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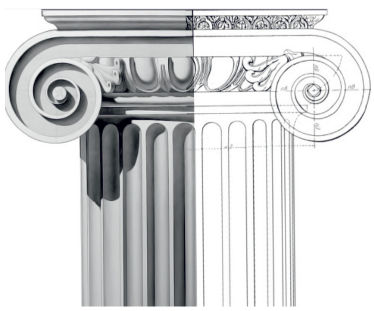

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Architecture

HISTORICAL DESIGN OF CANTILEVER SHELLS OF MODERNIST ARCHITECTURE

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Abstract

Introduction: Studying the historical design system of the pioneer concrete shells helps to reveal a relevant part of the History of Construction, which is also fundamental in acquiring the knowledge necessary to conserve and restore this iconic heritage. Cantilevered shells, like large domes, have been the most difficult to design and dimension when computers did not yet exist. **Methods:** The research included two phases: firstly, the selection and analysis of some of the most relevant pioneer cantilevered shells, and secondly, the comparative analysis of their design systems. **Result and discussion:** The analysis pointed out that the pioneer master engineers used different design systems. Pier Luigi Nervi and Eduardo Torroja mainly used scale model tests to check the structural behavior of their new continuous structural forms, Ildefonso Sánchez del Río always used ribbed shells and chose geometric forms that were easy to calculate manually, and Félix Candela used real size models for the tests. The result reveals the different paths that they used to design and build their relevant legacies, which nowadays belong to the international heritage of Modernist Architecture.

Keywords

Concrete shells, design system, cantilevered structures, Modernist Architecture.

Introduction

The formal and technological conquest of Modernist thin concrete shells is inseparable from the development of reinforced and prestressed concrete. The first vaults and concrete domes were built at the end of the 19th century using the pioneer patents, among others those of: J. Monier, F. Henebique, G. Schlüter and H. Habrich (Christophe, 1899). They were the precedents of thin concrete shells. Consequently, the thick concrete vaults and domes became shell structures, which were evolving, becoming bigger, thinner, and slender.

On the other hand, cantilevered structures made from wood and even such materials with low flexural strength as stone were used in buildings throughout the history. But what allowed building large cantilever structures was the discovery of new materials with high flexural strength and rigidity, such as iron and reinforced and prestressed concrete.

It is a fact that the appearance of the first shell structures of reinforced concrete in the second decade of the 20th century opened new possibilities of ˝flying˝. Undoubtedly, the thin and slender concrete shells that are “floating in the air” have not only a great complexity of design, but also special and disturbing attractiveness. We are going to analyze some selected pioneer cantilever concrete shells designed and built by several masters and reveal different design systems they followed to achieve their results.

Methods

The research included two phases. Firstly, the selection and analysis of some of the most relevant pioneer cantilevered concrete shells, which were designed using three different systems: the historical graphic statics method, the pioneer manual numerical dimension system by Franz Dischinger, and a physical reduced model.

Secondly, the comparative analysis of some pioneer types of cantilevered shell structures resulting in different resistant shapes and cantilever stiffening systems.

Results and Discussion

To understand the importance of the specific contributions to cantilevered concrete shells development, it is necessary to analyze them while simultaneously considering what was happening at that moment in the international context. How were the cantilevered shells designed during the *“Concrete Shells Adventure”?* It is well known that the cantilever structures are highly based on torque moment and rotational equilibrium. Loads, whether dead or live, must be balanced out on the cantilever section. They must be rigid, and the easiest way to get rigid shells is to use a set of rib-beams. This is the reason why most of the first cantilever concrete shells were designed with depth ribs.

In 1929, Pier Luigi Nervi (1871–1979), one of the most relevant protagonists of the pioneer *“Concrete Shells Adventure”*, designed his famous Florence football stadium — *Stadio Giovanni Berta* (Nervi, 1956), now known as *Stadio Artemio Franchi.* It was inaugurated in 1932. It is a cantilever concrete shell masterpiece, a pioneer building of Modernist Architecture, and an icon worldwide (Figure 1).

The structure of the grandstand and its cantilever roof form an ingenious resistant unity. It was made of reinforced concrete with a scenography image of resounding and nude modernity. Its roof is a pioneer cantilever ribbed shell. It consists of a set of 23 concrete modules formed by 8 pillars of different height supported by 2 inclined beams and 2 cantilever curved ribs. These cantilever ribs have an aerodynamic shape. Their total length is 22 m and their overhang is 17 m from the crossing point of two inclined supports. A light sheet of ceramic material is provided on them for support. The curved ribs have a shocking geometric shape that serves to balance the structural set by the large inclined foot, which crosses the inclined beam to the back pillar (Iori, 2009). In this respect, the grandstands act as a buttress resisting the overturning moment. The inclined beam starts from the head of the same pillar (Figure 2). The transverse bracing of the cantilever curved ribs is formed by a smaller curved ridge of reinforced concrete ribs between two main ribs (Figure 1, on the right). All the structural elements form an ingenious resistant unit, which demonstrates not only an

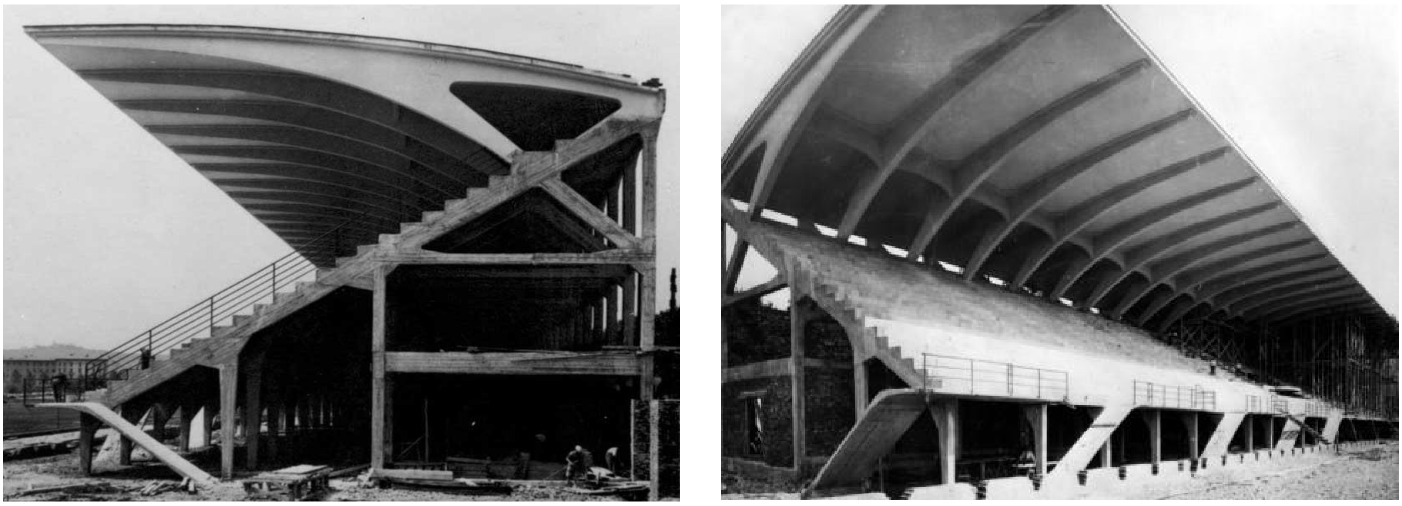

Figure 1. Florence football stadium (photographs) (archive: Fernando Cassinello)

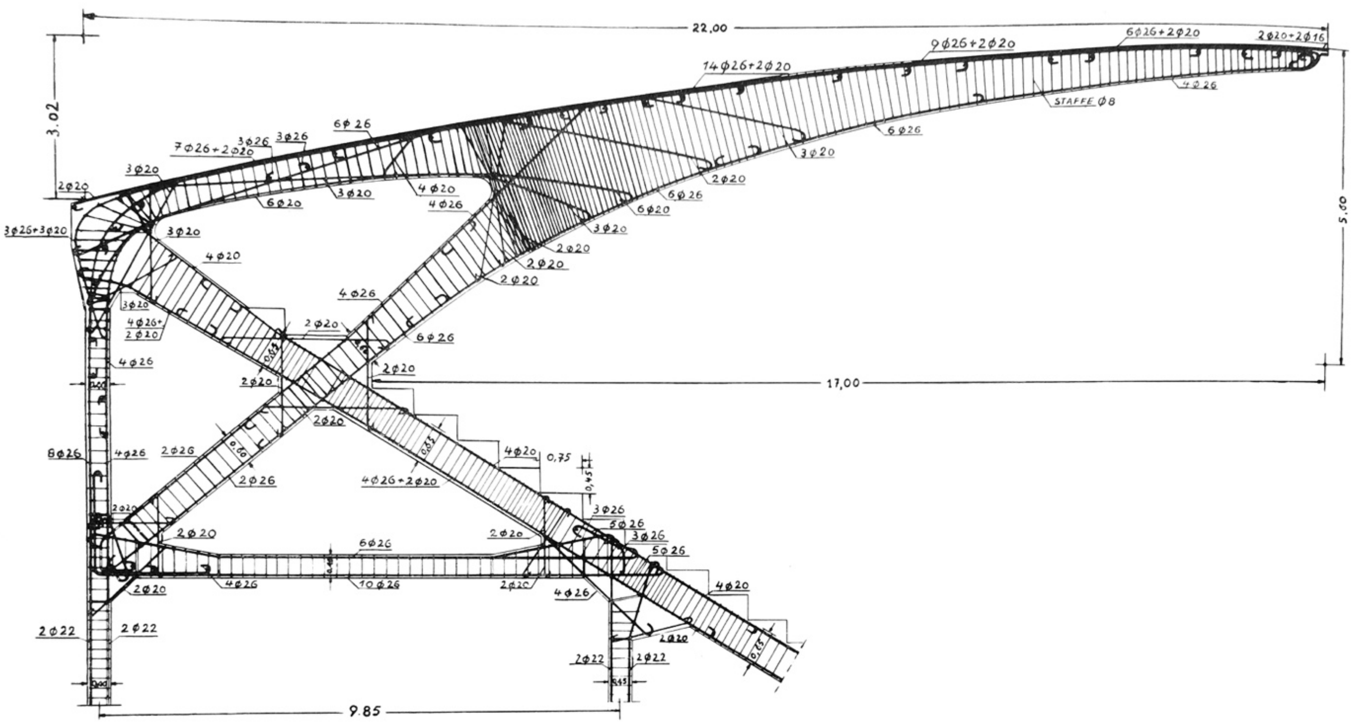

Figure 2. Florence football stadium (layout) (archive: Fernando Cassinello)

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optimal structural behavior, use of material and process of construction, but also the naked modernity image Pier Luigi Nervi managed to express.

At that time, Eduardo Torroja, another outstanding civil engineer of the 20th century, pointed out that it was impossible to design a new concrete shell with numerical calculations only. At that moment, they were using a complex and manual calculation system developed by Franz Dischinger (Dischinger, 1928). As Eduardo Torroja said, it was necessary to check the results by a physical model test. In the early 1930s, Torroja founded his company ICON. It was specializing in testing physical models as a method for analyzing structural behavior. The micro-concrete models for the *Algeciras Market* and *Recoletos Jai-alai Court*, both on a scale of 1:10, received particular acclaim (Cassinello, 2016). He earned international renown for his concrete shells: *Algeciras Market* (1935), *Madrid's Zarzuela Racecourse* (1935), and the *Recoletos Jai-alai Court*, also in Madrid (1936). *Zarzuela Racecourse* is the only one of his three famous concrete shells which is cantilevered.

In 1934, Torroja began the construction. The cantilever is a thin and continuous reinforced concrete shell without ribs or folds. It gives an impression of a fine wavy fabric that floats in the air above the bleachers (Figure 3). Its significantly Modern language and innovative structural form prompted the engineer's inclusion in the book *Art and Artist* (1956), along with relevant sculptors like Henry Moore, Ernst Mundt and Alberto Giacometti, photographers like W. Eugene Smith and painters like Paul Klee, among others (Torroja, 1956). This was only fair for Eduardo Torroja managed to achieve a remarkable feat of reinforced concrete architecture when this material was still in development.

The *Zarzuela Racecourse* has three bleachers, with the two outer 60 m long structures flanking a 30 m long central stand. Each unit consists of transverse portal frames spaced at 4.88 m, which in turn consist of a set of modules formed by a shell of double cantilever, one longitudinal (12.75 m) and one transversal (2.44 m), which is supported by a single pillar and not a shell on two pillars as some people wrongly assume. Eduardo Torroja chose the geometric shape of hyperboloid sectors for the design.

As he explains in his book *The Structures of Eduardo Torroja* (Torroja, 1958), he was looking for a double curvature surface to get the rigidity needed. He did not like to use ribs, he always thought on continuous shells resistant due to their geometrical structural shape. A threaded steel tie positioned at the rear provides the balance for these bold structural forms. It resembles an enormous Calder's sculpture. When the wind blows, you can see its slight movement in its articulated props on the pillars. The shell is 5 cm thick at the outer edge and 14 cm over the support.

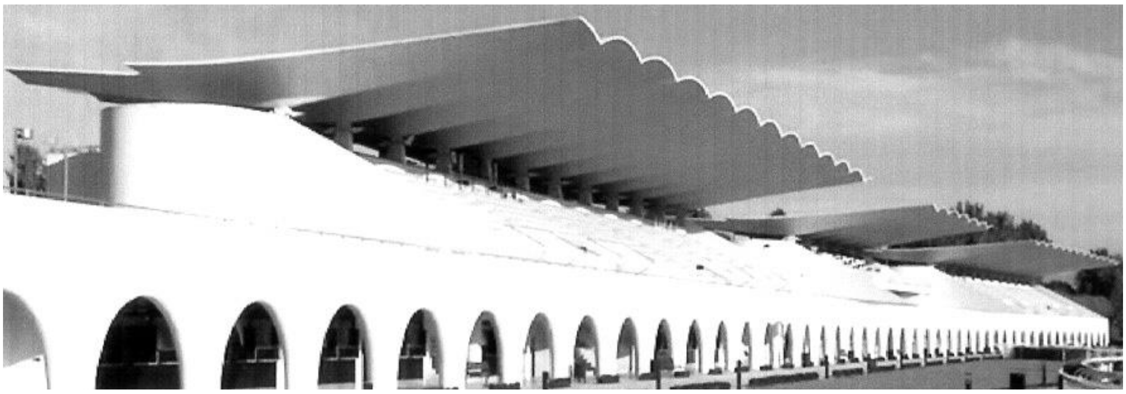

Figure 3. Cantilever concrete shell on the bleachers. *Hipódromo de la Zarzuela – Zarzuela Racecourse* (archive: Pepa Cassinello)

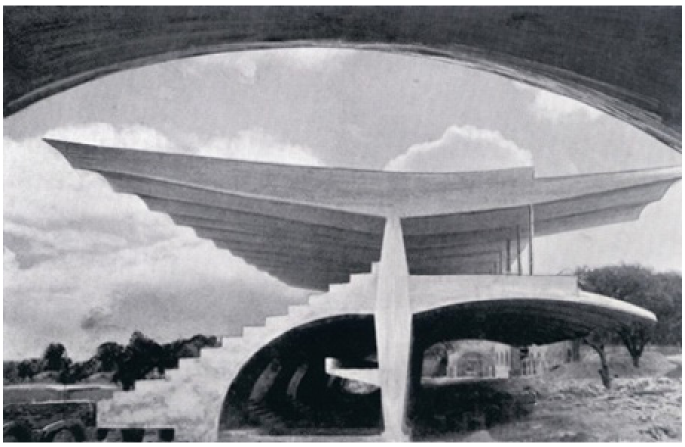

Figure 4. Zarzuela Racecourse. Photo by Sibily von Kassel (archive: Eduardo Torroja)

Figure 5. Alexander Calder's sculpture (archive: Fernando Cassinello)

Two decades before David P. Billington coined the term "Structural Art" at the University of Princeton (Billington, 1983), Eduardo Torroja had already built a gigantic reinforced concrete sculpture (Figure 4) like those mobiles made by Alexander Calder with steel bars and color plates (Figure 5). In fact, the concrete shells, that nowadays house the Eduardo Torroja Museum, are mobile sculptures. They are supported by Freyssinet-type joints that allow them to move on the pillars (Figure 6). On windy days, visitors may observe how they swing on them. Their balance is guaranteed by the metal braces located at the back of the large 12.80 m cantilever. Only Eduardo Torroja was able to create this innovative reinforced concrete structure, coining in his hands the birth of the inexhaustible *Era of the Structural Art* of reinforced and prestressed concrete, as Robert Maillart, Eugenne Freyssinet and Pier Luigi Nervidid. These four engineers were pioneers and titans of the reinforced concrete works during the new feeling that emerged in Modernity.

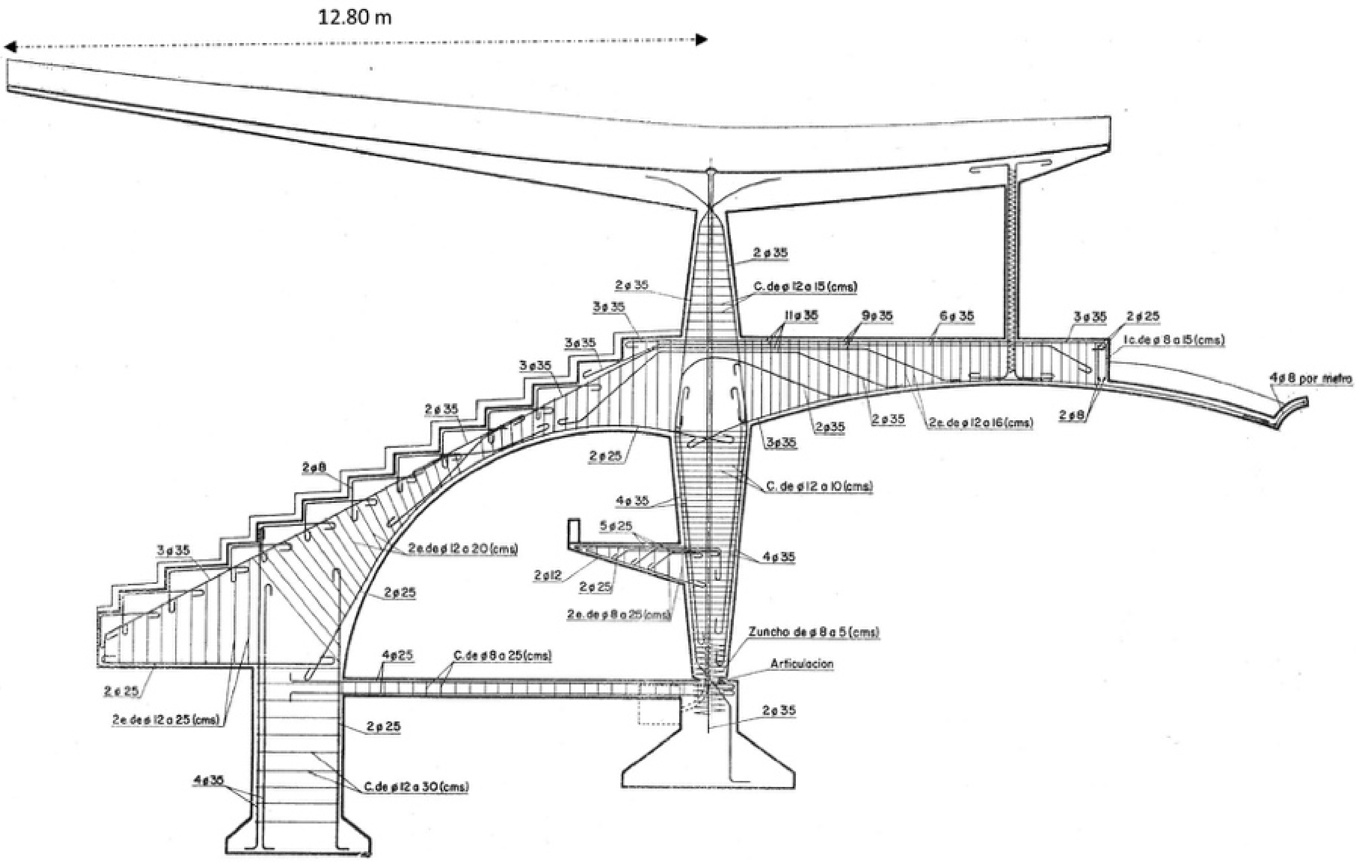

Figure 6. *Zarzuela Racecourse* (transversal section)
(archive: Eduardo Torroja)

In the case of the *Zarzuela Racecourse*, Eduardo Torroja conducted a test on a full-scale physical model (Figure 7). That approach verified not only structural behavior, but at the same time the complex construction process of this innovative structural cantilever form. In view of the complexity of building the junction between the two hyperboloid lobes, he decided to make a straight joint between them (Figure 8). In this way the final structural geometric shape is only similar, but not identical, to the intersection of two sectors of hyperboloids. These straight joints have a variable width, being wider over the pillar and more mats at the end of the cantilever. He checked the module's structural behavior under loads (Figure 9). It was tested under deadweight and snow loads and the results demonstrated that it had three times the resistance necessary.

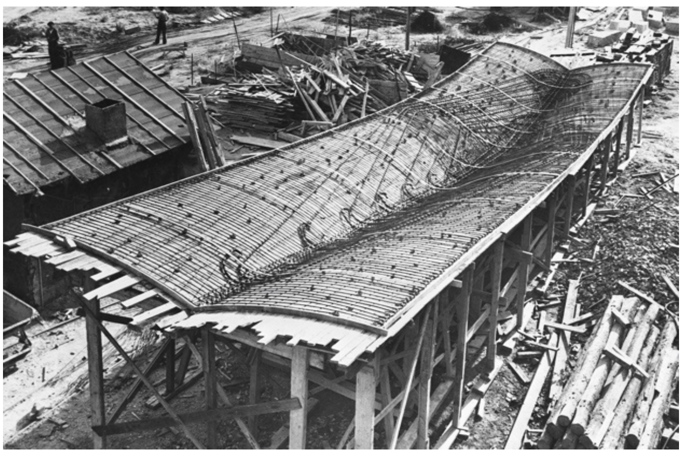

Figure 7. Full-scale model
(archive: Eduardo Torroja)

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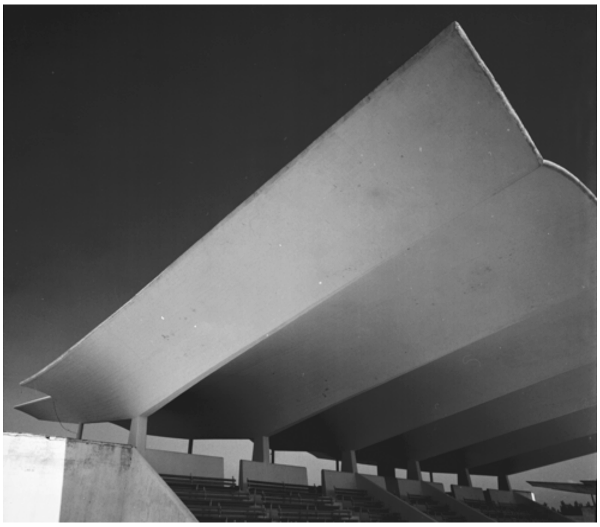

Figure 8. Cantilevered shells
(archive: Eduardo Torroja)

Figure 9. Load test of the cantilever module
(archive: Eduardo Torroja)

During the Second World War, the shortage of steel in Europe was one of the reasons why the use of prestressed concrete proliferated as it required less steel. In 1951, a cantilevered shell structure recalling the pioneering *Zarzuela Racecourse* was presented at the Hannover exhibition. It was built with prestressed concrete by German engineers Finsterwalder and Pistor, and architect Gütschow. Its geometrical shape corresponded to the spatial twist of three circular segments with an outer radius of 24 m (Figure 10) supported by ribs on the pillars. Its cantilever was 15.80 m, 3 m more than the Torroja's one, but with larger ribs.

