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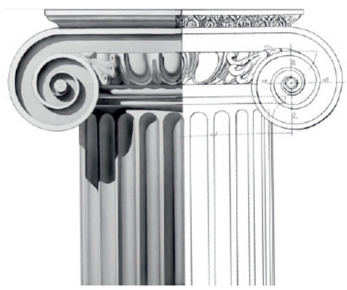

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PROFESSIONALS' PERCEPTIONS OF CULTURAL INFLUENCES ON TRADITIONAL HOUSES IN INDIA

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Abstract

Introduction: Culture has significantly influenced the architecture of traditional houses in various parts of the world for a long time, and several studies have addressed this aspect. Previous researchers have used different methods such as case studies, interviews, or questionnaire surveys with residents to understand this influence. However, past studies have not considered the opinions of professionals in the fields of architecture or culture regarding such influences, neither at the international nor at the national (India) level. **Purpose of the study:** Therefore, this study aims to understand the influence of intangible aspects of culture, particularly on the spatial organization of traditional houses in India, from the perspective of various professionals in related fields. **Methods**: Data for this study were collected through structured, in-depth interviews with professionals and were analyzed using content analysis with QDA Miner Lite software. The **results** show that most professionals feel that conformity to local climate, geology, and geography is the most important intangible cultural aspect, while courtyards are the most influenced tangible aspect of spatial organization in traditional Indian houses. **Conclusions**: The findings of this study will help various stakeholders in the fields of architecture, heritage conservation, preservation, and restoration to make informed decisions when planning transformations of such houses or when formulating policies to preserve the cultural identities of these houses.

Keywords: architecture; content analysis; culture; professionals' perceptions; structured in-depth interviews; traditional houses.

Introduction

Culture has significantly influenced the architecture of traditional houses in various parts of the world. The intangible aspects of culture have taken tangible form in various features such as spaces, elements, or components of traditional houses. Consequently, such houses have developed a sense of identity in the places where they are located. Several researchers in the past, using various methods, have addressed the influence of culture on the architecture of traditional houses, both internationally and at the national (India) level. Abed et al. (2022) conducted a questionnaire survey, interviews with residents, and field observations to document transformations in housing layouts, highlighting the socio-cultural impacts on the internal layout of public residences in Jordan. Jafari and Zabihi (2021) conducted case studies and interviews with residents to identify and introduce cultural and vernacular architectural features from past houses in northern Iran into contemporary residences. Maknun et al. (2019) used field surveys, including documentation of a traditional bamboo house and interviews with experts knowledgeable about its structure and construction, to explain the socio-cultural dimensions of the shape and structure of a traditional bamboo house within Makassar culture. Al Husban et al. (2018) conducted case studies and in-depth interviews with residents to explore the impacts of privacy, security, and circulation on spatial organization and hierarchy in the formation and design of apartments and detached houses in Jordan.

Turning to India, Ar.K. Dhiksha and Muppidathi (2024) used a literature review and comparative case study analysis to examine how regional and cultural influences have shaped traditional houses in different parts of India. Quoc et al. (2024) used secondary data, field surveys, and analysis of real-world cases to identify the influence of culture on the architecture of residential spaces. B and Amirtham (2024) documented a vernacular courtyard house in Kumbakonam, Tamil Nadu, and conducted unstructured interviews with residents to understand the relationship between the courtyard and its surrounding spaces. Kumari (2023) conducted case studies to identify cross-cultural influences in the evolution of houses in northwestern India between the 15th and 20th centuries CE.

From the literature review, it is evident that most past studies have employed case study or in-depth interview methods with residents of traditional houses as part of their data collection process. However, no study has been found that considers the opinions or thoughts of professionals involved in various fields related to architecture and culture to understand their perceptions regarding the influence of culture on the architecture of traditional houses, particularly on their spatial organization.

Nevertheless, some past studies have examined professionals' perspectives in related contexts. For instance, Brahmi and Sassi-Boudemagh (2024) conducted structured interviews with professionals who had used Building Information Modeling (BIM) for their projects, to better understand its advantages and disadvantages in the lifecycle of heritage renovation projects. Toan et al. (2022) conducted a questionnaire survey with construction practitioners to gain a comprehensive understanding of using BIM, benefiting stakeholders in the Vietnamese construction industry. Finau (n.d.) interviewed construction industry experts to identify cultural design elements that provide homes to people in California, deeply connecting with their cultural values and identities. Thus, it appears that the opinions of relevant professionals provide a deeper understanding of the concept under study.

Therefore, the main aim of this study is to understand the influence of culture on the architecture of traditional houses in India, especially with respect to their spatial organization, from the perspective of such professionals. The study further aims to interpret professionals' opinions to determine which intangible aspects of culture have influenced which tangible aspects of the spatial organization of traditional houses. The findings of this study will provide an outline encompassing both the tangible and intangible dimensions of culture related to the spatial organization of traditional houses in India. This will help various stakeholders in the fields of architectural, heritage conservation, preservation, and restoration to make informed decisions when planning transformations in the spatial organization of such houses or when formulating policies to preserve the cultural identities of traditional houses altogether.

Methods

Data for this study were collected through a structured, in-depth interview process. The different stages of the interview process are presented in Fig. 1. Data were collected from 18 June 2024 to 26 March 2025. Of the 42 professionals approached for the interview (stage 2 in Fig. 1), 21 professionals participated. According to Fridlund and Hildingh (2000), this is an appropriate sample size, as qualitative studies are often based on one to 30 informants. Of the 21 participating professionals, 90 % are architects with expertise in architectural conservation, sustainable architecture, landscape architecture, urban planning, urban design, and interior design; 5 % are anthropologists; and another 5 % are historians. Regarding gender, 67 % of the professionals are male, while the remaining 33 % are female.

First, the recorded interviews were transcribed by the author using Microsoft Word software. Two interviews were conducted in Bengali; therefore, they were first transcribed in Bengali and then translated into English. QDA Miner Lite — a Computer-Assisted Qualitative Data Analysis (CAQDAS) software that is more appropriate for analyzing data such as transcribed interview texts compared to other CAQDAS software — was used to conduct the content analysis (Onwuegbuzie et al., 2012). For this study, the conceptual content analysis method was employed, and the analysis was performed sentence by sentence, allowing flexibility in adding categories throughout the coding process. The existence of a concept was counted only once, regardless of the number of times it appeared in the transcribed text. Of the 21 professionals interviewed, 15 were individual participants, while the remaining six participated as partners in groups of two from three different firms. Therefore, during data coding, a total of 18 cases were considered. Since only one author was involved in the coding process, each transcribed text was coded at an interval of 10 days to ensure consistency. The codes obtained from the first interview text served as a starting point for the remaining transcribed texts. Although the professionals addressed various tangible aspects of traditional houses influenced by culture, this study mainly focuses on the influence of intangible cultural aspects on the spatial organization of traditional houses.

Results

This section presents the results obtained from the content analysis. Fig. 2 shows the codes obtained under the category 'intangible aspects of culture'. These codes represent the different intangible aspects of culture that influence the architecture of traditional houses. Figs. 3 and 4 respectively show the number and percentage of cases addressing each of the codes obtained under the same category.

Fig. 5 shows the various codes obtained under the category 'spatial organization of the house'. These codes represent the various tangible aspects of spatial organization influenced by the intangible cultural aspects identified earlier. Figs. 6 and 7 respectively show the number and percentage of cases addressing each of the codes obtained under the same category.

Furthermore, the responses received from the professionals were analyzed qualitatively by interpreting them with respect to the various tangible aspects of spatial organization presented in Fig. 7, in order to understand which intangible cultural

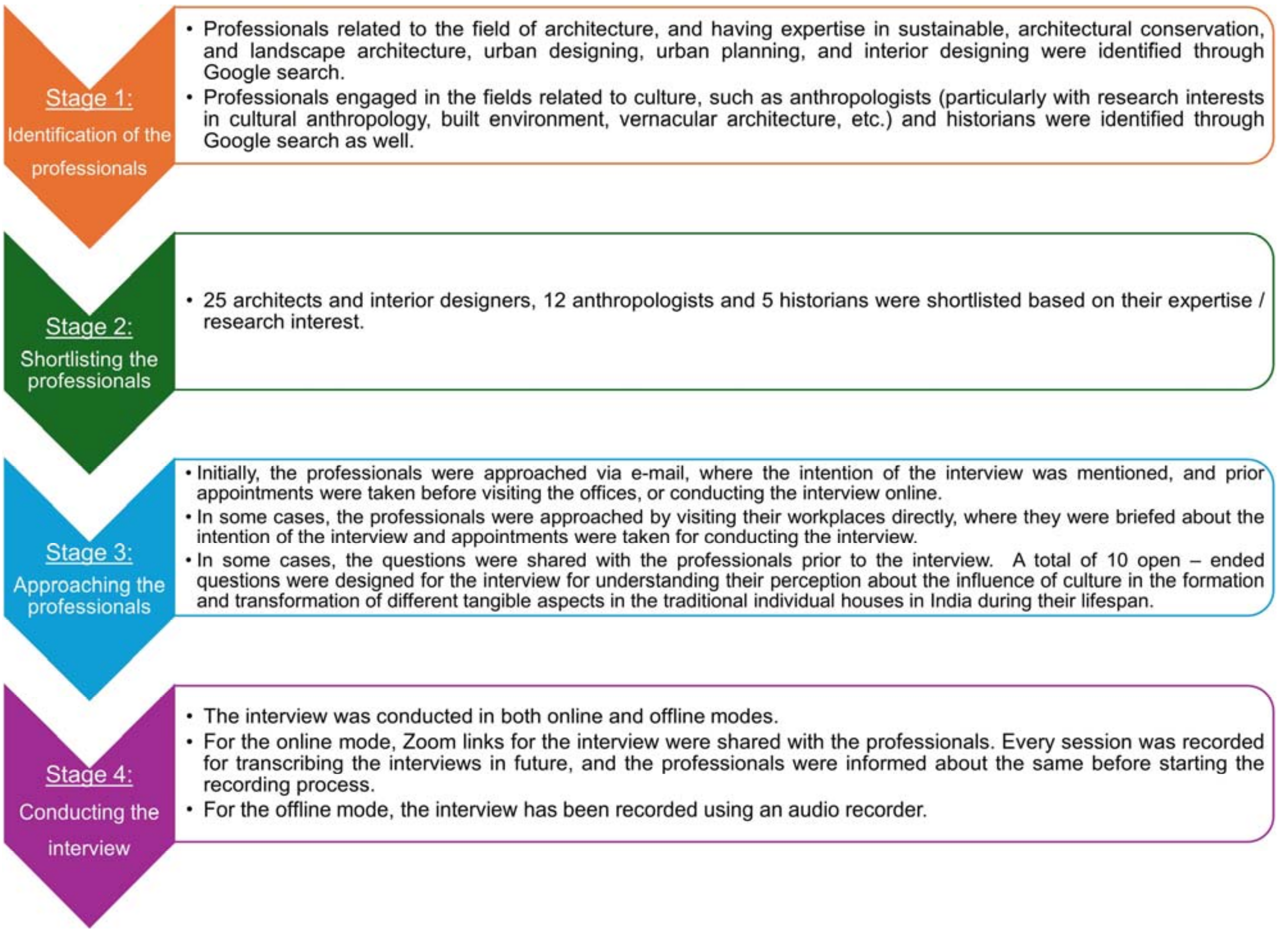

Fig. 1. Different stages of the interview with professionals

aspects have influenced them. The interpretations of participant quotations are presented in Tables 1 to 17.

Therefore, based on the interpretations of the responses received from the professionals, the tangible aspect(s) of the spatial organization of traditional houses that have been influenced by the corresponding intangible cultural aspects are presented in Fig. 8.

Discussion

From the quantitative content analysis, it is evident that most professionals (83.3 % of cases) believe that conformity to local climate, geology, and geography is the most important intangible cultural aspect influencing the spatial organization of traditional houses. This finding aligns with a study by Kamal (2021), in which the author noted that the architecture of traditional houses is climate-responsive in nature, and that the passive techniques implemented in the traditional houses of Lucknow are highly effective, providing thermally comfortable indoor spaces in both summer and winter.

Both the quantitative and qualitative content analyses reveal that courtyards are the most influenced tangible aspect of the spatial organization of traditional houses. Courtyards were addressed in 94.4 % of cases, and as shown in Fig. 8, they are influenced by a total of six intangible cultural aspects. Apart from climatic factors, courtyards also cater to gender segregation and maintain the privacy needs of residents, particularly women. In some houses, courtyards also served as occupational spaces for the residents.

Fig. 2. Codes obtained under the category 'intangible aspects of culture'

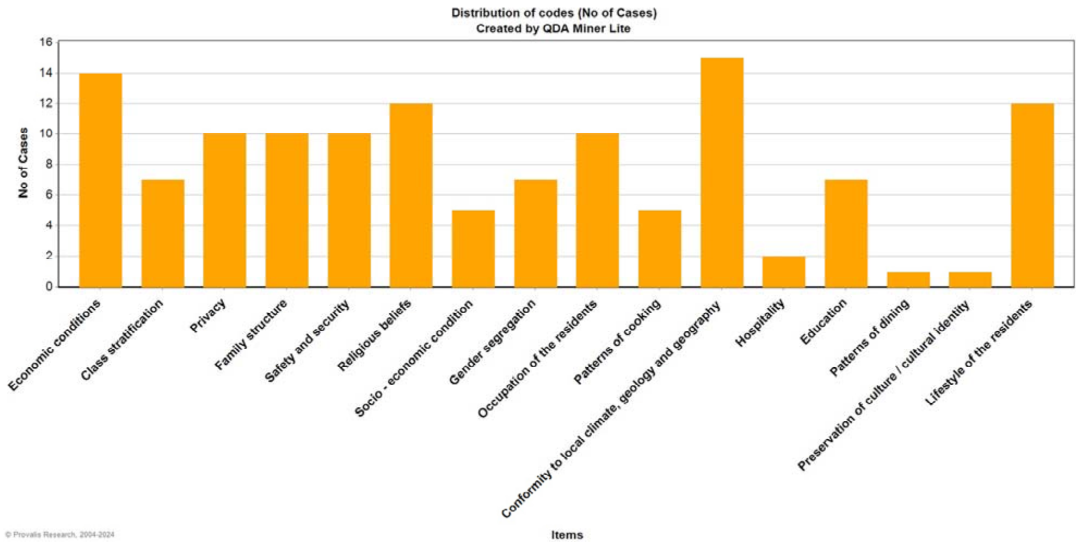

Fig. 3. Number of cases addressing each of the codes obtained under the category 'intangible aspects of culture'

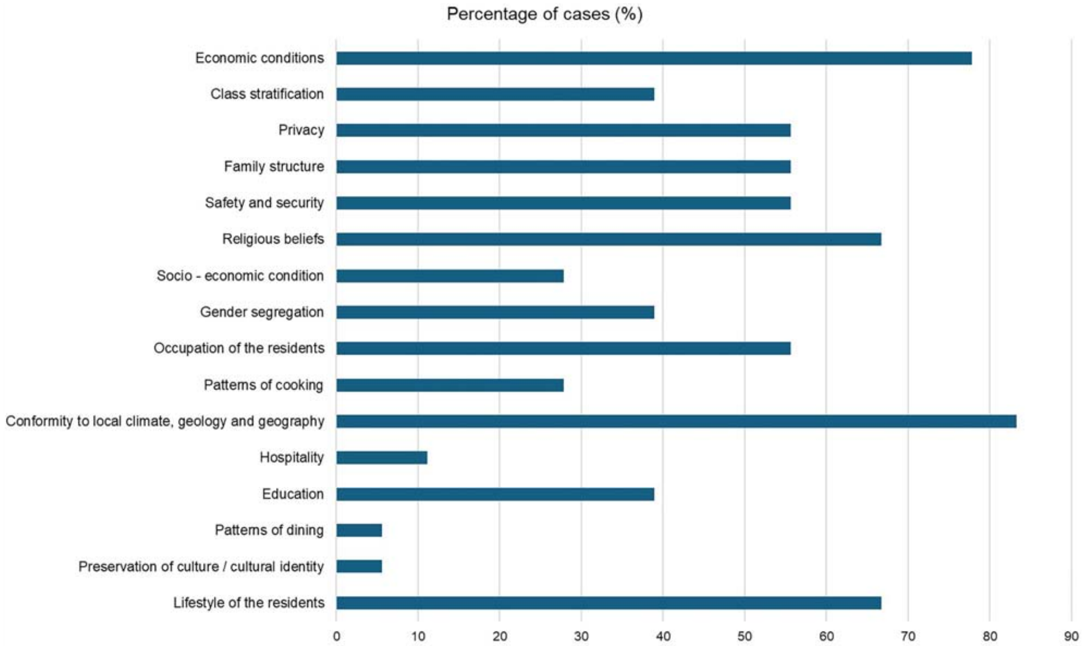

Fig. 4. Percentage of cases addressing each of the codes obtained under the category 'intangible aspects of culture'

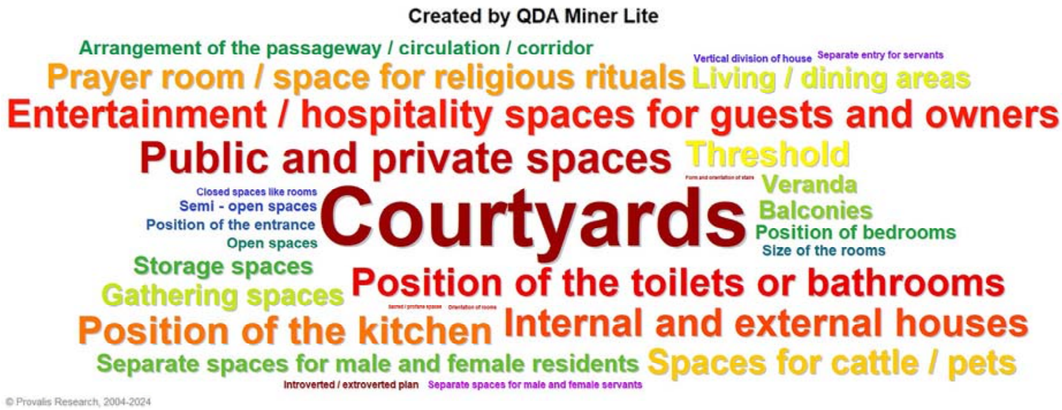

Fig. 5. Codes obtained under the category 'spatial organization of the house'

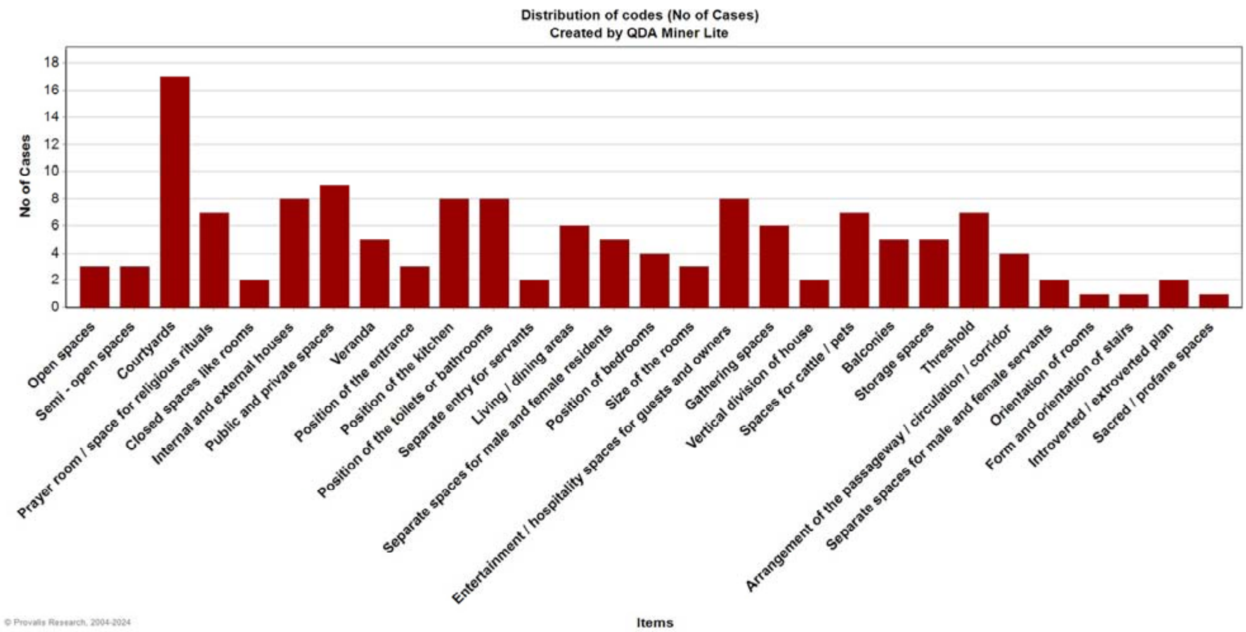

Fig. 6. Number of cases addressing each of the codes obtained under the category 'spatial organization of the house'

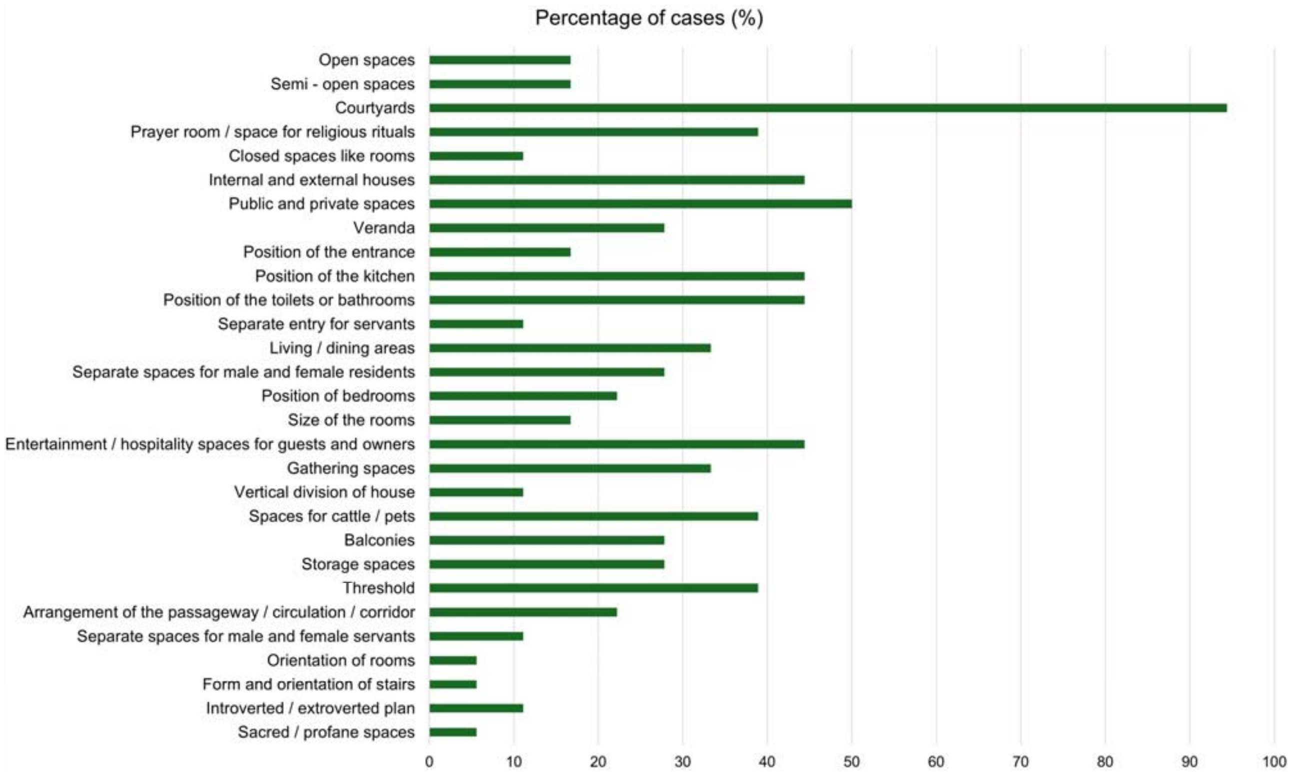

Fig. 7. Percentage of cases addressing each of the codes obtained under the category 'spatial organization of the house'

Table 1. **Open and semi-open spaces**

Professional No.	Participant quotations	Interpretation of the quotations
1 and 2	'If you look at the differences of architecture in the tropical countries and the temperate zones, you will see there is a lot of difference. In our part of the world, we have a lot of open spaces because we can afford open spaces, semi-covered-up open spaces'.	*Local climate, geology and geography* has influenced the open and semi-open spaces.

Table 2. **Courtyards**

Professional No.	Participant quotations	Interpretation of the quotations
1 and 2	"So, naturally, people of the tropical and subtropical countries can afford to spend a lot of time outside, so you will see the buildings there having courtyards, a lot of their lifestyles are dependent on these courtyards. But if you look at something like Scandinavian country, maybe, you will not see such things. And that's because it is not possible for them, for the most of the year to stay outdoors".	*Local climate, geology and geography* as well as the *lifestyle of the residents,* have influenced the courtyards.
3	"Today's lifestyle evolves around, you know that is, the status of women is different, so they don't need to be segregated into a separate courtyard".	*Gender segregation* and the need for *privacy* for women resulted in a public and a private courtyard in the external and internal house (inner sanctum of the house), respectively.
16	"It does look as such because the importance of a courtyard or importance of separation of spaces as per gender or separation of spaces as per the user…"	
8	"And for example, if you take Vijayawada, they prefer to build a courtyard house, because they try to allow hot air or make shallow… shallow spaces, so that they can overcome the heat or existing thing".	*Local climate, geology and geography* have influenced the courtyards.
18	"Historic time when the cultivation has become commercialized, and when you are getting a lot of grain, you have to store the grain, you cannot sell it immediately. So, you need courtyard, why? In front of here you also have to have this grain".	Courtyards became a necessity for residents for *occupational purposes*.
21	"The influence of different ethnic groups can be seen in the colonial or bungalow type and the courtyard houses of the wealthy Bengali families in Kolkata".	The *occupation* and *economic condition* of the residents often determined the number and size of courtyards in the houses.

Table 3. **Prayer room / space for religious rituals**

Professional No.	Participant quotations	Interpretation of the quotations
1 and 2	"But this Thakurdalan, this concept where he has the Durga Puja and everything, they were essentially done which sort of blends of the colonial West architecture with the Indian way of living".	Although there were Western influences in the architecture of the traditional colonial houses, the *religious beliefs* of the residents led to the incorporation of a prayer room or space for religious rituals.
10	"For example, somebody might have Tulsi plant, or somebody might have a small temple area in the courtyard".	Such spaces were influenced by the *religious beliefs* of the residents.
11	"… but the traditional house, that means the puja ghar, puja ghar cannot be changed in traditional houses during the renovation time".	Such spaces reflect the *religious beliefs* of the residents and also help *preserve the culture / cultural identity* of the houses.

Table 4. **Internal and external houses**

Professional No.	Participant quotations	Interpretation of the quotations
1 and 2	"And you have a concept of Andar mahal and Bar mahal. And so, this is a very interesting concept and it has shaped our lives in a different way. So, you have this Bar Mahal and because this has steamed out of our culture, this is how we have treated our women in a certain way, which is different from how European societies actually treat their women".	*Gender segregation* and the need for *privacy* for women, especially from male visitors or outsiders, resulted in external and internal house (inner sanctum of the house), respectively. This distinction between the two houses also helped in ensuring the *safety and security* of the residents.
11	"You talked about the Andar mahal and Bar mahal. In Rabindranath's time, the … many, many, many poems in its verse mentioned that Andar mahal is not allowed by the outsiders".	
15	"Baithakkhana ghor, is a place where you keep, and then the Andar mahal which is, which has a, which has a balcony, which gives access to the outside courtyard so that … the louvers so that you can penetrate, the outsiders cannot see you, the insiders can see you, the outsiders cannot see the insiders".	

Table 5. **Public and private spaces**

Professional No.	Participant quotations	Interpretation of the quotations
1 and 2	"So, you will see in some areas in some buildings we will see three layers, where one is completely private, then there is a semi-private or the public area where you know these Durga Puja, and all these things happen, and then you have a completely Bar mahal, which is completely for the other people".	The *privacy* needs of the residents, especially women, from outsiders or visitors, particularly male visitors, gave rise to public and private spaces in traditional houses.
10	"For example, earlier the location of the kitchen was kind of in the background of the house, not in the foreground because at that time only the belief system, their culture, they used to consider, probably not something that they will put in a public area, maybe in the semi-public area".	
16	"…a house might have two living rooms, one for people inside the house living in and others for interaction with guests as such, might have two dining areas, so these spaces being connected are very particular to cultures".	

Table 6. **Veranda**

Professional No.	Participant quotations	Interpretation of the quotations
16	"For example, verandas today we might see them very open, very leisurely, just providing parapet walls only to demarcate space, not much. But 50 years back, we can clearly see that verandas and these things had grills and were covered, so that nobody could enter. So, it was a multifold protection".	To ensure *safety and security* of the houses and their residents, the veranda spaces were covered.

Table 7. **Position of the toilets or bathrooms**

Professional No.	Participant quotations	Interpretation of the quotations
6 and 7	"So, people used to have the toilets outside your homes. Now they've got them inside their homes".	According to the belief systems of the residents of traditional houses in the past, toilets or bathrooms were placed outside the houses. However, due to changes in *residents' lifestyles*, such spaces have now been incorporated inside the houses themselves.
16	"So, certain things that are considered traditional at 50 years back, for example, residential buildings, specifically 50 years back, it was a norm to have washrooms, I mean bathrooms separated from the main building, which today is not preferred or not followed even if the building is traditional".	

Table 8. **Separate entry for servants**

Professional No.	Participant quotations	Interpretation of the quotations
1 and 2	"… and the people who used to…the sweepers, they had a very separate entry, and most residences don't even use those spaces".	The prevalence of *class stratification* led to separate entries for servants.

Table 9. **Living / dining areas**

Professional No.	Participant quotations	Interpretation of the quotations
17	"A courtyard or a living room or anything, if not a courtyard. Even houses without a courtyard, they would spend most of the room in … most of the time in the living room, and they will all sleep together. They will all play together".	Joint *family structures* were prevalent in the past, and all family members used to spend time together in such spaces.

Table 10. **Separate spaces for male and female residents**

Professional No.	Participant quotations	Interpretation of the quotations
18	"So, that means men's apartment, women's apartment".	The *religious beliefs* of the residents led to the creation of such spaces in traditional houses.
20	"I'm just talking like how this acts as a cultural thing, like when a woman is menstruating, right? So, she has a separate room. So, it's also part of the culture".	

Table 11. **Entertainment / hospitality spaces for guests and owners**

Professional No.	Participant quotations	Interpretation of the quotations
10	"What we want also to look at is what the importance of the guest was? How big did the guest areas use to be, in what manner did guests use to come, where did he use to sit and in what manner did we use to address the guest?"	*Hospitality* towards guests led to the creation of such spaces. They were also used for entertaining guests. The scale of such spaces was also influenced by the *occupation* and *economic* condition of the residents.
12	"By cultural I mean like Bengal and what I said that we have a Thakurbari, the style of this Nat Mandir …"	
13	"Higher income groups will have inviting cultures, like the famous and important persons are visiting their houses, so they need bigger spaces. Big gatherings will take place".	
15	"There was a dancing hall."	

Table 12. **Gathering spaces**

Professional No.	Participant quotations	Interpretation of the quotations
13	"Higher income groups will have inviting cultures, like the famous and important persons are visiting their houses, so they need bigger spaces. Big gatherings will take place".	The *economic* condition and *occupation* of the residents influenced the scale of gathering spaces in traditional houses.
17	"A courtyard or a living room or anything, if not a courtyard. Even houses without a courtyard, they would spend most of the room in … most of the time in the living room, and they will all sleep together. They will all play together".	Since joint *family structures* were prevalent in the past, several family members used to gather and spend time together in such spaces.
20	"So, when we have a micro level as we have already discussed about the courtyard space, right, so we have a courtyard for social gathering. Every kind of weddings, all the beautiful events or festivals, all family gatherings happen there".	Festivals related to the *religious beliefs* of the residents were celebrated in such spaces, where social gatherings took place.

Table 13. **Vertical division of house**

Professional No.	Participant quotations	Interpretation of the quotations
8	"And in North India… North India, like Himachal Pradesh, where they will build the same house with two different levels, where at one and a half feet height they will start building the floor and above that the proper house is built or else they will build a house where the cattle will be kept… kept on the ground floor so that it automatically creates the heat, which can be directly transferred to the first level where humans stay".	*Local climate, geology and geography* led to the construction of such houses.

Table 14. **Spaces for cattle / pets**

Professional No.	Participant quotations	Interpretation of the quotations
8	"And in North India… North India, like Himachal Pradesh, where they will build the same house with two different levels, where at one and a half feet height they will start building the floor and above that the proper house is built or else they will build a house where the cattle will be kept… kept on the ground floor so that it automatically creates the heat, which can be directly transferred to the first level where humans stay".	*Local climate, geology and geography* led to cattle being housed inside dwellings, providing warmth to the residents.
9	"Or having a front yard or having … or having a backyard or adding those perimeter walls inside which more space used to be created and there is a granary and there is a… cattle you know, what we call it… a shed".	The residents' *occupation* often led to the incorporation of cattle sheds in traditional houses.
13	"Before in every house, separately in a corner they mandatorily had a cattle shed".	
18	"So, and also we used to have lot of cattle sheds".	
14	"But earlier there were cows in the houses, there were elephants, there were horses because those were the means of transportation. There were other, other infrastructure you require for that because you need stables for horses, you need to keep their food, you need to make them clean".	Cattle or animals were also kept for transportation. In addition, wealthy residents kept horses or elephants to showcase their *economic* affluence.

Table 15. **Balconies**

Professional No.	Participant quotations	Interpretation of the quotations
13	"There were jharokhas. The queens used to watch something from the jharokhas only".	*Gender segregation*, *privacy*, and *safety and security* needs of the residents led to the incorporation of such spaces in traditional houses.
16	"Elements. Yes, it could be ornamentation, it could be different balconies, it could be pillars, it could be façade … uh, it could be different … uh, statues, for that matter. All those architectural elements."	The balconies and other elements help *preserve culture / cultural identity* of the houses.

Table 16. **Storage spaces**

Professional No.	Participant quotations	Interpretation of the quotations
9	"Or having a front yard or having … or having a backyard or adding those perimeter walls inside which more space used to be created and there is a granary and there is a… cattle you know, what we call it… a shed".	The residents' *occupation* influenced the storage spaces in traditional houses.
13	"The one who used to save the country… you will find a different type of houses of those people …they will keep all their arms and weapons there".	

Table 17. **Threshold**

Professional No.	Participant quotations	Interpretation of the quotations
9	"It was kind of…some kind of a… a screening process, you know. Any visitor directly does not enter into your house. They have to go through a certain sequence of spaces before they can really be received well by the… the hosts".	The aspect of *gender segregation, privacy*, and the *safety and security* needs of the residents created thresholds beyond which certain people were not allowed inside the houses, or women were not allowed in certain parts of the houses.
10	"Some of the people they will come in the verandah area and they will return from the veranda area only, verandah at the entrance, right?	
11	"If you go in a tribal house, tribal people house, you don't go inside the houses, you restrict some… at the first time you … you have to restrict yourself in a place".	
16	"For example, previously there was a barrier for people inside the house. That was to protect them from any kind of external people coming into the house, guest, it could be guest, or it could be… yeah, yes, yeah. Threshold is better word than a barrier, ok".	
18	"Like I showed you, my house. That verandah system, males can enter, beyond which males cannot go."	

Other significant tangible aspects include the distinction between internal and external houses (or the inner sanctum of the house versus the external house), as well as the presence of strong thresholds within the houses. Historically, these thresholds catered to gender segregation by restricting women's movement from the inner sanctum to the external house. Furthermore, male visitors or outsiders were restricted from entering certain spaces or the inner sanctum of the houses, thereby ensuring the privacy, safety, and security of the residents.

Therefore, from the results, it can be concluded that the intangible cultural values of the residents were translated into various tangible aspects of the spatial organization of traditional houses. Conversely, if transformations occur in these tangible aspects, this will also reflect a transformation in the intangible cultural aspects over the lifespan of the houses. Thus, depending on the extent of the proposed or implemented transformations, they will result either in the retention of the cultural identities associated with the houses or in their loss. Consequently, sensible transformations should be proposed or carried out to considerably preserve the character and identity of such houses. These houses serve as a medium through which future generations, neighbours, or visitors from other places can better connect with the cultural values of the local people and experience a sense of belonging.

Sl. No.	Intangible cultural aspects	Tangible aspect(s) of the spatial organization of the traditional houses
1	Conformity to local climate, geology and geography	1. Open spaces
		2. Semi – open spaces
		3. Courtyards
		4. Vertical division of house
		5. Spaces for cattle / pets
2	Lifestyle of the residents	1. Courtyards
		2. Position of the toilets or bathrooms
3	Gender segregation	1. Courtyards
		2. Internal and external houses
		3. Balconies
		4. Threshold
4	Privacy	1. Courtyards
		2. Internal and external houses
		3. Public and private spaces
		4. Balconies
		5. Threshold
5	Occupation of the residents	1. Courtyards
		2. Entertainment / hospitality spaces for guests and owners
		3. Gathering spaces
		4. Spaces for cattle / pets
		5. Storage spaces
6	Economic conditions	1. Courtyards
		2. Entertainment / hospitality spaces for guests and owners
		3. Gathering spaces
		4. Spaces for cattle / pets
7	Religious beliefs	1. Prayer room / space for religious rituals
		2. Separate spaces for male and female residents
		3. Gathering spaces
8	Preservation of culture / cultural identity	1. Prayer room / space for religious rituals
		2. Balconies
9	Safety and security	1. Internal and external houses
		2. Veranda
		3. Balconies
		4. Threshold
10	Class stratification	1. Separate entry for servants
11	Family structure	1. Living / dining areas
		2. Gathering spaces
12	Hospitality	1. Entertainment / hospitality spaces for guests and owners

Fig. 8. Outline showing the influence of intangible cultural aspects on tangible aspects of spatial organization of traditional houses in India

Conclusions

Culture has influenced the architecture of traditional houses for a long time. This study focuses primarily on how various professionals in the fields of architecture and culture perceive this influence. Although the professionals addressed various tangible aspects of traditional houses influenced by intangible cultural aspects, this study has focused mainly on spatial organization. Both quantitative and qualitative content analysis were used to understand the influence of intangible cultural aspects on the tangible aspects of the spatial organization of traditional houses. The results show that the spatial organization of traditional houses is most strongly influenced by conformity to local climate, geology, and geography, and that courtyards are the most influenced tangible aspect of such houses. The findings of this study will help various stakeholders plan or carry out only necessary transformations in these houses while preserving a considerable part of their heritage. The findings will also assist in formulating more sensible policies regarding the conservation, preservation, or restoration of such houses, as they can be used to understand which tangible aspects of spatial organization, when altered, will result in changes to which intangible cultural aspects. This will further help retain the character and cultural identities associated with such houses, thereby creating a sense of place and ensuring cultural sustainability.

