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SEEING THE INVISIBLE. ANALYTICAL DRAWINGS BY CONSTRUCTION HISTORY PIONEERS. RESEARCH FIELD OVERVIEW

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Abstract

Introduction: The history of construction is a discipline that began to take shape in the mid-18th century and throughout the 19th century. We as researchers need to pay particular attention to how drawing facilitated progress during this period. This article attempts to provide an overview of the above, which is currently lacking. **Methods:** In this study, two lines of investigation intersect: the history of construction and the history of drawing, specifically drawing for scientific and technical representation. The main goal is to identify the sources (authors, lines of investigation) relevant to this field, as well as to characterize the role of drawing in the authors' work, and to describe the spread of drawing as nonverbal thinking. **Results:** We have identified a number of relevant authors, described their lines of research, and listed the functions fulfilled by drawing in each case. The functions include: hypothesizing about hidden structures, visualizing the construction processes, and providing a virtual definition for elements that make up a vault. We also review how some drawings acted as a visual model of the constructive reality, or how parallel drawings served as a reflection of the different buildings' size and scale. **Discussion**: This overview adjusts some points of reference for a general picture. For having a complete understanding of the subject, it will be necessary to identify more sources and to extend the geographical scope of this search in the future. There is still much research to be done on the spread of the drawings in question.

Keywords

History, drawing, construction, analysis.

Introduction

The history of construction is a relatively young discipline. Since 2000 — when the first International Congress on Construction History was held at the Madrid School of Architecture (ETSAM) — the history of construction has been consolidated through national and international congresses (in London, Cottbus, Paris, Chicago, Brussels, and soon in Lisbon), as well as through journals and scientific societies, as a well-defined and growing academic field.

However, this field owes a fundamental debt to the research carried out in the past. As this past research was fragmented, one of the vital research branches in the history of construction is its historiography, which teaches us about the methods, hypotheses, and tools used by those who can be considered its pioneers. Here, we have focused on studying the response presented to that question by those architects, scholars, or engineers who, throughout the 18th and 19th centuries (often conditioned by the «ideological» preference of one style of architecture over others), tried to understand the construction procedures of a particular period.

One of the methodological problems they had to face was how to make the invisible visible. It was a challenge to recreate the construction procedures of the past, often hidden, or known only from ruins, or completely lost because they were based on perishable materials. So was shedding light on the geometric principles and rules of defining the size of structural elements.

What role did drawing play in the resolution of this problem? Should we assume that drawing only reflected verbal thinking? Or was it, on the contrary, an indispensable conceptual tool that implied another form of autonomous thought, which made it complete? And in that case, what degree of autonomy did it have with respect to verbal thinking?

In a broad sense, the subject has been in the air for a long time, waiting for its formulation. The contribution of drawing to the birth of a neighboring discipline, the history of architecture, which emerged in France in the 19th century, was addressed in a seminal work by S. Talenti (2000). It was an exciting invitation to do the same in the field of the history of construction. The importance of non-verbal thinking in engineering was highlighted even earlier in E.S. Ferguson's groundbreaking study (1992). However, we still lack a study that would offer a comprehensive and complete answer to these questions in our field. This article proposes a method for approaching these questions and provides a provisional response: a synthesized, panoramic vision resulting from the application of the method.

Methods

Given the breadth of the question and the scarcity of previous works, the course of action from the very beginning was to review a series of monographs that, gradually, could shape an answer, demonstrated throughout different congresses and symposiums on the history of construction.

Over the course of this research — in which two lines intersect: the history of construction and the history of drawing for scientific and technical representation — a general method for a systematic study has emerged. It consists of a series of steps that have been followed in this article.

The first step is to identify relevant authors and texts. In many cases during the period in question, while the studies purported to review the architecture of a specific period, their sources were «masked» as a chapter or a section. The next step is to identify and characterize the types of constructive problems that they studied (and addressed graphically) and the methods that they used to solve such problems. Finally, we examine the role and characteristics of the drawings that were used. To identify the images capable of operating as «non-verbal thinking», we have considered two hypotheses.

On the one hand, the nascent history of construction, just as other disciplines, would benefit from the innovations that took place in drawing for scientific or technical purposes during the 18th and 19th century. In our research, we have tried to identify how construction historians applied this type of drawing — which we will be calling «operational» drawing — and the concrete results this led to.

On the other hand, we could say that the drawing process acted as a «conceptual mental frame» that encouraged further studies. A drawing is not a mere reproduction of reality. It is the result of intellectual labor that selects, highlights, abstracts, or eliminates specific sensory evidence of the object that it represents. In this way, it shows us a substitute for reality, meant to direct our attention to certain aspects of reality. Bearing this in mind, we have sought to single out those constructive analysis drawings that would perform this function in a particularly efficient way.

This article aims to illustrate how this method can shape this field of research and guide new studies. As it is based on a limited selection of monographs, it is not exhaustive. What follows is a concise overview of the results, indicating some relevant authors, the lines of research that they followed, and the functions assigned to drawing in each case. For an in-depth discussion of each specific topic mentioned in the article, the reader should consult the materials in this article's References section.

Roman Construction: Piranesi's Virtual Hypothesis

This review will begin by taking a look at Piranesi's work. His name inevitably evokes associations with the intensely emotional, almost oppressive impression made by his prints with scenes from Ancient Rome, which so convincingly convey the idea of the power to build on an enormous scale.

But, as we are captivated by the chiaroscuro of his engravings, we might forget that Piranesi (1756) also had a genuine interest in understanding the structures that he depicted (D'Amelio and De Cesaris, 2011; Pizzo, 2011). A good number of Piranesi's drawings boldly aimed to analyze the construction procedures. Some of these drawings were a kind of «virtual hypothesis», which revealed his perception of both what he could observe in situ and of the foundations or other inaccessible parts.

Piranesi would rely on previous «ready-made» visual representations of construction procedures that he could find in the Vitruvius editions. It is a known fact that the interpreters, editors, and translators who dealt with Vitruvius from the Renaissance onwards only had a text that was often ambiguous and difficult to interpret and lacked images. The engravings in some illustrated editions, such as those by C. Cesariano (1521) or G.A. Rusconi (1590), showed hypotheses about a specific construction process, which was probably based on generalized observations of existing ruins. By manipulating and integrating these images, Piranesi achieved if not a faithful reconstruction, then at least a plausible one (Giron Sierra, 2005) (Fig. 1).

These and other plates by Piranesi, depicting Roman construction, were very influential. Until the last third of the 19th century, they were practically the only source of authority on Roman construction. This form of sharing and distributing drawings has gone quite unnoticed. These drawings reappeared in the hands of other authors, often stripped of expressiveness to give them an aseptic and technical appearance (Giron Sierra, 2015).

Sometimes such image migration and manipulation were related to a change in the way of organizing information, which, in turn, was a response to an epistemological shift. Many of J.-B. Rondelet's plates on Roman construction are an example of this. Piranesi's images, which belonged to a conceptual framework where «knowing» meant showing many layers of information about a specific architectural object, had to be integrated into a new framework where «knowing» meant separating and comparing these layers with others from different sources. Piranesi's «palimpsests» had to be selected, reordered, and dressed into a neutral scientific language to place them into those thematic tableaux (Fig. 2).

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Reassembling the Greek Temple by Visualizing it under Construction: Pieces, Devices, and Movements

The authors of the generation that followed Piranesi opened two new fronts of study: Greek architecture (which Piranesi had underestimated, considering it inferior to Roman architecture) and Gothic architecture. But in fact, these two types of architecture required very different approaches from whoever wanted to document their history.

The first publications on Greek architecture mainly captured its picturesque aspect (Houel, 1782; Le Roy, 1758). However, the next generations would discover «in situ» that neither the forms nor the proportions of the temples were as they expected, not fitting the Vitruvian theory. It became clear that it was imperative to «learn to see» and to divorce one's mind from preconceived images. From J. Stuart and N. Revett (1762) onwards, drawing would become a vital tool for refining perception throughout the 19th century. Researchers would progressively improve drawing techniques to meticulously capture any subtleties and to accurately describe the curves and proportions and even the use of color (Pennethorne and Robinson, 1878; Penrose, 1851).

Initially, the study of construction and its representation would not be a central theme.

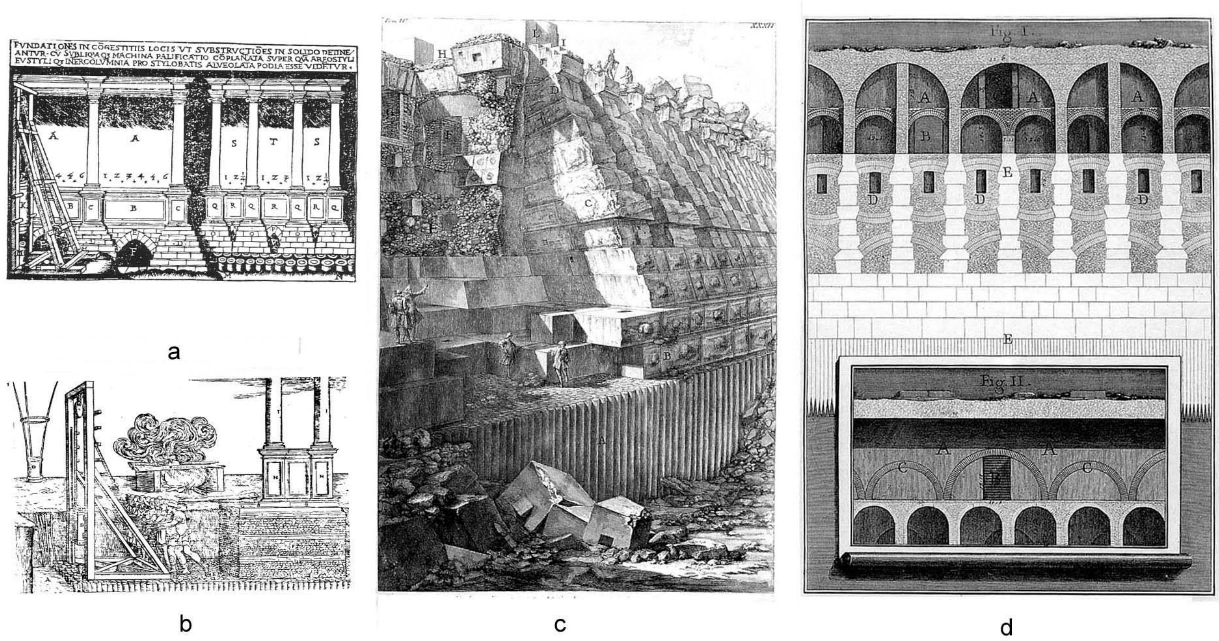


Figure 1. Roman construction and its invisible substructures. Graphic interpretations based on Vitruvius: a — Cesariano (1521); b — Rusconi (1590); c, d — construction of Marcellus' theater according to Piranesi (1756)

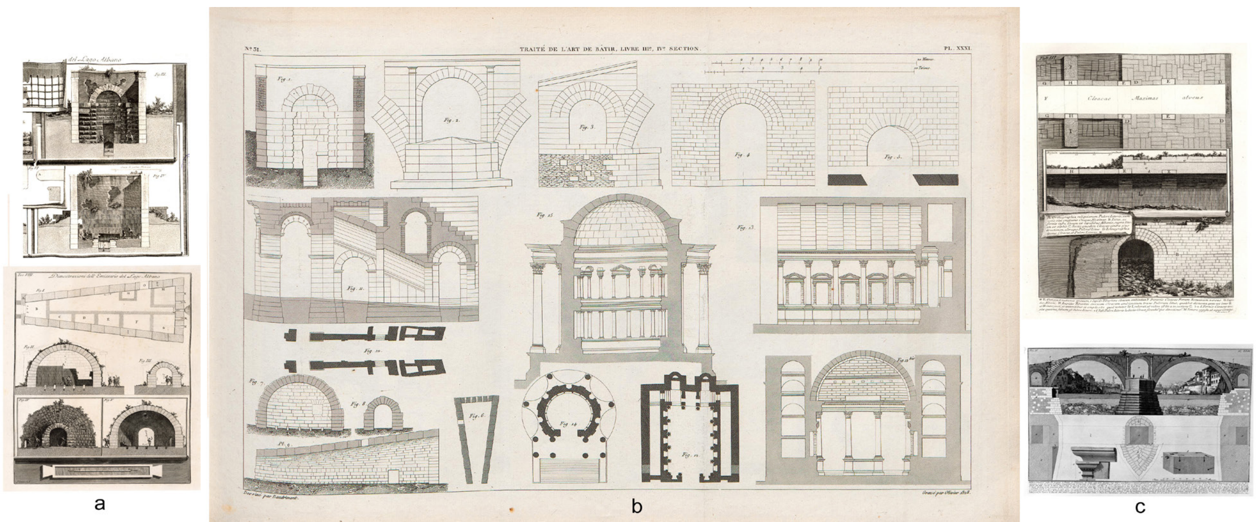


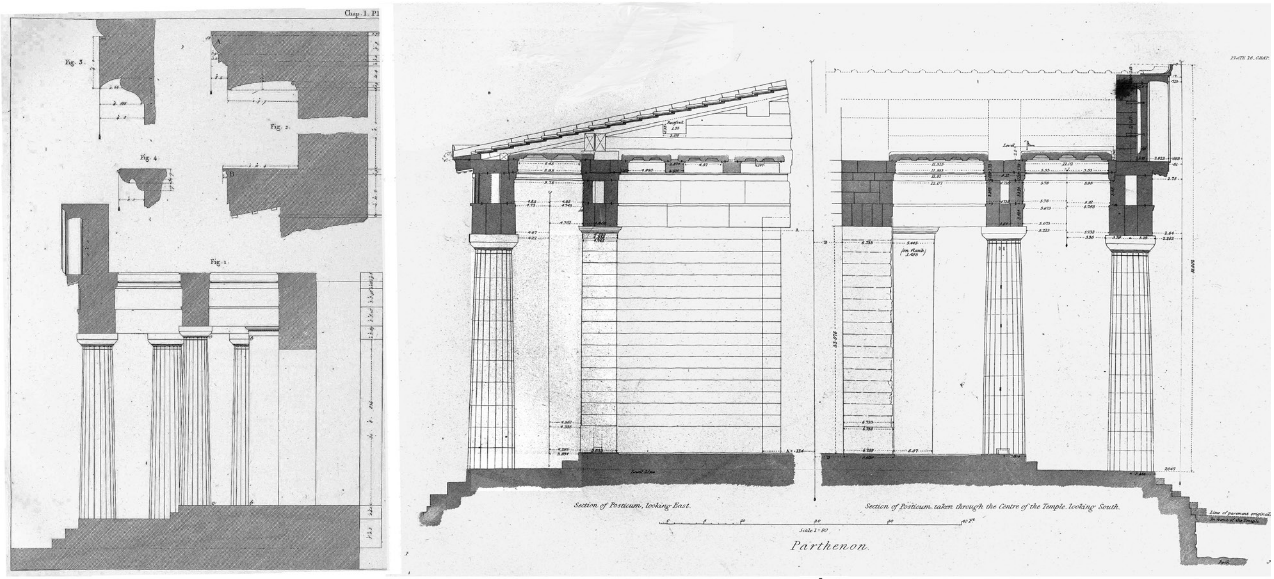
Figure 2. Left: a — Piranesi's Emisario del Lago Albano (1764). Right: c — Piranesi's (1761) Cloaca Maxima, d — Piranesi's (1756) Ponte Fabricio. Center: b — incorporation of those images in Rondelet (1830–1832)

The evolution of Greek temples seemed to be more relevant to the search for formal and optical improvements rather than to the optimization of their constructive resolution. Even so, there were various interesting comments and drawings, where rigorous surveys (both in elevation plan and in section) reflected not only the proportion and measurements of a temple, but also each joint, assembly piece, or degree of finish (Cockerell et al., 1830; Penrose, 1851; Wilkins, 1832) (Fig. 3).

Here, unlike in Roman construction, the problem of «seeing inside» the solid buildings was, in a way, solved. The temples' scattered remains made it possible to examine and reasonably describe the individual pieces (bases, columns, drums, lintels) that made them up. The real challenge was different: to recompose, so to speak, the building's carcass, and to reveal, as far as possible, how the various pieces were assembled and why they had been added (for example, for seismic resistance).

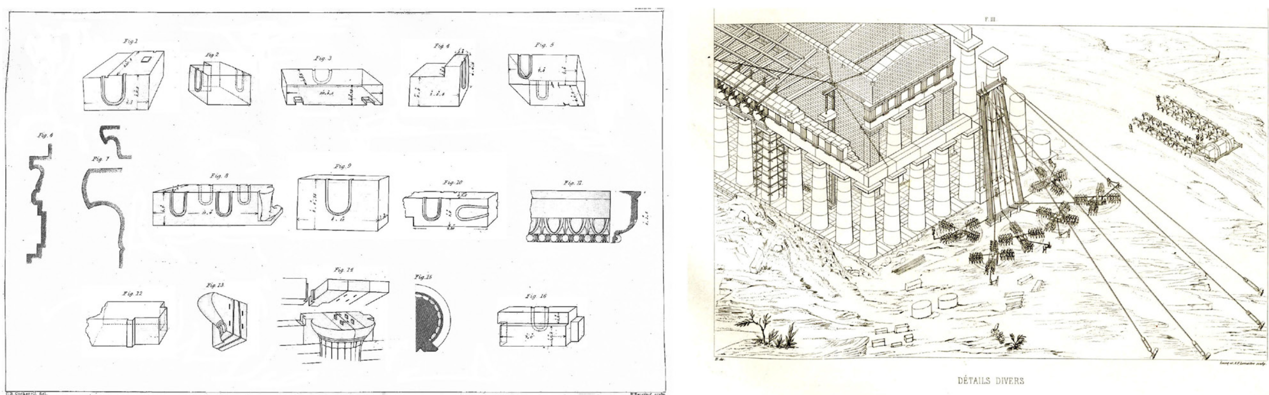
On the other hand, it was possible to reveal the stages and process of construction in a much more reliable way. There were even places where multiple stages of the construction process were evident. For example, in Selinunte, where a Greek temple seemed to have been suddenly abandoned mid-construction, the operations of extracting, transporting, lifting, and putting in place could be reconstructed easily. This led to the creation of drawings detailing how a particular piece was moved and set in its position (Cockerell et al., 1830) or comprehensive diagrams showing all the machinery involved in the temple construction in action (Hittorff and Zanth, 1870) (Fig. 4).

While the definition of the constructive section of the temple advanced with each new exploration,



a b

Figure 3. Left: a — early surveys of Greek temples, focused primarily on their forms and proportions: J. Stuart and N. Revett (1762, 1825). Right: b — an additional description of constructive features, mid-19th century (Penrose, 1851)



a b

Figure 4. Three-dimensional views required by the visualization of ashlar pieces for reconstructing the lifting and joining operations and eventually the entire construction process: a — perspectives in (Cockerell et al., 1830); b — axonometric projection of Temple S in Selinunte under construction (Hittorff and Zanth, 1870)

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the interest in showing these techniques would lead to the occasional use of axonometry, a system that, despite being not much used in architectural drawing at the time, would allow for measuring and defining the three-dimensional form of each component. This trend is notable in some plates and illustrations (Blouet, 1833; Choisy, 1873; Hittorff and Zanth, 1870; Loviot, 1880; Wilkins and Gaudy, 1832), but at the end of the century, it gave way to recollections like those in (Perrot and Chipiez, 1898) (Fig. 5).

Gothic Construction: Robert Willis' Scientific Approach to Seeing the Invisible

The study of Gothic architecture was a more complicated task, as one could not count on a text of Vitruvius' authority to help with studying the building. To cope with this, the scholars of the first decades of the 19th century adopted a strategy that was rather reminiscent of the methods employed by naturalists. It was a matter of identifying, cataloging, and dating the building elements (windows, buttresses, pinnacles, pillars), drawing them separately, and later trying to deduce their language, rules, and chronological sequence. Various authors (Parker, 1836; Rickman, 1819) patiently compiled the formal catalogs of building elements.

But all this material, which could be used for describing the transformation and geographical distribution of architectural forms at best, was not enough to explain the reason for the architectural evolution. Researchers were beginning to see that it could be strongly conditioned by constructive

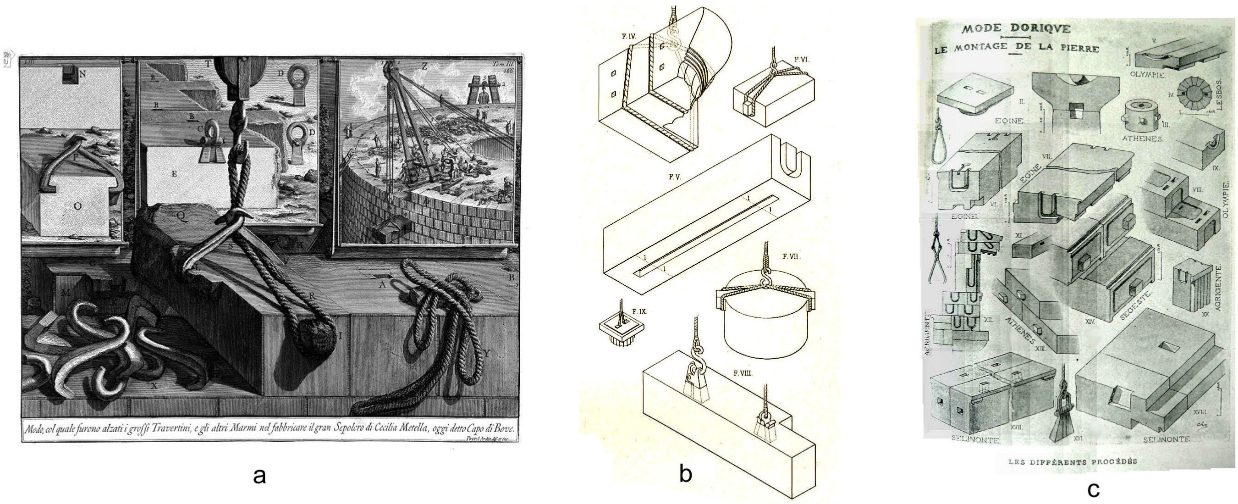


Figure 5. Representation of Greek temple lifting operations, based on interpretations of Vitruvius' ancient machinery. Left, a — Cecilia Metella's tomb under construction according to Piranesi (1756–1757); b — center: lifting devices used in the Selinunte temple (Hittorff and Zanth, 1870); c — a collection of ashlar pieces, adapted to be handled by different tools (Perrot and Chipiez, 1898)

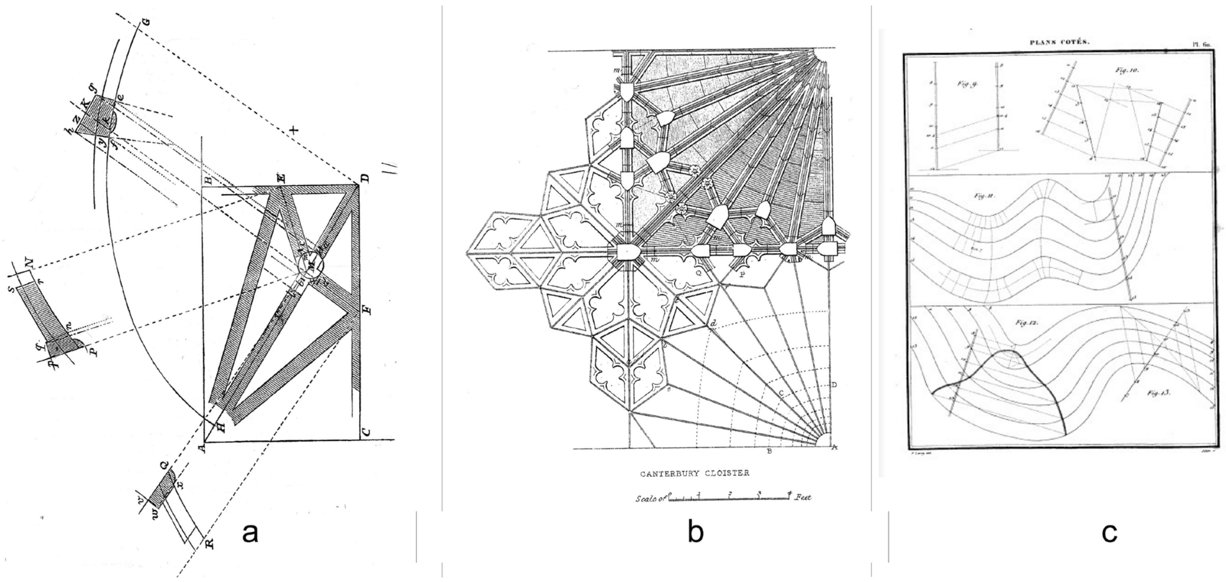


Figure 6. Use of advanced drawing techniques by R. Willis (1842) to study Medieval vaults: a — separate elements defined through the descriptive geometry procedures; b — the surface of the intrados depicted by contour lines. Such techniques may be found in French treatises, such as c — Ch.-F.-A. Leroy (1834), and occur rarely in English cartography

issues, unlike what we can observe in Greek architecture. The study of constructive issues would soon become crucial for certain historians. In this context, elements such as the vault and its supports emerged as a priority research topic. Their types and forms had to be described (Whewell, 1830). But above all, it was necessary to understand how they had been constructed.

Robert Willis pioneered in this field with fundamental work. The problem was not easy to solve. He could not count on enough Gothic ruined buildings (unlike with Greek architecture) to reassemble their vaults from the ruin pieces. Just like Piranesi during his attempts to understand Roman construction, he had to reveal the invisible.

And like Piranesi, Willis understood that the solution could only come to him if he drew the buildings. What Willis wouldn't do is rely on unprovable hypotheses. He realized that what was needed was the most accurate virtual anatomy of the vault. To do this, he would have to resort to a whole arsenal of graphic procedures, some of them recently developed (Giron Sierra, 2016).

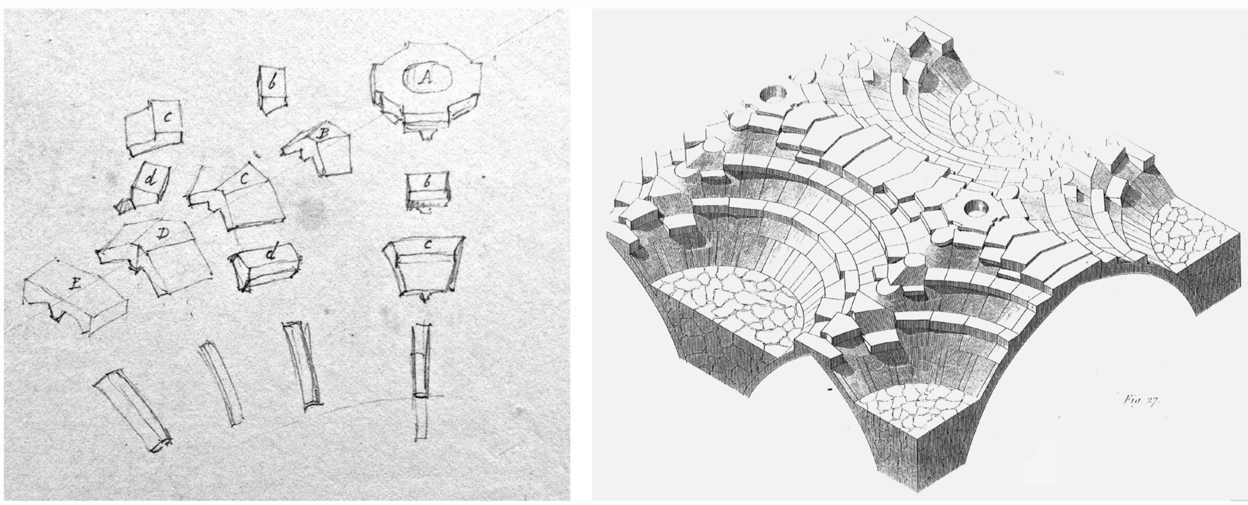
Willis realized that it was necessary to start with a rigorous survey of the two faces of the vault (its intrados and its extrados) and then, from these two surfaces, delve into the inner structure. To deduce and determine each piece's shape, he borrowed graphic procedures from descriptive geometry (a modern science of French origin). He also used contour lines — a technique that was just making its tentative first steps in English cartography — to describe the surface's curvatures (Fig. 6). Finally, he decided that the vaults' extrados needed to be shown in mensurable three-dimensional drawings (Fig. 7). To do this, he used a system of representation that W. Farish had recently invented: isometry (Farish, 1822). Thanks to those drawings, Willis obtained and communicated a better understanding of the relationship between the apparent form and the actual construction of an English Gothic vault.

Visual Models of Perception. Viollet-le-Duc and the Anatomy of Gothic Construction

In France, Viollet-le-Duc approached similar issues with unique ingenuity. If Willis' graphic ability to guess what was within a vault simply through drawing was truly striking, Viollet-le-Duc deserves as much admiration for his capacity to create memorable «graphic models». His anatomical drawings, once contemplated, create a lasting impression, shaping and refining our perception of a building's constructed reality.

To achieve this, Viollet-le-Duc progressively deployed novel anatomical strategies. For example, at first, Viollet-le-Duc (1847) represented the pieces of the «tas de charge» (springing point of an arch) as if they were scattered over a surface (Fig. 8a). Years later, he adopted another solution: he imagined the elements floating in three-dimensional space, separated but close enough to suggest that they were about to be coupled (Viollet-le-Duc, 1859) (Fig. 8b). This change references some innovations that had been introduced years before to medical anatomy visualization. As pointed out by researchers (Bressani, 1996), this procedure may have been inspired by Jean-Marc Bourgery (1831) (Fig. 8e) whose skull plate improved on previous illustrations such as Monro's (1759) (Fig. 8d).

Viollet-le-Duc likely also found inspiration in the stone-cutting treatises developed in the 18th century in France. Authors such as J.-B. De la Rue (1728), A. Frézier (1737), and M. Simonin (1792) studied the tracing operations to define the shape of the stones that made up the construction of typical



a b

Figure 7. Novel techniques that R. Willis explored when drawing the structure of Gothic vaults: a — separating the elements that make up the vault (unpublished study); b — showing the elements assembled on the reverse side of the vault (Willis, 1842), by using the isometric projection developed by W. Farish (1822)

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elements in contemporary architectural practice, such as niches, vaults, or domes. And they routinely illustrated them with three-dimensional images of each resulting piece (Fig. 9a). But Viollet-le-Duc's drawings went further. They had a different purpose and communicative power. They were capable of revealing the previously invisible construction of Medieval buildings with a single drawing that showed how all the components joined together and fitted in with the rest of the building (Fig. 8c).

The novelty of these drawings (just as Willis' work) made a strong impression on French researchers and led to the drawings' circulation and reproduction in other publications. The fact that the drawings appeared in a publication devoted to stone cutting (Lejeune, 1872), where they were celebrated with great admiration, suggests that they could be seen as an extension of this tradition. And, at the same time, as something that was opening up unexpected analytical possibilities (Fig. 9b).

