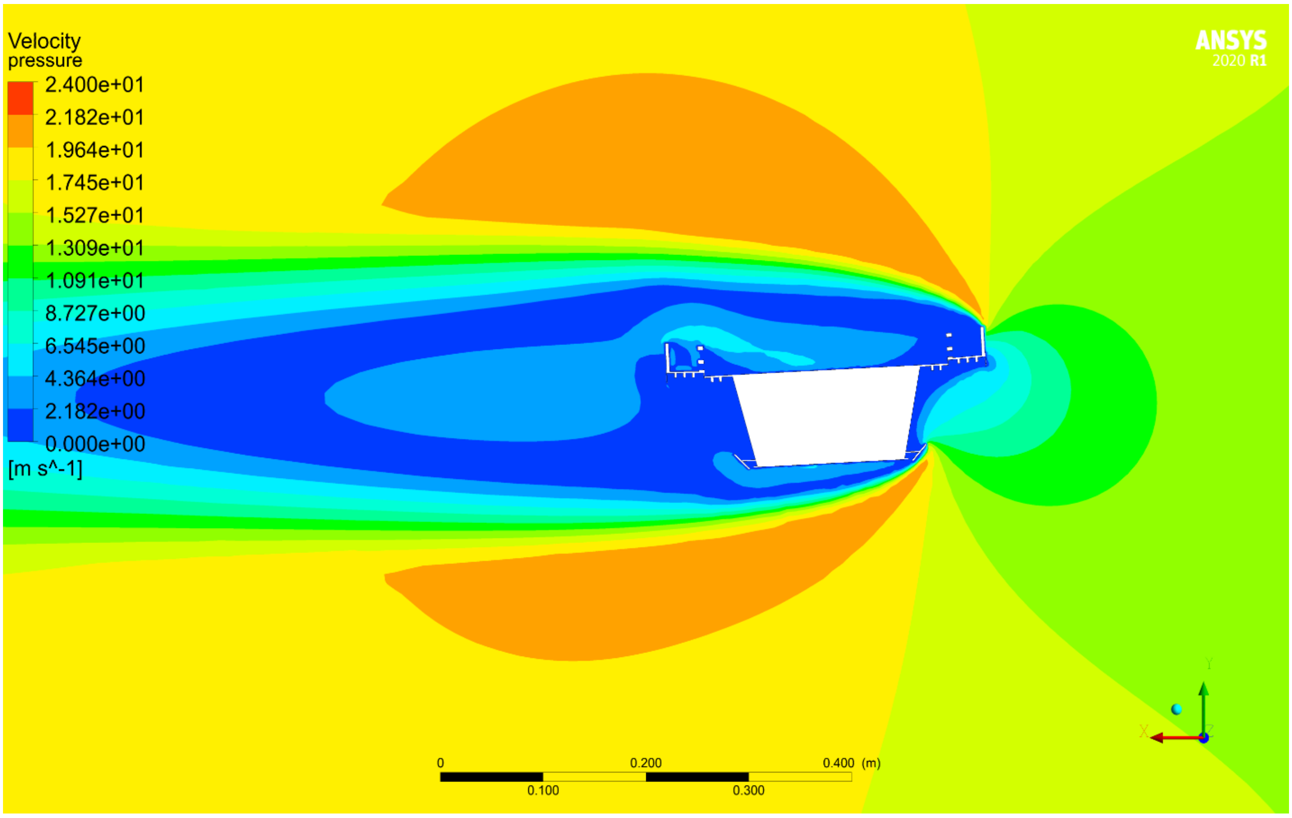

Figure 8. Flow velocity distribution at α = +3° (deflector of type 2)

Figure 9. Aerodynamic deflector, type 2 (model)

Figure 10. Sectional model of a span

amplitude dependence on the wind velocity.