In 1932, the Oviedo Stadium (Spain) was inaugurated (Figure 11). The structure of the bleachers and their cantilever reinforced concrete shell were designed by Spanish engineer Ildefonso Sánchez del Río (1898–1980). It was a cantilever concrete ribbed shell. Given the difficulty inherent in engineering these incipient thin shells, in the 1920s, he developed his own design system. It was based on the use of geometric shapes that could be designed, dimensioned and built in an easy way. For this reason, the concrete shells were formed by a set of identical ribs (beams or arches), with lightweight concrete elements built on top of them (Cassinello, 2011).

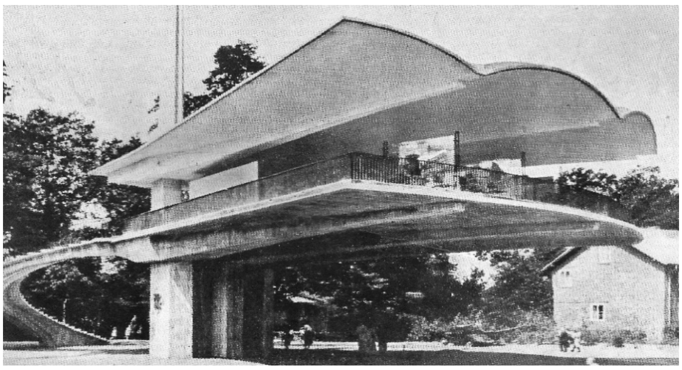

Figure 10. Hannover Exhibition. Coffee-restaurant.
1951 (archive: Fernando Cassinello)

Figure 11. Oviedo Stadium
(archive: Fundación Juanelo Turriano)

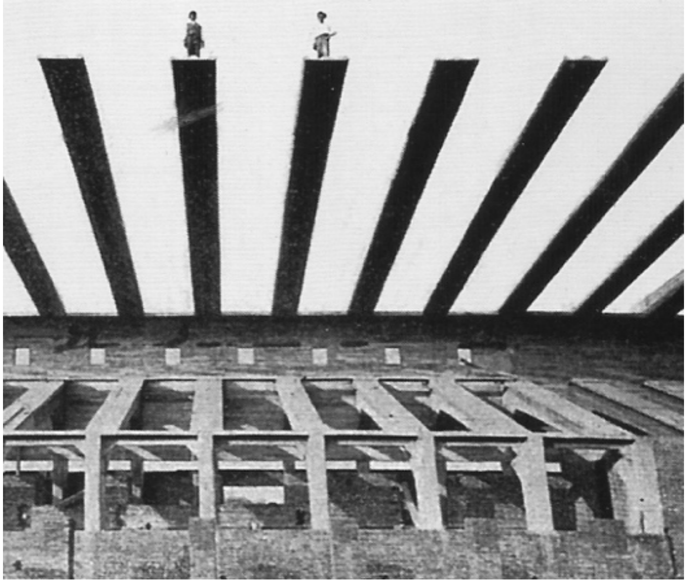

Figure 12. Flat ribs
(archive: Fundación Juanelo Turriano)

One of the most original aspects of this roof was that its cantilever was not curved, but consisted of a variable flat section with ribs 15 m long and 1 m wide (Figure 12). Similar to Pier Luigi Nervi's design, the structure of the inclined grandstand and its cantilever roof formed a resistant unity, which guaranteed the balance (Figure 13).

This concrete shell consisted of a set of concrete flat ribs with light domed prefabricated fibrocement plates (Uralita) bolted on them. This way, the weight and the cost of the roof were optimized.

From 1925, Sánchez del Río used this system to build many concrete umbrellas. In 1972, he inaugurated the livestock market at Pola de Siero – *El Paraguas*. It was an octagonal concrete shell umbrella 40 m in diameter, which means 20 m of cantilever only 3.5 cm thick. A dimension never exceeded by a reinforced concrete umbrella anywhere in the world. To know the structural behavior, an experimental test was made by the Institute founded by Eduardo Torroja. It has 8 radial ribs of square sections. The concrete ribbed shells are hanging from the middle-section of the ribs (Figure 14).

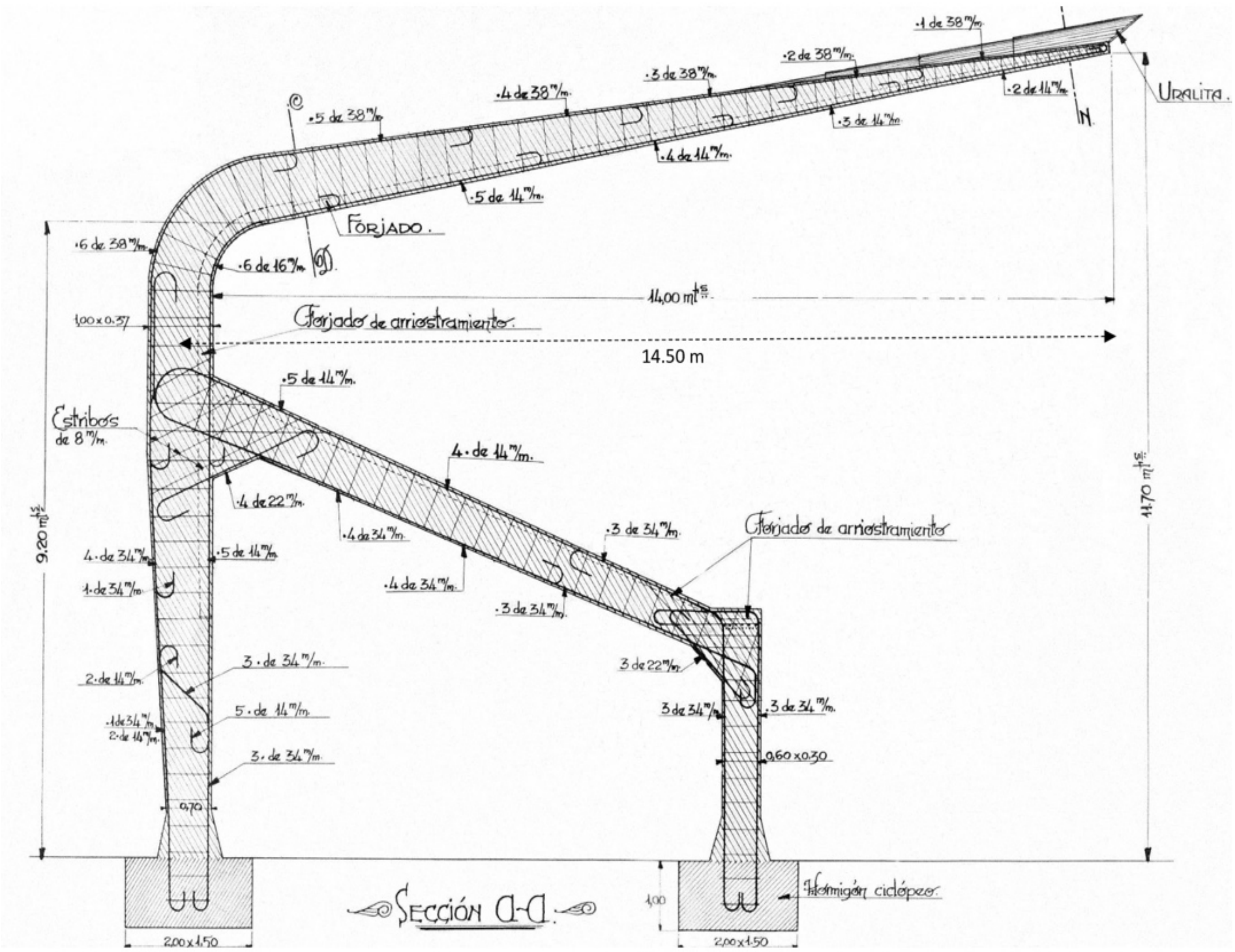

Figure 13. Oviedo Stadium under construction
(archive: Fundación Juanelo Turriano)

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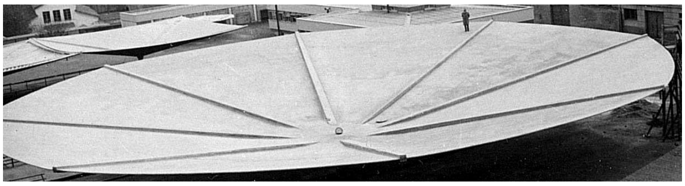

Figure 14. Livestock market at Pola de Siero
(archive: Fundación Juanelo Turriano)

In the 1950s, architect Félix Candela (1910–1997) founded his own company "Cubiertas Alas" in México. In two decades, he built the largest number of concrete shells ever built.

Félix Candela used full scale model to check his designs (Cassinello, 2010). He built experimental shells with different geometric shapes. He built the Ctesiphon Vault in 1949, the Fernández factory conoid in 1950, and the umbrella at Las Aduanas in 1953 (Figure 15). While at first he experimented with different geometries, most of his *oeuvre* was based on hyperbolic paraboloids, or ˝hypars˝, a form that enabled him to generate a wide variety of shells whose strength was derived from their double curvature geometry. Another considerable advantage of these structural forms was that they optimized construction costs because concrete could be cast to simple formwork built with a board arranged along the straight lines generated by the hypars. Candela created umbrellas by joining four straight-edged hypar surfaces (Figure 16).

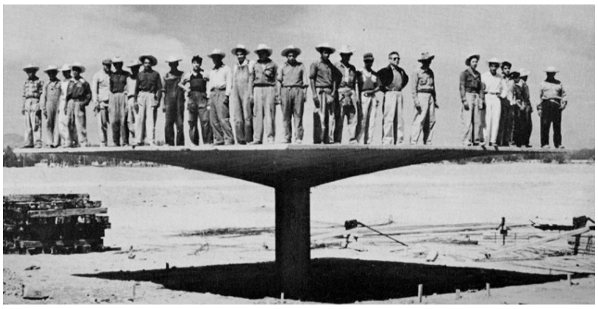

Figure 15. Las Aduanas. México
(archive: Fernando Cassinello)

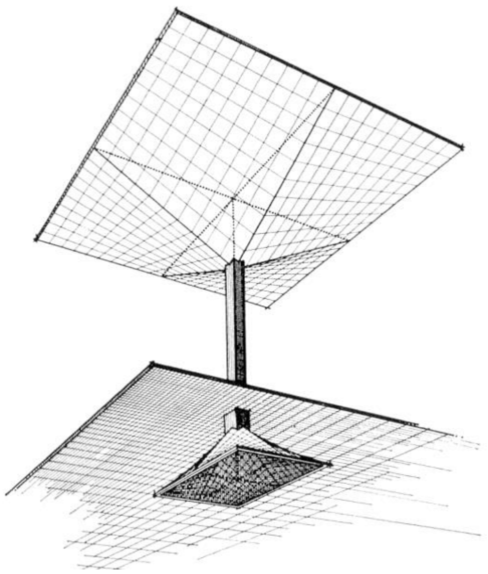

Figure 16. Umbrela hypar
(archive: Fernando Cassinello)

He analyzed thin reinforced concrete shells and developed simplified methods for their design. He concluded that if the shell support system could be regarded as isostatic, static equilibrium equations for membranes would suffice to solve the problem. Further to this reasoning, Candela devised a way to simplify thin concrete shell engineering, teaching himself to create new structural forms and contributing to revolutionize and disseminate an understanding of such structures. He authored a book titled "A new philosophy of structures" (Candela, 1962). Not only did Candela learn to design free edge shells with no ribs on his own, but as David P. Billington said, he also learned the discipline of thinness. His most famous works were able to save 30 m between supports with only 4 cm thickness, among them are the restaurant of the Manantiales in Xochimilco (1957) and the Bacardi bottling plant (1958) (Candela, 1985). With respect to the cantilever shells, the umbrellas reached 12 meters on the side resulting in a 6 m cantilever. In 1982, with Spanish architect Fernando Higueras, Candela designed the Murcia Airport (Spain), unfortunately not built. The hypar umbrellas had 24 m on side, cantilevers reaching 12 m with 5 cm thickness (Blanco García and García Ríos, 2018).

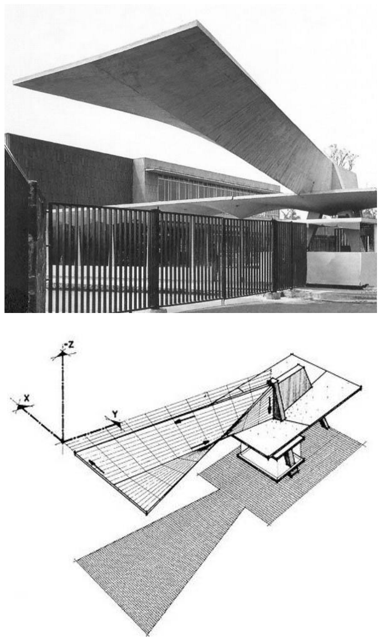

Figure 17. Lederle laboratories
(archive: Fernando Cassinello)

The cantilevered shell of the Lederle laboratories reached 12 m (Faber, 1963) (Figure 17). But it was in his sculptures that he achieved the longest cantilevers. This is the case of the Band at Social Security's in Santa Fe, Mexico City (1956) (Figure 18). It is a large overhang supported by a vertical element that is braced in two small concrete walls anchored to the ground to prevent overturning as can be seen in the model made for the exhibition commemorating his centenary (Cassinello, 2010) (Figure 19). The roof is formed by three equal folded pieces and each one covers a triangular area. Its cantilever is 12.5 m. Candela's cantilever sculptures are undoubtedly iconic pieces of Modernist Architecture.

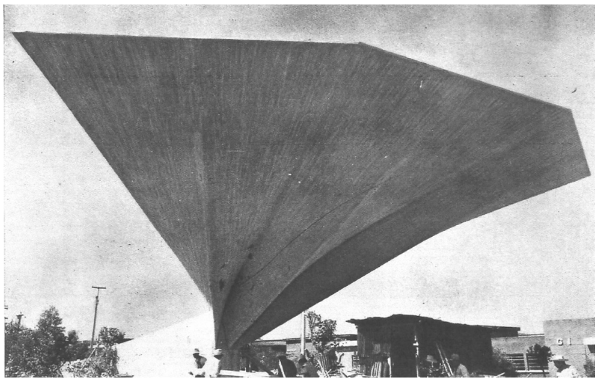

Figure 18. Band Shell
(archive: Fernando Cassinello)

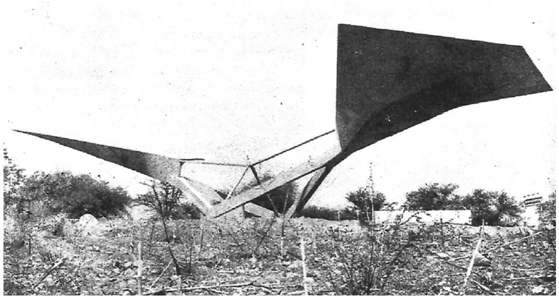

Figure 20. Tequesquitengo
(archive: Fernando Cassinello)

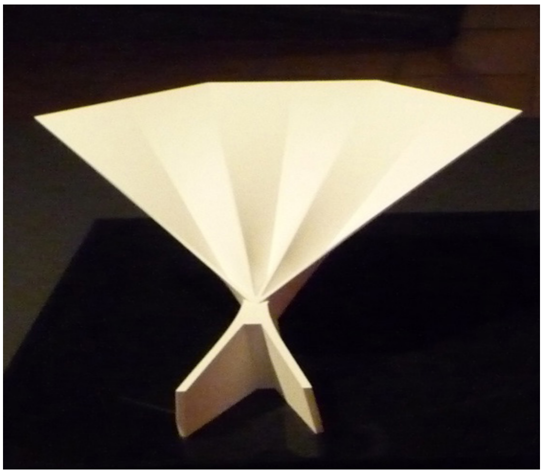

Figure 19. Exhibition model
(archive: Pepa Cassinello)

Figure 21. *Plaza de los Abanicos*
(archive: Fernando Cassinello)

During the 1950s, he designed other cantilevered concrete shells such as the one at the Lake Tequesquitengo (México, 1957). It was formed by two cantilever shells connected by reinforced concrete V-beams and tie rods that guarantee the balance. The fans were formed by 4 folded sectors 4 cm thick and a 10 m cantilever (Figure 20). Another is the one designed for the *Plaza de los Abanicos* in the Lomas de Cuernavaca (México). It is located on a sheet of water. It is formed by three shells that are in the vertices of a triangular plant with a side of 10 m. The shells are folded concrete plates 4 cm thick and a 6 m cantilever. In the upper part, there are cylindrical perforations that favor the decrease of the wind pressure. The whole structure is balanced by straps that connect the three fans. The tubes that shoot water jets and bathe the structure hang from these straps (Figure 21).

Candela used folded hypars as an alternative to his umbrella (hyperbolic paraboloid) since folded plates were one of the types of concrete shells that proliferated most in the 1950s and 1960s. The concrete cantilever shells were fundamentally built by using a folded surface because they are the easiest to build, for the formwork and reinforcement are planar. Structurally, as in corrugated shells, the amplitude of the fold increases the depth of the shell to absorb bending without thickening the shell, a cost-effective solution to stabilize and stiffen the element as a whole.

In 1958, the UNESCO building was inaugurated. It was designed by Marcel Breuer, Bernard Zehrfuss, Eeron Saarinen and Pier Luigi Nervi. At its entrance, an exempted canopy was built generated by two different cantilevered ruled surfaces (Figure 22). They are united by a segment of a parabolic dome, which holds the two cantilevers. This was the best solution to balance the big horizontal resultant force. The bigger one follows a parabola in a vertical plane, with the vertex downwards and is 10 m of cantilever. The other is a 5.30 m conoid cantilever.

In 1959, Spanish architect Julio Lafuente (1921–2013) built the *Tor Di Valle Hippdromein* in Rome, collaborating with engineers Gaetano Rebecchini and Calogero Benedetti. The cantilever concrete shells are formed by 17 umbrellas generated, as the Candelas's ones, by joining four straight-edged hypars (Lafuente, 1960). The fundamental differences consist in these umbrellas having large prestressed concrete ribs, although they are bigger and reach 19.50 m of cantilever (Figures 23 and 24).

Figure 22. UNESCO canopy, 1958
(archive: Fernando Cassinello)

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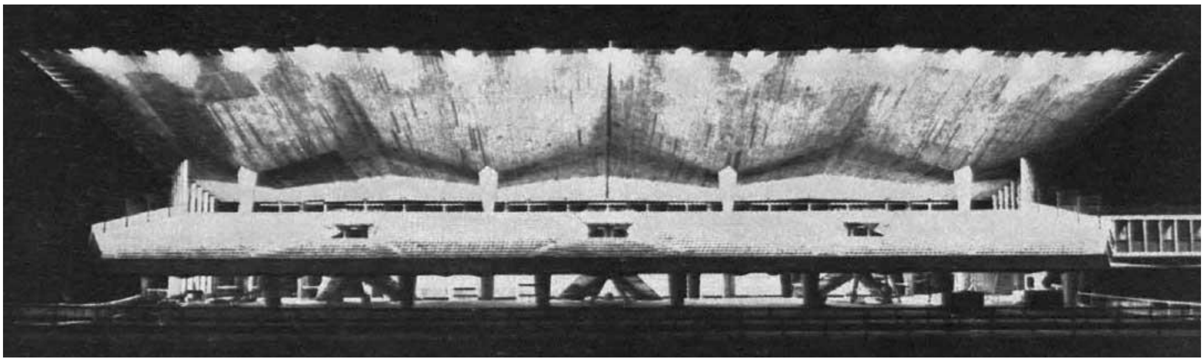

Figure 23. *Tor Di Valle Hippdromein*, 1959
(archive: Fernando Cassinello)

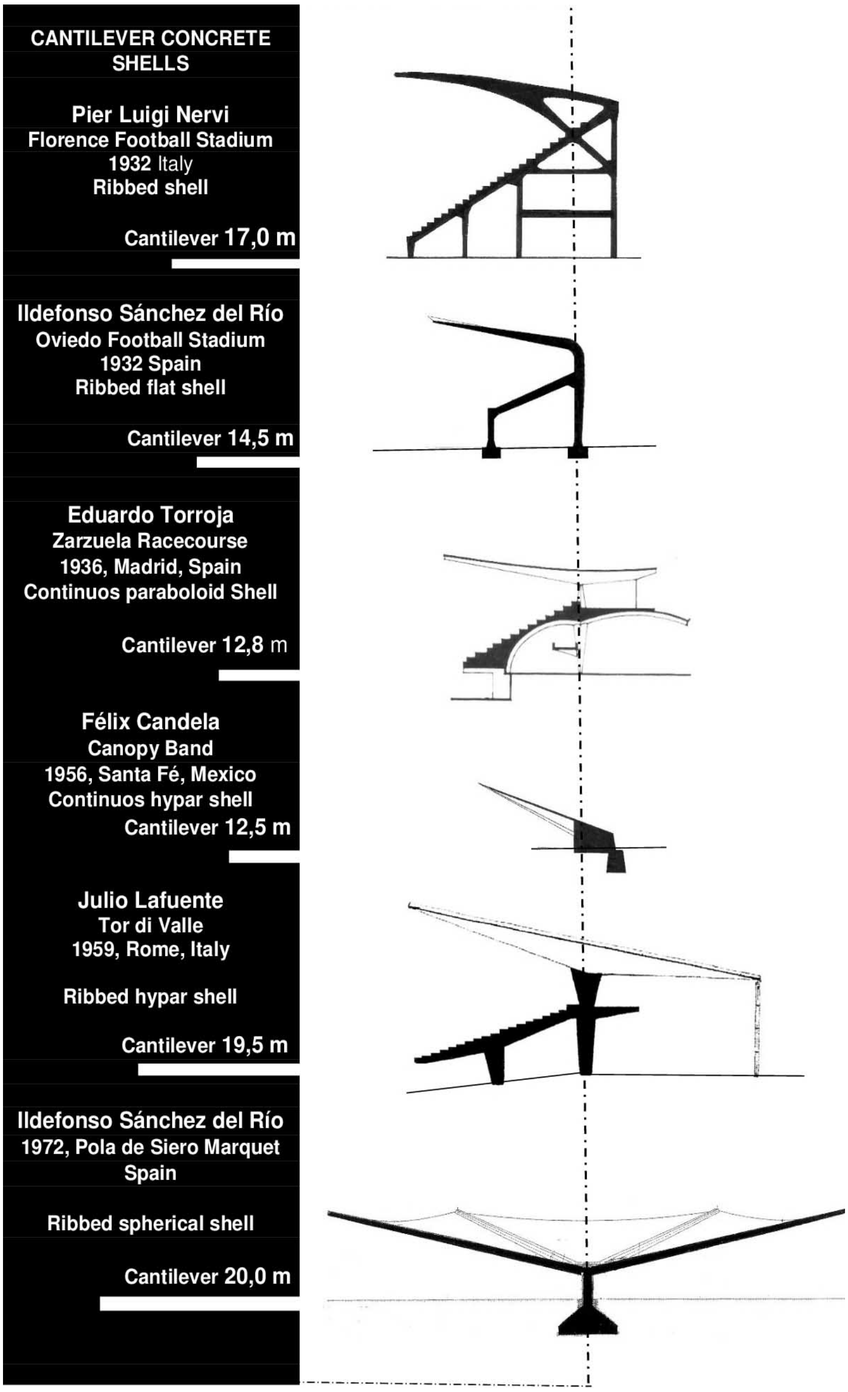

Figure 24. Comparison of cantilever length
(archive: Pepa Cassinello)

Conclusions

Of all the types of pioneer concrete shell structures, those with the largest and thinnest cantilevers were the most difficult to design. In this article, we analyzed only a small sample of the cantilevered structures built by some pioneer master shell builders, but it was enough to point out the structural design systems they used to build efficient and iconic concrete shells, as well as the structural forms they used, and what cantilever sizes they reached.