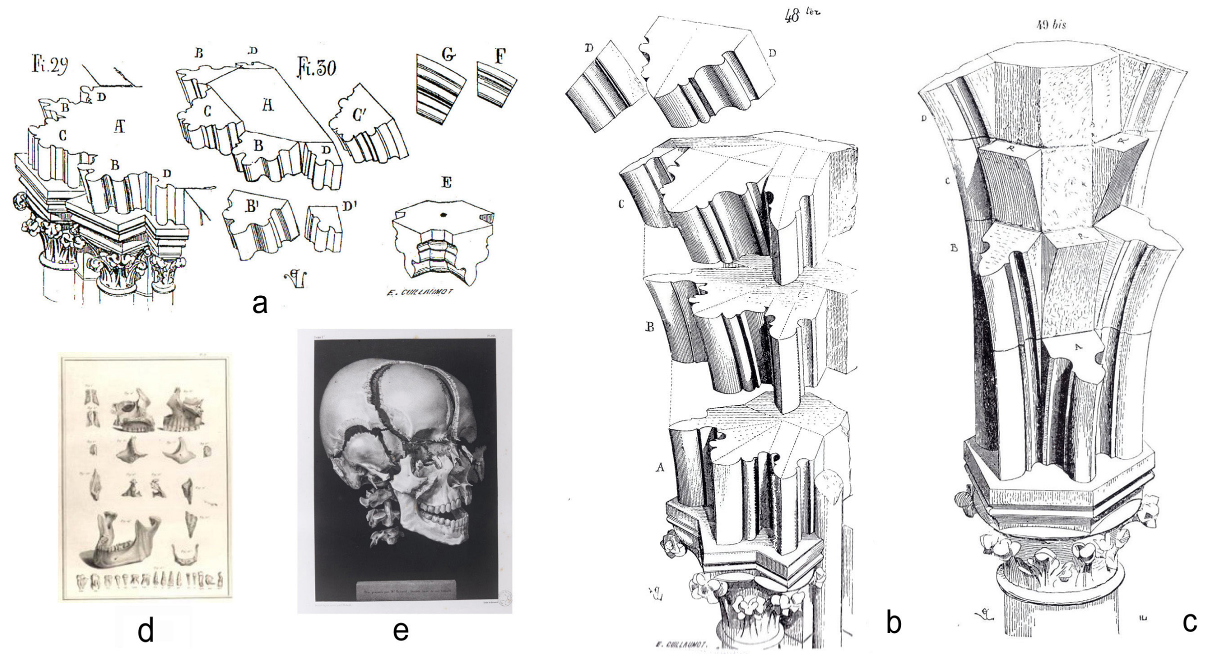


Figure 8. a — the Gothic «tas de charge» of a disassembled vault in (Viollet le-Duc, 1847). Two later versions by Viollet le-Duc (1859) showing: b — each element and its integration with others, and c — integration with the rest of the building's fabric. A similar visual innovation had previously occurred in anatomical science: compare d — A. Monro (1759) with e — J.-M. Bourgery (1831)

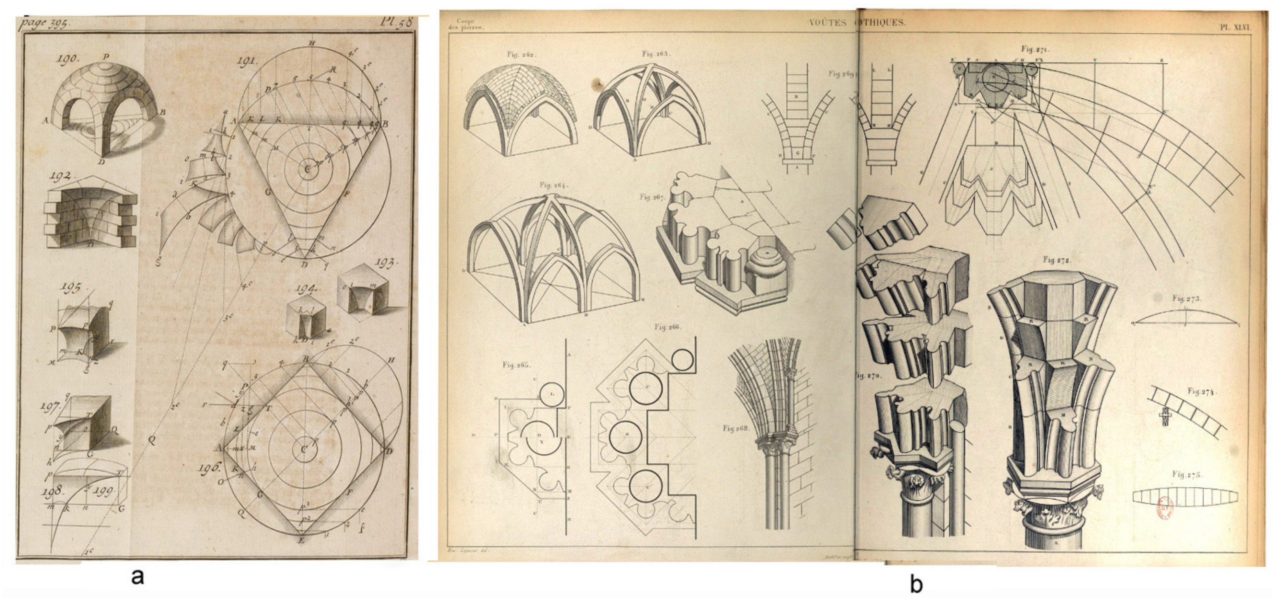


Figure 9. Viollet-le-Duc's anatomies were welcomed as an advanced, innovative new step in the visualization of stone cutting. a — a sample of Frazier's treatise (1737); b — a plate from J.-B. Lejeune's treatise on the topic (1872), with an addition of selected analytical drawings by Viollet-le-Duc

Roman Construction According to Choisy: a Virtual Model for a Clear Vision

In the last third of the 19th century, a fundamental and difficult research issue was still pending: researchers still did not know how Roman vaults had been built. Vitruvius did not describe them, so the only way to solve this enigma was to directly inspect shapeless ruins, composed of an amalgam of concrete and brick that could not be disassembled into pieces. The solution was ultimately found by an engineer, A. Choisy (1873).

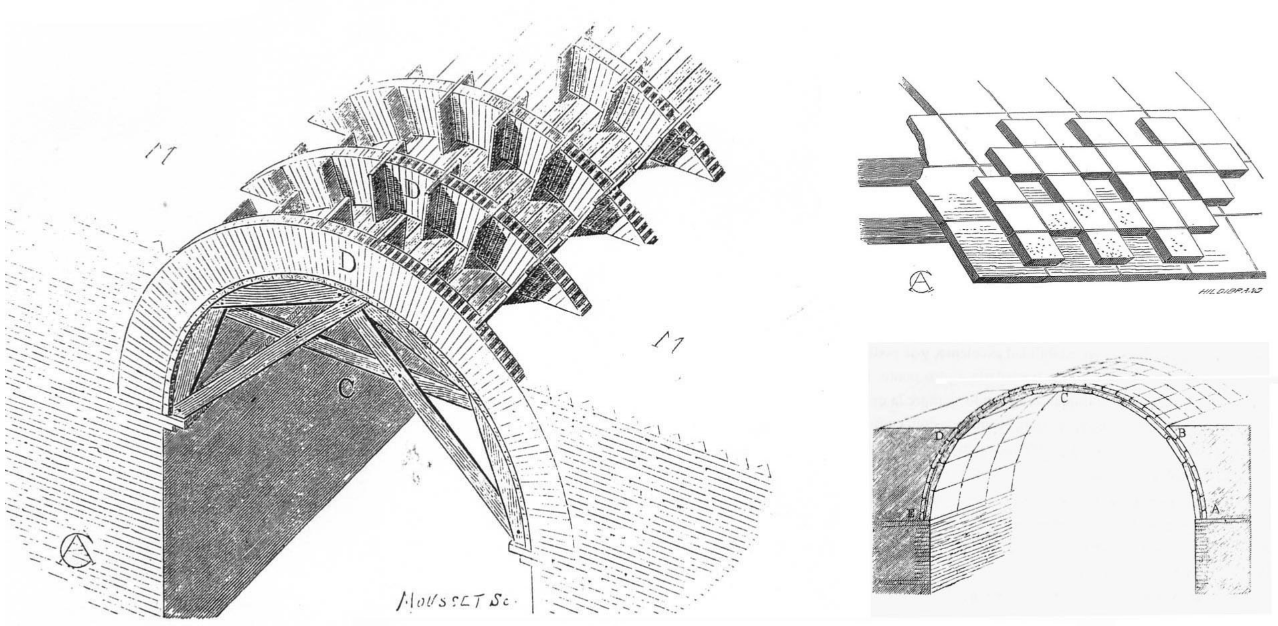
Choisy assured the reader that his work was based on his own notes. But a survey of those ruins, no matter how careful and faithful, could not automatically lead to a solution. The French «pensionnaires» in Rome had already carried out excellent surveys of the ruins' vaults. And yet, the researchers that had wondered about the process of building those vaults had not been able to unravel their secrets (Vaudoyer, 1826–1832).

As Choisy saw, the point was to realize that the analysis of the Roman vault was not an anatomical problem. What was required was a definition of the sequence of operations involved, as well as their functions, in as clear a way as possible. In order to arrive at this definition, he needed a reasonable hypothesis about what could have happened in a Roman building site and a good strategy for visualizing this.

The economic factor was key: the researcher had to examine how Romans had dealt with expensive temporary structures. The assumption that the ancient builders could have used scaffolding and timber falsework, similar to contemporary practices, had caused Piranesi and Viollet-le-Duc to make considerable mistakes in their interpretations of Roman vaults or domes. This mental framework had to be abandoned. Choisy's starting point was the idea that in Rome, timber had been a scarce commodity that the Roman builders had tried to use as little as possible. From that point of view, everything suddenly made sense: it was now easy to understand that the lattice ribs or the brick lining in the concrete had once been the formwork.

With this idea in mind, Choisy was able to «read» the ruins and produce drawings that illustrated their different theoretical construction stages (Fig. 10). Thus, he managed to translate one of the procedures that French engineers used for project commentary to historical construction analysis. He was probably familiar with the impressive chronological illustrations that J.-R. Perronet had published at the end of the 18th century (Perronet, 1782–1789) to explain his bridge projects, a narrative closely related to a great interest in controlling the economy of resources and optimizing time.

It is a paradox that the same engineering background that made him acutely aware of the importance of «technical time» in construction processes seemed to lead him to disregard the importance of «historical time». As it has been pointed out, one of the weaknesses of *L'art de Bâtir Chez les Romains* is precisely the absence of a historical perspective of the buildings' development (Lancaster, 2009).



a b

Figure 10. For Choisy (1873), the Roman vault's construction was not to be treated as an anatomical problem. Describing the sequences of operations and their role was paramount. Sparing timber in the temporary structures would have been crucial. This figure shows: a — lattice ribs, and b — brick lining, as self-supporting formworks

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The next step for Choisy was to demonstrate the results of his research. Choisy would be aware, as Viollet-le-Duc was, that with drawings of sufficient quality, he could create a substitute image of reality: a «cleaned-up» image, capable of modifying our perception in the future. This way, future researchers would see more clearly what had been happening in those ruins and gain more knowledge on the matter.

So it was necessary to choose the criteria both for the system of representation and the narrative strategy. As Choisy himself confessed when he received the medal of honor awarded to him by the RIBA in 1904, Willis' drawings had made a strong impression on him in his youth. This probably explains why he resorted, somewhat surprisingly, to axonometry. While it was, in fact, a system of representation that was particularly well-adapted to scientific and objective knowledge, until that point, it had had very little presence in construction studies. Choisy would handle it flexibly, adopting trihedrons where the angles formed between the measurement axes could vary at will. He chose not to adhere to the English isometrics, or to the more usual continental, «cavalière» perspective.

As for the narrative strategy, he sought one that would help him to see the vault and the successive stages of its construction at a glance. To do this, Choisy resorted to a traditional solution with a very long history; it allowed him to synthesize the whole process in a single image: the layered drawing (see, for example, G.A. Rusconi, 1590; or B.F. Bélidor, 1750) (Fig. 11).

Choisy's plates finally offer a sharp and distinct view of both the elements amalgamated in the vault's mass and its construction stages. Choisy, aware that what he shows is an idealization, adds some arboreal elements to the drawing, to remind us that what we see now lies in ruins.

This image is fascinating in its ambiguity since it allows us to «finally see clearly» what is happening amid the confusion of ruins, while also warning us that what we are contemplating is almost literally a figment of our imagination. All the same, those images made a great impression on other scholars.

Some of them, as J. Durm, did not fully agree with the «neatness» of the drawings and decided to «improve» them by making more down-to-earth (and clumsier) versions (Hassler and Pliego, 2009). The

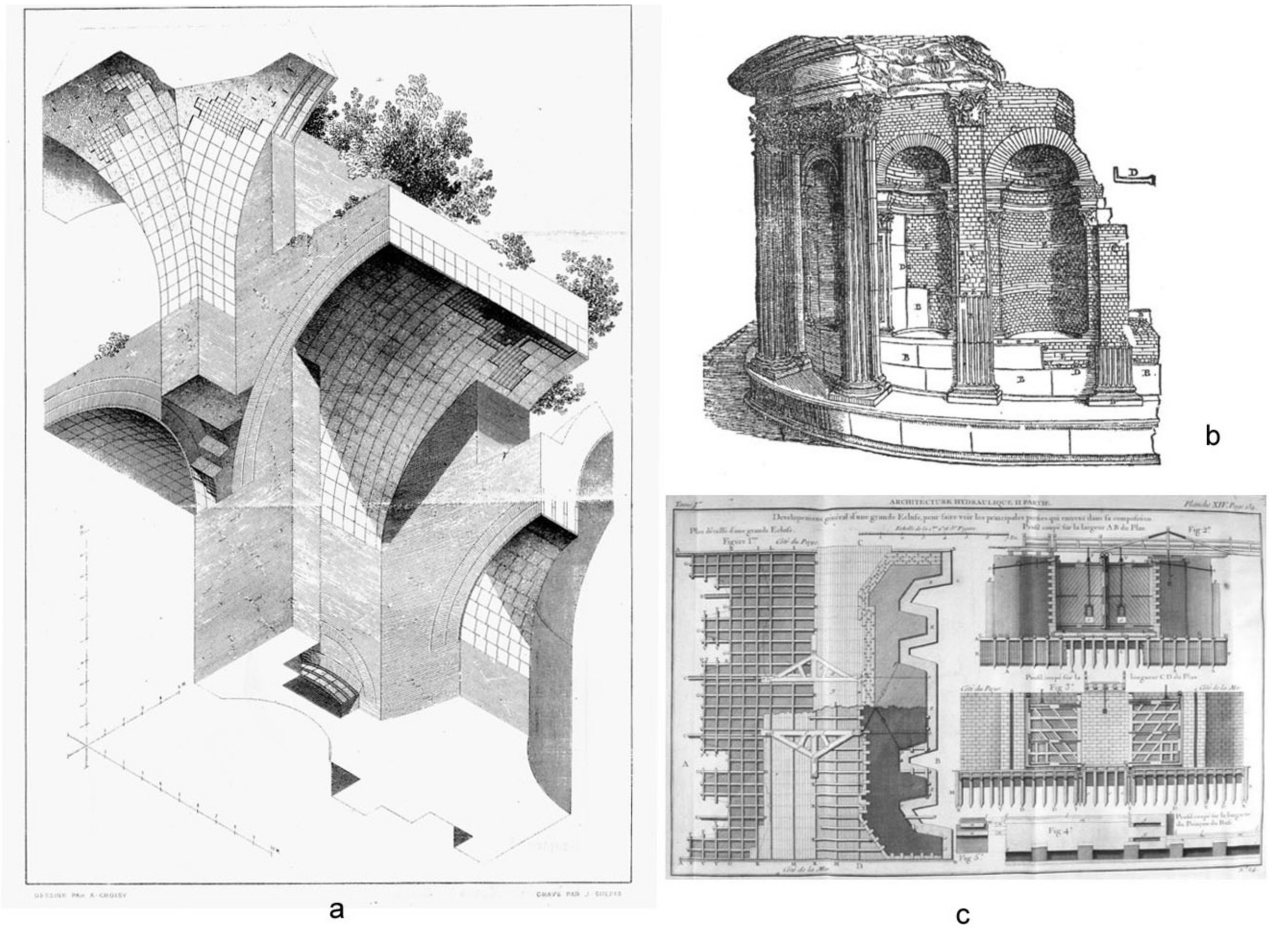


Figure 11. a — to conclude his research, Choisy (1873) created drawings allowing for an «at a glance» reading of a Roman vault and its successive construction stages. He relied on a time-tested narrative device, easy to find in Vitruvius' editions, b — (Rusconi, 1590); or engineering treatises, c — (Bélidor, 1750)

spread and diversification of those images deserve further research (Fig. 12).

Lost Timber Construction Systems. Choisy's Graphical Method for «Reading» Them in Stone Buildings

So far, we have seen how drawing helped interpret the hidden parts of a stone building or recreate a specific ruin. But the history of construction has another branch, which was still mostly unexplored in the last third of the 19th century: ancient timber construction. That was a difficult subject since by their very nature, the timber structures were very perishable and had largely disappeared. Could drawing help researchers find out what they had looked like and virtually restore them?

Since the middle of the century, various explorations had revealed that the stone tombs and monuments of different ancient peoples and civilizations could often be interpreted as the petrification of a previous timber structure (Fellows, 1839) (Fig. 13a). It became increasingly clear that this metamorphosis was a relatively common phenomenon: buildings constructed in stone in Etruria, Asia Minor, Persia, or India, among other regions of the world, preserved a fossilized carcass of another structural system (Viollet-le-Duc, 1863) (Fig. 13b). Based on a sum of these contributions, Choisy, in his *Histoire de l'Architecture* (1899), introduced a procedure for «recovering» many lost timber structural systems (Giron Sierra, 2009) (Fig. 13c).

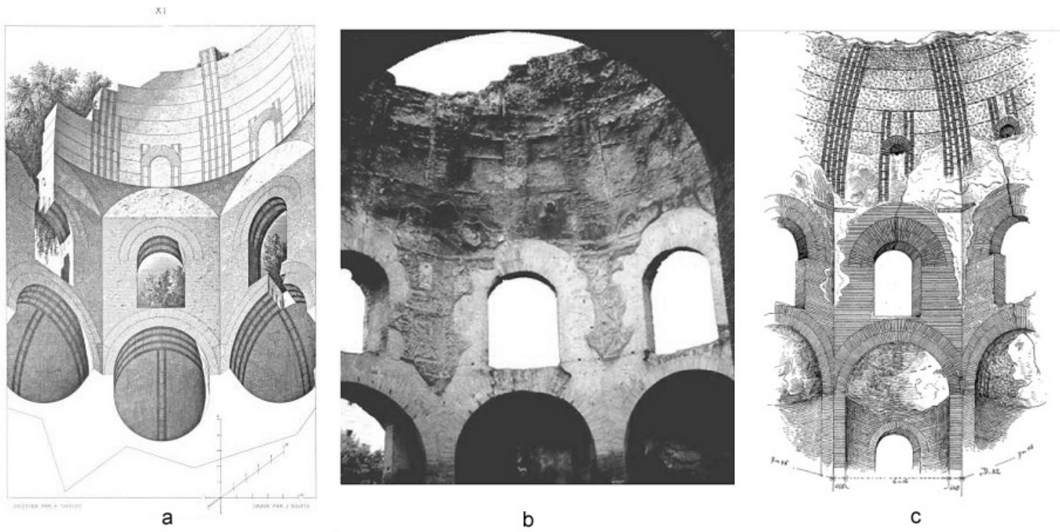


Figure 12. Choisy's drawings as an idealized visual model and their alterations. Compare: a — the Temple of Minerva Medica (Choisy, 1873) with b — a photograph of its real state. Those images had a significant impact; c — some scholars (Durm, 1885) even «improved» them to make them closer to reality, which stripped the drawings of their communicative power

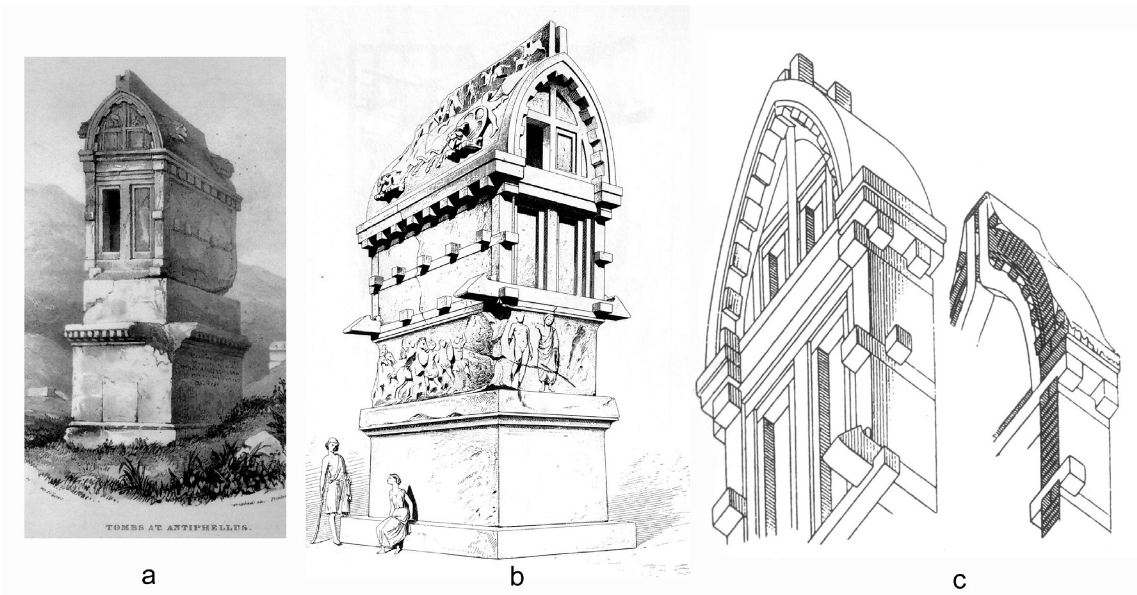


Figure 13. Depictions of antique petrified timber structures, as recognized by scholars. a — Lycia Sarcophagus (Fellows, 1839); b — (Viollet-le-Duc, 1863); c — Choisy's drawings (1899)

From the photos and illustrations by other authors, Choisy made deductions about the pieces of the primitive timber structures, which had supposedly been «petrified» in those monuments, and how they had been assembled. This way, he revealed something invisible, in this case not because it was hidden inside the construction, but because it had undergone a metamorphosis and had been replicated in stone. These sketches present a hypothesis that we can eventually compare with other well-documented procedures of making timber structures (Figs. 14a, b).

Crossing and Comparing Construction Systems: The Parallels

Various studies that began to appear in the middle of the 18th century aimed to discover the laws or patterns that could have governed the evolution of the past's different architectural styles (Leroy). Many scholars throughout the 19th century joined this research. As shown by Durand's impressive pioneering contribution (1799), the scholars relied on a graphic tool, the «parallel»: a panel of buildings drawn to the same scale. Parallels were particularly useful for an in-depth approach to a vital point: the influence of real dimensions on each type of architecture and its evolution over time.

Parallels may unveil the structural design rules used in the past and how they were affected by scale change. For example, they made it possible to investigate whether the geometrical principles for dimensioning the domes were independent of their size (Patte, 1770). Or to deduce empirically, based on sufficient case studies, a formula for designing a particular element (for example, a formula for determining the stability of a wall, as in Rondelet, 1802–1810). It was also possible to examine the changes that a single building element underwent as it grew in size and to determine its ultimate dimensional limits, as was the case, for example, with the Rondelet roof truss studies in 1802–1810 (Giron Sierra, 2015).

Parallels were also used to measure the relative «efficiency» of building systems from the past. For example, scholars relied on parallels to determine whether Gothic architecture was «superior» to Renaissance architecture, efficiency-wise. One way to compare their performance was to evaluate how much it «cost» — in terms of investing in a certain mass of structural material — to cover a space (Durand, 1799–1800) (Fig. 15a). With plans drawn to the same scale, it was easy to examine each system and determine how much space was taken up by the walls of the buildings and other structural elements and how much free space was left (Rondelet, 1802–1810) (Fig. 15b). By arranging items in chronological order, researchers were also to infer from parallels whether a style «progressed», that is, whether its performance was optimized over time.

Those comparative drawings may also show how growing in size affects an element's design (Reynaud, 1850) (Fig. 16a). Or highlight the difference between the scale limits that each building system could reach. For example, (Durm, 1885) demonstrates this by «inserting» sections of Gothic temples into the vaults of the Maxentius Basilica in Rome (Fig. 16b)

Discussion

This article has outlined a way to answer the questions regarding the extent of drawing's contribution to solving the problem of «seeing the invisible», which the pioneers of the history of construction asked themselves during the 17th to 19th century.

To do this, we have followed a method that has allowed us to make a first provisional overview, based on a selection of monographs. We have observed, as far as possible, the chronological account, highlighting some pioneers in the history of construction, identifying the problems that they

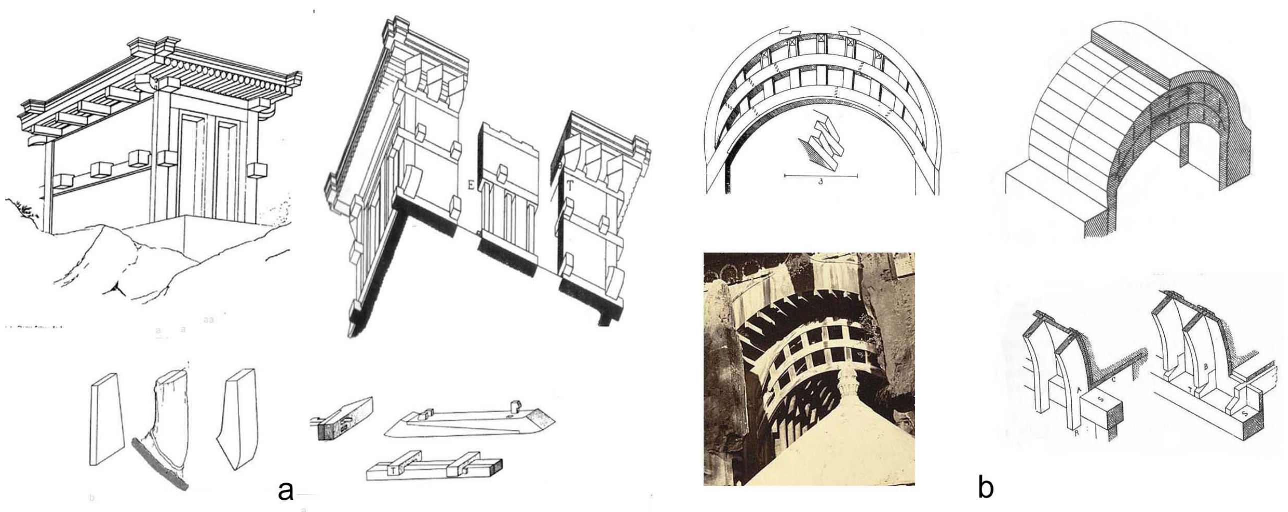


Figure 14. a — Lycia monuments (Benndorf, 1884); b — a photo of Indian cave architecture (Le Bon, 1887). To the right of each image, note Choisy's (1899) hypothesis visualizing the respective primitive timber structure systems

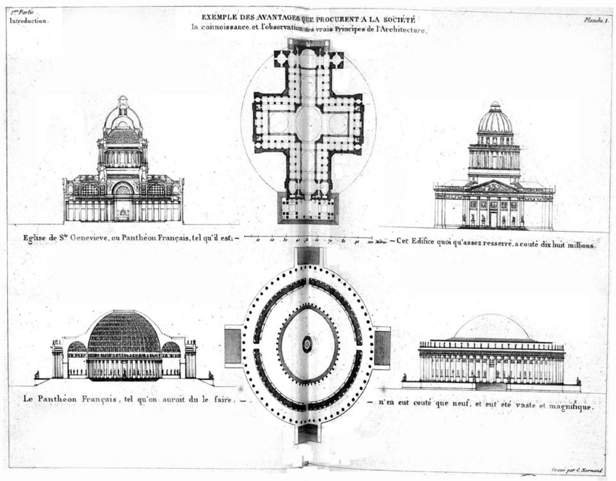
faced and the methods that they used for addressing these problems, and studying the role of drawing in each case (i.e. whether drawings were used for analyzing, showing, or comparing).

This synopsis shows the general picture. Due to space limitations, the study of the materials we have presented cannot be exhaustive. It is based on a limited number of very relevant authors. We have identified many other authors that should be included in a more comprehensive and detailed study (such as Canina, Chipiez, Curtius, Dieulafoy, Gauthier, Parker, Patte, or Perrot), but have deliberately set them aside. In order to have a complete picture, it will also be necessary in the future to identify and research more sources (probably «hidden» in chapters or sections of works on architecture) and to extend the geographical scope of this search, which is limited in this study to Western Europe.

Likewise, the possible impact of some innovations on the scientific drawings produced during that period remains to be studied. As for the images that were important as the «mental frame», there are some studies about their dissemination (Gil and Giron Sierra, 2009; Hassler and Pliego, 2009). But much remains to be done if we are to have the full picture, including the image distribution maps and the studies of their versions, impact on other authors, and their relationship with other texts (conflicting, independent or not).

Conclusion

The provisional conclusion that we have reached in this study is that drawing emerged as a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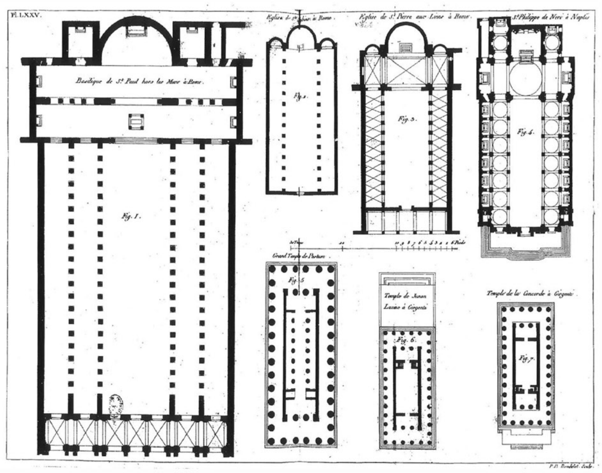
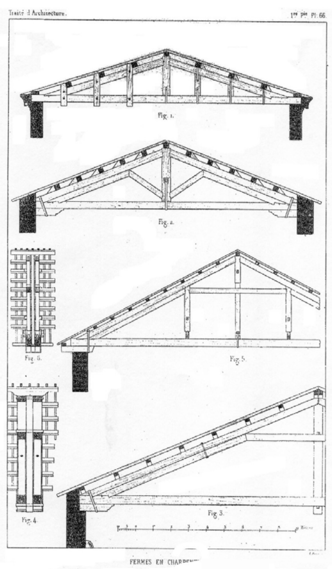

b

Figure 15. The parallel as a tool for investigating the effectiveness of different construction systems and comparing the mass taken up by the structure with the free space: a — Durand, 1809; b — Rondelet, 1802–1810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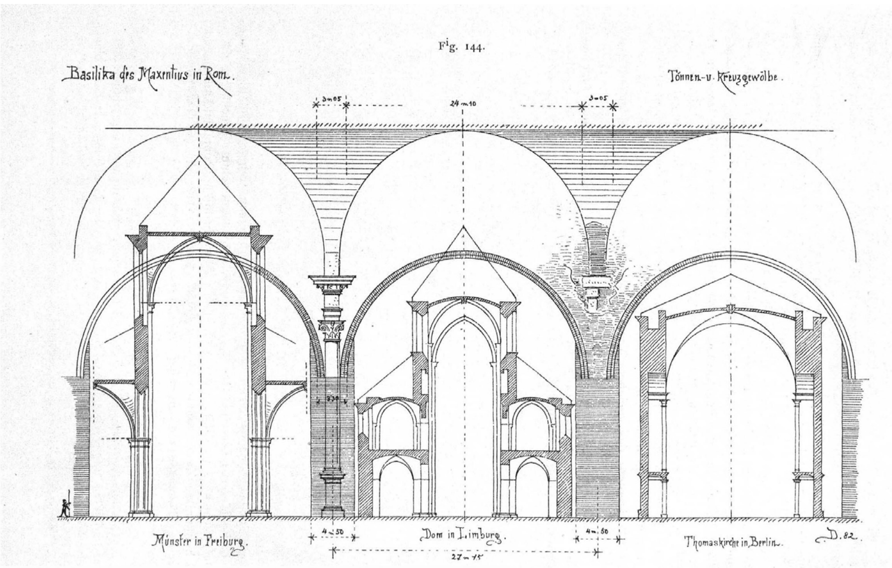

b

Figure 16. The parallel as a tool for determining the scale limits for different elements and construction systems: a — roof trusses in (Reynaud, 1850); b — a comparison of spaces covered by Gothic and Roman constructions (Durm, 1885)

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fundamental non-verbal way of thinking among the pioneers of the history of construction in the 18th and 19th century.

It allowed them to analyze, assemble, and virtually dismantle a structure or extract dimensioning rules based on operational drawings (the scientific and technical drawing type developed in the 19th century); these insights could be circulated and transmitted using drawings that acted as «mental frames».

We have pointed out how drawing was used for exploring plausible graphic hypotheses about the hidden aspects of Roman construction, while combining «in situ» observation with materials borrowed from indirect sources, such as the drawings in Vitruvius' edition (Piranesi, 1756), or for imagining the lost timber structure systems in buildings that would exhibit their petrified versions (Choisy, 1899). We have seen how the scientific and technical drawing (descriptive geometry) procedures that appeared throughout the 19th century allowed scholars to deduce the processes of transport and placement of the pieces making up the Greek temple from dispersed fragments (Cockerell et al., 1830, Hittorf and Zanth, 1870; Penrose, 1851) or to apply a rigorous anatomic structure to the «non-destructive analysis» of the Medieval vaults (Willis, 1842). We have also observed how other novel scientific drawing procedures, such as parallels on the same scale, were used in the 18th–19th century for studying, through comparisons, how size and scale affected the rules for designing various structural systems and for analyzing system efficiency (Durm, 1885; Rondelet, 1802–1810).

On the other hand, we have pointed out how in some cases, drawing became a «substitute» for reality, capable of orienting and clarifying the perception of entities that are difficult to discern in the observable construction. We have found the «mental frame» effect in Viollet-le Duc's anatomical drawings, which made the viewer «see» the different parts of the «tas de charge» of a Medieval vault separately and just before being assembled at the same time, as well as in Choisy's 1873 work that clarified the different layers that compose the construction of the Roman vaults, or in another work of Choisy (1899), which brought the original timber structure, lost within the stone, into the spotlight.

These drawings, which were the result of careful research into reality using the construction anatomy visualization techniques already established in the 17th–18th centuries (Rusconi, Belidor, Perronet, among others), became the non-verbal expression of analytical thought. This, with different degrees of autonomy and independence from the text, would later circulate among other construction historians.

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ASSESSMENT OF TRADITIONAL ARCHITECTURE OF LUCKNOW WITH REFERENCE TO CLIMATIC RESPONSIVENESS

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Abstract

Introduction: Traditional architecture, all over the world, has many characteristics that ensure thermal comfort. In the past, people built their houses in harmony with the environment, while also optimally utilizing the building materials available locally. The traditional built form was climate-responsive; it evolved over centuries of experience and observations of climate and nature. The traditional local architecture of Lucknow (a North Indian historical city) has employed some ingenious natural and passive techniques to maintain thermal comfort within the building, particularly during the hottest hours of the day. In this paper, we discuss the traditional built form of Lucknow through the lens of its climatic appropriateness, especially during the hottest hours of the day. **Methods**: The research methodology involves the study of the thermal performance of two traditional houses and one modern dwelling unit in Lucknow during the climatic extremes, i.e. summer and winter, by means of on-site monitoring of temperature and relative humidity. **Results and discussion**: We have summarized the comparative analysis of the thermal performance of traditional houses and modern houses and drawn conclusions from the factors that are responsible for providing thermal comfort. The analysis shows that the use of natural and passive techniques in the traditional buildings of Lucknow is very effective in terms of providing a thermally comfortable space, warm in the winter and cool in the summer.

Keywords

Traditional architecture, climatic design, climate responsiveness, Lucknow, India.

Introduction

The construction sector is one of the main contributors to energy dependence and consumption. The depletion of energy resources and the risk of global warming are creating a need for sustainable development in the construction sector, based on renewable energy and energy efficiency (Robert and Kummert, 2012). The dependence of architecture on energy for achieving a habitable space that is comfortable during all seasons and external climatic conditions is a highly non-viable proposition. The promotion and propagation of energy-dependent architecture is a significant lacuna on the architects' part. The architects have not incorporated the insights of the bioclimatic design principles and have merely left all lighting and ventilation to the mechanical and energy-consuming devices (Coch, 1998). At a time when humanity is facing the worst effects of climate change, energy crisis, and rapid urbanization, it is logical to look for ecologically sustainable design (Bay, 2010). The building should respond to the climate of the region where it is situated. All architectural design should respond to the environment and harness its beneficial aspects. This response can be achieved through layout design, orientation, and the scale of the building, all of which should be relevant to the context (Krishan et al., 2001).