Author's Note

This study is a part of an ongoing PhD research work of Manali Basu at the School of Planning and Architecture, Vijayawada, India.

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ВОСПРИЯТИЕ ПРОФЕССИОНАЛАМИ ВЛИЯНИЯ КУЛЬТУРЫ НА ТРАДИЦИОННЫЕ ДОМА В ИНДИИ

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Аннотация
Введение: Культура на протяжении долгого времени оказывала значительное влияние на архитектуру традиционных домов в различных частях мира, и ряд исследований уже рассматривал этот аспект. Для понимания данного влияния предыдущие исследователи использовали такие методы как тематические исследования, интервью или анкетные опросы жителей. Однако в прошлых работах не учитывалось мнение профессионалов в области архитектуры или культуры относительно подобных влияний: ни на международном, ни на национальном (индийском) уровнях. **Цель исследования**: Таким образом, данное исследование направлено на понимание влияния нематериальных аспектов культуры, в частности на пространственную организацию традиционных домов в Индии, с точки зрения различных специалистов в смежных областях. **Методы**: Данные для этого исследования были собраны с помощью структурированных глубинных интервью с профессионалами и проанализированы с использованием контент-анализа в программном обеспечении QDA Miner Lite. **Результаты** показывают, что большинство специалистов считают соответствие местному климату, геологии и географии наиболее важным нематериальным культурным аспектом, в то время как внутренние дворы являются наиболее подверженным влиянию материальным аспектом пространственной организации традиционных индийских домов. **Выводы**: Результаты данного исследования помогут различным заинтересованным сторонам в области архитектуры, сохранения наследия, консервации и реставрации принимать обоснованные решения при планировании преобразований таких домов или при разработке политики по сохранению их культурной идентичности.

Ключевые слова: архитектура; контент-анализ; культура; восприятие профессионалов; структурированные глубинные интервью; традиционные дома.

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STRUCTURAL BAMBOO CULMS IN THE EUROPEAN REGULATORY CONTEXT: TOWARDS A BAMBOO ARCHITECTURE

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Abstract
Introduction: Existing international standards and national building codes for structural bamboo culms provide sufficient information to safely use bamboo culms as a structural material in Europe. **Methods:** This paper analyses the literature related to the characterization, performance, and standardization of structural bamboo culms, as well as the literature on structural building codes — including national codes that already address structural bamboo culms — in order to address whether the current European regulatory context permits their use. **Results:** Despite the need for design guides related to fire safety, structural bamboo culms are suitable within the European regulatory context. This is because the structural Eurocodes and other regulatory texts that coexist with them (e.g., the Spanish 'Código Técnico de la Edificación') are performance-based. Building fire safety is incorporated into building codes through a combination of passive and active features, such as fire-rated building elements, appropriate means of egress, and fire detection and suppression systems, among others, allowing the implementation of bamboo culms as a structural material. **Discussion:** Despite the research still needed to better understand bamboo as a building material, structural bamboo culms are legally permitted within the current European building regulatory context, even as a permanent building structure.

Keywords: bamboo; European standards; structural bamboo standards; structural design; codes.

Introduction

Bamboo is a crucial partner for human development. This is especially true in times of global warming due to bamboo's carbon sequestration performance, as it is becoming increasingly urgent to find alternatives to mainstream materials such as plastic or cement, whose environmental impact can no longer be sustained at the current rate — particularly considering the building industry's carbon emissions. The President of the European Commission, Ursula von der Leyen, explicitly mentioned bamboo as a key material in the European Green Deal (Von der Leyen, 2020).

Over the last decades, in experimental applications (mostly temporary structures) as well as in permanent structures, bamboo culms used as structural elements have demonstrated that the true potential of this material has yet to be fully realized. As a natural material that has not been researched as extensively as industrial materials, there is still immense research ahead to better understand bamboo culms as a structural material. This is particularly relevant in the current global scenario, especially when supposedly well-informed reports — such as the one published by the United Nations Environment Programme (UNEP, 2023) titled 'Building Materials and the Climate: Constructing a New Future' — mention bamboo only as a fully industrialized product (with associated energy consumption and carbon emissions). In contrast, bamboo culms are worth considering even for structural purposes. This paper addresses the crucial question of whether it is legally possible to build with structural bamboo culms within the European regulatory context.

Materials and Methods

This research traces the origins and approaches to building standardization and regulation, as well as the path followed so far to standardize structural bamboo culms. Its main goal is not to identify legal voids where bamboo culms might be used structurally in Europe, but rather to ascertain whether the technical feasibility required to rely on structural bamboo culms exists — to the same extent as for mainstream materials accepted and used within the current European regulatory context, such as steel, concrete, or timber.

The main methods used in this research are descriptive (exposing characteristics of the phenomenon studied) and deductive (moving from general logical reasoning to a concrete fact). The method used to draw conclusions from a set of principles is therefore a logical one. The chosen approach consists of a critical analysis of available literature on the characterization, performance, and standardization of structural bamboo culms, combined with a comparative analysis of building codes for structural design, as well as national codes that already incorporate structural bamboo culms.

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Results and Discussion

Standards before the Industrial Revolution

There is archaeological evidence of measuring instruments or measurement standards dating back around five thousand years (Moro Piñeiro, 2020). However, it is only during the last century and a half — first with electricity and later with the automotive industry — that these technical advances have been applied in fields other than the military. There is, in fact, an intimate relationship between standardization and the birth and rise of civilizations, from Mesopotamia to the Western European empires. As Lelgemann (2004) states: "It is of utmost importance to recognize the fact that (nearly) all ancient buildings and towns are established according to an obviously standardized set of precise non-metric ancient length units".

Geometry and structure are intrinsically related, as Eduardo Torroja pointed out in such a poetic manner. Most methods used throughout history to build as safely as possible in any given period are unknown. However, written records aimed at anticipating material performance — dating from the dawn of the scientific revolution — make it possible to trace how the interrelations between geometry and mechanics have been approached, later allowing codification in standards and norms.

According to Cervera (1983), Leonardo da Vinci (1452–1519) — whose writings range from arithmetic, geometry, painting, perspective, architecture, statics, and mechanics to fortifications, warfare, poisons, bird flight, anatomy, optics, astronomy, and so on — also studied many of the problems considered today within the disciplines of strength of materials and structural design. He made progress building on the medieval school of Jordanus Nemorarius and his "Elementa super demonstrationem ponderum" (Elements on the Demonstrations of Weights), heirs to Euclid's school. In Da Vinci's work (1493), there are notes and recorded experiments on strength, tension, bending deflection, forces in arches, beam design and proportions, compression, what is now called buckling, and even soil mechanics — including both experimental and theoretical expositions.

Leonardo makes clear in his notes that there is a relationship between the length and cross-section of a given structural element, together with the load carried by the element and the distribution of that load along its length, and how the structural element 'curves', as shown in Fig. 1. He states (Da Vinci, 1493): "Four 4-bend beams, tied together in a beam, will bend as much as a 1-bent beam, when loaded in the middle with the same weight".

Galileo Galilei (1564–1642), starting from the notion of strength against given stresses and considering those stresses both longitudinally and crosswise to a structural element, establishes the mathematical relationship between the two: lengthwise stress and crosswise stress (Fig. 2). The relationship is set as proportional between 'absolute strength' and 'relative strength', referring to axial stress or bending, respectively (Galileo, 1638).

It was probably the challenging issue of overcoming the purely geometrical character of the strength problem, together with the inherent difficulty of theoretically addressing the scale issue, combined with Leonardo's practice of exploring different cross-sections by using bundles as an experimental model, that prevented him from finding relationships between the strengths of beams of different depths — although he managed to do so for different widths.

In the very same volume by Leonardo in which these studies are shown, the Codex Matritensis, there is a drawing (on page 92 of the volume, shown here in Fig. 3) of what is popularly known as 'Leonardo's Bridge', which is further developed with detailed drawings of the joints in the Codex Atlanticus (Ceraldi and Russo Ermolli, 2004).

There is evidence of built examples belonging to this structural typology from several centuries before Leonardo was alive, such as a scroll painting by Zhang Zeduan depicting the 'Qingming Festival on the River', in which the so-called 'Bianhe Rainbow Bridge' in Henan Province (China) is shown. According to Yang et al. (2012), more than a hundred surviving bridges of this type exist, and the typology was inscribed on UNESCO's Urgent Safeguarding List of Intangible Cultural Heritage in 2009. This linkage between Leonardo's bridge and traditional timber arch bridges in China raises the question of Leonardo's inspiration — perhaps even graphic sources — coming from the Far East. The approach of varying cross-sectional performance

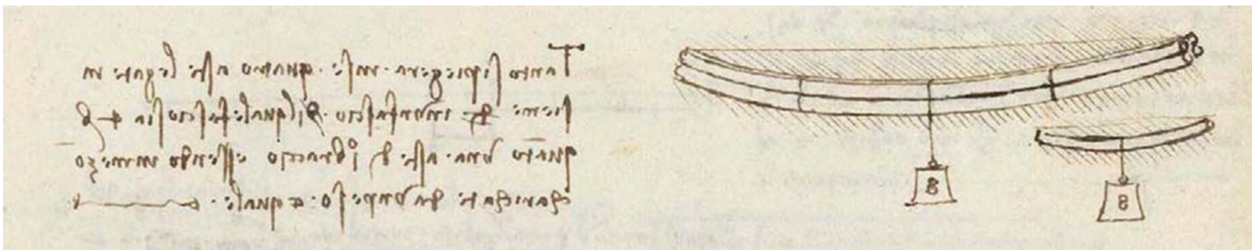

Fig. 1. Leonardo's drawings and notes on loaded beams' 'curves', as deflections. Source: Image extracted from Da Vinci, 1493

Fig. 2. Galileo's drawing representing the relationship between 'absolute strength' and 'relative strength' of a loaded axial structural element, considering different kinds of stresses: lengthwise and crosswise. Source: Image extracted from Galilei, 1638

by adding elements to a bundle rather than using larger cross-section elements is directly related to bamboo structural design, where cross-sections are determined by the natural size of bamboo culms and the common way to increase effective sections is by adding elements to a bundle.

Resuming the development of structural design conceptualization in Europe, L.M.H. Navier represents, two centuries after Galileo, the culmination of the theory of strength of materials (despite unresolved problems related to shear stress and torque), initiating the path toward the theory of elasticity and ultimately resulting in the field of structural design.

The Industrial Revolution Onwards

Newton's Philosophiæ Naturalis Principia Mathematica, which contains the fundamentals of infinitesimal calculus and the mathematical foundation of classical mechanics, was published in the late 1600s. Although the principles of the modern theory of elasticity also date back to the 17th century, Timoshenko's Theory of Elasticity was published in 1934. The finite element method became common practice only in the second half of the 20th century.

This demonstrates that the most powerful mathematical methods available to scientists and engineers before then had resided essentially in geometry. To provide historical perspective on the importance of geometry in structural design in the recent past, it is worth mentioning the Crystal Palace (Fig. 4), designed by Sir Joseph Paxton (1803–1865) and built between 1850 and 1851, as well as the 300-meter tower (Fig. 5) by Gustave Eiffel (1832–1923) and his company, built between 1887 and 1889.

These two structures were possible before the British Empire or the French Republic created their respective standardization committees.

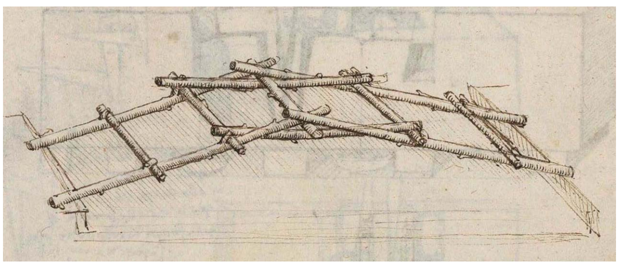

Fig. 3. Leonardo's drawing of a bridge structure, seemingly replicating the concept behind the traditional 'Rainbow Bridge' structural typology in China. Source: Image extracted from Da Vinci, 1493

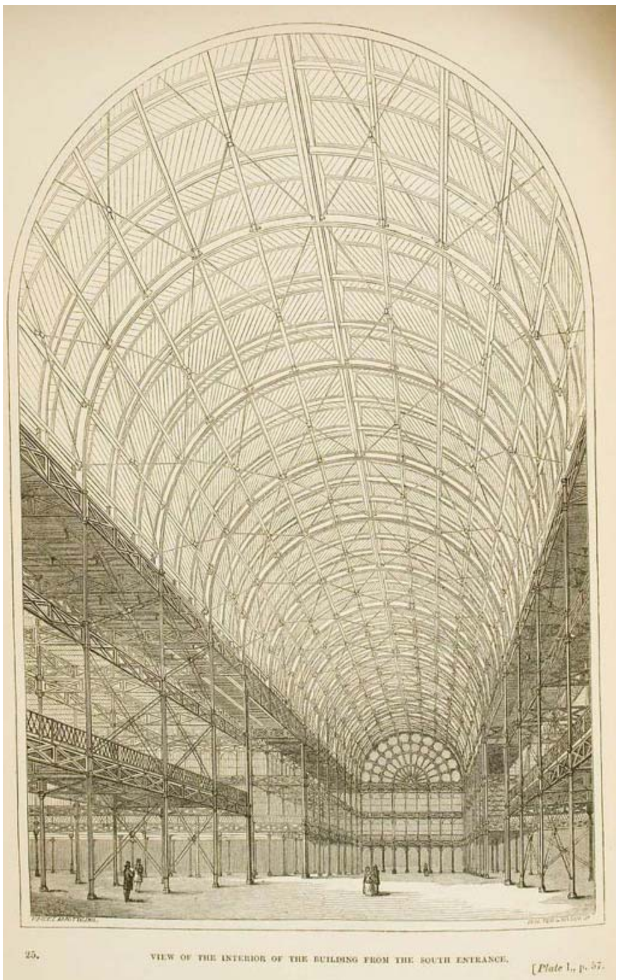

Fig. 4. Crystal Palace, built between 1850 and 1851, before the creation of the British Empire's standardization committee, and using the Imperial British System. Source: Image extracted from the Official Descriptive and Illustrated Catalogue of the Great Exhibition 1851, Volume 1

Nevertheless, in both cases, well-developed systems of weights and measures were used: the Imperial British System and the decimal metric system (the latter had been adopted in France the same year Napoleon Bonaparte became First Consul, 1799). Both systems — the Imperial British System and the decimal metric system — are still in use today.

Frei Otto, in his comments on the history of rod structures (Dunkelberg, 1985), considers vegetal materials such as reeds, cane, or bamboo as a direct precedent of ancient stone structures, pointing out the formal similarities between the Mudhif building typology in Mesopotamia and the stone temples of Ancient Egypt. He also reminds us that successful structural inventions do not remain within individual cultural circles. On the contrary, they quickly expand, regardless of borders and boundaries. Another particularly striking example is the resemblance between tents made of bamboo culms and pagodas. In any case, the similarity — both written and spoken — between the word ‘column’ and the word ‘culm’ is evident.

There are endemic bamboo species on every continent except Europe and Antarctica. Therefore, in those countries where the Industrial Revolution sparked, there were no bamboo resources to consider as raw material in the first place. Some of those European countries governed overseas colonies where the material was available, but there was no interest in researching alien resources whose reliable, long-lasting use requires specific knowledge and care.

Fig. 5. The 300-meter tower (Eiffel Tower), built between 1887 and 1889, before the creation of any French standardization committee, and using the decimal metric system, which was implemented in France in 1799. Source: Image extracted from the Library of Congress website

Earliest Attempts to Standardize Bamboo Culms

In 1953, research requested by the Department of Housing and Urban Development was published by the U.S. Department of Agriculture. This research (McClure, 1953) is broadly focused on practical aspects of bamboo as a building material, as its title itself states: ‘Bamboo as a Building Material’. It gathers built examples from Indonesia, Thailand, Colombia, Ecuador, Peru, El Salvador, and Guatemala, including some construction details regarding joinery. It is remarkable that one tenth of the volume is about ‘bamboo reinforcement of concrete’ — perhaps because it had been briefly researched in the 1930s and expectations for that research were still high and increasing. Perhaps it is the principle of reinforcing a brittle-failure material with a ductile one that is most surprising. About a fifth of this publication by Floyd A. McClure deals with the issue of differences among bamboo species used in housing, providing dimensional ranges for the most commonly used bamboo species as a building material, under the title ‘Some Bamboos Used in Housing’ (Fig. 6).

Two decades later, the Colombian architect Oscar Hidalgo-López published a book (Hidalgo-López, 1978) that includes the mechanical properties of several bamboo species cultivated in Puerto Rico, gathered by G. E. Heck in 1950, including *Guadua angustifolia, Bambusa vulgaris, Bambusa arundinacea, Bambusa tulda,* and *Dendrocalamus strictus*. The modulus of elasticity (MoE) in bending is provided for each of them, and the MoE in tension and compression parallel to the fibres is also provided for the first species, *Guadua angustifolia*.

Before then, in 1930, J. C. Espinosa tested specimens of *Bambusa spinosa* (or *Bambusa blumeana*) in bending and in compression parallel to the fibres. Espinosa concluded that a piece of bamboo with a cross-sectional diameter of 9.55 cm, when loaded at the centre over a span of 152.5 cm, could support 0.5 tons, equivalent to 5 kN. At the same time, a piece of the same cross-sectional size and 122 cm long, loaded in compression parallel to the fibres, could support 4 tons, equivalent to 40 kN. As the wall thicknesses of the tested specimens were recorded, it is possible to calculate the limit state stress of the tested sample.

Both McClure and Hidalgo-López mention earlier primary research on the mechanical properties of bamboo conducted by H. F. Meyer and B. Ekelund and published in China in 1923, but apart from being

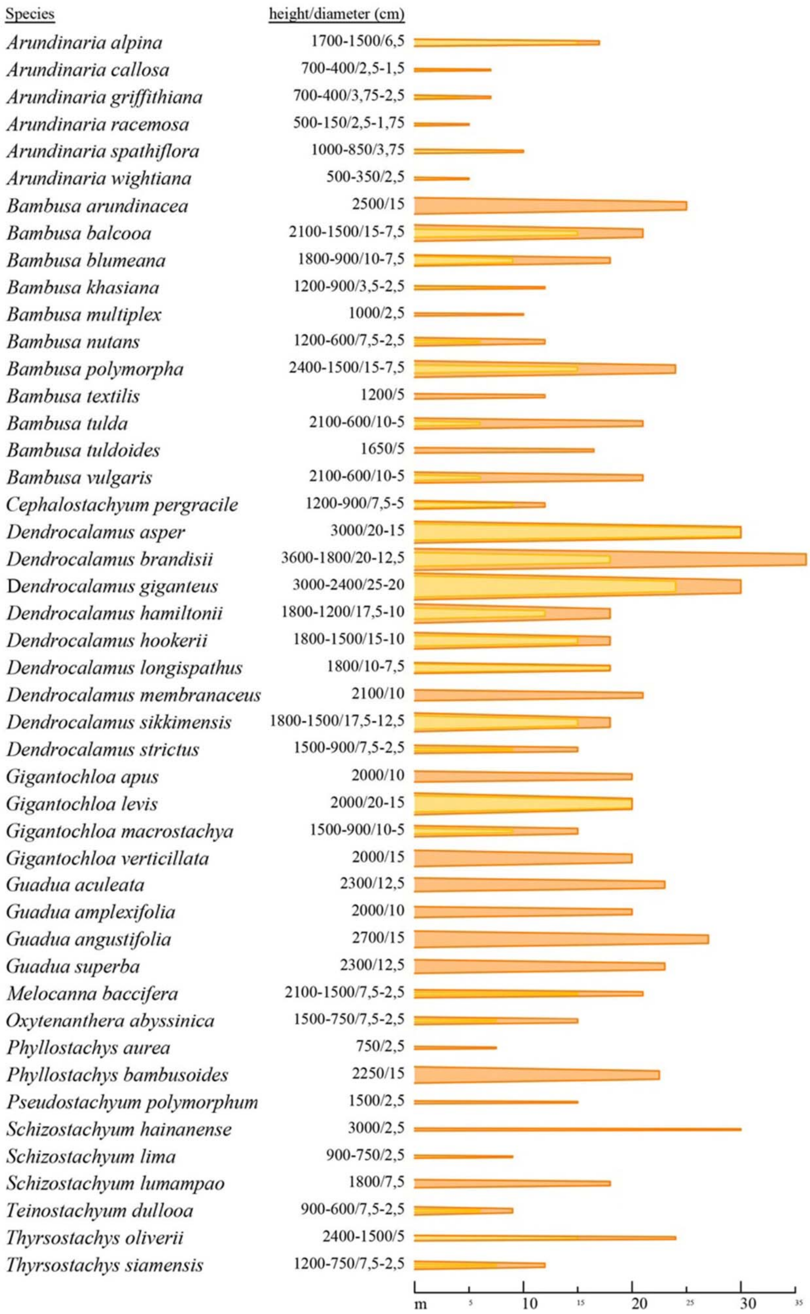

Fig. 6. Sizes of ‘some bamboos used in housing’. Own production, based on McClure (1953)

quoted (McClure, 1953; Hidalgo-López, 1978; Arce, 1993), there is no record of this publication.

The first documented systematic approach to bamboo as a structural material considering its own particular performance — starting from the microscopic level of material characterization, moving through its performance under different stresses (particularly tension and compression parallel to the fibres), and ending at the macroscopic level with structural design formulas — is Oscar Antonio Arce-Villalobos’ doctoral thesis (Arce, 1993). This represents a leap forward toward the future development of specific standards for bamboo structural design, and it is therefore among the few references considered by the earliest standards.

One of the major contributions — despite its simplicity — to the later development of bamboo structural design is the ratio of external diameter to wall thickness of culms. Arce-Villalobos provided statistical data showing that the mean thickness / diameter ratio is 0.09 with a 97 % confidence limit, while being aware of (and pointing out) the natural diversity of every bamboo culm, even within a single culm along its entire length.

Another remarkable finding by Arce-Villalobos is a correlation of 0.4 between tensile strength and density for *Bambusa blumeana*. In addition, he states that changes in cross-section and changes in MoE along bamboo culms affect their critical load, and that calculating the critical load as a function of these properties (cross-section and MoE) gives a conservative estimate if the influence of the nodes is ignored.

Research has been conducted on the existence of codes and standards for structural bamboo culms (Amede et al., 2021; Adier et al., 2023), but it makes little or confusing distinction, if any, between engineered bamboo products and structural bamboo culms. It is crucial to emphasize the distinction between these types of products because of their extremely different environmental impact: engineered bamboo products have higher carbon emissions than cement or engineered lumber (Xiaoxiao et al., 2022), whereas structural bamboo culms may even have a positive environmental impact in terms of carbon sequestration and embodied energy if harvested regularly and at the proper age, before becoming over-mature.

In addition, from a socio-economic perspective, the transformation process from a living plant to a building product is much more accessible for ‘structural bamboo culms’ than for ‘structural engineered bamboo’, because the former requires mostly labour, while the latter requires machinery and adhesive products. There is increasing interest from authorities and stakeholders in including bamboo culms in building codes and standards, both national and international.

The first code on bamboo culms dates back only to 2000. It was titled AC162 — Acceptance Criteria for Structural Bamboo. It was published in California and was developed by the International Code Council of the United States of America. As described in the section below, the Colombian code on structural bamboo (ICONTEC, 2010) set a milestone that has not been surpassed in scope and depth to date.

Table 1. **Allowable design stresses (moisture content = 12 %). Source: ICONTEC, 2010 *Internodes filled with cement**

Stress	F_i (MPa)
Bending F_b	15
Tension F_t	18
Compression, parallel F_c	14
Compression, perpendicular F_p*	1.4
Shear F_v	1.2

Table 2. **Modulus of Elasticity. Source: ICONTEC, 2010**

Modulus	E_i (MPa)
Average $E_{0.5}$	9,500
5th percentile $E_{0.05}$	7,500
Minimum E_{min}	4,000

Now, 25 years after the publication of the first code in California and 15 years after the Colombian one was approved, ISO standards for bamboo culms and for engineered bamboo products are available (these products are beyond the scope of this paper). National codes that specifically include structural bamboo culms exist in Colombia, Ecuador (INEN, 2011), Peru (ICG, 2012), and India (BIS, 2018).

The Pioneering Building Code of Colombia

In 2010, the Colombian code for seismic-resistant structures, NSR-10 (ICONTEC, 2010), was approved. It includes a specific chapter on bamboo structures built with the most common species in Colombia, Guadua angustifolia Kunth, or simply Guadua. NSR-10 utilizes allowable stress design (ASD), based on previous characterization of Guadua. Therefore, NSR-10 is considered a precedent for applying the ASD approach, which is permitted by ISO 22156:2021 in combination with ISO 22157:2019, using Guadua as the subject species. Moreover, NSR-10 served as the reference for Ecuador (INEN, 2011) and Peru (ICG, 2012) when adopting their own national structural bamboo codes.

The allowable design stresses and the MoE included in NSR-10 for Guadua angustifolia Kunth are shown in Table 1 (note the difference in orders of magnitude between bending, tension, and compression parallel on the one hand, and compression perpendicular and shear on the other) and in Table 2, respectively.

Due to the anisotropic nature and heterogeneity of this organic material, safety coefficients are defined within the code to obtain the ‘modified service stress’ from the ‘service stress’ for each type of stress. Some of these coefficients are applied depending on the stress type (bending, shear, compression parallel), while others are applied in general, such as:

– load duration (ranging from 0.9 for permanent dead loads to 2.0 for impact loads);
– moisture content (ranging from 1 to 0.7);
– temperature (ranging from 1 to 0.4);
– combined action (1.1 when four or more elements work together and are located less than 0.5 m from each other).

The most restrictive coefficient is the one related to service temperature: it is 0.4 when the expected room temperature is between 52 °C and 65 °C. Above this temperature, the use of structural bamboo culms is not recommended. Although other organic materials may be more severely affected by long-term loads, bamboo culms experience a serious drop in mechanical performance due to high room temperatures more than due to any other condition.

ISO Standards Related to Structural Bamboo Culms

In 2004, the first edition of ISO standards on bamboo from a structural perspective was published. It consisted of two volumes: ISO 22156:2004 — Bamboo — Structural design and ISO 22157:2004 — Bamboo — Determination of physical and mechanical properties. Despite being the first international attempt to address bamboo culms as a structural material and to develop a structural design standard for them while providing guidelines for characterizing particular bamboo species, it was still not possible to perform a proper structural design for any type of building structure based solely on those ISO standards.

In 2013, the revision procedure began, resulting in a suite of material and design standards for full-culm bamboo: ISO 19624:2018 — Bamboo structures — Grading of bamboo culms, ISO 22157:2019 — Bamboo structures — Determination of physical and mechanical properties of bamboo, and ISO 22156:2021 — Bamboo structures — Bamboo culms — Structural design. The adoption of widespread methods familiar to engineers has overcome the previously existing obstacles to using structural bamboo culms in construction. Two approaches are permitted by ISO 22156:2021: allowable load-bearing capacity design (ACD) and ASD. ACD requires the application of ISO 19624:2018 to determine the moment capacity for each grade previously assigned to members, whereas ASD is based on material properties as defined in ISO 22157:2019. The possibility of developing column axial load tables and beam flexural load tables based on the practical use of ISO 19624:2018 and ISO 22156:2021 has already been demonstrated (Harries et al., 2022).

Eurocodes and the Technical Building Code

Structural Eurocodes, which are used in most European countries, are performance-based codes. Although Eurocodes are widely adopted across European countries, in some countries they are the only regulatory texts (e.g., France and Germany), whereas in others they coexist with additional regulatory texts (e.g., Italy). Finally, there are a few countries, such as Spain, where national codes prevail over the Eurocodes. The Technical Building Code — in Spanish, "Código Técnico de la Edificación" — which is applicable in Spain, is also a performance-based code (CTE, 2022).

Therefore, in Spain as well as in the rest of Europe, a particular material or construction system does not need to be explicitly included in the code to be used in a building project, as long as a competent technician justifies that its performance fulfils the code's requirements and provides the specifications needed to meet them. The code includes supporting documents called Basic Documents (Documentos Básicos, DB), which address mainstream practices. In the structural domain, these include documents on masonry, steel, and timber. Concrete is not included in the DB-SE because a separate complementary standard deals with it. Thus, to date, five structural materials are explicitly considered by the CTE and the Eurocodes: steel, masonry, timber, concrete, and aluminium.

In Europe, besides the temporary ZERI Pavilion at Expo Hannover 2000, there is another significant example of structural bamboo culms still standing over twenty years after completion: the Vergiate Pavilion (Vantomme et al., 2003), finished in 2003, covering 32 by 16 metres. According to Donini et al. (2022), it is feasible to design a building using structural bamboo culms in compliance with the Italian regulatory framework, as long as it is supported by the international standard on structural bamboo culms. That standard provides characteristic and design values for bamboo (as well as correction factors) while also indicating how to verify the performance of bamboo culms and their connections. Nevertheless, the need for design guides related to fire safety is evident.

Regarding Fire Safety

A critical aspect of the structural design of a building is to rate its structural performance in the event of fire. Mena et al. (2011) report a charring rate of 0.24 mm/min when bamboo is used as a finishing element and 0.20 mm/min when used as a structural element for Guadua, but these values are based on only two tests. As Correal (2020) states, building fire safety is incorporated into building codes through a combination of passive features — such as prescriptive measures for fire-rated building elements or appropriate means of egress — and active features, such as fire detection and suppression systems.

According to Gutierrez (2020), the structural fire performance of load-bearing bamboo systems must be understood before they can be used with the same level of confidence as more traditional and widely used construction materials such as concrete or steel. His experimental research found that at a temperature of 250 °C, a reduction factor of 0.1–0.2 for compressive and tensile strengths parallel to the fibres should be applied to bamboo culms, whereas the reduction factor for their MoE should be 0.7.

Gutierrez notes that the mechanical properties of bamboo culms at elevated temperatures are not available in design guidelines or scientific literature, indicating the need to include this information in future bamboo building codes and design guidelines. In the Eurocode and the CTE, the mechanical response for materials that undergo charring is defined by the charring rate, resulting in a progressive reduction of the element's cross-section.

After conducting fire tests on load-bearing bamboo bahareque wall systems (also known as light cement-bamboo frame, LCBF) using specimens of 1050 mm × 1050 mm — first exposing the specimens to fire and then calculating the residual capacity of the walls — Salzer et al. (2016) concluded that all specimens achieved a 60-minute fire resistance rating, which was the target resistance of the study. They pointed out that the configuration of the covering was a key factor in providing sufficient protection to the structural members. In addition, a detailed assessment of the mechanical resistance of bamboo poles after fire exposure showed that initial charring after failure of the protective cover does not immediately jeopardize the load-bearing capacity of the system and could possibly be taken into account in system performance assessments. Further research is required to determine safety factors and mechanical properties for structural bamboo culms in the event of fire.

Despite the limited research carried out to assess the performance of exposed bamboo culms in fire, a 24 mm thick gypsum-based plasterboard provides a 60-minute fire resistance rating (FRR) (Kaminski et al., 2016). The document in the CTE (2022) related to the fire resistance of walls, ceilings, and doors that define fire compartments allows a 60-minute FRR for above-ground residential, educational, and administrative buildings up to 15 m tall.

Conclusions

1. The existing international standards and national building codes that include structural bamboo culms provide sufficient information to safely use bamboo culms as structural elements in Europe, given that the Structural Eurocodes and other national codes that coexist with them are performance-based.
2. This is currently limited to *Guadua angustifolia Kunth* bamboo species harvested in Colombia, due to the design values included in the Colombian structural code, NSR-10.
3. Following the ISO standards, other bamboo species — and/or specimens from other sourcing locations — may be characterized to perform structural design, resulting in long-lasting, safe structures.
4. Structural bamboo culms are legally permitted within the current European regulatory context, even as a permanent building structure.
5. As a natural resource that has not been researched as extensively as fully industrialized materials, there is an immense amount of research ahead to better understand bamboo culms as a structural material.
6. Research to better understand the mechanical performance of structural bamboo culms in the event of fire is particularly relevant for determining evidence-based safety factors.

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БАМБУКОВЫЕ СТВОЛЫ В СТРОИТЕЛЬСТВЕ В ЕВРОПЕЙСКОМ НОРМАТИВНОМ КОНТЕКСТЕ: НА ПУТИ К БАМБУКОВОЙ АРХИТЕКТУРЕ

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Аннотация

Введение: Существующие международные стандарты и национальные строительные нормы, касающиеся использования бамбуковых стволов в строительстве, предоставляют достаточно информации для безопасного использования бамбуковых стволов в качестве конструкционного материала в Европе. **Методы**: В данной статье анализируется литература, связанная с характеристиками, эксплуатационными свойствами и стандартизацией бамбуковых стволов в области строительства, а также литература по строительным нормам, включая национальные нормы, уже учитывающие использование бамбуковых стволов в строительстве, чтобы ответить на вопрос, позволяет ли текущая европейская нормативная база их использование. **Результаты**: Несмотря на необходимость в руководствах по проектированию, касающихся пожарной безопасности, строительные бамбуковые стволы являются приемлемыми в рамках европейского нормативного контекста. Это связано с тем, что европейские кодексы по строительным конструкциям и другие существующие нормативные документы (например, испанский «Технический строительный кодекс» («Código Técnico de la Edificación»)) основаны на эксплуатационных характеристиках. Требования пожарной безопасности зданий включены в строительные нормы через комбинацию пассивных и активных мер, таких как противопожарные строительные элементы, соответствующие пути эвакуации, системы обнаружения и тушения пожаров и другие, что позволяет использовать бамбуковые стволы в качестве конструкционного материала. **Обсуждение**: Несмотря на то, что исследования, необходимые для лучшего понимания бамбука как строительного материала, всё ещё актуальны, бамбуковые стволы разрешены к законному использованию в рамках текущей европейской нормативной базы в области строительства, в том числе в качестве материала для капитального строительства.

Ключевые слова: бамбук; европейские стандарты; строительные стандарты для бамбука; проектирование конструкций; нормы.

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CONCEPTS OF MUSEALISATION OF ARCHITECTURAL HERITAGE

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Abstract

The modern musealisation of architectural heritage requires a balance between preserving authenticity and adapting to its new functions. However, existing approaches are not systematized, which leads to subjectivity and inconsistency in decision-making. **As a result** of the research, a periodic model of physical musealisation concepts has been developed, systematizing groups of architectural elements (object, structure, interior, facade, plan, territory) and intervention approaches (preservation, restoration, adaptation, renewal, addition, substitution, removal). Correlations between the physical characteristics of objects and permissible strategies have been identified, and terminology for new musealisation concepts has been introduced. The introduction of a new status for architectural heritage is proposed — Objects of Cultural Interest (OCI), which will fill the gap between Objects of Cultural Heritage (OCH) and ordinary buildings. The higher the value category of an object (OCH), the narrower the range of permissible transformation strategies and vice versa, the lower the status (OCI), the wider the range of possible changes. The research creates a theoretical foundation for decision-making in musealisation projects, bridging the gap between theory and practice of heritage revitalization into museums, and also offers tools for working with objects of various types and degrees of preservation.

Keywords: musealisation; concept model; Objects of Cultural Interest (OCI); Objects of Cultural Heritage (OCH).

Introduction

Currently, the concept of "musealization" is still at the stage of formation in modern science (Kimeeva, 2022). Approaches to the musealisation of architectural heritage are developing amid a growing contradiction between the need to preserve the material authenticity of objects and the requirements for their adaptation to current socio-economic conditions. This process, which involves the transformation of historical buildings into museum objects, requires fundamentally new systemic solutions capable of overcoming the existing gap between theoretical principles and practical implementation.

The analysis of publications from the last decade reveals significant gaps in systematizing musealisation methods: theoretical works by Jokilehto (1986) and Bobrov (2017) focus on the philosophical aspects of conservation theory but do not offer practical tools for classification, whereas technical studies by Zhang (2024) and Krasilnikova (2025) examine individual technologies, such as laser scanning or BIM modelling, but do not establish links between the physical characteristics of objects and permissible interventions. Existing international standards (Venice Charter ICOMOS, 1964; Krakow Charter, 2000) provide important ethical guidelines but lack tools for selecting strategies in specific design solutions. This leads to a situation where each complex case of musealisation requires the invention of new approaches, which significantly increases time and financial costs, as well as generates professional conflicts.

In this context, the present research aims to develop an interactive periodic system of musealisation concepts that will allow:

– systematize existing concepts of architectural heritage musealisation according to their impact on the material elements of the object;

– identify the key parameters determining the choice of a musealisation concept;

– establish correlations between the physical characteristics of monuments and the range of permissible interventions.

Methods

Currently, research on the musealisation of cultural heritage objects and the historical environment is conducted primarily in three disciplines: museology, archaeology, and the architectural-urban planning sphere. The absence of a unified systematizing tool leads to subjectivity, contradictions in design solutions, and risks of harming heritage. This research is based on the analysis of musealisation design solutions in Europe, Asia, and the CIS countries. The research algorithm is structured according to the following principles:

– abstraction from certain properties of museums and musealisation zones whose area of responsibility lies primarily not in the architectural sphere but in museology, cultural studies, or archaeology;

– analysis of the theoretical research base or secondary data, i.e., scientific works of predecessors in this field, to avoid repeating hypotheses and to generate new scientific knowledge about the research subject;

– identification of the hierarchy of architectural elements of the object, approaches to possible physical intervention in the architecture of objects for museum creation, and establishing patterns of approach / element / classification of the musealisation object;

– synthesis of the identified data into a periodic model of physical musealisation concepts;

– application of induction methods (from particular cases to general classification principles) and deduction (from established principles to formulating terms and rules for new situations).

The presented examples of musealisation objects were evaluated from the perspective of architectural transformations of their individual elements and the physical actions required for these transformations. The results of these evaluations are presented in a table and are colour-coded according to the permissible uses of categories of architectural heritage, thereby bridging the gap between theory and practice.

Results and Discussion

The analysis of the implemented projects has revealed stable patterns in the musealisation of architectural heritage, on the basis of which a periodic model of concepts was developed. The structure of the model, analogous to the chemical system of Mendeleev's table, is organized according to the principle of increasing intensity of impact — from classical conservation to radical dematerialization. The periodic model of musealisation concepts (Fig. 1) demonstrates a clear dependency between the value of object elements, intervention approaches, and their possible connections.