In the 1930s, they used a complex and manual calculation system developed by Franz Dischinger in 1928. For this reason, they checked the results by testing physical models and sharpened their wits to find simpler design systems. From 1930s to 1970s, to build cantilever concrete shells, designers first used ribbed shells, such as Nervi and Sánchez del Río from the end of the 1920s. In the 1930s, Torroja built a 12.80 m cantilever using hyperbolic continuous shells without ribs or folds. Candela fundamentally used the geometric form of the hyperboloid parabolic and folded plates to build concrete canopies and umbrellas in the 1950s, which reached up to 12 m of cantilever.

During the 1950s and 1960s, folded plates were usually used to build cantilever shells because they presented an easier solution. A bigger cantilever shell umbrella was built by Sánchez del Río in 1972. It was a hanging ribbed shell 40 m in diameter with 20 m of a cantilever shell 3.5 cm thick.

Nervi and Torroja usually checked their structural intuition by scientific scale model tests, while Sanchez del Río and Candela used full-scale models.

On the other hand, Nervi and Sánchez del Río designed ribbed concrete shells. Ribs were the protagonists of their works. In the case of Sánchez del Río, it was due to the fact that his design system was based on the use of geometric shapes that can be decomposed in a set of equal ribs, thus simplifying the design process of the shell. The Nervi's ribs are quite different from the Sánchez del Río's ones. They follow the direction of the main moments at each point of a slab that works in two directions, subjected to a uniformly distributed load, or in other cases, they form a rigid frame to lead the prefabricated shell elements. It means a different design-system philosophy. Torroja and Candela built continuous concrete shells on supports or with cantilevers, although in a different time and following different paths.

Funding

The article was prepared as a part of three different Spanish research projects on the legacies of Eduardo Torroja, Félix Candela, and Ildefonso Sánchez del Río, and the research on historical cantilever concrete shell, which the author is developing as the director of the Eduardo Torroja Foundation. This article completes the dissemination made at the 2019 IASS congress by including the progress made in the ongoing research (Cassinello, 2019).

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Civil Engineering

ANALYSIS OF BENDING STEEL FIBER REINFORCED CONCRETE ELEMENTS WITH A STRESS-STRAIN MODEL

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Abstract

Introduction: Fiber concrete is a complex composite material with unique properties. Its behavior is accounted for in steel fiber reinforced concrete elements using simplified stress-strain models. The article describes an approach to the analysis of bending steel fiber reinforced concrete elements using stress-strain diagrams for compression and tension. **Purpose of the study:** The study is aimed to develop a method for the analysis of bending steel fiber reinforced concrete elements using stress-strain diagrams that will be simpler than the existing ones. **Methods**: The study is based on the traditional principles of the analysis of reinforced concrete structures. The method applied is described through equations for the equilibrium of forces affecting the longitudinal axis of the element and the ultimate bending moment. Internal forces in the element cross-section are expressed as relative strains whose diagram is nearly linear in accordance with the Bernoulli's hypothesis. **Results:** We present final equations to determine the load-carrying capacity of a bending element by standard cross-sections. The values of strength and stress-strain properties of fiber reinforced concrete and reinforcement serve as the source data for the calculations.

Keywords

Fiber concrete, steel fiber reinforced concrete, non-linear stress-strain model, fiber reinforced concrete and reinforcement stress-strain diagrams, relative strains.

Introduction

A trend for the sophistication of design solutions for buildings and structures, especially those made of reinforced concrete, has been observed in modern civil engineering with increasing frequency. Such solutions include space frameworks of buildings with an irregular grid of load-bearing columns and walls that are monolithically bound with ceiling slabs, transition slabs, structurally heterogeneous foundation slabs, frameworks of high-rise buildings with highly loaded massive columns, walls, stiffening cores, foundation slabs, and their connections (Karpenko, 2010). Such structures are characterized by various types of complicated stress-strain behavior. Reinforced concrete may be insufficient for their effective and rational use (Ashour and Wafa, 1993; Evdokimova, 2017).

The risk of progressive fracture determines the need to create structures with increased fracture toughness. In this case, steel fiber introduced into concrete is one of the solutions to the issue. Fiber lays the groundwork for more efficient operation of the structure, which is nowadays especially important due to the growing trend of building unique and high-rise structures.

In view of the above, steel fiber reinforced concrete (SFRC) has become widely used in recent decades. Structures made of SFRC have significant advantages over reinforced concrete ones, namely: increased crack resistance (fracture toughness), shock resistance, ultimate tensile strength, impermeability, freeze-thaw resistance, reduced shrinkage and creep (Talantova and Mikheyev, 2014; Zhavoronkov, 2017). Fiber reinforcement improves elements' resistance under tension and bending, increases shear strength and burst strength, reduces deformation, as well as reduces the consumption of main reinforcement and makes it possible to give up structural reinforcement (Bakhotskiy, 2013; Valente et al., 2017; Vorontsova, 2017).

Currently, SFRC structures are rarely used in residential construction in Russia. They are still most in-demand in the design of such structures as highway and airfield pavements, long-span bridges, shell-type structures, tunnels, and other kinds of outstanding structures (Brandt, 2008).

The physical nonlinearity of SFRC, without which accuracy and reliability of design solutions decreases, significantly affects the stress-strain state and behavior of all such structures. The main flaw of the existing models and methods of solving physically non-linear reinforced concrete problems is that they reduce the solution to multiple iteration procedures, which, for complex space systems, is an intractable problem even with state-of-the-art computing tools (Karpenko, 2010).

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Currently, there are various techniques that take into account the specifics of SFRC deformation at load. Thus, in the Regulations SP 360.1325800.2017 (Ministry of Construction Industry, Housing and Utilities Sector of the Russian Federation, 2018), analysis using the non-linear stress-strain model (NLSSM) is preferred in the design of buildings and structures since it ensures high reliability of assessment of strength and stress-strain properties (Eryshev, 2018). Nevertheless, standards still allow for analysis using the breaking stress method, which is the simplest task for designers.

Analysis using the NLSSM represents the successive approximations (iterations) method. The method implies breaking down the cross-section of a structural element into elementary sections and calculating average stresses in each of them based on the adopted analytical stress-strain relationships in fiber reinforced concrete (FRC) and reinforcement stress-strain diagrams. The transition from stresses to internal forces is made by means of numerical integration of stresses with respect to the height (width) of the element cross-section. After the condition of the equilibrium of internal forces is checked, stresses in broken-down sections are determined, whose value should not exceed the design values of the strength properties of materials. The problem is solved when the condition of the equilibrium of internal forces is met to the specified accuracy in relation to the previous iteration.

Various types of FRC and reinforcement stress-strain diagrams can be used for analysis: curvilinear (including those with a falling leg), simplified piecewise-linear such as Prandtl diagrams (bilinear, tri-linear, and quad-linear). Since SFRC behavior in compression does not differ much from that of reinforced concrete, stress-strain diagrams for them in the compression zone are taken equivalent. In most cases, during strength and stress-strain analysis, scientists neglect the tension zone in reinforced concrete structures, while it plays a significant role for SFRC. Dispersed reinforcement significantly changes the nature of the stress-strain relationship in the FRC tension zone, which affects the results of tests of FRC beam specimens (Evseyev, 2012; Morozov et al., 2016).

Therefore, since there are many analysis techniques and stress-strain diagrams, there is a particular uncertainty when choosing the stress-strain model for strength and stress-strain analysis to design buildings and structures.

Problem statement

In practice, the method of analysis using the NLSSM is very time- and labor-consuming and implies the usage of computing tools. Besides, updated standards (Ministry of Construction Industry, Housing and Utilities Sector of the Russian Federation, 2018) include no analysis techniques and algorithms that would describe stresses and forces in the element cross-section through FRC strains. It is also necessary to review the analysis results with the use of the existing NLSSM analysis techniques, in terms of breaking stresses and experimental results. That is why we suggest a simpler analysis method for bending steel fiber reinforced concrete elements.

Analysis basics

- The design model includes the stress diagram for both compression and tension zones of concrete.
- Stress-strain diagrams for FRC and reinforcement are adopted in accordance with the Regulations SP 360.1325800.2017 (Ministry of Construction Industry, Housing and Utilities Sector of the Russian Federation, 2018) and SP 63.13330.2018 (Ministry of Construction Industry, Housing and Utilities Sector of the Russian Federation, 2019). A tri-linear diagram (Fig. 1) is adopted for the FRC compression zone and a quad-linear diagram (Fig. 2) — for the tension zone. A bilinear diagram (Fig. 3) is adopted for reinforcement with the actual yield strength, and a tri-linear diagram (Fig. 4) — for reinforcement with the conditional yield strength.

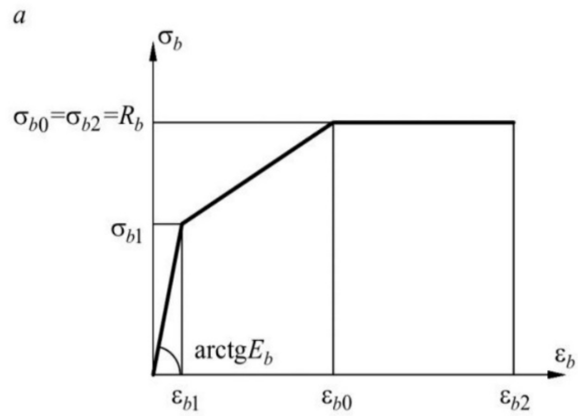

Fig. 1. A tri-linear stress-strain diagram for concrete

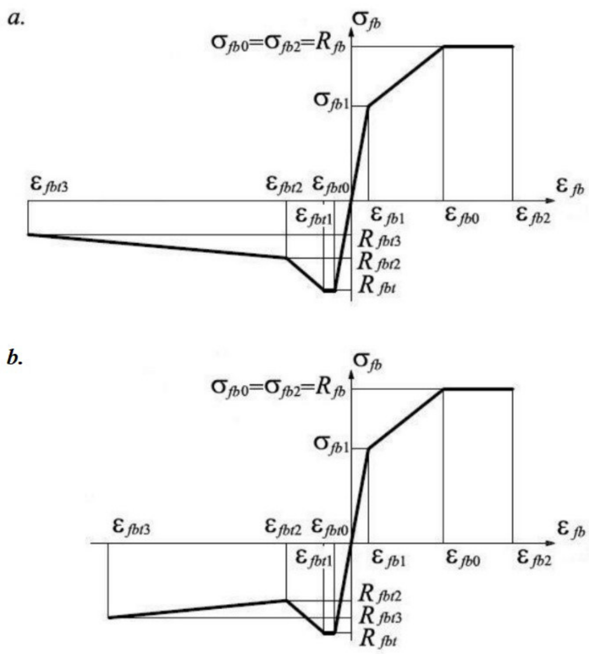

Fig. 2. A quad-linear stress-strain diagram for FRC

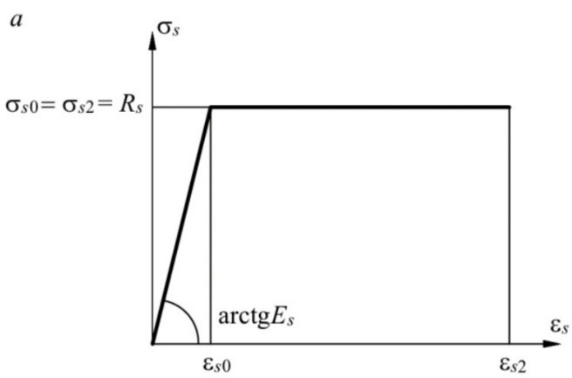

Fig. 3. A bilinear stress-strain diagram for reinforcement

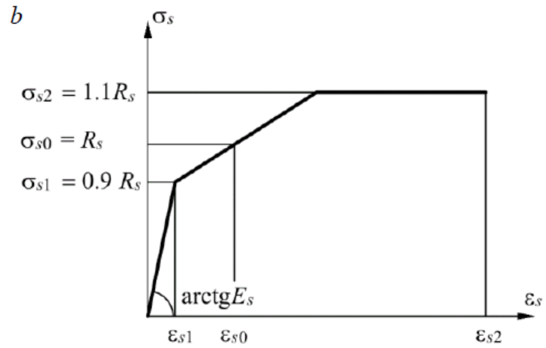

Fig. 4. A tri-linear stress-strain diagram for reinforcement

- Strains along the height of the cross-section are distributed according to the linear law (Bernoulli's hypothesis).
- The analysis is performed relative to the ultimate edge strains of FRC in tension and compression. If the ultimate relative strains of FRC in tension exceed the values of the same parameters for reinforcement, the least value is adopted in the analysis. This is due to the fact that the material is not engaged if the ultimate strains are exceeded.

Since there are no experimental data, the design value of the residual strength of SFRC in tension R_{fbt3} is calculated according to equation B.5 or B.7 in the Regulations SP 360.1325800.2017, and the design value of the residual strength of SFRC in tension R_{fbt2} is adopted as for subclass *c* (approximately an average value exceeding R_{fbt3} by 11%) according to Table 2 in the Regulations SP 360.1325800.2017, in line with the assigned class of FRC by the residual strength in tension. The SFRC class by the residual strength in tension is chosen depending on the calculated value of R_{fbt3} according to Table 2 in the Regulations SP 360.1325800.2017. If the calculated value R_{fbt3} exceeds the maximum value from the same table, R_{fbt2} is calculated by equation (1):

$$R_{fbt2} = 1{,}11 R_{fbt3} \tag{1}$$

This is because, for this parameter, there are no analytical relationships that could be associated with the SFRC tensile strength R_{fbt}, the residual tensile strength, R_{fbt3} fiber reinforcement coefficient μ_{fv} or some other parameters. This value as well as the SFRC subclass in terms of residual strength in tension is calculated experimentally using the method (BS EN 14651:2005+A1:2007 (British Standards Institute, 2005)) based on a test developed by RILEM. According to it, the value of R_{fbt2} corresponds to the load when the crack mouth opening displacement (CMOD) is 0.5 mm, and the subclass corresponds to the ratio between the values of the guaranteed strength of SFRC in tension when bent $R_{F2,5} / R_{F0,5}$ (Corporate Standard STO NOSTROY 2.27.125-2013) (National Association of Builders, 2015) (Fig. 5).

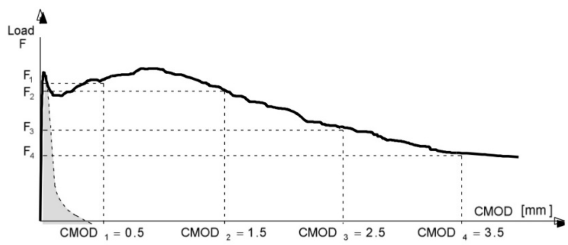

Fig. 5. Load vs. CMOD diagram for SFRC

Calculation method

Fig. 6 provides a design model of a bending SFRC element.

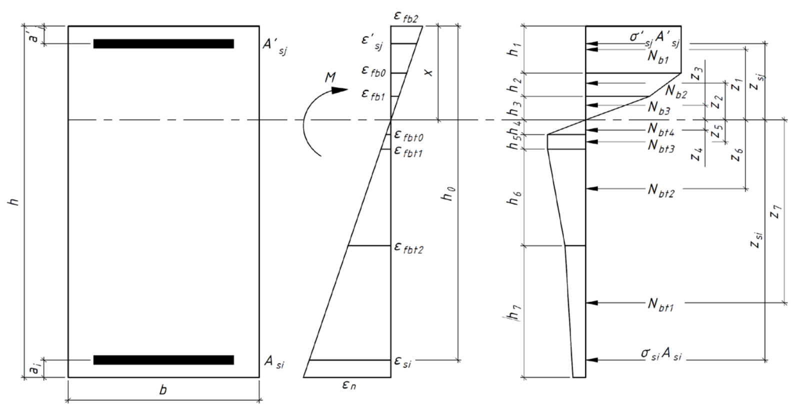

Fig. 6. Design model of a bending SFRC element

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A strain diagram in the element cross-section is constructed on the basis of linear distribution. The strain values are adopted in accordance with the selected stress-strain diagrams for a short-term load:

$\varepsilon_{fb2} = 0,0035 + 5 \cdot \left(\frac{R_{fb}}{R_b} - 1 \right) \cdot 10^{-3}$ — at the extreme fiber of concrete in the compression zone in accordance with (Rak, 2011);

$\varepsilon_{fb0} = 0,002$,

$\varepsilon_{fb1} = \sigma_{fb1} / E_{fb}$ — within the compression zone of FRC;

$\varepsilon_{fbt0} = R_{fbt} / E_{fb}$,

$\varepsilon_{fbt1} = \varepsilon_{fbt0} + 0,0001$

$\varepsilon_{fbt2} = 0,004$ — within the tension zone of FRC;

$\varepsilon_n = \varepsilon_{fbt3} = 0,02 - 0,0125\left(R_{fbt3} / R_{fbt2} - 0,5\right)$ — at the extreme fiber of concrete in the tension zone at $\varepsilon_{fbt3} \le \varepsilon_{s2}$, ε_{s2} — at $\varepsilon_{fbt3} > \varepsilon_{s2}$; ε'_{sj} — at the level of the center of gravity of compressive reinforcement;

ε_{si} — at the level of the center of gravity of tensile reinforcement.

The stress diagram in the compression zone includes three sections with a height of h_1, h_2 and h_3, and in the tension zone — four sections with a height of h_4, h_5, h_6 and h_7. Taking into account the forces in compressive and tensile reinforcement, we derive the equation for the equilibrium of forces affecting the longitudinal axis of the element:

$$N_{fb1} + N_{fb2} + N_{fb3} + N'_{sj} - N_{fbt1} - \\ - N_{fbt2} - N_{fbt3} - N_{fbt4} - N_{si} = 0. \qquad (2)$$

Forces in FRC are determined by the areas of corresponding sections of the stress diagrams, and in reinforcement — by the stresses and the area of the cross-section.

$$N_{fb1} = R_{fb} b h_1,\ N_{fb2} = 0,8 R_{fb} b h_2, \\ N_{fb3} = 0,3 R_{fb} b h_3,\ N_{fbt1} = 0,5 R_{fbt} b h_4, \\ N_{fbt2} = R_{fbt} b h_5,\ N_{fbt3} = 0,5(R_{fbt} + R_{fbt2}) b h_6, \\ N_{fbt4} = 0,5(R_{fbt2} + R_{fbt3}) b h_7, \\ N'_{sj} = \sigma'_{sj} A'_{sj},\ N_{si} = \sigma_{si} A_{si}. \qquad (3)$$

The height of the compression zone is calculated through the ratio $\varepsilon_{fb2} / x = \varepsilon_n / (h - x)$:

$$x = \frac{\varepsilon_{fb2} h}{\varepsilon_{fb2} + \varepsilon_n} = \frac{\varepsilon_{fb2}}{\chi}, \qquad (4)$$

where χ is the curvature of the element calculated by the following equation:

$$\chi = \frac{1}{\rho} = \frac{\varepsilon_{fb2} + \varepsilon_n}{h}, \qquad (5)$$

where ρ is the element curvature radius; h is the element height.

The section height values corresponding to the stress-strain diagram of SFRC are calculated on the basis of ratios between the strains, the height of the compression zone and the height of the section. The result is as follows:

$$h_1 = \frac{\varepsilon_{fb1}}{\chi},\ h_2 = \frac{\varepsilon_{fb0} - \varepsilon_{fb1}}{\chi},\ h_3 = \frac{\varepsilon_{fb1} - \varepsilon_{fb2}}{\chi}, \\ h_4 = \frac{\varepsilon_{fbt0}}{\chi},\ h_5 = \frac{\varepsilon_{fbt1} - \varepsilon_{fbt0}}{\chi}, \\ h_6 = \frac{\varepsilon_{fbt2} - \varepsilon_{fbt1}}{\chi},\ h_7 = \frac{\varepsilon_n - \varepsilon_{fbt2}}{\chi}. \qquad (6)$$

The strains in compressive and tensile reinforcement are calculated using the following ratios:

$$\frac{\varepsilon_{fb2}}{x} = \frac{\varepsilon'_{sj}}{x - a'_j},\ \frac{\varepsilon_{fb2}}{x} = \frac{\varepsilon_{si}}{h - x - a_i}, \qquad (7)$$

where a'_j and a_i are the distances from the center of gravity of compressive and tensile reinforcement to the extreme fiber of FRC in the compression and tension zones, respectively.