Bioclimatic architecture integrates the micro-climate and architecture for achieving thermal conditions that are comfortable to humans (Sayigh and Marafia, 1998). Bioclimatic concepts were widely implemented in the architecture of the early times, before the mass introduction of mechanical devices for altering the indoor comfort conditions. An in-depth understanding of traditional architecture gives us clues on sustainable design that offers a responsible approach to climate, energy consumption, and preserving the environment (Asquith and Vellinga, 2006). History has shown us that architectural built forms have evolved in response to the climate, lifestyle, and availability of building materials. Although housing typologies are the result of multiple determinants, climate and culture are the two most important determinants (Rapoport, 1969).

Climatic Design and Traditional Architecture

By understanding traditional architecture in terms of heat, humidity, air movement, light, and in relation to the physical environment, we learn vital lessons for the present design endeavours. In many traditional buildings, both primitive and vernacular, some ingenious solutions to the architectural problems of resisting extremes of weather and maintaining a comfortable indoor climate can be seen (Sangkertadi et al., 2008). The traditional buildings of the past provide the best pointers in this regard; we have outstanding evidence of them being climate-responsive and energy-conscious. The basic form of the traditional building employs a combination of mass, shade, and ventilation, which lets the building breathe in harmony with nature and ensures the comfort of the occupants inside. In traditional architecture, an effort is made toward utilizing natural resources as much as possible. The ancient structures were designed in such a way that there was no need for AC, coolers, or fans for creating a thermally comfortable environment. They had inbuilt features for providing thermal comfort. The familiar elements of regional architectural styles, i.e. verandas, balconies, projections, courtyards, air shafts, thick walls, high ceilings, ventilation apertures, etc. were designed to use the sun for warmth and light and to create shade and breeze for cooling. We can learn these climatic design lessons and seek inspiration by observing the long history of traditional architecture (Vissilia, 2009). The natural and passive systems in buildings use non-mechanical methods to maintain a comfortable indoor temperature and are a key factor in mitigating the impact of buildings on the environment. Their designs are based on years of experience, building upon the relationship between the structure and climate and implying a logical analysis, the consideration of appropriate principles, and the rational use of resources (Kamal, 2007).

Traditional architecture in India is vibrant in terms of variety, which can be witnessed across the length and breadth of the country. The concepts of space planning are well adapted to people's needs and the climate. Continuity of tradition needs planning, design regulations and guidelines as well as the establishment of a code of practice to govern and control the proper implications of immutables, regardless of whether the technology is new or traditional (Saleh, 1999). The traditional houses of Lucknow are climatically responsive buildings that have evolved over centuries of experience and observations of climate and nature. The traditional residential buildings in Lucknow have employed some ingenious natural and passive features and techniques to maintain thermal comfort inside. Despite the long, hot summer with the dry-bulb temperature of up to 45°C, humans feel comfortable inside these traditional buildings thanks to the utilization of natural and passive cooling techniques. The research in this paper involves the study of the thermal performance of two traditional houses and one modern dwelling unit in Lucknow during the climatic extremes, i.e. summer and winter, by means of on-site monitoring of temperature and relative humidity.

Figure 1. Map of India showing the location of Lucknow (Source: https://www.nationsonline.org/bilder/map_of_india50.jpg)

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Research Methodology

The research hypothesis is that the traditionally constructed and designed houses are more climate-responsive than the houses with modern constructional designs. Our research methodology involved the identification of various natural and passive design features employed in the traditional residential buildings in the old settlement of Lucknow. The research also involved the study of thermal performance through on-site monitoring of two traditional houses and one modern dwelling unit in Lucknow. We used both quantitative and qualitative methods of gathering data. These included:

1. Documenting the building's physical form and construction systems.
2. Recording the thermal performance parameters in all three buildings during the period of climatic extremes. Our experiments were conducted during the third week of January 2004 and the first week of June 2004. The temperature and relative humidity were measured with a digital thermo-hygrometer outside each building, as well as in different indoor spaces, every two hours over the course of a complete one-day cycle.
3. Comparing the buildings' thermal performance.

Lucknow: The Study Context

The city of Lucknow is situated in the plains of Northern India, on the banks of the Gomti River. It is the capital of Uttar Pradesh, the most populous state of India (Fig. 1). The city is famous for its rich Nawabi culture and traditions and its intricately carved buildings. The Nawabs (rulers) of Lucknow not only built fine structures in traditional styles and experimented with European architecture, but also created a novel hybrid style, which was an amalgamation of both Indian and European elements (Tandan, 2001). The city has the older habitations in the central part and the newer settlements all around it. The older buildings are located in the centre of the city, surrounded by newer settlements. The older areas of the city (south of the Gomti River) are characterized by high density and pre-colonial settlement structures. The outer and peripheral

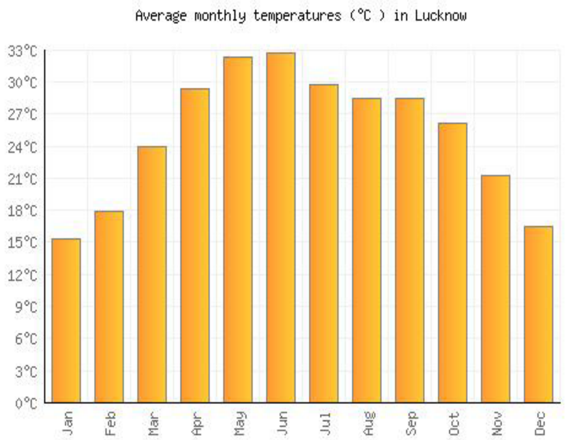

Figure 2. Average monthly temperatures (°C) in Lucknow (Source: https://www.weather2visit.com/asia/india/lucknow.htm)

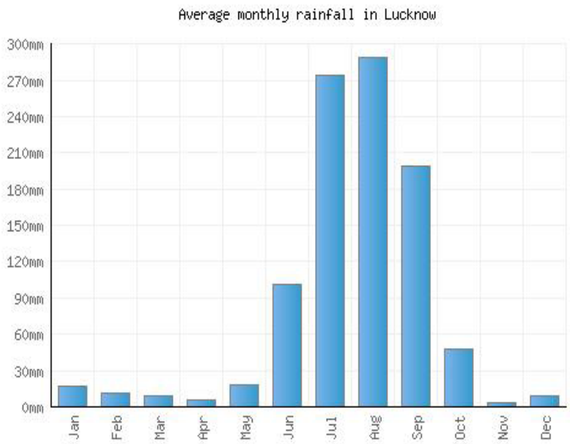

Figure 4. Average monthly rainfall data for Lucknow (Source: https://www.weather2visit.com/asia/india/lucknow.htm)

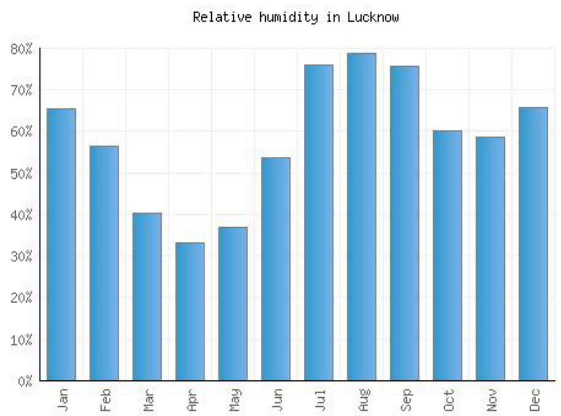

Figure 3. Relative humidity percentage in Lucknow (Source: https://www.weather2visit.com/asia/india/lucknow.htm)

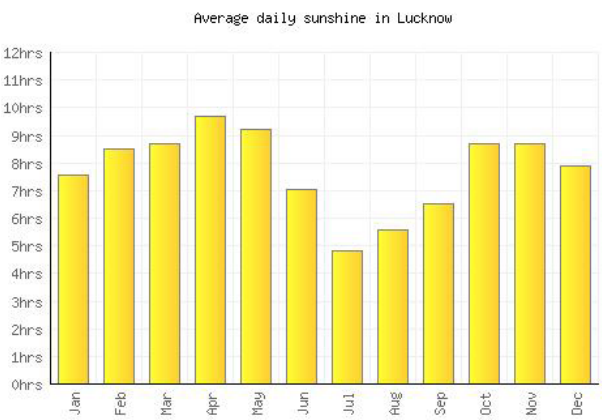

Figure 5. Average daily sunshine hours per month in Lucknow (Source: https://www.weather2visit.com/asia/india/lucknow.htm)

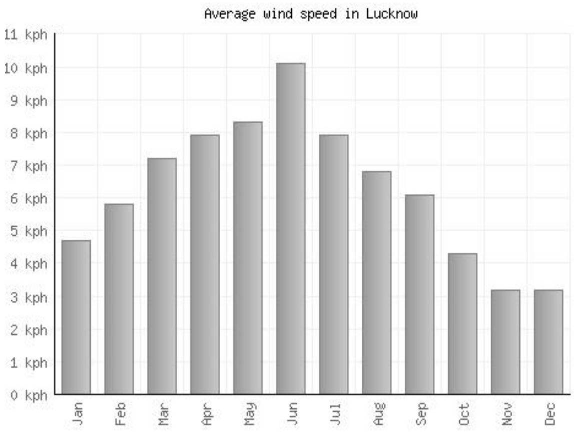

Figure 6. Average wind speed data in km/hour in Lucknow (Source:https://www.weather2visit.com/asia/india/lucknow.htm)

areas have primarily been settled in the post-independence period.

Climatic Data for Lucknow

Lucknow lies within a composite climate zone, having four main seasons: the summer, which is hot and fairly dry; the monsoon, which is less hot but humid; the period of moderate temperatures and humidity; and the slightly cold winter period. The climatic data for the last twenty years, published by the Central Building Research Institute, Roorkee, is summarized below (CBRI, 1989):

Air Temperature

The average monthly maximum temperature during the year's hottest month (May) is 41.2°C, while the average monthly minimum temperature during the year's coldest month (Jan) is 8.9°C (Fig. 2).

Relative Humidity

The relative humidity during the summer can be less than 25%; during the most humid months, the relative humidity is in the range of 78% to 82%, whereas the air temperature is in the range of 32.5°C to 34°C (Fig. 3).

Rainfall

Rainfall starts with the arrival of the monsoon season in the middle of June. Regular rains continue up to mid-September. The total annual rainfall is 940 mm (Fig. 4).

Solar Radiation and Sunshine

The sky is mostly clear throughout the year. The average solar radiation on a horizontal surface in June is 20.2 MJ/m^2 per day. Lucknow experiences 8 to 10 hours of sunshine for nine months (from October to June) and 5 to 6 hours during the remaining three months (Fig. 5). The sky remains normally overcast during the rainy season.

Wind Speed

The wind speed is in the range of 8 to 10 km/hour from May to September (Fig. 6). The predominant wind direction is east.

Traditional Architecture of Lucknow

The traditional architecture of Lucknow has evolved through the entire spectrum from individual buildings to settlement patterns; it responds to climate through form, thermal mass, spatial hierarchy, activity pattern, material, and construction.

Figure 7. Dense settlement plan of Lucknow (Source: the author of the paper)

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City Layout and Street Pattern

The city has two discernible entities: older buildings in the centre of the city and the surrounding newer settlements. The older areas of the city (largely south of the Gomti River) are characterized by high density and pre-colonial settlement structures (Fig. 7). The older urban settlement was compact and mostly planned around courtyards, which addressed the climate and the need for social interactions. The outer and peripheral areas have been settled in the post-independence period. The urban fabric is so tightly knit in the old city that the streets feel like elongated courtyards carved out through the dense building mass (Sinha and Kant, 2000). The streets in the older settlements are narrow and winding. The width of the streets varies from 3 to 5 m. As the streets meander slightly, there are no views down their entire length. The streets act as linkages and activity and interaction spaces. The height of the buildings is greater than the width of the streets, sufficiently so to create a shaded environment where the pedestrians can walk and share social activities in the streets.

House Form

Lucknow has its own traditions and culture, largely influenced by the religion and beliefs of its people. The traditional houses of Lucknow were built with three main considerations: privacy, segregation between men and women, and response to the hot climate. These factors have a great influence on the design of the houses that people still live in. There are two types of traditional residential buildings, depending on the socio-economic status of their inhabitants. The first type of traditional houses includes kothis, havelis, and palaces, which were commissioned by the Nawabs and their courtiers. These were the examples of outstanding Nawabi domestic architecture. Houses of the second type belong to middle-income people. The house plan and design are characterized by the presence of a courtyard, and sometimes an underground level as well. The houses open into the narrow streets through a hierarchy of spaces, such as the veranda, the entrance lobby, etc., which form a buffer zone between the street and the house (Fig. 8). The buildings are 2–3 storeys in height, frequently with a balcony on the first or second floor. This house type can be considered the generic traditional Lucknow house. It has a simple layout, with a veranda and a courtyard surrounded by rooms on all sides. The upper storey comprises one or two rooms with terraces, balconies, and pavilions.

Building Construction and Materials

The most common building materials used in the traditional houses of Lucknow are lakhauri bricks and lime. The thick masonry walls are constructed with lakhauri bricks and mortar, made out of lime and surkhi. The thickness of masonry walls generally varies from 45 to 90 cm (Fig. 9). The walls are sometimes rough or mostly finished with lime and stucco plaster. The elevation of a typical traditional house is decorated with stucco, featuring motifs and floral patterns made out of lime plaster. The dressing of doors and windows is done with standard sets of mouldings made out of lime mortar. The roofs and floors use two types of construction. One method involves laying closely positioned timber beams and covering them with reed or grass matting, with a thick layer (30–45 cm) of lime concrete on top (Fig. 10). The second type of roof construction is a jack arch vaulted ceiling, made out of bricks on steel girders covered in thick lime concrete with brick ballasts. In both cases, the roofs and floor are finished with lime and cement plaster.

Figure 8. Articulated street facade of traditional Lucknow houses (Source: the author of the paper)

Figure 9. Thick masonry of lakhauri bricks in traditional houses (Source: the author of the paper)

Figure 10. Heavy timber roof of traditional houses (Source: the author of the paper)

Figure 11. Exterior view of Rizvi House (Source: the author of the paper)

Experimentation and Setting of the Investigation

Rather than take detailed measurements of one building, we decided that it would be more efficient to take limited measurements in all three buildings, with the specific purpose of obtaining an overall view of the outdoor thermal environment instead of the variable micro-climate around the building. We must note that in the composite climate of Lucknow, the relative humidity has the most impact during the summer and the monsoon season, while being negligible in winter. Hence, the relative humidity was only measured during the summer months in all three houses. The main outdoor climatic parameters (air temperature and solar radiation) vary considerably throughout the year. The outdoor climatic data for Lucknow during the experiment period were obtained from the Indian Meteorological Department, which is not located in Lucknow. We found two stable zones, in June and December–January, which are also the periods for climatic extremes and therefore the obvious choice of a time frame for temperature observations. The tools available for measuring indoor parameters in this study were rather limited. Air temperatures and the relative humidity were measured with a digital thermo-hygrometer. The air velocity was measured at windows with a portable digital wind vane, which provides an index of the relative airflow through a room at different times of the day, but does not detect the actual air velocity in the room at any given time (Kamal, 2007).

Figure 12. View of the central courtyard of Rizvi House (Source: the author of the paper)

Thermal Performance of Traditional Architecture of Lucknow

Case Study 1: Rizvi House

This is a traditional courtyard house in Chowk, Lucknow, built around 1915 and meant to serve as a «Janana Imambara», or ladies' mourning place (Fig. 11). The mourning still takes place at the time of Moharram (first month of the Islamic calendar) in the Majlisi, or the mourning hall; for the rest of the year, the Majlisi is used as a living room. Rizvi House is a two-storey building with a small central courtyard, 7.05 x 6.4 m. The courtyard is surrounded by living spaces on three sides and has an entrance on the north side (Fig. 12). The Majlisi is a two-level hall, which opens into three Imambaras in the front, two mosques on the right (at both levels), and a room on the left.

Passive Features of Rizvi House

The layout of the house is slightly shifted towards the west, maintaining the NE-SW orientation. The largest openings and the entrance are on the NE side, i.e. in the windward direction. There are few openings on the southeast side and no openings on the southwest side. The absence of openings on the exterior surfaces helps reduce heat. The main entrance opens into the narrow shaded street, meaning that cool air flows from the street into the building. The courtyard creates shaded spaces and facilitates ventilation in the interiors through the openings facing the courtyard. The eaves project into the courtyard, which provides shade and keeps direct solar radiation from entering the rooms that open into the courtyard (Fig. 13). The jharokhas on the northern face of the building catch prevailing wind, thus maintaining air circulation in the rooms on the first floor. The walls on the ground floor are 90 cm thick; on the first floor, the wall thickness decreases to 60 cm. The masonry walls are constructed out of lakhauri bricks and finished with lime plaster (Fig.

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14). The roof is 36 cm thick; its structure includes a jack arch with lakhauri bricks on steel girders, finished with lime concrete. The massive walls and heavy roofs offer greater thermal resistance and hence increase the thermal time lag. The exterior and interior of the building are whitewashed, which helps reflect solar radiation.

Thermal Performance of Rizvi House in the Summer

Figure 15 shows the thermal performance of different spaces inside and outside the building in the summer. The temperature in the room on the north side was found to be more stable as compared to other rooms. The outdoor temperature fluctuation was in the range of 17–18°C, whereas the indoor temperature fluctuation was around 5–6°C. The maximum indoor temperature was 8–9°C lower than the corresponding outdoor temperature. While the outdoor air temperatures changed from 25 to 43°C, the air temperature in the courtyard fluctuated between 26 and 33°C. This was due to the small, two-level shaded courtyard, which helps cool the airflow inside the rooms and ensures ventilation throughout the building even when the weather outside is calm. The outdoor relative humidity varied from 22 to 55%, but the relative humidity in different indoor spaces varied from 32 to 45%, which was within the comfort zone (Fig. 16). We found that the maximum external surface temperature—that of an exposed wall in the afternoon—reached 54°C, whereas the temperature of the wall's surface inside the house was 33°C. This can be attributed to the time lag, occurring due to the wall's massive, 45 cm thickness. The temperatures in different spaces on

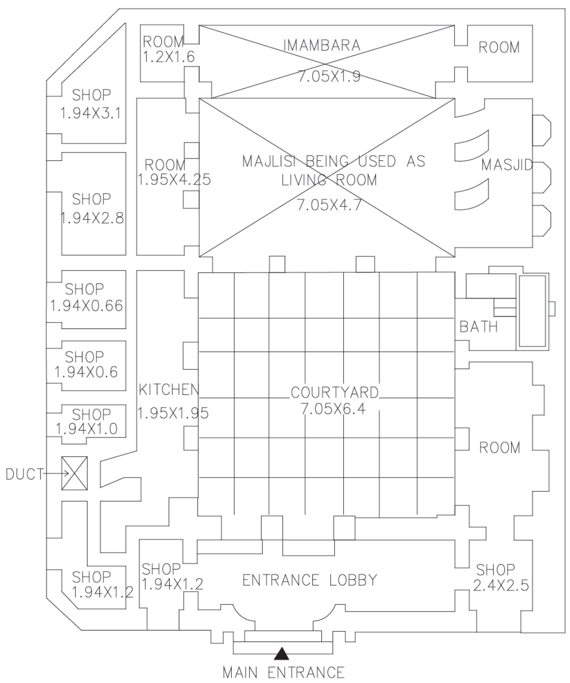

Figure 13. Ground-floor plan of Rizvi House
(Source: the author of the paper)

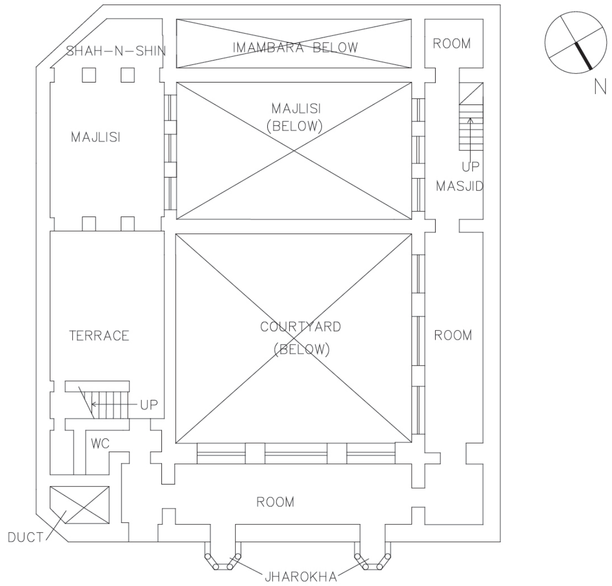

Figure 14. First-floor plan of Rizvi House
(Source: the author of the paper)

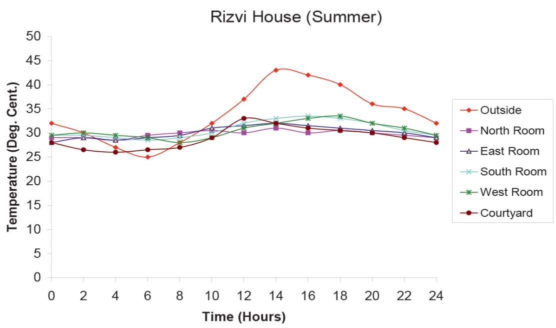

Figure 15. Summer temperature in different spaces in Rizvi House (Source: the author of the paper)

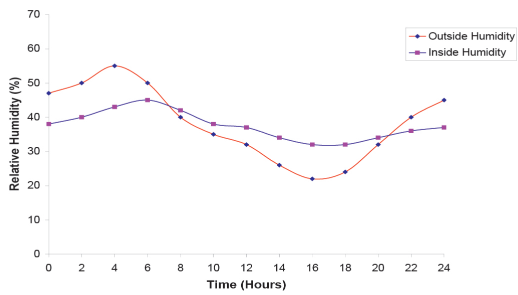

Figure 16. Relative humidity in Rizvi House in the summer
(Source: the author of the paper)

Figure 18. View of the central courtyard of Qaiser Jahan House (Source: the author of the paper)

Figure 19. Two-level room with timber ceiling in Qaiser Jahan House (Source: the author of the paper)

the first floor were consistently higher by 1 to 1.5°C.

Thermal Performance of Rizvi House in the Winter

It is clear from the graph in Figure 17 that the outdoor temperature fluctuated from 8.5 to 22°C, but the indoor temperature in different spaces was never less than 16°C, even though the inside of the building received very little direct solar radiation. The indoor temperature fluctuation in different rooms was in the range of 4–5°C.

Case Study 2: Qaiser Jahan House

This is the courtyard house of the late Mrs. Qaiser Jahan Begum, which is around 125 years old. The house opens into a narrow street through an entrance lobby, which also opens directly into the courtyard (Fig. 18). The square-shaped (10.75 x 10.0 m) courtyard is centrally located, enclosed by rooms on three sides, and has an entrance on the west side. There is a two-level hall on the eastern side of the courtyard; the other three sides are surrounded by single-level structures. The two-level hall opens into an Imambara and two bedrooms. This hall is also used as a «mourning place» during Moharram (Fig. 19). The configuration of Qaiser Jahan House is shown in Figure 20.

Passive Features of Qaiser Jahan House

The house opens into the narrow street, which is shaded by the balcony and projections of the buildings on both sides. The entrance to the house is through a lobby, which opens into the central courtyard. As the courtyard gets heated up during the day, the hotter air rises and the denser cool air, which is drawn from the shaded streets, rushes into the courtyard, ventilating the interiors of the surrounding rooms. The absence of openings on the exterior surfaces helps reduce heat. The two-level entrance on the southwest side shades the building from the afternoon sun. The walls are 60 cm thick and constructed out of lakhauri bricks finished with lime surkhi plaster. The roof is 45 cm thick and constructed out of brick ballast, mixed with lime surkhi mortar and laid on timber planks supported by timber beams (Fig. 20). The massive walls, heavy roof, and timber ceiling offer greater

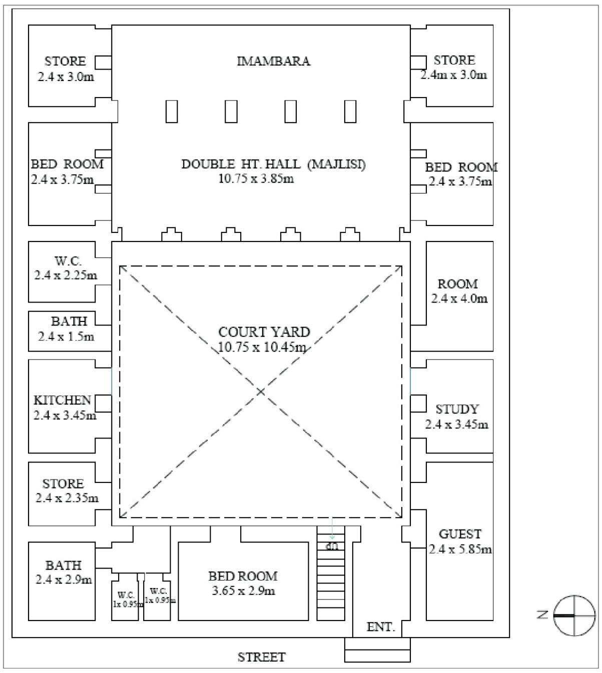

Figure 20. Ground-floor plan of Qaiser Jahan House (Source: the author of the paper)

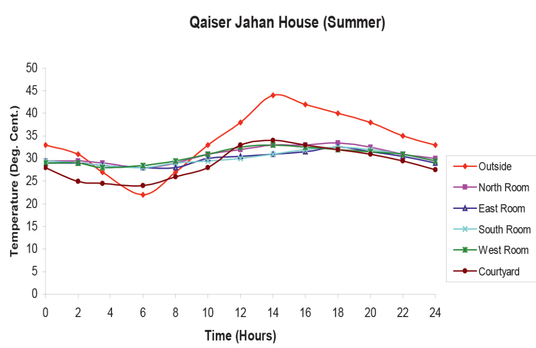

Figure 21. Summer temperature in different spaces of Qaiser Jahan House (Source: the author of the paper)

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thermal insulation and increase the thermal time lag. The ventilation apertures facilitate the stack effect and extract the warm air from the rooms. There is also vegetation in the surroundings, which provides evaporative cooling. The exterior of the building is plastered with lime mortar and whitewashed, which reflects the solar radiation to some extent.

Thermal Performance of Kaiser Jahan House in the Summer

Figure 21 shows the thermal performance of different spaces inside and outside the building on June 6. The outdoor temperature fluctuation was in the range of 12–13°C, whereas the indoor temperature fluctuation was around 4–5°C. The maximum indoor temperature was 9–10°C lower than the corresponding outdoor temperature. While the outdoor air temperatures changed from 22 to 44°C, the air temperature in the courtyard fluctuated between 24 and 34°C. The temperature in the courtyard of Qaiser Jahan House was found to be a little higher than in the courtyard of Rizvi House in the afternoon and a little lower in the early morning. This can be attributed to the bigger courtyard in Qaiser Jahan House as compared to Rizvi House. The outdoor relative humidity varied from 20 to 56%, but the relative humidity in different spaces varied from 31 to 46%, which was within the comfort zone (Fig. 22). The overall relative humidity, in this case, was lower than in Rizvi House, because of the bigger courtyard and more cross ventilation in the rooms. We found that the maximum external surface temperature—that of an exposed wall in the afternoon—reached 55°C, whereas the temperature of the wall's surface inside the house was 34°C. This can be attributed to the time lag due to the wall's massive, 60 cm thickness.

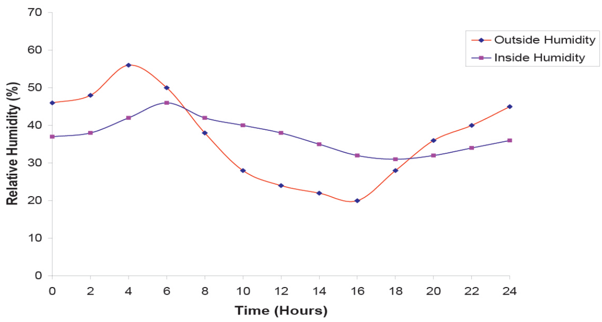

Figure 22. Relative humidity in Qaiser Jahan House in the summer (Source: the author of the paper)

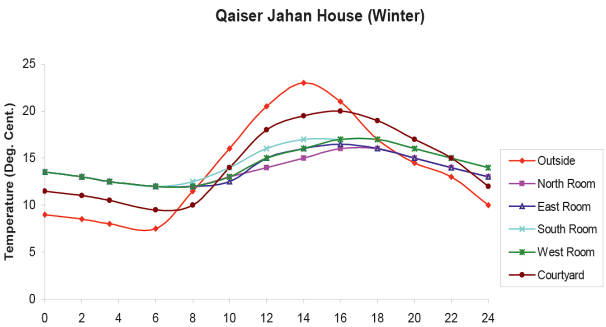

Figure 23. Winter temperature in different spaces in Qaiser Jahan House (Source: the author of the paper)

Thermal Performance of Kaiser Jahan House in the Winter

The temperatures measured in different rooms of Qaiser Jahan House were found to be slightly higher during the daytime and slightly lower during the night, as compared to Rizvi House. This can, once again, be attributed to the presence of a bigger courtyard in Qaiser Jahan House. As shown in Figure 23, the outdoor temperature fluctuated between 7.5 and 23°C, but the indoor temperature of different spaces was never less than 12°C. The indoor temperature fluctuation in different rooms was in the range of 4–5°C.

Case Study 3: LDA House

This building is a MIG (Middle Income Group) house, which was built by the Lucknow Development

Figure 24. Front view of the contemporary LDA House (Source: the author of the paper)

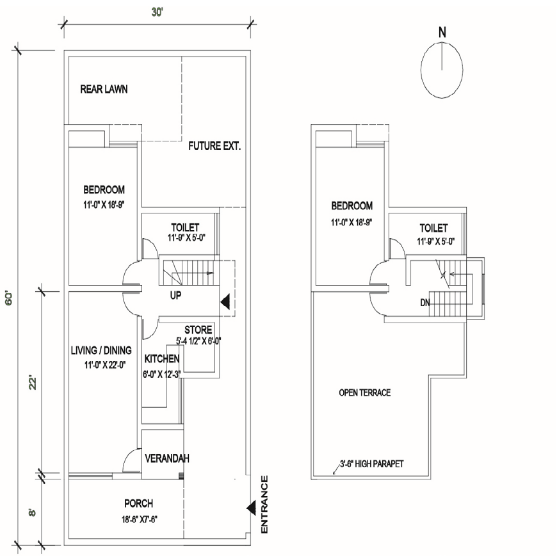

Figure 25. Ground- and first-floor plan of LDA House (Source: the author of the paper)

Authority in Aishbagh, Lucknow, around 40 years ago (Fig. 24). It is a double-storey building with a living room, a kitchen, a bathroom, and a bedroom on the ground floor and a bedroom and a bathroom on the upper floor. The construction consists of 23-cm-thick load-bearing brick masonry walls and a 6»-thick roof. The rooms are 3.0 m tall and openings have 0.9 x 1.2 m dimensions.

Salient Features of LDA House

This building is a part of semi-detached row housing and is compactly planned, with a small front and rear yard. Energy consumption was not considered as a design criterion for houses of this type. There are only a few openings, which face the front and rear yard; this obstructs free air movement and does not provide cross ventilation. The living room is located on the western side without proper shading, which causes discomfort in the summer (Fig. 25). The roof of the first floor is a 10-cm-thick R.C.C. structure, finished with small brick ballast and cement sand mortar. The roof is a major source of heat gain for the upper floor due to the absence of appropriate terracing. There is no proper sunshade over the first-floor openings on the south and west side, hence the openings do not cut the solar radiation in the afternoon and heat up the interiors due to the high transmittance of glass. Nor is there any proper projection on the terrace level on the south and west side to shade the walls on the first floor. This causes the walls to heat up, thus letting the heat into the rooms through conduction. The plastered exterior surface with whitewash reflects solar radiation to some extent.

Thermal Performance of LDA House in the Summer

The room temperature in different spaces was found to be above the slightly warm range. The outdoor temperature fluctuation was in the range of 19°C, whereas the indoor temperature fluctuation was in the range of 7°C. The maximum indoor temperature was 6–7°C lower than the corresponding outdoor temperature. In this case, we could clearly observe that the indoor temperature of this house was 4–5°C higher than the temperature of the traditional house during the same hours of the day (Fig. 26). This can be attributed to the thin walls, the R.C.C. structure, and the lack of proper wall shading. The outdoor relative humidity varied from 23 to 54%, but the relative humidity in different indoor spaces varied from 28 to 42%. The overall relative humidity with reference to thermal comfort was slightly lower than in any traditional house (Fig. 27)

Thermal Performance of LDA House in the Winter

The room temperature in different spaces was found to be below the slightly cool range. The outdoor temperature fluctuation was in the range of 15°C, whereas the indoor temperature fluctuation was in the range of 6°C. The maximum indoor temperature was 3°C lower than the corresponding outdoor temperature. In this case, we could clearly observe that the indoor temperature of this house was 4–5°C lower than the temperature of the traditional house during the same hours of the day (Fig. 28). This can be attributed to the thin (23 cm) brick masonry walls and the 10-cm R.C.C structure without proper wall shading.