Alongside the term "Object of Cultural Heritage" (hereinafter OCH), the introduction of a new legal status for potentially valuable objects is proposed — "Object of Cultural Interest" (hereinafter OCI), which serves as an intermediate link between OCH and ordinary buildings. The OCI possesses presumed value (historical, architectural, urban planning, social, etc.) but is not included in official protection registers. This status, analogous to "Buildings of Local Interest" in Cambridge, protects the object from demolition and the problems of "non-obvious heritage", providing flexibility in the management and architectural transformation of the object (Building of Local Interest, 2025). Thus, the gradation of permissible intervention approaches in relation to the status of the object is divided into three legends:

– orange: concepts suitable for OCH of any level and for OCI;

– green: concepts suitable for regional and local levels and for OCI;

– grey: concepts suitable only for OCI.

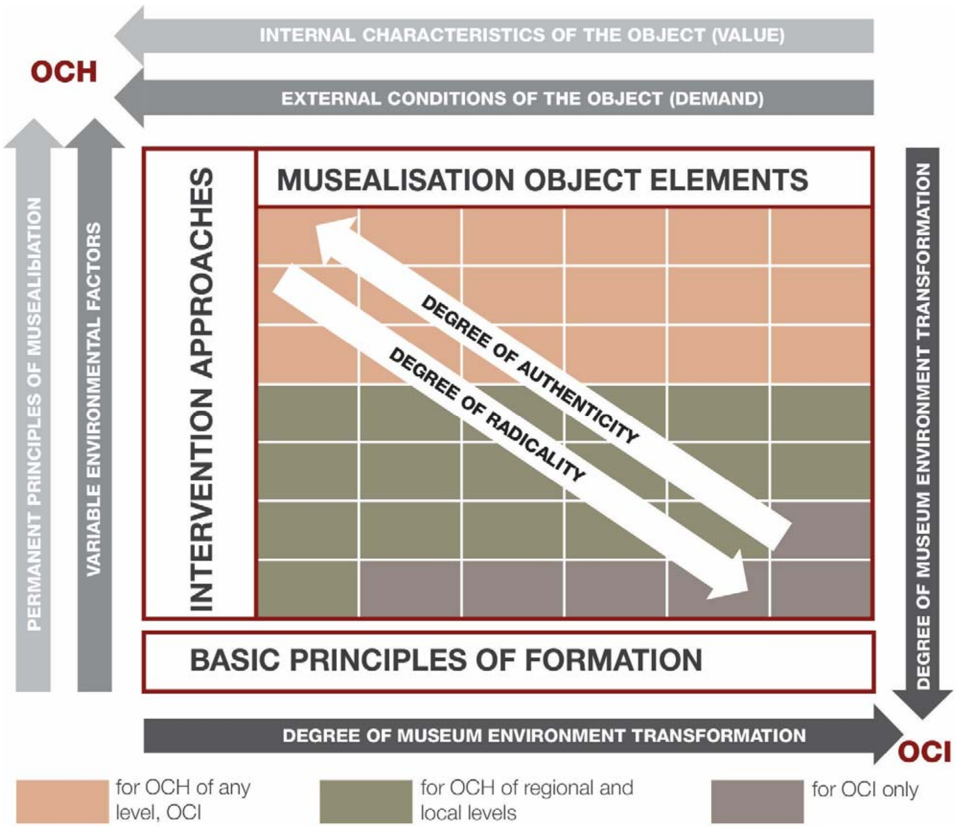

Fig. 1. Model of logical connections of musealisation concepts for architectural objects

Thus, the model classifies and establishes the dependency of various properties of object elements on the “charge” of their changes. Changes within a group (from bottom to top, from OCI to OCH): the degree of transformation of the historical environment decreases, while the constant principles of musealisation and variable environmental factors increase. Changes within periods (from right to left, from OCI to OCH) are: the degree of transformation of the historical environment decreases, while the internal characteristics of the object and external conditions of the object increase. Changes along the diagonal (from OCI to OCH) are: the degree of transformation of the historical environment decreases, while the degree of authenticity increases.

According to Russian federal law “On Objects of Cultural Heritage”, OCH can be divided into three types: monuments, ensembles, and sites of interest. However, in many cases, existing historical environment territories are not territories of architectural ensembles or sites of interest, but rather a collection of individual monument objects from different periods and scales, which leads to their logical selection as the basis for a research unit (Alekseev et al., 2012). Similar to research in chemistry or physics, scientists delve deeper into the “molecular” structure of studying objects and phenomena. Furthermore, Ponomareva’s dissertation on the musealisation of the urban environment (Ponomareva, 1994) subjected the monument to division into individual elements, each carrying its own value and characteristics, which can now be supplemented and presented as **groups of the model** — vertical columns classifying concepts according to object elements, which can be divided into 2D (planar) and 3D (volumetric) ones:

– 3D object: a building that is an Object of Cultural Heritage (legalized or to be identified in the future), with a wide range of valuable qualities: historical, architectural-urban planning, etc.

– 3D interior: the internal environment of the object, forming an ergonomic and emotionally rich atmosphere appropriate to its purpose, including interior design, finishes, object furnishings, overall concept, etc.

– 3D structure: the interconnected set of vertical and horizontal load-bearing structures of the object, ensuring its strength, rigidity, and stability, including the type of structures, materials, engineering solutions, etc.

– 2D facade: the external enclosing structure of the building, performing aesthetic, protective, and communicative functions, including composition, materials, decorative elements.

– 2D plan: the organization of the internal space of the building, determining the relationship between rooms, their functionality, and usage scenarios.

– 2D landscape: the natural-anthropogenic environment surrounding the object of cultural heritage or cultural interest, historically and functionally linked to it as an integral part, including: relief, vegetation and water elements, small architectural forms, etc. (GOST R 56891.4–2016).

The hierarchy of intervention levels is primarily displayed as a gradation of the main concept — as described by Jokilehto with four levels of preservation (conservation → restoration → reconstruction → → recreation) (Jpokilheto, 1986) or through the lens of basic strategies, as in Shchenkov’s works (ruin conservation → stabilization → fragmentary restoration → complete restoration → adaptive regeneration) (Schenkov, 2004). Often, the main approach to heritage preservation through restoration is classified according to individual actions on object elements, as in Shumilkin’s research (archaeological, synthetic, and stylistic restoration) (Shumilkin, 2023). Such research has been conducted in the context of preserving historical buildings without provisions for museum perspectives. However, together with the analysis of implemented musealisation projects, they allow us to see the global essence of possible changes, which can be expressed in the form of periods of the model — horizontal rows classifying concepts according to the essence of intervention:

– preservation — approaches to protecting and maintaining the object in its original discovered state, aimed at ensuring the physical integrity, authenticity, and value of the object;

– restoration — approaches aimed at recreating and ensuring the pristine condition and authentic value of the object based on historical data and research;

– adaptation — approaches aimed at improving the understanding of the object’s value, emotional perception, involvement in the socio-cultural context of the environment, but without irreversible intervention;

– renewal — approaches aimed at modernizing or rebooting the object to ensure contemporary use;

– addition — approaches aimed at incorporating new permanent or temporary elements that can expand the useful area of the building, improve operating conditions, or other criteria of the object;

– substitution — approaches aimed at substituting lost or irreparable elements of the object, either matching the original or a new architectural vision that enhances the attractiveness and value of the object;

– removal — approaches aimed at dismantling elements of the object due to unavoidable circumstances.

The cells of the model are the concepts of musealisation of architectural heritage — the main paths, ideas, or conceptions for solving the problem underlying the design of architectural-spatial environments (Fig. 2). The terminological hierarchy

INTERVENTION APPROACHES	ELEMENTS OF THE MUSEALISATION OBJECT					
	3D			2D		
	OBJECT	INTERIOR	STRUCTURE	FACADE	LAYOUT	LANDSCAPE
PRESERVATION	integrated conservation	interior conservation	structural conservation	facade conservation	layout conservation	landscape conservation
RESTAURATION	integrated restauration	interior restauration	structural restauration	facade restauration	layout restauration	landscape restauration
ADAPTATION	integrated adaptation	interior adaptation	structural adaptation	facade adaptation	layout adaptation	landscape adaptation
RENEWAL	integrated renewal	interior renovation	structural renovation	facade renovation	layout renovation	landscape renovation
ADDITION	integrated reconstruction	interior reconstruction	structural reconstruction	facade reconstruction	layout reconstruction	landscape reconstruction
SUBSTITUTION	integrated substitution	interior substitution	structural substitution	facade substitution	layout substitution	landscape substitution
REMOVAL	cultural translocation	interior translocation	structural translocation	facade translocation	layout translocation	landscape dematerialisation

BASIC FORMATION PRINCIPLES	sustainable development	contextual insertion	technological implementation	digital promotion	inclusive visiting	flexible functioning

for OCH of any kind, OCI

for OCH of regional and local levels, OCI

for OCI only

Fig. 2. Periodic model of physical musealisation concepts

is: vertically, increasing activity (from protection → → to transformation → to removal); horizontally, increasing the scale of impact (from the whole → to elements).

The proposed terminology system unites traditionally established concepts, contemporary expressions, and new borrowed terms reflecting modern approaches to the transformation of architectural heritage. Established concepts have already firmly entered the professional lexicon of architects or archaeologists and require no additional explanation, as their meaning is enshrined in regulatory documents and scientific literature: conservation, restoration, reconstruction, renovation. Contemporary terms require clarification for this research, as they are not enshrined in regulations but have been actively used in publications or project activities in recent decades:

– revitalization (Latin “re” — renewal, “vita” — life) — the process of renewing and enlivening urban space, unlocking new possibilities for old territories (Anisimova, 2018);

– substitution (Latin “substitution” — substitution, replacement) — the process of replacing existing elements or structures with new ones, substituting one element for another that occupies a similar position in the object and performs an equivalent function (Sobotka et al., 2021);

– translocation (from Latin “trans” — across, “location” — placement) — the physical relocation of an object and / or to a new location, preserving material and historical integrity with irreversible intervention and museum use (Şahin and Tutkun, 2020);

– dematerialization (Latin “dematerialization” — depriving of materiality) — the process of physical liquidation of a specific historical territory, as a result of which its value is preserved and exists only in the form of documents, records, archives, etc. (Shemyakin, 2024; Frey and Kirshenblatt-Gimblett, 2002).

The model of musealisation concepts for architectural objects has structural and logical parallels with the periodic table of elements, but with a fundamentally different purpose — not the classification of chemical elements, but the systematisation of methods for transforming objects of cultural heritage or cultural interest into objects of museum display. While Mendeleev’s periodic table reflects the immutable laws of elements, the table of musealisation concepts represents variable design strategies, where the hierarchy of values may depend on the cultural context. The basic principles of forming a musealised space are highlighted in a separate row, as they represent universal trends of our time. Just as in chemistry the laws of thermodynamics do not fit into the cells of the periodic table but govern the behaviour of all elements, these principles are not tied to specific approaches but set the general framework for any musealisation project, ensuring its compliance with modern cultural, technological, social, and other requirements.

These principles include:

– sustainable development — in the context of musealisation, a principle based on the position of culture as a key factor in achieving the SDGs, contributing to social integration, economic growth through creative industries and cultural tourism, and the full integration of culture into national and international development strategies, according to the Valletta Principles of 2011;

– contextual integration — a principle based on the need for harmonious embedding of the object into the surrounding environment, which implies visual consistency with the historical landscape, functional interconnection with infrastructure, and semantic continuity (Krasilnikova, 2025);

– technological implementation — a principle based on the integration of modern technical solutions into the process of managing or preserving the object, including engineering innovations (automated climate control systems, monitoring sensors, thermal imagers, etc.), digital tools (BIM modelling, laser scanning, etc.);

– digital promotion — a principle based on the use of virtual technologies to expand the possibilities of presenting the object, providing for the creation of digital archives, the development of interactive formats (VR / AR tours), the organization of online access to museum collections, etc.;

– inclusive visiting — a principle based on ensuring equal access to cultural heritage and museums for all categories of visitors, which implies architectural accessibility, cognitive inclusion, social engagement, etc.;

– flexible functioning — a principle based on the ability of the musealized space to adapt to changing conditions, including functional transformation of spaces, modular organization of exhibitions, dynamic programming of cultural events, etc. (Pérez 2022).

The methodology for applying the model of musealisation concepts is based on 6 steps:

– step 1: determining the value category of the object; identifying whether it is an Object of Cultural Heritage of federal, regional, local significance, or an Object of Cultural Interest.

– step 2: decomposition of the object into element groups. Visual, historical, and scientific analysis is conducted to assess the value of each group: object (as a whole), interior, structure, facade, plan, landscape.

– step 3: assessment of the physical condition. Determining the degree of preservation of each valuable element and the possibility of its preservation.

– step 4: selection of permissible strategies based on the model matrix. The value category (step

1) determines the “permissible palette” of strategies (intervention approaches): preservation, restoration, adaptation, renewal, addition, substitution, removal. The higher the status, the narrower the spectrum.

– step 5: concept development: correlating the chosen strategies with the new museum function. Both a general idea and a package of solutions for each group of elements are formulated.

– step 6: verification against musealisation principles. Evaluation of the concept and discussion: controversial decisions, deviation from the recommended range of strategies, loss / gain balance, prediction of consequences.

Each musealisation concept presented in the table can be illustrated with specific examples (Fig. 3), demonstrating its application in real projects. For example, preservation (conservation) of historical facades during the construction of “Tishinsky Boulevard” in Moscow emphasizes the priority of authenticity and historical memory, while renewal (renovation) of the facades of historical houses in the Paper Museum in Dongshan Village, China, reflects adaptation to modern functional requirements and cultural context. Adaptation (revitalization) of ruins in the case of the Columbus Museum in Germany allows the ruined elements to be presented as part of a new interior space without harmful physical intervention, and addition (reconstruction) of glass lifts in the St. Olaf Tower of Vyborg Castle in Russia illustrates the harmonious integration of new engineering elements into a historical context. These examples not only confirm the universality of the proposed classification but also show how the choice of concept depends on the type of value of the object, the specific element of the object, and the level of the heritage object subject to transformation.

As an object for analysis, consider the Basilica Cistern in Istanbul. This masterpiece of 6^{th}-century Byzantine engineering, known as the “Sunken Palace”, is comparable in status to an Object of Cultural Heritage of federal significance in Russian practice. Consequently, all orange-coloured concept cells are available to it, representing the gentlest intervention approaches. Visual analysis of the heritage’s physical appearance shows that the object does not possess valuable facades or surrounding landscape, as it is hidden underground, nor does it have valuable interiors or planning solutions due to its functional purpose as a reservoir. The key and unique value of this heritage lies in its structural-engineering solution: the vaulted ceiling of the cistern is supported by 336 columns brought from various ancient temples. Hence, the choice of musealisation object elements narrows down to the “structure”, and the intervention approaches remaining are: preservation, restoration, and adaptation. The Basilica Cistern used all three strategies: part of the structural system underwent extensive conservation to avoid collapse due to new construction and infrastructure above the reservoir; some columns and capitals were restored, as the site had long been abandoned and polluted; and for new museum use, walkways, lighting, and ventilation systems were added.

When inappropriate concepts are applied to an Object of Cultural Heritage of high value, the resulting solution can be either a failure (the loss of value outweighs the new opportunities) or a success (the new opportunities outweigh the loss of part of the value). The bold case of the reconstruction of the Hermitage General Staff Building by Studio 44 serves as a clear example where the concept goes beyond the limits of permissible architectural interventions and provokes discussion in the professional community. The ambitious project not only restored the facades and covered the inner courtyards with lighting structures but also cut through the internal spaces with through enfilade openings. Such a radical intervention into the structure of a monument included in the UNESCO World Heritage list has garnered both international recognition and public criticism regarding the loss of the value of classical architecture in favour of creating a contemporary museum.

However, not all bold decisions to transform an object for musealisation purposes end successfully. The Turkish government flooded an entire historic city for urbanization purposes, including an open-air museum, archaeological sites, and hundreds of medieval and ancient buildings. The ancient city of Hasankeyf was founded before our era and was part of many states, including the Roman, Byzantine, and Ottoman empires. In 1981, part of the city was declared an archaeological site. The city was not simply flooded but relocated to a new site, attempting to imitate the old settlement. However, the museum, previously located in the city centre, was built on the outskirts and deprived of interaction with the local community. Through removal and relocation, authorities managed to save only eight individual buildings. The concept of translocation of objects with the loss of the authentic landscape as a strategy for preservation and reconciling opposition ended in disaster and became a symbol of “absent heritage”, a constant reminder of a lost culture (Aykaç, 2023).

The presented table is built not only on the hierarchy of classifications of cultural heritage objects and their value (I-historical, II-architectural, III-scientific or technical, IV-aesthetic, V-social) but also on the constant principles of musealisation. The principles of musealisation are based on a hybrid fusion of ICOM and ICOMOS recommendations on restoration (Prutsyn et al., 1990; Ikonnikov, 1985) and musealisation (Kaulen, 2012). Their integration

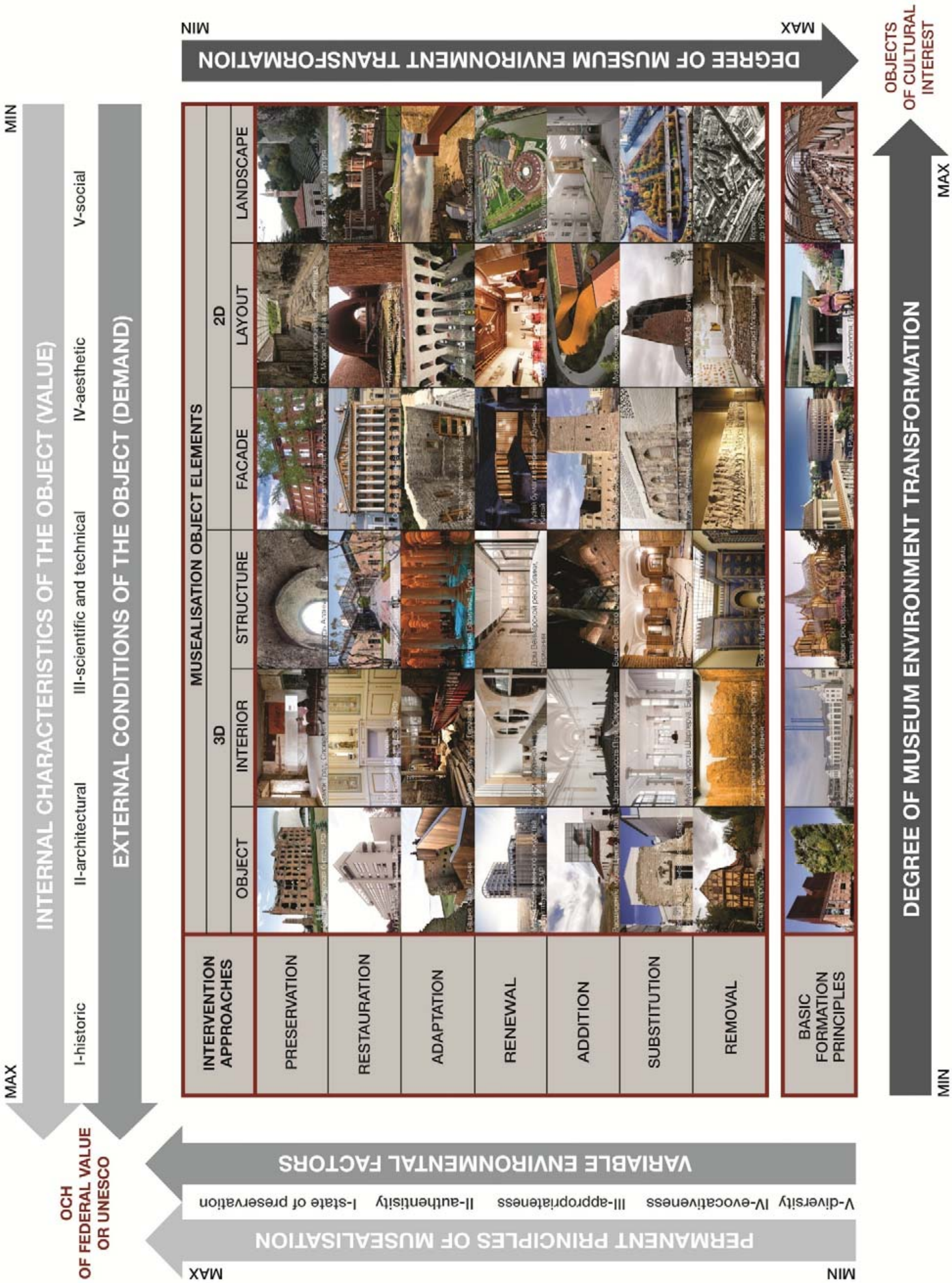

Fig. 3. Periodic model of musealisation concepts with examples

gives rise to a new phenomenon — the conceptual foundations for transforming objects into museums or museum spaces. They serve as a guarantee that the process of architectural transformation maintains a balance between preserving the authenticity of the heritage and its adaptation for contemporary use and perception. The principles can be formulated as follows:

I — Principle of preservation of the object, natural-cultural landscape, and spirit of place. Priority of the physical preservation of the material substance of the monument as the fundamental basis for any action. Any intervention must minimize the risks of loss or damage to authentic elements (ICOMOS, 1964). Exhibition activities must exclude the threat and risk of destruction, ensuring preservation by all possible means (Kaulen, 2012). Musealisation must preserve not only the material structure but also the totality of meanings, the atmosphere, the connection of the object with the surrounding landscape and cultural context (Prutsyn et al., 1990).

II — Principle of authenticity and credibility. Correspondence of musealized objects to the level of scientifically based information about their original appearance. The authenticity and credibility of the environment must be equal to the degree of research, to avoid preserving “false” value (ICOMOS, 1964). All stages of work with cultural heritage objects must be accompanied by documentation describing actions, materials used, etc.

III — Principle of appropriateness. Any intervention in an architectural heritage object must be appropriate in relation to the historical environment, cultural context, significance of the object, and memorial memory (Prutsyn et al., 1990; Ikonnikov, 1985). The principle allows for balanced decisions in “grey areas” where rules or standards do not provide a clear answer. It requires professionals to exercise respect, a sense of proportion, and cultural sensitivity.

IV — Principle of impressiveness. It is necessary not only to preserve architectural heritage but also to enhance its ability to emotionally affect the viewer, to make a strong impression, to convey the spirit of the era and the power of history or culture (Kimeeva, 2022; Ikonnikov, 1985). Without “showmanship”, but with the translation of scientific data into the language of emotions and personal discoveries.

V — Principle of diversity in functional-spatial structure. The pursuit of creating a unified but diverse and inclusive natural-cultural landscape, ensemble or object. Extensive use of additional functions alongside core museum functions (trade, catering, sports, recreation, etc.) (Pérez, 2022; Kaulen, 2012). Rejection of universal approaches to concepts.

The development of musealisation methodology implies continuous interaction between the constant and the changing context. Following the constant principles that form the ethical core, the question of variable environmental factors, which constitute the contextual field, inevitably arises. Thus, for an OCI, a permissible solution might be replacing outdated infrastructure with modern facilities to optimize museum access and comfort, as the priority would be activating the social potential of the place. However, for a high-level OCH, such simplification is unacceptable, as each decision requires a comprehensive analysis of the multi-layered context, including: the history of the formation of the environment; socio-functional connections in the past and present; climatic and urban planning conditions; strategic project goals and budget constraints; current regulations and protection standards; engineering-structural possibilities and risks. The two pairs of guiding elements of the model — “value-needs” and “principles-factors” — are in a state of constant interconnection and mutual influence, showing a coordinate system for concept formation and logical connections for making balanced decisions.

Conclusions

This article has examined the periodic model of physical musealisation concepts, which is a practical methodology for the revitalization of historical objects into a museum environment or tourist attractions. Musealisation concepts have come a long way from classical methods of preservation, such as conservation or restoration, to bold architectural transformations, such as substitution and translocation. A key aspect of the scientific understanding of musealisation as a process of transforming space into a museum is the analysis of ways to modify an existing object to form a museum environment. The conducted research has made it possible to systematize the concepts of musealisation of architectural objects in the form of a universal periodic model, where instead of energy levels — intervention approaches, and instead of electrons in the outer energy level — the elements and values of objects. The model of musealisation concepts has made it possible to:

- systematize previously disparate practices into a single logical system;
- visualize the relationship between the value of an object, its physical elements, and permissible methods of work;
- offer flexible tools both for working with valuable heritage (narrowing the choice) and for the creative revitalization of less significant objects (expanding possibilities);
- create a platform for dialogue between conservationists and innovators, ensuring a reasoned balance between authenticity and adaptation.

The introduction of the “Object of Cultural Interest” (OCI) status theoretically substantiates work with mass heritage, forming a flexible system: OCH (rigid regime) → OCI (flexible regime) → ordinary objects, which is relevant for historical urban environments. The model serves as a connecting link and an "interface" between theory, normative regulation, and real design, offering a much-needed systematic approach in our professional activity for the conscious and responsible transformation of architectural heritage in the face of new cultural challenges.

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КОНЦЕПЦИИ МУЗЕЕФИКАЦИИ АРХИТЕКТУРНОГО НАСЛЕДИЯ

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Аннотация
Современная музеефикация архитектурного наследия требует баланса между сохранением аутентичности и адаптацией к новым функциям, однако существующие подходы не систематизированы, что приводит к субъективности и непоследовательности решений. **В результате** исследования создана периодическая модель физических концепций музеефикации, систематизирующая группы архитектурных элементов (объект, конструктив, интерьер, фасад, план, территория) и подходы вмешательств (сохранение, восстановление, приспособление, обновление, добавление, замещение, изъятие). Выявлены корреляции между физическими характеристиками объектов и допустимыми стратегиями, введена терминология для новых концепций музеефикации. Предложено внедрение нового статуса для архитектурного наследия — объекты культурного интереса (ОКИ), которые восполнят пробел между ОКН и рядовыми сооружениями. Чем выше категория ценности объекта (ОКН), тем меньше спектр допустимых стратегий его трансформации; чем ниже статус (ОКИ), тем шире спектр возможных изменений. Исследование создает теоретическую основу для принятия решений в проектах музеефикации, восполняя пробел между теорией и практикой ревитализации наследия в музеи, а также предлагает инструментарий для работы с объектами различного типа и степени сохранности.

Ключевые слова: музеефикация; модель концепций; объекты культурного интереса (ОКИ); объекты культурного наследия (ОКН).

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URBAN TECHNICAL INFRASTRUCTURE IMPACT ASSESSMENT METHODOLOGY FOR PLANNING DECISIONS DEPENDING ON TURKISH LEGISLATIVE FRAMEWORK

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Abstract

Introduction. This article is positioned theoretically at the intersection of four keywords: urban planning, urban renewal, impact assessment, and technical infrastructure. Studies aiming to measure “impacts on technical infrastructure” are quite rare and tend to focus exclusively on national-level critical infrastructure, ignoring the local / urban scale. Filling this gap, **this article specifically aims** to propose an Urban Technical Infrastructure Impact Assessment (UTIIA) methodology to measure the impacts of changing planning decisions on drinking water, sewage, and rainwater systems, addressing a decision dichotomy (whether a planning decision constitutes a plan amendment or a plan revision) that is particularly common for urban renewal applications in the Turkish planning experience.

Keywords: urban technical infrastructure impact assessment; urban renewal; plan amendment; plan revision; technical infrastructure.

Introduction

Bridging Urban Planning, Technical Infrastructure and Impact Assessment

Today, 55.3 % of the world’s population lives in urban settlements. The UN predicts that this figure will reach 68.4 % by 2050 (UN, 2018).

Parallel to the spatial demands of such an exponentially increasing urban population, two simultaneous phenomena are observed: on one hand, densification of existing built-up areas, transformation / land-use change of unbuilt areas, and changes to urban social infrastructure areas within the existing urban fabric; on the other hand, urban spatial expansion beyond existing settlement boundaries.

In this context, while resource management of cities — where huge populations concentrate — becomes a major topic, the management of natural resources, public investments, and assets (including social and technical infrastructure facilities) emerges as related subtopics.

From the same perspective, urban sprawl is characterized and criticized in terms of inefficient use of urban technical infrastructure investments within the planning literature of various geographies. As an antidote, the keyword “urban compactness” is being informed by carrying capacity and life-cycle assessment arguments of existing infrastructure investments and facilities. Achieving enriched urban environments in terms of quality of life is only possible and depends on a measurable compatibility between impact assessment-driven decision-making processes and existing technical infrastructure investments. It is also worth mentioning that aiming for efficient use of urban technical infrastructures as public investments is the main idea of this article.

Departing from this idea and grounding it in the current Turkish planning system, this paper proposes an impact assessment methodology to measure the impacts of changing planning decisions on urban technical infrastructure systems. This methodological proposal reflects the major findings of a research project on a regulation proposal for infrastructure impact assessment, carried out for the Turkish Ministry of Development (Ağaçcıoğlu et al., 2017).

The keywords urban planning, urban renewal, technical infrastructure, and impact assessment each have a massive literature. Due to the subject and intention of this article, a literature review and gap analysis is carried out by examining double and multiple intersections of these keywords.

Zone 1: Urban Planning, Renewal and Impact Assessment Relation

When the urban planning literature is refined by intersecting urban renewal and impact assessment keywords (Fig. 1 — Zone 1), it is observed that studies under this subtopic show a fragmented nature in terms of their subject matter.

Chan (2017) investigates the social impact assessment of an urban renewal project from a “right

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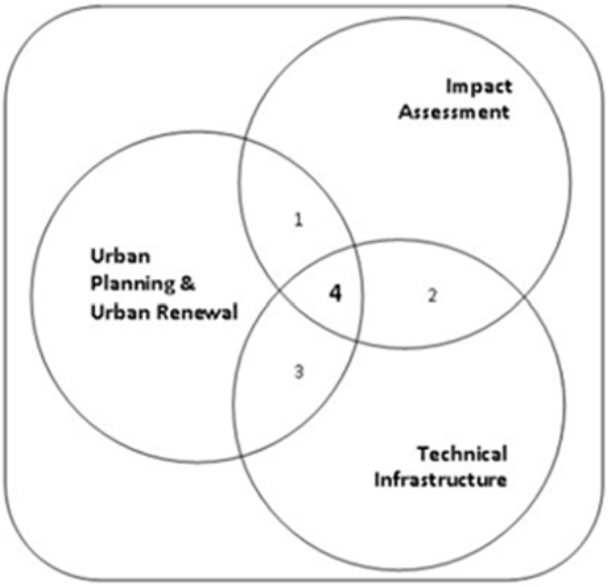


Fig. 1. Literature Review Fields

to the city" perspective, while Cheung and Leung (2008) try to clarify the effects of urban renewal on quality of life by considering subjective quality of life parameters, and Amis (2001) evaluates the impacts of a slum improvement project in India. Quite differently, linking the subject to mega-projects, Forouhar and Hasankhani (2018) examine local resident satisfaction with an urban renewal mega-project developed as a public-sector renewal intervention; Park et al. (2016) concentrate on risk factor evaluation of mega-projects; Lawanson and Agunbiade (2018) evaluate the social and environmental effects of a mega-project on indigenous communities; while Parkes, Lettieri, and Bogle (2016) propose an environmental impact assessment model based on an Olympic Park case study considering the construction, staging, and post-event phases of the mega-event. Consequently, it can be said that impacts of various projects of different scales and themes play a pivotal role in this literature.

Zone 2: Impact Assessment and Technical Infrastructure Relation

The relationship between impact assessment and technical infrastructure (Fig. 1 — Zone 2) hosts the widest and most diversified literature. From this perspective, Bonnel et al. (2002) aim to highlight the direct and indirect effects of transportation infrastructure investments in 13 European cities, while Chia et al. (2016) explore the linkages between environmental impact assessment and project process integration, professional governance, and public engagement in three transportation projects. El-Gafy et al. (2011) focus on environmental impact assessment of three plan alternatives for a transportation project, and Wu et al. (2014) measure the impacts of a highway project on landscape and ecosystems. Mahmood and Keast (2016) introduce a new methodology to measure the probable impacts and applicability of a large-scale (bridge) infrastructure project. Within the same literature, while Monzón et al. (2013) measure the spatial equity impacts of a high-speed railway investment using accessibility as a lens, Mottee and Howitt (2018) similarly focus on the social impacts of a new rail link, and Dimitriou et al. (2015) explore the economic impacts of a mega-infrastructure pipeline project.

In this bounded literature, "critical infrastructure" appears as a major keyword, referring to important infrastructure serving national and international scales. The fundamental ideas of these studies are risk assessment and precautionary actions / policies against natural threats (such as flooding, earthquakes, typhoons). Pant et al. (2018), for instance, propose a multi-dimensional infrastructure failure assessment methodology against flooding for national critical infrastructures (including electricity, airports, telecom masts, water towers, and wastewater treatment facilities) in the Thames catchment area. Very closely, while Emanuelsson et al. (2014) explore flood risk assessment for infrastructure networks, Neumann (2011) links urban planning to critical infrastructure in the context of sustainability.

In summary, this specific literature either concentrates on the impacts of infrastructure projects using tools such as environmental impact assessment (EIA) (El-Gafy et al., 2011; Chia et al., 2016; Paudel et al., 2025; Raafat et al., 2026), social impact assessment (SIA) (Mottee and Howitt, 2018), or economic impact assessment (Dimitriou et al., 2015), or shows a clustering around the "critical infrastructure" keyword (Pant et al., 2018) and deals with the resilience of technical infrastructures against natural risks (VROM, 2006) or related assessment methodologies (Emanuelsson, 2014).

Zone 3: Urban Planning, Renewal and Technical Infrastructure Relation

Starting in the late 1980s, the literature at the intersection of these keywords (Fig. 1 — Zone 3) mostly views technical infrastructure rehabilitation (and upgrading) as a tool component of urban renewal. For instance, Button and Pearce (1989) develop a cost-benefit analysis of infrastructure restoration for an urban revitalization project from an economic perspective. Similarly, Olanrewaju (2001) aims to evaluate the planning and implementation of infrastructure upgrading based on Urban Renewal Board studies in Badia (one of the low-income settlements in Lagos). From a different perspective within the same literature, Garrido-Jiménez, Magrinyà, and Consuelo del Moral-Ávila (2018) perform technical infrastructure calculations to assess economic outcomes in terms of municipal operating costs and revenues for diversifying urban patterns.

Partly similar to this article's point of view, while Hunt and Rogers (2005) explore a city center revitalization project solely in terms of its new water and energy demands considering sustainable solution options, Grimaldi et al. (2017) take the missing link between urban plans and water infrastructure planning as their departure point, comparing the relationships between regulatory and planning instruments. Neumann (2011) discusses the relationship between urban planning and infrastructure network planning through the lenses of life cycle / demand-capacity approach, demand management, and infrastructure demand assessment.

Very parallel to this last subset of articles, this study aims to propose an impact assessment methodology to systematically measure the impacts of planning decisions on urban technical infrastructure. However, beyond this general aim, the study introduces several original and innovative contributions that distinguish it from the existing body of literature.

First, it conceptualizes infrastructure not merely as an outcome of projects, but as a dynamic system that is directly shaped by planning decisions, thereby shifting the analytical focus from "impacts of infrastructure projects" to the largely neglected question of "impacts on infrastructure systems caused by spatial planning interventions". This reframing aligns with the "networked infrastructure" perspective of Graham and Marvin (2001), who argue that urban infrastructure is a dynamic socio-technological configuration reconfigured by planning and policy.

Second, the study develops a multi-dimensional and integrative assessment framework that simultaneously brings together urban renewal, impact assessment, and technical infrastructure within a single analytical model — an intersection that remains underexplored in current research. In this sense, the study occupies a distinct position in Zone 4 (Fig. 1), moving beyond fragmented approaches that typically address these domains in isolation. This integrated approach addresses what Tschupp et al. (2025) describe as the "siloed sector" problem, where a lack of cross-sectoral coordination leads to critical infrastructure bottlenecks during urban development.

Third, and more importantly, the proposed methodology introduces a novel operational mechanism based on the concept of "infrastructure tolerance / carrying capacity", which enables the quantification of whether a planning intervention can be accommodated within existing infrastructure systems or necessitates comprehensive plan revision. This capacity-based threshold approach transforms impact assessment from a descriptive or ex-post evaluation tool into a decision-support mechanism for ex-ante planning governance.

Furthermore, while the current literature predominantly focuses either on (i) the impacts of urban projects, mega-projects, and mega-events without explicitly addressing their consequences for infrastructure systems, or (ii) the impacts of infrastructure projects themselves — often at national or critical infrastructure scales — this study uniquely contributes by operationalizing impact assessment at the local / urban scale, where planning decisions and infrastructure capacities most directly interact. In doing so, it also bridges an important institutional and methodological gap between strategic-level assessments (such as SEA) and project-level assessments (such as EIA), which typically overlook local land-use planning processes. As noted by Partidário (2023), this "tiering" gap often leaves local planning decisions without a systematic assessment of their cumulative environmental and physical impacts.

Finally, the proposed UTIIA methodology is grounded in the specific legislative and planning context of Turkey, yet it offers a transferable analytical framework that can be adapted to other planning systems facing similar challenges of infrastructure capacity, urban renewal pressures, and fragmented decision-making.

Departing from these identified gaps and limitations in the existing literature, this article therefore not only proposes a new assessment methodology but also contributes a conceptual reframing, methodological innovation, and decision-oriented toolset for integrating infrastructure considerations into planning practice.

Changing Landscape of Impact Assessment and Positioning Infrastructure Impact Assessment within the Current Literature

After the wide-ranging use of project-level EIA, a growing number of assessment tools has been observed in the literature. Some relatively new assessment types that play a pivotal role include: Social Impact Assessment (Vanclay, 1999; Vanclay, 2002), Post-Disaster Impact Assessment, Demographic Impact Assessment, Economic Impact Assessment, Equality Impact Assessment, Gender Impact Assessment, Climate Impact Assessment, Cultural Impact Assessment, Cultural Heritage Impact Assessment, Cumulative Impact Assessment, Health Impact Assessment, Human Rights Impact Assessment, Socio-economic Impact Assessment, Sustainability Assessment, and Transportation Impact Assessment (Glasson et al., 2012; Morgan, 2012; Özügül, 2023).

Such a diversification and specialization trend can be seen as a result of demand for a more comprehensive scope, better integration, and a more extensive scale both in practical and theoretical grounds. The model presented in this article, parallel to some recent studies (Wang et al., 2020), summarizes the implementation guideline of a new and special type of assessment not currently found in the literature and focuses on an urban-scale “infrastructure impact assessment”.

Hamada (2015) conceptualizes urban infrastructure facilities as lifeline systems supporting the protection and sustainability of human life in cities and classifies these systems under four subtopics:

1. Water supply and purification systems: including water, sewage, and river facilities.
2. Energy systems: including electric power, gas and liquid fuels, and local cooling / warming.
3. Information and communication systems: including telephone, information, and broadcast facilities.
4. Transportation systems: including roads, railroads, ports, and airports.