The result is as follows:

$$\varepsilon'_{sj} = \varepsilon_{fb2} - \chi a'_j,\ \varepsilon_{si} = h\chi - \varepsilon_{fb2} - a_i \chi. \qquad (8)$$

The ultimate relative strains of reinforcement are limited by: $\varepsilon_{s2} = 0,025$ — for reinforcement with the actual yield strength; $\varepsilon_{s2} = 0,015$— for reinforcement with the conditional yield strength.

Taking into account equations (3) and (6), equation (2) will take the following form:

$$\frac{R_{fb} b}{\chi}\left(\varepsilon_{fb2} - 0,2\varepsilon_{fb0} - 0,5\varepsilon_{fb1}\right) + \sigma'_{sj} A'_{sj} - \\ - \frac{b}{2\chi}\Big(R_{fbt}\left(\varepsilon_{fbt1} - \varepsilon_{fbt0} + \varepsilon_{fbt2}\right) + \\ + R_{fbt2}\left(\varepsilon_n - \varepsilon_{fbt1}\right) + R_{fbt3}\left(\varepsilon_n - \varepsilon_{fbt2}\right)\Big) - \sigma_{si} A_{si} = 0, \qquad (9)$$

where strains in reinforcement are calculated depending on the adopted stress-strain diagram. It should be noted that with strains $\varepsilon_n \le \varepsilon_{fbt2}$, there will be no section with a height of h_7, and the diagram in the tension zone will be tri-linear since the fourth section of the tensile diagram starts at strains exceeding ε_{fbt2}. Therefore, the member $R_{fbt3}\left(\varepsilon_n - \varepsilon_{fbt2}\right)$ in equation (9) will not be considered.

Thus, we obtain the equation for the equilibrium of forces, expressed through strains. The first two members that determine the forces in concrete and reinforcement of the compression zone are adopted to be positive, the second ones that determine the forces in concrete and reinforcement of the tension zone are adopted to be negative. The condition of the equilibrium will be met if these two parts are equal. Therefore, we need to determine edge strains in the element cross-section when equation (9) is satisfied.

Two options are possible in the calculation of the sum of the forces:

1. Option 1 — the sum of the members in the left part is less than zero.
2. Option 2 — the sum is more than zero.

In the first case, we need to reduce strains ε_n at the constant value of strain ε_{fb2} (thereby increasing the height of the concrete cmpression zone) to a certain value when condition (9) is met with sufficient accuracy. This condition can be written as follows:

$$\left|\sum_{i=1}^{n} N_i\right| \le 0,1 \text{ (kH)}. \qquad (10)$$

Strains ε_n are calculated by equation (11):

$$\varepsilon_n = \frac{2R_{fb}\left(\varepsilon_{fb2} - 0,2\varepsilon_{fb0} - 0,5\varepsilon_{fb1}\right) -}{R_{fbt2} + R_{fbt3} - R^A}$$

$$\frac{-R_{fbt}\left(\quad {}_{fbt} - \varepsilon_{fbt0} + \varepsilon_{fbt2}\right) +}{}$$

$$\frac{+R^A\varepsilon_{fb2} + R_{fbt2}\varepsilon_{fbt1} + R_{fbt3}\varepsilon_{fbt2}}{}, \qquad (11)$$

where the force in compressive and tensile reinforcement is calculated through the yield strength of reinforcement steel taking into account concrete reduction (for R_{sc}), by equation (12):

$$R^A = \frac{2}{bh}\left(R_{sc}A'_{sj} - R_s A_{si}\right). \qquad (12)$$

If strains of compressive or tensile reinforcement by equation (8) are less than the values of ε_{s0}, the second iteration is made. In it, stresses $\sigma'_{sj} = \varepsilon'_{sj}E_s$, $\sigma_{si} = \varepsilon_{si}E_s$ are used instead of R_{sc} and R_s in equation (12).

With strains $\varepsilon_n \le \varepsilon_{fbt2}$, the members $R_{fbt3}\varepsilon_{fbt2}$ and R_{fbt3} are not taken into account in equation (11).

In the second case, we need to reduce strains ε_{fb2} at the constant value of strains $\varepsilon_n = \varepsilon_{fbt3}$ or $\varepsilon_n = \varepsilon_{s2}$ (depending on what relative strains are less) to meet condition (9) with the set accuracy (10).

Strains ε_{fb2} are calculated by equation (13):

$$\varepsilon_{fb2} = \frac{R_{fb}\left(0,4\varepsilon_{fb0} + \varepsilon_{fb1}\right) + R_{fbt}\left(\varepsilon_{fbt1} - \varepsilon_{fbt0} + \varepsilon_{fbt2}\right) +}{2R_{fb} + R^A}$$

$$\frac{+R_{fbt2}\left(\varepsilon_{fbt3} - \varepsilon_{fbt1}\right) + R_{fbt3}\left(\varepsilon_{fbt3} - \varepsilon_{fbt2}\right) - R^A\varepsilon_{fbt3}}{}. \qquad (13)$$

The condition of the strength of bending SFRC elements is written as $M \le M_{ult}$, where M is the moment from external forces; M_{ult} is the ultimate bending moment that the element cross-section can take. The value of M_{ult} is determined relative to the neutral axis. The distances from the forces occurring in concrete and reinforcement to this axis will be as follows:

$$z_1 = \frac{\varepsilon_{fb2} + \varepsilon_{fb0}}{2\chi},\; z_2 = \frac{13\varepsilon_{fb0} + 11\varepsilon_{fb1}}{24\chi},$$

$$z_3 = \frac{2\varepsilon_{fb1}}{3\chi},\; z_4 = \frac{2\varepsilon_{fbt0}}{3\chi},\; z_5 = \frac{\varepsilon_{fbt0} + \varepsilon_{fbt1}}{2\chi},$$

$$z_6 = \frac{R_{fbt}\left(2\varepsilon_{fbt1} + \varepsilon_{fbt2}\right) + R_{fbt2}\left(\varepsilon_{fbt1} + 2\varepsilon_{fbt2}\right)}{3\chi\left(R_{fbt} + R_{fbt2}\right)},$$

$$z_7 = \frac{R_{fbt2}\left(2\varepsilon_{fbt2} + \varepsilon_n\right) + R_{fbt3}\left(\varepsilon_{fbt2} + 2\varepsilon_n\right)}{3\chi\left(R_{fbt2} + R_{fbt3}\right)},$$

$$z_{si} = \frac{h\chi - \varepsilon_{fb2} - a_i\chi}{\chi},\; z'_{sj} = \frac{\varepsilon_{fb2} - a'_j\chi}{\chi}. \qquad (14)$$

The equation for the ultimate bending moment with account for dependences (3), (6) and (14) will take the following form:

$$M_{ult} = \frac{R_{fb}b}{24\chi^2}\left(12\varepsilon_{fb2}^2 - 1,6\varepsilon_{fb0}^2 - 4\varepsilon_{fb1}^2 - 1,6\varepsilon_{fb0}\varepsilon_{fb1}\right) +$$
$$+\frac{b}{6\chi^2}\left[R_{fbt}\left(3\varepsilon_{fbt1}^2 - \varepsilon_{fbt0}^2\right) + R^2 + R^3\right] +$$
$$+\sigma_{si}A_{si}\left(\frac{h\chi - \varepsilon_{fb2} - a_i\chi}{\chi}\right) + \sigma'_{sj}A'_{sj}\left(\frac{\varepsilon_{fb2} - a'_j\chi}{\chi}\right), \qquad (15)$$

where the moments from the tension zone of concrete with a height of h_6 and h_7 equal to the following:

$$R^2 = R_{fbt}\left(\varepsilon_{fbt2}^2 - 2\varepsilon_{fbt1}^2 + \varepsilon_{fbt1}\varepsilon_{fbt2}\right) +$$
$$+R_{fbt2}\left(2\varepsilon_{fbt2}^2 - \varepsilon_{fbt1}^2 - \varepsilon_{fbt1}\varepsilon_{fbt2}\right), \qquad (16)$$

$$R^3 = R_{fbt2}\left(\varepsilon_n^2 - 2\varepsilon_{fbt2}^2 + \varepsilon_{fbt2}\varepsilon_n\right) +$$
$$+R_{fbt3}\left(2\varepsilon_n^2 - \varepsilon_{fbt2}^2 - \varepsilon_{fbt2}\varepsilon_n\right). \qquad (17)$$

It should also be noted that with strains $\varepsilon_n \le \varepsilon_{fbt2}$, there will be no section with a height of h_7, and the member (17) will not be taken into account in equation (15).

Conclusions

The growing popularity of SFRC structures requires special attention of designers to strength and stress-strain analysis. In this regard, analysis using the non-linear stress-strain model with the use of various stress-strain diagrams for materials is highly important for studies. Firstly, such analysis is very time- and labor-consuming; secondly, it is used as verification analysis, which is not very convenient in terms of design.

To eliminate these flaws, a method based on elastoplastic stress-strain diagrams for FRC and reinforcement has been developed. In this method, the value of the element curvature is adopted as a variable of successive approximation, and the forces in the FRC compression and tension zones to the neutral axis are found as the areas of the diagram sections with their own centers of gravity.

This method makes it possible to avoid numerical integration with multiple iterations along the entire height

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of the cross-section, since only one value is a variable. Besides, it allows us to calculate the load-bearing capacity of SFRC elements, which, in its turn, depends on the strength and stress-strain properties of base materials.

However, this method has a flaw: analysis uses such characteristics of FRC that can be determined only by means of experiments.

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РАСЧЕТ ИЗГИБАЕМЫХ СТАЛЕФИБРОЖЕЛЕЗОБЕТОННЫХ ЭЛЕМЕНТОВ С УЧЕТОМ ДЕФОРМАЦИОННОЙ МОДЕЛИ

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Аннотация

Фибробетон сложный композитный материал с уникальными свойствами. Его работа учитывается в сталефиброжелезобетонных элементах по упрощенным моделям деформирования. В статье рассматривается подход к расчету сталефиброжелезобетонных изгибаемых элементов с использованием диаграмм деформирования фибробетона на сжатие и растяжение. **Цель исследования:** Разработка метода расчета сталефиброжелезобетонного изгибаемого элемента по диаграммам деформирования, отличающегося более простым подходом по сравнению с существующими. **Методы**: В основе метода лежат классические принципы расчета железобетонных конструкций. Метод описывается уравнениями равновесия усилий на продольную ось элемента и предельным изгибающим моментом. Внутренние усилия в сечении элемента выражаются через относительные деформации, эпюра которых имеет линейное очертание в соответствие с гипотезой плоских сечений. **Результаты**: Представлены итоговые расчетные формулы для определения несущей способности изгибаемого элемента по нормальным сечениям. Исходными данными для расчета являются значения прочностных и деформативных характеристик фибробетона и арматуры.

Ключевые слова

Фибробетон, сталефиброжелезобетон, нелинейная деформационная модель, диаграммы деформирования фибробетона и арматуры, относительные деформации.

USING GEODESIC DOMES OF WOOD AND THERMOPLASTICS FOR ROTATIONAL CAMPS IN THE ARCTIC AND NORTHERN TERRITORIES

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Abstract

Introduction: The use of modern construction materials and technologies makes it possible to take a different view of such long-span spatial structures as geodesic domes that seem quite familiar for architects and engineers. **Methods:** Based on studies of Russian and foreign researchers, the authors of the article suggest using the space between two geodesic domes for residential, administrative as well as laboratory and research facilities. **Results:** It is suggested to use this type of structures of wood and thermoplastics for rotational camps in the Arctic and Northern territories. **Discussion:** The authors conduct experimental studies to justify that it is possible to manufacture joint connections of various types of plastic.

Keywords

Housing construction, architecture, civil engineering, frozen sample testing.

Introduction

The practice of using geodesic domes dates back to the founder of the “geodesic dome” project, Buckminster Fuller. R. B. Fuller had developed a spatial structure of a dome in the form of a hemisphere made of tetrahedrons since 1947. He applied for a patent in 1951. Geodesic domes brought international recognition to R. B. Fuller (a ˝golden dome˝ was built for the American National Exhibition in Moscow in 1959, and in 1967 — the US pavilion at the International and Universal Exposition in Montreal) (LiveInternet, 2020).

The practical use of the building outline geometry proposed by R. B. Fuller is based on the division of space by vectors. The main unit of this division is a tetrahedron. Its faces are located at the shortest distance that connects two points on a curved surface (geodesic lines). The above division allows us to achieve optimal space-filling and the most complete utilization of the structural strength of materials.

The main advantages of geodesic domes are as follows:

– high load-bearing capacity (the more the dome is, the higher it is);

– fast assembly as compared to traditional frame and frameless methods of construction;

– the weight of the dome elements reduces the cost of materials and preparatory works;

– one of the structural and technological features of spatial dome structures is the installation of frame elements from marked rods and nodes, which reduces the construction time. The cellular structure will allow the assembly of blocks of cells, which will significantly reduce the construction time of the building (Wu and Takatsuka, 2006);

– dome structures have an ideal aerodynamic shape with high resistance to seismic, wind and hurricane impacts. Scientists continue to study the possibility of using geodesic domes by changing their shape, configuration, manufacturing material and many other parameters (Guan et al., 2018);

– cellular configuration of many available Diamatic dome templates is particularly convenient for conversion with mutual element support. This is due to the fact that at any vertex only three elements of the lattice rods intersect, regardless of the number of rod elements used to form the polygon of the node (Rizzuto, 2018);

– Coating with the use of natural renewable energy sources. The use of the surface of geodesic domes is a great option in this case (Porta-Gándara and Gómez-Muñoz, 2005).

The disadvantages of geodesic domes include the fact that the production of modern building materials is aimed primarily at the construction of buildings made of rectangular materials (plywood, glass, rigid blankets).

Thus, triangular cells of geodesic domes will require additional labor to trim and fit the material to create external enclosing structures with a large overspend, increasing the cost and complexity of manufacturing the building as a whole. It should be noted that all existing patented solutions use metal for nodes and connections (in the form of bolts, pins with washers and nuts), which extremely negatively affects the condition of the dome structure in general in harsh chemical environments. As a rule, these are warehouses for salines, chemical fertilizers, reagents, etc. (Zhivotov and Latuta, 2019).

One of the great Fuller’s projects was Cloud Nine. According to his idea, airborne habitats could be created from giant geodesic spheres, which might be made to

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levitate by slightly heating the air inside (Fig. 1). Geodesic spheres (structures of triangular components arranged to make a sphere) become stronger as they become bigger, due to how they distribute stress over their surfaces. In theory, such structures can be gigantic. As a sphere gets bigger, the volume it encloses grows much faster than the mass of the enclosing structure itself. Fuller suggested that the mass of a mile-wide geodesic sphere would be negligible compared to the mass of the air trapped within it. He suggested that if the air inside such a sphere was heated even by one degree higher than the ambient temperature of its surroundings, the sphere could become airborne. He calculated that such a balloon could lift a considerable mass, and hence that 'mini-cities' or airborne towns of thousands of people could be built in this way (Ongreenway, 2020).

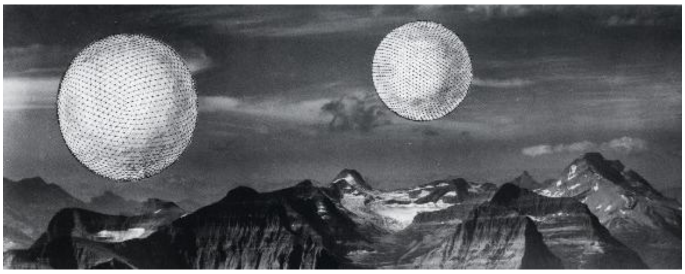

Fig. 1. Houses according to the Fuller's idea (created by R. B. Fuller)

Such buildings primarily serve as industrial enterprises and factories, warehouses, public and exhibition halls.

In November 2019, an experimental dome was erected over a residential house in Yakutsk, Yakutia (Tomsky, 2019). It has various sensors for measuring the humidity and temperature, including in the area of the house foundation located in permafrost conditions (the first experimental dome in Yakutsk).

Sweden also has similar experience in creating a second-level space above residential houses (Forumhouse, 2020).

Fig. 2 demonstrates the idea of covering blocks with a dome.

Fig. 2. A settlement under a dome (Ignatyeva, 2019)

Methods

Architectural solutions for dome spaces

The authors propose considering the functions of the above examples more widely, using geodesic domes to cover rotational camps in the Arctic and other Northern regions (Fig. 3). The climate in these regions significantly complicates the conditions of life and work. The creation of a special microclimate in the inner space will have a positive impact on the emotional and physical condition of people. Modern engineering systems and equipment ensure the self-sustainability of life under such a dome.

Fig. 3. A geodesic dome above a rotational camp (possible architectural solutions)

Based on studies of Russian and foreign researchers, the authors of the article suggest using the space between two geodesic domes for residential, administrative as well as laboratory and research facilities (Fig. 4).

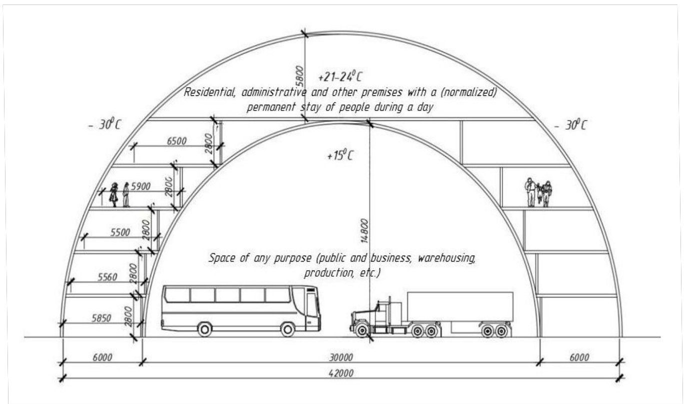

Fig. 4. Space between two domes

It should be noted that all existing patented solutions use metal for nodes and connections (in the form of bolts, pins with washers and nuts), which extremely negatively affects the condition of the dome structure in general in harsh chemical environments and at low temperatures below zero.

However, there are also solutions made of wood and polymeric materials (Bushin et al., 2017). Based on the above solutions, the authors continue to study joint connections of wood and polymers with various temperature conditions.

In the construction market, there are small prefabricated houses available (Icedom, 2020).

Domes of various sizes can be provided for outdoor events. The structure is characterized by extreme wind resistance. It can withstand static loads such as alternating lighting and sound, and provides many opportunities for specific equipment options (DOMZELT Deutschland, 2020).

The construction market also suggests combining geodesic domes with earth-sheltered buildings (Geodesic Earthworks, 2020).

STUDYING THE FORMATION OF THE ARCHITECTURAL FORM IN COMPARISON TO THE NATURAL MORPHOGENESIS USING COMPUTER MODELING

Results

1.1. Determining the mechanical characteristics of materials for dome buildings

In the Arctic and Northern territories, matters of the fast erection of buildings, optimization of logistics flows and use of high-strength materials that can withstand ambient temperatures below zero for a long time are important. In the authors' opinion, such materials include those based on wood and plastic.

An empirical study was conducted with experimental testing of samples of heat-resistant polyamide 6 (caprolon, PA6) (standard / fiber-filled / extruded) used in the specified temperature ranges from +200 to -60 degrees.

In the course of the experiment, we studied the properties of the materials under short-term tension loads at normal temperatures of 18–22°C. The preparation for the experiment was conducted directly in the mechanical laboratory of the Saint Petersburg State University of Architecture and Civil Engineering. We measured the width and thickness of the sample test section in three points: at the edges and in the middle.

The experiment was conducted in accordance with the requirements using a 10-ton universal electromechanical Instron 5982 machine (Fig. 5b) with the maximum tensile load of 100 kN. We marked the grip areas at the opposite sides of the transversal axis of symmetry, recorded the minimum cross-section area of the samples, as well as the batch numbers and the serial numbers of the samples in the batch (Table 1).

Table 1. Samples

Sample No.	Description
1	Standard
2	Fiber-filled
3	Extruded

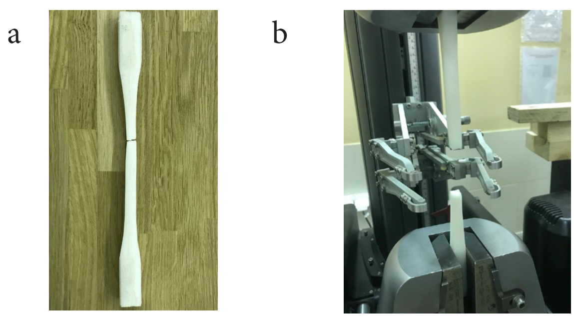

Fig. 5. A sample and the tensile machine. Photo by D. Zhivotov.
a — the destroyed sample; b — the sample
in the Instron 5982 tensile machine

The experimental data are given in Table 2. The same data are presented in the form of deformation vs. load (Fig. 6) and shifting vs. load curves (Fig. 7).