Summary of the Findings

The simultaneous monitoring of outdoor and indoor thermal conditions of two traditional houses together with those of one modern house in Lucknow has shown that the thermal capacity of the traditional houses, which have courtyards and a compact and self-shading design, has many advantages when it

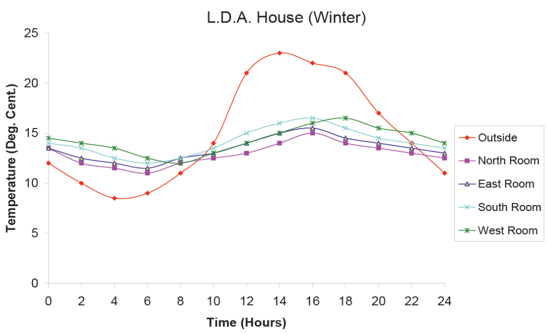

Figure 26. Summer air temperature in different spaces in LDA House (Source: the author of the paper)

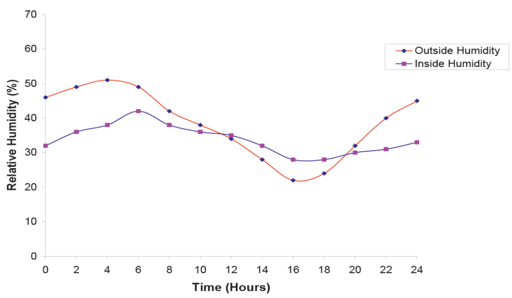

Figure 27. Relative humidity in LDA House in the summer (Source: the author of the paper)

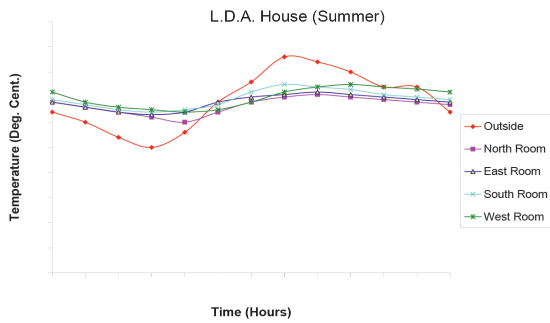

Figure 28. Winter air temperature in different spaces in LDA House (Source: the author of the paper)

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comes to limiting the daytime indoor temperature rise during the hot seasons. During the winter, the thermal capacity of the traditional houses plays a major part in maintaining near-comfort indoor conditions during the night, even when the external temperature drops as low as 7ºC. The comparative analysis of the thermal performance of the traditional and modern houses is summarized as follows:

1. The data collected shows that the indoor air temperature in the two traditional buildings is 2–3°C lower in the summer and 2–3°C higher in the winter, as compared to the indoor temperatures in LDA house.

2. The difference between the outdoor and indoor temperature in the traditional buildings is greater than in LDA house, suggesting a better comfort level in traditional buildings.

3. In the traditional houses, the indoor air temperature fluctuation was not more than 4–5°C while the outdoor temperature fluctuated in the range of 18–20°C.

4. There was a thermal time lag due to the heavy thermal mass, i.e. the thick masonry walls and heavy roof construction system found in the traditional houses of Lucknow. The time lag of the whole system is around 10 hours. This allows for comfort at all times of day. The resulting temperature difference was almost 12°C. This means that when the outdoor temperature at noon on a summer day was around 45°C, the indoor temperature would be around 35°C.

5. In the summer, the average maximum indoor temperature in different rooms of the traditional house was 10–12°C lower and the average minimum indoor temperature was 3–4°C higher than the respective outdoor temperature, whereas in LDA house the average maximum indoor temperature was 5–6°C lower and the average minimum indoor temperature was 7–8°C higher than the respective outdoor temperature.

6. In the winter, there was a 4–5°C temperature difference between the average maximum indoor temperature in different rooms and the maximum outdoor temperature, and a 5–6°C temperature difference between the average minimum indoor temperature and the minimum outdoor temperature. In LDA. house, there was an 8–9°C difference between the average maximum indoor temperature in different rooms and the maximum outdoor temperature, and a 4–5°C temperature difference between the average minimum indoor temperature and the minimum outdoor temperature.

7. The peak indoor temperatures in the traditional buildings occurred at about the same time as the peak outdoor temperatures, but the time lag was around 24 hours due to the massive thickness of the walls, whereas in LDA house, the peak indoor temperature occurred around 6 p.m., while the peak outdoor temperature occurred around 2 p.m.

8. The courtyard system in the traditional buildings ensured ventilation through the building even during the periods when the outdoor conditions were calm. The courtyard temperature was 1–2°C higher in the late afternoon and 2–3°C lower in the early morning, as compared to the indoor temperatures in the rooms. The courtyards are open to the sky or partially shaded with overhangs. This also creates shaded spaces, thus reducing heat gain. As the solar radiation enters the courtyard, the air in the courtyard becomes warmer and rises up. To replace it, the cool air from the ground level flows through the openings into the room, thus producing airflow. During the night, the process is reversed.

9. The areas of the building directly exposed to the sun were 2–3°C warmer in the traditional buildings due to the thick, massive walls, whereas in LDA house, they were at times 7–9°C warmer than the corresponding ambient air temperature.

10. The openings in the traditional houses, such as windows, vents, and the skylight, provided cross ventilation, by creating a stack effect. The ventilation apertures, such as jharokhas or jaalis, induce forced ventilation into the interiors of the buildings. The air movement occurs because of the presence of the courtyard and the difference in indoor and outdoor temperature, which creates air circulation. The contemporary house has poor air circulation, as there is no avenue for cross ventilation.

11. Traditional buildings have various features that help lower the daytime temperature: structural elements like shading devices; buffer spaces like courts, verandas, etc.; wind catcher screens; recessed openings; water bodies; and vegetation. There are very few, or hardly any such features in modern-day houses.

Conclusion

It is clear from the study that appropriate use of materials, spatial organization, construction techniques, and passive design features could bring about the much-desired comfortable environment inside the house. Natural cooling can be achieved by the proper orientation of the building, an appropriate layout, a good landscape design, proper shading devices, and a properly designed roof, overhangs, external surface finish, and vertical shadings, oriented in an optimal way in relation to the sun and wind. We can infer from the analysis of our experiments that the traditional building form, structure, and materials were originally selected to suit the climatic conditions and ensure optimal comfort and shelter from climatic factors invading indoors, without any mechanical means, i.e. heaters, fans, coolers, air conditioners, etc. The traditional architecture of Lucknow features well-shaded buildings with heavy facades and limited openings on the external elevation. The basic form of the traditional building employs a combination of mass, shade, and ventilation, which lets the building breathe in harmony with nature and ensures the best range of comfort conditions for the occupants inside. The principles of good thermal design used in traditional buildings are still valid today, and it would still be possible for modern designers and architects to incorporate these design principles into buildings that are suitable for modern-day living, in order to conserve energy and provide better thermal comfort. Perhaps the solution lies in rediscovering the features and techniques used in traditional buildings and recreating them in the contemporary architectural form.

The region-specific built forms are a result of centuries of experimentations, shaped by social, cultural, religious, and technological influences. They would be continuously refined by subsequent generations, albeit at a very slow pace and through trial and error, depending on societal characteristics, technology, and materials. As a result, these built forms served the purpose very well, being rooted in their locale; they satisfied the functional, climatic, and aesthetic aspirations of their users. It is known that the value of traditional regional architecture is not limited to it being cultural heritage, which is reason enough for its study. Such architecture also has tremendous potential for influencing the current architectural trends in the respective region (Krishna and Rewatkar, 2006). The real challenge is to achieve maximum thermal comfort at a minimum energy cost, through adjusting various energy conservation measures and techniques at the building design and construction stage. It is an architect's responsibility to be mindful of the climate and aim for energy efficiency and human comfort while designing modern-day buildings. There is a need for establishing a planning and design methodology, based on the philosophy of translating the spirit of the old into an idiom of the new design, instead of mere superficial recreation. An architect needs to understand how to blend lessons from the traditional heritage together with modern technology in building design. Hence it is essential to take the wisdom of the past and evolve the built form, creating the more humanized, more climate-responsive, and more environmentally friendly buildings of tomorrow.

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SYNERGISTIC ANALYSIS OF THE HISTORICAL AND CULTURAL DEVELOPMENT OF INDUSTRIAL ARCHITECTURE

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Abstract
Introduction: By determining the importance of industrial architecture as an object of cultural value, it is possible to identify the new principles for preserving the identity of a historical location. **Purpose of the study:** We aim to research different periods in the formation of the architectural and spatial layout of industrial buildings and structures; to determine which principles are applied when the buildings and structures are adapted for reuse. **Methods:** In this article, we use a synergistic approach to studying the specifics of the historical and cultural development of industrial architecture. **Results and discussion:** After analyzing the target of our study as a self-organizing system, as well as taking a look at its relationship with various structures, depending on the nonlinearity of the ongoing processes, we came to the conclusion that the emergence of different stylistic trends in industrial architecture can be viewed through the lens of significant historical periods, or bifurcations, which were the result of human activity in the past and would influence the functional development of the resulting space in the future. This approach reflects sociocultural needs and unlocks the potential for reusing historically significant industrial sites in various ways.

Keywords
Synergistic approach, industrial architecture history, time-space relationship, genius loci.

Introduction

The architectural heritage of large cities is represented by a wide range of different architectural movements and types of buildings. The time-space relationship is reflected in the variety of style combinations from different eras; these are inextricably linked to the growth of urban space, as well as to compositional techniques, form-making methods, the technological capabilities of a certain time period, and the boldness of architectural thought. In the life of society, buildings and structures act as a means of communication, reflecting certain traditions, customs, experiences, ideas, and feelings, especially when several generations engage in dialog at once. This is what informed the Washington Charter, which defines the principles and methods necessary for the conservation of historic towns and urban areas that help to "promote the harmony of both private and community life in these areas and to encourage the preservation of those cultural properties, however modest in scale, that constitute the memory of mankind" (ICOMOS, 2021).

Stylistic features in architecture arose and developed not only sequentially, but also nearly simultaneously, complementing each other as a result of the interaction (Kholodova, 2010). Once Sigfried Giedion said that in order to understand the true nature of a certain period in the development of architecture, it is not enough just to study public buildings, representative residences, and monuments. In the course of historical events, it was the construction of modest utilitarian buildings that led to the decisive development of new architectural techniques and opportunities (Morozova, 2008).

Industrial architecture is subjected to historical process development just as much as the construction of administrative, religious, cultural, public, and residential buildings. Industrial architecture originates simultaneously with the urban community. It grows and transforms together with the city, becomes firmly woven into the urban structure, and has a significant impact on its changes, in addition to reflecting the social environment of its time. The development of this type of architecture is driven by the emergence of more and more new technical, technological, and economic capabilities. As the relationship between humankind and the production machine evolves, the development timeline of architectural and spatial forms in industrial architecture evolves as well (Myslin, 1936). The dynamics of this development can be considered using a synergistic approach.

Methods

The synergistic approach is a set of different principles that are based on considering the object of the study as a self-organizing system. Synergetics considers a certain relationship of a group of structures and defines it as a state that arises as a result of many options for the development of fundamental systems,

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which evolve progressively due to the nonlinearity of internal states and processes (Zhuikov, 2011).

The main principles of the synergistic approach are as follows:

- architectural sites must be studied as systems, which are: developing; open (the openness of a site characterizes its ability to exchange information, energy, etc.); complex; and nonlinear (nonlinearity determines the presence of various development variations that depend on random external or internal influences);
- the self-organization of these systems is initially chaotic and unstable, which leads to the formation of possible fluctuations, or oscillations, deviating from the average values of the processes typical of these systems;
- there are certain alternative ways of system development, which are formed at the points of bifurcation; this creates a choice of direction for further development;
- the future development of the system shapes its actual state, in which attraction factors (attractors) act as an end in itself, determining the direction of the system development (Nekrasova and Nekrasov, 2009).

The synergistic approach is based on the idea of the functional dependence of the past on the present, and the present on the future (Kholodova, 2010). Thus, if we consider the development of architecture as the core of synergistic analysis, we will be able to perceive the emergence of different stylistic directions and types, resulting from historical development, as a synthesis of the interaction between various elements and the methodological apparatus of the space self-organization theory. It is also useful to take into account the approach of Moses Kagan, who studies the highest form of a self-organization process, resulting in the development of an anthropocentric sociocultural system. The complexity of these structures is multiplied by the complexity of development that occurs as a result of conscious human activity (Mamutova, 2012).

Results and Discussion

In the course of historical events, there were three bifurcations, or turning points that influenced the change in the perception and actualization of industrial architecture from the point of view of a more figurative spatial perception (Figs. 1, 2):

1 — a massive transition from manual labor (Fig. 1) to mechanical labor in the 18th and 19th century, considered one of the most important events in the history of mankind that shaped the world we live in today (Fig. 2);

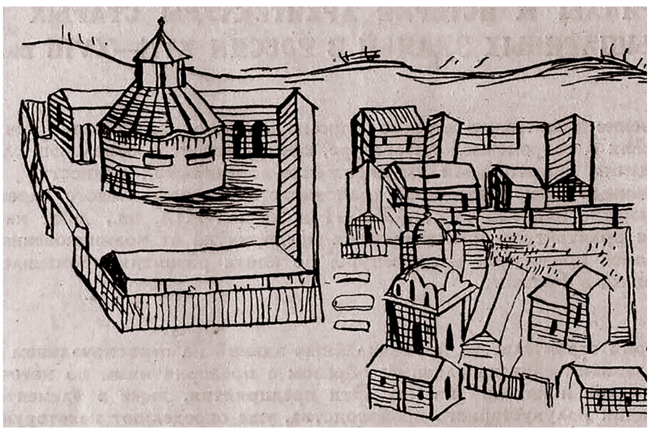
2 — the development of continuous flow-line, electricity-powered machine production at the end of the 19th and the beginning of the 20th century (Fig. 3);

3 — the digital revolution of the late 20th and early 21st century (Fig. 4).

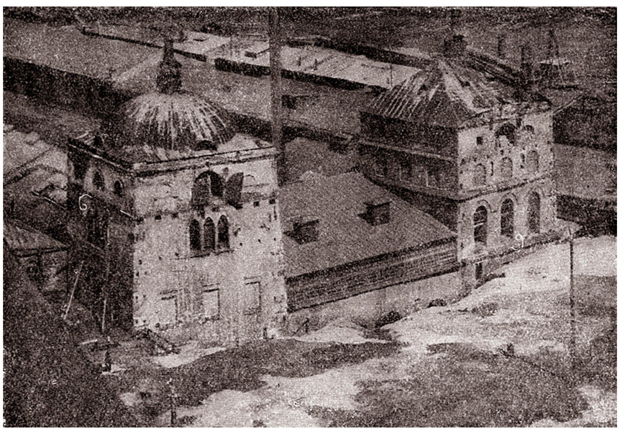
As a result of three industrial revolutions, spurred on by the changes in socioeconomic relations, scientific and technological progress, and urbanization, many production processes have been reconsidered and transformed. In most cases, this has led to the withdrawal of industrial sites to city outskirts; and in some cases, industrial production has completely lost its relevance and industrial sites have been abandoned. Thus, “gray spots” or “gray belts” of abandoned industrial architecture have formed among the historical buildings of many cities. This creates possible fluctuations and an unfavorable environment that affects the emotional state of the local residents. The influence of the time factor also has an impact, leading to the gradual destruction of buildings and the lack of security. Nevertheless, all of the above creates a special appeal for creative youth (Voznyak, 2018).

If we are aware of the various properties of the architectural and planning layout of industrial

1)



2)



Figures 1, 2. Development of industrial architecture in the 17th through 19th century:
1) Industrial architecture of the 12th and 13th century, before the First Industrial Revolution, as exemplified by the Cannon Foundry Yard in Neglinnaya Street. Moscow plan of 1610 (Podolsky, 1936)
2) Blast-furnace building of the Nevyansk factory, late 18th century (Podolsky, 1936)

3)

4)

Figures 3, 4: Development of spatial and architectural solutions for industrial complexes over the course of historical events from the 19th through the 21st century:
3) Nevskaya paper-spinning manufactory. St. Petersburg, Russia, 1895 (source: Citywalls, 2020)
4) Innovative industrial center. Chiayi, Taiwan, 2011. Photo © Bio-architecture Formosana (source: architime.ru)

architecture spaces, of the requirements for their development, and of the laws conducive to their self-organization, we will be able to manage the existing system more conscientiously and approach the issues of its future use more reasonably. Modern approaches to the preservation of abandoned industrial buildings account for various influence factors and the perception of incoming information.

The formation of semantic unity between the existing historical environment, the selected site and the human user's demands follows certain principles in accordance with aesthetic shaping and practical application.

For a synergistic analysis of reusing abandoned industrial architecture, the backbone factors are:

- the human user acting as an attractor, and the activity of this user, which informs a specific request for shaping a new internal space in the existing environment;
- the historical significance of the selected site;
- the sociocultural significance of the site's reuse, as well as its possible fluctuations;

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- the space-time relationship as a source of information, that is, the spatial layering of historical development in the past, present, and future (Shevelev and Stupak, 2017).

The existing experience in adapting abandoned industrial buildings fully highlights the relevance of this issue. The analysis of works on this subject has helped us trace the co-evolution of humankind and architecture, while also making it possible to draw up a rough scale of priority directions for the reuse of abandoned industrial culture sites. The shifts in functional usage types tend to "undulate" from mass consumption to individual use and back again. The multiple existing approaches to functional usage directly depend on temporal, geographical, historical, cultural, economic, environmental, and social factors. We could say that one of the main approaches here is the typological approach, which characterizes the purpose of the site that is being adapted: work, housing, or leisure (Gelfond, 2011). The current link between the site and the environment, the financial capabilities of the customer, and the specific sociocultural needs of the local community help narrow down the functional content. This gives us a more systemic understanding of the prospects for reusing abandoned industrial sites while respecting the location's historical significance.

Synergistic Analysis of Industrial Architecture Reuse

The building's original function once determined its architectural and spatial layout, and in the future, the new function will be affected by the temporal changes, accommodating for the existing form. This trend becomes evident in the re-purposing of the abandoned Eveleigh Rail Yards in Sydney, Australia (Figs. 5–8).

5)

6)

7)

8)

Figures 5–8: Transformation of the abandoned Eveleigh Rail Yards, built in Sydney, Australia, in the 1880s, into Carriageworks, a modern center for performing arts (theater, experimental dance, acrobatic shows)
5) Carriageworks of the Eveleigh Railway Complex (circa 1880s, designed by George Cowdry), State Rail Authority Records, New South Wales State Archives and Records (source: Heritage Council of Victoria, 2021)
6) Carriageworks of the Eveleigh Railway Complex (photo by Michael Nicholson)
7) Carriageworks pre-construction (source: OCP Architects, 2021)
8) Carriageworks performing arts center in Sydney, Australia (circa 2006, photo by Michael Nicholson)

Time and motion "burst into" the integral structure and impose "new demands" (Gelfond, 2011). One of the earliest types of re-purposing industrial architecture was the creation of museum and exhibition spaces. The three-dimensional planning features of this type of architecture had a suitable unique compositional layout, large open spaces, and an already established transport infrastructure, perfect for meeting the consumer demand. Urban planning and economic aspects influenced the subsequent stages of the sites' adaptation, which led to the development of public and business venues, shopping centers, and residential spaces. Based on the "pattern language" theory (Mehaffy, 2012), which Karasev and Denisenko discuss in their paper, Reorganization of Industrial Territories and Architectural Objects with Considering Adaptive Processes, the specific feature, in this case, is the

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openness to transformation. This allows for switching between several different concepts, depending on consumer demand, and thus encourages the trend of combining the business, public, and housing functions (Karasev and Denisenko, 2020). Adaptive reuse is a promising area in the development of architecture, as it helps to bring abandoned industrial buildings back to life and revive the genius loci.

In this article, we use the basic principles of the synergistic approach as a basis for predicting which functional purpose abandoned industrial architecture is most likely to be reused for. The current state of the cultural and social consciousness is determined by the interconnection between the chaotic environmental, political, and economic developments, the “information explosion”, the changes in the nature of human labor, and the scientific and technological progress. For a more accurate prediction of re-purposing the industrial sites and eliminating the fluctuation probability, it is particularly important to be aware of the past and the present. As we build upon an aggregate set of the main principles for choosing the new function, including urban significance, historical importance, conservation status, spatial planning layout, and sociocultural impact (Bessarabova and Evtushenko-Mulukaeva, 2019), we should not lose sight of the projected transformations in society. In this case, the openness of complex nonlinear systems forming the site that is being used is characterized by a multitude of functions and the modularity of the future spatial layout. From the synergistic standpoint, it is worth considering the mutual links between the new functions and their subsequent impact on the existing transport infrastructure, the environmental management, and the impact on industrial architecture safety levels and on the community’s social life. The actual progress of managing the site’s functions will contribute to the subsequent choice of alternatives for developing the spatial transformation and filling the site with innovative content.

The evolution of industrial architectural styles is pushing the boundaries of re-purposing industrial sites. The architectural and spatial features of adapting abandoned industrial buildings and structures are shaped by the direct interaction between the old, i.e. the historical structure, and the new, i.e. the new target function. The new functional planning and compositional solution for arranging the internal layout should fit harmoniously into the existing environment. Re-purposing the selected site may have different degrees of impact on the integrity of its historical design. This is why the extent to which the site’s existing structure is going to be physically disrupted is determined by the preservation of its cultural significance and the revival of the genius loci (Bloszies, 2013). Regular fluctuations in sociocultural needs and economic opportunities continually support the claim that re-purposing historically significant industrial architecture is highly relevant.

Conclusions

The modern adaptation of abandoned industrial complexes helps to take a fresh look at the historically formed urban structure, as well as renew the interest in local history and improve the city’s economic, cultural, and social wellbeing. The preservation of the value of abandoned industrial factories and plants is a suitable response to the needs of modern human life. At the same time, the authenticity of the site is preserved and expressed both through the interconnection of the site’s internal space and the environment, and through the figurative interaction between modern city life and historical genius loci. Such a synthesis allows the visitor to become part of a historical landmark, bringing it back to life and filling it with a new function. In the context of synergistic analysis, it is by adapting abandoned industrial architecture to meet modern needs and by using the opportunities of today that we create all kinds of fluctuations, which depend on the site’s past functional purpose and will affect its new use in the future. The predicted transformations of modern society are already affecting the relationship between the historically formed structure and the future existence of its new iteration.

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СИНЕРГЕТИЧЕСКИЙ АНАЛИЗ ИСТОРИКО-КУЛЬТУРНОГО РАЗВИТИЯ ПРОМЫШЛЕННОЙ АРХИТЕКТУРЫ

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Аннотация
Определение значимости промышленной архитектуры как объекта, имеющего культурную ценность, поможет выявить наиболее перспективные направления его функционального перепрофилирования с сохранением идентичности исторического места. **Цель исследования:** Изучение периодизации формирования архитектурно-пространственной организации индустриальных зданий и сооружений как модели самоорганизующейся системы, а также определение различных принципов их адаптации для повторного использования. **Методы:** В данной статье специфика историко-культурного развития промышленной архитектуры рассматривается с помощью синергетического подхода. **Результаты и обсуждение:** Анализируя изучаемый объект как самоорганизующуюся систему, его взаимосвязи с различными структурами в зависимости от нелинейности происходящих процессов, мы пришли к выводу, что появление разных стилистических направлений в промышленной архитектуре можно рассмотреть через призму знаковых исторических периодов - бифуркаций, которые стали результатом деятельности человека в прошлом и повлияли на функциональное развитие создаваемого пространства в будущем. Этот подход отражает социально-культурные потребности и раскрывает потенциал различных возможностей повторного использования исторически значимых промышленных объектов.

Ключевые слова
Синергетический анализ, история развития промышленной архитектуры, взаимосвязь времени и пространства, память места.

RECONSTRUCTION AND RESTORATION OF HISTORICAL MONUMENTS: INTERNATIONAL EXPERIENCE

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Abstract
Introduction: In addition to recognizing and taking into account the vital need for the maintenance and repair of historical structures, this study will focus on their inherent design potential at the intersection of the new and the old. **Purpose of the study:** The study aims to review the approach to restoring such landmarks as the library in Vyborg and the Arsenal building in the Nizhny Novgorod Kremlin. We will also focus on the restoration of more mundane structures. In addition to historical monuments, this study will look at instances when there is no attempt to return the buildings to some idealized version of the past, but instead, the restoration process is used to celebrate the qualities of the buildings' age in the here and now, and to recognize that they are living, evolving, and constantly changing entities. **Methods:** The study uses the method of analysis, which we apply to the standard solutions for various purposes and objects, in the form of structural and technological protection of cultural heritage sites during their restoration and adaptation. The use of modern restoration materials and protective structures' construction technologies will help protect the environment while taking into account LEED, BREEAM, the Energy Star program (the USA), and the GREEN ZOOM standards. **Results**: We offer selected examples from contemporary practice in Europe, the United States, and Russia to illustrate these approaches to restoration, including two student-led architectural installations that explore the creative intersection between the new and the old. **Discussion:** Discussing the execution of specific restoration and reconstruction projects reveals the importance of international cooperation in the development of educational strategies and practices in the field of conserving and restoring the cultural heritage. The growing volume of conservation and restoration work is putting pressure on the development of research approaches and methodologies aimed at solving practical problems. At the same time, the restorer must be mindful of continuity with the past when reconstructing the more mundane and utilitarian structures that can benefit from less restrictive approaches to the intersection of the old and the new.

Keywords
Architectural heritage, restoration, adaptation, innovation, historical building structures, European experience, Russian experience, American experience, architectural installations.

Introduction

The preservation of architectural monuments periodically involves conservation and restoration, which is provided with a theoretical rationale. The conservation and restoration methods used are fluid and require each restorer to take a creative approach to solving the project-specific issues. Conservation of a cultural heritage site is defined as research, survey, and design and production work, including the complex of emergency activities aimed at protecting a cultural heritage site that faces rapid destruction, as well as preventing the site's deterioration (Jurow, 1978). In Russia, monument restoration is currently classified under the protection of cultural heritage sites, according to Article 41 of Federal Law No. 73-FZ of the Russian Federation of June 25, 2002.

The activities specified in conservation projects are carried out in order to prevent the building's further destruction under the influence of atmospheric precipitation. That is why the issue of conducting this type of work under the protection of outdoor canopies over cultural heritage sites is particularly relevant. The existing structural and technological solutions for the construction of outdoor canopies over cultural heritage sites during restoration and adaptation can be supplemented and improved with the use of new technical solutions for geodesic domes made out of timber and high-strength polymers (Handel, 2013). This will not only significantly reduce the strain in the load-bearing structures, as compared to metal and reinforced concrete, but also provide an opportunity to take care of the environment in accordance with European LEED, BREEAM, the Energy Star program (the USA), and the Russian GREEN ZOOM standards (Tuan, 1974).

The methods of conservation and restoration used in this case require each restorer to take a creative approach to resolving the issues specific to a given project (Lowenthal, 1985).

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When determining the appropriate technique for restoring a public landmark, it is crucial to assess its historical and architectural value. Structures that have less historical significance can offer the designer a greater license to creatively employ a broader range of modern building materials. A decision on reconstruction can only be made when the structure's architectural value is low or when the historical structure is in a neglected state of disrepair, requiring immediate intervention to preserve and extend its service life. Reconstruction is also possible when it is necessary to replace the site's utility system in accordance with the modern requirements of a constantly developing city.

To determine the technical condition of a building, it is necessary to have information about its actual structural strength, stiffness, the presence and location of its rigid joints, uniformity, material density, etc. (Lysova and Shalygina, 1979).

The Russian experience of restoration with modern construction materials and technologies can be exemplified by some of the outstanding monuments in St. Petersburg, many of which are under UNESCO protection.

Methods

Chapter 7 of Federal Law «On Objects of Cultural Heritage of the Peoples of the Russian Federation» prescribes a number of concepts that define the possible measures to be taken in order to preserve a cultural heritage site: conservation (Article 41), repair (Article 42), restoration (Article 43), adaptation of the site for modern use (Article 44), etc. (Federal Law No. 73-FZ of June 25, 2002). Restoration and adaptation are currently considered the most relevant. The concept of «reconstruction» is not included in the Federal Law, but the Town-Planning Code of the Russian Federation (clause 14) allows for certain measures in a situation where there are few protected landmarks on the site (Town-Planning Code of the Russian Federation No. 190-FZ of December 12, 2004). Besides, sub-clauses 14.1−14.3 provide the additional necessary clarifications for the definitions.

The authors of this study suggest using the geodesic dome design for preserving cultural heritage sites, both during restoration and adaptation and during the conversion into a museum.

This issue has already been raised by undergraduates of the Saint Petersburg State University of Architecture and Civil Engineering. In particular, in his final master's thesis in 2018, Ayat Alnajar proposed solutions for the construction of enclosures over historical buildings and structures, using the preservation of cultural heritage in Jordan as an example.

This technical solution has a number of advantages when applied to archaeological work and the restoration of cultural heritage sites:

1. There is no precipitation in the work area.
2. The microclimate remains favorable for both the cultural heritage site and the restorers throughout the restoration process.
3. The team can move freely while carrying out technological operations in the work area.
4. Work can be done at any time of the year 24/7.
5. The risk of work deadline disruption is reduced.
6. The restoration quality improves.

Researchers and experts around the world continue studying renewable energy from natural sources. Using the geodesic dome surface is an excellent solution to this issue (Pastukh and Zhivotov, 2020).

The use of modern building materials in the restoration of historical landmarks will not only significantly upgrade and strengthen the supporting structures but also provide an opportunity to take care of the environment, taking into account European LEED and BREEAM, the Energy Star program in the USA, as well as the Russian GREEN ZOOM standards.

Over the recent years, we have been seeing the active introduction of innovative technologies. New methods of restoration and adaptation of cultural heritage sites are being applied in various Russian cities in order to meet the needs of modern society. We would like to refer to specific historical landmarks in Nizhny Novgorod and Vyborg to illustrate this approach.

We will also consider examples from foreign experience, modest in scale but still important, in that they provide a frame of reference for evaluating the preservation strategy. These examples include the work on the creative solution that was used to breathe life into the ruins of a Gothic church that had been badly damaged in World War II and remained so until its restoration in the 1990s, in Müncheberg, Germany. During the Küppersmühle renovation in Duisburg, Germany, Herzog and de Meuron were asked to convert an iconic industrial facility into a museum to house postwar German art.

We will also offer two student-led projects that use an investigation of the ordinary as a catalyst for design, resulting in new architectural installations that both emerge from the existing environment and amplify and reveal its aspects.

Results

1. Architectural Heritage Sites in Russia

1.1. Building of the City Library Named After N. K. Krupskaya, Architect Alvar Aalto (1933−1935), Vyborg

The Library is considered a cultural heritage site of federal significance in modern Russia. The renovation of the Library in Vyborg was an important process and an interesting example of restoring and preserving modern architecture. The aim of the restoration was to restore the building's architectural value, as well as to meet the modern needs for functionality and security. The necessary funds were allocated from the Russian budget for the restoration of the building in 2010, with the assistance of the federal authorities, former President of Finland Tarja Halonen, and Russian President Vladimir Putin. The «rescue» of the Library in Vyborg was carried out jointly by Russian and Finnish experts and supported by the International Council on Monuments and Sites (ICOMOS) and the city administration of Vyborg. The great value of the Library building is recognized by the authorities in Moscow and St. Petersburg.

The new Library opened on October 13, 1935, was designed by young but already famous architect Alvar Aalto. He used three solutions that are now regarded as central to his approach. The first solution is a revolutionary lighting system in the reading hall, with fifty-seven individual apertures in the ceiling. They supply a steady diffused light that is reflected off the walls, which have a matte finish and are whitewashed with lime. The second solution is the noteworthy design of the reading hall, with a desk for librarians that is as solemn as a church pulpit. The third solution is a lecture hall with a wave-shaped ceiling made out of light wood, which is a very appealing feature (Figure 1).

The restoration accounted for the prospect of Aalto's Library being potentially added to the UNESCO World Heritage List. This meant preserving all the existing original elements at the beginning of the restoration and reproducing the lost elements as accurately as possible. At the same time, the building still had to remain functional as a library, so it needed to meet the modern requirements for library technologies, security, energy conservation, etc. The task was significantly facilitated by the availability of a complete set of initial design documentation and a number of models of individual elements. A detailed photo survey, taken immediately after the construction was completed, was also an important tool for restoring the original appearance of the Library. The on-site survey, started in 1987 by Vyborg architect Sergey Kravchenko, was continued by experts from the St. Petersburg Scientific Research Institute «Spetsrestavratsiya». After the completion of the most urgent work in 1994, successive sub-projects were launched to restore the building's individual parts and elements. The Finnish Committee's supervision over the work process and staff training ensured a high quality of work (Figure 2).

The restoration of the Library in Vyborg, designed by legendary Finnish architect Alvar Aalto, lasted for almost 19 years and received the highest award of a prestigious organization — Europa Nostra Award 2015. The preservation of the Library was celebrated during a joint ceremony, the European Union's Cultural Heritage and Arts Awards / Europa Nostra Awards, at the Oslo City Hall in Norway.