A similar categorization is accepted as a starting point, and evaluation of the impacts of planning decision changes on sanitation, sewage and rainwater systems, transportation systems, and electricity infrastructure is aimed for the proposed model.

Transforming Planning Agenda in Turkey

Since 1993, the mainstream assessment route of Turkey has been dominated by project-based EIA practices. Just after the approval of a new regulation on Strategic Environmental (Impact) Assessment (SEA) in 2017, plans, policies, and programmes became subject to an obligatory impact assessment process. Under this regulation, the plans covered are strategic and sectoral plans (tourism master plan, transportation plan, etc.), management plans (watershed and river basin management plan, etc.), and socio-economic and mezzo-scale spatial plans (regional plans, environmental master plan, etc.)[1]. Within this context, local plans that define land uses, population, densities, and spatial rules fall outside the coverage of assessment systems. Departing from this point, local spatial plan assessment appears as a clear gap and grey area between the scopes of SEA and project-led EIA.

To clarify the relationship between planning and impact assessment practices, it would be better to define the (hierarchy of) the current comprehensive planning system of Turkey on one hand, and the contradictory nature of planning decisions — which becomes more visible in current discussions on transforming planning trends (such as urban renewal, mega-projects, etc.) also causing uncertainties — on the other.

Contours of the Current Planning System

According to the current legislative context, Turkey’s planning system has a hierarchical structure starting from the national level (Table 1). As upper-level instruments, National Development Plans (macro-scale socio-economic plans defining sectoral policies and investments within a five-year period) and National Spatial Strategy Plans (orienting spatial strategies, infrastructure, transport, and other spatially relevant investments and decisions) are foreseen. These national plans are to be complemented by regional-level plans, namely: Regional Plans (which are not obligatory and are supposed to combine national-level aims, objectives, and policies with regional strategies and decisions) and Territorial Spatial Strategy Plans (which can be prepared at varying regional scales and reflect decisions at the regional territory) (OECD, 2017; Özügül et al., 2017).

Functioning as mezzo-scale plans, Land Development Plans have the same geographical scope as Territorial Spatial Strategy Plans. These plans are used to guide lower-level land-use plans in terms of defining main decisions about settlement, development zones, and sectoral relations.

At the local (urban) level, there are two types of land-use plans. Being the first type, Master (Land Use) Plans’ conformance to Land Development Plans is a legal obligation. Master (Land Use) Plans organize the location and growth directions of settlements and main urban functions (residential, commercial, industrial zones, urban facilities, urban technical infrastructure, etc.) and the spatial

[1] http://www.mevzuat.gov.tr/Metin.Aspx?MevzuatKod=7.5.23492&MevzuatIliski=0&sourceXmlSearch=Stratejik%20%C3%87evresel%20De%C4%9Ferlendirme%20Y%C3%B6netmeli%C4%9F.

Table 1. **Plan Hierarchy in Turkish Planning System**

Level	Plans	Scale	content	Institution
National	National Development Plan	No scale	Socio-economic	Presidency of Strategy & Budget
	National Spatial Strategy Plan	1/250,000; 1/500,000 or more	Spatial	
Regional	Regional Plans	No scale	Socio-economic	Presidency of Strategy & Budget
	Territorial Spatial Strategy Plan	1/100,000; 1/50,000	Spatial	Regional Development Agencies Ministry of Environment and Urban
Sub-regional (city and its	Land Development Plans	1/100,000; 1/50,000; 1/25,000	Spatial	Ministry of Environment and Urban Planning
Urban	Master (Landuse) Plans	1/10,000; 1/5,000	Spatial	Metropolitan City Municipalities (Provincial) Governorships
	Implementation Plans	1/1,000	Spatial	Local Municipalities

distribution of population density. Determining the spatial reflections (both 2D and 3D) of general decisions of Master / Land Use Plans, Implementation Plans (as the second type of local plan) must show conformance to them.

In addition to this top-down legally binding hierarchical planning structure — which is the main route of planning for the Turkish case — a paradigmatic shift toward strategic planning has been observed since the 2000s. As a result of this shift, sectoral and special plans such as Tourism Master Plans, Agriculture Master Plans, Coastal Zone Management Plans, Transportation Master Plans, Watershed Management Plans, Earthquake Risk and Mitigation Plans, etc., have emerged within the planning agenda as non-obligatory strategic types of plans (İbişoğlu and Özügül, 2022; Yılmaz and Alkan, 2024; Yılmaz et al., 2023).

From "Urban Planning" to "Urban Renewal"; Growing Infrastructure Uncertainties

The above-mentioned urban land-use plans, which are prepared by local municipalities, must be holistic and consistent due to the current Turkish legislative system. On the other hand, besides sectoral and special plans, most urban mega-projects (mostly decided by the central government) and urban renewal projects (central government or local municipality projects) can be major drivers of deformation of the integrity and consistency of these local plans.

Within the scope of this study, the integrity and consistency problem will be examined through the impacts of planning decisions on urban technical infrastructure (including sanitation, sewage and rainwater systems, transportation systems, and electricity infrastructure). As is well known, urban technical infrastructure systems are planned and designed in accordance with the projections of a given urban system's future demands, and local (urban) plans are the base documents for these projections. While master plans direct urban space primarily through density and land-use decisions, implementation plans convert these decisions into built environment values (floor area ratio, total construction area, building heights, etc.). Considering the interdependent nature of local plans and infrastructure investments, unless urban mega-projects and renewal projects are developed in an integrative manner (in terms of land-use and density conformity between these projects and their vicinity), great infrastructure uncertainties will be created. From this perspective, Fig. 2 represents the hypothetical uncertainty patches in a holistic urban plan.

Consequently, once an urban mega-project or a renewal project is introduced into the land-use plan of a given territory, three probable paths emerge for the adaptation of these external and individual projects to the current plan: first, making a new plan (if an essential change in the planning problematic is observed); second, revising the existing holistic land-use plan in accordance with these projects (if the main aims and objectives of the existing plan remain but the holistic calculations must be revised to sustain the quality of urban space); and third, making partial amendments to the existing plans (if the effects are minor). Also, depending on the related national legislative documents, the proposed model particularly aims to calculate the magnitude of the effect caused by the planning decision on the

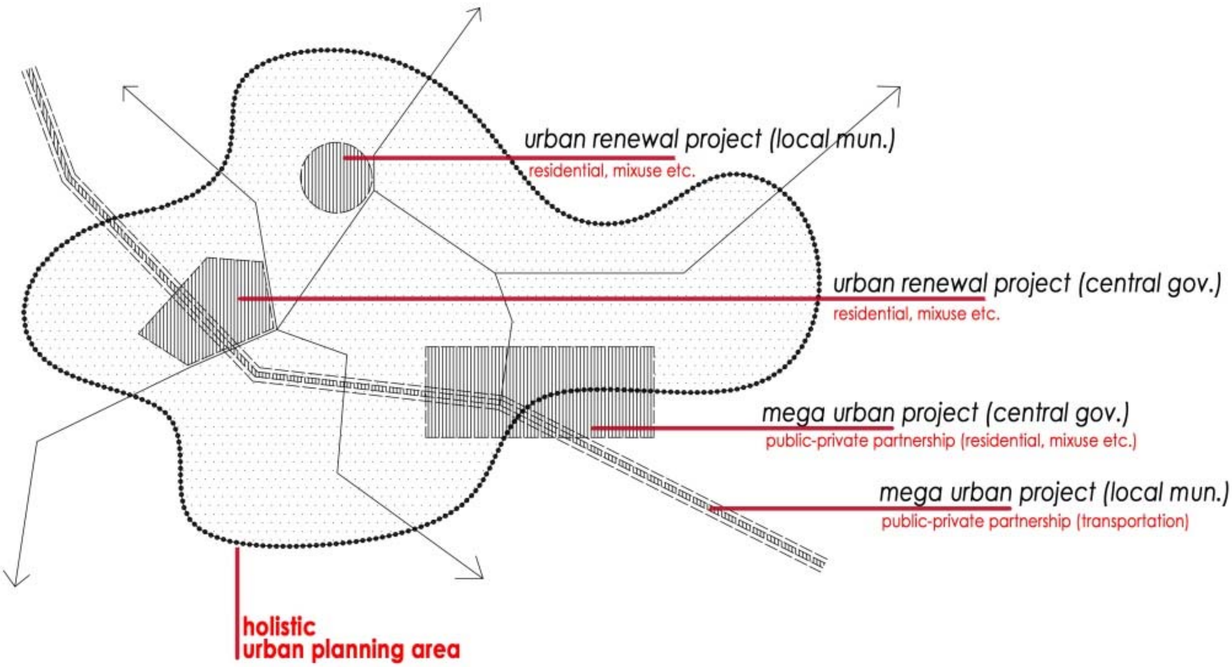


Fig. 2. Uncertainty Patches in a Holistic Urban Plan

existing technical infrastructure on the one hand, and to serve in deciding the correct path on the other.

Methodology

The method used in developing the impact assessment model proposed in this article is the focus group. A focus group is a "non-standard technique for information gathering based on an apparently informal discussion among a group of people selected on the basis of specific characteristics, outlined according to the cognitive purposes of the research" (Acocella and Cataldi, 2021). What makes the focus group technique — in which qualitative data is obtained through group discussions — unique is its ability to generate data and information that is difficult to access outside the interaction and participation environment used in this technique (Morgan, 2019). First used in the behavioral sciences, the technique has been used for almost 100 years in a wide range of scientific fields such as education, sociology, communication, health sciences, organizational behavior, program evaluation, psychotherapy, social psychology, gerontology, political science, policy research, sociology, anthropology, information systems, management, and marketing (Stewart and Shamdasani, 2015).

Although it is stated that a group size of 6–8 people is generally optimal (Bloor et al., 2001), 2–5 experts can also be used in "mini focus group" type applications consisting of high-level experts (Ochieng et al., 2018).

In developing the impact assessment model that is the subject of this article, the focus group technique was used in two main research stages. The first stage involved identifying the possibilities and limitations of planning, the impact of urban renewal on technical infrastructure, and the "current state" of the impact assessment system in Turkey. The second stage was the "strategic decision and model generation" stage, where the structure and parameters of the infrastructure impact assessment model were determined.

A total of seven participants from the following disciplines took part in regular weekly focus group meetings for one year: Drinking Water, Sewage and Rainwater (three expert participants), Energy and Communication (one expert participant), Urban and Regional Planning (two expert participants), and Transport (one expert participant). Furthermore, two focus group meetings were conducted with representatives of two directly relevant public institutions, namely the Istanbul Water and Sewerage Administration (ISKI) and Ilbank Inc. (ILBANK). The findings of the aforementioned meetings are presented in the section titled "Model Abstraction" of this paper, while the conclusions regarding the model parameters are outlined in Table 2. It presents only those parameters identified for the categories of drinking water, sewage, and rainwater infrastructure, which fall within the scope of this paper. The parameters predicted to have direct and significant effects on the implementation detail of the model are taken as the basis for further consideration.

Urban Technical Infrastructure Impact Assessment Model Proposal (UTIIA)

Model Abstraction

Before introducing the proposed model, basic related concepts need to be explored. Conceptually, any change that does not contradict main plan decisions, deform plan holisticity, or cause urban infrastructure deficiencies (in the existing plan) could be defined as a "plan amendment" (minor changes in a plan without a major revision). On the other hand, if an external plan decision causes a major negative impact regarding the three above-mentioned threats, "plan revision" (by which a major revision of the whole plan is meant) appears as the major plan instrument.

The main function of the proposed UTIIA model is to orient decision-makers to differentiate planning amendments from planning revisions. To distinguish planning amendments from planning revisions using this model, "tolerance level" must be calculated as the measurable threshold of a planning amendment. In other words, the tolerance level is limited by the carrying capacity of the planned urban technical infrastructure systems. Any plan decision tolerated

Table 2. **Parameters derived from focus group findings**

Infrastructure category	Parameters	
	Direct & Significant	**Indirect & Ignorable**
Drinking Water Infrastructure	Current land-use type, planned land-use type, population density and FAR (Floor Area Ratio) as basic determinants of population	Climate, socio-economic structure, losses and leakages, water consumption per capita, fire flow, emergency needs, type of water distribution (topography, pumping)
Sewage Infrastructure	Current land-use type, planned land-use type, population density and FAR as basic determinants of population	Slope of terrain and road, climate and underground water level, socio-economic structure, size of drainage basin
Rainwater Infrastructure	Size of drainage area, BCR (Building Coverage Ratio), vegetation, ground permeability, slope, population, current land-use type, planned land-use type	Socio-economic structure, distance to the discharge point

by the planned infrastructure capacity could be accepted, while any excessive planning decision implies a plan revision.

The proposed model works in a stepwise manner, and the outline of the steps is presented below (Fig. 3).

Step 1: "Determination of the planned infrastructure capacities" due to population and land use.

Step 2: "Determination of the proposed change in master land-use plan and / or related implementation plan". The main question in this step to answer is: what changes in the holistic (original) plan / plans according to proposal?

Step 3: "Determining technical infrastructure impacts of the proposed changes". Within this step, the proposal's content and technical infrastructure categories are related in terms of predicted impact types (no impact, indirect impact, direct impact).

Step 4: "Calculating impacts of the proposal on each technical infrastructure category in detail". In this step, after the related additional technical infrastructure loads are calculated, a comparison is carried out between the planned capacity and the additional loads to determine whether the carrying capacities are exceeded or whether the planned capacities can tolerate the proposal.

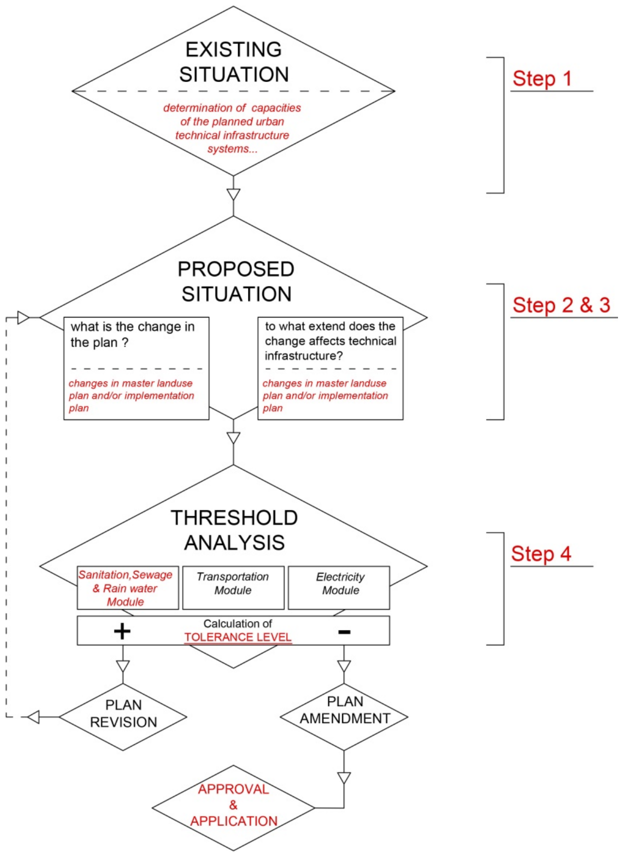


Fig. 3. The Main Structure of the Proposed Model

In the following section, impact calculation details (which are the tools to measure the magnitudes of the impacts) are presented for drinking water, sewage and rainwater systems.

Calculation Details and Components of the Model

While calculating the impacts of a plan proposal on the drinking water system, the evaluation basically depends on an examination of whether the additional load of the proposal remains within the operating time of the existing infrastructure (which is 25 years) or not.

Here, the time to reach total population (T_{tp}) and additional projected population generated by the proposal (A_p) play a pivotal role. Within this evaluation process, the operation start-up year of the existing infrastructure project (*X*), population growth rate and projection method, a 35-year population projection, and the year the plan change was made (*Y*) are needed and should be determined as baseline information. Total population is the sum of the initially projected population (P_p) of the given area for which the drinking water infrastructure was constructed and the additional projected population (A_p) generated by the plan change. Time to reach total population should be calculated according to population growth rate and projection method assumptions given in the national regulations on drinking water and wastewater systems. To decide whether the plan change should be accepted as a "plan revision" or a "plan amendment", the duration calculated by the formula (Y–X) + T_{tp} (see Table 2 for stepwise calculation details) must be compared with the effective operating time (25 years) of the given site's infrastructure. If the calculated duration is more than 25 years, the plan change could be accepted as a plan revision. Otherwise, the given case is a plan amendment where the impact on drinking water is tolerable and no additional public investment is needed (Fig. 4).

Impacts on sewage infrastructure should be evaluated in two main steps. The first step is the same calculation process as that carried out for drinking water infrastructure. The only difference is that the process proceeds to the second step if the calculated duration ((*Y-X*) + Ttp) is found to be less than 25 years (otherwise, the plan proposal is a plan revision). Within the second step, an additional verification emerges to determine whether the sewage channel can tolerate the additional load. To execute this step, the existing fill rate (*He*) and the diameter of the sewage channel (*Dc*) must be known. The fill rate of the sewage channel can be calculated as a function of these components (*Fr = He/Dc*), where 50 % of the channel fill rate is the critical threshold (*Ht*). As a result, if the sewage channel fill rate exceeds 50 %, the case can be

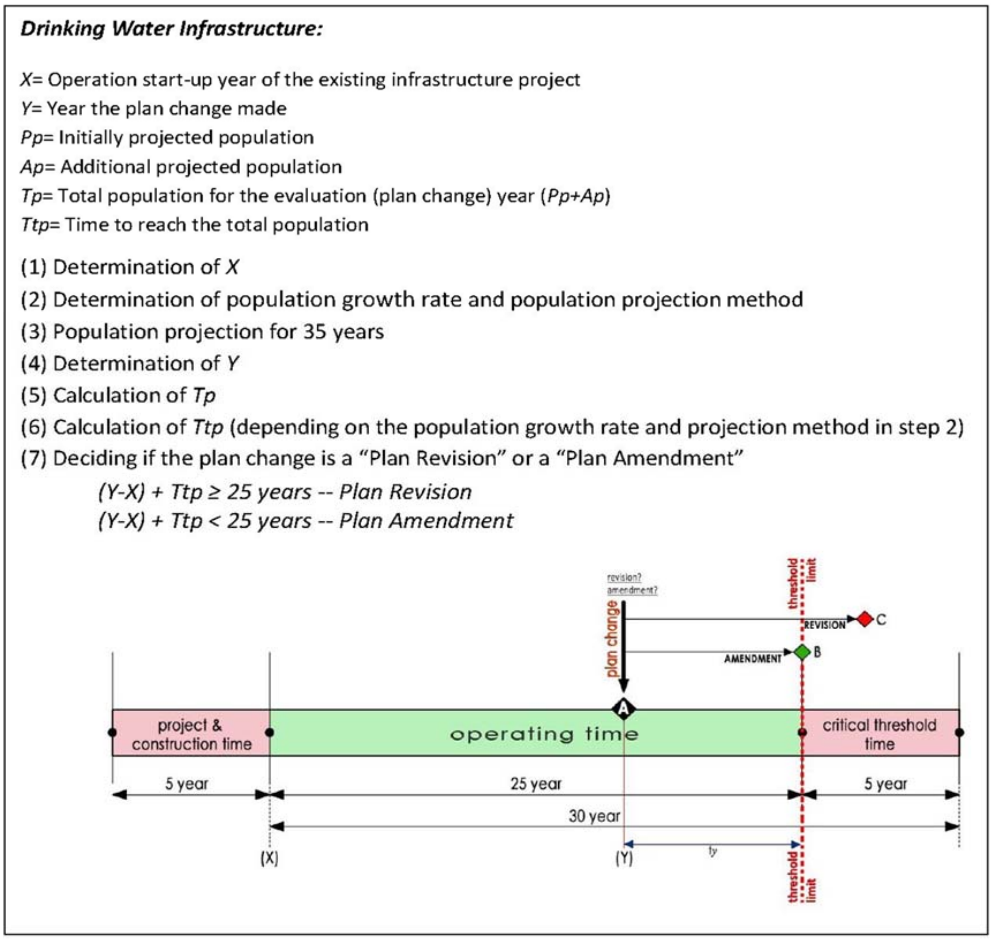


Fig 4. Components and Calculation Details of Impacts on Drinking Water Infrastructure (Adapted from Ağaçcıoğlu et al., 2017)

designated as a plan revision; if not, the given plan proposal is a plan amendment (Fig. 5).

To calculate the infrastructure impacts of a plan proposal on the rainwater system, land-use decisions must be considered to find the average surface run-off coefficient of the urban environment. In the national "Regulation on Rainwater Collection, Storage and Discharge System", surface run-off coefficients are given for different land-use types. The higher these coefficients are, the lesser the additional load on the existing rainwater channel will be. Departing from existing land-use proportions, the average surface run-off coefficient and rainwater flow and fill rate of the rainwater channel, the calculation of the difference generated by the plan proposal on the same components will be performed for the given urban environment. At this point, it is worth mentioning that existing conditions must be determined because it is assumed that not all land-use coverage is changed by the plan proposal. Within this impact evaluation category, the fill rate of the rainwater channel (considering the plan proposal effects) (F_{rr}) is calculated by dividing the existing rainwater level (H_{erl}) by the channel diameter (D_{cr}). The obtained fill rate must be compared with the threshold level (given as 90 % in the same national regulation) to decide whether the plan proposal is a plan revision ($F_{rr} \geq H_{tr}$) or a plan amendment ($F_{rr} < H_{tr}$) (Fig. 6).

As a conclusive remark for this section, it is important to highlight that the proposed UTIIA model works as a stepwise process for each of the three given infrastructure impact categories. In other words, if the plan proposal implies a plan revision for any of the above-mentioned impact assessment categories, then the holistic result should be considered a plan revision by the planning authority.

Discussion and Conclusion

Parallel to neo-liberal critiques, the socio-economic and environmental impacts of urban (renewal) projects and mega-projects have been central discussions in the current urban policy and management literature throughout the last three decades. Starting in the 2000s, the impacts of infrastructure projects and, more recently, impacts on critical infrastructure have also been widely researched issues (Neumann, 2011; Emanuelsson et al., 2014; Pant et al., 2018). Recalling the relevant literature, Batouli and Mostafavi (2017) addressed the sustainability of infrastructure systems using

Sewage Infrastructure:

X= Operation start-up year of the existing infrastructure project
Y= Year the plan change made
Pp= Initially projected population
Ap= Additional projected population
Tp= Total population for the evaluation (plan change) year (*Pp+Ap*)
Ttp= Time to reach the total population
Ht= Threshold fill rate of a channel which is 50% [*]
He= Existent fill rate of a channel
Dc= Diameter of sewage channel
Fr= Fill rate of sewage channel (*He/Dc*)

1sth Step: Verification of Operating Time of the Project

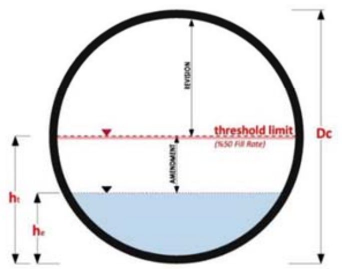
(1) Determination of *X*
(2) Determination of population growth rate [**] and population projection method [*]
(3) Population projection for 35 years
(4) Determination of *Y*
(5) Calculation of *Tp*
(6) Calculation of *Ttp* (depending on the population growth rate and projection method in step 2)
(7) Deciding if the plan change is a "Plan Revision"

(Y-X) + Ttp ≥ 25 years -- Plan Revision
(Y-X) + Ttp < 25 years -- 2^{nd} Step

2nd Step: Verification of Channel Fill Rate

(1) Determination of *He & Dc*
(2) Calculation of *Fr* (*He/Dc*)
(3) Deciding if the plan change is a "Plan Revision" or a "Plan Amendment"

Fr ≥ Ht (50%) -- Plan Revision
Fr < Ht (50%) -- Plan Amendment



[*] see 06 January 2017 dated *"Regulation on Wastewater Collection and Removal Systems"*, Appendix *"1.3.2.1. Future Population"* (https://resmigazete.gov.tr/eskiler/2017/01/20170106-1.htm)
[**] see 12 October 2017 dated *"Regulation on Drinking And Using Water Supply and Distribution Systems"*, Appendix 1 (https://resmigazete.gov.tr/eskiler/2017/10/20171012-1-1.pdf)

Fig. 5. Components and Calculation Details of Impacts over Sewage Infrastructure, (Adapted from Ağaçcıoğlu et al. (2017)

a case study on roads and a model called "Service and Performance Adjusted Life Cycle Assessment" (SPA-LCA). In their literature review on the use of multi-criteria decision-making methods in sustainable infrastructure design, Navarro, Yepes, and Martí (2019) identified several methods, including AHP, TOPSIS, and PROMETHEE. In contrast to the model proposed in this paper, the above-mentioned studies do not emphasize the interconnection between impact assessment and urban renewal. Upon examination of the literature on urban renewal in relation to impact assessment, it becomes evident that studies have been conducted on various aspects, including social impacts (Yung et al., 2015; Glasson and Wood, 2009), impacts on quality of life (Eni and Abua, 2014), health impacts (Bacigalupe et al., 2010), and economic impacts (Bello and Nwosu, 2011). However, there is a paucity of studies on impacts on technical infrastructure.

Filling this gap would also serve to improve the efficiency of public resource use, which plays a pivotal role within the aims of most urban administrative authorities.

Such resource efficiency demands strong integration between infrastructure investments and holistic local-level urban plans. Any uncontrolled intervention in holistic plans would deteriorate the integration and the initially formed (healthy) plan-

Rainwater Infrastructure:

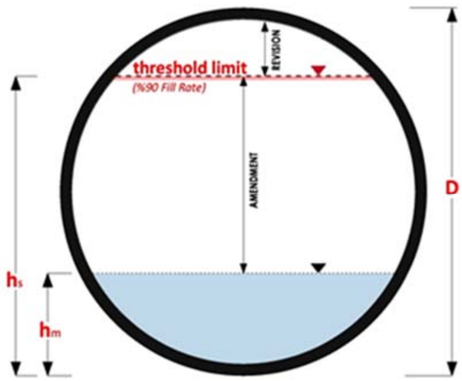
Htr= Threshold fill rate of a rainwater channel which is 90% [*]
Herl= Existent rainwater level of a channel
Dcr= Diameter of rainwater channel
Frr= Fill rate of rainwater channel (*Herl/Dcr*)

(1) Determination of existing landuse proportions
(2) Determination of existing surface run-off coefficient
(3) Determination of existing rainwater flow & fill rate of rainwater channel
(4) Calculation of landuse proportions due to plan change
(5) Calculation of average surface run-off coefficient [*] of the urban environment due to plan change

Landuse Type	*Surface run-off coefficient*
Trade:	
city centre......	*0.70 – 0.95*
subcentre......	*0.50 – 0.70*
Residential:	
single storey residential areas......	*0.30 – 0.50*
multi-storey (detached) residential areas....	*0.40 – 0.60*
multi-storey (row) residential areas......	*0.60 – 0.75*
adjacent areas (including rural zones)......	*0.25 – 0.40*
multi-storey apartment blocks......	*0.50 – 0.70*
Industrial zones:	
Light industry......	*0.50 – 0.80*
Heavy industry......	*0.60 – 0.90*
Parks......	*0.20 – 0.35*
Playfields......	*0.20 – 0.40*
Unbuilt areas......	*0.10 – 0.30*

(6) Determination of rainwater flow & fill rate of rainwater channel due to plan change
(7) Deciding if the plan change is a *"Plan Revision"* or a *"Plan Amendment"*

Frr ≥ *Htr* (90%) -- *Plan Revision*
Frr < *Htr* (90%) -- *Plan Amendment*



[*] see 23 June 2017 dated *"Regulation on Rainwater Collection, Storage and Discharge Systems"*, Appendix 2 (https://resmigazete.gov.tr/eskiler/2017/06/20170623-8.htm)

Fig. 6. Components and Calculation Details of Impacts on Rainwater Infrastructure (Adapted from Ağaçcıoğlu et al., 2017)

infrastructure interdependence, as is frequently seen in Turkish planning practice. Such interventions are mostly observed as a consequence of a project-based partial decision-making process in the Turkish experience. Here, impact assessment could be conceptualized as an ex-ante evaluation tool to understand and measure the impact magnitude of plan decisions (which would otherwise remain uncertain) and to prevent the previously mentioned disintegration problem.

The proposed UTIIA methodology is such a potential tool to measure the impacts of plan changes for most Turkish metropolises where urban renewal, mega-projects, mega-events, etc., are major drivers of uncertainty patches. UTIIA would serve the topics briefly summarized below:

– Strengthening the integration of planning & impact assessment, infrastructure investments & planning decisions, and policy-plan-programme level SEA & project-led EIA;

– Aiding the planning authority to justify plan proposals and decide whether a planning change should be considered a plan revision (which necessitates new infrastructure investment) or a plan amendment (which can be tolerated by existing infrastructure);

– Clarifying how to implement current national regulations on Wastewater Collection and Removal, Drinking and Using Water Supply and Distribution, and Rainwater Collection, Storage and Discharge Systems;

– Understanding the sufficiency of existing urban technical infrastructure in a given area under a plan change probability and improving public resource efficiency through infrastructure investment duration optimization as a preliminary calculation for a more detailed cost-effectiveness examination.

As a result, the proposed UTIIA can be seen and developed as a specialized impact assessment type positioned within the diversifying impact assessment family on the one hand, and a useful decision-making process for a more rational planning practice in the Turkish case on the other.

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МЕТОДОЛОГИЯ ОЦЕНКИ ВОЗДЕЙСТВИЯ НА ГОРОДСКУЮ ТЕХНИЧЕСКУЮ ИНФРАСТРУКТУРУ ПРИ ПРИНЯТИИ ПЛАНИРОВОЧНЫХ РЕШЕНИЙ С УЧЁТОМ ТУРЕЦКОЙ ЗАКОНОДАТЕЛЬНОЙ БАЗЫ

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Аннотация

Введение. Данная статья расположена на пересечении четырёх ключевых теоретических понятий: городское планирование, реновация городской среды, оценка воздействия и техническая инфраструктура. Исследования, направленные на измерение «воздействия на техническую инфраструктуру», встречаются довольно редко и, как правило, фокусируются исключительно на критически важной инфраструктуре национального уровня, игнорируя локальный / городской масштаб. Восполняя этот пробел, **настоящая статья ставит своей целью** предложить методологию оценки воздействия на городскую техническую инфраструктуру (ОВГТИ) для измерения влияния изменяющихся планировочных решений на системы питьевого водоснабжения, канализации и ливневой канализации, а также обращается к проблеме дихотомии решений (является ли планировочное решение корректировкой плана или пересмотром плана), что особенно характерно для практик реновации городской среды в турецком опыте планирования.

Ключевые слова: оценка воздействия на городскую техническую инфраструктуру; реновация городской среды; корректировка плана; пересмотр плана; техническая инфраструктура.

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CREEP OF POLYMER COMPOSITE SHEET PILES WITH A POLYURETHANE MATRIX

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Abstract

Introduction. A progressive method for manufacturing building products from polymer composite materials based on reactive oligomers is the pultrusion method, which allows the production of thin-walled products with an arbitrary profile shape, including sheet piles. The scientific and technical literature contains insufficient information on the creep of glass-filled sheet piles with a polyurethane matrix under different levels and durations of bending loads, which complicates the prediction of the durability of these products. Objective is to establish the dependence of the creep modulus of domestic glass-filled sheet piles with a polyurethane matrix on the magnitude and duration of bending load along and across the pultrusion direction. **Methods:** the creep of glass-filled polyurethane sheet piles was studied using a lever-type test bench developed by the authors. **Results:** the influence of stress level (0.2–0.95 σ_{bend}) and duration of bending load on the deflection magnitude and creep modulus (GOST 57714–2017) of glass-filled polymer sheet piles with a polyurethane matrix along and across the pultrusion direction was studied. It was shown that no failure of the polyurethane composite sheet pile of grade ShK-200UM occurs within 10,000 hours at stress levels of 0.2 and 0.5 σbend. Failure of 50 % of the composite sheet pile samples with a polyurethane matrix at a stress level of 0.7 σbend occurs after 2,638 and 9,434 hours when tested across and along the pultrusion direction, respectively. By extrapolating the experimental “stress-strain” dependencies, the creep of polyurethane composite sheet piles for a period of up to 50 years was predicted.

Keywords: polyurethane sheet pile; pultrusion; deformation; deflection; creep modulus; stress level.

Introduction

One of the progressive methods for manufacturing building products from polymer composite materials (PCM) is the pultrusion method, based on producing composite profile products by pulling reinforcing glass, basalt, or carbon fibers impregnated with a binder based on reactive oligomers (polyester and epoxy oligomers or polyurethanes) through a heated forming die. This method allows the production of building products with stable strength properties both along the length of the product and across their cross-section. The pultrusion method is used to produce thin-walled products with arbitrary profile shapes (rods, pipes, angles, plates, channels, boxes, etc.). The pultrusion method is widely used for the production of both composite reinforcement (Stelanova et al., 2013; Seleznev et al., 2020; Seleznev et al., 2022) and composite sheet piles (Gritsenko and Nesterov 2015; Kokareva et al., 2015; Nemolochnov, 2019; Donetsky et al., 2017).

In the production of polymer composite sheet piles (PCSP), polyurethanes are preferred as the polymer matrix due to their high strength characteristics, wear resistance, chemical resistance, and good adhesion to fillers, while glass fiber is most often used as the fibrous filler. Compared to metal sheet piles, they have high strength and load-bearing capacity, resistance to various aggressive environments and bacteria, low weight, relatively low cost, and are environmentally friendly (Shanmugam, 2004; Levachev et al., 2019; Nemolochnov et al., 2019; Kornev et al., 2025). Some of the first domestic building products made from polymer composites using the pultrusion method were glass-filled polyurethane sheet piles of grades ShK-150UM and ShK-200UM, which have high performance characteristics (Nemolochnov, 2019; Donetsky et al., 2017; Nemolochnov et al., 2019; Kornev et al., 2025). A wide range of sheet pile profiles allows selecting sheet piles for any soil and structural requirements. Sheet pile walls are most often used (Gritsenko and Nesterov, 2015; Kokareva et al., 2015; Nemolochnov, 2019; Nemolochnov and Levachev, 2016; Levachev et al., 2018):

– for strengthening coastlines, canals, and protecting water bodies;

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– in the construction of port (berths, breakwaters, docks) and hydraulic engineering (dams, locks) structures, collectors, tunnels, and other underground structures;

– for constructing anti-filtration curtains on construction sites and protecting building foundations and bases, strengthening and enclosing excavation pits, trenches, slopes, and inclines;

– in the construction of water collectors and treatment facilities, urban improvement, and the creation of artificial reservoirs;

– for organizing sludge storage and storage facilities for chemically active substances.

Significant disadvantages of polymer composite sheet piles include:

– anisotropic properties of the sheet pile material depending on the direction of the applied load (longitudinal or transverse) and the type of load (tension or compression). This applies to both the strength and deformation characteristics of PCSP;

– brittle nature;

– low creep modulus and, consequently, low sheet pile stiffness leading to high deformability of structures;

– a more complex process of driving the sheet pile into the ground compared to metal sheet piles.

The main physical and mechanical characteristics of polymer sheet piles have been examined in considerable detail by domestic (Kokareva et al., 2015; Donetsky et al., 2017; Nemolochnov et al., 2019; Kornev et al., 2025) and foreign (Shanmugam, 2004; Levachev et al., 2019; Giroux and Shayo, 2003; Shao and Shanmugam, 2004; Ferdous et al., 2018) researchers. However, these publications contain practically no data on the actual load-bearing capacity of domestically produced PCMs and data on the creep of composite sheet piles under different levels and durations of bending loads. This limits the use of composite sheet piles in the construction industry and, in particular, in hydraulic engineering construction. Therefore, the aim of this work was to establish the dependence of the creep modulus of polyurethane glass-filled sheet piles on the magnitude and duration of bending load along and across the pultrusion direction.

Subject, Tasks and Methods

The objects of study were glass-filled PCSPs with a polyurethane matrix of grades ShK-150UM and ShK-200UM, the layout of individual elements of which is shown in Figs. 1 and 2. Samples of glass-filled polyurethane sheet piles obtained by pultrusion were provided by the company “Umatex”. The main dimensions and operational characteristics of a single element of the studied sheet piles with a polyurethane matrix are given below:

ShK-150UM / ShK-200UM:
Section width, mm — 600 / 400;
Section height, mm — 145 / 200;
Section thickness, mm — 6 / 8;
Cross-sectional area of the pile, cm² — 61.6 / 58.6;
Permissible bending moment, kNm/m — 98 / 225;
Section modulus, cm³/m — 429 / 937;
Tensile breaking stress, MPa:
along the pultrusion direction — 770 / 770;
across the pultrusion direction — 150 / 150;
Tensile modulus of elasticity, GPa:
along the pultrusion direction — 33.4 / 33.4;
across the pultrusion direction — 14.1 / 14.1.

The creep of the polyurethane composite sheet pile of grade ShK-150UM was studied at stress levels from 0.21 to 0.95 σ_{bend} and a bending load duration of up to 3000 hours, and for the sheet pile of grade ShK-200UM — at stress levels of 0.2, 0.5, and 0.7 σ_{bend} and a load duration of up to 10,000 hours. The creep of glass-filled polyurethane sheet piles was determined using a lever-type test bench under three-point bending (Fig. 3) in accordance with the requirements of GOST R 57714–2017. Samples for creep testing of glass-filled polyurethane sheet piles along and across the pultrusion direction were obtained in accordance with the requirements of GOST R 56810–2015. For each given stress level, 12 PCM samples were tested.