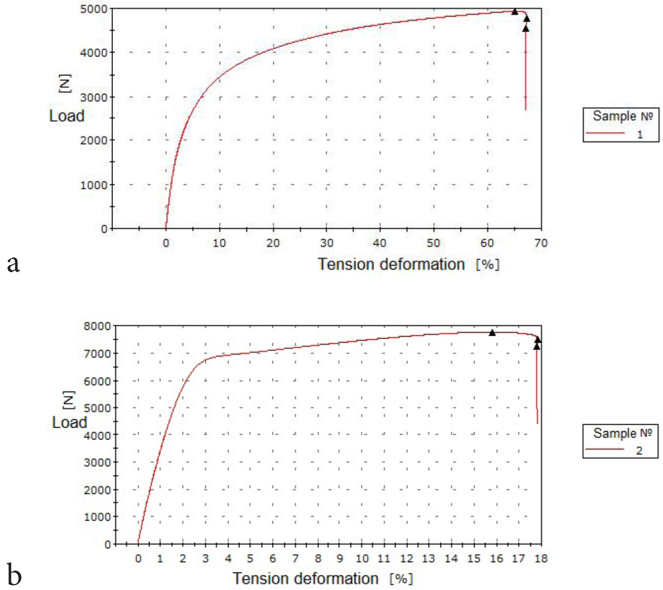

Fig. 6. Tension deformation vs. load diagram:
a — standard; b — fiber-filled

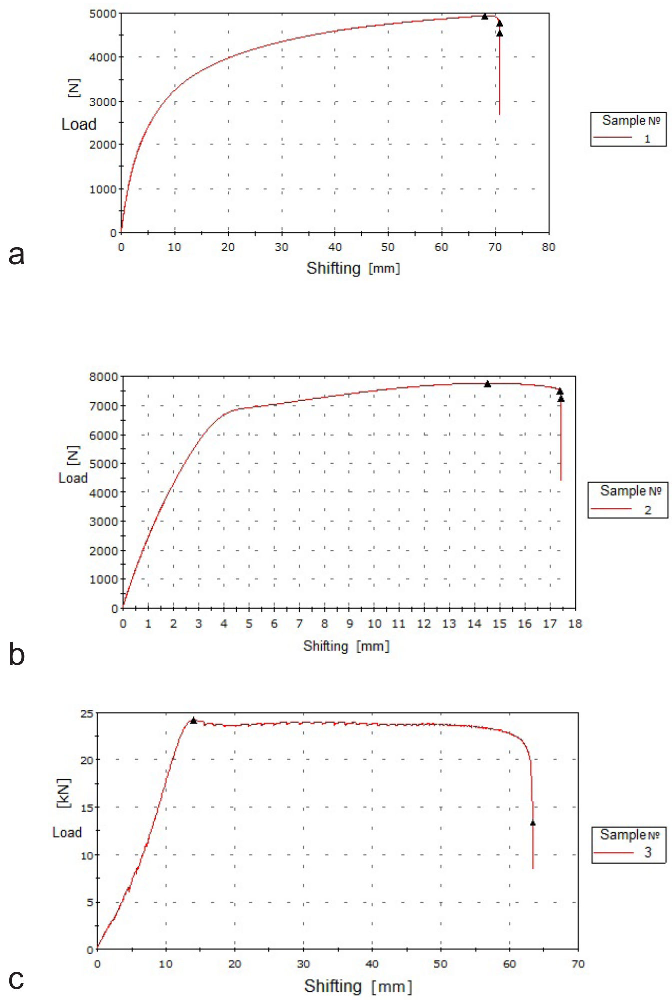

Fig. 7. Shifting vs. load diagram:
a —standard normal PA6; b — fiber-filled PA6; c — extruded PA6

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The test results are given in Table 2

Table 2. Test results

No.	Load [kN]	Breaking stress [MPa]	Modulus [MPa]	Breaking elongation [%]	Sample	Section, a*b, mm2
1	4.94	49.38	267.99	67.07	Standard PA6	10x10=100
2	7.76	77.62	2484.15	17.79	Fiber-filled PA6	10x10=100
3	24.20	68.04	68.56	105.55	Extruded PA6	353

The test results and the nature of breakage are related, which indicates the reliability of the data. The diagrams and figures show changes occurring in the samples, characteristic of brittle materials under a load. All the samples were destroyed gradually, the deformation values gradually increased under a load, transitioning from plastic flow to brittle fracture.

1.2. Tensile testing of a joint connection for dome structures

The sample was manufactured in accordance with the regulations, by means of milling a solid material of joint elements.

The following materials were used for the nodal joint:

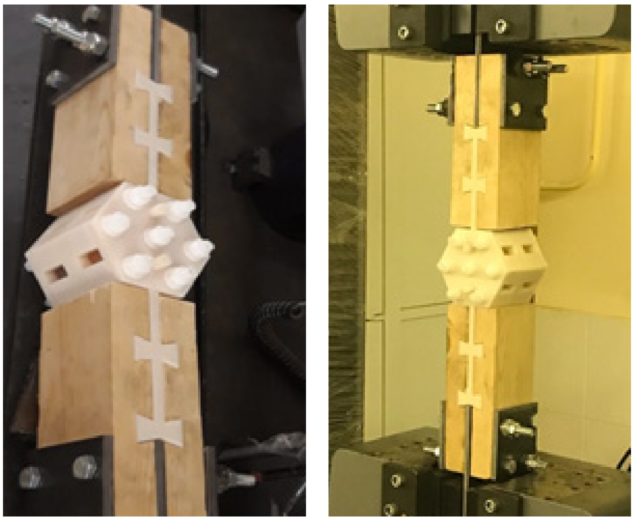
– pinewood of normal moisture for the rods;

– fiber-filled polyamide PA6 for the housing, covers; diameter — 12 mm, in the form of threaded pins, nuts and washers for the assembly of the edge joint;

– steel plates, width — 8 and 10 mm, for lifting gear and center adjustment of the transferred tensile stresses;

– steel bolts, nuts and washers, diameter — 10 mm, for the assembly of the fittings node.

The preparation for the experiment was conducted directly in the mechanical laboratory of the Saint Petersburg State University of Architecture and Civil Engineering at normal temperatures of 18–22°C. The sample was assembled before the experiment (Fig. 8a).



a b

Fig. 8: a — the assembly; b — the tested node in the Instron 5998 tensile machine. Photo by D. Zhivotov

The experiment was conducted in accordance with the requirements using a 20-ton universal electromechanical Instron 5998 machine (Fig. 8b) with the maximum tensile load of 200 kN.

In the course of the experiment, we analyzed the mechanical characteristics of the node made of wood and plastic material. We studied the behavior of the material under a load, phase deformations and the shifting vs. load relationship.

Fig. 9 shows the test data as a shifting vs. load curve. One sample was tested. Its photos are given in Fig. 10.

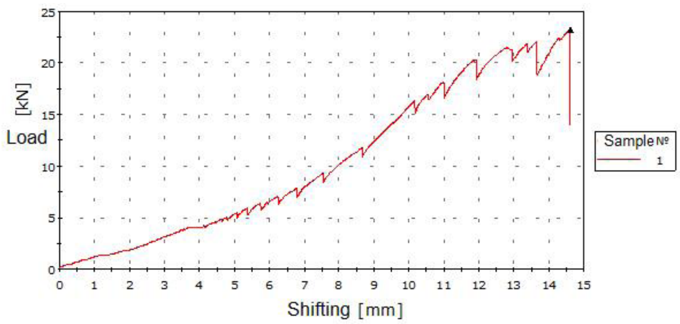


Fig. 9. Shifting vs. load diagram

Fig. 10: a — the destroyed node, b — the destroyed elements of the node. Photo by D. Zhivotov

The fiber-filled node was destroyed gradually. The deformation values gradually increased under the load, transitioning from plastic flow to brittle fracture. A comparison of the test results with calculations confirms that they are identical.

The destruction occurred in pulling out the blade from the node housing when the load reached 70% of the expected value of 23.22 kN due to the insufficient cross-section.

Discussion

1. Various physical and mechanical properties of plastic intended by manufacturers require additional studies and analysis to be used as a load-bearing structural member, in order to find an optimal solution ensuring a balance between the and the necessary properties.

2. The results of determining the tensile strength of the material in normal conditions were obtained at temperatures of –20, –40 and –60°C for extruded polyamide and block polycarbonate.

3. The destruction occurred when the blades broke off the node body due to the stress concentration in this point. The authors decided to continue the construction of the joint by increasing the cross-section area and flattening corners.

4. The experimental studied showed that the suggested design is quite viable. In the course of the experiment, the behavior of individual elements and the node as a whole was studied. Additional studies are required to test the node with destruction in the node body along the minimum cross-section.

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ПРИМЕНЕНИЕ ПРОСТРАНСТВЕННЫХ ГЕОДЕЗИЧЕСКИХ КУПОЛОВ ИЗ ДЕРЕВА И ТЕРМОПЛАСТОВ ДЛЯ ВАХТОВЫХ ПОСЕЛКОВ В АРКТИКЕ И СЕВЕРНЫХ ТЕРРИТОРИЯХ

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Аннотация

Использование современных строительных материалов и технологий позволяет взглянуть на, казалось бы, привычные архитектору и инженеру большепролетные пространственные сооружения в виде геодезических куполов, с другой стороны. **Методы:** Авторы статьи, основываясь на исследованиях отечественных и зарубежных ученых, предлагают использовать пространство между двумя геодезическими куполами для размещения жилых, административных и лабораторных исследовательских объектов. **Результаты:** Предлагается рассмотреть возможность использования этих типов конструкций из дерева и термопластов для вахтовых поселков на арктических и северных территориях. **Обсуждение:** Проводятся экспериментальные исследования для обоснования возможности изготовления узловых соединений из различных видов пластмасс.

Ключевые слова

Жилищное строительство, архитектура, строительство, испытание замороженного образца.

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Urban Planning

ON EVALUATING THE CONDITION OF THE SAINT PETERSBURG HISTORIC CENTER

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Abstract

Introduction: This study was prompted by the introduction of the urban environment quality index into the system operated by the Russian Ministry of Construction Industry, Housing and Utilities Sector (Minstroy). We note that the ˝environment-centric˝ methodologies were already worked on and applied to housing studies in Leningrad as far back as during the 1970–1980s, and that the insights from these studies can now be used for analyzing the current state of the urban environment. **Purpose of the study and methods:** The information reviewed in this article gives us the first glimpse of the tangible urban environment in the historic center of Saint Petersburg. Many features of this part of the city are reminiscent of other European metropolises, but the fact that the historic center is split into three parts by vast waterways, that the construction began from the ground up in the middle of the wilderness, and that the active urban development phase lasted only a century and a half (from the 1760s to the 1910s), has a major part to play. **Results:** We use quantitative data to describe the features of the Saint Petersburg historic center and compare our findings to the features of European metropolises, across such parameters as spatial geometry, transportation and pedestrian links, and environmental conditions. Our study reveals a number of issues that challenge the quality of life in this part of the city. We also offer a critique of the regional norms for construction and reconstruction in historic districts, which offer a biased view of the situation and do not offer any ways of optimizing it.

Keywords

Historic center of Saint Petersburg, urban environment, multi-factor analysis, urban planning.

Introduction

The execution of the Housing and Urban Environment National Project has breathed life into numerous activities relevant to urban development. In the context of strategic planning and public governance, much emphasis has been given to the multi-factor analysis of the urban environment and the qualimetric method of its assessment, which are now in active use (Urban Environment Quality Index, 2019).

The community of architects and urban planners had a particularly keen interest in the subject of the urban environment during the 1970s and 1980s, when the various definitions of this concept, both domestic and foreign, as well as its theoretical and practical aspects, were seeing extensive development and discussion (Gutnov, 1984; Kogan, 1982; Lynch, 1982, 1986; Vysokovsky, 1989, Yargina et al., 1986).

Today, some experts believe that it is best to stop discussing this, while others point to the multi-factor nature of the ˝urban environment˝ concept[1]. It would be reasonable to assume that architects and urban planners will respond very positively to the tools for evaluating the tangible aspect of the urban environment and the conditions of urban environment formation, which have been introduced at the Minstroy. Multi-factor analysis has already proven to be effective when used as a means of meeting strategic goals. Therefore, we believe it justifiable to apply this methodology on the local level as well, for assessing the condition of urban districts.

Subject, tasks, and methods

Methodologically, our study is founded on a comprehensive approach that includes the research and analysis of information available in print and online sources relevant to the urban development of Saint Petersburg. We also analyze graphics. The information reviewed in this article gives us the first glimpse of the tangible urban environment in the historic center of Saint

[1] See fragments of a discussion in Moscow in 2007. Bart Goldhoorn: a better word choice is “urban space”, not “urban environment”. I. M. Korobyina: An urban environment is something far bigger than a public space. Ye. V. Ass: Reducing an urban environment to architecture would be an oversimplification. This concept is far more complex. We can view it as an integrated whole, founded on the social, technological, sanitary, hygienic, and environmental aspects. Then there is the aesthetic aspect, which both brings all of this together and exists as its own entity (Fanaylova, 2007).

Petersburg. Many features of this part of the city are reminiscent of other European metropolises, but the fact that the historic center is split into three parts by vast waterways, that the construction began from the ground up in the middle of the wilderness, and that the active urban development phase lasted only a century and a half (from the 1760s to the 1910s), has a major part to play.

Results and discussion

Saint Petersburg historic center area. Starting from 2002, Saint Petersburg has been applying regional-level regulations to reconstructing its historic districts, with special emphasis on open-air public spaces. The urban (urban planning) environment is defined as “a system of streets, embankments, parks, public gardens, water bodies, buildings, structures, and other elements that make up an urbanized space where the urban population engages in various everyday activities” (TSN 30-306-2002 (Administration of Saint Petersburg, 2003)).

We are suggesting a study that is founded on the environment-centric approach and assesses the quality of life in the part of the Saint Petersburg city center that is classified as a World Heritage Site and covers an area of 5356.8518 ha (Saint Petersburg Union of Restorers, 2019). The historic center of Saint Petersburg — which is classified as a “federal city” — accounts for approximately 3% of the city territory and over 10% of its population. In terms of aggregate parameters of use intensity, the center of Saint Petersburg is comparable to such metropolises as Paris or Rome (Table 1).

Table 1. Intensity of urban space use

Parameter	City				
	Saint Petersburg		Paris		Rome
	Historic center	City	City	Agglomeration	See Note 2
Area size (km²)	53.57	1439	105.4	814	1287.36
Population (thousands of people)	See Note 1	5361	2202	10,620	2,875,805
Population density (people per km2)		3837.41	20,781	13,050	2234

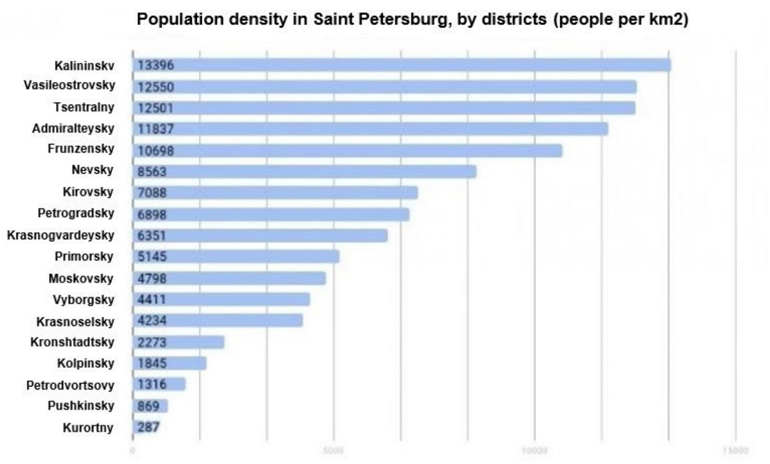
Note 1. According to Territorial Construction Regulations TSN 30-306-2002, “The historic center limits coincide with the administrative boundaries of Admiralteysky, Vasileostrovsky (except for the northwestern part of the island), Petrogradsky, and Tsentralny Districts”. Consequently, the statistics for the districts listed in the TSN reflect the ways in which the population uses the historic center of Saint Petersburg:

Admiralteysky District — population 162 thousand people, area size 13.82 km², population density 11,387 people per km²

Tsentralny District — 216,939 people, area size 17.12 km², population density 12,501 people per km²

Vasileostrovsky District — population density 12,550 people per km²

Petrogradsky district — population density 6898 people per km²



(Yemtsov 2019)

To summarize, the average population density of the city center (even counting an outlier like Petrogradsky District) is 10,843 people per km²

Note 2. In Rome, urbanized development does not amount to more than approximately one fourth of the area within the city limits, so the actual population density here approaches 10,000 people per km²

Fig. 1 is a fragment of a Saint Petersburg city plan, which helps highlight the general impression of the nature of the urban environment in the center

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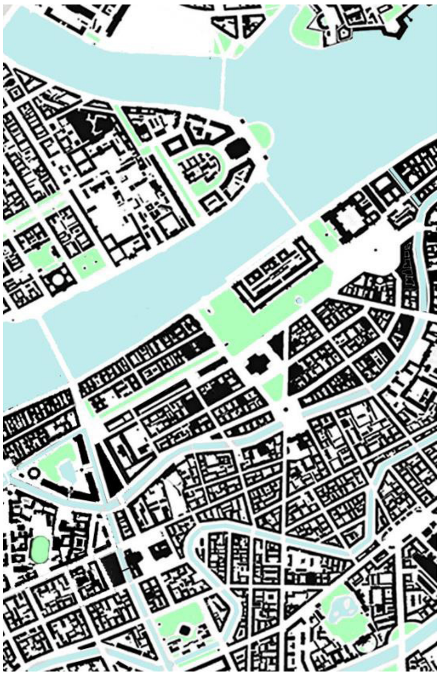

Fig. 1. Fragment of a plan of the Saint Petersburg center

List of main urban environment parameters in the Saint Petersburg city center

During an assessment of the urban environment conditions in 2002, the following observation was included in the regional regulations: "the historic city center has the most complete urban design, historical and cultural value, usage intensity, and functional diversity". These regulations focus mostly on the spatial parameters of the city center, which is described as having "a high usage intensity, ... a dense street and road network, ... small blocks with high development density, a perimetric layout of residential development, compact spaces within the residential blocks, and well-developed intra-block pedestrian pathways" (Administration of Saint Petersburg, 2003). However, there is no concrete evidence to support these statements. Nor is any attention paid to the insights into the urban environment conditions that were gained by urban researchers over the previous period.

The work of the graduates from the Institute of Civil Engineers during the 1920s and 1930s was the precursor of the environment-centric approach. This school of thought was known for its pragmatic take on resolving various issues of urban development. A. S. Nikolsky in particular noted that it was unacceptable to rely on intuition alone; he believed that even in spatial planning, "aesthetic taste needs to make way to a scientific approach" (Barkhin et al., 1975). A. V. Samoylov, in turn, highlighted the multi-aspect nature of architect's work and called for interpreting an architectural structure as "an element of the urban planning complex and synthesis of technology, economics, artistic concept, and functional purpose" (Barkhin et al., 1975). In the 1970s, these ideas inspired researchers from LenNIIProekt and Leningrad Civil Engineering Institute (LISI), who took an interest in housing quality assessment as multi-factor analysis, basing it on the qualimetric method, which had just started gaining prominence at the time (Azgaldov and Raykhman, 1973; Azgaldov and Senderova, 1977; Lavrov et al., 1981). Their research was based on a broad range of parameters, including those shared by the Leningrad Zonal Research Institute of Experimental Design and the Leningrad Research and Design Institute for the Elaboration of Master Plans and Development Plans (Makhrovskaya, 1974; Platonov et al., 1973).

Urban life in the center of Saint Petersburg has changed dramatically since then, and most of the urban environment data from the aforementioned studies has lost relevance. Therefore, the current priority goal is to create a new, up-to-date reference database. The urban environment monitoring system has also changed over the recent years, and the scope of publicly accessible data has shrunk; as a result, the objectives tree that we are proposing at this stage of our research (Table 2) may be considered a gateway into an immensely vast field.

Table 2. Features of the urban structure

1.Spatial geometry		2. Communication links		3. Environmental factors		4. Usage		
1.1. Open-air public spaces	1.2. Residential spaces (blocks)	2.1. Transport links	2.2. Pedestrian links	3.1. Green spaces, access to water	3.2. Environ mental conditions	4.1. Land management	4.2. Operating conditions	Public infras tructure

1. Spatial geometry in the city center

1.1. Open-air public spaces. The Saint Petersburg Strategy for Preserving the Cultural Heritage highlights the importance of those parts of the cityscape that reflect the three-dimensional spatial layout of the city center, namely the configuration of the central waterways, the city skyline, the river panoramas, the architectural ensembles of the major city squares, and the layout of the main streets (Repository for legal documents, standards, regulations and specifications, 2019b). The open-air public space configuration in the historic city center has remained largely unchanged since the beginning of the 20th century.

The period between the 1760s and the 1830s (and also, in part, the early 1840s) contributed the most to the formation of Saint Petersburg open-air public spaces. Active urban development began with Catherine the Great's decision to ˝make the orderly state and condition and magnificence of Saint Petersburg such as befits the capital city of a realm most vast˝ (Punin, 1990). This desire to make Saint Petersburg a proper representative of its nation was also shared by Alexander I. The construction projects on the banks of the Neva embodied the ˝passionate love towards anything gigantic, anything colossal in its physical dimensions˝ (*Grabar*, 1910), which was typical of that era in history. A gargantuan size was what set apart the landmark architectural monuments and other urban structures of that period. The first large-scale development project involved restructuring the central waterways. The Catherine Canal was deepened, the river beds were reshaped in a more streamlined way and surrounded with standardized urban structures along the banks, over 30 km of embankments were cased in granite, and the architectural complex on the Spit of Vasilyevsky Island began to take shape. The second major initiative was the transformation of the glacis surrounding the Admiralty fortress: it gave way to an enormous complex of central city squares, which served as a link between the Neva water area and the architectural ensemble of the Admiralty. This created a "single, uninterrupted open-air space, bringing together numerous waterways, squares, avenues, streets, and small parks" — the foundation for the landscape in the historic core of Saint Petersburg (Shvidkovsky, 2007).

The system did suffer significant losses during subsequent reconstruction: by the early 20th century, the Admiralteyskaya and Kollezhskaya squares had ceased to exist, the Teatralnaya Square had lost some of its aesthetic, and the panorama over the 400-meter-long main facade of the Admiralty building had been blocked out. The re-purposing of the spacious (50 ha) glacis around the Peter and Paul Fortress lacked a systemic approach and therefore can hardly be considered a positive development. These acts of "barbaric urban planning" (Lisovsky, 2004; Roslavlev, 1928) have so far gone unnoticed. The claim that the urban environment in the historic city center has properly completed its development is being promoted by territorial regulations (TSN 30-306-2002) and shared by a number of distinguished experts.

In the 1920s, the city center stopped undergoing active development. The spatial layout remained the same as at the beginning of the 20th century up until the 1990s. The conservation of open-air public space parameters is a matter of special importance in Saint Petersburg. The conservation efforts focus on the landmarks that define the aesthetic of the streets, squares, and embankments. The Committee for the State Preservation of Historical and Cultural Monuments (KGIOP) maintains a list of 2110 heritage buildings, while 7783 sites — "architectural ensembles, buildings and utility structures, parks and gardens, ponds and canals, monumental sculptures and park ornaments, historical burial sites and points of archaeological interest" — are protected by the state.

1.2. Residential spaces (blocks). The total area covered by residential blocks in the center of Saint Petersburg is believed to reach 2114 ha (MLA+ 2019). Unlike the open-air public spaces, which have seen thorough studies and systemic classification, the vast spaces that have been "tucked away" into residential blocks remain a terra incognita. Even today, we are still lacking an appropriate expert-level description of these areas. Territorial regulations describe intra-block spaces as "buildings, structures, and other elements" forming a part of a system that "...makes up an urbanized space where the urban population engages in various everyday activities". The statement that the historic center has "small blocks with high development density, a streamlined development module, and a perimetric layout of residential development" (TSN 30-306-2002) appears rather contradictory.