Figure 1. Library building in Vyborg as a vivid example of functionalism and «regional modernism». Photo by O. A. Pastukh, 2020

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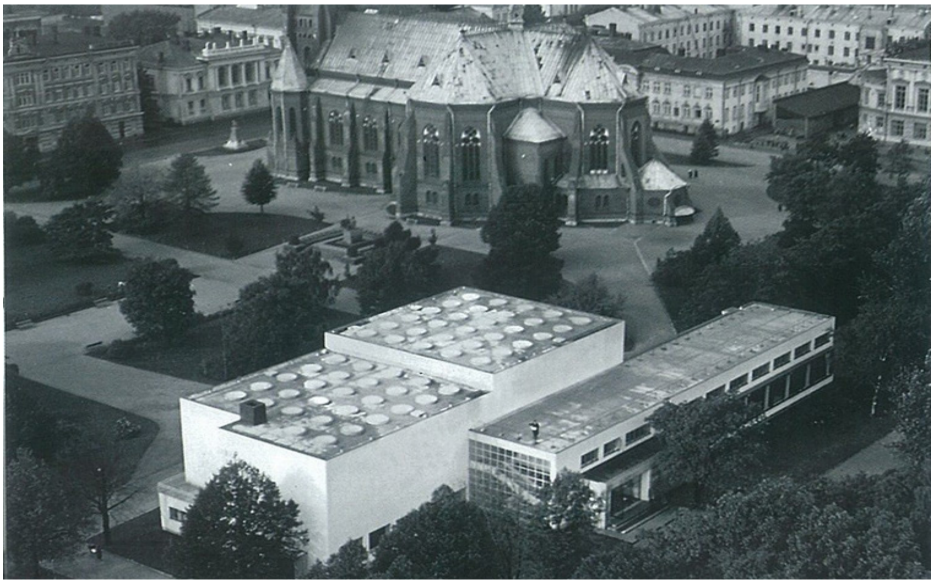


Figure 2. Alvar Aalto Library building, 1933−1935, the city ensemble

1.2. Arsenal building on the territory of the Kremlin, Nizhny Novgorod

The Arsenal building (1840−1843), built in the classical style, is located in the heart of Nizhny Novgorod, in the Kremlin. The Kremlin's territory is mostly occupied by the municipal and regional authorities, and culture is represented only by official academic institutions, such as the Philharmonic Society and the Art Museum. The architectural aspect of the Arsenal building has always been secondary in importance. The functional aspect of the Arsenal is secondary as well: while built for storing weapons and ammunition, it was never used in this capacity, as the military significance of the fortress had already been lost by the middle of the 19th century. After the revolution of 1917, the building was used as an archive by the Cartographic Service of the Ministry of Defense for many years, until being transferred to a branch of the NCCA (National Center of Contemporary Art) in 2003. The ambitious idea to create a branch of the NCCA in this building belongs to architect Evgeny Ass, as well as to A. Gor and L. Saprykina, heading the Center's Nizhny Novgorod branch (Farahat and Osman, 2018). The appearance of the Arsenal has not changed. The facades of the building have been carefully restored. The roof is painted with verdigris, as was the custom in the 19th century (Figure 3).

The quality of the spaces created in the Arsenal after the reconstruction can be considered almost perfect. The vaults and walls of the Arsenal building date back to the 19th century, but the interiors are notably modern. Architect Evgeny Ass has recognized, identified, and emphasized the monument's advantages and turned the utilitarian building into a fully-fledged public space. The architecture quite accurately reflects the strategy that the NCCA Nizhny Novgorod branch adheres to when promoting contemporary art in the Volga region (Pastukh, 2016). The space's architectural solution is based on a clear articulation of the old and the new. The red brick walls and vaults, as well as the Kremlin wall that is integrated into the building, have been carefully restored and have had plaster cleaned off them. The cast-iron flooring on the ground floor has been well preserved. The uneven man-made surfaces of the historical structures contrast with the obvious technological efficiency of the modern elements that have been introduced into the interior. The authentic features have not been replaced by replicas; rather, new designs catch the eye without trying to mimic the high antiquity (Kharlamov, 2011). The color scheme is laconic: red brick, black cast-iron flooring on the ground floor, and grayish-white modern additions (Figure 4).

2. Renovation of American Historical Sites. Student-Led Projects

2.1. RedBARN Installation

In addition to the above, one of the authors has contributed to student projects that examine similar situations. These projects strip away any functional agenda and allow for a creative approach, which is informed by an examination of the current environment. The redBARN installation project began with a detailed analysis of an existing historical barn located in central Indiana, USA. The insights from this analysis informed a site-conditioned response, where the architectural response «draws all of its cues (reasons for being) from its surroundings» (Irwin, 1985).

In this project, the student team was asked to spend some time exploring the historical barn at a leisurely pace. The students were from the central Midwestern region of the USA, so they were familiar with this type of building. They were then asked to write about their experience in the barn and their

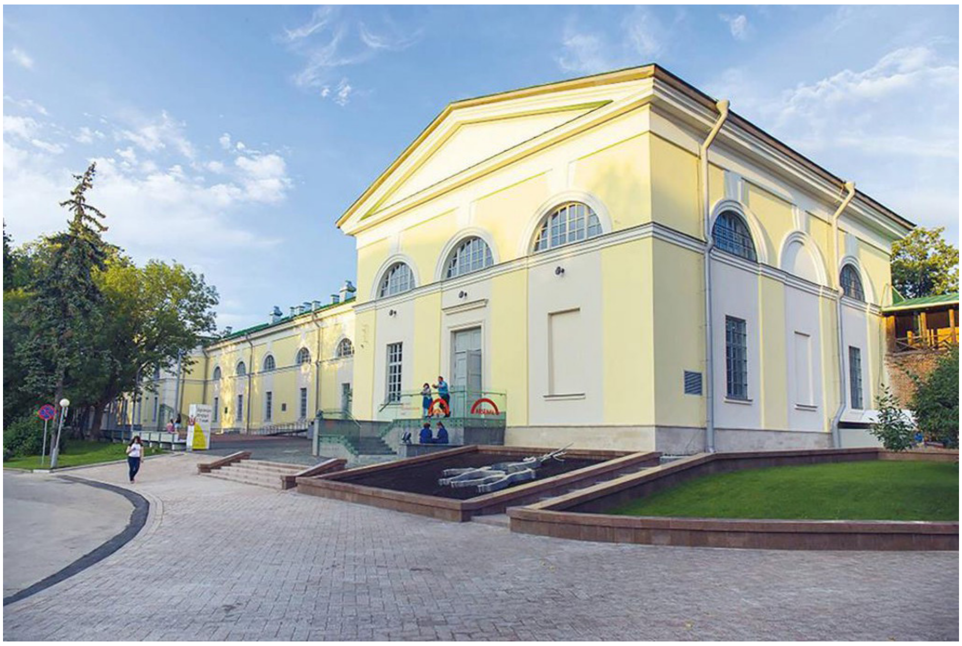


Figure 3. Arsenal building in the Nizhny Novgorod Kremlin. Photo by O. A. Pastukh, 2016

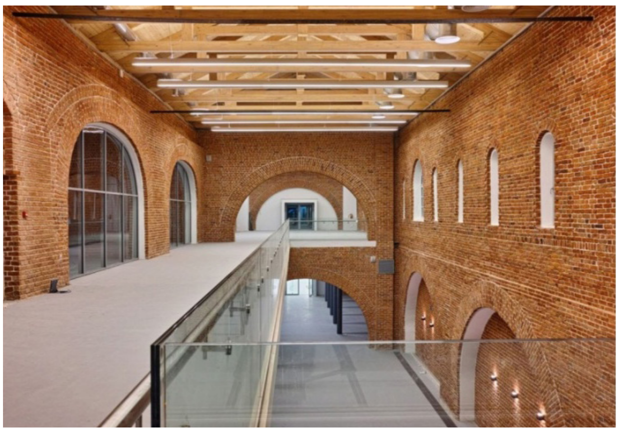
perception of its space, focusing on their emotional response. Certain themes emerged: the quality of light, the feeling of unease while walking on the aged floorboards in the loft, the touch, the age, the dense smell of dust, and the sensation of time. The installation's centerpiece is four steel boxes suspended within the barn, calibrating the scale of the space. Each box contains a series of hand-blown glass vessels filled with items precious to the barn. In the spirit of Carlo Scarpa's intervention at Museo di Castelvecchio, the final installation remains independent of the existing structure. It is integrated into the barn very delicately and contrasts with it in material and scale (Figure 5).

2.2. Irving Theater Installation

In another student project, the Irving Theater Installation, students were asked to propose installations that would amplify or reveal the resonant qualities of the existing space. Paul Reynolds, a fourth-year architecture student, identified an old opening in an existing wall as a point of interest at the theater, which was in an advanced state of dilapidation and decay. Collaborating with a group of contemporary dancers, Reynolds created an installation that provides a platform for creative movement and amplifies both the potential and the understanding of the existing environment. The Reynolds installation treats the existing structure with the reverence and respect typically reserved for something precious and is attached through a cleverly designed system of compression joints, which clamp to the existing opening when loaded. Leather pads are used as supports where the platform meets the existing structures, and no fastenings are needed to secure it in the existing opening. The platform can be installed and removed without a trace!

Although not dealing strictly with issues related to conservation and restoration, these types of

a.



b.

Figure 4. Modern interiors of the Arsenal building in the Nizhny Novgorod Kremlin. Photo by O. A. Pastukh, 2016

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a. b.

Figure 5. RedBARN Installation, Gray/Williams 2004; Irving Theater Installation, Gray/Reynolds, 2008

projects encourage students to develop a more profound understanding of the inherent potential that lies in the creative engagement with the existing environments, in addition to giving them a conceptual framework for building upon restoration's rich potential throughout their professional careers.

3. Renovation of Historical Sites in Europe: International Experience

3.1. Küppersmühle Renovation in Duisburg, Germany, Herzog and de Meuron

During the Küppersmühle renovation in Duisburg, Germany, Herzog and de Meuron were asked to convert an iconic industrial facility into a museum to house postwar German art. Narrow strips of vertical glazing are crisply incised into the building's facade, overlapping with the existing openings, which have been filled but not erased. The approach reveals a conviction that the intersection between the new and the old will result in something richer and more interesting than what would have emerged if the existing structure had been either demolished, left unchanged, or recreated. We find the same concept in the Italian aesthetic, where the layers of different modifications through time and history are often worn with pride on buildings' facades (Figure 6).

3.2. Gothic Church in Müncheberg, Germany

In Müncheberg, Germany, a creative solution was used to breathe life into the ruins of a Gothic church that had been badly damaged in World War II and remained in that state until its restoration in the 1990s. To help raise money for the restoration, the parish partnered with the municipality to share the space as both a spiritual and a civic center, creating a hybrid structure that breathed a new life into the historical building. Architect Klaus Block inserted a new structure, housing a library, a community office, a council chamber, and lavatories, into the shell of the existing cathedral, creating a rich interplay of the new and the old (Figure 7).

Discussion

Reconstruction of historical objects using modern construction materials is a topic that draws the attention of construction industry professionals and

Figure 6. Building facade, Firenze, Italy; window detail, Küppersmühle, Herzog & de Meuron, 1999

the general public. Residents, officials, architects, representatives of the business community and investors, as well as large construction companies must reach a consensus and have their interests represented as they discuss how to preserve historical monuments. This problem should be discussed at the international, national, city, municipal, and local level, and the discussion can be extended to the service life of ordinary residential buildings, which are often outdated and inefficient.

Saving energy and improving energy efficiency in construction and utilities is a global priority. It is known that buildings account for 40% of energy consumption in many countries around the world (Caird et al., 2012). Old housing stock, as a rule, suffers from significant heat loss and overheats through the enclosing structures.

Therefore, the most important measures in the construction sector include reducing energy consumption, using renewable energy sources in order to lower energy dependence on oil-producing countries, and reducing greenhouse gas emissions. The building's microclimate can be negatively affected by the refusal to use environmentally friendly natural materials and the use of outdated air purification technologies for climate control.

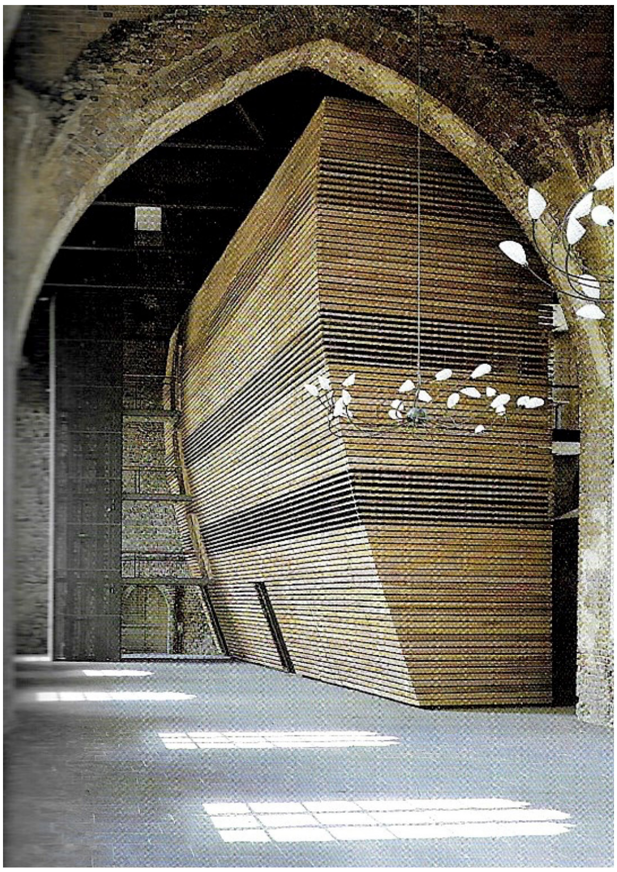
In order to upgrade the housing stock, save energy, and use the natural resources more rationally, authorities from the capitals of all eight World Green Building Council member nations (the USA, Australia, Spain, the UK, Japan, the UAE, Russia, and Canada) launched a special urban program. This program was designed for the long term. Its objective was not only to upgrade the old housing stock and preserve historical monuments but also to improve the living conditions and promote a greater sense of community among the local residents (Pastukh et al., 2019).

Green standards are aimed at regulating a sustainable approach to construction, assessing the buildings' degree of compliance with the basic requirements, and speeding up the transition from the traditional design and construction of buildings and structures to sustainable practices. Basic principles of sustainable construction:

1. creating safe conditions that are favorable to human health;
2. limiting the negative impact on the environment;
3. considering the interests of future generations.

It is interesting to hear what well-known practitioners in the field of preserving the historical urban environment and individual monuments think about introducing modern construction materials and organizing the reconstruction process,

a.



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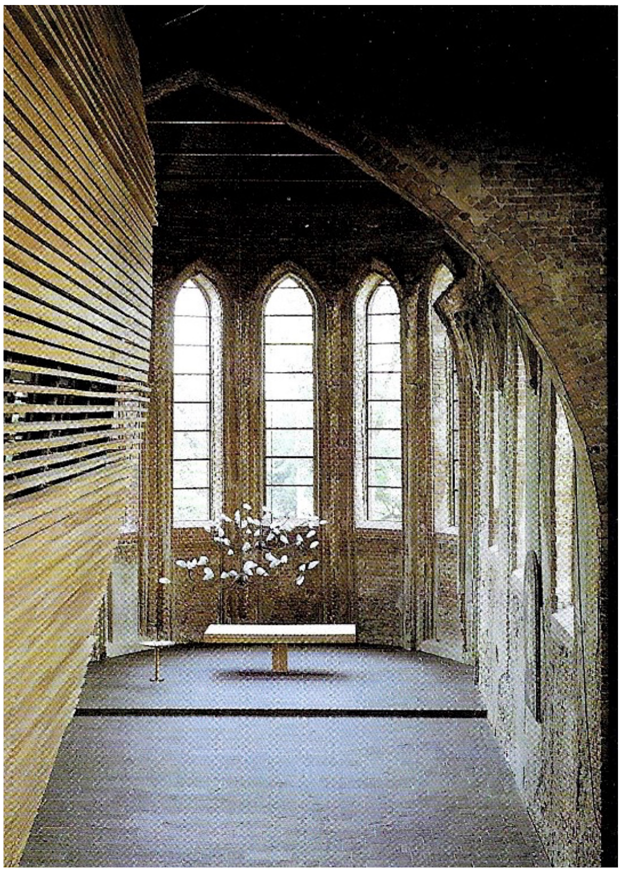

Figure 7. Building of the Gothic church, Müncheberg, Germany

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depending on the specifics of their work experience.

Over the recent years, the state of the environment in the world has not changed much for the better. The ongoing natural disasters force humanity to think about the need to reduce CO^2 emissions and to create technical solutions that will help use natural materials with minimal waste during the production process. In construction, these include sustainably harvested timber and timber-based materials. Timber is a constantly renewable resource; it is also easy to process and does not leave any inorganic substances after use (Pastukh et al., 2020).

Polymer materials are of interest as well, due to their technical, physical, and mechanical properties. The wide range of properties of these materials, altered through various manufacturing methods, opens up a lot of opportunities for scientific and technical solutions in the future.

Solutions for the production of metal geodesic domes and reinforced concrete structures are widely used in modern practice. However, the authors of this paper believe that the combination of timber and polymer materials in geodesic dome construction is the most advantageous option from every point of view: that of engineering, funding, economics, energy, and even environmental issues.

Conclusions

By using construction materials and technical solutions taken from the official catalogs of construction companies, one can design buildings that meet the requirements of international standards such as LEED, BREEAM in Europe, Energy Star in the USA, and the Russian standards of green construction (GREEN ZOOM). A set of measures for the renovation of specific historical monuments sets a direction for the improvement and development of the entire territory and is aimed at creating a comfortable urban environment and improving the economic viability and long-term development of both individual districts and cities as a whole.

Shielding cultural heritage sites with geodesic domes, made out of timber and composite materials, will create favorable conditions for the preservation, conservation and restoration activities in all weather conditions.

The technical solution for creating a geodesic dome in the form of a protective shield over cultural heritage sites will slow down the process of their deterioration, improve restoration quality, reduce the risks of performing low-quality work, and allow for the restoration of objects of any complexity in any weather conditions.

As for the execution of specific restoration and reconstruction projects, the importance of international cooperation in the field of restoring and protecting cultural heritage is quite clear. The growing volume of conservation and restoration work is contributing to the urgent need to develop scientific approaches and methodologies that will help solve practical problems. Therefore, engineering practices relevant to the conservation of architectural monuments require close attention and cooperation of various experts, primarily architects, restorers, engineers, and archaeologists.

Preservation of historical and cultural monuments is the main task of engineering conservation and restoration. Each monument has inherent individual features, which add special value. Production methods must be constantly improved, thus reducing labor intensity.

Much has been done in Russia to preserve the cultural heritage of the past, including architectural, cultural, and historical monuments. The capabilities of modern construction equipment and new construction materials are almost limitless. Currently, one can straighten, restore, lift, move, and save any monument, even in a state of disrepair, without changing its appearance. The use of modern construction materials in the reconstruction of historical monuments will not only extend the monuments’ service life but also contribute to preserving the environment on our planet.

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РЕКОНСТРУКЦИЯ И ВОССТАНОВЛЕНИЕ ИСТОРИЧЕСКИХ ПАМЯТНИКОВ: МЕЖДУНАРОДНЫЙ ОПЫТ

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Аннотация

Помимо признания и учета важности и необходимости технического обслуживания и ремонта исторических сооружений, в настоящем документе основное внимание будет уделено присущему им проектному потенциалу на пересечении нового и старого. **Цель исследования:** Подход к реставрации таких памятников, как библиотека в Выборге, здание Арсенала Нижегородского кремля, но также будет сделан акцент на реставрации обычных. В дополнение к памятникам, в этой статье будут рассмотрены примеры, которые не пытаются вернуть здания к какой-то идеализированной версии из прошлого, а скорее используют процесс реставрации, чтобы отпраздновать качества возраста, как они существуют в настоящем, чтобы признать построенную среду живой, развивающейся и постоянно меняющейся. **Были использованы следующие методы:** Анализ типовых решений для различных целей и объектов в виде структурно-технологических приемов охраны объектов культурного наследия при проведении реставрационных и адаптационных работ. Для того чтобы сохранить использование современных материалов в реставрации и технологий строительства защитных сооружений, он будет заботиться об окружающей среде с учетом стандартов LEED, BREEAM, программы Energy Star в США и GREEN ZOOM. **Результаты:** Авторы предложили избранные примеры из современной практики в Европе, США и России, чтобы проиллюстрировать эти подходы к реставрации, включая две студенческие архитектурные инсталляции, которые исследуют творческое пересечение нового и старого. **Обсуждение** хода реализации конкретных проектов реставрации и реконструкции показало важность международного сотрудничества в разработке образовательных стратегий и практик в области реставрации и охраны культурного наследия. Растущий объем консервационно-реставрационных работ оказывает давление на развитие научных подходов и методик решения практических задач. В то же время реставратор должен признать, что преемственность с прошлым может существовать при реконструкции более приземленных и утилитарных структур, которые могут извлечь выгоду из менее ограничительных подходов к пересечению старого и нового.

Ключевые слова

Архитектурное наследие, реставрация, адаптация, инновации, исторические строительные конструкции, европейский, российский и американский опыт, архитектурные инсталляции.

THE PRACTICE OF USING THE GOLDEN SECTION IN ARCHITECTURE IN THE CITY OF RYAZAN

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Abstract
Introduction: At present, the preservation of unique architectural ensembles is one of the most urgent problems of sustainable development in historical settlements. In the context of transforming the settlement's environment while minimizing the discordant impact of new construction, it is important to study the development sites that will be used as the basis for modern planning. **Method:** The article applies the method of geometric analysis to the historical buildings of the city of Ryazan, which exhibit classical architecture traits and were designed by the 19th- and 20th-century architects, in order to assess their compliance with the rules of classical composition, specifically the use of golden section proportions. We also talk about the golden section in general, reviewing its history and the rules of its application in architecture. **Results:** We emphasize the inseparable link between architecture and geometry. Our study proves that the golden section principles were used by architects during different historical periods. In the context of the invariably high interest towards the creative heritage of architects from the 19th and 20th centuries and the need to build upon their historical experience, it is highly relevant to approach the modern architectural practice from the standpoint of using the canon of Neoclassical architecture.

Keywords
Golden section, golden ratio, cultural heritage sites, architecture, geometric analysis, buildings, structures, Neoclassical period, proportionality, design technique, geometric progression, facade, column, stylobate, entablature, capital, form-making.

Introduction

The beginning of the reform that divided Russia into governorates, as well as the deployment of new principles of regular structural development, saw the creation (as per the general plan issued by Catherine the Great) of a new square, buildings, and street layouts that have survived to this day. The designs of these sites belong to the Neoclassical style; some examples include: the building of the men's gymnasium, the drama theater in the Sobornaya Square, and the indoor market in the Bazarnaya Square. Some of Ryazan's buildings and structures make up the historical development stock, serving as the background for the emerging Soviet architecture, which, in turn, was the link between the architecture of the past and modern architecture (Guseva and Pravdolyubova, 2017a).

We have made an attempt at studying various cultural heritage sites and at understanding their true features, as well as the cause-and-effect relationship between expressive architectural details and building elements from different periods. To achieve this goal, we have made a selection of historical buildings, dating from the second half of the 18th century to the 1960s. As a result, we have examined over a dozen architectural and cultural heritage sites in Ryazan and the Ryazan Region.

This particular paper focuses on two of these buildings, functionally diverse and still in use for their intended purpose:

- the men's gymnasium, built in the 19th century by architect M. F. Kazakov and currently housing the polytechnic university;
- the drama theater building, which is the main image-shaping landmark of the Teatralnaya Square.

The concept of the golden section, elevated to the rank of the main aesthetic principle, was described by Leonardo da Vinci as the «Golden Number» (Kvashina and Gorovenko, 2017). His teachings faded into oblivion for almost two hundred years; it was not until the middle of the 19th century that another attempt was made to formulate the general principles of proportionality and the golden («divine») ratio (Piljasov, 2012).

There are infinite irrational numbers; however, a select few of them hold a special place in the history of spiritual and material culture, architecture, and mathematics. One of such numbers is the Phidias number (phi), which equals 1.618... and is the result of solving a geometrical problem: dividing a line segment into two unequal parts in such a way that the ratio of its larger part to the smaller part is the same as the ratio of the entire segment to the larger part (Suprun et al., 2019).

This mathematical proportion was used for form-making in the art of architecture. Its purpose was to facilitate a harmonized, holistic perception of the man-made urban environment. Architecture, which intersects with geometry in many ways by its sheer nature, has a long history of using measurements and observing proportions (Kalashnikova and Gorovenko, 2016). The golden section principle also lies at the foundation of construction metrology. The ratio of the general structure to the specific details in different structures' proportions presents sufficient material for studying the development of the golden section canon, as represented by harmonizing the appearance of urban buildings (Gamm and Gorovenko, 2016). The emergence of a new world view and new methodologies in the design of buildings and structures, as well as the advent of new construction techniques and modern materials, creates a new attitude to form, proportions, and aesthetic (Guseva and Pravdolyubova, 2017b). The quintessential goal of this study is an attempt to trace the application of this methodology to designing Neoclassical buildings and structures, as well as its interpretation in Ryazan's architecture in the 1930s and 1950s.

We limited our efforts to demonstrating the results of analyzing the geometry of a limited number of public buildings, which represent the Neoclassical school of architecture, with a particularly in-depth look at the geometric proportions of individual elements and fragments. «The composition of churches is perfectly measured, and the architects must follow these measurements with utmost diligence. They arise from proportion.

And proportion is the balance between the parts of any work of architecture separately and as a whole, in relation to a single part, which any harmonious measurement is founded on. For the fact of the matter is that no church shall have proper composition without harmony and proportion, and without being divided into parts the same way as a well-built human body. After all, nature did create the human body in a very particular way, so that the face, from the chin to the hairline, equals one tenth of the body's length... the head and the neck, from the upper chest to the hairline, equals one sixth... the foot equals one sixth» (Shevelyov, 1995).

Only when we do understand the role of proportionate division into parts and the ratio of the parts to the whole, only then shall we understand the measurement canon that the architects of the past had mastered (Shevelyov, 1995). The goal of architectural measurement is to bind all elements of the building together with a proportional relationship so that everything would be unified and all the individual elements would be subordinated to the core (Radzyukevich, 2014).

«Each work of art, just like any living being, has its own proportions, its own sequence of rhythmically measured flows, dictated by the form. This makes our goal quite clear: use the living, everlasting examples from the architecture of the past to demonstrate how the compositional structure, association imagery, and proportion measurements are all tied together, thus making it possible to experience the profound meaning of true professional mastery» (Shevelyov, 1995).

It has been common practice in mathematics, since the Renaissance at the latest, to single out a specific method of dividing an entity into two unequal segments; this method is based on two different types of relationship between the parts and the whole: additive and multiplicative. This was how the proportions of the golden section, known back in ancient times, were described during that period (Gorovenko and Gorovenko, 2017; Grinchenko and Shchapova, 2018). The unity of the additive and multiplicative relationship is where the deep meaning of the golden section lies; this unity is the key to the phenomenon of form-making, which can be clearly seen on the surface of mathematical knowledge. The notion of the additive relationship shows that the whole has a structure. The simplest, most elementary whole entity is made out of two parts. In mathematics, the abstract representation of this structure is the operation of addition: part *a* plus part *b* equals the whole, *c*. In geometry, this can be illustrated by a line segment divided in two. If these two parts of the segment are unequal, and the ratio of the smaller part to the larger part is the same as the ratio of the larger part to the whole, this means that the additive relationship and the multiplicative relationship overlap, and the line segment is divided according to the golden section principle. The multiplicative relationship means that all parts of a structurally organized whole are subject to the same growth principles (Bondarenko, 2019; Stakhov, 1984, 2012). Mathematical tools show that both the parts of the whole and the whole itself have the same capacity for changing their parameters: within a single living body, all parts grow according to one law: the law of geometric progression. The more one part grows, the larger (by the same multiplier) the other part becomes, and the whole with it $(a:b = b:c)$. Consequently, the whole (c), if examined independently from the surrounding context, always remains identical to itself at any point throughout its existence.

Numerically, the golden section can be described as follows: $\Phi^{-1} = 0.618$ and $\Phi^{-2} = 0.382$.

Analyzing the Building of the Ryazan Regional Drama Theater

As the first item for examination, we propose the building of the Ryazan Regional Drama Theater, awarded with the State Badge of Honor. The theater was founded in 1787. It has undergone a number of reconstructions since then. The building we see today dates back to 1961.

We based our analysis on the building's dimensions, as follows:

width — **34.5** m;

depth — **62** m;

height — **28** m.

Let us now compare the ratio of the building's overall dimensions and the golden section canon, i.e. ratio of the smaller part to the larger part and the larger part to the whole:

$$height + width = depth,$$
$$28 + 34 = 62. \quad (1)$$

In this case, at the initial calculation stage, the golden section formula is fully justified, as that the sum of the smaller and larger parts is equal to the whole.

$$\frac{height}{width} = \frac{28}{34.5} = 0.81. \quad (2)$$

$$\frac{width}{depth} = \frac{34,5}{62} = 0.58(0.6). \quad (3)$$

$$\frac{height}{depth} = \frac{28}{62} = 0.45(0.5). \quad (4)$$

Further calculations show that the width/depth and height/depth ratios approach the Phidias number, 0.618.

Let us make a proportion:
assuming that x is the height of the roof (architrave + frieze + cornice + pediment);
and 28-x is the height of the building (columns + capital).

Then

$$\frac{x}{28-x} = \frac{28-x}{28}. \quad (5)$$

After solving for x, we find that:
x = 10.7 m (≈11 m);
28 – 10.7 = 17.3 m (roof height).

These calculations give us the following: the canonical ratio of the smaller part to the larger part is identically equal to the ratio of the larger part to the whole, which confirms that the building is structured according to the golden section principle.

The drama theater's linear dimensions:

- width — **34.5** m;
- depth — **62** m;
- height — **28** m;
- column circumference — **5.2** m. The circumference formula C = πd helps us find the diameter 5.2:3.14 ≈ **1.65**m;
- column spacing — **2.33** m;
- the distance between the two outer columns on either end — **0.6** m;

Figure 1. The building of the Ryazan Regional Drama Theater, awarded with the State Badge of Honor

- roof height (architrave + frieze + cornice + pediment) — **10.7 m;**
- entablature width ≈ **4** m;
- stylobate length — **34.5** m.
- pediment height — **6.7** m: column height + capital — **17.3** m.
- the capital height equals:

$$\frac{17.3}{8} = 2.1625\,m. \qquad (6)$$

The column shaft height equals: 17.3 - 2.16 = 15.4 *m.*

Let us now measure the colonnade against the theater's rectangular facade. The canon golden section theory is based on the assumption that the column symbolizes the human body (Pankratova, 2018; Stakhov, 2004). This leads to the 1:5 proportion requirement (equal to the ratio of the foot to the overall human height). This proportion requirement applies to a single column (including the capital) and the entire colonnade (Litvinenko and, Luchkova, 2015; Shevelyov et al. 1990).

According to Plato, the mean average is the average derived from two extreme values.

If the task is to make a ratio between the numbers 1 and 5, the best ratio will be √5, since 1:√5 = √5:5.

The Parthenon ratio is 1:5, which directly points to the proportions of the Parthenon as a mean average of 1 and 5, i.e. 1:√5 = 0.447. After all, if the column shaft has 1:5 proportions, then the links between the columns in the colonnade (the column spacing) should be the average of the two extreme values, namely the diameter and height of the column shaft; whereas the stylobate width should be the average of the order height and the stylobate length.

The measurements show that:

$$\frac{\text{Lower diameter of the corner column}}{\text{Shaft height of the corner column}} =$$

$$\frac{1.65+1.65\text{m}}{15.14\text{m}} = 0{,}2179;\ 1:5\ (+0.0179).$$

$$\frac{\text{Lower diameter of the corner column}}{\text{Shaft height of the corner column}} =$$

$$1{,}65 + \frac{1{,}65}{15{,}14} = 0{,}2179;\ 1:5\ (+0.0179).$$

$$\frac{\text{Lower diameter of the middle column}}{\text{Shaft height of the middle column}} =$$

$$\frac{1.65}{15.14} = 0.1089;\ 1:5\ (-0.0179).$$

$$\frac{\text{Cappital abacus width}}{\text{Column height with capital}} =$$

$$\frac{2{,}16}{17{,}3} = 0.1248;\ 1:5\ (-0.0752).$$

$$\frac{\text{Column spacing}}{\text{Column shaft height}} = \frac{2{,}33}{15{,}14} = 0.1538;\ 1:5\ (-0.0462).$$

$$\frac{\text{Pediment height}}{\text{Column shaft height}} = \frac{6.7}{15.14} = 0.4425:\sqrt{5} = 0.447;\ (-0.0045).$$

$$\frac{\text{Column height + capital}}{\text{Stylobate length}} = \frac{17.3}{34.5} = 0.4942:\sqrt{5} = 0.447;\ (+0.0472).$$

These measurements show that the rectangle of the theater's main facade reinforces the association: the human body is likened to the body of a column and the body of the entire building (colonnade). This reaffirms that the building's metric features of the Regional Drama Theater fit the golden section canon completely.

Analyzing the Building of the Polytechnic Institute

The polytechnic institute is located in a heritage building that dates back to the 19th century (designed by M. F. Kazakov). It is a striking example of Russian Neoclassical architecture and an integral part of the surrounding ensemble in Lenina (formerly Astrakhanskaya) Street.

Plan view of the building's dimensions:

$$\frac{width}{depth} = \frac{54}{90} = 0.6.$$

The measurement proportions of the central facade:

$$\frac{height\ of\ the\ central\ facade}{height\ of\ the\ side\ wings} = \frac{25{,}20}{20{,}4} = 1{,}23.$$

$$height\ of\ the\ pediment + height\ of\ the\ first\ floor\ with\ the\ basement = = height\ of\ the\ central\ facade$$

3.8 + 7.75 = 11.55

$$\frac{width}{height} = \frac{24.0}{21.4} = 1.12.$$

Figure 2. The building of the polytechnic institute

Vertical articulation ratio

$$\frac{height\ of\ the\ second-floor\ window}{height\ of\ the\ column\ shaft}=\frac{4.5}{7.0}=0.64.$$

Our calculations allow us to assert that the building's overall dimensions match the golden section principle.