The method for determining the creep of composite sheet piles is based on studying the deflections of PCSP samples measuring 120×12×7 mm as a function of the duration of a constant bending load at a given temperature and ambient humidity. The distance between supports was 100 mm. To measure

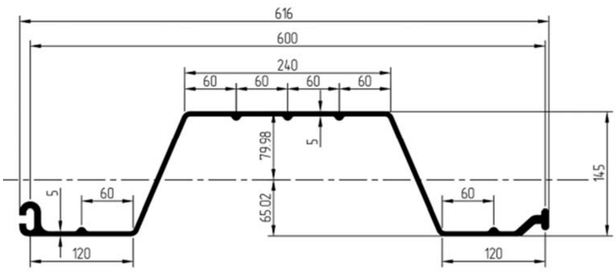

Fig. 1. Cross-section of an individual element of a composite sheet pile of channel profile, grade ShK-150UM

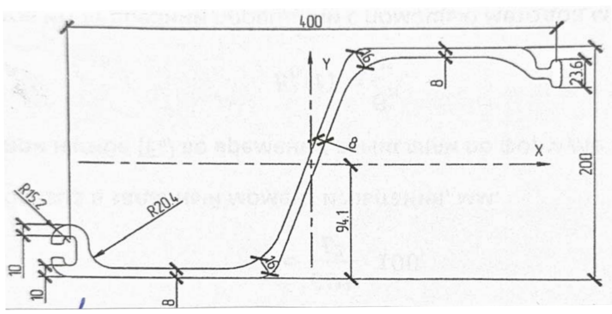

Fig. 2. Layout of an individual element of a composite glass-filled sheet pile with a polyurethane matrix, grade ShK-200UM

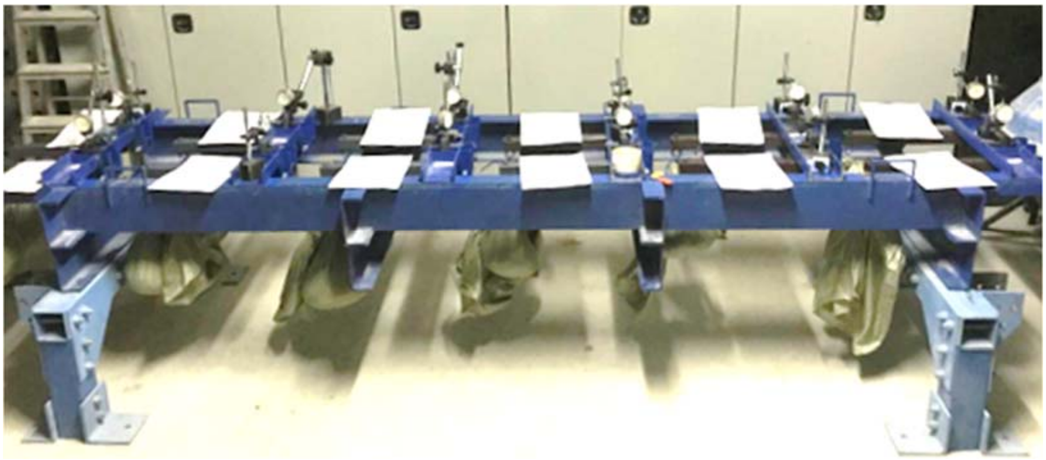

Fig. 3. Lever-type test bench for studying the creep of composite sheet piles

the deflections of the composite sheet pile, IC-50 dial indicators with a division value of 0.01 mm were used. Tests of glass-filled composite sheet piles with a polyurethane matrix were conducted on samples cut along and across the pultrusion direction of the sheet pile. Deflections of the composite sheet piles were measured at 1, 6, 12, and 30 minutes, and 1, 2, 5, 20, 50, 100, 200, 500, 700, 1000, 2000, 3000, 5000, and 10,000 hours after load application. The bending stress (σ_{bend}, MPa) was calculated using Formula 1:

$$\sigma_{\text{bend}} = \frac{3FL}{2bd^2}, \quad (1)$$

where:

L — distance between support centers, mm;

b — sample width, mm;

d — sample thickness, mm.

The relative strain of the extreme fibers of the composite sheet pile sample during bending (r, %) as a function of load duration (t) was calculated using Formula 2:

$$r = \frac{6Db}{L^2}100, \quad (2)$$

where D — sample deflection at a given test time, mm.

The bending creep modulus of the composite sheet pile (E_n, MPa) for a bending load duration of t hours was calculated using Formula 3:

$$E_n(t) = \frac{\sigma_{\text{bend}}}{r}. \quad (3)$$

The experimental results were processed using statistical methods in accordance with the recommendations of GOST R 50779.22–2005 (ISO 2602:1980).

Research Results and Discussion

The results of determining the relative strains of the extreme fibers and the creep modulus of the glass-filled polyurethane sheet pile of grade ShK-150UM along and across the pultrusion direction at bending stress levels from 0.21 to 0.95 σ_{bend} are given in Tables 1 and 2, and the isochronous graphical dependencies are shown in Figs. 4 and 5. Using interpolation methods, the bending stresses in the sheet pile along and across the pultrusion direction were calculated as a function of a relative strain of the extreme fibers equal to 1 % under

Table 1. **Bending creep of polyurethane sheet pile grade ShK-150UM along the pultrusion direction**

Relative stress level at bending, %	Time (hours)											
	0.1		1		10		100		1000		3000	
	***r*, %**	***E*, MPa**	***r*, %**	***E*, MPa**	***r*, %**	***E*, MPa**	***r*, %**	***E*, MPa**	***r*, %**	***E*, MPa**	***r*, %**	***E*, MPa**
0.21	0.68	26881	0.69	26270	0.71	25687	0.73	24857	0.77	23832	0.79	23334
0.28	0.91	27468	0.93	27006	0.95	26344	0.98	25506	1.02	24439	1.04	24161
0.41	1.22	29717	1.27	28554	1.30	28049	1.34	27163	1.41	25901	1.44	25218
0.57	1.64	30732	1.69	29894	1.72	28884	1.81	27867	1.91	26465	1.98	25516
0.65	1.63	34958	1.64	34710	1.65	34307	1.69	33601	1.76	32346	1.80	31588
0.76	2.41	27876	2.48	27131	2.53	26571	2.62	25640	2.74	24511	2.77	24251
0.85	3.21	23187	3.29	22640	–	–	–	–	–	–	–	–
0.95	2.97	28130	–	–	–	–	–	–	–	–	–	–

Note: Maximum bending stress along the pultrusion direction is taken as 880 MPa; *r* is relative strain of extreme fibers during bending; *E(t)* is bending creep modulus at time *t*.

Table 2. **Bending creep of polyurethane sheet pile grade ShK-150UM across the pultrusion direction**

Relative stress level at bending, %	Time (hours)											
	0.1		1		10		100		1000		3000	
	r, %	*E*, MPa	*r*, %	*E*, MPa	*r*, %	*E*, MPa	*r*, %	*E*, MPa	*r*, %	*E*, MPa	*r*, %	*E*, MPa
0.22	0.35	24060	0.37	23275	0.37	22097	0.42	20201	0.46	18620	0.47	17998
0.35	0.64	21777	0.66	20864	0.70	19916	0.73	18936	0.77	17868	0.79	17455
0.46	0.84	21461	0.87	20775	0.92	19746	0.98	18495	1.06	17072	1.09	16615
0.59	1.05	22012	1.07	21603	1.09	20869	1.15	20038	1.21	19115	1.23	18806
0.65	1.28	19864	1.34	18977	1.37	18222	1.46	17422	1.54	16519	1.57	16207
0.82	2.45	13034	–	–	–	–	–	–	–	–	–	–
0.93	2.59	13996	–	–	–	–	–	–	–	–	–	–

Note: Maximum bending stress across the pultrusion direction is taken as 390 MPa; *r* is relative strain of extreme fibers during bending; *E*(*t*) is bending creep modulus at time *t*.

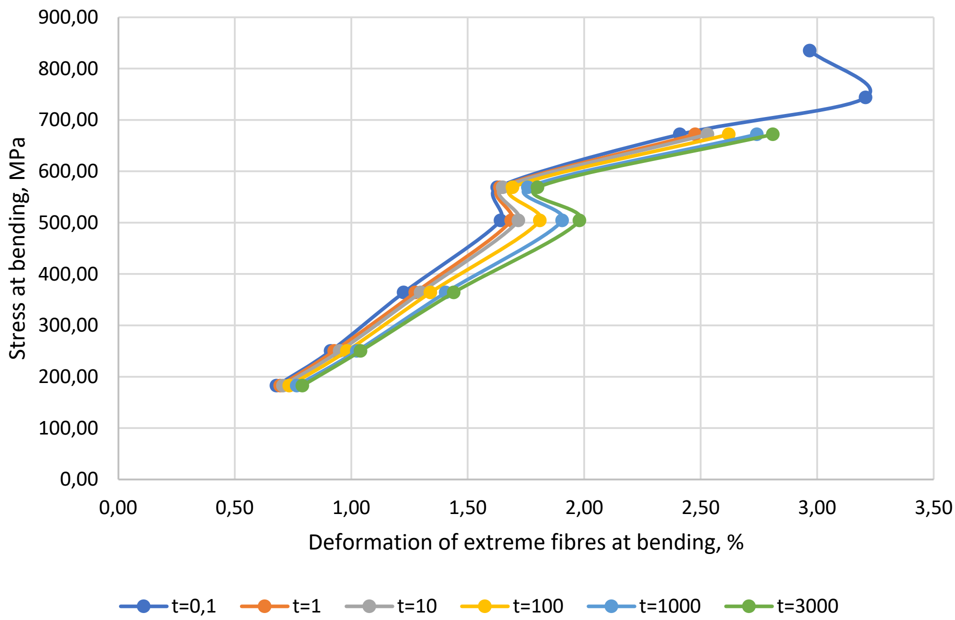

Fig. 4. Isochronous “stress-strain” curves of composite sheet pile ShK-150UM along the pultrusion direction under different durations of bending load

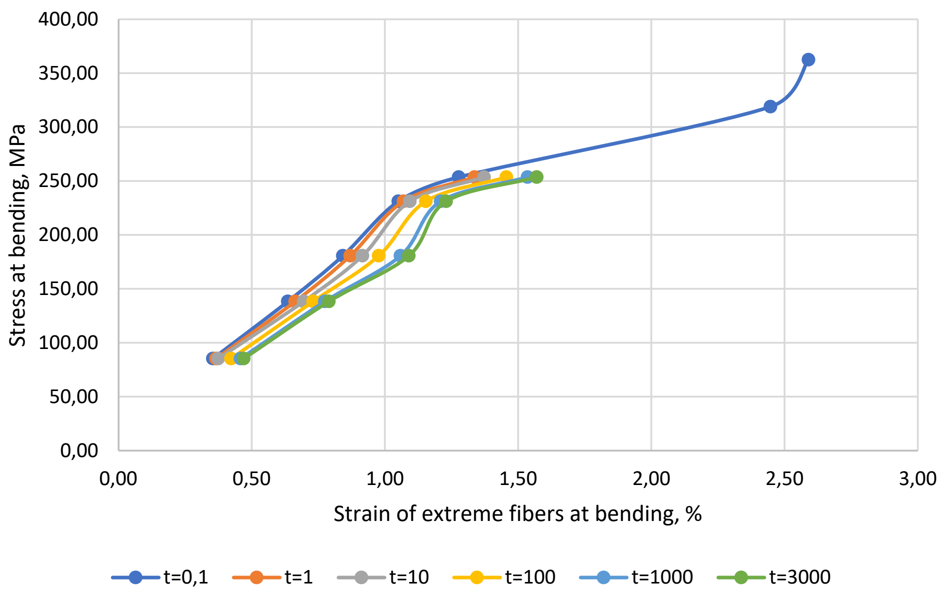

Fig. 5. Isochronous “stress-strain” curves of composite sheet pile ShK-150UM across the pultrusion direction under different durations of bending load

a bending load for 1000 hours. These stresses along and across the pultrusion direction of the glass-filled polyurethane sheet pile of grade ShK-150UM are 244 and 172 MPa, respectively.

The creep of glass-filled polyurethane sheet piles was studied in more detail using the example of the grade ShK-200UM sheet pile. The deflections, limiting strains of the extreme fibers, and creep modulus of the glass-filled composite sheet pile with a polyurethane matrix of grade ShK-200UM along and across the pultrusion direction as a function of bending load duration at stress levels of 0.2, 0.5, and 0.7 σ_{bend} are given in Tables 3 and 4 and Figs. 6–8. The stress levels during PCSP testing corresponded to bending stresses of 176, 440, and 616 MPa along, and 78, 195, and 273 MPa across the pultrusion direction of the sheet pile.

Based on the experimental data presented in Tables 3 and 4, dependencies of the relative strains of the extreme fibers (Fig. 7) and the bending creep modulus (Fig. 8) of the glass-filled polyurethane sheet pile along and across the pultrusion direction at stress levels of 0.2, 0.5, and 0.7 σ_{bend} were plotted in logarithmic coordinates. The dependencies of the relative strains of the extreme fibers during bending of the polyurethane sheet pile on the duration of the bending load can be represented as third-degree polynomials:

− along the pultrusion direction:

- at stress level 0.2 σ_{bend}:

$y = 0.0007x^3 + 0.0004x^2 + 0.0088x - 0.1427$;

- at stress level 0.5 σ_{bend}:

$y = 0.0007x^3 + 0.0004x^2 + 0.0058x + 0.2077$;

- at stress level 0.7 σ_{bend}:

$y = 0.0011x^3 + 0.0012x^2 + 0.0027x + 0.3257$;

– across the pultrusion direction:

- at stress level 0.2 σ_{bend}:

$y = 0.0004x^3 + 0.0015x^2 + 0.0183x - 0.38$;

- at stress level 0.5 σ_{bend}:

$y = 0.0008x^3 + 0.0007x^2 + 0.0093x + 0.0354$;

- at stress level 0.7 σ_{bend}:

$y = 0.0004x^3 + 0.0031x^2 + 0.0146x + 0.1844$,

where *y* is the logarithm of the strains of the extreme fibers of the polyurethane sheet pile;

x is the logarithm of the duration of the bending load.

The dependence of the creep modulus of the glass-filled composite sheet pile with a polyurethane

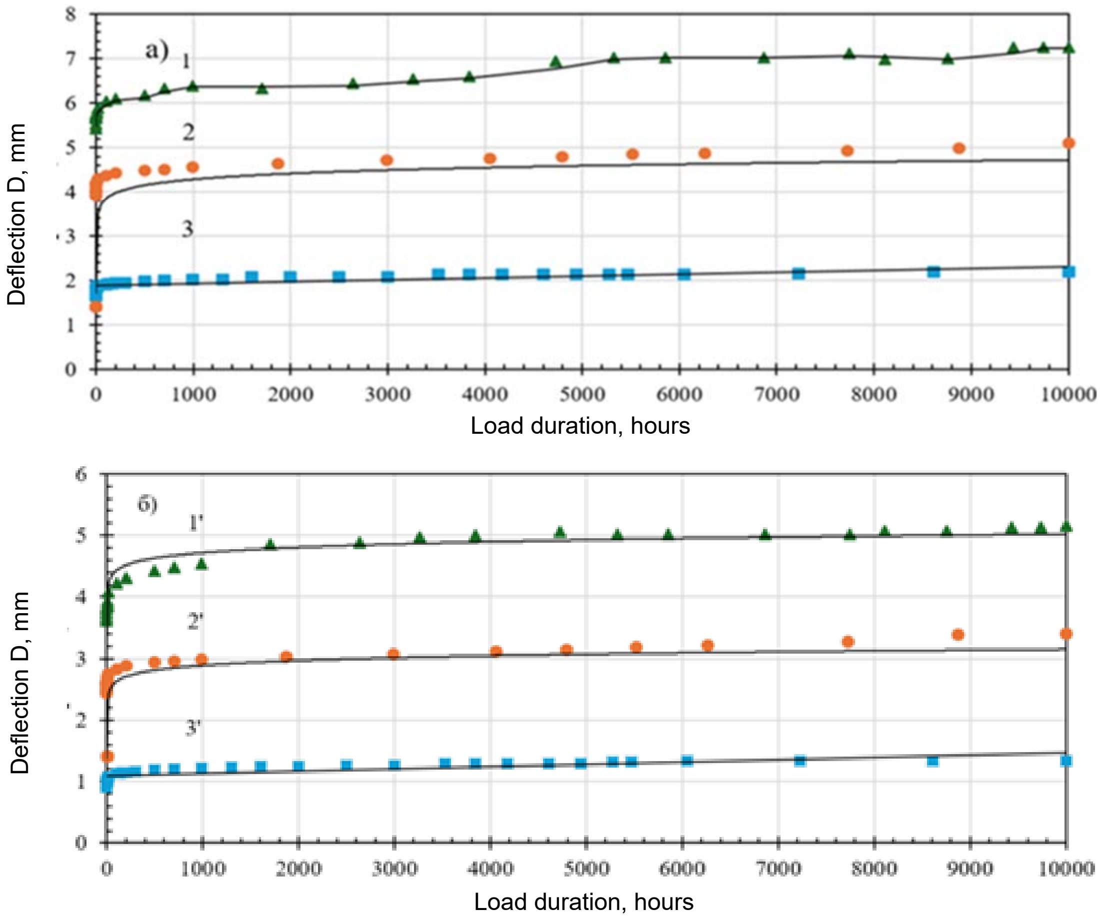

Fig. 6. Dependencies of the deflection magnitude of composite sheet pile grade ShK-200UM along (a) and across (b) the pultrusion direction on the duration of bending load: 1, 1' — at stress level 0.2 σ_{bend}; 2, 2' — at stress level 0.5 σ_{bend}; 3, 3' — at stress level 0.7 σ_{bend}.

Table 3. **Deflection magnitudes, strains, and creep modulus of glass-filled sheet pile with polyurethane matrix at stress levels of 0.2 and 0.5 $σ_{bend}$**

Load duration *t*, hours	Along the pultrusion direction			Across the pultrusion direction		
	Deflection, mm	Strain, %	Creep modulus, MPa	Deflection, mm	Strain, %	Creep modulus, MPa
0.02	1.73/3.99	0.69/1.55	25555/28629	0.96/2.49	0.39/1.03	19829/19035
0.1	1.76/4.06	0.71/1.58	25036/28158	0.97/2.56	0.40/1.06	19494/18556
0.2	1.77/4.13	0.71/1.61	24902/27549	0.98/2.59	0.41/1.07	19325/18352
0.5	1.79/4.15	0.72/1.62	24680/27415	1.00/2.61	0.41/1.08	19012/18190
1.0	1.80/4.17	0.72/1.62	24518/27302	1.01/2.64	0.42/1.09	18827/17977
2	1.82/4.19	0.73/1.63	24302/27151	1.02/2.66	0.42/1.10	18581/17844
5	1.83/4.23	0.73/1.65	24113/26921	1.04/2.71	0.43/1.12	18245/17507
20	1.86/4.28	0.75/1.67	23754/26619	1.08/2.75	0.45/1.14	17600/17268
100	1.91/4.36	0.77/1.70	23133/26105	1.13/2.83	0.47/1.17	16813/16818
200	1.94/4.42	0.78/1.72	22837/25791	1.16/2.88	0.48/1.19	16421/16545
500	1.96/4.49	0.79/1.75	22512/25396	1.19/2.94	0.49/1.21	16007/16187
700	1.98/4.51	0.80/1.76	22282/25276	1.20/2.96	0.50/1.22	15763/16068
1000	2.00/4.54	0.80/1.77	22099/25132	1.22/2.98	0.50/1.23	15544/15959
2000	2.08/4.64	0.83/1.81	21368/24566	1.25/3.03	0.52/1.25	15168/15684
5000	2.12/4.80	0.85/1.87	20926/23806	1.29/3.15	0.53/1.30	14667/15105
10000	2.20/5.08	0.88/1.98	20104/22543	1.34/3.40	0.55/1.40	14160/13992

Note — The numerator shows the values of deflection, strain, and creep modulus of the PCS (polymer composite sheet) at a stress level of 0.2 $σ_{bend}$, and the denominator shows the values at a stress level of 0.5 $σ_{bend.}$

Table 4. **Deflection magnitudes, strains, and creep modulus of glass-filled sheet pile with polyurethane matrix at stress level 0.7 $σ_{bend}$**

Load duration *t*, hours	Along the pultrusion direction			Across the pultrusion direction		
	Deflection, mm	Strain, %	Creep modulus, MPa	Deflection, mm	Strain, %	Creep modulus, MPa
0.02	5.43	2.03	30567	3.62	1.45	18992
0.1	5.53	2.06	30025	3.67	1.47	18727
0.2	5.63	2.10	29484	3.75	1.50	18333
0.5	5.68	2.12	29228	3.83	1.53	17979
1.0	5.72	2.13	29029	3.85	1.54	17861
2	5.74	214	28924	3.88	1.56	17718
5	5.77	2.15	28776	3.94	1.58	17411
20	5.87	2.19	28294	4.08	1.63	16818
100	6.02	2.24	27629	4.22	1.69	16214
200	6.10	2.27	27262	4.31	1.73	15920
500	6.17	2.30	26935	4.42	1.77	15519
700	6.33	2.36	26314	4.49	1.80	15285
1000	6.40	2.38	26074	4.55	1.82	15053
2000	6.34	2.36	26196	4.86	1.95	14087
5000	6.95	2.59	23821	5.06	2.02	13528
10000	7.25	2.71	22895	5.14	2.07	13213

matrix on the duration of the bending load can be represented by the following equations:

− along the pultrusion direction:

- at stress level 0.2 $σ_{bend}$:
  $z = 4.3881 – 0.0007x^3 – 0.0004x^2 – 0.0088x$; $R^2 = 0.9951$;
- at stress level 0.5 $σ_{bend}$:
  $z = 4.4358 – 0.0007x^3 – 0.0004x^2 – 0.0058x$; $R^2 = 0.9915$;
- at stress level 0.7 $σ_{bend}$:
  $z = 4.4639 – 0.0011x^3 – 0.0012x^2 – 0.0027x$; $R^2 = 0.975$;

– across the pultrusion direction:

- at stress level 0.2 $σ_{bend}$:
  $z = 4.272 – 0.0004x^3 – 0.0015x^2 – 0.0183x$; $R^2 = 0.9977$;
- at stress level 0.5 $σ_{bend}$:
  $z = 4.2546 – 0.0008x^3 – 0.0007x^2 – 0.0093x$; $R^2 = 0.9864$;
- at stress level 0.7 $σ_{bend}$:
  $z = 4.2518 – 0.0004x^3 – 0.0031x^2 – 0.0146x$; $R^2 = 0.9929$,

where *z* is the logarithm of the creep modulus of the composite sheet pile;

x is the logarithm of the duration of the bending load.

The dependence of the bending stresses of the polyurethane sheet pile grade ShK-200UM along and across the pultrusion direction on the relative strains of the extreme fibers is shown in Fig. 9. From Fig. 9, it follows that at stress levels of 0.2 and 0.5 $σ_{bend}$, failure of the glass-filled polyurethane sheet pile along and across the pultrusion direction does not occur during testing for 10,000 hours. At the same time, at a stress level of 0.7 $σ_{bend}$, failure of 50 % of the studied sheet pile samples occurs after 2,638 and 9,434 hours when tested across and along the pultrusion direction, respectively, and failure of the first

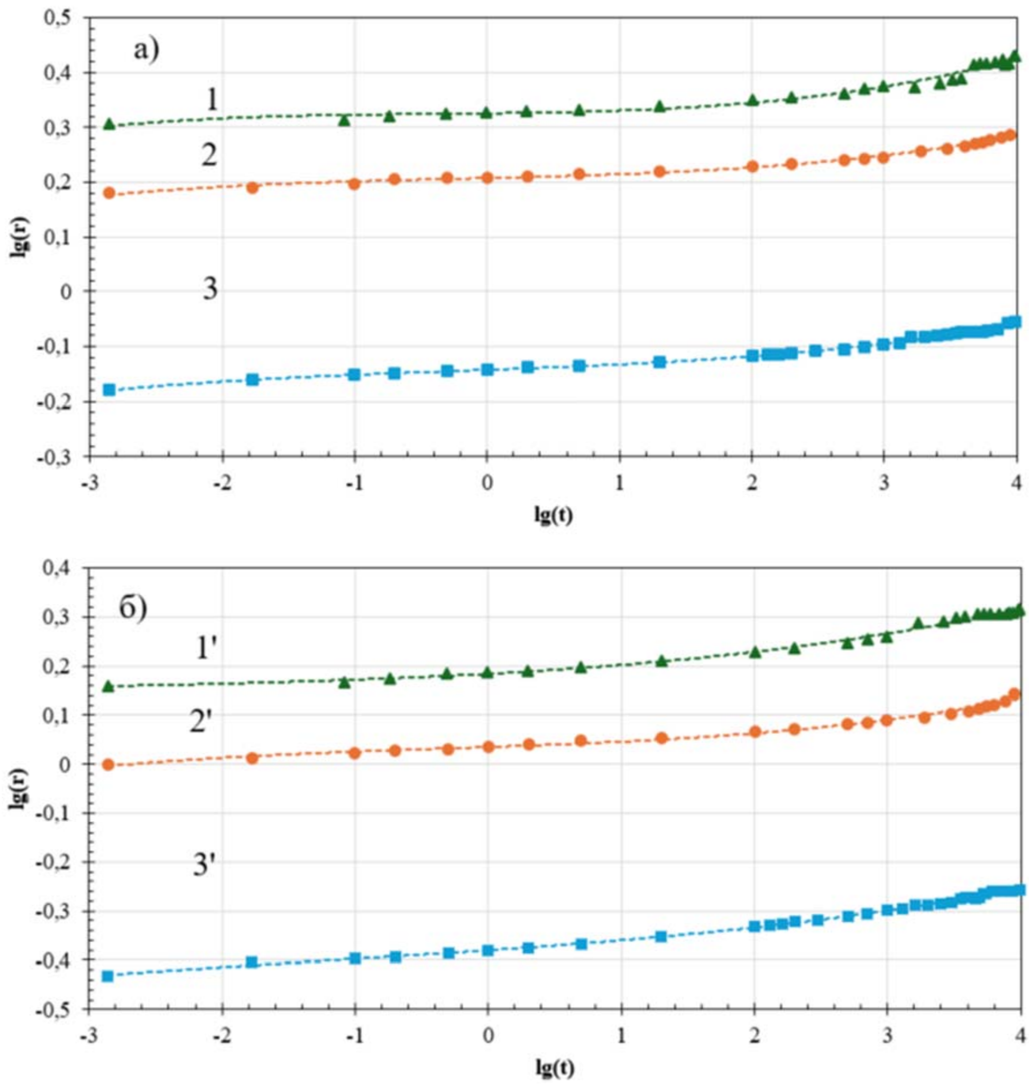

Fig. 7. Dependencies of the logarithm of the relative strains of the extreme fibers of the glass-filled composite sheet pile with polyurethane matrix during bending along (a) and across (b) the pultrusion direction on the logarithm of the bending load duration: 1, 1' — at stress level 0.7 $σ_{bend}$; 2, 2' — at stress level 0.5 $σ_{bend}$; 3, 3' — at stress level 0.2 $σ_{bend}$

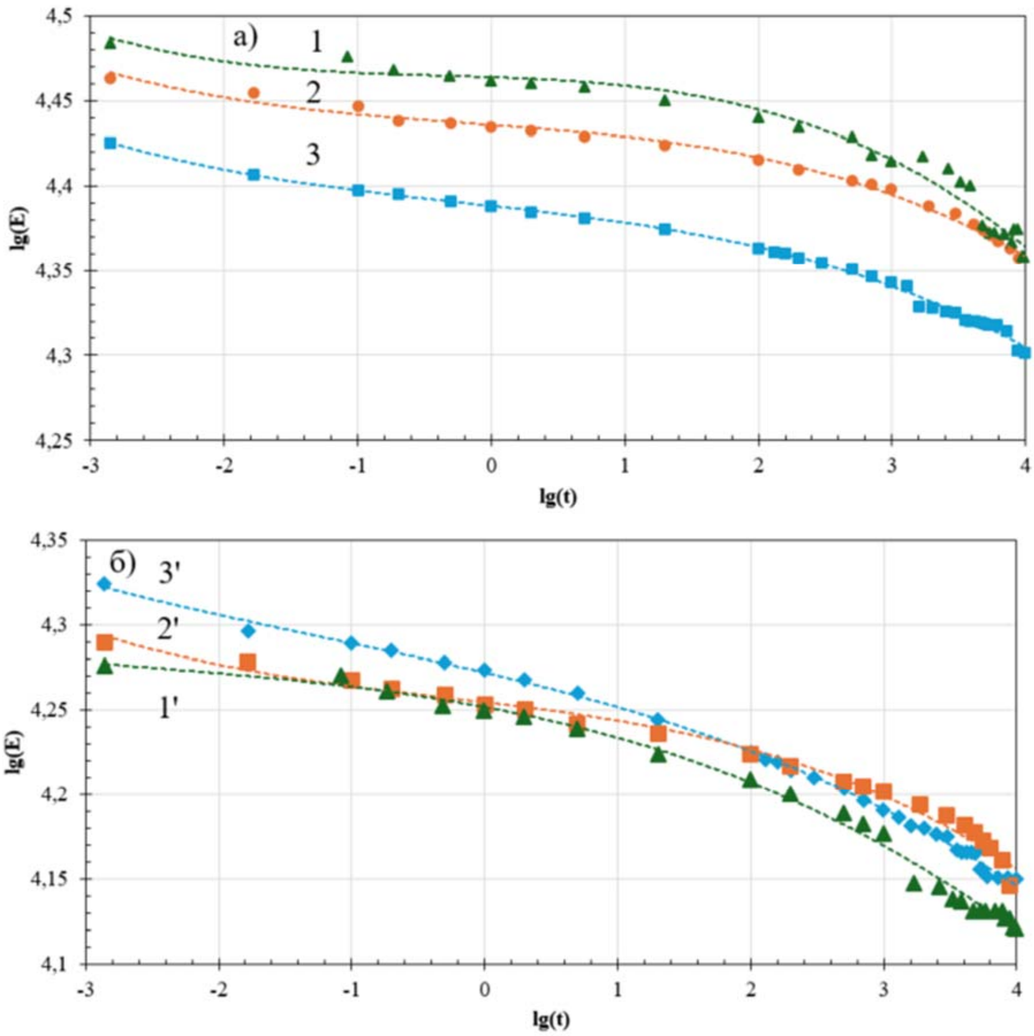

Fig. 8. Dependencies of the logarithm of the creep modulus of the glass-filled composite sheet pile with polyurethane matrix along (a) and across (b) the pultrusion direction on the logarithm of the bending load duration: 1, 1' — at stress level 0.7 σ_{bend}; 2, 2' — at stress level 0.5 σ_{bend}; 3, 3' — at stress level 0.2 σ_{bend}

sheet pile samples occurs after 1,702 and 200 hours, respectively. In accordance with the requirements of GOST R 57714–2017, the stresses at a relative strain of the extreme fibers during bending equal to 1 % under a bending load for 1,000 hours were calculated. The calculated stress values along and across the pultrusion direction are 253 and 153 MPa, respectively, which corresponds to 30 % and 40 % of the bending strength of the composite sheet pile. It should be noted that for the polyurethane sheet pile of grade ShK-200UM, the stress under bending loads along the pultrusion direction is 3.7 % higher, and the stress across the pultrusion direction is 12.4 % lower than for the PCSP of grade ShK-150UM.

It should be noted that approximating the dependencies of the relative strains of the extreme fibers and the creep modulus of the glass-filled composite sheet pile with a polyurethane matrix by linear functions is only possible in the steady-state creep region:

- at a stress level of 0.2 σ_{bend} — up to 5,631 hours;
- at a stress level of 0.5 σ_{bend} — up to 2,615 hours;
- at a stress level of 0.7 σ_{bend} — up to 604 hours.

A sufficiently accurate approximation of these values is achieved using third-degree polynomials. Extrapolating the obtained values to a period of up to 50 years (438,000 hours), additional "stress-strain" isochrones were constructed for 100,000 hours and 438,000 hours (Fig. 9, curves 7 and 8). The limiting strain under long-term loading was taken as the strain values of the extreme fibers that do not lead to failure, determined as the lower bound of the one-sided confidence interval with a probability of 0.95 according to GOST 50779.22–2005. The stresses leading to failure of the studied glass-filled sheet pile material with a polyurethane matrix under a load duration of 50 years, calculated from the isochronous curves based on extrapolation data, are 465 and 189 MPa for the longitudinal and transverse pultrusion directions, respectively,

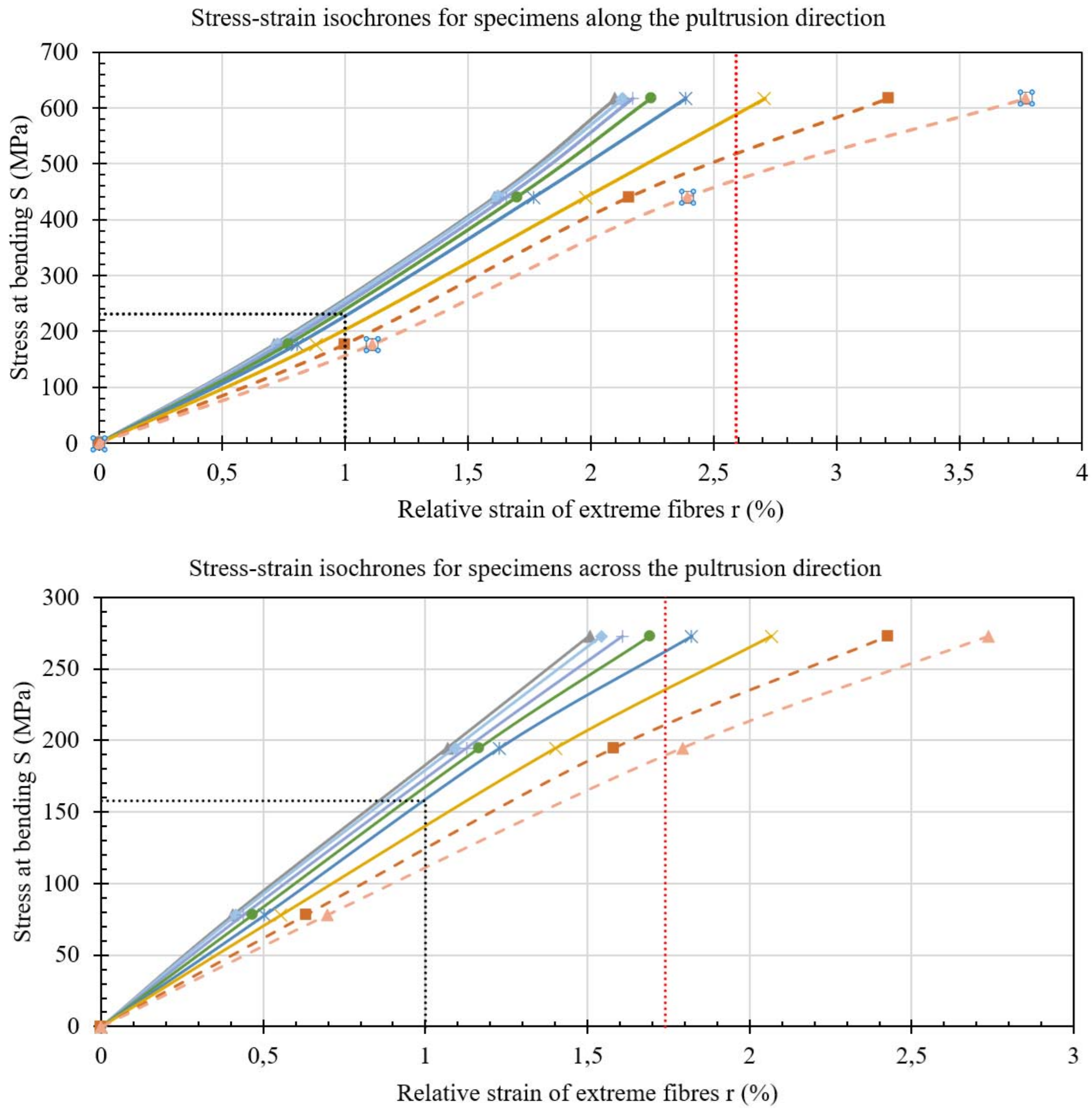

Fig. 9. Dependencies of the bending stress of the glass-filled composite sheet pile with polyurethane matrix along (a) and across (b) the pultrusion direction on the relative strain of the extreme fibers at: 1–10 min; 2–1 hour; 3–10 hours; 4–100 hours; 5–1,000 hours; 6–10,000 hours; 7–100,000 hours; 8–438,000 hours

which corresponds to 53 % and 49 % of the bending strength of the composite sheet pile.

Conclusions

As a result of the performed experimental studies, the influence of the stress level and duration of the bending load on the creep parameters of glass-filled composite sheet piles with a polyurethane matrix along and across the pultrusion direction was established. It was calculated that the stresses in the studied glass-filled PCSPs under a bending load for 1000 hours and a relative strain of the extreme fibers equal to 1 % are, along and across the pultrusion direction for sheet piles of grades ShK-150UM and ShK-200UM, 244 MPa, 172 MPa, and 253 MPa, respectively. These stresses in the glass-filled polyurethane sheet pile of grade ShK-200UM across and along the pultrusion direction occur at 30 % and 40 % of the bending strength of the PCSP, respectively. It was shown that failure of the polyurethane sheet pile of grade ShK-200UM does not occur within 10,000 hours at stress levels of 0.2 and 0.5 σ_{bend}. Failure of this sheet pile at a stress level of 0.7 σ_{bend} occurs after 2,538 and 9,434 hours when tested across and along the pultrusion direction, respectively, during PCSP production. By extrapolating the experimental “stress-strain” dependencies, the stress leading to failure of ShK-200UM under a bending load duration of 50 years was calculated: for the longitudinal and transverse pultrusion directions, the breaking stresses are 465 and 189 MPa, respectively, which corresponds to 53 % and 49 % of the bending strength of the composite sheet pile.

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ПОЛЗУЧЕСТЬ ПОЛИМЕРНЫХ КОМПОЗИТНЫХ ШПУНТОВ С ПОЛИУРЕТАНОВОЙ МАТРИЦЕЙ

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Аннотация
Введение. Прогрессивным методом производства строительных изделий из полимерных композитных материалов на основе реакционноспособных олигомеров является метод пултрузии, позволяющий производить тонкостенные изделия с профилем произвольной формы, в том числе шпунтовые сваи. В научно-технической литературе недостаточно сведений о ползучести стеклонаполненных шпунтов с полиуретановой матрицей при различном уровне и продолжительности воздействия изгибающих нагрузок, что затрудняет прогнозирование долговечности указанных изделий. **Цель исследования:** установление зависимости модуля ползучести отечественных стеклонаполненных шпунтов с полиуретановой матрицей от величины и продолжительный воздействия изгибающей нагрузки вдоль и поперек направления пултрузии. **Методы:** ползучесть стеклонаполненных полиуретановых шпунтов исследовали с помощью испытательного стенда рычажного типа, разработанного авторами. **Результаты:** изучено влияние уровня напряжений (0,2–0,95 $б_{изг}$) и продолжительность воздействия изгибающей нагрузки на величину прогиба и модуль ползучести (ГОСТ 57714–2017) стеклонаполненных полимерных шпунтов с полиуретановой матрицей вдоль и поперек направления пултрузии. Показано, что разрушения полиуретанового композитного шпунта марки ШК-200УМ в течение 10000 часов при уровне напряжений 0,2 и 0,5 $б_{изг}$ не наблюдается. Разрушение 50 % образцов композитного шпунта с полиуретановой матрицей при уровне напряжений 0,7 $б_{изг}$ происходит через 2638 и 9434 часа при испытании соответственно поперек и вдоль направления пултрузии изготовления шпунта. Экстраполяцией экспериментальных зависимостей «напряжение–деформация» спрогнозирована ползучесть полиуретановых композитных шпунтов на период до 50 лет.