It is widely known that even at the earliest stages of the city's development, residential blocks already spanned across incredibly vast areas: their size reached 210 x 66 sazhens (447.3 x 140.6 m) on Vasilyevsky Island and 220–225 x 50–56 sazhens (426–553.8 x 106.5–110.7 m) in the Moskovsky (Liteyny) district. This type of development was later used as guidelines for settling uninhabited areas (Sementsov, 2006a). Fig. 2 allows us to compare the spatial parameters of residential development in the center of Saint Petersburg and Paris; this comparison clearly disproves the statement in the regional regulations that we just cited.

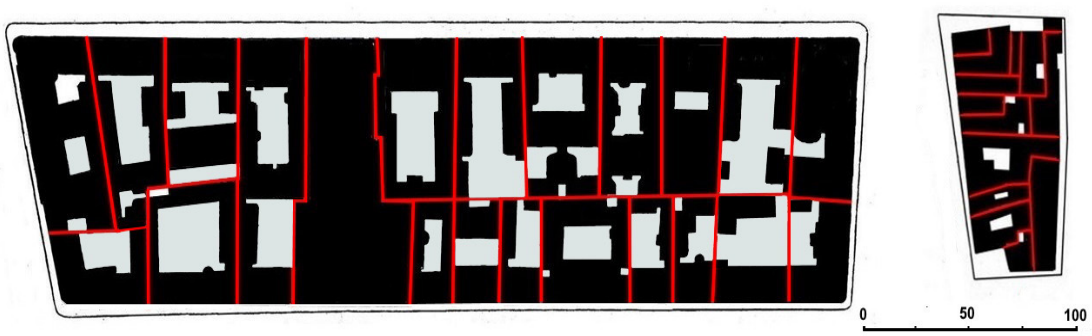

Fig. 2. Residential development in the city center: on the left — Saint Petersburg (block 1220 between Nevsky Prospekt and Stremyannaya Street), on the right — Paris (Beaubourg area, Place Igor-Stravinsky)

It is far from difficult to determine the perimeter of residential blocks in the historic area of Vasilyevsky Island. It is 1174 m. Notably, the average perimeter of urban residential blocks is 746 m in the center of Saint Petersburg, 465 m in Rome, 308 m in Paris, and 217 m in London. The average residential block in Saint Petersburg is five times bigger than its Parisian counterpart (Yavein, 2012).

The large size of the residential blocks also defined their development typology. Figs. 1 and 2 show that the

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center of Saint Petersburg is dominated by a "grid-like segmented layout of the compact perimetric morphotype" (Kozhaeva, 2011). It differs from the historic centers of older cities, including Paris, in that it has a well-developed and consistently structured courtyard system within the residential blocks.

In historic European cities, residential block depth rarely exceeded 30–40 m, and houses usually received natural light from street-facing windows, which could be occasionally supplemented with light wells of minimum size[2]. In New York, the size of inner courtyards in residential development areas occupied by five-story buildings reached 26 m2 (Architecture and Urban Planning, 2019).

In Saint Petersburg, the residential buildings and their wings located in the central part of the block received natural light through a courtyard system. A study conducted in the 1970s shows that the Saint Petersburg cityscape is dominated by residential blocks that are 40–140 meters wide, while the most common type of intra-block layout is a rectangular courtyard framed by buildings along the perimeter (Fig. 3).

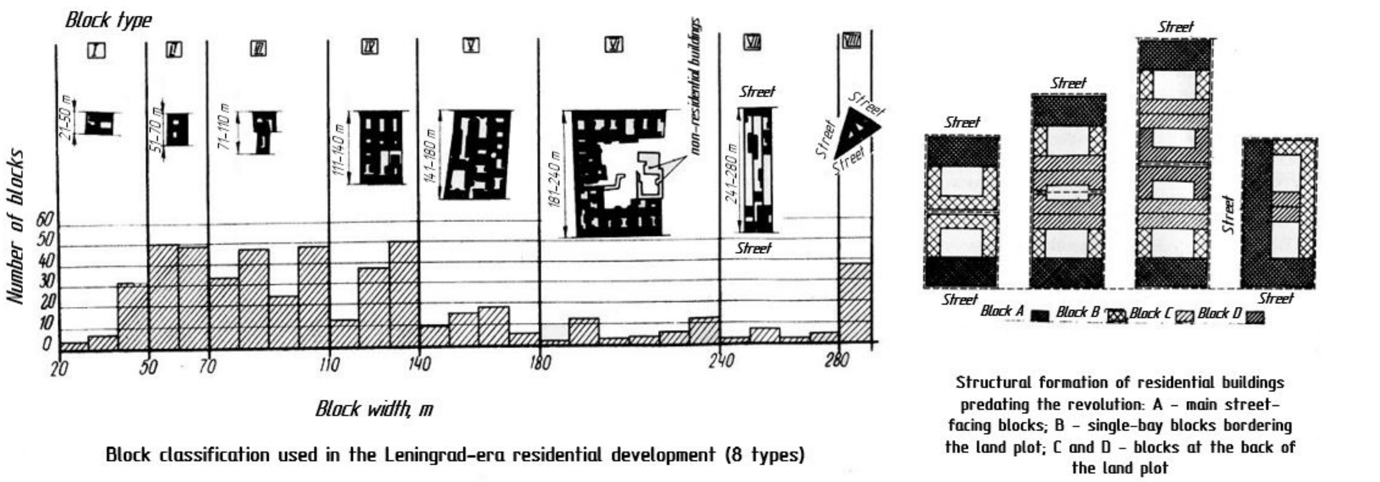

Fig. 3. Spatial parameters of intra-block areas in the historic center of Saint Petersburg (Platonov et al., 1973)

As the city kept developing, residential areas became more tightly packed, while intra-block lighting worsened: new stories were added on top, additional wings were crammed into the land plots, and the officially permitted courtyard size kept shrinking. In the 1760s, the norm was 21.5 x 42.6 m (894.4 sq. m); and in 1835, the official threshold for small-size land plots could be as low as 10.7 x 12.8 m (136.1 sq. m). Starting from 1882, the 136.1 sq. m size was the official recommendation for the main courtyard on the land plot; notably, the permissible width was cut down to 6.4 m (Sementsov, 2006b).

When comparing Figs. 2 and 4, we see that the "grid-like segmented layout of the compact perimetric morphotype" in the center of Saint Petersburg underwent significant changes in the late 19th and especially in the early 20th century: the new land plot parameters were not compliant with the traditional development module, the continuous chain of building facades got broken up by cour d'honneurs, firewalls were preserved in fragments only, and instead of 1 or 2 courtyards per plot, there were now as many as 5–11.

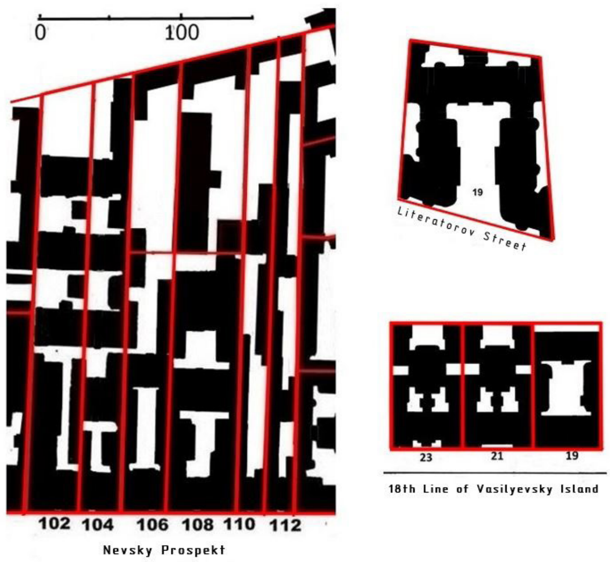

Fig. 4. Spatial parameters of land plot development in the late 19th and early 20th century

[2] In Paris, even as recently as in the early 1930s, the minimum permissible size of an inner courtyard could reach 30 m^2; for courtyards facing utility rooms only (including servants' quarters), the threshold could be reduced to 8 m2 (Reglement sur les hauteurs et les sail lies des batiments dans la villc be Paris 18 sept. 1902. Arrete du 22 Juin, 1904).

The development within the residential blocks contrasted against the open-air public spaces. The aesthetic aspect had barely any role to play in urban planning now, giving way to pragmatic goals. A single composition module would often be no bigger than a dozen meters, and would rarely reach 30–40 meters. Rather than being strictly regulated, city planning was predominantly spontaneous. Modern researchers point to the unique nature of this “extraordinary example of new structural formation”, which they call “anti-architecture” (Kirikov, 2004). This “different Petersburg” is now recognized as an “inextricable part of the urban whole” and an “under-appreciated chronicle of the city’s culture” (Kozyreva, 2015).

Communication links. The role of the transport and communication links as a defining element of urban development first became evident in Saint Petersburg during the latter half of the 19th century. As the construction hotspot kept expanding, new alleyways were added to the city layout, in order to improve Nevsky Prospekt links with the adjacent city districts: towards Nadezhdinskaya Street (now Mayakovskogo Street) in 1858, towards Pushkinskaya Street in 1874, and towards Suvorovsky Prospekt in 1900. Later on, such additions were deemed a palliative measure, and some suggestions were voiced regarding a complete transformation of the entire central street network (Enakiyev, 1912). However, unlike in many other European cities, the reconstruction efforts of the latter half of the 19th and early 20th century only affected a limited segment of the transportation route network in the Saint Petersburg center. The route layout that we are seeing today has been preserved since the early 1840s when the streets in the Saint Petersburg center were considered a structural part of the open-air public spaces, and the relevant tracing and spatial planning solutions had to account for the idea that the capital’s urban environment was representative of the whole nation.

The regional regulations claim that the modern Saint Petersburg city center is characterized by a “dense street and road network... and well-developed intra-block pedestrian pathways”, yet do not provide any concrete data to verify this (TSN 30-306-2002). According to the information provided in the Regional Strategy for the City Transportation Development, the street density in the center of Saint Petersburg is recorded at 11 km per 1 sq. km (Official Website of Legal Information 2019). In the historic part of Vasilyevsky Island, the figures tend to drop to 7.6 km per sq. km, as shown by our calculations. When assessing the situation, we could take into account that the average citywide street-and-road network (SRN) density (km per sq. km) is 12.4 in New York, 15.0 in Paris, and 16.9 in Barcelona (Pavlikova, 2013).In light of the above, the statement that Saint Petersburg has a “dense street and road network” in its center lacks factual foundation: the parameters of the Saint Petersburg city center fall behind even the averaged values characterizing the entire area of major cities in other countries (Table 3).

Table 3. Street and road network (SRN) density in the largest cities

Parameter	City				
	Saint Petersburg		Paris	London	New York
	City average	Historic center	City average		
Number of cars per 1000 people	330		253	213	305
SRN density (km per km^2)	3.8	11.6	15.0	9.3	12.4
SRN size (m^2 per 1 person)	10				32
Sources					
(Nikolayenko, 2015; Studme.org, 2019)					

The traffic load on the urban environment has increased manifold over the recent years. In the early 20th century, there were fewer than 10 thousand cars in Saint Petersburg; in 1970, the number rose to approximately 40 thousand; and in 2017, it reached 1.68 million (Kommersant, 2018; Za Rulem, 2019). Official sources claim that currently, “the central area... of Saint Petersburg is suffering from drastic SRN overload, as well as from the resulting environmental degradation, which may increase even further due to rising motorization rates if no measures are taken to resolve the issue” (Official Website of Legal Information, 2019). It is quite obvious that the SRN has reached its full capacity. Another observation is that the system that was developed to facilitate travel within Saint Petersburg “is far from the generally accepted norm. There is a need for reducing the traffic load and better utilizing the resources offered by pedestrian pathways” (Albin, 2016). On the other hand, the pedestrian pathway system in the center of Saint

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Petersburg is distinguished by the minuscule share of lanes, walkways, and alleys within the residential blocks. The pedestrian space is limited to a sidewalk system that flanks the red line along the blocks' extensive perimeter.

The optimal layout for the best balance between comfortable driving and walking is believed to be "blocks with a lateral dimension of 80–110 m" (RBC, 2018), or 100–150 m (Fomina, 2014). The historic center of Saint Petersburg is dominated by elongated blocks that do not meet the recommended specifications. For instance, the English Embankment is 1.3 km long but borders a mere 3 residential blocks. At the southern end of Nevsky Prospekt (from Liteyny Prospekt), residential blocks stretch as far as half a kilometer; while the Fontanka bank between Nevsky Prospekt and Pestelya Street is home to 800-meter blocks. Even in the former military districts, with their average-sized blocks, the distance between crossings can be as large as 280–320 meters (Sementsov, 2006a).

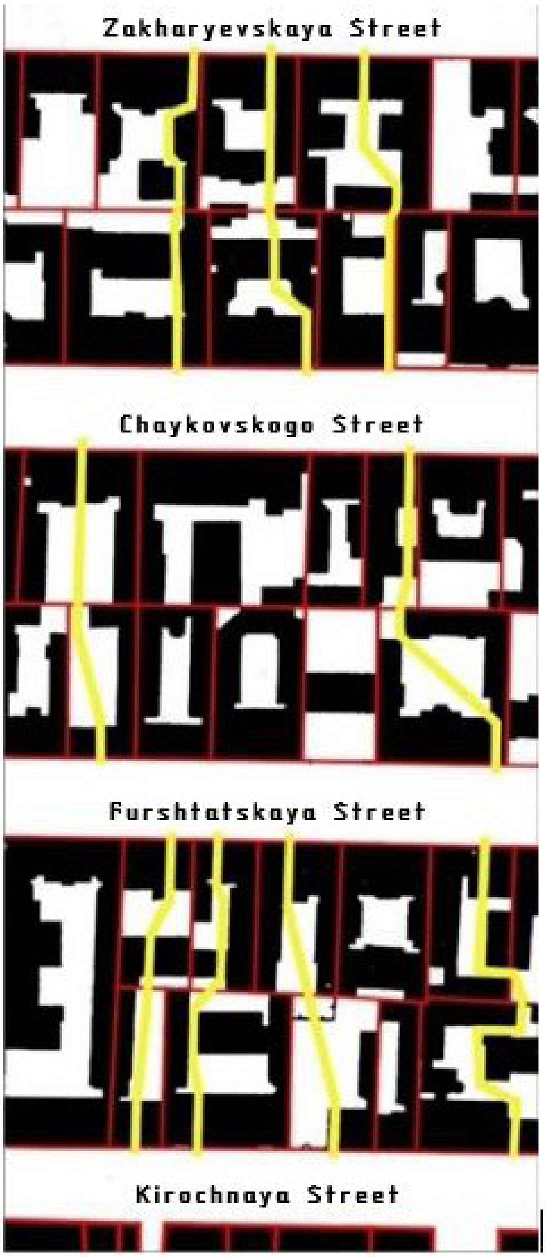


Fig. 5. Double-exit courtyards in the central residential blocks (1970–1990s)

The state of the environment along the sidewalks of the overloaded traffic lanes prompts a very negative response. Pedestrian safety is also a matter of concern. Pedestrians account for over 60 percent of all fatalities on the Saint Petersburg roads, as well as for a major share of injuries received in road accidents (Official Website of Legal Information, 2019).

The number of road accidents in the Admiralteysky and Tsentralny Districts exceeds the city-wide average twofold (Likhacheva, 2001). In some cases, pedestrians are injured by cars that veer off the road into the sidewalk. The General Administration for Traffic Safety (GIBDD) acknowledges that Nevsky Prospekt has "unfavorable traffic safety conditions": there were 73 road accidents here in 2018, with 3 people dead and 88 injured; in 2019, the general figures remained the same, but the number of fatalities rose twofold (Kudin, 2019).

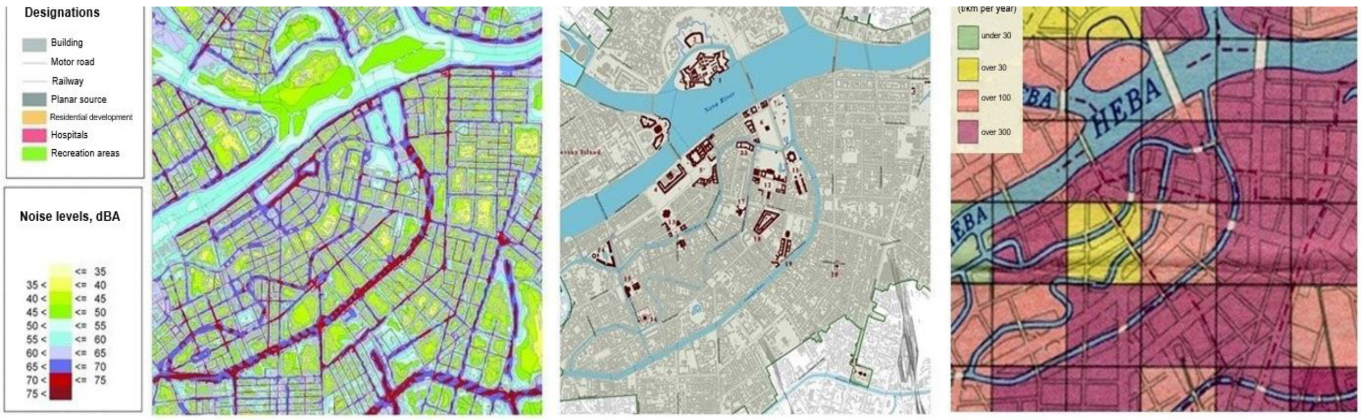
An analysis of the situation prompts a conclusion that pedestrian pathways in the center of Saint Petersburg need to be separated from traffic (Shesterneva, 2007). The regional regulations mentioning "well-developed intra-block pedestrian pathways" suggest that this might be possible (Administration of Saint Petersburg, 2003). However, what is truly reflected in this statement is the situation unique to the period from the 1960s to the 1980s, when the urban development conditions allowed the locals to create their own pathways by taking shortcuts across the residential blocks (double-exit courtyards). The spontaneous emergence of these pedestrian links made the urban environment in the center more passable, which it had sorely needed (Fig. 5).

This pedestrian network is now being actively dismantled, and many double-exist courtyards are getting closed off. When they just emerged, the city administration was indifferent (it did not even make any attempts to record their existence); nor is it taking any steps to preserve this system today (812 Online, 2014).

The current strategy includes suggestions on "reconstructing the sidewalks to reflect the actual pedestrian traffic intensity, designing high-comfort areas, and adding pedestrian zones to the historic center of Saint Petersburg" (Official Website of Legal Information, 2019). This is supposed to involve redistributing the limited space in the city center and splitting it between vehicles and pedestrians, which will inevitably result in conflicts.

Environment. Natural features. The center of Saint Petersburg has an unmatched potential when it comes to bodies of water: "The astounding balance between architectural landmarks and waterways is the key distinguishing feature of the Saint Petersburg historic center, as well as its main source of appeal... The bountiful waters of the Neva River have given the city its unrivaled scale and visual splendor; the river is Petersburg's main square and central street" (Committee for the State Preservation of Historical and Cultural Monuments, 2019). The waterway density at the historic core of the city fluctuates between 17.4 m per ha (Admiralteysky District) and 12.7 m per ha (Tsentralny District), which is significantly higher than the figures for the peripheral districts (Shundrina, 2017). In addition to other benefits, the broad rivers and canals help ventilate the city streets, by carrying fresh breezes from the Gulf of Finland into the historic central districts.

The size of green areas in the center of Saint Petersburg is 6 sq. m per capita, which is 2–3 times less than at the city's periphery (Repository for legal documents, standards, regulations and specifications, 2019a). Now for the air quality: in 2013, Saint Petersburg was named one of the most polluted cities in Russia. Air pollution is the worst in the Admiralteysky, Tsentralny, and Vasileostrovsky Districts (78.house, 2019). 85.9% of atmospheric emissions come from cars. Air quality tends to deteriorate along the streets in the historic center (Ligovsky Prospekt and Obvodny Canal, Liteyny, Vladimirsky, and Zagorodny Prospekt, the vicinity of the Moskovsky railway station terminal) (Yandex.Realty, 2019).



A B C

Fig. 6. Environmental conditions in Saint Petersburg. A — noise pollution in the city center (Karpovka, 2017), B — architectural landmarks in the city center (Unesco, 2019), C — atmospheric emissions (78.house, 2019)

Saint Petersburg ranks fifth among the noisiest metropolises in the world. The territories subjected to the greatest sound pressure are the Admiralteysky, Tsentralny, and Petrogradsky Districts. As shown in Fig. 6A, the main source of noise in the city center is the traffic flow.

This diagram allows us to conclude that the intra-block areas, which are insulated from noise and emissions by a solid row of street-facing buildings along the red lines, manage to retain a relatively comfortable environment quality. That said, there are certain depressed areas at the core of the residential blocks, even in the gentrified "golden triangle". "In major blocks with a complex structure, the development would often stop before it reached the core, and with time, the unfinished spaces became deserted and dilapidated" (Yavein, 2012). Intra-block residential spaces were originally meant for low-income tenants with modest demands, so they did not have a particularly high consumer appeal (Yukhnyova, 2008). And today, their parameters often do not meet even the minimal sanitation and hygiene requirements (Kovalev, 2019). There was an attempt to clear intra-block spaces of "low-value buildings in the courtyards" during the 1960s (Ikonnikov, 1965). In a market economy, residential premises located in side wings are hardly of any interest to potential buyers (Lapechenkova, 2013), and no-one "as much as thinks of relocating people from communal flats in the second- and third-tier courtyards" (Saint Petersburg Projects, 2019). These sections of intra-block areas may have the potential for future reconstruction.

Terms of land ownership and use. The 2010s saw the development of various projects aimed at developing intra-block spaces in the center of Saint Petersburg for public benefit (Administration of Saint Petersburg, 2013). Much time has passed since then, but none of these projects have ever become a reality, because active urban development in the historic center is stunted due to the lack of clarity in the land use system. Between 1703 and 1918, the city's development was based on the private home ownership principle: the land plot and the buildings on it were considered a single business unit and served their proprietor as a source of income. The landlords collected income from apartment tenants and paid taxes. They were also the sole party responsible for making decisions regarding property renovation (as dictated by their business circumstances). This arrangement, recorded as an underlying clause in 1910, is illustrated in Fig. 7. The white color corresponds to state-owned land (in this case, the street), and the yellow corresponds to private land.

Between 1918 and 1991, the entire city and the buildings in it were the property of the state ("the people"). This arrangement is shown in the section of the figure that corresponds to the year 1960. The final section of the figure illustrates the modern arrangement (as of 2010). The housing reform resulted in most of the apartments being privatized (as shown in the figure by multiple colors). The stairwells and passages under the buildings were given to the tenants for shared use (yellow color).

And finally, the streets and those apartments that were not privatized are still city property (white color). The cross-hatching stands for the courtyards with unclear terms of land use: there is no land tax levied on this part of the plot, the ownership rights belong to the city, but in most cases, the courtyards are used by the building's tenants, who keep the gates closed and do not allow trespassing. This type of home ownership and land use does not provide any economic incentives for development, while the legal aspects of decision-making are extremely fuzzy.