Let us now check the main facade's rectangle for compliance with the Parthenon ratio.

$$\frac{\text{Lower diameter of the corner column}}{\text{Shaft height of the corner column}}=$$

$$\frac{2}{7}=0.2857;\ 1:5\ (+0.0857).$$

$$\frac{\text{Lower diameter of the middle column}}{\text{Shaft height of the middle column}}=$$

$$\frac{1}{7}=0.1428;\ 1:5\ (-0.0572).$$

$$\frac{\text{Capital width}}{\text{Column height with capital}}=$$

$$\frac{0.7}{7.7}=0.09;1:5\ (-0.1100).$$

$$\frac{\text{Column spacing}}{\text{Shaft height}}=$$

$$\frac{1.5}{7}=0.2142;1:5\ (=0.0142).$$

$$\frac{\text{Order height (column + entablature)}}{\text{Stylobate length}}=$$

$$\frac{9.3}{16}=0.5812;\ 1:\sqrt{5}\ (-0.1342).$$

$$\frac{\text{Estimated average column diameter}}{\text{Column spacing}}=$$

$$\frac{1}{1}=0.6667;\ 1:\sqrt{5}\,(-0\ 2197).$$

$$\frac{\text{Pediment height}}{\text{Column shaft height}}=$$

$$\frac{3,8}{7}=0.5428;\ 1:\sqrt{5}\,(+0.0958).$$

$$\frac{\text{Column height + capital}}{\text{Stylobate length}}=$$

$$\frac{7,7}{16}=0.4812;\ 1:\sqrt{5}(+0.0342).$$

Main facade windows

First floor

$$\frac{\text{Lighting aperture width}}{\text{Lighting aperture height}}=1.75/2.850=0.614.$$

Second floor

$$\frac{\text{Lighting aperture width}}{\text{Lighting aperture height}}=1.75/4.5=0.614.$$

Third floor

$$\frac{\text{Lighting aperture width}}{\text{Lighting aperture height}}=1.75/1.75=1.$$

A dimension analysis of the polytechnic institute building reveals an adherence to the golden section principle in the designs of the architects of the past.

The spacing of the facade columns and the measurements of the stylobates, entablatures, and pediments, which we analyzed in relation to the Parthenon proportions, once again highlight how the architects of the past perceived and mentally processed the harmony of the world, how they managed to create a flawless architectural form, and why and how the fruits of human labor are connected with the fundamental laws of the universe.

The golden section principles also (indirectly) apply to our color perception of the play of volume and light within the architectural environment around us (Safiulina and Shmurnov, 2014; Radzyukevich and Marchenko, 2015). It is common knowledge that the human brain automatically absorbs up to 90% of visual cues as part of visual perception. Therefore, the perfectly measured form that follows the golden section principle subconsciously encourages our mind to process the features of the architectural landmark, its color scheme, dimensional composition, or the surrounding landscaped parks (Gorneva et al. 2013; Prokofieva, 2015). The analysis of the color substance that contributes to the generalized perception of architectural solutions, with respect to their dimensions and color (spectral) composition, applies the essential principles of the golden section not only to the proportions and division of the lines, segments, details but also to the balance and harmony that should be maintained when selecting cold and warm colors and their respective wavelengths. When making a fraction of their proportions, we arrive at the same number, 1.6 (with a slight approximation).

The magic of the number 1.6 and its profound impact of creating a perfect harmony of forms and colors gives human beings an instinctive drive towards creative pursuits.

Conclusion

In the light of modern urban planning policy, it is highly relevant to radically increase urban comfort and reduce the number of cities with an unfavorable environment, in addition to designing a procedure that will allow the new generation of architects to become directly involved in ensuring a comfortable quality of life in cities. One of today's main goals is the creation of an environment that favors sustainable development, as dictated by the concept for the development of historical settlements, the support and promotion of cultural and tourism opportunities, and the development of a cultural heritage economy up to 2030, approved by the Ministry of Culture of the Russian Federation. The program of transforming the architectural environment is aimed at integrating the modern additions organically into the urban planning structure while retaining the original development and informed by studying the architectural environment and the objects that shape it. Since the integrity of the architectural environment is primarily ensured by the complementary scale and proportionate dimensions and elements of different buildings, one of the fundamental factors of the transformation described above is the use of modern design techniques that are based on a comparative analysis of classical design methods with historical roots, in addition to the main systems of architectural modules and proportions.

The architectural environment of a historical settlement continues to form throughout the entire period of the settlement's existence; history shows that architects from different historical periods keep returning to the classical systems of measuring proportions, which they interpret in the context of their time's socio-economic conditions and construction technology progress. In this regard, even as our rapidly changing reality abounds with technocratic innovations, we must not forget the classical canons of the architect's profession. The theory of the golden section reflects the unbreakable bonds of historical continuity that exist between the discovery of the geometric laws of the universe and the creation of today's man-made architectural landmarks.

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ПРАКТИКА ПРИМЕНЕНИЯ ЗОЛОТОГО СЕЧЕНИЯ В АРХИТЕКТУРЕ РЯЗАНИ

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Аннотация

В настоящее время одной из актуальных проблем устойчивого развития исторических поселений является сохранение своеобразия архитектурного облика. В контексте преобразований среды поселений с минимизацией диссонирующего воздействия нового строительства важны исследования объектов застройки, которые составят основы современных методик проектирования. **Методы:** В статье используется метод геометрического анализа исторических зданий города Рязань, имеющих признаки классической архитектуры и запроектированных архитекторами XIX - XX веков, на соответствие правилам классической композиции, в частности - на применение пропорций по принципу золотого сечения. **Результаты:** В статье изучается золотое сечение в целом, его история, рассматривается применение правила золотого сечения в архитектуре, показана неразрывная связь архитектуры с геометрией. В ходе работы доказано, что принципы золотой пропорции использовались архитекторами разных эпох. В условиях неизменно высокого интереса к творческому наследию архитекторов XIX - XX веков и необходимости использования их исторического опыта, существует актуальность подхода к современной архитектурной практике с точки зрения использования канонических постулатов классической архитектуры.

Ключевые слова

Золотое сечение, золотая пропорция, объекты культурного наследия, архитектура, геометрический анализ, здания, сооружения, эпоха классицизма, соразмерность, методика в проектировании, геометрическая прогрессия, фасад, колонна, стилобат, антаблемент, капитель, формообразование.

Civil Engineering

CONSTRUCTION OF LOW-RISE BUILDINGS IN THE COASTLAND AND WATER AREAS

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Abstract
Introduction: Artificial islands for new construction and works in a dry environment are created in water areas by installing enclosures, which allow buildings to remain rigid and stable and withstand the influence of climatic factors. **Purpose of the study:** We aim to develop a method for the construction of low-rise buildings in the coastland and water areas with the least labor effort required to erect buildings and ensure their safe operation. **Methods:** In the course of the research, we have performed theoretical studies in the field of experimental construction and analyzed the results of Russian and foreign scientific research related to the construction of buildings in water areas. **Results:** We have examined methods for the construction of waterproof enclosures in water areas that make it possible to erect buildings in a dry environment in open water areas with unstable wave conditions. Such methods reduce labor efforts, decrease the term of construction, and improve performance indicators.

Keywords
Water area, waterproof enclosures, cofferdam, pontoon platforms, pier foundations, coastland, telescopic piles.

Introduction

By the start of the 21st century, there were many projects for the construction of buildings of various purposes on artificial islands. Such architects as N. Foster, R. Piano, E. van Egeraat, and A. Asadov dealt with the matters of design and construction in water areas. Their projects were not implemented. However, they boosted the development of similar projects.

Additional territories for new construction are created by means of artificial islands in water areas (Zadvoryanskaya, 2008). This issue is usually addressed when dealing with design concepts of buildings and structures in cities and countries with high exposure to flood risk (Karmazin, 1973). For instance, in the Netherlands, three artificial islands were created by means of hydraulic filling (Mikhailova, 2016; Zhogoleva and Bedulin, 2018). In the Black Sea water area, at a distance of 13 km from the Adler airport, an artificial island was built that connects to the mainland via two tunnels and a footbridge. In Venice, entire neighborhoods are built in water areas. The structures are supported by piles sunk into the sea bed (Ilicheva, 2016).

Starting with 1933, territories for passenger port construction on the coast of the Gulf of Finland in Leningrad were hydraulically filled. A three-story administration building, a water tower, and other structures were built in the area in 1935–1937. The General Plan of Leningrad provided for the construction of 700 ha using water areas (Tilinin and Vorona-Slivinskaya, 2018).

In Saint Petersburg, in the western part of Vasilyevsky Island, 400 ha of new territories were hydraulically filled along the coastline of the Gulf of Finland, Marine Facade and a passenger sea port were built (Tilinin and Vorona-Slivinskaya, 2018; Verstov and Gaido, 2013).

Environmental disasters and infill development around the world force people to search for new accommodation.

Methods and Materials

At the first stage, when designing a building in a water area, it is necessary to solve tasks related to pre-construction activities under normal conditions.

When preparing for the construction of low-rise buildings in hydraulically filled territories, the following works shall be performed:

- construction of enclosing dams along the perimeter of the future development area;
- dredging of the water area, excavation of clay deposits and sandy soil required for hydraulic filling.

Results

Currently, when artificial islands are built in water areas, steel sheet piles forming a cellular

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structure are used to support excavations. To drive guide elements in cells or to drive several pre-assembled elements in stacks joined on top with rigid caps, special floating equipment is used. Within a structural cell being formed, the stacks are driven down to the design elevation using a vibratory driver fixed to each of the stacks.

The use of large-diameter (up to 16 m) shells made of coiled steel is the most efficient method for the erection of waterproof enclosures (Yudina et al., 2020).

With the help of a crane, coiled steel is firmly fixed in a stand, located on the coastline, to be uncoiled. The sheets are laid in an overlapping manner (with an overlap of 50–100 mm) and welded. These shells are transported to the installation site with the use of flotation equipment, where they are installed into position on a crushed rock base with a crane and filled with sand using vibration (Fig. 1).

To ensure that the joints between the shells are waterproof, sheet piles are installed between them (Fig. 2).

To accelerate sand dewatering within the territory made by the shells, well points lowering the water level (down to 20 m) are installed.

After the final stabilization of sand settlement within the sheet piling area, the erection of buildings is started (Fig. 3).

Due to pre-assembly on the shore, enclosures made of coiled steel reduce labor effort almost by half and metal consumption — by 2.5 times (as compared with steel sheet piling).

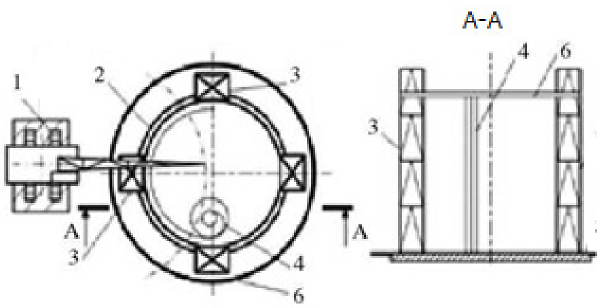

Figure 1. Diagram of a stand for shell manufacturing:
1 — crane; 2 — guide ring in the upper level of the shell;
3 — assembly towers; 4 — coiled steel being uncoiled;
5 — guide ring

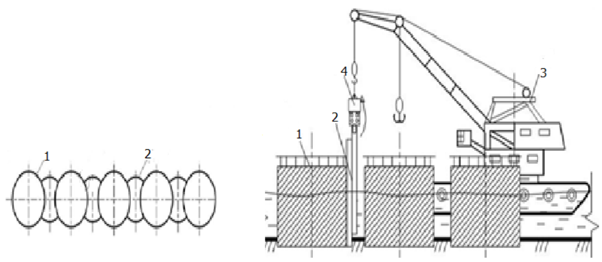

Figure 2. Diagram of the joints between the steel shells, made with the use of sheet piles:
1 — shells; 2 — sheet piles; 3 — crane; 4 — vibratory driver

The works carried out using flotation equipment are technically challenging and labor-intensive. Besides, they represent one of the most important activities performed when erecting buildings in water areas. Many operations have to be conducted directly in situ, in the water or underwater. The cofferdam was invented especially for such cases. It is rather widely used to make enclosures when building artificial islands in water areas. It consists of temporary waterproof cases used for construction and repair underwater (Figs. 3, 4) (Jin, 2012; Kramola.info, 2019).

The cofferdam is built directly in the water. Then water is pumped out of it, and the cofferdam is used for construction in a dry environment. It can also be built on the shore and then floated out and sunk into place.

The cofferdam is erected as follows:

- A special welded metal structure with piles of a certain length fixed in the water is installed on the bottom. The required length is determined by analyzing the depth, layers of the underwater soil, and seasonal temperature fluctuations. In case of inadequate pile length, the external water pressure can destroy the cofferdam;
- Water is pumped out from the cofferdam using high-duty pumps.

Generally, cofferdams are made of steel elements. Recently, inflatable cofferdams have been started to be used as well. Their advantage is repeated use. Such structures are currently considered to be state-of-the-art. However, they cannot be installed wherever it is required.

Building cofferdams is labor-intensive and expensive, but they make it possible to perform construction works in places where it is virtually impossible. Engineers must carefully design these in order to ensure safe construction. Cofferdams are used everywhere, both in civil and industrial engineering. In particular, they were used to build bridges over such wide rivers as Mississippi, Hudson, and Ohio, to eliminate the consequences of the accident at Fukushima, and to build locks on most dams. On the one hand, the use of a cofferdam

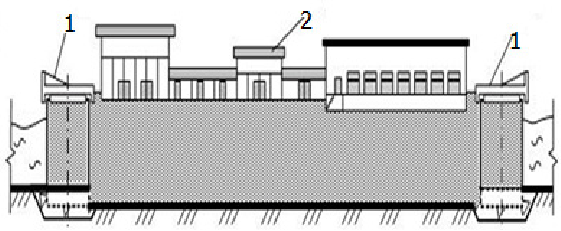

Figure 3. Diagram for the erection of buildings and structures on an artificial island:
1 — superstructure; 2 — buildings to be erected

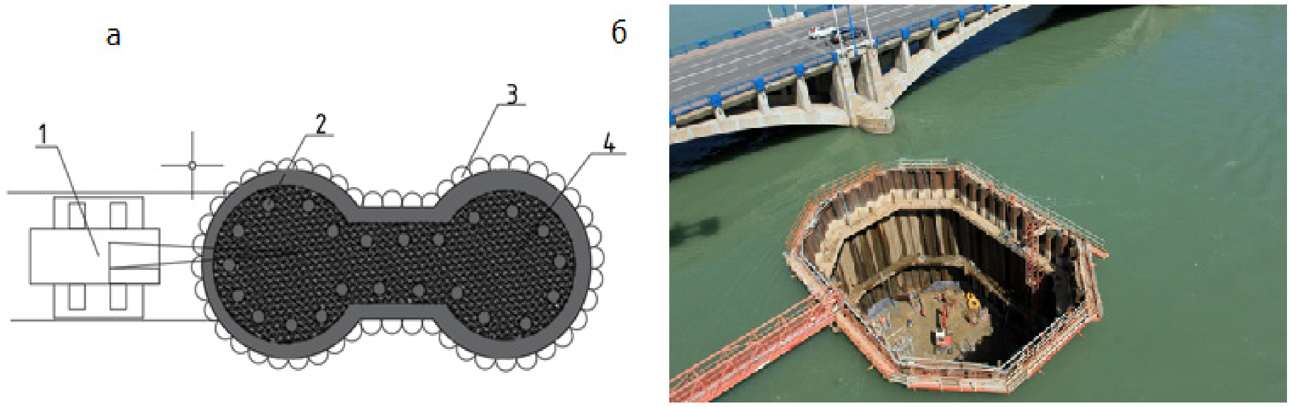

Figure 4. Cofferdam structure: a — cofferdam construction diagram; b — finished cofferdam; 1 — assembly crane; 2 — piles lowered into the water; 3 — welded metal structure; 4 — concrete base

in the water makes construction easier. But on the other hand, due to high labor-intensity, its application is limited (Kramola.info, 2019).

Construction in the water, with account for the architectural and planning designs of buildings and other specifics of construction, requires design documentation to be developed, including documents on choosing the foundation type and measures to ensure safe operation.

For a long time, structures were built on a pile foundation made of tree trunks. Nowadays, traditional pile foundations are almost replaced by new structural elements, such as pier foundations.

The process of pier foundation installation is nearly the same as the process of pile installation. Piers are made on the shore and then delivered to the installation site using flotation equipment. Before installation, on the top and bottom edges of foundation slabs and blocks, special indelible marks are made that are used to fix the position of the slabs' and blocks' axes. The bearing surfaces of such slabs and blocks shall be clean.

During the construction of a bridge in France, piers with a diameter of 90 m and a height of 65 m were used to transmit the load to the ground. Foundations with single-column and multi-column (frame) piers, as well as combinations of pile and pier foundations, are also used in construction.

It is also possible to use pontoon platforms during the construction of buildings in water areas. Pontoons can be made of various materials: steel, reinforced concrete, plastic, timber. Metal pontoons are lighter than concrete ones. Besides, they are high-strength and have reliable locks that do not self-open (Valtanen, 2016).

To choose the material for a pontoon platform, it is necessary to calculate its capacity based on the foundation load. The construction of a pontoon platform involves the manufacture and installation of special pontoons fixed to each other in a single floating platform that can withstand the load of the entire building.

The use of telescopic piles is another promising direction. They serve as an alternative when preventing water-related hazards and can be used when building a pontoon platform (Spagnoli and Weixler, 2013).

Sections of telescopic piles are able to extend. In case the water level becomes higher, the building comes up as a fishing float. In other words, it rises together with the pontoon platform. Telescopic piles are made of light and strong teflon material. The lighter the pile material, the less is the section thickness of the pontoon platform. This is due to the fact that the vertical movement of the pile section depends on the weight of the pontoon and the building erected upon it. A pile made of teflon material must have sufficient strength in order to withstand high water and floods.

To improve the quality of construction on the coastland and in water areas, it is necessary to study the characteristics of the territory, the construction product (building), the processes of its erection, and the conditions of the water environment. Using these factors, we can develop an accurate organizational and technological model, taking into account the special conditions of building construction (Sandan, 2012).

When preparing for the construction on the coastland and in water areas, we shall bear in mind the following: the method used to build waterproof enclosures; the climatic factors; the characteristics of the water body; the conditions of machinery disposition as well as the conditions of materials and structures' storage on the coastland, etc.

A building erected in a water area cannot properly operate without utilities. Most often, autonomous equipment is used for that purpose, since it is not always possible to connect to municipal networks. For instance, solar panels, diesel or wind generators can be installed. Solar collectors can be used to provide heat. Pumps and filters are installed for the purification of water collected from water bodies (Samogorov and Khodotova, 2014).

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Conclusion

After the analysis of construction projects in water areas, we arrived at the following conclusion: in the nearest future, the technologies considered can solve a number of issues related to the creation of additional territories for new construction and favorable conditions for accommodation. To ensure the prospective development of this direction in construction, we need to account for both the climatic environment and architectural and planning designs.

Waterproof enclosures used when building artificial islands, made of large-diameter shells sunk to the bottom of a water body and filled with sand, make it possible to perform construction and installation works, needed to erect a building, in a dry environment. This method reduces the duration and labor intensity of operations in open water areas with unstable wave conditions.

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СТРОИТЕЛЬСТВО МАЛОЭТАЖНЫХ ЗДАНИЙ В ПРИБРЕЖНОЙ ЗОНЕ И НА АКВАТОРИИ

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Аннотация
Создание на акватории искусственных островов для нового строительства и производства работ насухо решается путем устройства ограждений котлованов, позволяющих сохранять жесткое и устойчивое положение здания на воде и противостоять климатическим факторам. **Цель исследования:** Разработка технологии строительства малоэтажных зданий на акватории и в прибрежных зонах с наименьшими трудозатратами на их возведение и обеспечение безопасной эксплуатации объектов. **Методы:** Теоретические исследования в области экспериментального строительства, анализ научных разработок отечественных и зарубежных исследователей по развитию строительства объектов на воде. **Результаты:** Рассмотрены технологии устройства водонепроницаемых ограждений на акваториях, позволяющих выполнять работы по возведению зданий в сухом пространстве (насухо) на открытых акваториях с неустойчивым волновым режимом, что позволит сократить трудоемкость работ, сроки возведения объекта и повысить технико-экономические показатели.

Ключевые слова
Акватория, водонепроницаемые ограждения котлованов, коффердам, понтонные основания, пилонные фундаменты, прибрежная зона, телескопические сваи.

Urban Planning

HISTORICAL CITY EVALUATION IN THE CONTEXT OF MORPHOLOGICAL THEORIES (ISTANBUL, LAST OTTOMAN PERIOD)

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Abstract

Introduction: The historical city core of Istanbul developed under the influence of the religions and cultures that were brought in during the Roman, Byzantine, and Ottoman periods. This study investigates the effect that the 19th-century modernization, urban arrangements, road system changes, and sociocultural textures had on urban morphology on the Historical Peninsula of Istanbul, which had symbolic value. We review the morphology of Istanbul during the 19th century, a historical period when the city was undergoing new development and restructurization. We also develop an analysis methodology in order to examine this process in more detail, by following the methods of the researchers who carried out morphological studies. **Purpose of the study and methods:** In our research, we apply three different urban morphology methods, examining the development of the city, its effects on the urban tissue, and the newly developed and demolished areas. Firstly, we investigate historical plans in line with the Conzenian method and discover the urban tissue typologies of the historical city by using the Caniggia approach. Furthermore, we use the space syntax method developed by Bill Hillier in order to interpret the changes, differences, and similarities in the urban form, and draw axial lines to illustrate the integration of settlements and street systems shaped in the context of the relationship between people and space. **Results:** We discover the effects of development practices on the morphological structure of spaces and show how urban forms and cultures intertwine over time.

Keywords

Urban morphology, urban development, space syntax, urban typology, urban tissue.

Introduction

Cities are structures that live (are born, grow, become damaged, and die, partially or completely). They keep evolving and responding to the development of local geography. It is a fact that most life systems are centered around people. There is much diversity in both the observable general forms (circular, linear, or fractal) that shape the life system structure, and the appearance of the street systems (organic or inorganic) formed by buildings, spaces, and many other features (Courtat et al., 2011).

According to Gauthiez (2004), various methods have been used in the theory and analysis of urban morphology since the end of the 19th century. The contribution and importance (especially in terms of architectural topology) of the Italian urban morphology schools, first that of Saverio Muratori and then of Gianfranco Caniggia, as well as the contribution of the English school founded by M. R. G. Conzen, are well known today. In his works, Saverio Muratori researches various values inherent to urban formation stages: from buildings in historical city centers where the texture was compact, to the suburban, town, and district scale, where the texture was sensitive to a wide range of solutions. Caniggia tended to emphasize operational aspects by simplifying Muratori's theoretical system. More precisely, by focusing on the typo-morphology of the special architectural entity (which is far from theory), he examined the change of the core elements, such as type, texture, and shape, in the formation of the structure over the course of the historical process. The aim of his studies was to gain an understanding of the above (Cataldi et al., 2002). According to Conzen (1975), who focused on the term «morphogenetic» to describe and explore the living character (physical, social and economic change processes) of settlements such as towns and cities, urban morphology is inherently concerned with distinguishing, characterizing and explaining urban landscapes in accordance with their geographical origins. Based on Whitehand (2001) research, urban morphology can be demonstrated by working with the Conzenian approach of sharp analyses and their effective integration, which can answer and express various questions, such as how

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the urban landscape has developed historically and how it is linked to the fabric of urban history. The (Conzenian) theory formulated by Conzen (1960), as well as Conzen's research, shows that identification of urban areas consists of three components (the morphogenetic method, cartographic representation, and terminological sensitivity). Within this hierarchy, there are three components of the urban form, namely the ground plan (streets, parcels, and block plans), the building form (three-dimensional form), and the land use. The Conzen method concerns not only the layout of towns and cities but also their other local combinations of these «three form components», with tiny disaggregated homogeneous cells that combine to form the urban landscape.

Urban morphology studies have drawn the attention of many researchers, who are interested in analyzing the development of cities in terms of the historical approach. They have expressed their understanding in different ways and from different perspectives. Known as a new and innovative theory that appeared in the quantitative analysis of spatial configuration in the late 20th century, «Space Syntax», developed by Bill Hillier (1984), explores the structure of cities within a morphological approach by attempting to measure spaces. This theory is based on the philosophy of Henri Lefebvre (1901–1991), who argued that spaces are a social entity and that space needs social interpretations of its definition (Lantz, 1991). This study highlights the importance of morphological studies, using the Historical Peninsula of Istanbul as an example. We present a comparative study of different morphological approaches to urban form. The period of world history selected for this study is very interesting and complicated. We look at the Byzantine traces in Istanbul and examine how the city evolved during Turkey's modernization process. We discover both urban specifics and the new conditions created in the city. Within the scope of this study, we analyze the oldest settlement area of Istanbul using different methods in line with urban morphology, specifically the Conzenian and Caniggia theory and the space syntax theory. The changes, differences, and similarities in the urban form are interpreted through GIS and cartographic maps. The aim of the study is to investigate the emergence of urban forms by summarizing the historical periods and to reveal the interactions of urban development with urban textures of spaces.

Methods

The methodology is derived from the examination of three urban morphological approaches. The first stage of our morphological analysis will be based on the Conzenian practice. Afterward, we will employ a typo-morphological analysis based on the Caniggia approach. This will be followed by new research, where we apply space syntax to examine the changes in the urban morphology of the Historical Peninsula. While explaining the historical development process of the urban form and the results of its spatial internal structure, we investigate the morphological character and emphasize the three types of morphological methods in the analysis of the urban texture.

M. R. G. Conzen (1960) divided (both in his theory and his later works) the historical urban landscape components of the city into three basic forms, which can be described in simple terms as: the nature and intensity of history, the land use, and the built environment. With an integrated approach, this concept emphasizes a hierarchy in which the land use and the building forms are included as parcels within the framework of the city plan. The Conzenian method suggests that these three complexes can be combined at the local level as the smallest cells of the urban landscape to create morphologically homogeneous areas. According to Larkham (1998), urban units create a hierarchy with a combination of these homogeneous cells, which provides a reference for urban landscape changes. As a follower of Muratori's work, Caniggia focuses on the creation of typo-morphology, stating that the city is not a static object but a process. He further develops this idea by studying the historical process of the shaping and transformation of cities. In the historical morphological analysis of the Historical Peninsula of Istanbul, the examination of urban morphological development in the structure of cities through only the Caniggia approach can set the limits, while Conzen's clear definition of the city plan and its elements and development in time as an analytical tool constitutes a starting point for our typo-morphological study. Conzen and other researchers focused their work on the physical form and development of cities. Although the theories proposed by the researchers were relevant to the formation of the city, they did not touch upon the social relations in the urban space. However, philosophers such as David Harvey (born 1935) and Henri Lefebvre (1901–1991) focused on this aspect and developed social cognition theories on urban space, aiming to understand the social meanings of the urban physical form.

Space syntax is a theory that emerged at the University College London between the late 1970s and the early 1980s. It was developed by Hillier and Hanson (1984) to describe and analyze the spatial forms of the built urban environment. The general idea of this method is to divide urban spaces into parts that are the starting points of the human experience, and then turn these parts into maps or graphs and subject them to numerical analysis. Bill Hillier defined space syntax in urban analysis in three ways. Firstly, it is a set of techniques used to examine the spatial textures of buildings and cities. Secondly, it is based on the belief that there is a mutual relationship between the social structure and the urban space since the latter has a dimension that affects the social structure and even the different layers of this structure. Thirdly, it makes it possible to create a series of theories by trying to «read» a city and its different components by bringing together the social, economic and conceptual relations between the city's physical components (Hillier et al., 2010). Thus, by analyzing the topological relations of these aspects, which can be expressed through the description of space based on human experiences, as well as by applying the network/graph theory, we can divide the urban and architectural spaces into two different entities: «integrated» or «segregated».

Results and Discussion

Historical Peninsula of Istanbul. The multi-layered historical urban evolution of Istanbul has been driven by the city's geography, topographic features, and the trends of different civilizations. Therefore, the Historical Peninsula of Istanbul has been shaped by different urban layers where we can observe examples of different urban forms. The city of Istanbul was a Greek settlement in the 7th century BC and became a Roman colony around 100 BC. Later on, it became the capital of the Byzantine Empire and reflected the original structure of the Roman cities. After the Ottoman conquest, the increasing Muslim community of Istanbul brought their own way of life to the city; therefore, the urban form was reshaped by this sociocultural system. The cosmopolitan nature of the empire is reflected in the city's active growth process during the Ottoman period. Ethnic groups were one of the main sociocultural assets of the city and were allowed to live in all districts during this period. The creation of new districts was based on the «neighborhood» system. A «neighborhood» was the smallest administrative unit of the Ottoman land management system (Celik, 1988). These developments, which reshaped the urban structure of the Historical Peninsula, also brought new land uses. Both the new city plan and the land use transformations directly affected the organic growth of the city, specifically its neighborhoods, religious centers, and squares.

This study focuses on the origins of the old urban transformation in the Ottoman Empire between 1800 and 1900. In a broader context, our research is based on the evaluation of this transformation's impact on the urban form during this period, which is an aspect of studying the Historical Peninsula of Istanbul, the capital city of the Ottoman Empire. In the 19th century, when different regions underwent systemic transformations, the Ottoman city of Istanbul was divided into three main central areas. The «Old City» was the largest area, as well as Istanbul's administrative and commercial center. Galata was a non-Muslim settlement and trade center for foreigners, along with its extension, Pera. Uskudar was the oldest residential area on the Asian side. Apart from this main center, other prominent areas included Eyüp, which was a sacred settlement for the Muslim communities, and the residential areas on the European side, Kasımpaşa and Beşiktaş. In addition, there were agricultural areas and various villages and settlements scattered along the Bosporus shores of Istanbul. As we can understand from the above, the urbanization efforts of the Ottoman Empire started in the 19th century. The Ottoman intellectuals who visited European cities during this period became the advocates of designing Istanbul as a European city, influenced by the urban planning movements in Europe (Baysun, 1963). This goal was to be achieved by adhering to specific urban planning guidelines: that is, the «ideal», regular urban fabric with wide roads in a grid plan, surrounded by rectangular or square building plots.

Evaluation of the Developmental Direction. M. R. G Conzen's morphological approach, which focuses on the historical development of cities, has been one of the most important concepts that explain the concept of the morphological period. Conzen divides the urban environment into three parts: the city plan, the building texture, and the land and building use (Conzen, 1960). These three components of the urban fabric include concepts based on urban development processes. The permanence of these three key factors that make up the urban environment also changes over time. The city plan, or the ground plan, is useful for «reading» the development of the city. Out of the urban form components, it is the most resistant to change.

The Historical Peninsula has different morphological periods. During the Ottoman period, it reached urban prosperity, which is sufficiently documented in cartographic records. The historical data illustrates the division into morphological periods according to historical research. In the 19th century, researchers that worked between the last period of the Ottoman Empire and the early Republican period adopted modern approaches to the urbanization process. At the time, the plans for the changes that would later create the morphological structure of the city in the urban planning aspect also began to emerge. In particular, major fires were common due to the multi-layered urban texture of the Byzantine period and the narrow and unplanned street structure of the city of Istanbul; so, as a result of the planning decisions, the area changed, which led to a great evolution in the urban model (Crane, 1988). These efforts resulted in the first generalized rules for the urban fabric, which had not been present in the urban structures built in the 18th century AD. As mentioned before, Ottoman intellectuals wanted Istanbul to meet the standards of European capitals, such as Paris, Vienna, and London. In an attempt to give a Western image to the Historical Peninsula of Istanbul, the original urban structure of the Ottoman

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Empire, with its dead-end streets, public and empty spaces, was rapidly transformed and completely changed.

The urban structure turned into an orthogonal layout, causing the formation of new settlements and public areas for the rapidly increasing population. During this period, the public spaces that used to be part of the old Roman layout were replaced by the «courtyards», or in other words, new public spaces within the architectural structure of mosques and other complexes. These urban courtyards now constitute the main nodes of the city. In the periods of Islamic rule, the structure of the ancient Roman period, which consists of diagonal, straight streets that open into squares, was replaced by an organic structure. To summarize, radical changes took place within the holistic morphological structure of the city under the influence of different periods and cultures. The shaping of the urban form in the eastern suburbs (the Asian part of the city) began in 1850. The borders of the Istanbul city morphology lie on the port side of the eastern suburbs.

Morphological Forms of Urban Tissues and Urban Blocks — (18th–19th Century). Typo-morphological studies focus on the physical and spatial structures of cities and define the urban form by adhering to the detailed classification of the types of buildings and open spaces. Buildings and spaces can be classified depending on the core type of their character. According to (Moudon, 1997), these different types translate into typologies of buildings and the associated open spaces that define the essence of the buildings' fabric. Caniggia, a follower of Muratori, created a method for describing the components and types and how they developed throughout the historical evolution of the forms. He called this method «procedural typology». Caniggia examines the urban tissue by looking at the relations between the parcels and roads, paths/routes, and focal points created in the city.