Ключевые слова: полиуретановый шпунт; пултрузия; деформация; прогиб; модуль ползучести; уровень напряжений.

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HEAT-EFFICIENT SOLUTIONS FOR WALL-BASEMENT SLAB CONNECTIONS IN LIGHTWEIGHT STEEL-FRAMED CONSTRUCTIONS FOR ARCTIC REGIONS

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Abstract

Introduction: In Arctic regions, due to the scattered layout of settlements across vast territories and low population density, combined with logistical and transport difficulties, one of the promising technologies is the construction of rapidly erected buildings based on lightweight steel-framed (LSF) constructions. Thermal protection of such buildings in climatic conditions with design outdoor air temperatures of −44 °C to −58 °C is a relevant and complex challenge, especially due to the presence of thermal bridges in the form of steel profiles. Operational experience with LSF buildings on pile foundations shows that the main problems arise on the ground floor where a ventilated crawl space is used to preserve frozen soil. **Objective**: Development of heat-efficient solutions for wall-basement slab connections in LSF buildings for Arctic regions with extreme climatic conditions. **Methods:** To reduce the impact of thermal bridges in the form of steel profiles at the wall-basement slab connection, the use of thermal break (TB) beams is proposed. Numerical simulations of 3D models of different types of wall-basement slab connections were conducted using the certified HEAT 3 software. The results were compared with typical structures based on minimum interior surface temperature, heat losses, and effective thermal resistance. **Results:** As a result of implementing the new design, the influence of thermal bridges was minimized by shifting the steel profiles into the warm zone, creating a thermal break using beams, and maintaining the continuity of the building's thermal envelope. At an outdoor temperature of −55 °C, the minimum interior surface temperature in the wall-basement slab connections, unlike in typical solutions, exceeds the dew point. Compared to standard solutions, reduced thermal resistance of the external wall-basement slab connection were increased by 8.1 %, and the partition wall-basement slab connection — by 15.4 %.

Keywords: thermal bridge; lightweight steel-framed (LSF) constructions; thermal break; wall-basement slab connection; thermal resistance.

Introduction

The Arctic zone of the Russian Federation is characterized by a high proportion of dilapidated housing and a low level of infrastructure in populated areas (Polovinkin and Fomichev, 2013; Kornilov et al., 2023). For example, in the Arctic regions of Yakutia, 31.7 % of the total housing stock has a deterioration rate of over 65 %. Moreover, the housing stock mainly consists of wooden beam and log houses — 72.67 % of the total (Kornilov et al., 2023). Meanwhile, it is known that thermal energy losses through external enclosing structures are the main ones and account for more than 50 % in the structure of the building's thermal energy costs for heating during the heating period (Vatin et al., 2012; Gorshkov, 2010). Considering these circumstances, the development of the Arctic zone of the Russian Federation and its extreme natural and climatic conditions requires the creation of a comfortable living environment in Arctic settlements. The advancement of construction and the introduction of innovative technologies for house-building are essential conditions for improving the quality of life in Arctic territories and, accordingly, for the effective development of the Arctic. Construction methods must be adapted to the specific features of Arctic settlements: the vast distances between communities, low population density, difficult logistics and transport infrastructure, short building seasons, and the lack of a local construction industry and qualified builders. Under such conditions, one of the most promising approaches for Arctic regions, recognized internationally (Rodrigues et al., 2018; Liang et al., 2022; Santos, 2017), is the construction of low-rise buildings using lightweight steel-framed (LSF) constructions.

The structural basis of LSF technology includes cold-formed steel profiles with open or closed cross-sections, including perforated thin-walled profiles (thermal profiles) with thicknesses up to 3 mm designed to improve thermal performance. The structural solutions of LSF fully align with the concept of dry construction and frame housing. Many researchers (Santos, 2017; Moga et al., 2022; Anpilov et al., 2024; Soares et al., 2014; Soares et al., 2017) note the advantages of LSF: the possibility

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of factory prefabrication, architectural flexibility, combining load-bearing and enclosing functions in thin-walled profiles, and ease of assembly. One study (Soares et al., 2014) highlights the potential for recycling and reusing LSF elements, which reduces the environmental impact when buildings are dismantled at the end of their life cycle. A significant advantage of LSF buildings in remote and hard-to-reach Arctic regions is their transportability and fast, all-season installation (Kornilov et al., 2023). In permafrost conditions, the low weight of LSF buildings allows for the use of screw piles or surface structural foundations (Fig. 1).

At the same time, the main disadvantage of lightweight steel-framed (LSF) buildings is the presence of numerous thermal bridges, represented by the steel profiles (Liang et al., 2022; Anpilov et al., 2024). Multilayer enclosing structures are commonly used to improve thermal performance and reduce the impact of thermal bridges. A large volume of research on various types of LSF envelope assemblies has been conducted under the leadership of Paulo Santos and his collaborators (Santos, 2017; Moga et al., 2022; Soares et al., 2014; Soares et al., 2017; Santos et al., 2014; Roque and Santos, 2017; Santos et al.,2024). In particular, some studies (Soares et al., 2017; Santos et al., 2014) propose the use of phase change materials (PCMs) in the envelope layers of LSF buildings. The use of denser materials in combination with mineral wool — such as gypsum board, oriented strand board (OSB), and expanded polystyrene (EPS) panels in external walls, and a cement-sand screed on the floor — enhances thermal inertia and heat-storage capacity. This approach is especially useful for achieving indoor comfort in warmer climates.

The location of the thermal insulation within an LSF wall directly affects its thermal protection capability. Numerical simulations (Santos et al., 2014; Roque and Santos, 2017; Santos et al., 2024) have shown that for the same total thickness of insulation, the thermal performance may vary significantly depending on where the insulation is placed. The best performance is observed when EPS insulation panels are located on the exterior of the steel-framed wall. Other studies (De Angelis and Serraa, 2013) compare various wall compositions that include combinations of mineral wool, EPS boards, air cavities, the relative position of steel studs, etc. Air cavities used to route utilities may result in free air circulation inside the wall structure if sealing is insufficient, increasing heat losses through convection. Experimental and numerical simulations (Santos et al., 2013) have been conducted to determine the thermal properties of modular wall panels with internal air cavities, both with and without perimeter insulation. To mitigate heat losses from internal convection, Milovanović et al. (2022) recommend to completely fill the space between steel studs with mineral wool, and to install OSB and insulation materials on both sides. Additional modeling of wall connections with ceilings and roofs, taking into account steel columns, confirmed that external insulation significantly reduces the influence of thermal bridges. It is also essential to install reliable vapor barriers on the interior side of the wall to prevent moisture accumulation in the insulation layer (Bessonov et al., 2023). In some cases, the internal space of LSF walls is filled with materials like polystyrene concrete (Leshchenko and Semko, 2015) or foam gypsum (Bulatov et al., 2018).

Studies (Plotnikov, 2016; Sergeev et al., 2018; Petrosova et al., 2013) present the results of research on the influence of perforations in steel studs on the thermophysical characteristics of framed walls. The presence of longitudinal holes with staggered spacing in the web of the profile increases the thermal resistance of the steel stud, which overall leads to a slight increase in the minimum interior surface temperature of the envelope structure. However, even with the use of thermal profiles, to meet the regulatory requirements for single-layer walls in cold regions, the use of additional external insulation remains necessary (Plotnikov, 2016; Sergeev et al., 2018). It should be noted that field experimental

A B

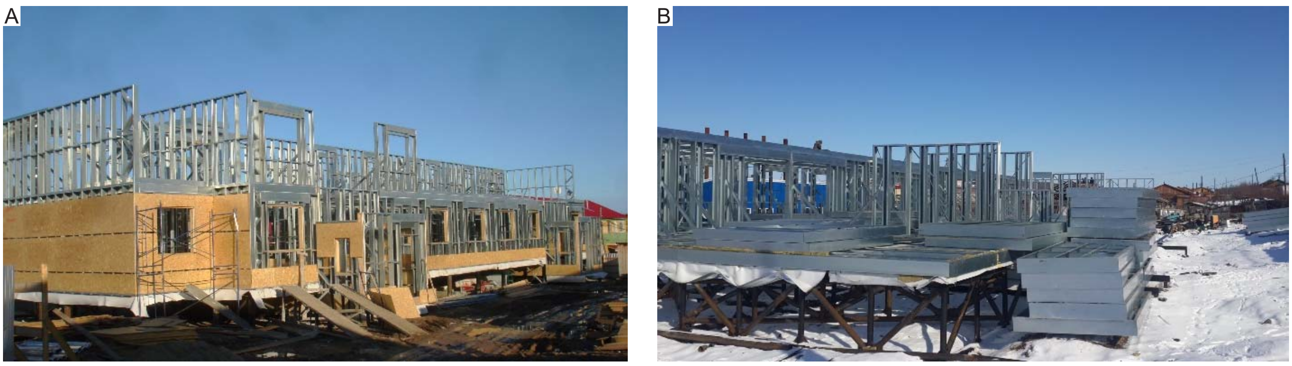


Fig. 1 Installation of the frame for a 16-apartment LSF building in Olenyok settlement (Republic of Sakha (Yakutia)) on screw (A) and pile (B) foundations (from the archive of LLC “Adgezia-MK”)

studies of a residential building with single-layer walls made of thermal profiles, conducted in the Leningrad region (Petrosova et al., 2013), do not fully reflect the thermal protection capabilities of the structure. This is because the tests were performed under relatively mild outdoor temperatures, from −7 °C to −13 °C. In low-rise LSF buildings, most of the defects and weaknesses typically appear during severe cold weather, when high air infiltration occurs.

The arrangement and size of thermal bridges formed by thin-walled steel profiles directly affect the thermal performance of the building envelope. One study (Santos and Poologanathan, 2021) presents the results of simulations of internal partitions and external walls with varying spacing and cross-sectional dimensions of C-shaped steel studs. Laboratory tests of a wall fragment confirmed a strong correlation between experimental values of thermal resistance and results from numerical simulations using ANSYS and TERM software. The greatest impact on the thermal performance of walls is made by the flange width, thickness of steel profiles, and spacing between studs (Santos and Poologanathan, 2021). In some works (Santos and Mateus, 2020; Santos et al., 2023; Santos and Ribeiro, 2021), to reduce the impact of thermal bridges, the use of thermal break (TB) strips — materials with low thermal conductivity — is proposed. These are placed along the flanges of the steel profiles. Numerical and experimental researches (Santos and Ribeiro, 2021) confirmed that for external thermal insulation composite systems (ETICS) with additional EPS insulation, the most effective configuration includes placing TB strips on the external flange of the steel studs. The thickness and thermal conductivity of these TB strips significantly influence the wall's thermal resistance. Moreover, the use of reflective foil insulation on both sides of the wall, in combination with TB strips, has been shown to substantially improve the wall's thermal efficiency (Santos and Ribeiro, 2021).

In the extreme conditions of the Arctic zone of the Russian Federation, the thermal protection of low-rise framed buildings is significantly influenced by increased air infiltration, especially at very low outdoor air temperatures and high wind speeds (Kornilov and Gerasimov, 2015; Kornilov and Nikiforov, 2018). Currently, to improve airtightness, during the construction of low-rise lightweight steel-framed (LSF) buildings in the territory of the Republic of Sakha (Yakutia), a monolithic reinforced concrete basement is used along steel foundation beam (Fig. 2). However, the issue of temperature regime disruption in LSF buildings remains unresolved: the steel stud profiles and the reinforced concrete basement slab create direct thermal bridges. Therefore, the aim of the research is to justify thermally efficient solutions for the wall-basement slab connection of low-rise LSF buildings in Arctic regions with extreme climatic conditions. Numerical simulations will be conducted to evaluate the temperature field and optimize heat loss reduction in the area of the wall-basement slab connection, including the use of thermal breaks to improve thermal efficiency.

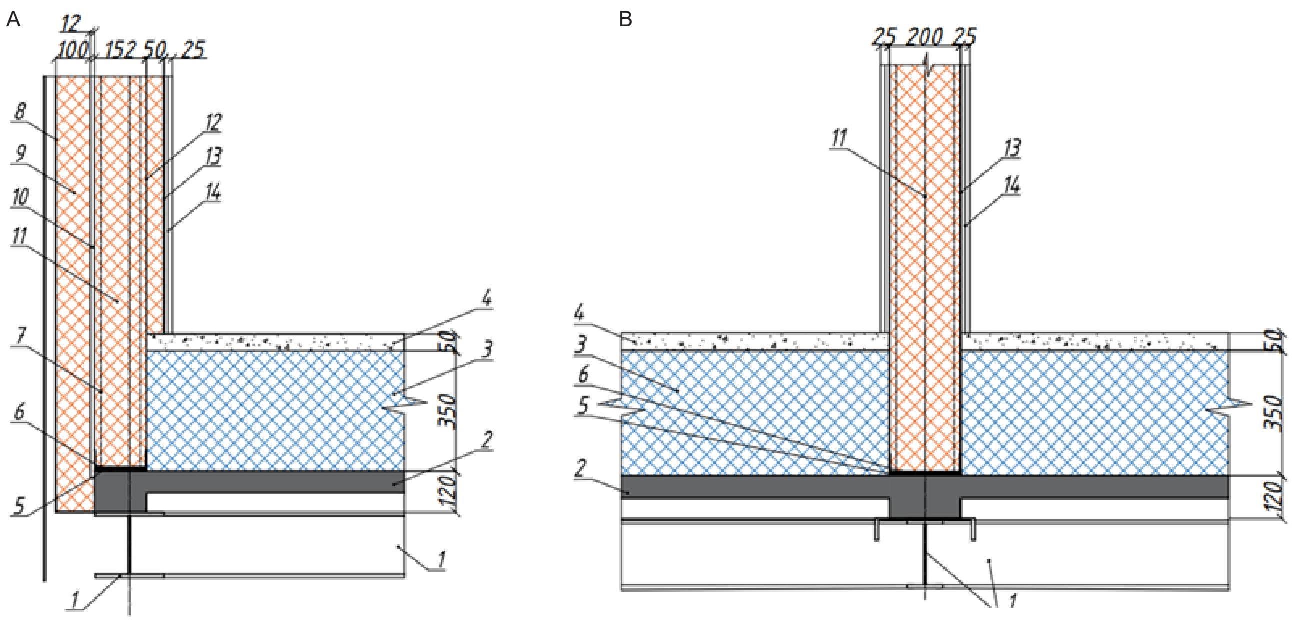


Fig. 2. Typical solutions for joints of external (A) and partition (B) wall-basement slab connections:
1 — foundation steel beams; 2 — reinforced concrete basement slab; 3 — EPS insulation; 4 — cement-sand screed; 5 — polyethylene backing layer; 6 — guide steel profile; 7 — steel stud; 8 — weather barrier; 9 — external insulation; 10 — OSB board; 11 — LSF wall with glass wools; 12 — internal insulation; 13 — vapour barrier; 14 — gypsum plasterboard

Methods

In previous studies (Kornilov and Nikiforov, 2018) the main principles for designing building envelopes made of lightweight steel-framed (LSF) constructions in extreme Arctic climates were outlined: multilayer external walls with ensured airtightness; positioning of steel frame profiles within the warm zone of the building at the wall-basement slab connections; and the use of multi-layer thermal inserts made of low thermal conductivity materials in the wall-basement slab connection. Based on these principles, a new design solution for the wall-basement slab connection has been developed. The main concept involves the use of a thermal break (TB) beam aligned with the axes of internal and external walls. The supports are spaced at 1200 mm intervals in such a way that they do not align vertically with the steel stud profiles, as shown in Fig. 3. Expanded polystyrene (EPS) boards of grade PPS35 or extruded polystyrene boards are used as thermal insulation in the basement slab. The lower layer of thermal insulation (200 mm thick) is laid directly on the reinforced concrete slab, including between beam supports. The ends of the EPS boards along the perimeter must align with the edge of the slab. After the TB beams are installed, steel guide profiles are fastened using anchors through 10 mm thick polyethylene thermal break (TB) strips. Vertical steel stud profiles, typically spaced 600 mm apart according to modular design standards, are mounted onto the guides. The wall is then assembled using a standard LSF framing system with thermal insulation materials. For external walls, additional thermal insulation layers on both sides are provided to ensure thermal protection and fire resistance of the steel frame. The upper insulation layer and the cement-sand floor screed are installed after wall assembly (Fig. 3).

To assess the thermal performance of the proposed LSF wall-basement slab connection nodes, fragment models were created and simulated using the certified HEAT3 software. This software is designed for 3D steady-state and transient heat transfer simulations and complies with EN ISO 10211:2022.

The basic value of the required thermal resistance of the enclosing structure according to SP 50.13330.2024 "Thermal Protection of Buildings" is taken depending on the degree-day of the heating period (HDD). For Arctic regions in the Republic of Sakha (Yakutia), the HDD ranges from 11.088 to 12.581 °C·days/year, according to SP 131.13330.2025 "SNIP 23-01–99. Construction Climatology". When designing settlements in the Arctic regions of the republic, the required (normative) thermal resistance values are 5.28–5.80 m²·°C/W for walls, and 7.74–8.49 m²·°C/W for roofs and basement slabs. The design outdoor temperature for the coldest five-day period with a 0.92 probability is −44 °C to −58 °C. In the course of numerical analysis of the investigated thermal bridges, the design outdoor air temperature was set to t_{ext} = −55 °C, and the indoor air temperature to t_{int} = +21 °C. The numerical analysis of the study thermal bridges was performed at the calculated outdoor temperature of t_{ext} = –55 °C and indoor air t_{int} = +21 °C. The heat transfer coefficients of the internal and external surfaces of enclosing structure

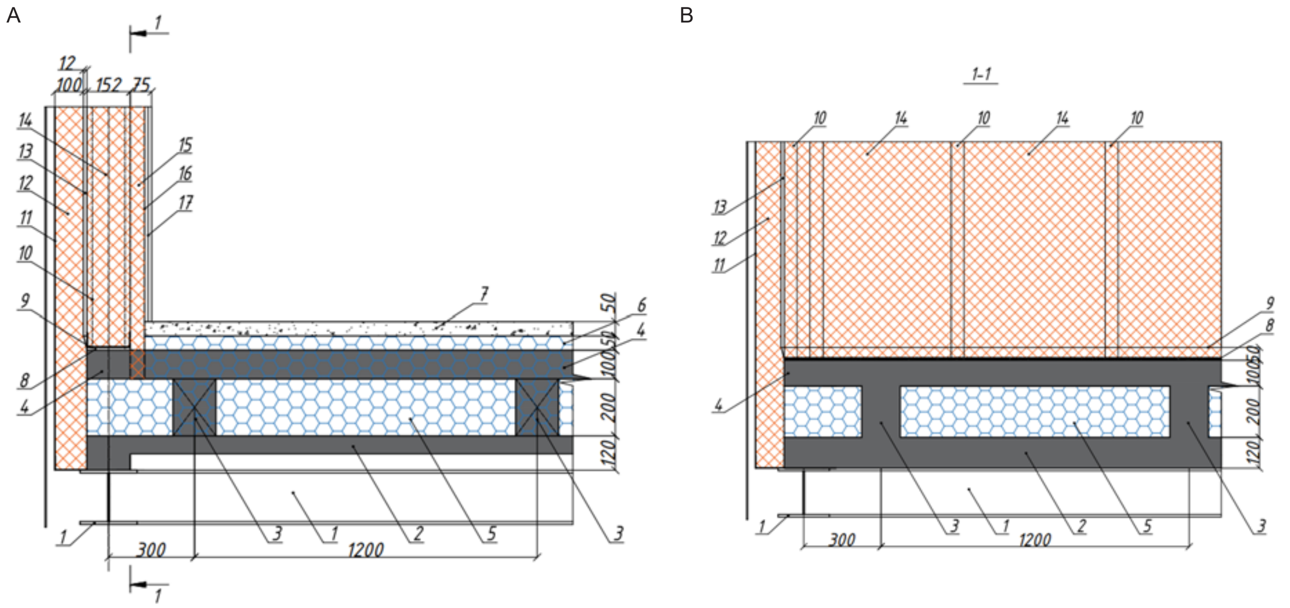


Fig. 3. Heat-efficient solution for the corner section of an external wall-basement slab connection: 1 — foundation steel beams; 2 — reinforced concrete basement slab; 3 — beam supports; 4 — TB beam; 5 — EPS insulation; 6 — top layer of EPS insulation; 7 — cement-sand screed; 8 — polyethylene backing layer; 9 — guide steel profile; 10 — steel stud; 11 — weather barrier; 12 — external insulation; 13 — OSB board; 14 — LSF wall with glass wools; 15 — internal insulation; 16 — vapour barrier; 17 — gypsum plasterboards

units according to SP 50.13330.2024 are adopted as 8.7 W/(m²·°C) and 23 W/(m² ·°C), respectively.

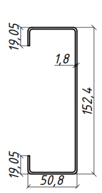
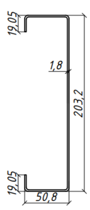
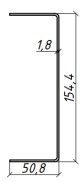
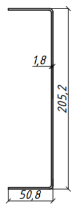
Previous research (Roque and Santos, 2017, Kornilov and Gerasimov, 2016) showed that external thermal insulation on LSF walls is most effective at minimizing thermal bridges created by steel studs. However, to meet fire resistance requirements for steel-framed walls, a 50 mm thick internal insulation layer is also required on exterior walls, and on both sides of interior walls. In the studied structures, S152×51×1.8 steel studs spaced 600 mm apart, and T152×51×1.8 steel guide profiles are used. The thermal resistance of walls and basement slabs was first calculated separately. Material specifications for walls and the basement slab are provided in Table 1.

This study presents numerical simulations of 3D models for the following components:

– external wall-basement slab connection;

– corner section of external wall-basement slab connection;

Table 1. **Characteristics of enclosing structure elements**

Building element	**Layer (Internal to External)**	**Thickness [mm]**	**λ, W/(m·°C)**	**Note**
External wall	Gypsum plasterboard	12.5	0.25	
	Gypsum plasterboard	12.5	0.25	
	Vapour barrier			Neglected
	Glass wool	50	0.04	
	Glass wool	150	0.04	
	OSB board	12	0.13	
	Glass wool	100	0.04	
	Weather barrier			Neglected
	Vented air layer			Neglected
	Profiled sheet			Neglected
Partition wall	Gypsum plasterboard	12.5	0.25	
	Gypsum plasterboard	12.5	0.25	
	Vapour barrier			Neglected
	Glass wool	150	0.04	
	Vapour barrier			Neglected
	Gypsum plasterboard	12.5	0.25	
	Gypsum plasterboard	12.5	0.25	
Basement slab	Cement-sand backing screed	50	0.76	
	Parchment	1		Neglected
	EPS insulation	350	0.04	
	Vapour barrier			Neglected
	Reinforced concrete slab	63	1.92	
Steel stud profile	S152×51×1.8  S203×51×1.8 	1.8	58.0	Steel studs are installed at 600 mm intervals
Guide steel profile	T203×51×1,8  T203×51×1,8 	1.8	58.0	Guide profiles are installed onto beams using TB strips
TB strip	Polyethylene strip 150 and 200 mm wide	10	0.039	TB strip is installed on TB beam
TB beam	Reinforced concrete		1.92	
	Larch wood		0.18	

λ is thermal conductivity for operating conditions A.

– partition wall-basement slab connection;

– external and partition wall-basement slab connection.

The TB beam and their supports can be made of reinforced concrete or wood, specifically Siberian larch. While timber offers better thermal performance, it is less durable than reinforced concrete. In the simulations, TB beams were initially modeled using reinforced concrete.

A comparison of the thermal performance of the proposed structural solutions with typical ones is carried out according to the following criteria:

– minimum temperature on the inner surface of the building envelope (in this case, on the floor);

– heat losses through a fragment of the building envelope;

– reduced thermal resistance R_{eff} (m²·°C/W) of the envelope fragment, which is calculated using the formula:

$$R_{eff} = \frac{t_{int} - t_{ext}}{Q} S,$$

where: t_{int} is indoor air temperature, °C;

t_{ext} is outdoor air temperature, °C;

Q is heat losses through the envelope fragment, W;

S is surface area of the inner side of the envelope fragment, m².

The temperature on the inner surface of the building envelope should be higher than the dew point temperature. At the calculated value of the indoor air temperature in residential premises in winter, t_{int} = +21 °C with a relative humidity of φ_{int} =50 % of the indoor air, the dew point temperature is t_p = +10.2 °C, with φ_{int} = 55 % — t_p = +11.6 °C. In northern areas with particularly low external temperatures, the actual relative humidity in the rooms does not exceed 30 %. With this in mind, the dew point temperature is considered in this paper at a humidity of 50 %.

Results and Discussion

Exterior Wall Made of LSF

In a previously conducted study (Kornilov and Gerasimov, 2016), four types of multilayer walls were analyzed. It was concluded that, from the standpoint of meeting thermal protection requirements for buildings in cold regions and minimizing installation costs, the most optimal solution is an LSF wall with external thermal insulation. In this study, an exterior wall configuration is examined with an additional 50 mm layer of internal thermal insulation to meet fire safety requirements for residential buildings. For comparison purposes, the following wall types were analyzed: an external wall without steel studs, an LSF wall with external insulation, and an LSF wall with both external and internal insulation. To maintain consistency across the models, the total thickness of mineral wool insulation was kept constant at 300 mm.

Field investigations of LSF buildings on pile foundations in extremely cold regions have shown that one of the recurring issues is insufficient fit of mineral wool boards within the profile sections due to flange bends and the protruding ends of self-tapping screws. The resulting voids inside the stud profiles allow cold air to penetrate and circulate freely, as clearly shown in the thermogram (Fig. 4). This problem can be mitigated by filling the lower parts of the steel studs with polyurethane foam or inserting mineral wool strips inside the profile prior to installing gypsum board and OSB sheathing. Based on this, the numerical heat transfer simulations for the wall-basement slab connection assume full filling of the steel profiles with insulation.

The key element for improving the thermal performance of the exterior wall is the continuous external thermal insulation, which serves as a thermal break for the steel frame and other conductive elements such as plastic anchors used for attaching insulation boards and steel brackets of ventilated façade systems. This has also been confirmed by similar studies (Milovanović et al., 2022; Santos and Mateus, 2020; Kornilov and Gerasimov, 2016). The modeling results for a wall with both external and internal insulation show that heat losses increased by 15.9 % and the reduced

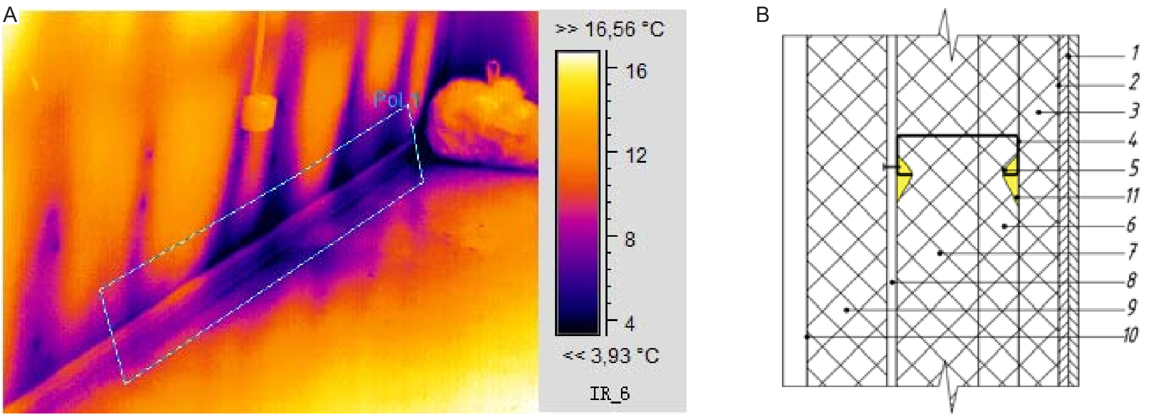


Fig. 4. Thermogram of LSF wall at temperature t_{int}=+16.5ºC and t_{ext}= –34.0 ºC (A) and cavity inside the steel stud profile (B)

thermal resistance decreased by 13.7 % compared to a wall model without steel studs (Table 2). The calculated reduced thermal resistance of the LSF wall is 6.78 m²·°C/W, which exceeds the normative value for Arctic regions.

Table 3 shows the temperature distributions inside the wall structures. In a double-layer wall, the 0 °C isotherm being located inside the outer thermal insulation layer at the locations of the steel posts due to their high thermal conductivity. The heat losses through the double-layer wall is the highest compared to other models. The use of an internal layer of thermal insulation to ensure fire resistance leads to a more uniform temperature distribution on the inner surface of the wall. However, the 0 °C isotherm bypasses the steel studs from the inside, which can be problematic in practice. Minor defects in the installation of mineral wool boards can lead to low interior surface temperatures and potentially condensation in the presence of high air infiltration. The minimum temperature is observed at vertical zones corresponding to steel stud locations and is t_{min} = +18.92 °C, which is a 4.6 % difference from a wall without steel studs.

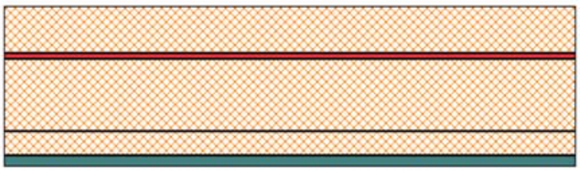
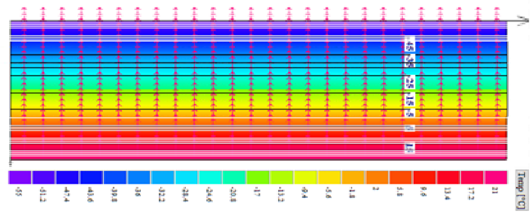
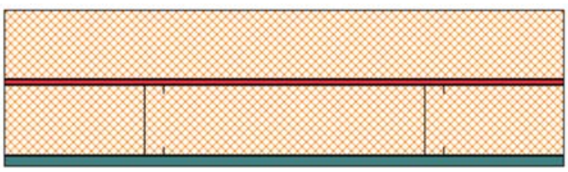
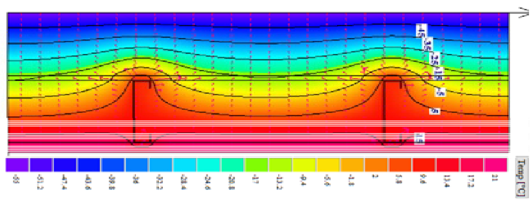
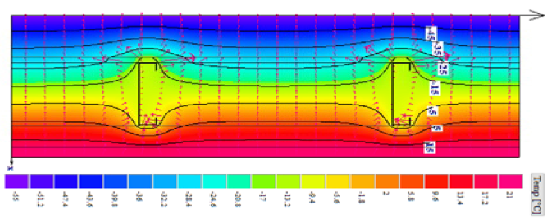
External Wall-basement Slab Connection

Table 4 presents the results of heat transfer simulations for the external wall-basement slab connection. In the typical solution, the steel studs in contact with the reinforced concrete slab act as direct thermal bridges, which is evident from the temperature distribution inside the connection. A 10 mm polyethylene strip placed between the guide profiles and the slab does not affect the temperature distribution within the assembly due to its small thickness. As a result, the minimum interior surface temperature at the steel stud locations is t_{min} = 10.48 °C.

Table 2. **Results of numerical analysis of exterior walls**

Wall type	**Thermal characteristics**		
	Minimum surface temperature t_{min}, °C	**Reduced thermal resistance R_{eff}, m²·°C/W**	**Heat losses Q, W**
Wall without steel studs	19.74	7.86	13.92
LSF double-layer wall with external insulation	16.81	6.34	17.25
LSF three-layer wall with external and internal insulation	18.92	6.78	16.13

Table 3. **Results of thermal transfer modeling of the external walls**

Calculation model	**Temperature distribution**
Wall without steel studs	
	
LSF wall with external insulation	
	
LSF wall with external and internal insulation	
	

In the proposed solution for the external wall-basement slab connection, thermal bridges in the form of steel profiles are shifted into the warm zone of the building using thermal break (TB) beams. The EPS inserts within the TB beams are joined with the external wall insulation, thereby ensuring the continuity of the building's thermal envelope. The effectiveness of using a TB beam is clearly visible from the heat flow direction in the temperature distribution along the vertical section of the external wall-basement slab connection (Table 4). The minimum surface temperature reaches t_{min} = 16.18 °C, which significantly reduces the risk of moisture condensation on the interior surface of this connection. The reduced thermal resistance of the proposed connection is 8.1 % higher than that of the typical solution.

Corner Section of the External Wall-basement Slab Connection

The corner section of the basement slab in buildings with pile foundations is one of the most critical thermal zones, as it is exposed to cold from three directions. At this junction, two adjacent steel stud profiles are used to connect the external walls, increasing the number of thermal bridges (Table 6). While heat loss is already a concern due to thermal bridging, an even more serious consequence is the very low surface temperature that can occur in the corner area. In the typical solution, the minimum surface temperature is only t_{min}= 2.42 °C, which is significantly below the dew point temperature t_p = 10.2 °C (Table 5). This can lead to surface condensation on gypsum board panels, deterioration of thermal performance and structural integrity, and mold growth in mineral wool insulation.

With the use of a TB beam and external wall insulation, the thermal performance of the corner joint is significantly improved. The interior surface temperature rises to t_{min} = 11.07 °C, exceeding the dew point temperature. Heat losses through the joint decrease, and the reduced thermal resistance reaches R_{eff} = 5.63 m²·°C/W, which is 8.9 % higher than that of the typical solution (Table 6).

Partition Wall-basement Slab Connection

Partition walls use T203×51×1.8 guide profiles and S203×51×1.8 stud profiles. The wall assembly

Table 4. **Results of thermal transfer modeling of the external wall-basement slab connection**

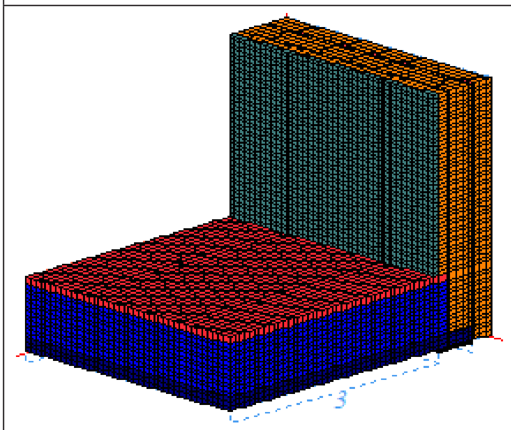
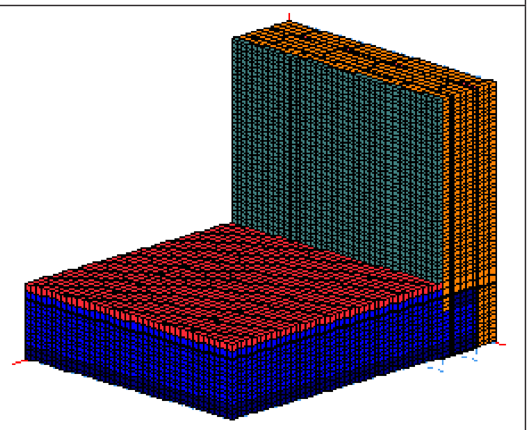
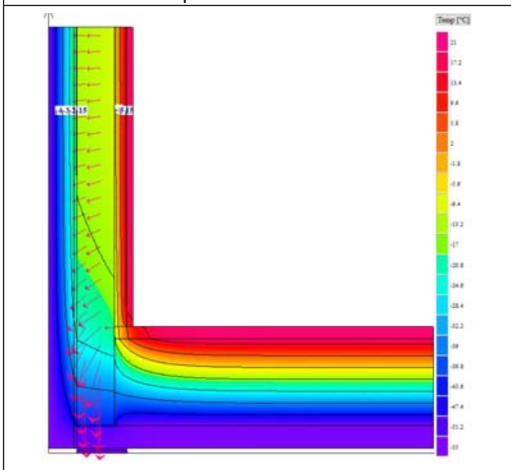
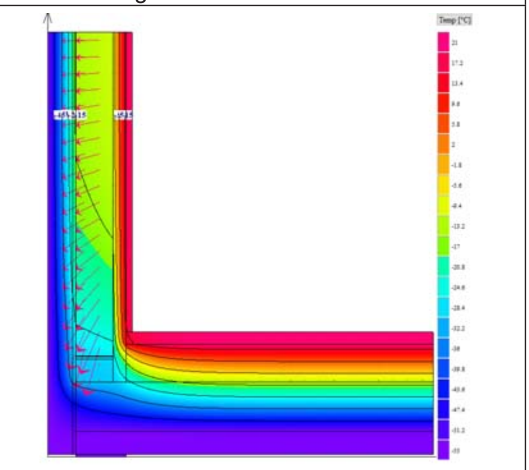
Typical solution	Proposed solution
Calculation model	
	
Temperature distribution in a vertical section along the wall of a steel stud	
	

Table 5. **Results of numerical analysis of wall-basement slab connections**

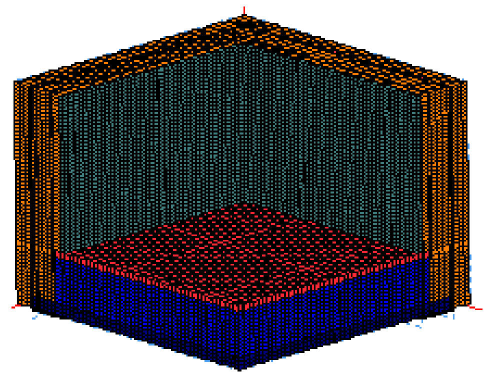
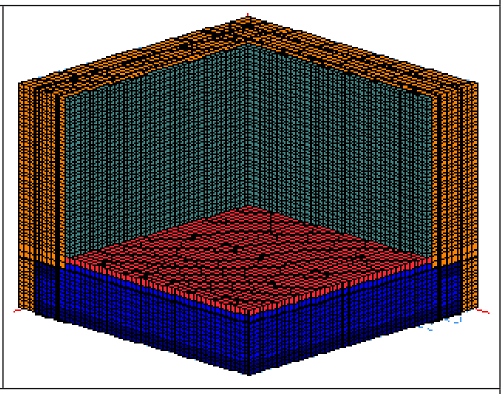
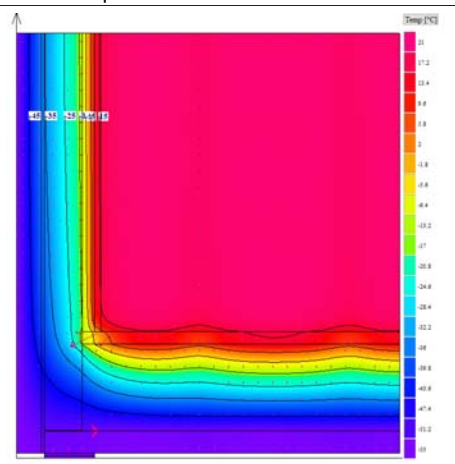
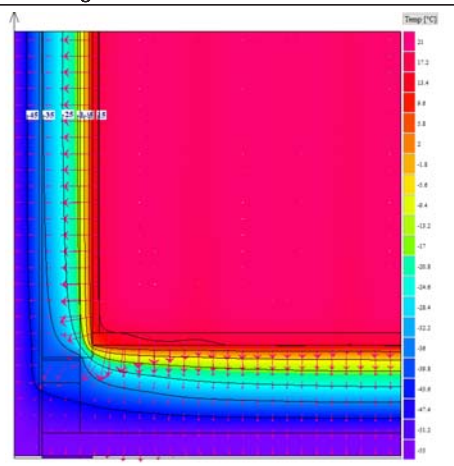
Element connection	Typical solutions			Heat-efficient solutions		
	Thermal characteristics					
	t_{min}, °C	R_{eff}, m²·°C/W	Q, W	t_{min}, °C	R_{eff}, m²·°C/W	Q, W
External wall-basement slab	10.48	6.27	34.91	16.18	6.78	32.28
Corner section of the external wall-basement slab	2.42	5.17	63.53	11.07	5.63	58.35
Partition wall-basement slab	12.89	6.51	33.60	14.42	7.51	29.13
External and partition wall-basement slab	4.64	4.93	88.68	10.25	5.13	85.34

t_{min} is minimum temperature on the inner surface of the enclosing structures;
R_{eff} is reduced thermal resistance;
Q is heat losses.

is detailed in Table 1. In the typical configuration, guide profiles are anchored directly to the reinforced concrete basement slab using polyethylene strips, which do not effectively function as a thermal break — as seen in the temperature distribution (Table 7). The minimum temperature on the interior surface, at the steel stud locations, is t_{min} = 12.89 °C, while between studs the temperature in the corner area reaches up to 20.1 °C.