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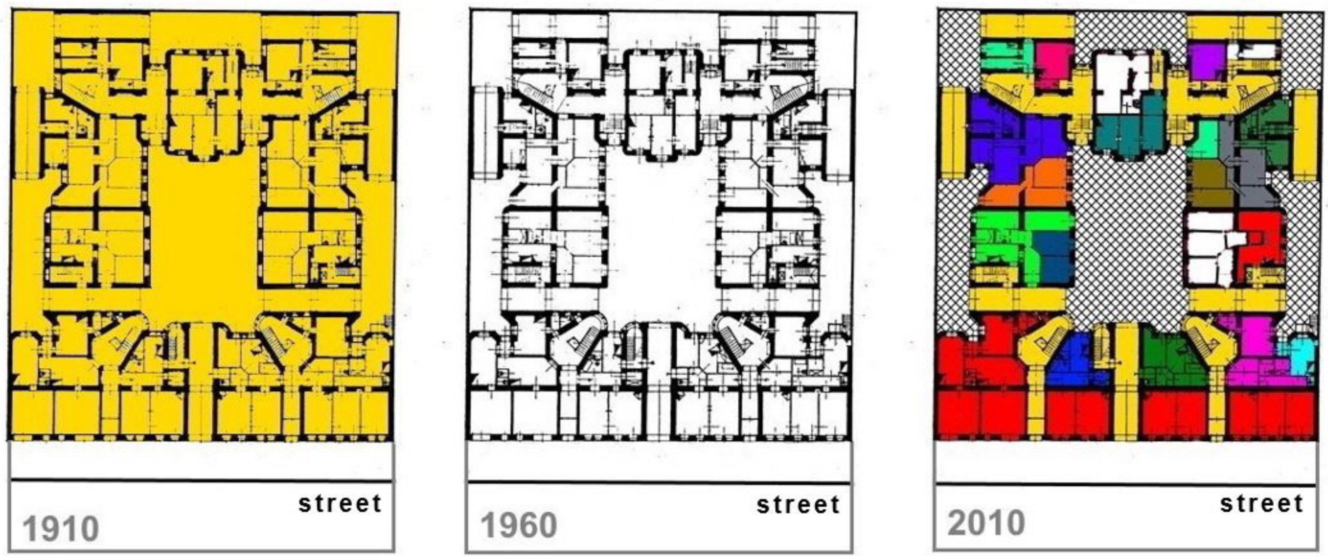

Fig. 7. Changes in the terms of land ownership and use

Architects lament that 'the building owners privatize adjacent areas, thus taking them away from the city... the courtyards get blocked off, and stop being city property" and point to "the lack of a coherent urban planning strategy and fence-sitting on the part of the city administration" (Fanaylova, 2007). The legislation flaws make themselves quite evident: "Both the federal laws and municipal guidelines for construction business are far from perfect. In addition to causing legal conflicts, they create a breeding ground for corruption" (Olkhovskaya, 2012). High-profile experts believe that this issue is strategic in nature and was caused by the haphazard housing reform: "For the longest time, the country trapped itself in an institutional conundrum. We are still there today" (Yasin, 2006).

Conclusions and recommendations

The multi-factor analysis of the ***historic center of Saint Petersburg*** reveals that the specifics of everyday life in this part of the city have been defined by the course of the city's growth and development. The formation of the spatial environment in the historic center "completed (or abruptly came to a halt) a hundred years ago, and has not seen any dramatic changes since" (Kirikov, 2014). The historic center of Saint Petersburg has received international recognition for its outstanding architecture and aesthetics, and is officially classified as a World Heritage Site (Administration of Saint Petersburg, 2015).

The everyday life in the ***historic center of Saint Petersburg*** is currently affected by:

– unsafe environmental conditions (noise and emission pollution) caused by traffic overload;

– unresolved issues of land ownership and use;

– dilapidated areas within residential blocks;

– low pedestrian network density; low levels of pedestrian safety and comfort;

– small share of green areas;

– extensive strain on the historic public spaces.

The conceptualization of the "Reconstruction and Development of Historic Districts in Saint Petersburg", as per the Territorial Construction Regulations (TSN 30-306-2002), requires a major overview. As demonstrated above, the regulations reference a subjective assessment of the situation, with no factual evidence. Furthermore, the document focuses solely on the spatial parameters of the open-air infrastructure and does not cover the vast areas within residential blocks. Nor does it reflect the issues affecting reconstruction efforts due to the unfavorable traffic and environmental conditions in the city center.

Saint Petersburg's official strategy for preserving the cultural heritage promises "certain benefits" to compensate for "some discomfort associated with living in specially protected areas" (Repository for legal documents, standards, regulations and specifications 2019b). But, as we have seen above, this "discomfort" is currently exacerbated even further, as the traffic load on the historic center keeps growing. Making adjustments to the street and road network would be impossible in this part of Saint Petersburg out of historical conservation concerns, so the only way out of the situation would be to improve the pedestrian pathway system and make central residential blocks "publicly accessible, to pedestrians at least" (Linov, 2012a, 2012b).

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ОБ ОЦЕНКЕ СОСТОЯНИЯ ГОРОДСКОЙ СРЕДЫ ИСТОРИЧЕСКОГО ЦЕНТРА САНКТ-ПЕТЕРБУРГА

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Аннотация

Публикация инспирирована внедрением индекса качества городской среды в систему Минстроя РФ. Отмечается, что методики, основанные на «средовом подходе», в Ленинграде прорабатывались и использовались при исследовании жилища уже в 1970-1980-е годы, а сейчас этот опыт можно использовать для анализа современного состояния городской среды. **Цель исследования и методы:** Настоящая публикация представляет обзор информации, позволяющей получить первое представление о материальной городской среде в историческом центре Санкт-Петербурга. Многие показатели напоминают о других европейских метрополиях, но сказывается то, что территория центра разделена на три части широкими водными просторами, что застройка началась на пустынной территории, а на активный этап ее развития приходится всего полтора столетия (1760-е -1910-е годы). **Результаты:** С привлечением количественных данных дается характеристика исторического центра Санкт-Петербурга, которая сопоставляется с европейскими метрополиями по показателям геометрии пространств, транспортно-пешеходных коммуникаций и экологического состояния и показывает наличие проблем, усложняющих жизнедеятельность населения в этой части города. Критике подвергаются региональные нормативы реконструкции и застройки исторически сложившихся районов, которые основаны на субъективной оценке ситуации и не определяют путей ее оптимизации.

Ключевые слова

Исторический центр Санкт-Петербурга, городская среда, многофакторный анализ, городское планирование.

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SEMANTIC ANALYSIS OF THE FIRST CITIES FROM A DECONSTRUCTION PERSPECTIVE

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Abstract

Introduction: Deconstruction is looking for any meaning, semantics and concepts and then shows how all of them seem to lead to chaos, and are always on the border of meaning duality. **Purpose of the study:** The study is aimed to investigate urban identity from a deconstruction perspective. Since two important bases of deconstruction are text and meaning and their relationships, we chose the first cities on a symbolic level as a text and tried to analyze their meanings. **Methods:** The study used a deductive content analysis in three steps including preparation, organization and final report or conclusion. In the first step, we argued deconstruction philosophy based on Derrida's views accordingly. Then we determined some common semantic features of the first cities. Finally, we presented some conclusions based on a semantic interpretation of the first cities' identity. **Results:** It seems that all cities as texts tend to provoke a special imaginary meaning, while simultaneously promoting and emphasizing the opposite meaning of what they want to show.

Keywords

Deconstruction, text, meaning, urban semantics, the first cities.

Introduction

Expressions are an act of recognizing or displaying a particular concept. The purpose of each expression is to communicate something. Sometimes notes, lines, shapes, colors, and perhaps all the constituent elements of a building or a city can be a kind of an expression, a sign giving a special meaning. Since people live in a built environment, they begin to assign meaning and create signs for objects, with each one expressing a specific concept. With different expressions, we try to show different concepts (Anderson and de Saussure, 2018; Coward and Ellis, 2016; Stoltz, 2019). Symbolic codes create the so-called Kevin Lynch legibility and readability by making marks in objects, behaviors, and mentalities (Lynch, 1960, 1995).

Urban semiotics is based on a kind of a semantic load on all urban phenomena that extensively uses the process of differentiation. The differentiation is considered as a factor for identification and recognition and as a value that is located among many urban symbols (Almeida, 2018). Urban semiotics relate the fusion of ideology and power structures to human urban space. The analysis consists in the investigation of public imagination and meaning code articulated with space (Gottdiener and Lagopoulos, 1986; Pipkin et al., 1983). Consequently, the space is known when the symbolic meaning and its complex impact on human behavior have been recognized (Harvey, 1970, 2009).

Different meanings can be shown through spatial forms. Just as a text contains a message, the spatial forms of a city, like the letters of a text, can be considered to have a specific meaning (Gualberto and Kress, 2019; Leone, 2019; Stojiljković and Ristić Trajković, 2018). If the city contains signs and symbols, then the meaning of these symbols can be understood by people; we should seek to understand the meaning that people receive from their built environment (Knox, 1984).

As a result, traditionally in urban semantics, urban signs and symbols have a special meaning and try to show that special meaning to the audience. By recognizing the meaning of these symbols and signs and their differences, the researcher can reach a general meaning of the urban identity that a city wants to narrate. The aim of this study is to criticize this traditional urban semantics approach from a deconstructionist perspective; and in this respect to examine the urban identity of the first cities. Based on this idea, the research consists of four parts as follows: first, the method and steps of this research are described; then, the philosophy of deconstruction is studied based on Derrida's views; in the third part, the common symbols and symbols of the first cities are examined; finally, the concepts and symbols of the first cities are critically deconstructed.

Research method

This research used a qualitative content analysis method in the semantic reading of the city's identity. In analyzing the qualitative content of this research, by examining the concepts, terms and connections between these concepts, we attempted to deduce and reveal the hidden patterns in written documents and observations. Using deductive logic, we did it in three steps of preparation, organization and reporting. In the preparation step, the deconstructive perspective on text and symbol analysis is examined first. In the organizational step, the elements, symbols, signs and common concepts of the first cities are brought together, and in the final step, the interpretation and report of these symbols of the first cities are presented based on the deconstructionist perspective.

Content in content analysis refers to any document that indicates the relationship between human beings. Therefore, the paintings engraved in caves, music, books, articles, manuscripts, postcards, movies, etc., we call content. Accordingly, content analysis is a method of analyzing qualitative studies by which data is summarized, described, and interpreted. When researchers intend to test or verify the validity of a theory, model, or hypothesis, they use a deductive content analysis (Anandarajan et al., 2019; Kyngäs and Kaakinen, 2020). Accordingly, since this study seeks to investigate the validity of deconstruction theory in the field of urban semantics, we used the method of deductive content analysis and chose the first cities as a text.

Results

A. Step 1: basic concepts in deconstruction

Hans Gadamer argued the idea that there is a fundamental unity between thought, language, and the universe, and that it is within the language that our present horizon is constructed and addressed. According to poststructuralists, the meaning of any identity can be achieved through language. The focus of this movement is on the role of language in poststructuralist theories. It can be clearly seen in the views of Jacques Derrida, Michel Foucault, Roland Barthes (Aitken and Valentine, 2015; Harari, 2019; Parkes, 2012; Poster, 2019). The term deconstruction was coined by French philosopher Jacques Derrida (1930–2004). Deconstruction acts to illuminate another meaningful layer in a text. The underlying meaning that hides itself, however, is there. The text is multi-meaningful in this respect and does not have a specific meaning, and as much as it refers to a particular meaning, it also refers to its reversal (Culler, 2007; McQuillan, 2017). Each text is a complex combination of symbols and signs; we can never know what these symbols mean. A symbol wants to point to something, and there is a difference between that symbol and that concept. It is this difference and distance that determine the meaning. But since it is never possible to say with certainty what the symbol refers to, the meaning is uncertain (Sallis, 1987). Accordingly, in deconstructing the critique, Derrida's deconstruction view claims that the true meaning of the text is unattainable. Accordingly, each text is a complex combination of symbols and signs that, when searching for its meaning, shows conflicting meanings simultaneously. These contradictory meanings are also due to the fact that no word has a completely independent meaning and concept, and it finds meaning only when we understand its opposite meaning and with the help of that opposite, it acquires the meaning. Accordingly, Derrida argues that the meaning is not directly present in the symbol, sign, because the meaning of a word and symbol is what that sign is not, and because each word is constructed by its difference from other words. The meaning is never fully present in the word itself; it is rather made up of differences with other words, in other words, the meaning is "delayed", and as much as its meaning is due to itself, it is also due to its opposite meaning, by which it has found the meaning (Michelfelder and Palmer, 1989; Sallis, 1987; Wolfreys, 1998).

There is no escape from contradiction according to Derrida. Deconstruction considers how philosophical texts, when setting the definition as the starting point, do not pay attention to this fact that all these behaviors which led to definition, have an inner order, the order in which everything has been defined due to what was not before it (Evans, 1991; Wood and Bernasconi, 1988). In a text with such a broken foundation, the meaning, both the superior and the opposite one, disappears. Accordingly, the text is turned to multi-meanings; and because of countless interpretations, the final meaning is lost (Derrida and Bennington, 1993; Freshwater and Rolfe, 2004; Payne, 1993; Wood, 1992; Wolfreys, 1998). Derrida showed that all texts are based on dual orders, such as existence/non-existence, man/woman, where the first member of each pair is considered as the meaning and has a preference. In all those schools of thought, there is a hypothetical vantage core or an Archimedean point. These hypothetical vantage cores came in view of deconstruction, as being useless and non-hierarchical of that was previously discovered, and what was considered constant and logical became unreasonable and void, with the interpretation itself containing many misconceptions (Naas, 2003; Wolfreys, 1998).

B. Step 2: the first cities

The city as the first form of civilization and the center of holiness, power and wealth always possessed an ideal and sacred meaning. It tended to portray its socio-philosophical aspirations towards the future and its destination that led to the emergence of different ideals (Morris, 2013; Nas, 2011; Seasoltz, 2005). Several studies showed the definitive impact of the subject of the worldview on the genesis of the first cities (Ghirshman, 1961; Rohl, 1999). A city acts as a physical crystallization of the society that shaped it and tries to show their valuable concepts. Valued and sacred signs in the cities, naturally, are guaranteed and continuous mechanisms that can re-generate or, vice versa, eliminate and degrade semantic loads over time. The first cities were basically created as symbolic centers of ceremonies (see Fig.1). Thus, the city is a symbol of the world and it has the power to organize and regulate wider areas (Bryce, 2009; Potts, 2006; Osborne, 2014).

The number of the cities that are called "the center of the world", "the heart of the world", "the axis of the world", etc., is interesting. In mythology, most cultures come across a concept called "the world axis". This centrality is actually reflected in the culture itself. In other words, cultures have always considered themselves the center of the universe, and they have imagined that they have the closest relationship with the Lord and Creator of the universe because of this centrality. In these cultures, the geographical position was usually a focal point, therefore it was sanctified (Clark, 2013; Hibbert, 1987; Morris, 2013).

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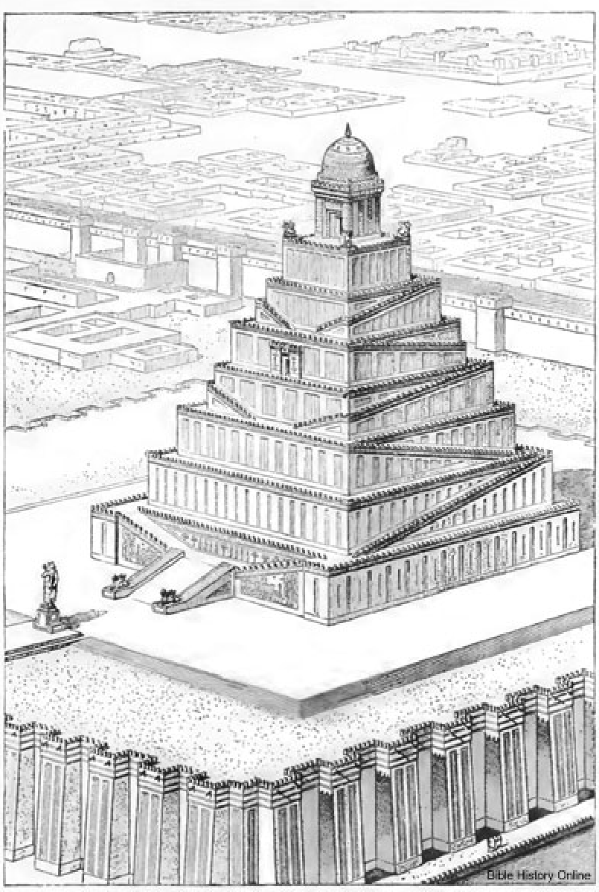

Figure 1. The first cities as symbolic centers of ceremonies. Drawing of a Ziggurat with seven stages. Source: Bible History Online

According to a semantic study of the elements, concepts and symbols of the first cities, we see common concepts in most of them. There are symbols trying to express specific meanings to the audience, which can be considered the basic and underlying principles of the most of urban symbols made in the first cities. These meanings are: the center of the world defying a subordinate position; a manifestation of perfection and divine order in contrast to the disorder of the outer world; eternal presence and stability versus instability, mortality.

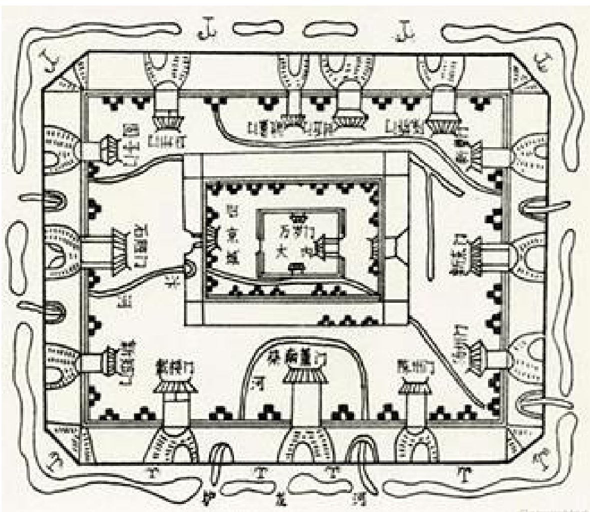

Figure 2. Chinese cartographic view of the city. Source: N.S. Steinhardt, 1999

We further investigated the concepts in Chinese first cities.

C. The first cities of China

Ancient Chinese cities have been described as a symbol of the order of the universe. The texture of the gates, the fences, the order of the streets, the location of the city center and its nature have all been aspects of astrobiology. In this view, sacred things are real and only sacred things are safe. Biological complexes and buildings are similar to their celestial specimens and must be consecrated before they can become habitable. This sanctification was made possible by the connection between heaven, earth, and the underworld.

In the cosmological landscape, the first cities of China are a vehicle designed to capture and redistribute Qi, the divine breath, the power that animates human affairs and carries with it the mandate of heaven. It is embodied in the magic square, *Feng.*

The main features of such urban models are based on centralism, with the emphasis on the main world, focalism and the existence of a fence. In such first city models, the fence is seen as a sacred place rather than playing a defensive role (Morris, 2013).

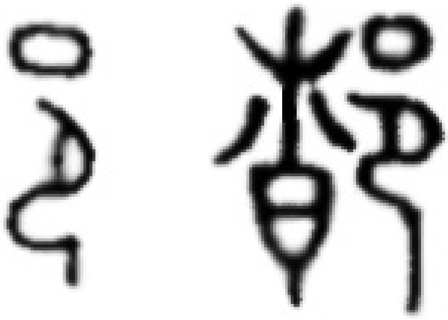

Figure 3. Sample of the Shang Dynasty ideograph for the first cities of China. Source: chaz.org

For example, in Fig. 3, we have the Shang Dynasty ideograph for “city”. It is a kneeling person beneath a city wall. The kneeling person signifies submission to the state and the burden of citizenship. It recognizes that a city is most essential for the people who live within its walls. The city wall is not simply a matter of defense. Cosmologically, it creates a divine vessel that centers God’s rule on earth and projects the power of the state. Hence, traditional Chinese cities and the governments they nurture are primarily sacred in their fundamental nature. On the right, the ideograph for “capital” adds the symbol for a granary, which evolves into the symbol for a market.

A Chinese city was a means of capturing cosmic forces and distributing them throughout the earth, and to identify a point as a city, the Chinese considered the following criteria: an altar to the god of soil, fences, and a temple for ancestors. The city, which symbolizes the acquisition of the divine forces and the safe place from the chaotic outer world, was separated from it by fences. The city is a sign of eternity and constant presence that manifests itself in the temple of the ancestors. A Chinese city was a solution by which the presence and immortality could forget inexistence and nullity; it assumed the form of denial and overcoming of death that declares its presence in the temple of the ancestors. The state of the city, as a place to obtain the divine forces, conveys a state of stability and resilience, and through its sacredness, creates a feeling of security for the audience. The city becomes a place where God and the earth come together and open their gates to the corners of the world, giving it a sacred state (see Fig. 4). In fact, all symbols, sings and concepts of the city are plays, conventions, and solutions for men and power structures to show their eternal presence.

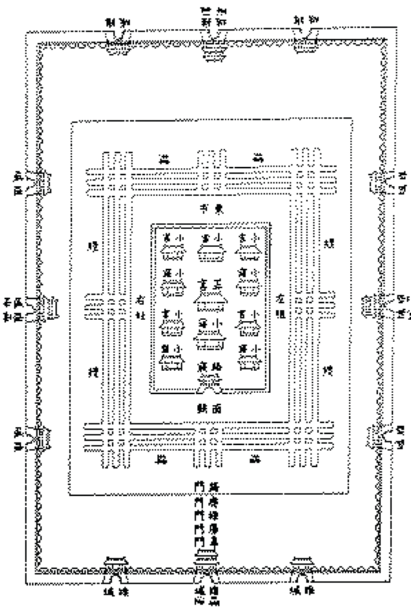

Figure 4. Structure of ancient Chinese cities, China. City, Han[1]. Source: Chaz.org

Conclusion

The third step or conclusion in content analysis is the result of the analysis of the previous two steps. It has already been mentioned that deconstruction states that since all concepts are relative, no exact meaning can be considered for any symbol. Moreover, when we look at symbols and signs from a structural point of view, we see that in addition to the literal meaning that we assume for symbols, the opposite meaning is quite conceivable for them as well. Each symbol has two meanings: the literal meaning and another meaning that is in conflict with the literal one, which is due to their relative nature. The second step was to answer the question, what are the common symbols and signs of the first cities? What did the first cities tend to mean semantically? And as mentioned, we see common concepts among most of the first cities: centrality and focalism in the world; manifestation of perfection and divine order; eternal presence, stability and order.