In the context of our research, we analyze the six historical morphological settlements that the urban typo-morphology of the city of Istanbul split into at the beginning of the 19th century:

a) The settlement in the historical city center was at the core of Istanbul's history and spread from the center of the Hagia Sophia mosque. During this period, mosques seemed to play a central role, while the rest of the city was restructured around them and divided into a series of segments. The city blocks had irregular geometric shapes and were surrounded by very narrow streets and few green spaces.

b) The Galata settlement was connected to the port, and its urban structure resembled the appearance of the Mediterranean colony cities. Within the urban structure of Pera, the area was divided by the main thoroughfare and the major roads were linked by the square, which connected the thoroughfare to Galata. The urban tissue showed a similar structure: namely the narrow street networks, either regulated or radial. Many streets were randomly connected to the central point.

c) The Uskudar settlement had the main avenue structure parallel to the harbor; the blocks were also shaped parallel to this avenue and then became more scattered when moving inward. The further, inland part of the settlement had developed urban textures consisting of irregular geometric shapes surrounded by narrow streets and few

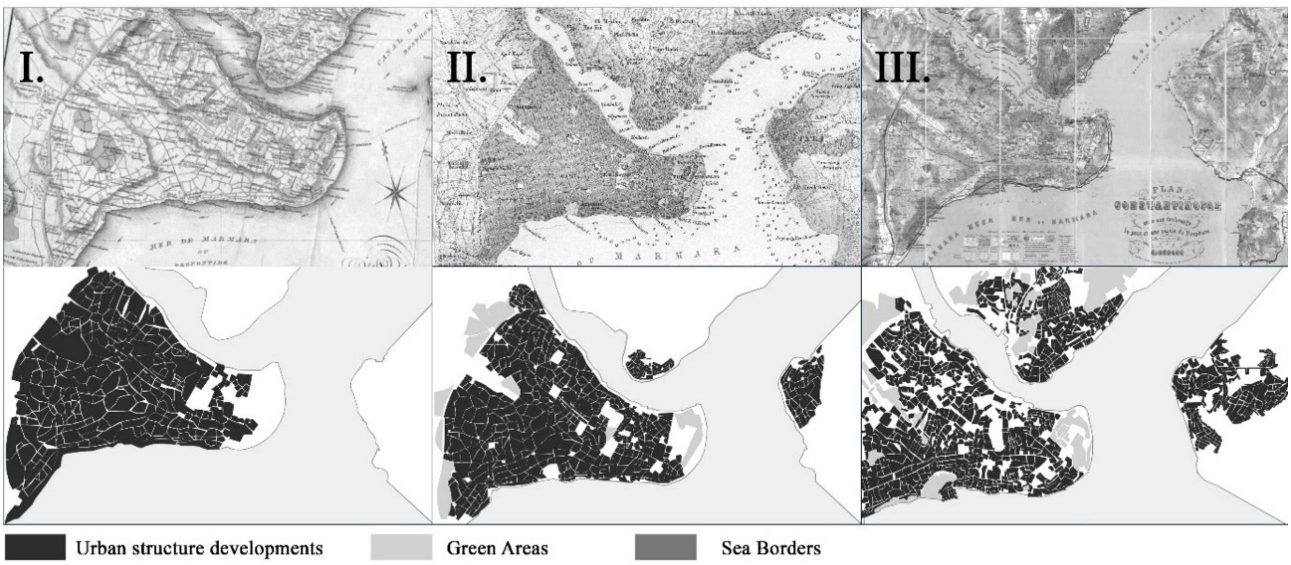

Figure 1. Morphological development analysis with the help of maps
I. Morphology of the urban structure, based on Kauffer and Joseph de Hammer's map of 1813
II. Morphology of the urban structure, based on Barry Lawrence Ruderman's map of 1855
III. Morphology of the urban structure, based on Carl Stolpe's map of 1882–1900

green areas. However, the street flow structure changed direction frequently depending on the topography.

d) The Eyüp settlements were characterized by low density and irregular development plots scattered through the terrain. The typical narrow

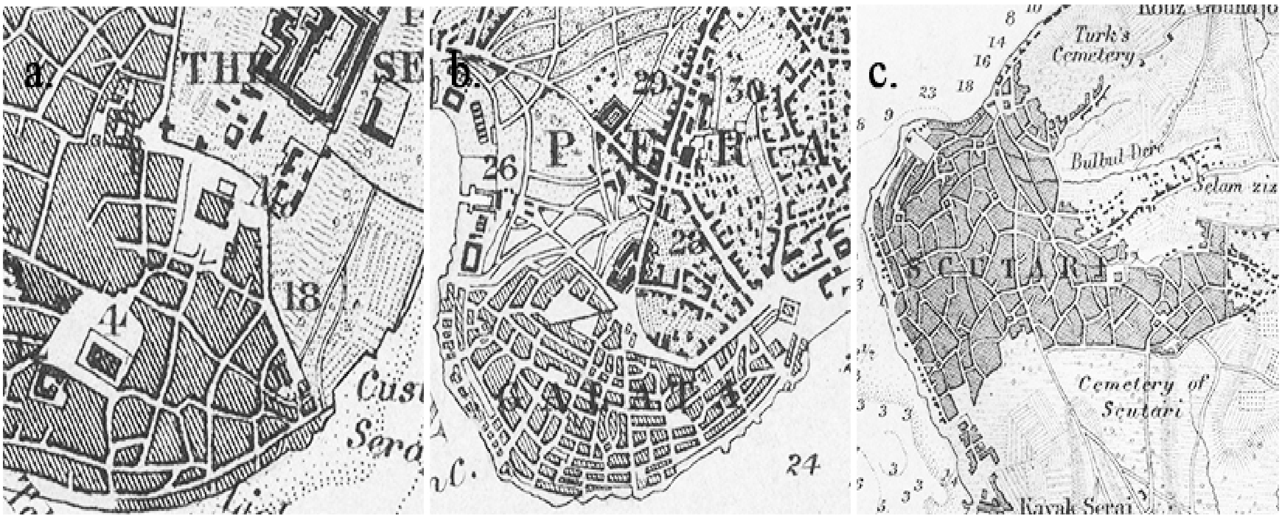

Figure 2. Typo-morphological types of Istanbul's three main central regions, based on François Kauffer's map (1751–1801)

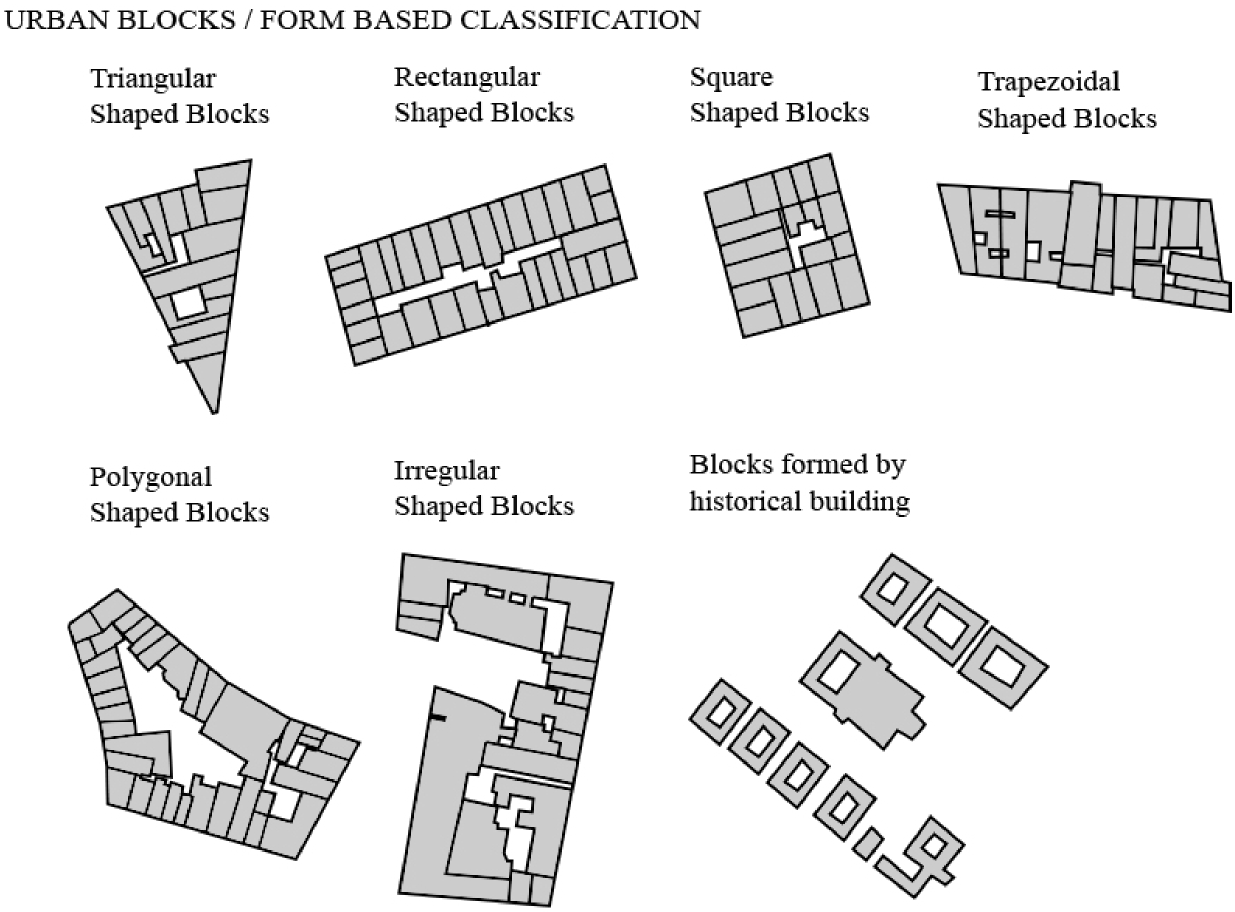

Figure 3. Typo-morphological types of Istanbul's three areas, excluding the main centers, based on François Kauffer's map (1751–1801)

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street network was perpendicular to the Golden Horn.

e) The tissue was developing irregularly due to preexisting empty plots or agricultural plots, and thus parcels were arranged at random: sometimes radially and sometimes linearly.

f) The parcels of different types, textures, and sizes that emerged along the harbor were also divided into different areas. The Beşiktaş development was the internal north extension of the original fractal form and laid parallel to the port lines. The existence of irregular empty parcels in the area led to the creation of an organic structure, corresponding to the fractally arranged settlement parcels.

g) Settlements that reflected the historical characteristics of Byzantium were located closer to the city walls. The parcels developed from outside the walls towards the city. The city's defining old narrow streets and remaining parcels had various irregular geometric shapes. The empty back side of the city walls had parcels that were used for agricultural purposes. The agricultural blocks also had irregular geometric shapes and were surrounded by very narrow streets that had a radial structure and spread out towards the walls, as they were meant to provide access to the interior of the city.

The tissue, which depends on the characteristics of the streets and blocks in general, as well as on the character it creates, can be defined within a block or a land plot, unlike other parcels and street structures. According to Kropf (1996), street/block patterns' characteristics are elements that will persist over time in identifying these textures. Moreover, they tend to preserve historical evidence and are suitable for historical interpretation.

The urban issue in Istanbul varied, in line with the modernization movements that started in the 19th century. The triangular and trapezoidal form of the blocks, derived from the organic and radial street systems, along with some fractal system features, directly affected the different shapes of the urban blocks; sometimes, rectangular blocks were formed. Thus, the parcel structures shaped by blocks have had a positive impact on the city's «readability», providing today's researchers with opportunities for interpretation. The religious buildings in the old city center in particular have created individual parcels, while also affecting the formation of the geometric shape of the blocks (reference or corresponding axis) located in their immediate surroundings.

Sociological Development of the Historical Peninsula of Istanbul. The space syntax theory, which is used to investigate the relationships between society and space, provides a method for discovering facts about the spatial position of buildings and settlements and for gaining an understanding that human beings are part of the spatial configuration. This can be achieved not only by revealing differences in the morphological structures of the man-made space model but also by defining the differences in the relationships between different constituent elements and events. Thus, space becomes a strong determining factor and a powerful tool for creating spatial exploration through the transfer of these differences and culture to building forms and settlement forms (Hillier, 1996). Space plays an instrumental role in organic settlements. What shapes the structure of space is human movement. The types of settlements where land is used extensively show different characteristics than cities that are shaped by buildings of symbolic importance, where space is more organized and less used. Both of these spatial structures have been shaped in the city of Istanbul, due to its historical background as a blend of many different cultures. During the Byzantine period, the symbolic city structure was dominant and was

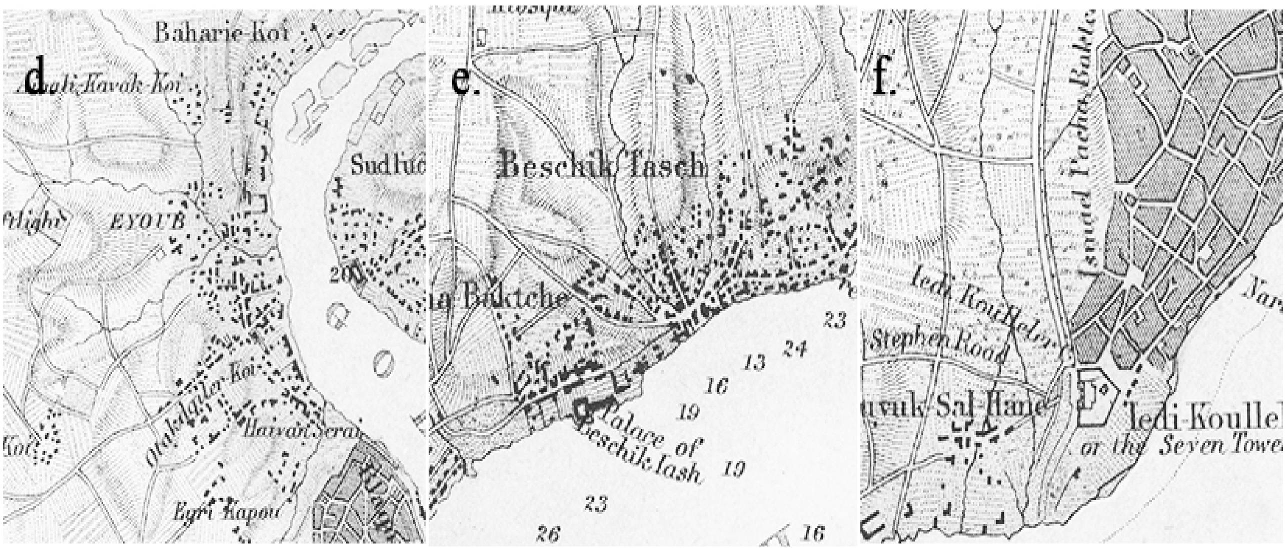

Figure 4. Classification of block types on the Historical Peninsula (1887–1891)

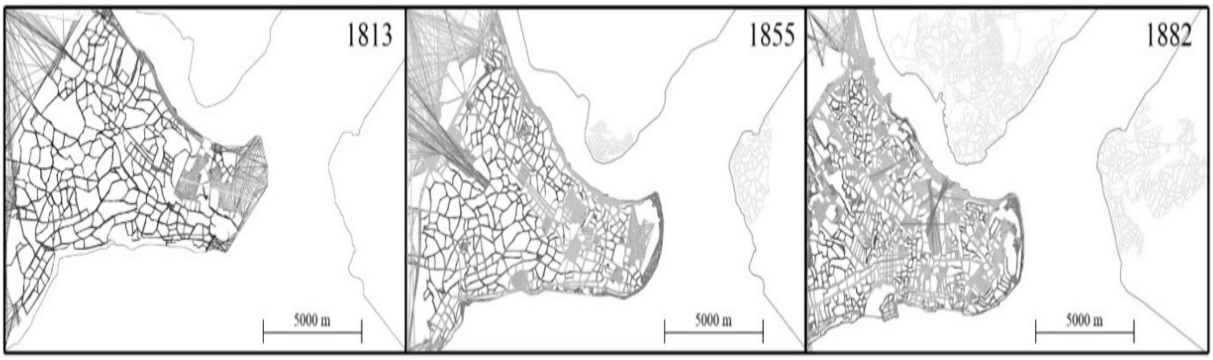

Figure 5. Axial maps of the Historical Peninsula between 1813 and 1882. The lines are shaded in gray-scale, corresponding to the integration of the city. The most integrated spaces are shown in dark gray and most segregated spaces are shown in light gray

represented by the main axis, connecting the main forms that were considered symbols, as well as by the specific geometry. Although the city retained its symbolic structure under Islamic rule after the Ottoman conquest, the ceremonial functions of the main streets lost their importance due to the lack of geometry, as compared to the Byzantine period. However, the 19th-century renovation movement, which preserved Istanbul's character as the capital of the empire, caused the main streets to gain more importance. Other results of the renovation included the establishment of new settlements, the construction of new transportation routes, and the creation of new monuments. As such, the city still remains symbolic, although this depends on where the Islamic lifestyle is particularly evident (Kubat, 1999). The basic theoretical argument of space syntax is based on analyzing the spatial structures of settlements to find out which information can be revealed about the respective social norms; therefore, we have been able to use this method to explore the nature of Istanbul's morphological structure and the spatial and social relationships within its historical areas. Layout plans are represented by axial maps, which are very useful for seeing and experiencing a city and analyzing the patterns of its settlements syntactically. Thanks to these maps, the axial connections are accessible on a global scale, and it is possible to obtain a visible and accessible axial line. The size of a settlement's open-space structure is measured by the number of axial lines. In this context, we adopted the space syntax method in order to understand the spatial relationships within the Historical Peninsula and to read the city objectively.

Integrated axial line sets can be obtained with axial line maps. The spatial structure size values depend on the percentage of selected areas and the size of residential areas. The data obtained through space integration shows how many paths and turns one must take to go from a specific area to all other areas within the settlement system. Any additions or deletions within the settlement can also be deduced from the information obtained from this data. Moreover, integration data helps identify the area's most integrated and most segregated parts. In this context, we compared three axial maps from 1813 to 1882 through syntactic evaluation to define the changes during the 19th-century modernization of the Historical Peninsula (Figure 5). An examination of the space syntax data revealed that the lowest integration value appeared in 1813. Towards the middle of the 19th century, the city structure condensed towards the inner Old City, and the number of streets increased. Moreover, the street systems that emerged due to the interventions into the urban structure created new squares, which made the city less homogeneous. Although the average percentage of integration has increased over time, it can still be said that, since the street systems are geometrically irregular, the overall integration of the city has not developed and the city has become more segregated. There is another reason why the city is now less integrated: during the modernization efforts, the grid street system was deployed only in certain parts of the city, while the other settlements were allowed to develop organically.

Conclusions

The theories and applications of urban morphology allow researchers to express their understanding in different ways and from different perspectives by synthesizing comparative morphological studies. Their research covers the fields of geography, architecture, archeology, history, science, and philosophy, all of which are seeing extensive interdisciplinary discussion. In this study, we examined the methods of researchers working on urban morphology, particularly with the aim to discover the forms of cities. We focused specifically on the Conzenian approach, the process typology

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approach, and the Space Syntax theory, which was recently developed by Bill Hillier. In this context, we attempted to discover the morphological structure that 19th-century innovations brought to the historical city of Istanbul, by using historical maps. In general, there were two types of urban morphological changes on the Historical Peninsula of Istanbul. At first, during the Roman and Byzantine periods, the city had a symbolic morphological structure with regular geometry, followed by settlements with more irregular structures, which were formed under the influence of Islam after the Ottoman conquest. In the 19th century, the Ottoman Empire was influenced by the Western city culture; that was when European city arrangements were introduced to the parts of the city affected by fire or to the very sophisticated districts like Galata. However, the Conzenian and Caniggia theories reaffirm that Western-style radial arrangements are not a suitable solution for every neighborhood of a city like Istanbul. One of the most important factors affecting the structure of cities is time. Specifically, human contributions and street systems are the most effective and permanent factors in determining these changes.

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PREREQUISITE FOR ACCIDENT-FREE TRAFFIC AT SIGNAL-CONTROLLED INTERSECTIONS

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Abstract
Introduction: Improving intersection capacity will not be possible without accounting for traffic safety. **Purpose of the study:** We aim to determine the prerequisite for accident-free traffic at signal-controlled intersections with turning traffic flows. **Methods:** In our study, we used the methods of observation, comparison, and mathematical analysis. **Results:** We have carried out a field observation of traffic intensity at signal-controlled intersections in the city of Yekaterinburg, focusing on vehicles that moved when the green light was on. We have also analyzed traffic flow moving in three directions in the same lanes. We have discovered that traffic accident likelihood is the highest (54%) at four-way intersections. Three-way intersections account for 44% of traffic accidents, while the remaining 2% of accidents occur at multi-way intersections. Furthermore, we have determined the additional factors that impact safety in turning traffic flows at intersections. Our study demonstrates that in order to ensure maximum intersection capacity, the duration of the traffic signal cycle must be adjusted with the minimum safe distance between vehicles in mind.

Keywords
Traffic safety, traffic signal cycle duration, signal-controlled intersection.

Introduction

The rise in the number of vehicles within the street and road network over the recent years has made it necessary to adjust the assessment of traffic signal cycles, and justify this adjustment through research. Today, large cities experience major fluctuations in the excess duration of the traffic signal cycle, which can reach 150 seconds, 180 seconds, 200 seconds, or even more. Therefore, the number of traffic accidents at intersections remains high, especially at intersections with turning traffic flows. This means that the current methods of setting up traffic signal modes need to be changed.

An analysis of studies by different authors from various countries shows that traffic safety at intersections largely depends on intersection traffic management; notably, ensuring safety is reduced to calculating the duration of the traffic signal cycle.

This prompts a conclusion that one of the main problems of traffic management lies in determining the appropriate duration of the traffic signal cycles that would simultaneously ensure maximum capacity and traffic safety at signal-controlled intersections. The current methods of assessing traffic signal cycles are centered around the key concept of saturation flow. But none of these methods account for the changes in traffic speed rate at intersections with turning traffic flows. When making a turn, vehicles tend to change speed due to a number of factors, such as situations when the vehicle in front slows down abruptly either before the turn or directly after the turn, as well as the sudden emergence of road obstacles (pedestrians), bumps on the traffic lane, etc. In light of the above, the goal of this study is to find the prerequisite for accident-free traffic at signal-controlled intersections with turning flows, by using the methods of observation, comparison, and mathematical analysis. This prerequisite is essential for determining the duration of the traffic signal cycle.

Methods

The observation methods used in our study have shown that the concept of «saturation flow» has completed a lengthy development process, sufficient for its efficient application to traffic management at signal-controlled intersections.

The need for traffic management arises when the road users' paths intersect on the same plane. If traffic intensity is low, traffic is managed through priority traffic signs. As traffic intensity rises, especially if traffic was already intense along the main road, minor road traffic becomes reduced or almost impossible. At the same time, the number of accidents at such intersections also tends to rise. This creates a need for signal control.

It is a known fact that about 40% of all RTAs occur at intersection conflict points. A look at accident statistics in cities reveals that the number of RTAs at intersection conflict points is even higher there. Simultaneously, this reduces intersections' traffic capacity. According to Gorev (2013), the common intersection classification includes the following types:

– three-way intersections (intersections where three approach routes join together);
– four-way intersections (the most widespread type, where four approach routes join at different angles);
– multi-way intersections (uncommon intersections with five or more approach routes).

Analysis of the number of RTAs allows us to conclude that almost all of them occur at the intersection of traffic lanes with moving vehicles when the vehicles' trajectories overlap. These include places when the traffic flow merges or splits. RTA observation practice shows that traffic flows overlap, merge, and split most commonly at intersections where traffic moves in different directions (Gorev, 2013). The analysis of RTAs in different regions allows us to conclude that, despite the significant difference in traffic conditions, the overall distribution of accident locations reaffirms the conclusion above.

Figure 1 illustrates the possible configurations of intersections according to Matson et al. (1960), which still exist today.

Intersections with differing geometrical features have a great impact on determining the duration of the traffic signal cycle. Restriction of traffic flows at intersections when not of all the intersection's reserve capacity has been used up is caused by irrational traffic signal operation and the increasing number of RTAs. This creates long lines of vehicles at the approaches to the intersection. The conditions at one intersection may spread to other intersections, which will render traffic management on the relevant road segment impossible (Tsarikov, 2010).

The emergence of traffic signals as a tool for managing traffic and pedestrian flows led to new types of tasks, as the duration of traffic flow movements in different directions now needed to be regulated without involving a traffic controller. This prompted an assumption that traffic signals would help improve the traffic capacity of signal-controlled intersections. The common belief when determining the green light duration is that all vehicles are moving regularly and simultaneously. But field observations of actual vehicles on the road disprove this belief. The largest deviations in irregular traffic flow occur in that segment of the flow that includes several vehicles that both start and stop moving at a green light.

Such random timing of vehicle start-up has been known for a long time. But still, all calculations keep being built on the assumption that it is possible to determine the number of vehicles by referencing

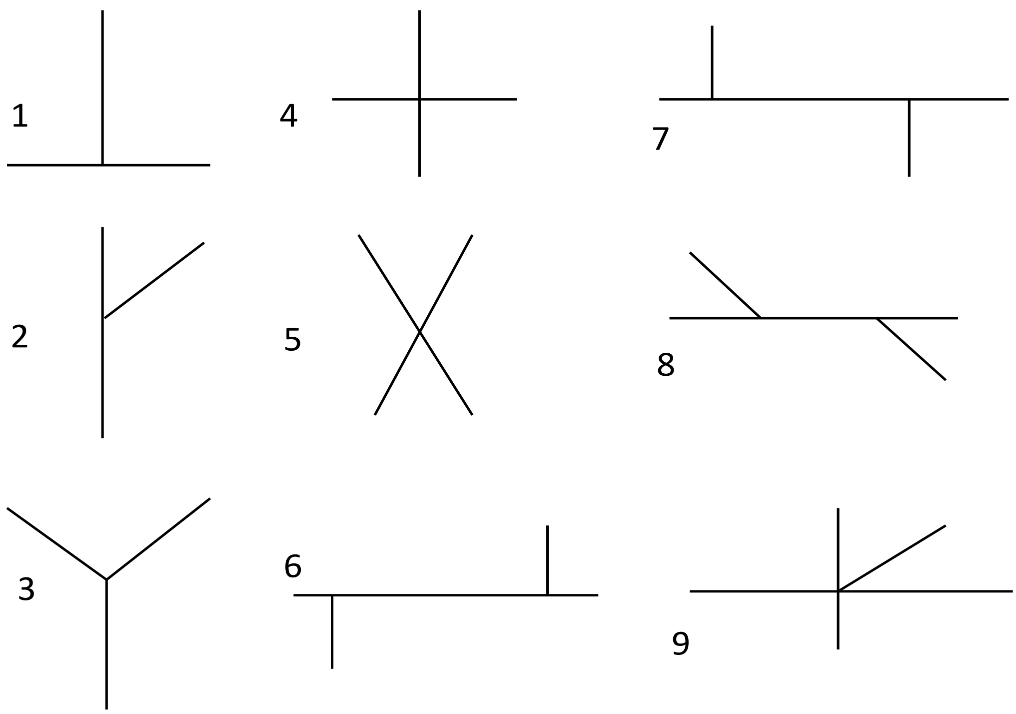

Figure 1. Types of intersections: 1, 2, 3 — three-way intersection; 4, 5, 6, 7, 8 — four-way intersection; 9 — multi-way intersection

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traffic flow segments with stable parameters.

Therefore, introducing the concept of «saturation flow» has become necessary for properly assessing the duration of traffic signal cycles. In fact, this concept now lies at the core of assessing traffic signal cycle duration. An analysis of studies by different authors from various countries shows that the definition of what we call saturation flow is based on a number of assumptions, all of which, in turn, stem from empiric observations. For instance, Wodrop (1952) defines saturation flow as traffic flow that occurs when vehicles are following one another at minimum achievable headway. During each phase, vehicles arrive in traffic flow q, with the appropriate subscript being added; the interval, therefore, equals *1/q*. Some vehicles stop for the duration of the red light, which equals r. When the light goes green, the first vehicle in line dashes ahead; but this happens due to acceleration, rather than lost time a. The vehicles that follow move at equal intervals without waiting. During this time period, when vehicles move one after the other at minimum achievable headway, traffic flow p becomes the «saturation flow». For the remaining green light duration, vehicles arrive and leave at intervals of *1/q* without delay.

Yu. A. Kremenets (Kremenets and Pechersky, 1977) believes that saturation flow exists in situations when vehicles move most actively at a green light in a dense traffic flow.

The Guidelines on Traffic Management in Cities define saturation flow as the highest intensity of traffic moving at a green light, measured in vehicles per hour. It is recommended to measure the saturation flow during field observations, provided that the number of vehicles in the traffic flow before the intersection meets the requirements (Ministry of Internal Affairs of the USSR, Ministry of Housing and Utilities of the RSFSR, 1974).

The Guidelines on Designing Urban Streets and Roads interpret saturation flow as the highest number of vehicles moving in a traffic lane at a speed of 15 km per hour when the traffic flow is uninterrupted (Central Research and Design Institute for Urban Development of the National Committee for Civil Engineering and Architecture, 1980).

Yu.A. Vrubel notes that saturation flow occurs when there is a certain average value that characterizes the departure of vehicles from the stop line at the intersection at a green light (Vrubel, 1988).

Further attempts to give saturation flow a more accurate definition were also made by authors specializing in traffic management, who presented the following interpretations of the saturation flow concept:

- for example, saturation flow could be interpreted as the number of vehicles that pass through an intersection over a given period of time, namely when the green light is on (Canada) (Teply et al., 1995);
- another example is the number of vehicles that pass through an intersection over a certain period of time under base conditions. Base conditions are conditions when the green signal is available and no lost times are experienced (USA) (Transportation Research Board, 2000);
- the next example is the highest number of vehicles that pass through an intersection over a certain period of time and are capable of leaving the intersection while the green light is still on (Germany) (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2001).

As noted by A. G. Levashev in his study, a possible way to improve the results of design operations in traffic management at signal-controlled intersections would be to improve the accuracy of describing traffic flow characteristics, as well as propose new study methods or adjust the current methods for actual real-life traffic (Levashev, 2004). A. G. Levashev himself proposes a method for calculating the ideal saturation flow at signal-controlled intersections. This method requires designing a regression model that would help pinpoint the moment when the vehicle’s position in the «queue» and the time frame (for a passenger car) get balanced. A. G. Levashev believes that the viability of this model is reaffirmed by traffic observation statistics.

As we summarize the proposals for defining the ideal saturation flow, we note the following: all authors agree that this requires describing the various characteristics of the traffic flow that moves through an intersection at a green light; notably, the traffic flow in this context only includes passenger cars. Aside from the above, there also are a number of factors that are necessary to ensure that the saturation flow is ideal: the lane should be 3.6 m wide; the slope inclination at the approach to the intersection should be 0%; the road surface should be dry; there should be no interference on the part of parking cars and public transport stops; there should be no conflicting pedestrian, bicycle, or vehicle flows, or any trucks or buses in the traffic flow (Transportation Research Board, 2000).

We carried out our field observations of traffic flows moving in three directions along the same lanes between 2010 and 2019. The study involved almost 500 intersections. For our analysis, we selected intersections with high traffic intensity and turning flows. To reaffirm the results of our analysis, we contrasted reference data against the traffic conditions at real-life intersections with the highest number of RTAs per year. Our analysis of the intersections in question shows that 72% of them are signal-controlled, while 28% are not controlled (Fig. 2).

By using the comparison method, we were able to contrast the actual number of vehicles passing through the intersection against the reference number. Our field observations showed that during the green interval, braking tends to occur in a part

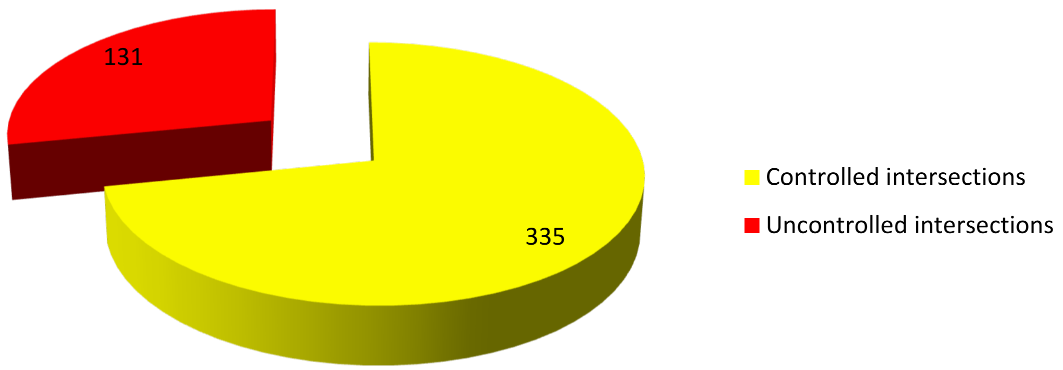

Figure 2. Distribution of accident-prone intersections

of the traffic flow moving through intersections with turning flows, for a variety of reasons, including situations when the vehicle in front slows down abruptly either before the turn or directly after the turn, as well as the sudden emergence of road obstacles (pedestrians), bumps on the traffic lane, and the presence of turning flows. Notably, braking happens from two to five times, depending on the intersection's configuration. For this reason, the actual number of cars that end up passing through the intersection with turning flows is significantly lower than the reference number, determined by applying the current method of assessing the duration of the traffic signal cycle (Webster and Cobbe, 1966). As the vehicle in front abruptly decelerates, this may cause the vehicle behind to crash into it. Therefore, it is necessary to set the minimum value for a safe distance between moving vehicles; this value can later be used for determining the green interval duration. The movement of vehicles at a green light at a minimum safe distance will be the prerequisite for accident-free traffic. The green interval must be adjusted for the minimum safe distance between moving vehicles $S^0_{\min}$ (1) (Gasilova, 2017):

$$S^0_{\min} = \left(V_2^0 t_{2d} - V_1^0 t_{1d}\right) + \frac{2}{3}\left[V_2^0\sqrt{\frac{2V_2^0}{\alpha_2}} - V_1^0\sqrt{\frac{2V_1^0}{\alpha_1}}\right], (1)$$

where V_1^0 is the speed of the first vehicle; V_2^0 is the speed of the second vehicle; t_{1r} is the response time of the first vehicle's driver; t_{2r} is the response time of the second vehicle's driver; t_{1rd} is the first vehicle's brake drive response delay; t_{2rd} is the second vehicle's brake drive response delay;

$$t_{1d} = t_{1r} + t_{1rd};\ t_{2d} = t_{2r} + t_{2rd};\ \alpha_i = \frac{j_i}{T_i - t_{id}},$$

where $i = 1$ is the first vehicle, $i = 2$ is the second vehicle; j_1 is the deceleration of the first vehicle; j_2 is the deceleration of the second vehicle; t_{1db} is the first vehicle's deceleration build-up time; t_{2db} is the second vehicle's deceleration build-up time;

$T_1 = t_{1d} + t_{1db}$; $T_2 = t_{2d} + t_{2db}$.

When we use the current method for determining the green interval duration, the resulting value does not account for the impact of the aforementioned factors on the number of vehicles that pass through the intersection. In other words, the current methodology of calculating the duration of the traffic signal cycle needs to be changed in a way that will allow for both determining the green interval duration and accounting for the minimum safe distance.