Based on the results of the experimental studies, it was established that the deflector design (type 2) under consideration reduces the vibration amplitude at high wind velocities, and there is no unlimited increase in the amplitude of torsional vibrations characteristic of divergence. Meanwhile, the amplitude of vibrations under vortex excitation increases significantly. Thus, before assessing the applicability of this model, we need to evaluate the maximum allowable amplitude of span vibrations.

In general, based on the analysis of the preliminary numerical modeling and conducted experimental studies, it is fair to say that all the studied designs of fairings and deflectors do not have a significant positive effect on the stability of a single-girder span with geometric characteristics close to those studied. First of all, this is due to the dimensions of the fairings and deflectors under consideration. They do not introduce significant changes in the flow pattern. The phenomenon of vortex resonance excitation in the range of wind velocities between 20 and 30 m/s persists, even when the most effective model with the deflector of type 2 is used, while the amplitude of vibrations changes, and the critical wind velocity, at which the peak of the vibration amplitude is observed, increases slightly. It is important to note the local effect from the deflector of type 2, which eliminates the possibility of divergence.

Conclusions and Discussion

The regulatory documents applicable in the Russian Federation contain only instructions for the performance of studies on the aerodynamic stability of bridge structures. The method of conducting such studies is partially described in the industrial standards as well as the scientific and technical literature. The international documents provide recommendations on the performance of experimental studies with the use of wind tunnels. However, the regulatory documents contain no recommendations for the improvement of the stability of bridge structures in wind.

Most studies assessing the effectiveness of various aerodynamic dampers addressed particular bridge structures at the stage of design. Besides, most of the structures studied are suspension and cable-stayed long-span bridges. As for girder bridge structures, they have been studied less. Meanwhile, in recent years, the construction of long-span girder bridges has been extensively developed.

To assess the effectiveness of the design of aerodynamic dampers, an integrated computational and experimental approach was chosen. At the first stage, we conducted preliminary numerical modeling, and, as a result, obtained a qualitative pattern of wind flow over the span under consideration. At that stage, various designs of aerodynamic dampers were considered. Based on the flow pattern analysis, the most effective option was selected. At the second stage, experimental modeling in a special wind tunnel was conducted for the selected fairing/deflector design. Such an approach makes it possible to significantly optimize the time and cost of studies by reducing the number of physical tests performed.

For a span with one main girder, it was established that the deflector design (type 2) under consideration reduces the vibration amplitude at high