In the proposed solution with a TB beam, the minimum temperature on the interior surface rises to t_{min} = 14.16 °C, significantly higher than in the typical configuration. The 0 °C isotherm lies much deeper inside the assembly, indicating better protection from cold penetration. Steel profiles are located entirely within the warm zone. The reduced thermal resistance of the proposed connection is R_{eff} = 7.51 m²·°C/W, compared

Table 6. **Results of thermal modeling for the corner section of the external wall-basement slab connection**

Typical solution	Proposed solution
Calculation model	
	
Temperature distribution in a vertical section along the inner surface of the wall	
	

to R_{eff} = 9.02 m²·°C/W for the clear basement slab area without any framing.

External and Partition Wall-basement Slab Connection

This connection combines steel studs from the partition wall and two studs from the external wall, making it the location with the highest concentration of thermal bridges, which affects both the temperature distribution and heat losses (Table 8). In the typical solution, the minimum surface temperature in the floor corner between the two walls is only t_{min} = 4.64 °C, far below the dew point temperature.

In the proposed solution, the TB beam support is shifted away from the corner, creating a thermal break zone in the joint between the exterior and partition walls. With the TB beam made of reinforced concrete, only the supports remain as a thermal bridge (Table 8), but the minimum temperature on the interior surface increases to t_{min}= 10.25 °C. The reduced thermal resistance improves to R_{eff} = 5.13 m²·°C/W, which is 4.1 % higher than in the typical solution.

Wooden TB Beams

TB beams made of Siberian larch are preferable from a thermal performance perspective, although they are less durable than reinforced concrete. Siberian larch, when properly treated, offers high strength and fire resistance. Numerical analysis shows that when wooden TB beams are used instead of concrete ones, the thermal properties of the connections improve even further. For example, the minimum surface temperatures and reduced thermal resistance values for connections using wooden TB beams are:

− external wall-basement slab: t_{min} = 16.62 °C, R_{eff} = 6.75 m²·°C/W;

− corner section of external wall-basement slab: t_{min} = 11.93 °C, R_{eff} = 5.79 m²·°C/W;

− partition wall-basement slab: t_{min} = 17.19 °C, R_{eff} = 7.74 m²·°C/W;

− external and partition wall-basement slab: t_{min} = 14.44 °C, R_{eff} = 5.93 m²·°C/W.

Conclusions

Based on the operational experience of low-rise lightweight steel-framed (LSF) buildings on pile foundations in the extreme climate conditions of the Arctic regions of Yakutia, the use of thermal break (TB) beams is proposed for the connection of walls with reinforced concrete basement slabs. This design solution reduces the impact of thermal bridges formed by steel profiles by shifting them into the warm zone, introducing a thermal break, and ensuring the continuity of the building's thermal envelope.

Numerical simulations of 3D models for various wall-basement slab connections were carried out under an extremely low outdoor temperature of t_{ext} = −55 °C, characteristic of Arctic regions. In typical solutions, steel guide and stud profiles in contact with the basement slab act as direct thermal

Table 7. **Results of thermal modeling for the partition wall-basement slab connection**

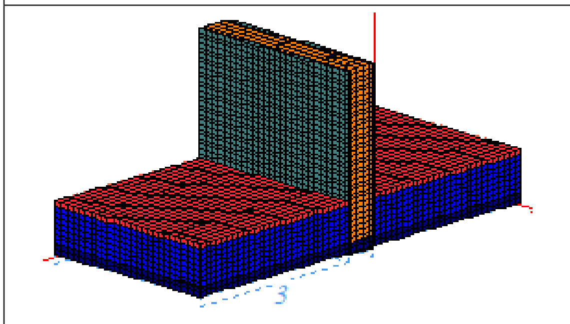
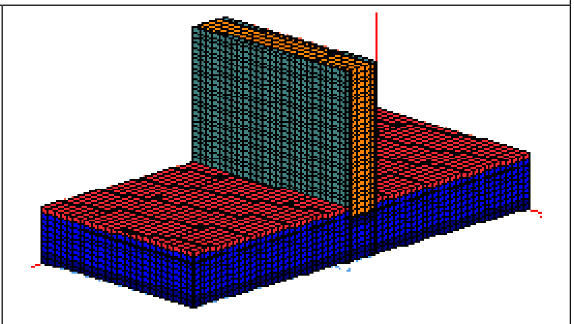
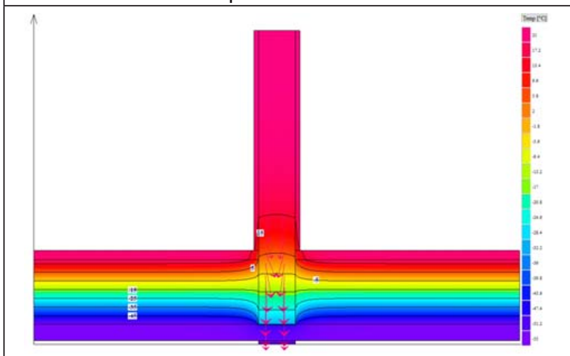
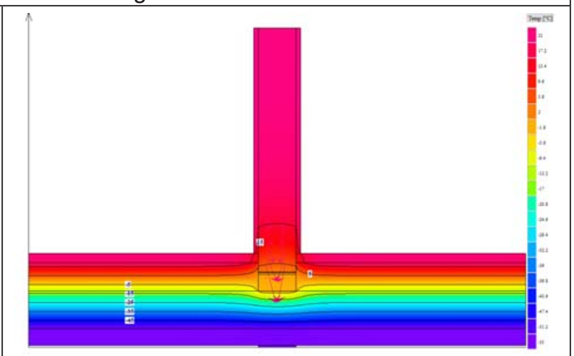
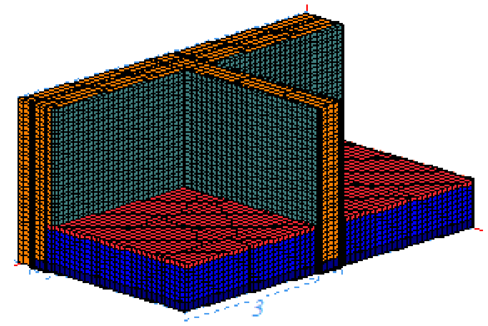
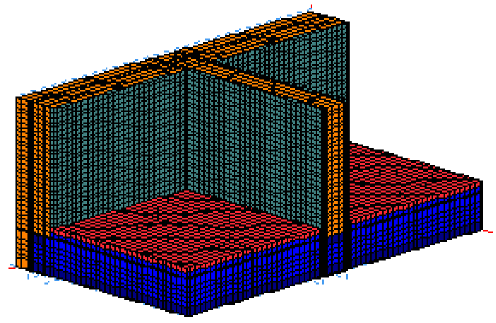
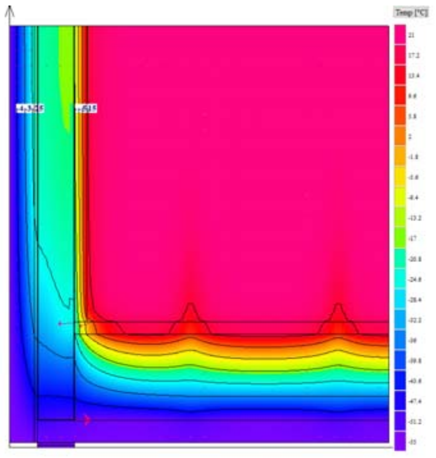
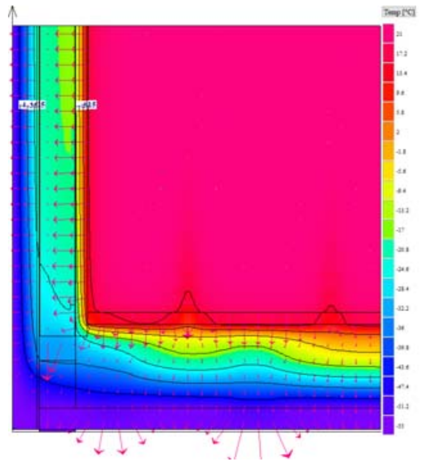
Typical solution	**Proposed solutions**
Calculation model	
	
Temperature distribution in a vertical section along the wall of a steel stud	
	

Table 8. **Results of thermal modeling for the external and partition wall-basement slab connection**

Typical solution	Proposed solution
Calculation model	
	
Temperature distribution in the vertical section along the surface of the partition wall	
	

bridges, which was confirmed by heat transfer simulation results. The polyethylene strip between the steel profiles and the basement slab has an insignificant effect on the internal temperature distribution due to its small thickness. In the corner section of external wall-basement slab connection and external and partition wall-basement slab connection, the minimum surface temperature was found to be below the dew point, which can lead to surface condensation on gypsum board, loss of thermal performance, structural degradation, and mold growth in mineral wool insulation.

The results of thermal simulations confirm the effectiveness of TB beams in the analyzed connections. In contrast to typical solutions, the minimum temperature on the inner surface of wall-basement slab joints with reinforced concrete TB beams exceeds the dew point. Compared to conventional configurations, the reduced thermal resistance increased by:

– 8.1 % for the external wall-basement slab connection;

– 8.9 % for the corner section of the external wall-basement slab connection;

– 15.4 % for the partition wall-basement slab connection;

– 4.1 % for the external and partition wall-basement slab connection.

When using timber, particularly durable Siberian larch, as the material for TB beams, the thermal performance of wall-basement slab connections improves even further.

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ТЕПЛОЭФФЕКТИВНЫЕ РЕШЕНИЯ СОПРЯЖЕНИЙ СТЕН С ЦОКОЛЬНЫМ ПЕРЕКРЫТИЕМ ЗДАНИЙ ИЗ ЛЕГКИХ СТАЛЬНЫХ ТОНКОСТЕННЫХ КОНСТРУКЦИЙ ДЛЯ АРКТИЧЕСКИХ РАЙОНОВ

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Аннотация
Введение: В арктических районах с учетом разбросанности поселений на обширных территориях при малой плотности расселения, трудности логистики и транспортной инфраструктуры одним из перспективных технологий является строительство быстровозводимых зданий из легких стальных тонкостенных конструкций (ЛСТК). Тепловая защита таких зданий в климатических условиях с расчетной температурой воздуха –44 °C …–58 °C является актуальной и трудной задачей с учетом термических мостов в виде стальных профилей. Опыт эксплуатации зданий из ЛСТК на свайных фундаментах показывает, что основные проблемы возникают на первом этаже при наличии проветриваемого подполья для сохранения мерзлых грунтов. **Цель:** разработка теплоэффективных решений сопряжений стен с цокольным перекрытием зданий из ЛСТК для арктических районов с экстремальными климатическими условиями. **Методы:** С целью снижения влияния термических мостов для соединений стен из ЛСТК с цокольным перекрытием предложены терморазрывные (ТВ) балки. Численные исследования 3D-моделей различных соединений стен с цокольным перекрытием проведены с использованием сертифицированной программы HEAT 3. Сравнение результатов с типовыми конструкциями выполнено по минимальной температуре на внутренней поверхности ограждающих конструкций, тепловым потерям и приведенному термическому сопротивлению. Результаты: **В результате** применения новых решений минимизировано влияние термических мостов путем смещения стальных профилей в теплую зону, создания терморазрыва с помощью балок и обеспечения неразрывности тепловой защитной оболочки зданий. При температуре наружного воздуха –55 °C минимальная температура на внутренней поверхности соединений стен с цокольным перекрытием, в отличие от типовых решений, превышает температуру точки росы. По сравнению с типовыми решениями приведенное сопротивление сопряжения наружной стены с плитой перекрытия подвала увеличивается на 8.1 %, сопряжения перегородочной стены с плитой перекрытия подвала — на 15.4 %.

Ключевые слова: тепловой мост, легкие стальные каркасные конструкции, терморазрыв, соединение стены и плиты перекрытия подвала, тепловое сопротивление.

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ISSUES OF DETERMINING THE RESOURCE OF BEARING CAPACITY OF ANCIENT TIMBER STRUCTURES ELEMENTS

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Abstract
Introduction: The resource of bearing capacity (RBC) of timber structures in historical buildings and structures with an operational life of 100 years or more cannot be determined without considering their specific characteristics. At the same time, this problem has important theoretical and practical significance for assessing the technical condition, preservation, and restoration of cultural heritage sites. **Objective**: to systematize scientific data on the influence of various factors on the RBC of ancient timber structure elements. **Methods**: The operational bearing capacity of timber structure elements is mainly determined by the thermofluctuation mechanism of cellulose macromolecule ("skeleton" of wood) failure, which leads to strength degradation, creep, as well as physical wear. Assessing the combined effect of these factors allows determining the RBC of the structure. Furthermore, with long service lives, it is necessary to additionally consider possible changes: climate, landscape, properties of protective-decorative coatings, structural and spatial-planning solutions, spatial position, functional purpose, status of the object as a monument, as well as the legislative framework for design and restoration. A refined assessment should include an analysis of the influence of construction technological features. **Results**: A comprehensive analysis has demonstrated the need for joint consideration and interrelations of force and environmental impacts, deformation and strength properties of wood, physical wear and defects, and the complex nature of the stress-strain state of timber structure elements in historical buildings and structures to assess their RBC, as well as to develop a strategy for ensuring a balance between mechanical safety and the preservation of the cultural and historical value of the objects.

Keywords: resource of bearing capacity; ancient timber structures; long-term strength; physical wear; geometric nonlinearity; physical nonlinearity.

Introduction

Ancient timber structures, as an important part of cultural heritage, not only carry rich historical information but also serve as material evidence of traditional construction technologies. Many valuable historical timber buildings have undergone multiple repairs, and when assessing and surveying these structures, accurately determining the resource of bearing capacity (RBC) of their elements faces a number of challenges (Wang, 2008). Firstly, due to the long service life of historical buildings, original construction data and long-term strength data are absent, making it difficult to predict the degradation patterns of timber element characteristics under permanent loads. Secondly, the diversity of wood species used in construction and the heterogeneity of their properties complicate the assessment of the structure's mechanical characteristics. The mechanical properties of different tree species vary, and natural defects such as wormholes and knots increase the complexity of material inspection. Differences in strength across different areas of wood affect the reliability of the entire structure (Bode et al., 2019). Furthermore, the combined impact of environmental factors (e.g., temperature and humidity fluctuations, biological degradation) and loads further complicates the analysis of the resource of bearing capacity of elements. Existing methods for predicting long-term strength have limitations and cannot accurately model the complex influence of real operating conditions.

At the same time, during the long-term operation of historical buildings, mechanical damage and biological degradation of timber structures gradually accumulate. In addition to creep and cracking of elements caused by the thermofluctuation mechanism, damage in timber structures often includes irregular components such as local rot, insect infestation, and traces of historical repairs. These factors are difficult to quantify using standard methods. Moreover, in the practice of preserving valuable historical buildings, there is a contradiction between the principles of historical restoration and modern structural safety requirements. In the process of identifying irregular damage, intervention into the original structure must be minimized. For this purpose, non-destructive methods such as stress wave testing (SWT), infrared thermography (IRT), and others are used to determine the extent and location of damage. In some cases, changes in the spatial position of the building are even analyzed to ensure its preservation (Korolkov, 2020). The aim

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of this work is to systematize scientific data on the influence of various factors on the resource of bearing capacity of ancient timber structure elements.

Heterogeneity of Wood Properties

The RBC of ancient timber structures significantly depends on the heterogeneity of wood properties, which manifests in aspects such as material aging, environmental impacts, and structural damage. Wood is a unique natural building material with structural heterogeneity. The annual rings, formed by layers of cells during tree growth, lead to differences in material strength depending on the wood species and fiber direction (Glebov, 2018). Furthermore, natural defects in wood, such as knots and wormholes, as well as accumulated decay processes over time, further enhance the influence of heterogeneity on the long-term strength of the material (Riggio et al., 2018).

Wood defects can be divided into the following three types: 1) natural defects occurring in the living tree; 2) defects arising during drying and processing of wood; 3) defects caused by fungi, insects, and wood borers (Vakin et al., 1980). Natural wood defects include knots, cracks, etc. Knots disrupt the continuity of wood fibers (Gubenko and Khandrov, 2015), leading to stress concentration and a 10–50 % reduction in material strength (GOST 2140–81). During long-term cycles of temperature and humidity changes in building structures, the difference in shrinkage rates between knots and surrounding fibers increases, causing radial cracks, further reducing the longitudinal tensile strength and shear resistance of the element (SP 64.13330.2017). Apart from natural defects, processing inaccuracies of timber structure elements can lead to excessive tightness or loosening of connections. Under long-term loads, excessive tightness causes initial stress concentration, and subsequent wood creep leads to the formation of hidden cracks. Loose connections under dynamic loads accelerate wood wear, reducing joint stiffness. In traditional Chinese timber structures, tougong joints were widely used, where the processing accuracy of elements was a critical factor for structural safety (Kirichkov, 2020).

Wood density is one of the key factors determining its mechanical properties and RBC. It usually depends on the tree species, growth conditions, trunk height, and harvesting location. Higher density wood generally possesses increased resistance to compression, bending, and shear, whereas lower density wood exhibits greater plasticity but lower stiffness. Wood density increases with slower diameter growth, a greater number of annual rings per centimeter, and a higher proportion of latewood. This leads to improved mechanical characteristics (Brunetti et al., 2013). Within a single trunk, these properties vary with height and radius. Along the trunk height, the best indicators are observed at the base, gradually decreasing towards the crown. In the radial direction, mechanical properties strengthen from the pith to the bark, reach a maximum, and then begin to decrease again (Papulova, 2014). During long-term operation, wood density affects its durability and resistance to environmental impacts. Denser wood, due to its compact structure, usually has lower hygroscopicity and better resistance to biological degradation (fungi, pests), allowing it to maintain its bearing capacity longer under cyclic temperature and humidity changes. Conversely, low-density wood without antiseptic treatment, when exposed to prolonged moisture or pests, can degrade rapidly, leading to loss of bearing capacity (Borovikov and Ugolev, 1989; EN 408).

The heterogeneity of wood significantly affects the RBC of ancient timber structures, manifesting in differences in wood species and the uneven distribution of natural and accumulated damage. To ensure the long-term safe operation of historical buildings, it is necessary to apply non-destructive testing methods for scientifically based prediction of the RBC of different wood types.

Complexity of Interrelated Environmental and Load Impacts

During the long-term operation of historical buildings, the combined impact of environmental factors (temperature, humidity) and mechanical loads significantly accelerates the degradation of material properties, which in turn affects the RBC. Wood as a natural polymer material is a network structure formed by cellulose, hemicellulose, and lignin through hydrogen and covalent bonds. The long-term degradation of its properties is mainly due to the thermofluctuation mechanism. Temperature and humidity fluctuations lead to repeated cycles of moisture absorption and loss by wood fibers, causing volume changes and internal stresses, making the viscoelastic properties of the material more pronounced.

The Soviet scientist S.N. Zhurkov established that the thermofluctuation mechanism reveals the process of gradual damage accumulation in solid materials (including wood) under the action of stresses and environmental factors, driven by thermally activated processes at the atomic or molecular level (Yartsev and Kiseleva, 2009). According to this theory, material failure is essentially a statistical process of chemical bond breakage induced by the combined action of thermodynamic fluctuations and mechanical stresses. This process is described by the Zhurkov equation:

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right),$$

where:

τ is time of the material failure under load σ,

τ_0 is atomic vibration period (~10^{-13} c),

U_0 is initial activation energy of the chemical bond (in the absence of stress),

γ is stress sensitivity coefficient, reflecting the structural properties of the material,

k is Boltzmann constant,

T is absolute temperature.

It has been established that even in the absence of external loads, damage in wood accumulates nonlinearly over time (Kovshov, 2020). The main load-bearing elements of wood are microfibrils composed of cellulose molecules linked by hydrogen bonds and van der Waals forces. The Zhurkov equation demonstrates that the synergistic influence of the environment enhances the effect of the thermofluctuation mechanism on the strength characteristics of wood (Yartsev, 2003) (Table).

It follows that the thermofluctuation mechanism is the direct cause of the reduction in bearing capacity of timber structure elements during long-term operation. V.P. Yartsev conducted strength tests of pine under longitudinal and transverse bending in various temperature and humidity conditions. The experiment involved gradual heating in a thermostat, and material samples were soaked in various solutions to obtain test samples with different moisture contents, allowing the determination of the material's strength characteristics under different temperature and humidity conditions.

Experimental studies have shown that increasing temperature and humidity accelerates the failure process of timber structures, reducing the long-term strength of the material, especially the bending resistance. An increase in temperature changes the glass transition temperature of lignin: at high temperatures, lignin softening leads to intense interfiber sliding, reducing the fatigue life of timber elements and accelerating wood creep. Under high humidity conditions, water penetration destroys hydrogen bonds between cellulose molecules, reducing the stiffness of the material. Simultaneously, the load promotes the propagation of microcracks along weakened zones. The dependence of wood strength on temperature and humidity is shown in Fig. 1 (Koval and Trunina, 2024). A more complex aspect is that the dynamic combination of temperature, humidity, and load can activate microbial activity: at humidity >20 % and temperature 15-30 °C, brown rot fungi metabolize intensively, secreting cellulases that primarily destroy cell walls in loaded areas. Such biomechanical coupled degradation in hidden parts of historical buildings (e.g., column bases inside walls) often goes unnoticed until sudden loss of bearing capacity occurs (Varfolomeev, 2010; Samoilov, 1996).

Ancient timber structures, which operated for decades or even centuries, undergo degradation of their characteristics under the combined influence of temporal, environmental, and load factors. Traditional research has two main problems: firstly, the natural aging of materials occurs over extremely long periods, requiring prolonged monitoring and making it difficult to quickly assess

Thermal fluctuation regime depending on environmental factors

Influencing Factors	*Effect on Thermal Fluctuations*	*Manifestations of Wood Degradation*
Temperature increase	When kT rises, the probability of chemical bond breakage significantly increases	Accelerated creep, loss of strength
Humidity change	Water molecules penetrate hydrogen bonds, reducing the effective activation energy U_0	Stress change and chemical bond breakage, leading to cracking and rot of wood
Loading	Dynamic loads lead to local temperature increases, promoting chemical bond breakage	Development of fatigue cracks

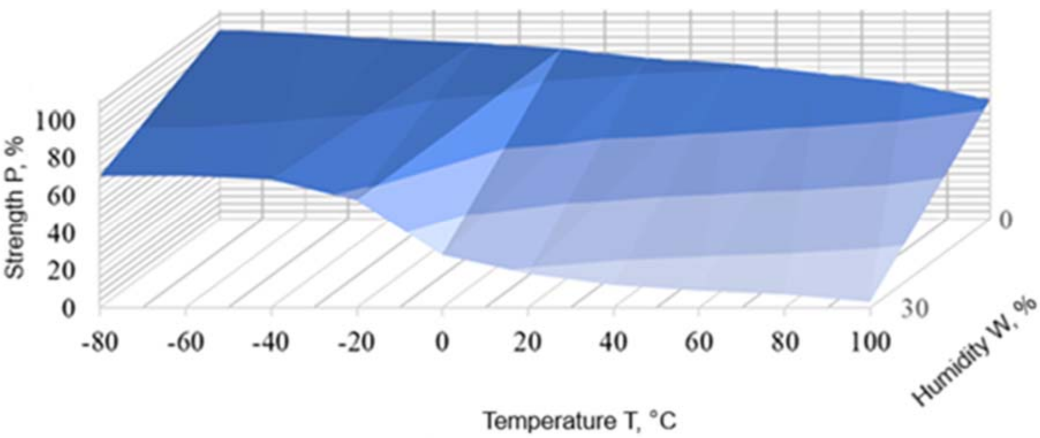

Fig. 1. Graph of the dependence of wood strength on temperature and humidity (Koval et al., 2024)

RBC; secondly, it is difficult to accurately assess the combined influence of temperature-humidity fluctuations (thermofluctuation mechanism) and biological damage during the long-term operation of historical elements, which directly affects their long-term strength indicators. Although linear loading allows rapid testing, the resulting “reduced time” is too short and does not reflect real long-term characteristics. Based on Zhurkov’s kinetic theory and the Yu.M. Ivanov model, P.S. Koval proposed an accelerated testing method under nonlinear loading (quadratic-parabolic loading) to determine the long-term strength of wood. The key idea is to apply slowly increasing stress, which increases the time to failure, effectively modeling the behavior of structural elements under long-term loading (Koval and Kushnir, 2024; Koval, 2024; Ivanov, 1972). This method combines Zhurkov’s fracture kinetics with nonlinear loading, expanding the experimental methodology for assessing long-term strength and significantly reducing testing time while increasing the practical value of the data. The thermofluctuation mechanism indicates that the reduction in material bearing capacity is the result of the combined impact of multiple factors. However, most modern loading tests control only one variable, making it difficult to model the combined influence of various factors during long-term operation. To investigate material strength under complex environmental impacts, it is necessary to combine new testing methods with theoretical advances in materials science (Chernykh et al., 2023).

Stress Redistribution under Combined Damage Modes

During the long-term service of ancient timber structures, damage to elements (such as mechanical defects, surface corrosion, internal rot, weakening of joint connections) leads to significant stress redistribution within the structural system, altering the original design stress state. The change in the stress state of elements not only accelerates the development of damaged zones (e.g., loss of stability of fibers in the compressed zone or crack growth in the tension zone) (GOST R 58033–2017) but can also cause a chain reaction in adjacent structural elements (Lourenço et al., 2013).

In the case of historical buildings, due to fiber delamination in timber structures, human activity during operation is more likely to cause section damage (Fig. 2) or fiber cracking due to temperature-humidity fluctuations (Fig. 3), directly reducing the strength, stiffness, and bending capacity of the structure. To assess the bearing capacity of such structures, the concept of effective cross-section is applied, representing the part of the original section capable of withstanding loads. The effective section accounts for degradation zones and excludes damaged areas. For square sections, the maximum permissible value for edge or end delamination is one-third, and for buildings with increased safety requirements, this value is reduced with the introduction of an additional deformation coefficient (Nocetti et al., 2021).

When mechanical damage (cracks, holes) or biological attack (fungi, insects) occurs in timber elements, leading to material heterogeneity, significant changes in their mechanical characteristics are observed. The natural anisotropy of wood is exacerbated by damage, creating high-stress zones where actual stresses significantly exceed nominal values. Simultaneously, the modulus of elasticity of the element decreases due to material failure, leading to increased deformations under the same loads. Uneven stiffness distribution causes force flow redistribution, increasing the load on undamaged areas. When cross-section

Fig. 2. Mechanical damage (Cabaleiro and Riveiro, 2016)

Fig. 3. Fiber cracks

asymmetry is caused by corrosion or damage, under bending conditions the neutral axis shifts towards the stronger part of the section (Fig. 4). This leads to increased deformations on the damaged side and premature attainment of ultimate strains. Axial loads in asymmetric sections create an additional bending moment, forming a combined stress state (tension-bending or compression-bending). Transverse loads on asymmetric sections can cause torsion, exacerbating the uneven distribution of shear stresses.

During the long-term operation of historical timber frame buildings, mechanical damage and biological erosion caused by changes in the cross-section of timber elements reduce the moment of inertia of the section and cause a sharp decrease in bending stiffness (EI). Long-term operation leads to the formation of irregular cross-sections, requiring modern non-destructive testing methods for accurate area measurement. During the initial survey of historical buildings, visual strength grading (VSG) is used to identify weakened sections. In cases where visual strength grading does not provide sufficient accuracy, standard design cross-sections are adopted. For timber beams, the nominal cross-sectional area is usually determined as the average value of areas at fixed intervals or the average value in the middle part of the span (Fig. 5) according to studies (Osuna-Sequera et al., 2020; Piazza and Riggio, 2008; UNE 56544). Modern assessment methods include laser scanning, allowing the acquisition of two-dimensional sections in computer representation (Cabaleiro and Riveiro, 2016), and for hidden structural elements, core drilling is used to assess the cross-sectional area (Cabaleiro and Branco, 2018).

For timber structures with irregular cross-sections, the moments of inertia about the x and y axes are determined by the following integral expressions:

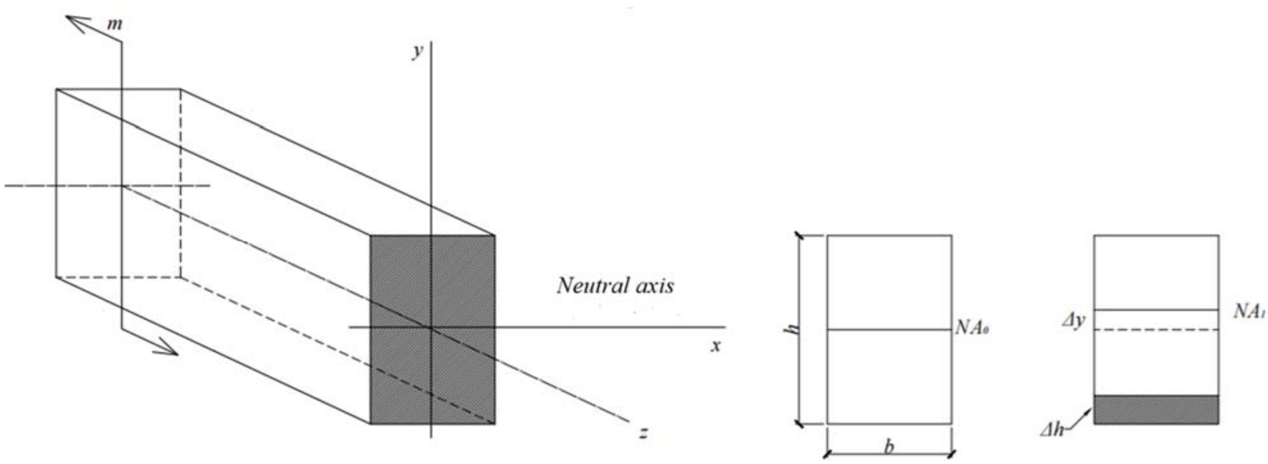

Fig. 4. Element damage leading to neutral axis shift (hatching indicates simplified damage)

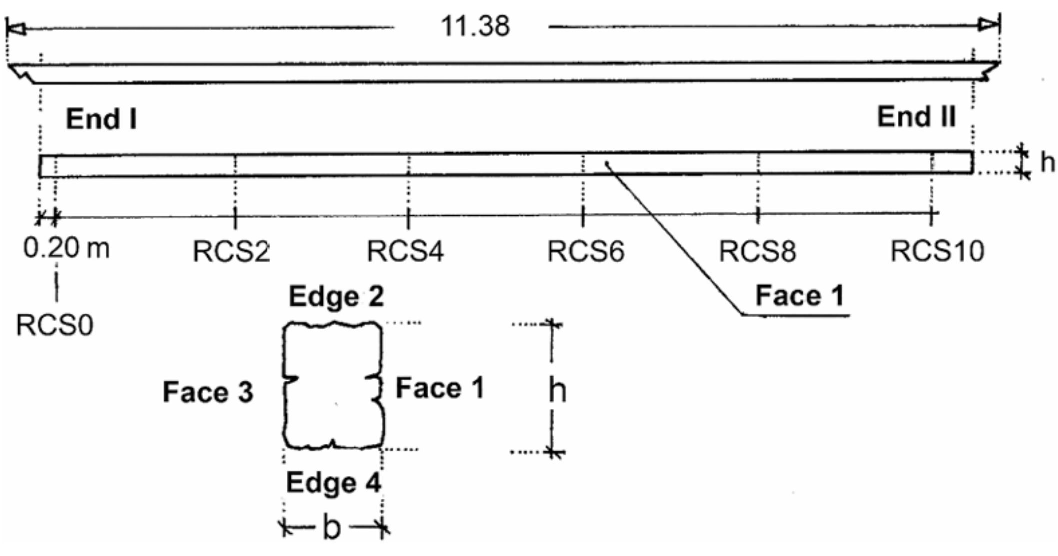

Fig. 5. Scheme for selecting the standard cross-section of a beam (Cabaleiro and Branco, 2018)

$$I_y = \int_A x^2 dA; \quad I_x = \int_A y^2 dA;$$

$$I_x = \sum_{i=1}^{n} I_{xi} \quad I_y = \sum_{i=1}^{n} I_{yi} \quad I_{xy} = \sum_{i=1}^{n} I_{xyi}.$$

Laser scanning allows obtaining an accurate digital model of the beam cross-section as a point cloud that fully corresponds to the actual contours (Fig. 6). For calculation purposes, the obtained section is divided into many triangular elements. The cross-sectional area is determined as the sum of the areas of all formed triangles. The moment of inertia of the section is calculated sequentially: first, the moments of inertia of individual triangular elements are determined, then the total moment of inertia of the section is calculated using the Steiner parallel axis theorem. This technique ensures an accurate assessment of the RBC of aging elements of ancient timber structures.

Balancing Safety Requirements and Historical Heritage Preservation

The study of the RBC of ancient timber structures faces two fundamental difficulties. On the one hand, it is necessary to ensure compliance with modern reliability standards for building structures. On the other hand, it is extremely important to preserve authentic materials, historical manufacturing technologies, and the original spatial configuration of the architectural heritage. International principles for the protection of architectural monuments place special emphasis on the principle of minimal intervention. However, in real engineering practice, a contradiction inevitably arises between the requirements of ensuring structural safety and the need to preserve the historical and cultural value of the object (EN 17121, 2019).

When conducting research on the resource of bearing capacity of historical structures, specialists often face a lack of long-term strength data for structures that have been in operation for many centuries. Of particular interest in this regard is the timber structural system of the Church of the Nativity in Bethlehem (Fig. 7). The preserved timber elements of this unique structure include roof trusses reconstructed by Venetian masters at the end of the 15th century, as well as a system of cedar beams dating back to the era of Emperor Justinian (6th century). Throughout its history — in the 11th, 15th, and 19th centuries — the structure underwent multiple repairs and modernizations.

During the survey of the Church of the Nativity in Bethlehem in 2012, it was found that centuries of exposure to atmospheric precipitation and fungal attack led to a loss of up to 75 % of the cross-sectional area in certain timber structure areas. Long-term operation with stress concentration around natural wood defects reduced bending strength by 30–50 %. A comprehensive analysis, including on-site rapid assessment and laboratory studies, revealed that 14 % of the original oak and pine elements do not meet modern bearing capacity requirements and require priority strengthening or replacement (Macchioni et al., 2012). The preservation of architectural monuments requires a comprehensive approach combining structural safety with maximum preservation of the authenticity of building materials.

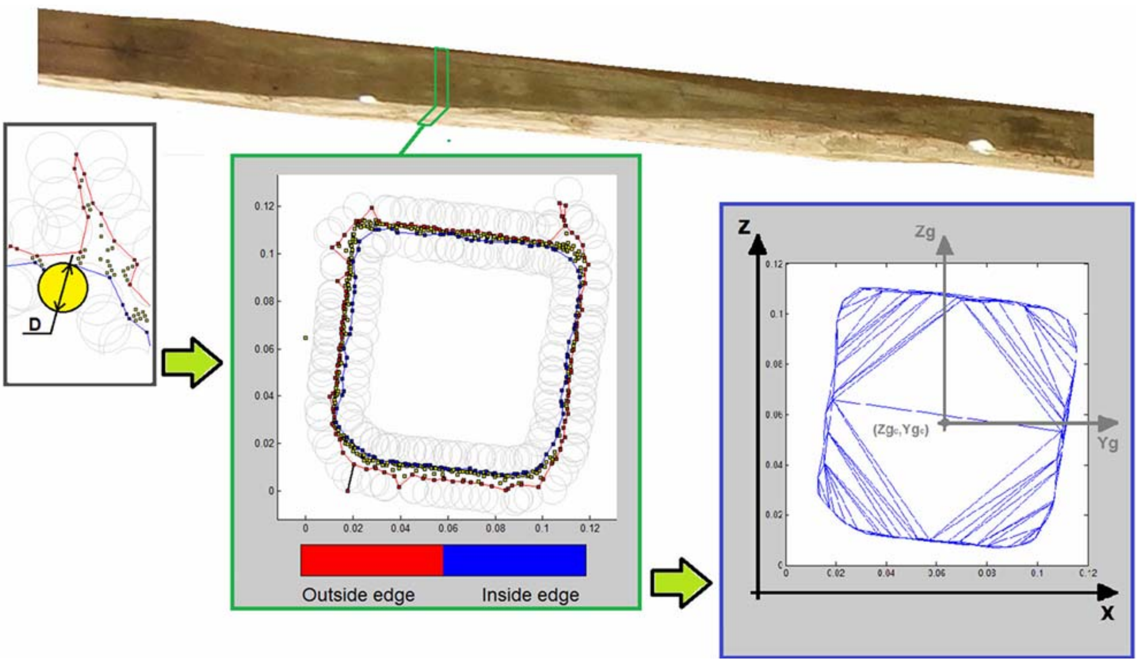

Fig. 6. Calculation of cross-sectional area and moment of inertia using the triangular segmentation method (Cabaleiro and Riveiro, 2016)

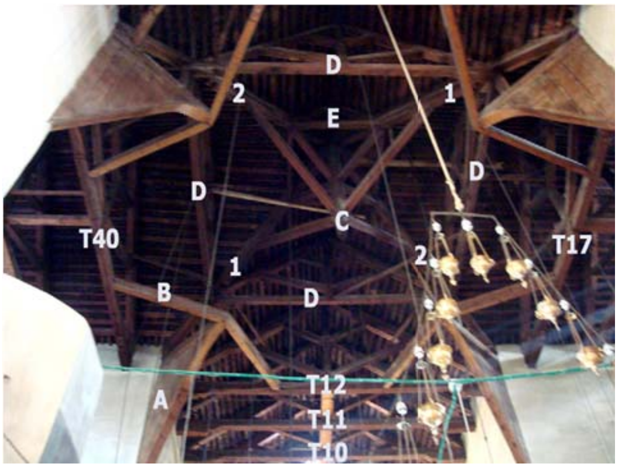

Fig 7. Star support system (Macchioni et al., 2012)

According to international restoration standards, special intervention criteria are established for historical timber structures. The replacement threshold for structural elements is set at 40 % of the original bearing capacity. For particularly valuable objects, this indicator may be adjusted to 40 %. In cases where the condition of elements exceeds this threshold, gentle conservation methods are applied, including treatment with epoxy compounds and antiseptic protection (ICOMOS; GOST R 55567-2013; GB 50165-2020; EN 16873:2016).