Results

We have obtained our experimental data at a four-way intersection with turning flows in the city of Yekaterinburg. The intersection is signal-controlled, with four phases. The green light duration during the turning flow phase is 57 seconds. The traffic intensity at the right turn is 487 vehicles per hour. We have examined the intersection to determine the distance between vehicles stopping at a red light, the distance between vehicles moving at a green light, and the structure of the traffic flows. We have discovered that when vehicles move straight ahead or turn right at the intersection, while staying in the same lane, the flow slows down between two and five times. Furthermore, this lag tends to affect vehicles in «batches», three cars each. In addition, we have reaffirmed that one of the most important factors that ensure traffic safety is the minimum safe distance between vehicles, which makes it possible to prevent RTAs in any traffic conditions.

We have discovered that traffic accident likelihood is the highest (54%) at four-way intersections. Three-way intersections account for 44% of traffic accidents, while the remaining 2% of accidents occur at multi-way intersections. The share of accident-prone intersections with traffic flows that move in two or three directions along the same lanes is 82%.

Calculations based on field observations have shown that the average speed of vehicles during the 57-second green interval is 4.3 m per second. If we determine vehicle speed without taking into account the deceleration of the traffic flow, then it is going to equal 5.39 m per second. This means that the actual speed is reduced by approximately 21% compared to the reference value. The practical assessment of the traffic signal cycle duration involves calculations in line with the current methodology, where the given value of the saturation flow does not change over the entire green interval duration. Research shows that vehicle speeds fluctuate greatly at different intersections, depending on visibility conditions, intersection configuration, climate, driver experience, and more. At the same time, in order to ensure traffic safety, it is necessary to be mindful of the minimum safe distance between vehicles, which, if we take vehicle speed at 4 m per second, equals 8.3 m. It is known that, in signal cycle duration calculations that follow the current methodology, the average length of a passenger car is assumed to equal 5 m. Experimental data shows that, when the speed equals 4.3 m per second, cars move at a distance ranging between 5 and 9 m from one another. That means that the sum of the car length and the distance between cars averages at 12.2 m. To ensure that the cars move at a speed of 4 m per second while maintaining the minimum safe distance, as obtained through analysis, this sum should equal 13.3 m.

Therefore, the green interval needs to be prolonged by 5.9 seconds, to allow for the safe passage of vehicles that did not have time to go past the intersection. Depending on the green interval duration in situations at the intersections when vehicles go straight and to the right along the same lane, the interval should be increased by an average of 8–15%, which can be taken into account by introducing an adjustment factor into the existing methods of assessing the signal cycle duration.

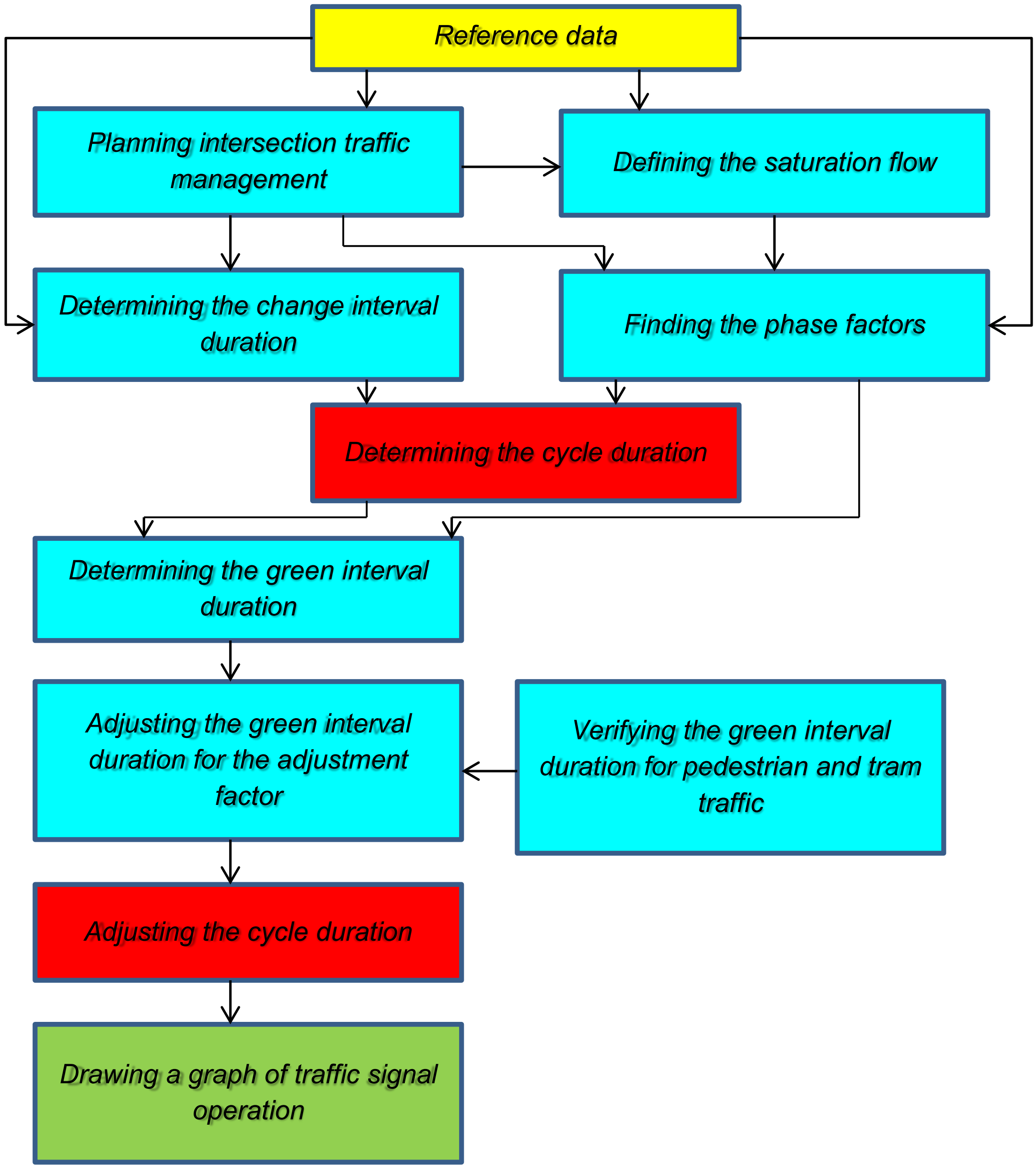

Figure 3. Proposed procedure for determining the duration of the cycle and its elements

The adjustment factor value k_a will range as follows: k_a = 0.08–0.15. After adjusting the duration of the green interval along the relevant traffic directions, it is necessary to adjust the duration of the signal cycle at the intersection with turning flows. A rough diagram of the process of assessing the traffic signal cycle duration after the aforementioned adjustment will look as follows (Fig. 3).

Discussion

As we contrasted the results of our field observations, aimed at determining the actual capacity of intersections with turning flows, against theoretical insights obtained through modern methods, we discovered that they differ greatly. This, along with the high accident rates at intersections, called for an explanation. The analysis of the situation has reaffirmed that the existing methods do not account for the most important traffic safety prerequisite: the movement of vehicles at a green light while maintaining the minimum safe distance.

Conclusion

Our research has allowed us to conclude that the prerequisite for traffic safety at signal-controlled intersections with turning flows is the movement of vehicles during the green interval, which should be measured with the minimum safe distance in mind. This will make it possible to adjust the existing methods of assessing the signal cycle duration while accounting for the minimum safe distance between cars.

Acknowledgment

The research team would like to thank Colonel Aleksey Sultanovich Gabdorakhmanov, deputy head of the State Road Traffic Safety Authority at the Sverdlovsk Region office of the Russian Ministry of Internal Affairs, for his help with our field observations of traffic at intersections in the city of Yekaterinburg.

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УСЛОВИЕ БЕЗАВАРИЙНОГО ДВИЖЕНИЯ АВТОМОБИЛЕЙ НА РЕГУЛИРУЕМЫХ ПЕРЕСЕЧЕНИЯХ

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Аннотация
Повышение пропускной способности пересечений невозможно без учета необходимости обеспечения безопасности дорожного движения. **Целью исследования** явилось определение условия безаварийного движения транспортных средств на регулируемых пересечениях при наличии поворотных потоков. Для выполнения исследования использовались **методы** наблюдения, сравнения и математического анализа. **Результаты:** Проведено натурное исследование интенсивности движения транспортных средств на перекрестках со светофорным регулированием г. Екатеринбурга, движущихся на разрешающий сигнал светофора. Выполнен анализ транспортных потоков, движущихся в трех направлениях по одним и тем же полосам движения. Установлено, что наиболее аварийными являются четырехсторонние пересечения (54 %). На трехсторонние пересечения приходится (44 %) ДТП, остальная часть (2 %) это многосторонние пересечения. Определены дополнительные факторы, влияющие на безопасность дорожного движения на пересечениях при наличии поворотных потоков. Показано, что для обеспечения максимальной пропускной способности длительность цикла светофорного регулирования должна определяться с учетом минимально безопасного расстояния между транспортными средствами.

Ключевые слова
Безопасность дорожного движения, длительность цикла светофорного регулирования, регулируемое пересечение.

AUTOMOTIVE SHOCK ABSORBERS' APPLICABILITY FOR DAMPING RESONANT OSCILLATIONS IN CONSTRUCTION MACHINES

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Abstract

Introduction: Many vibration transport and technological machines (VTTM) such as conveyors, screens, crushers, etc. operate in a high-frequency mode, or above resonance. Resonance occurs during machine start and slowdown, resulting in sharply rising values of the amplitude and velocity of oscillations. Resonance affects VTTMs adversely due to increased dynamic loads reducing machinery operating life and reliability and causing the noise. **Purpose of the study:** We aim to provide a theoretical substantiation for the possibility to apply automotive shock absorbers to VTTM oscillatory process control and develop an example of practical implementation for such a device. **Methods:** The method of controlling oscillatory processes in VTTMs lies in the use of dual-mode shock absorbers. In the operating mode, shock absorbers offer minimum resistance to motion. In the resonance mode, resistance increases, therefore, the amplitude decreases to a predetermined value. **Results:** We simulate the VTTM oscillatory process in order to determine the characteristics of a damping device, which ensures the suppression of resonant oscillations but does not affect the vibration operating process. We propose a new technical device implementing the required oscillation characteristics. The device is made in the form of a hydro-pneumatic shock absorber, similar to automotive shock absorbers in terms of design. Such a design makes it possible to offer slight damping of the machine's useful (operating) vibration, but, at the same time, damping increases significantly in the case of resonant amplitudes. The originality of our study lies in the development of a new type of hydraulic shock absorber, for which a utility model patent has been obtained. The scientific novelty of the study is in the mathematical description of oscillation damping with the new shock absorber, in the development of software for oscillatory process analysis according to the developed mathematical model, and in the results of computer simulation for shock absorber operation.

Keywords

Vibration, resonance, shock absorber, vibration transport and technological machines.

Introduction

The majority of vibration transport and technological machines (VTTMs) such as conveyors, screens, crushers, vibratory plates, etc. operate above resonance (Bauman and Bykhovsky, 1977; Kuzmichev, 2014). Resonance occurs when oscillations of a vibration machine start or stop. This phenomenon is accompanied by sharply rising values of the amplitude and velocity of oscillations. Resonance affects VTTM operation adversely: dynamic loads on the machine components increase, excess noise occurs, machinery operating life and reliability are reduced (Chelomey, 1981).

Machinery protection against the destructive effect of resonant amplitudes and increased vibration loads is a challenging issue and a top priority in VTTM design. There are various solutions available for damping resonant amplitudes. One of the most effective solutions is the use of telescopic hydro-pneumatic shock absorbers (Derbaremdiker, 1969; Dobromirov et al., 2006, Repin et al., 2020; Rotenberg, 1972) that were already tried and tested (in motor vehicles). In such hydro-pneumatic shock absorbers, the resistance coefficient changes in proportion to the velocity of oscillations.

Methods

This study focuses on oscillatory processes in VTTMs. The purpose of the study is to provide a theoretical substantiation for the possibility to design such mechanical devices as automotive shock absorbers for oscillatory process control and develop an example of practical implementation for such a device.

The proposed method of controlling oscillatory processes in VTTMs lies in the use of dual-mode shock absorbers. In the operating mode, shock absorbers shall offer minimum resistance to oscillatory motion. In the resonance mode, resistance shall increase in order to decrease the amplitude to a predetermined value.

Shock absorbers used in motor vehicles operate in two modes: throttle and valve ones (Demić and Diligenski, 2016; Dobromirov et al., 2006; Hrovat and Hubbard, 1982; Repin et al., 2020; Sani et al., 2008). At small amplitudes and, consequently, low velocities, the valves are closed, and the liquid is forced through the throttle channels in the piston. That is the throttle mode. With an increase in piston velocity, hydraulic resistance to its motion increases as well, and the valves open, reducing the resistance. That is the valve mode.

The damping force generated by such a shock absorber is as follows (Dobromirov et al., 2006; Repin et al., 2020; Rotenberg, 1972):

$$Pd = k \times v^i, \quad (1)$$

where k — resistance coefficient of the hydro-pneumatic shock absorber; v — velocity of vertical VTTM motion; i — power index.

The shock absorber characteristic may vary depending on the power i:

1) linear (at i=1.0);
2) progressive (at i>1)
3) regressive (at i<1).

Its type depends directly on the shock absorber design parameters. The coefficients k_c (compression stage) and k_e (extension stage) have different values. Figure 1 presents a progressive characteristic curve, which most corresponds to the specified conditions. This is a schematic representation since the actual characteristic curve will be nonlinear (shown by the dashed line).

However, due to their parameters, industrial shock absorbers cannot be used in VTTMs. The working stroke (amplitude of oscillations) in VTTMs, corresponding to the throttle mode, is 1–10 mm, while in industrial shock absorbers, it is by an order of magnitude greater. Besides, the damping value in the throttle mode is too high, at least tens of newtons, which leads to increased energy consumption per vibration process.

Therefore, it is required to develop a new shock absorber design, which would satisfy VTTM operating conditions to the fullest extent possible.

Results

Let us describe a method to substantiate the selection of hydro-pneumatic shock absorbers' parameters by means of simulating VTTM operation (Fig. 2).

The VTTM comprises housing 1 with the material and is driven by vibrator 2 generating directed oscillations. The VTTM is located on base plate 5, on four hydraulic shock absorbers 3 and four springs 4.

The forces acting on the VTTM can be described by the following equation (Kuzmichev, 2014):

$$P_i + P_s + P_d + G = F(t), \quad (2)$$

where P_i — inertia; P_s — spring force; P_d — damping force of the hydraulic shock absorbers; G — VTTM weight; $F(t)$ — external impact.

The force $F(t)$ created by the vibrator generating directed oscillations changes with time according to the following law (Bauman and Bykhovsky, 1977):

$$F(t) = F_0 \times \cos(\Omega t), \quad (3)$$

where F_0 — amplitude of the disturbing force of the vibrator generating directed oscillations; t — time, s; Ω — frequency of the vibrator generating directed oscillations, s^{-1}.

Using the equation, we can determine the restoring force of a vibration conveyor spring (Dobromirov et al., 2006; Repin et al., 2020):

$$P_s = -l \times c, \quad (4)$$

where l — spring travel during operation; c — spring stiffness, N/m.

Using this equation, we can find the damping force of the shock absorber, affecting the conveyor:

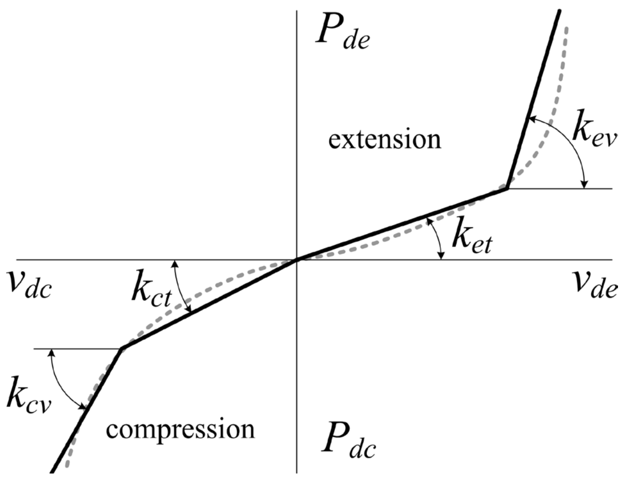

Figure 1. Shock absorber characteristic curve: P_d — damping force; v_d — piston velocity; k — resistance coefficient; subscripts: c — compression; e — extension; t — throttle mode; v — valve mode

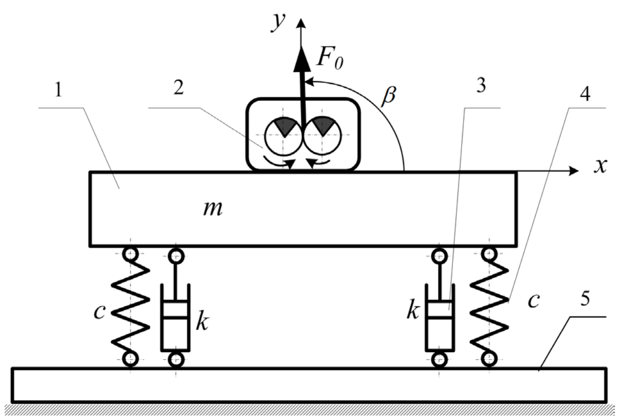

Figure 2. VTTM design model:
1 — VTTM housing; 2 — vibrator generating directed oscillations; 3 — shock absorbers; 4 — springs; 5 — base plate; m — VTTM weight with the material being moved; β — angle of the disturbing force

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$$P_d = -k \times v, \quad (5)$$

where v – velocity of the piston with the piston rod, m/s; k – resistance coefficient of the hydraulic shock absorber, Ns/m (Newton per second/meter).

Newton's Second Law can be written as follows (Kuzmichev, 2014):

$$m \times a = -c \times l - k \times v + F(t), \quad (6)$$

This equation describes a plane case and small forced oscillations (Chelomey, 1981); in the differential form, the equation of vibration conveyor motion will be as follows (Kuzmichev, 2014; Repin et al., 2020):

$$m \times y(t) + 2 \times c \times y(t) + 2 \times k \times y(y) = F(t), \quad (7)$$

where y — value of movement along the y axis.

The angle of the disturbing force and the angles of the shock absorber axes are taken identical to simplify the mathematical model. Therefore, we cancel their trigonometric functions in the equation.

As a result, equation (7) can be written in the following form:

$$\ddot{y}(t) + \omega_0^2 \times y(t) + h \times \dot{y}(t) = \frac{F(t)}{m}, \quad (8)$$

where $h = k/(2 \times m)$ — damping coefficient, N·s/(kg·m); $\omega_0 = (2 \times c/m)^{1/2}$ — eigen frequency of the conveyor, s^{-1}.

The amplitude of steady-state oscillations can be determined using the following equation (Demić and Diligenski, 2016):

$$A_{op} = F_0 \Big/ \left(m \times \sqrt{\left(\Omega^2 - \omega_0^2\right)^2 + 4 \times h^2 \times \Omega^2} \right). \quad (9)$$

The angular frequency $\Omega_0 = \sqrt{\omega_0^2 - 2 \times h^2}$ matches the maximum value of the amplitude A_{max}. The angular frequency is slightly less than the eigen angular frequency of the vibration system $\Omega = \sqrt{\omega_0^2 - h^2}$.

$$A_{max} = F_0 / \left(2 \times h \times m \times \Omega_0\right). \quad (10)$$

An increase in the shock absorber damping coefficient h will lead to a decrease in the maximum oscillation amplitude A_{max} and straightening of the resonant oscillations' curves $A(\Omega)$, which will make it possible to significantly reduce the phenomenon of resonant oscillations. At $h \geq \omega_0/\sqrt{2}$, resonant oscillations disappear completely (Chelomey, 1981).

Figure 3 presents the result of resonant amplitude calculation depending on the shock absorber resistance coefficient in Mathcad. Based on this calculation, the actual values of the damping coefficient h and the shock absorber resistance coefficient k are derived. An example of calculation for a test bench, performed in Mathcad, shows that the resistance coefficient should be not less than 2000 N·s/m to limit the maximum amplitude in the amount of 0.01 m. This is the maximum resistance to be developed by the shock absorber.

Then, based on the found characteristics of oscillations' damping, we selected parameters of the hydraulic shock absorber. In addition to that, we developed several shock absorber designs meeting the condition. The design (Fig. 4) obtained by utility model modernization (Repin and Litvin, 2017) is the most promising. Shock absorber resistance is found using the ratio between the values of amplitude oscillations and the values of piston travel l in the piston chamber. At a lesser amplitude l, there is a flow of liquid through the gap $\delta_{rs} = (d_s - d_r)/2$ between the rod and the sleeve. At a higher amplitude l, there is a flow of liquid through the gap $\delta_{ps} = (d_s - d\ )/2$ between the piston and the sleeve, which is significantly less than the gap described above. Therefore, in case of a higher amplitude, resistance to fluid flow is higher as well, which means that the shock absorber resistance coefficient is also higher.

The shock absorber operates as follows: the device is installed between the main and the oscillating parts of the vibration machine. In the operating mode, piston parts 3 and 5 move outside hydraulic sleeve 4. Therefore, the operating (steady-state) amplitude value A_{op} is less than the gap value l. Thus, in this operating mode, resistance to movement of two-point rod 2 includes the following forces: the rod friction force (in the point of contact with cylinder housing 1), the force of hydraulic friction in the moving parts inside the shock absorber, as well as the inertia of the moving parts of the shock absorber, such as the hydraulic piston and two-point rod. In this mode, the resistance coefficient of the hydraulic shock absorber is minimal.

In case of resonant oscillations when the amplitude exceeds the value of l, hydraulic pistons 3 and 5 will enter the internal cavity of sleeve 4. This

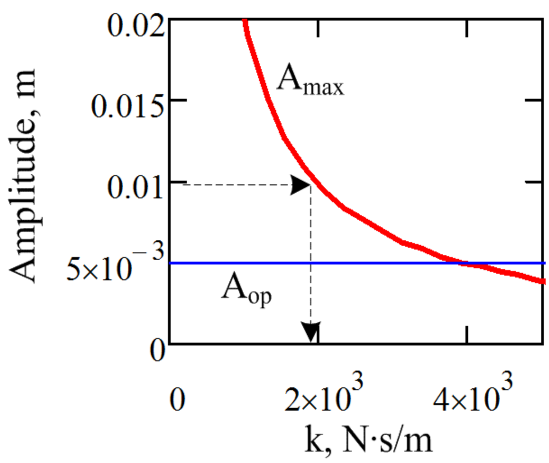

Figure 3. Dependence of the resonant amplitude of oscillations A_{max} in a VTTM on the shock absorber resistance coefficient

will cause a sharp increase in hydraulic resistance due to shock absorber liquid pushing through the gaps between sleeve 4 and hydraulic pistons 3 and 5. The resistance coefficient of the shock absorber will increase proportionately, and the amplitude of oscillations will decrease correspondingly.

Pin bush 6 is required in order to stabilize the movement of two-point rod 2 strictly along the axis of cylinder 1. Since the gap between the central hole of sleeve 6 and two-point rod 2 is quite large, there will be no friction between them. Holes in sleeve 6 allow the liquid to move freely inside hydraulic cylinder 1 of the hydraulic shock absorber.

During movement of two-point rod 2, compensating gas piston 7 counterbalances the changes in the internal volume of cavity B filled with liquid.

When developing a mathematical model of shock absorber operation, alternating processes of expansion and compression during the operation of the hydraulic shock absorber are taken into account.

At the compression stage, all energy from external forces is directed at overcoming the friction forces P_f in the shock absorber gaskets, at compressing gas P_g in the gas cavity, pushing liquid P_l through the gap between the sleeve and the two-point rod with the hydraulic piston, overcoming the gravity force G_g

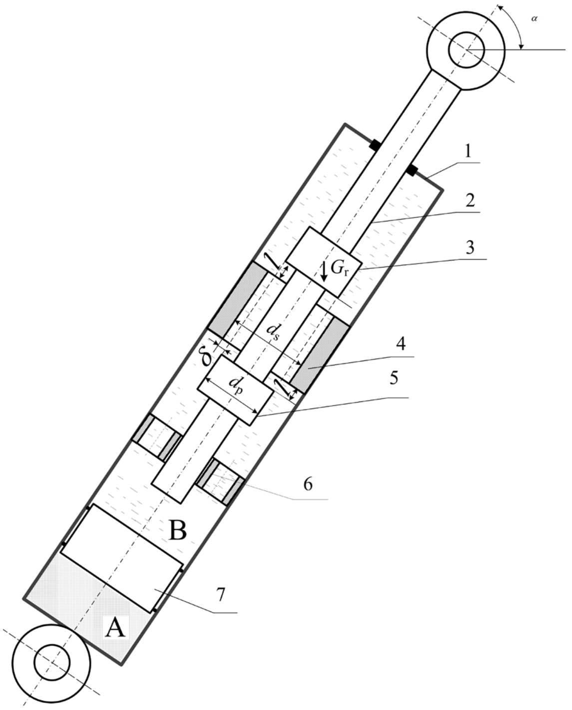

Figure 4. Shock absorber of resonant oscillations:
1 — cylinder housing; 2 — two-point rod; 3, 5 — hydraulic piston; 4 — sleeve; 6 — pin bush; 7 — compensating gas piston; A — cavity filled with gas; B — cavity filled with liquid; G_r — gravity force of the rod with the hydraulic piston; d_s — sleeve diameter; d_p — piston diameter; *δ* — gap between the two-point rod and the sleeve; *l* — distance from the sleeve to the hydraulic piston; *α* — shock absorber installation angle

and inertia P_i of the moving two-point rod with the hydraulic piston:

$$P_C = P_g + P_l + P_f + P_i - G_g \cos\alpha. \quad (11)$$

At the expansion stage, the force in the shock absorber is as follows:

$$P_E = P_g + P_l + P_f + P_i + G_g \cos\alpha. \quad (12)$$

The main difference between the presented shock absorber for damping of resonant oscillations and standard automotive shock absorbers is that there are different values of resistance P_l to liquid pushing through the different gaps in the shock absorber: liquid movement through the gaps between the sleeve and the rod has small resistance while its movement through the gaps between the sleeve and the piston has quite significant resistance. Therefore, it is the latter that has the most impact on the final characteristic of a hydraulic shock absorber. According to the mathematical calculations related to the hydraulics (Dalin and Mikheev, 2001), the value of resistance to movement of the hydraulic piston in the sleeve is expressed through resistance to movement of liquid through the described gaps between the sleeve and the two-point rod with the hydraulic piston:

a) if the amplitude of oscillations is less than the distance *l*, liquid flows through the gap between the sleeve and the rod

$$P_{l1} = \frac{\rho_l \times v_p^2 \times F_p^2}{2 \times g \times \mu^2 \times S_{rs}^2}. \quad (13)$$

b) if the amplitude of oscillations is more than the distance *l*, liquid flows through the gap between the sleeve and the piston

$$P_{l2} = \frac{\rho_l \times v_p^2 \times F_p^2}{2 \times g \times \mu^2 \times S_{ps}^2}, \quad (14)$$

where ρ_l — liquid density; F_p — area of the hydraulic piston; S_{rs} and S_{ps} — area of the gap between the two-point rod and the sleeve; area between the hydraulic piston and the sleeve; v_p — hydraulic piston velocity; μ — leakage coefficient that depends on the liquid viscosity and the size of the gaps (0.65–0.75).

The relationships between the effective area of the hydraulic piston and the gap area are as follows:

a) at downwards movement

$$F_{p\downarrow} = \pi \times d_p^2 / 4. \quad (15)$$

$$S_{ps} = \pi \frac{(d_s^2 - d_r^2)}{4}. \quad (16)$$

b) at upwards movement

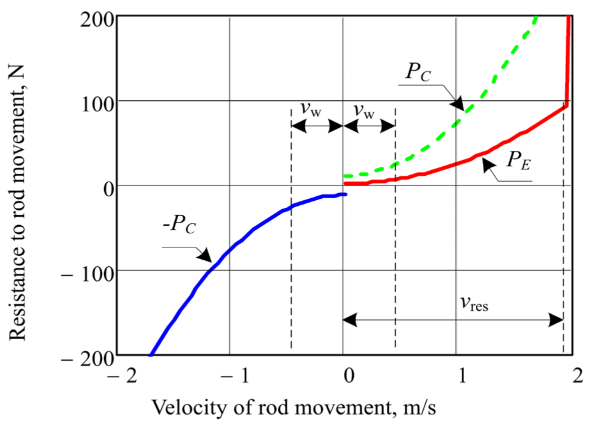

Figure 5. Hydraulic shock absorber characteristic: v_{res} — rod velocity when entering the resonance mode; v_w — rod velocity in the VTTM working mode (when the axis of oscillation is crossed)

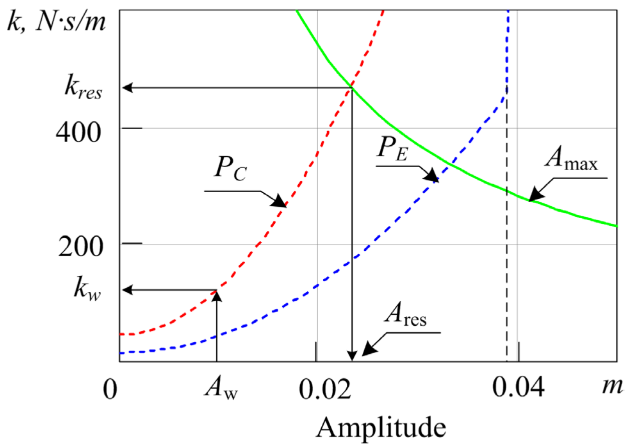

Figure 6. Dependence between the shock absorber resistance coefficient and the VTTM amplitude of oscillations: A_{res} — resonant amplitude; A_w — working amplitude of oscillations

$$F_{p\uparrow} = \pi\left(d_p^2 - d_r^2\right)/4. \tag{17}$$

$$S_{ps} = \pi\frac{(d_s^2 - d_r^2)}{4}. \tag{18}$$

Figure 5 shows the shock absorber characteristic simulated in Mathcad.

As seen from the diagram of the hydraulic shock absorber characteristic, the resonant velocity is limited to the resistance of the hydraulic shock absorber. It is clearly seen in the P_E *curve*. When the hydraulic shock absorber enters the internal space of the sleeve, a sharp increase in the force P_E occurs. The hydraulic shock absorber slows down the oscillatory process and, thus, limits the amplitude of oscillations.

Figure 6 shows a combination of the operating characteristics of a vibration transport and technological machine (Fig. 3) and the developed hydraulic shock absorber. This makes it possible to choose not only the required values of the shock absorber resistance coefficient in two modes (working and resonance modes) but also the required design characteristics of the hydraulic shock absorber such as: the size of the hydraulic pistons, the two-point rod, and the sleeve, as well as pressure in the gas chamber.

Discussion

Thus, through the theoretical study of the operation of the proposed shock absorber, we have shown that such devices can be applied in vibration transport and technological machines. Being able to operate in two modes (with a small and high resistance coefficient), the shock absorber virtually does not impede the oscillatory process in the steady-state mode of operation and, also, actively dampens resonant oscillations in transient modes.

Conclusion

In the course of the study, we performed the mathematical simulation of the oscillatory process in a vibration transport and technological machine with the installed damping device. We derived the mathematical expression for the damping coefficient, which ensures damping of resonant oscillations.

The new design of the VTTM hydraulic shock absorber was described. This design offers the minimum resistance in the operating mode and the required resistance upon the occurrence of resonant oscillations.

We also developed the mathematical model for the joint operation of the hydraulic shock absorber and a VTTM. The model was implemented in the Mathcad environment. The combination of the operating characteristics of the hydraulic shock absorber and a VTTM makes it possible to select the required parameters of the shock absorber resistance coefficient in the working and resonance modes. Besides, using this combination, we can choose the values of design characteristics for the hydraulic shock absorber in order to damp resonant oscillations.

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ПРИМЕНЕНИЕ АМОРТИЗАТОРОВ АВТОМОБИЛЬНОГО ТИПА ДЛЯ ДЕМПФИРОВАНИЯ РЕЗОНАНСНЫХ КОЛЕБАНИЙ В ТЕХНОЛОГИЧЕСКИХ МАШИНАХ

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Аннотация

Многие вибрационные транспортно-технологические машины (ВТТМ) – транспортеры, грохоты, дробилки и другие, работают в высокочастотном режиме, называемом зарезонансным. Явление резонанса возникает в периоды запуска и торможения машины, что вызывает резко-возрастающие значения амплитуды и скорости колебаний. На работе ВТТМ явление резонанса сказывается крайне негативно, ввиду повышения динамических нагрузок, которые снижают ресурс и надежность машины, вызывают шум. **Цель исследования**: Теоретическое обоснование возможности применения амортизаторов автомобильного типа для управления колебательным процессом ВТТМ и разработка примера практической реализации такого устройства. **Метод:** Метод управления колебательными процессами в ВТТМ заключается в использовании двухрежимных амортизаторов. В рабочем режиме амортизаторы создают минимальное сопротивление движению. В резонансном режиме сопротивление увеличивается, поэтому амплитуда снижается до заданного значения. **Результаты:** В статье выполнено моделирование колебательного процесса ВТТМ с целью определения характеристик демпфирующего устройства, обеспечивающего гашение резонансных колебаний и, в то же время, не влияющего на рабочий вибрационный процесс. Предложено новое техническое устройство, реализующее требуемые характеристики колебаний. Устройство выполнено в виде гидропневматического амортизатора, подобного по конструкции автомобильным амортизаторам. Особенность конструкции разработанного амортизатора позволяет обеспечить незначительное сопротивление полезной (рабочей) вибрации машины, но в то же время сопротивление амортизатора значительно увеличивается при возникновении резонансных амплитуд. Оригинальность данного исследования заключается в разработке нового вида гидравлического амортизатора, на конструкцию которого получен патент на полезную модель. Научная новизна заключается в математическом описании процесса демпфирования колебаний новым амортизатором, в разработке компьютерной программы расчета колебательного процесса по разработанной математической модели, в результатах компьютерного моделирования работы амортизатора.

Ключевые слова

Вибрация, резонанс, амортизатор, вибрационные транспортно-технологические машины.

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