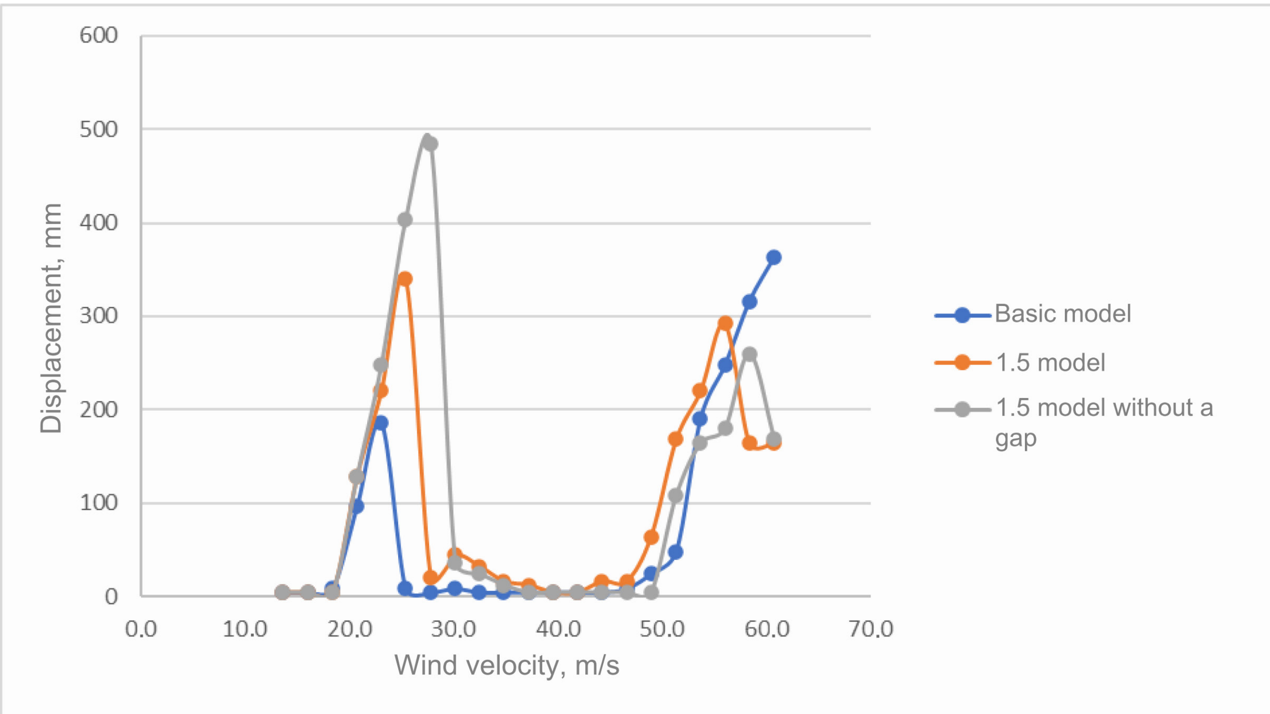

Figure 11. Vibration amplitude dependence on the wind velocity. Angle of attack: 0°

wind velocities, and there is no unlimited increase in the amplitude of torsional vibrations characteristic of divergence. Meanwhile, the amplitude of vibrations under vortex excitation increases significantly. Thus, before assessing the applicability of this model, we need to evaluate the maximum allowable amplitude of span vibrations.

Funding

This study was funded by the Ministry of Science and Higher Education of the Russian Federation (project: theoretical and experimental design of new composite materials to ensure safety during the operation of buildings and structures under conditions of technogenic and biogenic threats #FSWG-2020-0007).

All tests were carried out with the use of equipment of the Head Regional Shared Research Facilities and the Large Gradient Wind Tunnel, courtesy of the National Research Moscow State University of Civil Engineering.

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УСТОЙЧИВОСТЬ И НАДЕЖНОСТЬ БОЛЬШЕПРОЛЕТНЫХ МОСТОВЫХ КОНСТРУКЦИЙ

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Аннотация
Несмотря на то, что строительство большепролетных мостов в последнее время получило широкое распространение и развитие, до сих пор наблюдаются случаи потери устойчивости мостовых конструкций в ветровом потоке, а сама тема взаимодействия мостовых конструкций с ветром освещена в научно-технической литературе в недостаточной степени. **Цель работы:** Повышение конструктивной прочности и безопасности эксплуатации большепролетных мостовых конструкций путем проведения расчетно-экспериментального исследования влияния различных вариантов аэродинамических демпферов на их аэродинамическую устойчивость. **Методы:** Работа состоит из двух этапов: на первом этапе проводится предварительное двумерное численное моделирование влияния различных вариантов аэродинамических демпферов на обтекание пролетных строений мостовых конструкций выбранного типа ветровым потоком. На основании результатов предварительного двумерного численного моделирования выбраны наиболее эффективные конструкций аэродинамических демпферов и изготовлены их модели для проведения экспериментальных исследований аэродинамической устойчивости в специализированном стенде**. Результаты:** На основании полученных расчетных и экспериментальных результатов исследования проведен анализ эффективности различных вариантов аэродинамических дефлекторов и обтекателей, применяемых для повышения аэродинамической устойчивости рассматриваемых типовой конструкции моста. **Обсуждение:** Для пролетного строения с одной главной балкой установлена конструкция дефлектора, снижающая амплитуду колебаний на высоких скоростях ветрового потока.

Ключевые слова
Мостовые конструкции, аэродинамика, аэродинамическая устойчивость, экспериментальные исследования, численное моделирование, демпфирование, дефлектор, обтекатель.

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