To protect historical buildings from natural disasters and municipal works, such as floods, landslides, or infrastructure projects, as well as to meet the needs of tourism and scientific research, it becomes necessary to relocate individual historical timber structures to special protection zones. This process requires a comprehensive interdisciplinary approach combining the principles of structural mechanics, materials science, and climatology. There are many well-known cases of historical building relocation, such as the complex of timber buildings on Kizhi Island, the Skansen Open-Air Museum in Sweden, and the complete relocation of the Yongle Palace in Shanxi, China (Gushchina et al., 2014; Rentzhog, 2007; Wang, 2005). The process of relocating timber structures includes several critically important aspects: careful dismantling and subsequent reassembly of structural elements, thorough analysis of the climatic conditions of the new location (temperature-humidity regime, snow loads), as well as prediction of possible foundation settlement. Special attention is paid to working with historical materials. Since original timber structures were often created without antiseptic treatment, accurate diagnostics of the internal condition of the material are necessary before dismantling. During transportation, it is essential to minimize possible damage. When replacing lost elements, material compatibility must be considered: matching wood species, coordinating shrinkage coefficients, and ensuring long-term stability of connections (Kisternaya, 2000; Tiunov and Shashkin, 2020).

Conclusions

Ancient timber structures, as an important part of cultural heritage, present a complex and difficult task in assessing and preserving their RBC. The heterogeneity of wood, the combined influence of environment and loads, biological degradation, and other factors make traditional assessment methods insufficiently accurate for predicting the long-term performance of structural elements. Research on this problem is significant not only for ensuring the structural stability of preserved historical buildings but also for providing a scientific basis for the sustainable preservation of cultural heritage. Traditional assessment methods are unable to fully reflect the degradation patterns of material properties during long-term operation, necessitating the use of modern non-destructive testing methods and interdisciplinary research to address this complex challenge.

The heterogeneity of wood is due to natural differences in species, defects, and fiber direction, leading to a scatter in strength characteristics. Research on the RBC of historical buildings requires an accurate assessment of the uneven accumulation of damage in old wood during long-term operation. When repairing and surveying historical buildings, it is necessary to fully consider the property differences between new and old wood, as well as their compatibility.

The loss of wood strength is mainly due to the thermofluctuation mechanism, temperature and humidity fluctuations, and biological degradation. Experimental studies show that increasing temperature and humidity significantly accelerates wood creep and fatigue crack growth, especially reducing its bending strength. Under high humidity conditions, the activity of fungi and insect pests increases, further exacerbating material degradation. Most existing experimental and prediction methods control only individual influencing factors, whereas testing methods under long-term loads considering the combined impact of multiple factors require further development.

When studying the RBC of ancient timber structures, the long-term accumulation of irregular damage leads to changes in the shape and cross-sectional area of elements. This directly affects the strength, stiffness, and bending characteristics of the structure, and also significantly alters the initial stress state of elements, causing additional bending moments and torsion not foreseen in the design, accelerating structural failure. Accurate identification and measurement of weakened cross-sections of elements is an important part of RBC research.

In conclusion, it should be emphasized that the study of the RBC of ancient timber structures is an important scientific direction with both fundamental and applied significance. This research not only allows understanding of the aging mechanisms of wood under the influence of long-term operational and environmental impacts but also creates a scientific basis for the preservation of architectural heritage monuments. Particular attention in future research should be paid to the comprehensive analysis of interrelated factors, including changes in the physical and mechanical characteristics of wood, geometric transformations of element cross-sections, and the associated redistribution of internal forces. Promising directions include the development of improved non-destructive testing methods and the advancement of computer modeling. Solving these problems requires the combined efforts of specialists from various fields of knowledge, which will allow finding an optimal balance between the requirements of structural reliability and the need to preserve the historical authenticity of architectural objects.

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ПРОБЛЕМЫ ОПРЕДЕЛЕНИЯ РЕСУРСА НЕСУЩЕЙ СПОСОБНОСТИ ЭЛЕМЕНТОВ ИСТОРИЧЕСКИХ ДЕРЕВЯННЫХ КОНСТРУКЦИЙ

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Аннотация
Введение: Ресурс несущей способности (РНС) деревянных конструкций исторических зданий и сооружений, срок эксплуатации которых составляет 100 и более лет, не может быть определен без учета их особенностей. В то же время эта проблема имеет важное теоретическое и практическое значение для оценки технического состояния, сохранения и реставрации объектов культурного наследия. **Цель работы:** систематизация научных данных о влиянии различных факторов на РНС элементов исторических деревянных конструкций. **Методы:** эксплуатационная несущая способность элементов деревянных конструкций главным образом определяется термофлуктуационным механизмом разрушения макромолекул целлюлозы («скелета» древесины), что приводит к деградации прочности, ползучестью, а также физическим износом. Оценка совокупного эффекта от воздействия данных факторов позволяет определять РНС конструкции. Кроме того, при длительных сроках эксплуатации сооружения необходимо дополнительно учитывать возможные изменения: климата, ландшафта местности, свойств защитно-декоративных покрытий, конструктивных и объемно-планировочных решений, пространственного положения, функционального назначения, статуса объекта как памятника, а также законодательной базы проектирования и реставрации. Уточненная оценка должна включать анализ влияния технологических особенностей возведения. **Результаты:** комплексный анализ показал необходимость совместного учета и взаимосвязей силовых и средовых воздействий, деформативных и прочностных свойств древесины, физического износа и дефектов, сложного характера напряженно-деформированного состояния элементов деревянных конструкций исторических зданий и сооружений для оценки их РНС, а также разработки стратегии обеспечения баланса между механической безопасностью и сохранением культурно-исторической ценности объектов.

Ключевые слова: ресурс несущей способности; исторические деревянные конструкции; длительная прочность; физический износ; геометрическая нелинейность; физическая нелинейность.

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PROBABILISTIC RELIABILITY ANALYSIS OF A BENDING CLT ROOF SLAB BASED ON DEFLECTION CRITERION

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Abstract
Introduction: Cross-laminated timber structural elements are being actively introduced into the construction practice of residential and public buildings. A special factor in the design of CLT structures is the principles of ensuring their reliability, since a large amount of statistical data on the safety level of such structures has not yet been accumulated due to their relative novelty. **Objective of the study** is to develop an algorithm for probabilistic analysis of a bending CLT roof slab over a given service life based on the deflection criterion (linear displacements). **Methods**: The reliability indicator of a CLT roof slab is taken as the probability of failure-free operation, which is estimated by frequency based on random variable generation using the Monte Carlo method, employing an adopted mathematical model of the limit state. The numerical approach to reliability assessment, based on an analytical expression of the limit state, is the most effective approach due to the simplicity of algorithm implementation and reliable results when using various types of random variables. **Results**: An algorithm has been developed to evaluate the probability of failure-free operation of a CLT roof slab based on the deflection criterion when designing the panel for a design service life. Probabilistic analysis allows selecting the most efficient structural solution for a CLT roof slab for a given reliability index β. The influence of lamella thickness tolerance factors of the CLT roof slab on reliability (probability of failure-free operation) has been established.

Keywords: cross-laminated timber; deflection; probability of failure; bending; slab; reliability index.

Introduction

Cross-laminated timber (CLT) is actively used for load-bearing and enclosing structures of residential and public buildings and structures. From a structural point of view, a CLT roof slab is a factory-manufactured solid timber slab consisting of at least three orthogonally glued layers of solid or finger-jointed boards. This structural solution allows its effective use under various types of stress-strain states, including bending, in the form of beams and roof / floor slabs.

The global cross-laminated timber production market volume in 2023 amounted to USD 1,024.4 million and, according to forecasts (Fortune Business Insights, 2025), will grow from USD 1,174.1 million in 2024 to USD 3,537.9 million by 2032. It is also noted there that CLT structural elements have advantages in terms of construction assembly speed — building assembly reaches up to 14,000 square feet (1,300 m²) per day with 6 technical workers, while construction work of a similar scale using classical building materials can take several weeks and require significantly more labor. According to data (Zhang and Lan, 2022), the demand for CLT structural elements in the Pacific Northwest region will reach 0.190 million m³/year by 2035, compared to approximately 0.008 million m³/year in 2016–2018 (less than 1 % of the annual timber harvest volume in the Pacific Northwest region). In 2020, the global volume of cross-laminated timber production was estimated at 3.4 million cubic meters per year (De Araujo and Christoforo, 2023). The development prospects for constructing buildings and structures from CLT panels are also widely discussed in research (Younis and Dodoo, 2022; D’Amico et al., 2021; Anwar et al., 2024).

In a recent study (Kurzinski et al., 2022), it is noted that the technology of using cross-laminated timber in construction has only been introduced over the last three decades, as a result of which production and design standards for CLT structural elements are still under development. One of the key factors in regulating the calculation and design of CLT structures is the principles of ensuring their reliability and forming a system of design parameters and limit states.

The reliability of building structures within the current normative design method is ensured by using safety factors (partial factors) for design parameters in mathematical models of limit states. This method of justifying the reliability of building structures is called the limit state design method. Limit state design, developed by a team of Soviet scientists in the 1940s and first adopted into the USSR regulatory document system in 1955, has gained wide recognition worldwide and was subsequently

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used as the basis for ISO-2394 and the Eurocode system, where it is called the “partial factor method”. As noted in a study (Mkrtychev, 2022), “the limit state design method allows ensuring the required level of reliability of buildings and structures, which is confirmed by design, construction, and operation experience. However, this method has a number of disadvantages, for example, it is impossible to determine what level of reliability in quantitative terms is formed as a result of applying design codes, and whether this reliability level is the same for buildings and structures of different structural schemes and made from different materials”.

The next stage in the evolution of design codes is the use of full probabilistic calculations for building structures. This approach allows quantifying the reliability of a building structure or its individual element in the form of the probability of failure-free operation or the reliability index β. One of the key studies in this direction is the article (Köhler et al., 2016), which provides statistical information on random variables in CLT panel design and the main principles of probabilistic calculation.

Currently, there are already a number of studies containing algorithms for probabilistic reliability assessment of CLT slabs. Bending tests of a CLT slab were conducted (Solovev et al., 2024), and a methodology for probabilistic reliability analysis based on the strength criterion of normal sections of the panel was developed. The probability of failure of CLT panel building walls is assessed (Aloisio and Fragiacomo, 2021), depending on the peak ground acceleration (PGA) during an earthquake. Probabilistic reliability analysis of CLT panels under seismic loads is also considered in (Sun et al., 2018; Sun et al., 2020). The influence of load duration on the rolling shear strength of cross-laminated timber panels with different cross-sectional arrangements (five-layer and three-layer) was evaluated using probabilistic reliability analysis (Li and Lam, 2016).

Algorithms for probabilistic reliability analysis of CLT slabs under bending should also be supplemented with criteria of the second group of limit states, including deflection. Bending tests of CLT slabs, for example, (He et al., 2018; Song and Hong, 2018; O’Ceallaigh et al., 2018; Ma et al., 2021; Dong et al., 2021), show that the maximum permissible deflection according to aesthetic-psychological requirements in slabs occurs earlier than the maximum permissible normal or shear stresses, as noted in Fig. 1.

Thus, in a number of tasks, the factor of the second group of limit states (states exceeding which disrupts the normal operation of building structures, exhausts their durability resource, or violates comfort conditions) may become decisive when assigning cross-sectional dimensions of elements.

Subject, Tasks and Methods

The subject of this study is the reliability of a CLT slab under bending based on the stiffness (deflection) criterion. To develop an algorithm for probabilistic reliability analysis of a bending cross-laminated timber slab, it is necessary to solve the following tasks: formulation of a mathematical model of the limit state in analytical form; substantiation of the randomness / determinism of parameters in the limit state model with selection of the most reliable distribution functions of random variables and their parameters; development and automation of a calculation algorithm with analysis of factors affecting the reliability of the CLT slab. The Monte Carlo data generation method, which is most

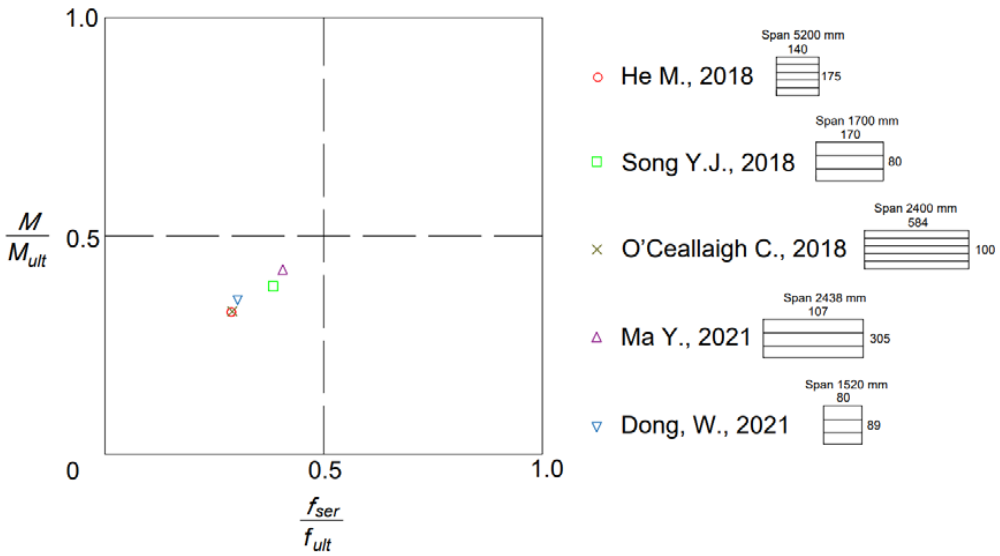

Fig. 1. Graphs of reaching maximum relative deflections during testing of CLT slabs depending on the relative ultimate bending moment based on strength

effective for simple analytical mathematical models of limit states and a set of different types of random variable distributions, is adopted as the reliability assessment method.

According to CSA O86-14 and the Canadian CLT Handbook (2019), the maximum deflection of a bending CLT slab can be determined by the formula:

$$\Delta = \Delta_{ST} + \Delta_{LT} \cdot \quad {}_{creep}, \qquad (1)$$

where Δ_{ST} is the elastic deflection caused by short-term and / or standard loads, without combination with permanent loads; Δ_{LT} is the elastic deflection caused by the action of long-term and permanent loads; K_{creep} is the creep factor, taken as K_{creep} = 2.0 for dry service conditions (DeSantis, 2023).

Loads can be classified by duration of application based on Eurocode 5 “Design of timber structures” (Table 1).

The deflection under a given uniformly distributed load q, acting perpendicular to the surface of a single-span slab (beam), can be calculated as the sum of deflections caused by the bending moment and transverse shear, using the effective bending stiffness $(E \cdot I)_{eff}$ and the effective shear stiffness $(G \cdot A)_{eff}$:

$$\Delta = \frac{5}{384} \frac{q \cdot l^4}{(E \cdot I)_{eff}} + \frac{1}{8} \frac{q \cdot l^2 \cdot k}{(G \cdot A)_{eff}}, \qquad (2)$$

where l is the span of the CLT slab; k is the shear correction factor, taken as 1.0 for rectangular cross-sections according to CSA O86-14.

For the case of a concentrated force *P* at mid-span, formula (2) becomes:

$$\Delta = \frac{1}{48} \frac{P \cdot l^3}{(E \cdot I)_{eff}} + \frac{1}{4} \frac{P \cdot l \cdot k}{(G \cdot A)_{eff}}. \qquad (3)$$

Table 1. **Classification of load duration according to Eurocode 5**

Load Duration Class	Cumulative Load Duration
Permanent	> 10 years
Long-term	6 months – 10 years
Medium-term	1 week – 6 months
Short-term	< 1 week
Instantaneous	not specified

The effective bending stiffness is calculated by the formula:

$$(E \cdot I)_{eff} = \sum_{i=1}^{n} E_i \cdot b_y \cdot \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i \cdot b_y \cdot t_i \cdot z_i, \qquad (4)$$

where E_i is the modulus of elasticity of the *i*-th layer of wood in the CLT slab; designations of geometric parameters are shown in Fig. 2.

The effective shear stiffness $(G \cdot A)_{eff}$ can be calculated by the following formula:

$$(G \cdot A)_{eff} = \frac{\left(h - \frac{t_1}{2} - \frac{t_n}{2}\right)^2}{\left[\left(\frac{t_1}{2G_1 \cdot b_y}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i \cdot b_y}\right) + \left(\frac{t_n}{2G_n \cdot b_y}\right)\right]}, \qquad (5)$$

where G_i is the shear modulus of the *i*-th layer of wood in the CLT slab; designations of geometric parameters are shown in Fig. 2.

In (Volynsky, 2006), statistical indicators of the properties of softwood timber in the USSR at 12 % moisture content are established. The average density of softwood timber is 485 kg/m³ (4.76 kN/m³) with a coefficient of variation of 18 %. The JCSS Probabilistic Model Code, Part 2 — Load models: 2.1 — Self-Weight states that for the self-weight of structural elements, a normal (Gaussian) distribution hypothesis can be used. The cross-sectional dimensions of the CLT slab and individual lamellas have certain tolerances established by the manufacturer’s standard and industry standards (e.g., GOST R 56706–2015 “Glued slabs made of cross-laminated timber. Technical specifications” and GOST 24454–80 “Softwood lumber. Dimensions”). In the absence of sufficient data for fitting a probability distribution, but having the variability bounds of dimensions as random variables, a uniform probability distribution for the geometric parameters of the cross-section is adopted at the first stage of reliability analysis.

The modulus of elasticity and shear modulus of wood have shown good convergence with a normal probability distribution in many practical studies (Solovev and Soloveva, 2025).

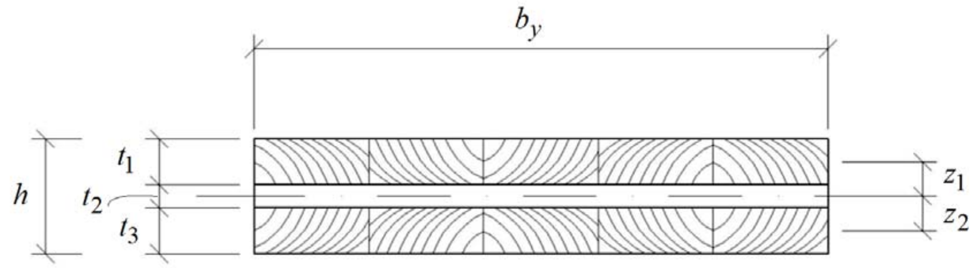

Fig 2. Geometric parameters of CLT panel cross-section using the example of a three-layer panel

Research Results and Discussion

Suppose the following statistical information for random parameters in the mathematical model of the limit state is known (Table 2).

Parameter values are given in N/m due to the adopted panel width b_y = 1 m.

The roof slab is represented by a design model of a single-span simply supported beam with a uniformly distributed load.

The maximum snow load values s over n years of operation of a CLT slab can be described by the Gumbel distribution law:

$$F(s) = \exp\left[-\exp\left(\frac{\alpha - s + \beta \ln n}{\beta}\right)\right], \qquad (6)$$

where α is the location parameter of the Gumbel distribution; β is the scale parameter of the Gumbel distribution.

For example, for a weather station near the city of Vologda, the following values were obtained over >50 years of observations: $\alpha = 86{,}9$ kg/m² (0,852 kPa), $\beta = 28{,}5$ kg/m² (0,280 kPa).

To generate random variable values using the Monte Carlo method, it is necessary to perform an inverse transformation of function (6) using the N.V. Smirnov method. Hence:

$$S_i = F^{-1}(s) = \alpha - \ln\left(-\ln(U\left[0;\ 1\right])\right) + \beta \ln n, \qquad (7)$$

where $U\left[0;\ 1\right]$ are generated values from a uniform distribution in the interval [0; 1].

The limit state function $g(X)$ can be written as:

$$g\left(\mathbf{X}\right) = \Delta_{ult} - \Delta\left(\mathbf{X}\right), \qquad (8)$$

where $\mathbf{X}$ is the vector of random variables (Table 2); Δ_{ult} is the maximum permissible deflection; $\Delta\left(\mathbf{X}\right)$ is the random deflection calculated from $\mathbf{X}$ values based on the mathematical model (1).

The probability of failure P_f can be calculated using Monte Carlo data generation as:

$$P_f \approx \frac{1}{N}\sum_{j=1}^{N} I\left[g\left(\mathbf{X}\right) < 0\right], \qquad (9)$$

where $I\left[g\left(\mathbf{X}\right) < 0\right]$ is the indicator function, which takes the value 1 if condition $I\left[g\left(\mathbf{X}\right) < 0\right]$ is true and 0 if condition $I\left[g\left(\mathbf{X}\right) < 0\right]$ is false; N is the number of initial data generations.

Based on the mathematical model of the limit state (8) and the statistical data in Table 2,

Table 2. **Statistical information for random parameters**

Random Variable	Probability Distribution		
	Distribution Function	Parameters	Note
Self-weight of CLT slab, γ	Normal distribution	$m_\gamma = 4850$ N/m³, $S_\gamma = 873$ N/m³	–
Weight of structures on CLT slab (insulation, membrane), q_1	Normal distribution	$m_{q1} = 250$ N/m, $S_{q1} = 25$ N/m*	–
Snow load, q_2	Gumbel distribution	$\alpha_{q1} = 869$ N/m, $\beta_{q1} = 285$ N/m*	Based on processing data from weather station No. 27026
Span, l	Deterministic value	$l = 4.0$ m	–
Thickness of slab layer elements (i=1, 3), $t_1 = t_3$	Uniform	$\underline{t_1} = \underline{t_3} = 39.0$ mm, $\overline{t_1} = \overline{t_3} = 41.0$ mm	According to GOST 24454–80
Thickness of slab layer elements (i=2), t_2	Uniform	$\underline{t_2} = 19.0$ mm, $\overline{t_2} = 21.0$ mm	According to GOST 24454–80
Slab width, b_y	Uniform	$\underline{b_y} = 996.0$ mm, $\overline{b_y} = 1004.0$ mm	According to GOST 56706–2015
Modulus of elasticity parallel to grain (layers 1, 3)	Normal	$m_E = 12.0$ GPa, $S_E = 1.8$ GPa	According to SP 64.13330.2017
Modulus of elasticity perpendicular to grain (layer 2)	Normal	$m_{E\perp} = 400$ MPa, $S_E \perp = 60$ MPa	According to SP 64.13330.2017
Shear modulus parallel to grain (layers 1, 3)	Normal	$m_G = 500$ MPa, $S_G = 50$ MPa	
Shear modulus perpendicular to grain (layer 2)	Normal	$m_{G\perp} = 500$ MPa, $S_{G\perp} = 50$ MPa	

100,000 values of each parameter were generated for a CLT slab over a 50-year service life, as shown in the histogram (Fig. 3).

If the obtained data array of maximum deflections is approximated by a normal distribution with distribution parameters fitted using the Distribution Fitter App of the MATLAB software package, the following parameters can be obtained: m_Δ = 0.0125 m, S_Δ = 0.0020 m.

It is proposed to approximate the obtained empirical distribution functions with a GEV (Generalized Extreme Value) distribution with the analytical form:

$$F(s(x),k)=\begin{cases}\exp(-e^{-s(x)}) \text{ if } k=0;\\ \exp(-(1+k\cdot s(x))^{-1/k})\\ \text{if } k\neq 0 \text{ and } k\cdot s(x)>-1;\\ 0 \text{ if } k>0 \text{ and } s(x)\leq -\dfrac{1}{k};\\ 1 \text{ if } k<0 \text{ and } s(x)\geq \dfrac{1}{|k|},\end{cases} \quad (10)$$

where $s(x)=\dfrac{x-\mu}{\sigma}$ is the standardized random variable, where μ is the location parameter, σ is the scale parameter; *k* is the shape parameter.

Using parameters k = –0,0775; σ = 0,0017 m and μ = 0,0117 m, obtained by fitting the distribution function through the Distribution Fitter App of the MATLAB software package for 100,000 generated deflection values $\Delta(\mathbf{X})$, a closer density distribution can be obtained (Fig. 3).

Let the maximum deflection be 20 mm. Calculate using (10):

$$\exp\left(-\left(1+k\cdot s(x)\right)^{-1/k}\right)=$$

$$=\exp\left(-\left(1-0,0775\frac{0,0200-0,0117}{0,0017}\right)^{-1/(-0,0775)}\right)=$$

$$=0,99779.$$

From 100,000 generations, in 99,723 cases the design deflection over 50 years of operation was less than 20 mm. Consequently, the reliability (probability of failure-free operation) of the CLT slab over 50 years of operation based on the deflection criterion is 99.723 %. The relative error in calculating the probability of failure-free operation using the approximation (10) and by frequency is 0.56 %. Therefore, the GEV distribution approximation can be used when there are computational difficulties with generating a large number of random parameters.

Thus, the presented algorithm for calculating the probability of failure-free operation can be reduced to the following steps:

1. Statistical parameters of distribution functions of random variables (according to Table 2) of the mathematical model of the limit state are established;
2. 100,000 values of each random variable are generated;
3. 100,000 values of the design deflection are calculated based on the mathematical model (1);

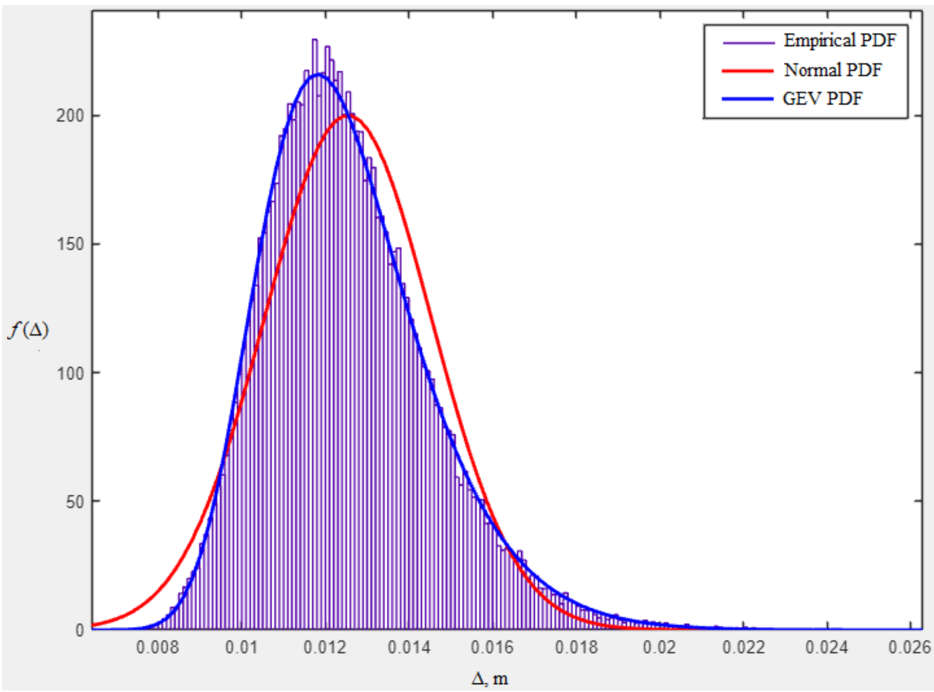

Fig. 3. Geometric parameters of CLT slab cross-section using the example of a three-layer panel: vertical axis: $f(\Delta)$ is probability density function of deflection Δ; horizontal axis: Δ is deflection value in meters

4. The empirical probability distribution function of the calculated values $\Delta(\mathbf{X})$ is approximated using the GEV probability distribution;

5. In the obtained analytical form of function (10), the variable x is replaced by the value of the maximum deflection Δ_{ult} and the probability of failure-free operation of the CLT roof slab is calculated;

6. Using the inverse Laplace function, the reliability index β is calculated from the obtained probability of failure-free operation.

According to the relationship equation between the probability of failure-free operation and the reliability index according to Eurocode 0 "Basis of structural design," the probability value obtained above corresponds to a reliability index $\beta = 2,77$.

There are various proposals for standardizing the reliability index and probability of failure (or failure-free operation). For example, (Marek, 2003) proposes the following values (Table 3).

If the data in Table 3 are taken as design values, then the reliability of the investigated CLT roof slab structure over a 50-year service life based on the deflection criterion can be considered assured under the given operating conditions. In the Table, the target reliability index β for structural elements of class RC2 over a 50-year service life is taken as β = 1.500 — the calculated reliability index for the CLT roof slab (β = 2.77) is also above this value.

However, the most effective solution for assigning the target reliability index of a building structural element or its probability of failure-free operation is an individual calculation based on the acceptable level of risk, expressed in financial equivalent of the damage cost from the occurrence of a "failure" event. More detailed information can be found in Solovev's study (Solovev and Soloveva, 2025).

An additional advantage of the developed methodology is also that the CLT roof slab can be designed for any service life, while the normative approach provides discrete division depending on the structural consequence class. Fig. 4 shows a graph of the decrease in panel reliability over time. This is mainly due to an increased probability of peak snow load occurrence over a longer service period.

Under known operating conditions of the CLT roof slab, it may be necessary to form a catalog for structures, which indicates, for example, permissible span values for the slab based on the required reliability level. The change in reliability level depending on the span for the investigated CLT roof slab under given operating conditions (Table 2) is shown in Fig. 5.

From Fig. 5, it can be seen that increasing the span of the CLT roof slab significantly affects its reliability based on the deflection criterion. Using the same slab for a span 1 meter longer leads to an almost 100 % probability of exceeding the maximum permissible deflection Δ_{ult}. In the case of unacceptably low probability of failure-free operation, a repeat reliability analysis can be performed for a shorter design service life of the slab (Fig. 4).

Table 3. **Standardized probability of failure values (Marek, 2003)**

Structural Consequence Class	First Group of Limit States	Second Group of Limit States
Low	0.000500 (β=3.291)	0.160 (β=0.995)
Medium	0.000070 (β=3.808)	0.070 (β=1.476)
High	0.000008 (β=4.314)	0.023 (β=1.995)

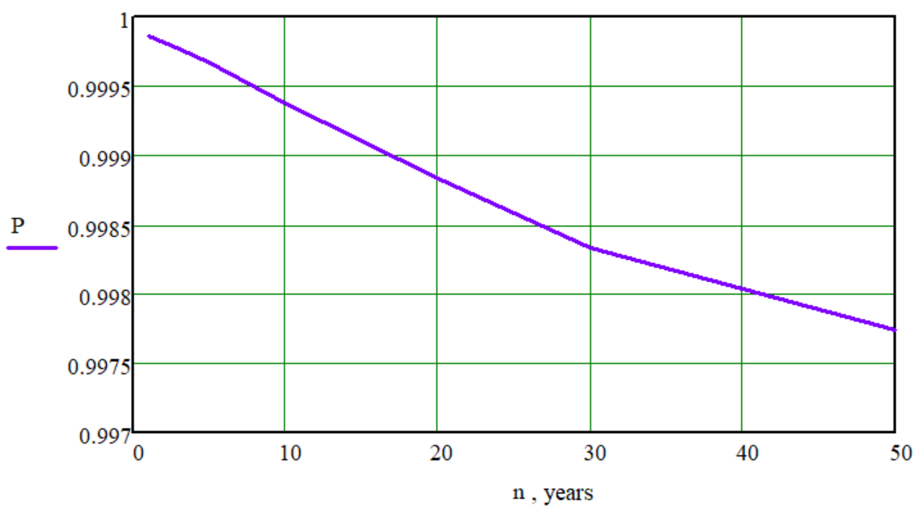

Fig. 4. Graph of reliability dependence of the designed CLT roof slab on the design service life

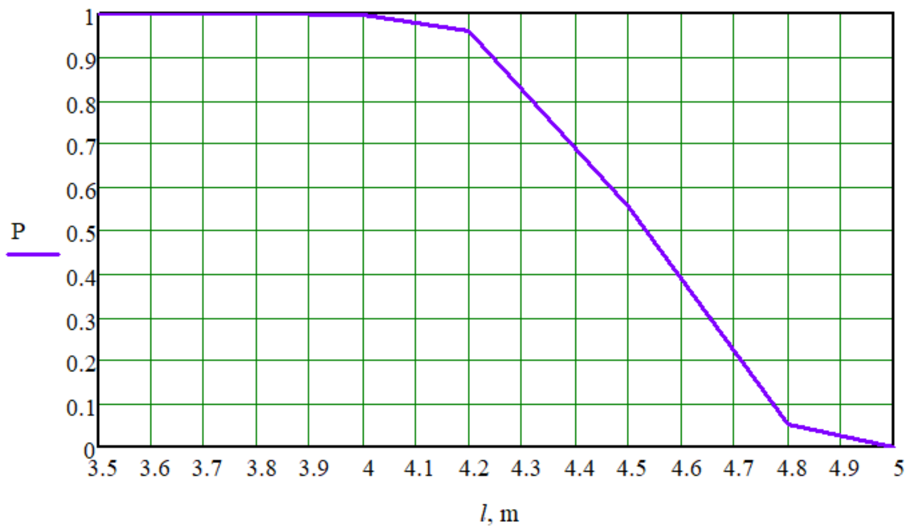

Fig. 5. Graph of reliability dependence of the designed CLT roof slab on span (based on deflection criterion)

Given statistical data from the manufacturer, such tables can be constructed for various structural panel options under different operating conditions (climatic regions, types of loads, etc.).

It is also possible to analyze the thickness tolerances of the panel lamellas t_i and their influence on reliability.

From Table 4, it can be seen that an increase in tolerance of 0.5 mm leads to a proportional increase in the probability of failure of approximately 0.06 %.

Probabilistic analysis allows identifying the factors whose variability most significantly affects reliability indicators, which will enable the formulation of control measures and, accordingly, ensure the required level of load-bearing capacity and serviceability of building structural elements.

Conclusions

1. Structural elements made of cross-laminated timber (CLT) began to be used in the 1990s, and the dynamics of their production and the construction of buildings and structures based on them have grown exponentially in recent years. Due to the fact that CLT structural elements are relatively new and do not have a sufficiently large volume of data on their durability, dynamics of load-bearing capacity and serviceability, an important scientific and technical task is the design justification of the required level of safety during the design and operation of buildings and structures made of CLT. One of the most effective tools for design reliability justification at present is full probabilistic calculations.

2. The paper proposed an algorithm for probabilistic reliability analysis of a cross-laminated timber panel based on the stiffness (deflection) criterion over a given service life. Using the developed algorithm for reliability analysis will allow selecting the most rational cross-section options for CLT roof slabs, taking into account the design service life of the building structure. Every 10 years, the expected reliability in terms of probability of failure-free operation decreases by approximately 0.5 %, which is associated with an increased probability of occurrence of a large snow load over a longer service period. Technical tolerances also affect reliability — an increase in tolerance of 0.5 mm leads to a proportional increase in the expected probability of failure by approximately 0.06 %.

3. Under known operating conditions of a CLT roof slab, it may be necessary to form a catalog for structures, which indicates, for example, permissible span values for the panel based on the required reliability level (according to load-bearing capacity and serviceability criteria). Given statistical data from the manufacturer, such diagrams can be constructed for various structural panel options under different operating conditions (climatic regions, types of loads, etc.) based on the probabilistic algorithm proposed in this study.

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Table 4. **Influence of lamella thickness tolerances of CLT roof slab on reliability**

Tolerance t_i	±0.5 mm	±1.0 mm	±1.5 mm	±2.0 mm	±2.5 mm
Reliability *P*	0.99818	0.99723	0.99713	0.99646	0.99603

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ВЕРОЯТНОСТНЫЙ АНАЛИЗ НАДЕЖНОСТИ ИЗГИБАЕМОЙ ПЛИТЫ ПОКРЫТИЯ ИЗ CLT ПО КРИТЕРИЮ ПРОГИБА

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Аннотация

Введение. Элементы строительных конструкций из перекрестно-клееной древесины активно внедряются в практику строительства жилых и общественных объектов. Особым фактором при проектировании строительных конструкций из CLT являются принципы обеспечения их надежности, т.к. на текущий момент не накоплено большого количества статистических данных об уровне безопасности таких конструкций в связи с их относительной новизной. **Цель исследования**: разработка алгоритма вероятностного анализа изгибаемой плиты покрытия из CLT в течение заданного периода эксплуатации по критерию прогиба (линейных перемещений). **Методы**: показателем надежности плиты покрытия из CLT принята вероятность безотказной работы, которая оценивается по частоте на основе генераций случайных величин по методу Монте-Карло на базе принятой математической модели предельного состояния. Численный подход к оценке надежности, на базе аналитического выражения предельного состояния, является наиболее эффективным подходом, вследствие простоты реализации алгоритма и достоверного результата при использовании различных видов случайных величин. **Результаты**: разработан алгоритм, позволяющий оценить вероятность безотказной работы плиты покрытия из CLT по критерию прогиба при проектировании панели на расчетный период эксплуатации. Вероятностный анализ позволяет подобрать наиболее эффективное конструкционное решение плиты покрытия из CLT на заданный индекс надежности β. Установлено влияние фактора допусков на толщину ламелей плиты покрытия из CLT на надежность (вероятность безотказной работы).

Ключевые слова: перекрестно-клееная древесина, прогиб, вероятность отказа, изгиб, плита, индекс надежности.

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