From the viewpoint of deconstruction, the constructed form known as the city hides its semantic foundations, which it claims in order to obtain eternal presence and identity, and in the meantime, the concept of the city is defined in terms of its superior dimensions. And it tries to implicitly reject the concepts against them, namely instability, non-existence, absence, by showing the concepts of stability, existence, presence, and so on. The city implicitly tries to cover up the facts and create what it lacks through its symbols. Therefore, it forms symbols that represent safety, permanence, and perpetual presence. In other words, the creation of such symbols is an unconscious reaction to the lack of such concepts in the city, and an attempt to overcome the fear of instability, insecurity, and death that is felt at all times. The city tries to cover them through its symbols, while this game of denial through symbols causes both these opposing meanings of existence and non-existence to be produced and reproduced at any moment, consciously or unconsciously. Behind their literal meaning, such symbols produce and reflect fears, shortages, and the lack of a permanent presence that history bears witness to. Then, each symbol puts its semantic roots in its contradictory meanings in addition to its literal meaning, and urban symbols become multifaceted. The identity that the first cities sought to show through their symbolism was a testament to the lack of such an identity, and that is why they tried to create it through symbolism, and that is why all those ceremonies and symbols were required. Symbols, in turn, indicate a lack of such an identity. The idea of purity and perfection and self-discipline becomes the source of impurity, imperfection and disorder. The notion is that perfection always has "imperfection" in it; it is as if perfection has always taken refuge in the flaw. Such symbolism forms when analyzed by deconstruction, what seemed perfection, acknowledge their imperfection. In fact, within each city, there are two types of cities. There is the first city, formed by the authority of that time, and, thus, understood and interpreted on this basis. Its logic and truth can be found; everything in it was reduced to the double contradictions like persistence/instability, real/unreal. But it also presents the second city, which is freed from the double contradictions; the logic and truth cannot be found in it, and with the roots devoid of their symbolic meaning, it loses any meaning at all. And so, the first city is the symbol for this second city. This latter aspect of urban identity is what deconstruction strives to show.

[1] The Kaogongji (Kao Gong Ji) was an official guide that set forth standards to be followed in various crafts and trades, including those for the structure of a provincial-level capital for a prince. It dates to the late Spring and Autumn period (about 500 BC), but the oldest surviving copy dates to 1235 AD. According to the Kaogongji: "When the builder constructs the capital, the city should be a fang (a four-sided orthogonal shape) nine li on each side with three gates each. Within the city are nine longitudinal and nine latitudinal streets, each of them 9 carriages wide. On the left (i.e. east) is the Ancestral Temple, on the right (west) are the Altars of Soil and Grain, in front is the Hall of Audience and behind the markets".

The Kaogongji, which disrupts movement within the city by having a large, walled administrative district in the center, was used by early states particularly in southern China and owes much of its spatial arrangement to the field well system, which places activities that directly support the ruler in the center of a three-by-three grid (source: Chaz.org).

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Surface Transportation Engineering Technology

A METHOD FOR THE COMPARATIVE ASSESSMENT OF THE TECHNICAL QUALITY OF DUMP TRUCKS WITH DIFFERENT STRUCTURES

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Abstract

Introduction: An analysis of the special-purpose road construction machinery market reveals an immensely diverse range of vehicles that can be used in construction. Due to this diversity, users may experience difficulties when choosing a dump truck from a range of vehicles with identical performance parameters. The final choice is often based on the user's subjective preferences and not always logically justified. This calls for designing a methodology that would make the choice of dump truck model less biased. **Purpose of the study:** The study is aimed to create a range of research and methodological tools for facilitating the comparative assessment of construction dump trucks that belong to the same category in terms of load capacity, but differ by structure. **Methods:** We compared and assessed our samples by contrasting the generalized vehicle quality parameters, as reflected by their technical quality coefficient. As research methods for collecting reference data for our assessment, we used information search, statistical analysis of information sources, expert studies, and mathematical modeling. **Results:** The comparative qualimetric assessment of the technical quality of different dump truck designs has prompted a conclusion that, when it comes to road construction, semi-trailer trucks are more preferable than chassis-based trucks. Specifically, semi-trailer dump trucks are characterized by better sustained performance, maneuvering ability, and terrain crossing capacity. **Conclusions:** The proposed method of technical quality comparative assessment allows for a more unbiased choice of dump trucks for road construction, based on analyzing their most vital performance parameters.

Keywords

Road construction, dump truck, performance parameters, technical quality, comparative assessment.

Introduction

An analysis of the special-purpose road construction machinery market reveals an immensely diverse range of vehicles that can be used in construction. This diversity may cause certain difficulties when choosing a dump truck from a range of vehicles with identical performance parameters (Faskhiev, 2016; Tselishchev and Faskhiev, 2017; Vygonnyi, 2015). The final choice is often based on the customer's subjective preferences or on the model's advertising campaign. Assessing the technical quality of various alternatives may help reduce bias (Dobromirov, 2000).

In cases of industrial product assessment, there are official guidelines (Regulatory Document RD 50-149-79) (State Committee of the USSR for Standards, 1979). They contain a list of the most important parameters out of the product's entire performance parameter range, as well as recommendations on how to use the expert evaluation method to find the weight coefficients for these parameters and subsequently determine the generalized technical quality index (which is a sum of the values obtained by multiplying each parameter by its weight coefficient). The guidelines (RD 50-149-79, 1979) contain an extensive list of technical equipment parameters that should be included in such assessments. The official recommendation is to select the most important parameters and provide the weight coefficient rationale for each industrial product on an industry-wide level, and then design a specific methodology in more detail. This method has been applied to many types of technical equipment; dump trucks, however, still lack such an assessment. Therefore, the creation of an assessment methodology, which will make it far easier for the consumer to choose the best dump truck out of a wealth of brands and models, is a highly relevant task.

Study objective, target, subject, and methods

Our objective is to design a methodology for the comparative assessment of construction dump trucks that belong to the same category in terms of load capacity, but differ by structure. Dump trucks are used for hauling bulk materials within a "storage base (quarry, railway station, pier, wholesale warehouse, etc.) — temporary storage facility at the (road) construction site" transportation system, across distances of over 10 km.

Our study targeted dump trucks with different types of structure. Modern road construction most commonly relies on single-unit dump trucks with a rigid chassis, or on semi-trailer dump trucks (Dobromirov, 2018a; Shiryaev et al., 2007). Among single-unit vehicles, greater preference is given to four-axle models, as they are more productive due to a greater body capacity (18–20 m3). In addition, the four-axle structure allows for a higher payload while staying within the recommended axle load limits. These vehicles also remain fairly efficient during medium and long hauls (ISO 337-1981) (ISO, 1981).

Semi-trailer dump trucks generally see more use for longer hauls. Their benefits include the high load capacity of the semi-trailer, even as it is used within the recommended axle load limits, as well as impressive traction and dynamic properties, ensured by the proper choice of the tractor unit (Hernandez et al., 2015; Rebrunova, 2011; Vakhlamov, 2003). Using trailers is one of the possible ways of improving vehicle performance and reducing shipping costs (Kravchenko, 2008).

The subject of our study is a method of mathematically assessing the technical quality of construction dump trucks. For the purposes of this study, we used such methods as information search, statistical analysis of information sources, expert studies, and mathematical modeling.

For conducting the comparative assessment of dump trucks' technical quality, we chose the four-axle rigid chassis KamAZ 65801-68 (T5) dump truck with an 8x4 wheel configuration and the three-axle KamAZ 65206-68 (T5) tractor unit with a 6x4 wheel configuration, coupled with the three-axle NEFAZ 9509-016-30 semi-trailer (KAMAZ, 2020; Kuznetsov, 2012).

A method for the comparative assessment of dump trucks' technical quality

We compared and assessed our samples by contrasting the generalized vehicle quality parameters, as reflected by their technical quality coefficient (Dobromirov, 2018b).

The technical quality coefficient is a consumer value parameter that is determined by the features that serve as the basis for its estimated structural performance. This performance is formed by a set of integrated parameters relevant to the vehicle's functionality and mobility. We believe it reasonable to divide these parameters into three groups (clusters): functional parameters, sustained performance parameters, and maneuvering ability parameters.

The functional parameters describe how well the vehicle performs its intended function (hauling bulk materials).

The sustained performance parameters reflect the vehicle's ability to move along its freight transportation route (which may include dirt roads of average quality, semi-paved roads, and blacktop roads, as well as slopes of different angles, as permitted by the road construction guidelines) at the maximum average speed possible.

The maneuvering ability parameters determine whether the vehicle is capable of maneuvering in confined spaces (such as quarries, open-pit benches, unloading sites, including places where the soil has a low load capacity) and climbing slopes that require the vehicle to strain its traction capacity to the limit.

Table 1 breaks down these integrated features to a measurable level (singular parameters). As singular parameters, we used those most relevant to dump truck performance. Parameter choice and the assessment of the parameters' weight coefficients in the context of integrated features' formation was based on expert evaluation.

Table 1. Group distribution of singular dump truck performance parameters

Functional parameters, Q_1		Sustained performance parameters, Q_2		Maneuvering ability parameters, Q_3	
Parameter	m_{ji} *)	Parameter	m_{ji}	Parameter	m_{ji}
1. Load capacity (G_l), t	0.45	1. Engine power-to-weight ratio (N_{eng}^{max} / G_0), kW/t	0.30	1. Number of driving axles	0.10
2. Body capacity (V_b), m^3	0.35	2. Maximum speed (V_{max}), km/h	0.35	2. Maximum slope elevation (α_{max}), degrees	0.15
3. Maximum dumping angle (α_{dump}), degrees	0.10	3. Number of transmission gears	0.10	3. Minimum turning radius (R_{min}), m	0.20
4. Number of dumping directions	0.10	4. Fuel consumption en route (q_r), l/100 km	0.25	4. Dimension range (H_d), m	0.15
				5. Specific wheel pressure level along the tread pattern (p_w), kPa	0.40

*) m_{ji} is the weight coefficient for a singular parameter.

The method for the qualimetric (qualitative) assessment of the technical quality level as a generalized quality index involves finding the value of each integrated parameter Q_j, which is based on the known values of the singular parameters q_{ji} and their weight coefficients m_{ji}. Each integrated parameter is assigned a weight P_j. The generalized quality index (technical quality level K_{tc}) is a sum of values obtained by multiplying each integrated parameter by its weight coefficient.

As per our recommendations (Dobromirov, 2018b), the methodology should be applied as follows:

– selecting the integrated parameters Q_j that serve as the basis for the dump truck's generalized quality index.

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These include the functional parameters, the sustained performance parameters, and the maneuvering ability parameters. Note that the j value for these integrated parameters falls within the 1–3 range;

– breaking down each integrated parameter Q_j into singular measurable parameters q_{ji}, where i is the sequence number of each singular parameter relevant to integrated parameter j. Notably, the number of singular parameters for each Q_j is individual and may range from 1 to n;

– determining the weight coefficient m_{ji} for each parameter q_{ji} in each group j (based either on an expert evaluation or on the personal experience of the person conducting the test). Important note: each group j must meet the following condition:

$$\sum_{i=1}^{n} m_{ji} = 1 \qquad (1)$$

– determining the integrated parameter value Q_j for each group of singular parameters:

$$Q_j = \sum_{i=1}^{n} m_{ji} \cdot q_{ji} \qquad (2)$$

where q_{ji} is the value of singular parameter i in group j; m_{ji} is the weight coefficient of singular parameter i in group j; n is the number of singular parameters in group j.

– determining weight P_j for each integrated parameter; just as in the case of m_{ji}, the following condition needs to be met:

$$\sum_{j=1}^{k} Pj \qquad (3)$$

where k = 3;

– determining the generalized quality index — the technical quality coefficient K_{ts}

$$K_{ts} = \sum_{j=1}^{3} P_j \cdot Q_j \qquad (4)$$

The resulting value K_{ts} should be used for comparing the quality levels of different models.

We suggest ranking the weight coefficients P_j within the system of integrated dump truck parameters Q_j as follows: functional parameters P_1 = 0.3; sustained performance parameters P_2= 0.45; maneuvering ability parameters P_3 = 0.25.

Results and discussion

When collecting reference data for the K_{ts} assessment in the vehicles of choice, we used the vehicles' technical features, traction, dynamic, and power capacity parameters, as well as fuel consumption efficiency, maneuvering ability, and terrain crossing capacity (Antonov, 1970a, 1970b; Dobromirov, 2016).

The dynamic features and fuel consumption efficiency graphs, based on our calculations, are shown in Figs. 1 and 2, respectively.

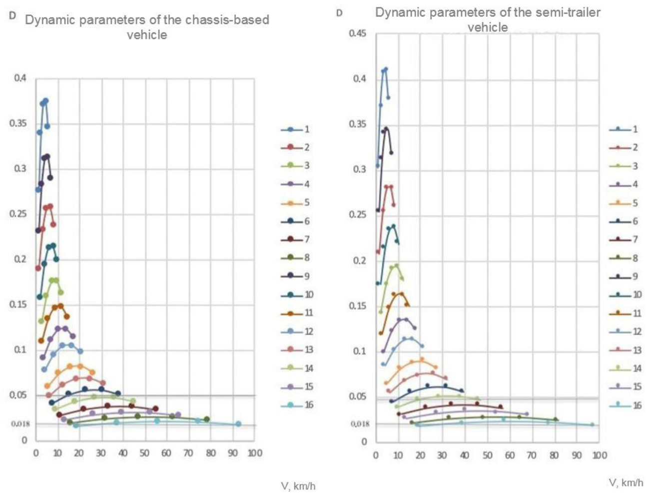

Figure 1. Dynamic features of dump trucks

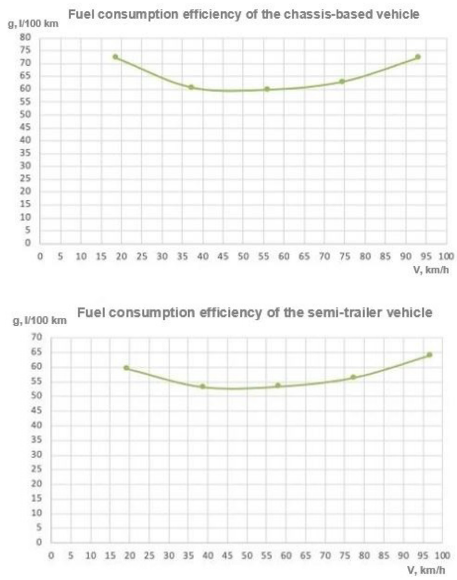

Figure 2. En-route fuel consumption graphs for vehicles moving at top gear

Then we used these parameter curves to determine the maximum vehicle speed, slope elevation, and en-route fuel consumption under typical conditions along the soil transportation route.

Figs. 3 and 4 provide diagrams that are needed to determine the vehicles' maneuvering ability parameters: the minimum turning radius (R_{min}) and the dimension range (H_d).

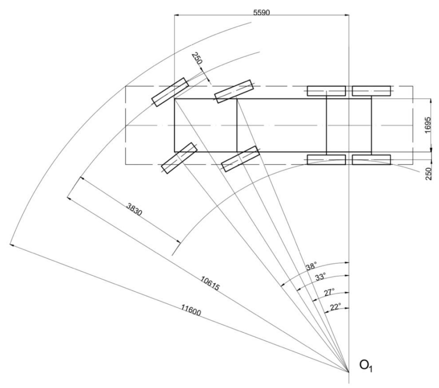

Figure 3. Diagram for determining the maneuvering ability parameters of the chassis-based vehicle

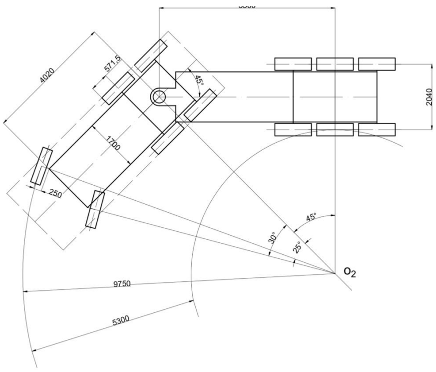

Figure 4. Diagram for determining the maneuvering ability parameters of the semi-trailer

The vehicles' terrain crossing capacity was contrasted against the average wheel-ground pressure. The wheel-ground pressure value was derived from two parameters: the average pressure in the contact area and the average pressure along the tread pattern.

In order to measure the average pressure in the contact area pc, we used the following equation:

$$p_c = \frac{G_w}{A_c} \ , \qquad (5)$$

where G_w is the vertical wheel load, N; A_c is the contour contact area, m², $A_c \approx B_t \cdot l_c$, where B_t is the tire section width, m; l_c is the length of the tire's contact area, m.

On hard-surface pavement:

$$l_c = 2 \cdot \sqrt{r_f^2 - r_{st}^2} \ , \qquad (6)$$

where r_f and r_{st} is the free and static wheel radii, m.

The average wheel pressure along the tread pattern p_{tr} is derived from the following dependency:

$$p_{tr} = p_c / k_{tr} \ , \qquad (7)$$

where k_{tr} is the lug-to-void ratio. For the road pattern k_{tr}, ranges between 0.6 and 0.8.

In Russian practice, the usual range of wheel pressure on the hard-surface pavement is as follows: $p_c \leq 0.6$ MPa, $p_{tr} \leq 0.85$ MPa.

The KamAZ 65801-68 (T5) dump truck with an 8x4(2) wheel configuration is equipped with NR 701 12.00 R24 tires (free wheel radius 0.615 m, static wheel radius 0.575 m, tire section width B_t= 0.319 m). The maximum wheel load is 45,000 N. Accounting for these parameters, the average pressure values are as follows: p_c=0.316 MPa, p_{tr}=0.526 MPa.

The KamAZ 65206-68 (T5) tractor unit has a 6x4(2) wheel configuration and is coupled with the NEFAZ 9509-016-30 semi-trailer. The semi-trailer has three axles with one tire per each. This tractor unit is equipped with KAMA NR203315/80 R22.5 tires (free wheel radius 0.542 m, static wheel radius 0.505 m, tire section width 0.315 m). The minimum wheel load is 23,750 N.

The NEFAZ 9509-016-30 semi-trailer is equipped with KAMA NT201385/65 R22.5 tires (free wheel radius 0.542 m, static wheel radius 0.490 m, tire section width 0.385 m). The minimum semi-trailer wheel load is 45,000 N.

Our assessment has revealed that for the semi-trailer truck, p_c =0.248 MPa, p_{tr}=0.413 MPa.

Using the vehicles' technical specifications and the results of our calculations, we compiled the following table of reference data for assessing the technical quality (Table 2).

Table 2. Reference data for a comparative assessment of the dump truck technical quality

Reference data		
Parameters	KamAZ 65801-68 (T5) 	KamAZ 65206-68(T5) with the NEFAZ 9509-016-30 semi-trailer 
Load capacity G_l, kg	32,425	34,750
Configuration	8x4	6x4 + 3-axle semi-trailer
Platform capacity, m³	20	30
Dumping angle, degrees	50	45
Number of dumping directions	1	1
Gross vehicle weight G_{gross}, kg	50,000	44,000
Power capacity N_e, kW (hp)	315 (428)	315 (428)
Number of transmission gears	16	16
Static wheel radius r_{st}, m	575 ± 7	505 ± 8
Estimates		
Engine traction power Pt_{max}, N	183,657	176,591
Dynamic factor D_{max}	0.375	0.471

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Maximum speed V_{max}, km/h: blacktop (0.018) dry soil (0.05)	93.15 37.6	96 46.5
Fuel consumption q when driving on a blacktop road, l/100 km	59.8	53.47
Slope elevation a, degrees blacktop (0.018) dry soil (0.05)	21 19	27 25
Minimum turning radius R_{min}, m	10.615	9.75
Dimension range H_d, m	3.83	5.3
Average pressure of the wheel's contact surface on the ground p_c, N/cm^2	31.57	24.8
Average wheel pressure along the tread pattern p_{tr}, N/cm2	52.61	41.33

Table 3 illustrates K_{ts} assessment results for the dump trucks that we are comparing

Table 3. Assessment results for generalized and integrated parameters

	Parameter	Parameter value q_{ji}		Parameter weight coefficient m_{ji}	KamAZ 65801-68	KamAZ 65206-68 + Nefaz semi-trailer
Functional parameters						
1	Load capacity, t	32.425	34.75	0.45	14.6	15.64
2	Body capacity, m^3	20	30	0.35	7	10.5
3	Dumping angle, degrees	50°	45°	0.1	5	4.5
4	Number of dumping directions	1	1	0.1	0.1	0.1
					26.7	30.74
	$Q_1(P_1 = 0.3)$				8.01	9.22
Sustained performance parameters						
1	Power-to-weight ratio, kW/t	6.3	7.16	0.3	1.89	2.15
2	Maximum speed, km/h	93.15	96	0.35	32.6	33.6
3	Number of transmission gears	16	16	0.1	1.6	1.6
4	Fuel consumption en route, l/100 km	59.8	59.8	0.25	10.05	11.63
					46.14	48.98
	$Q_2(P_2 = 0.45)$				20.76	22.04
Maneuvering ability parameters						
1	Number of driving axles	2	2	0.1	0.2	0.2
2	Maximum slope elevation, degrees	21°	27°	0.15	3.15	4.05
3	Minimum turning radius, m	10.615	9.75	0.2	1.877	2.05
4	Dimension range, m	3.83	5.3	0.15	0.93	0.705
5	Specific wheel pressure along the tread pattern, N/cm2	52.61	41.33	0.4	0.956	5.468
					7.113	12.47
	$Q_3(P_3 = 0.25)$				1.77	3.12
	K_{tc}				30.54	34.38

Our analysis of the generalized and integrated technical quality parameters makes it clear that using a semi-trailer dump truck for construction purposes would be preferable to using a chassis-based truck. Specifically, the semi-trailer dump truck is characterized by better maneuvering ability, sustained performance, and terrain crossing capacity, while also being capable of carrying larger loads.

Conclusions

The proposed method of technical quality comparative assessment allows for a more unbiased choice of dump trucks for road construction, based on analyzing their most vital performance parameters.

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МЕТОДИКА СРАВНИТЕЛЬНОЙ ОЦЕНКИ ТЕХНИЧЕСКОГО УРОВНЯ САМОСВАЛОВ РАЗЛИЧНЫХ КОМПОНОВОЧНЫХ СХЕМ

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Аннотация

Анализ рынка специальной техники для дорожно-строительной отрасли показывает огромное разнообразие применяемых автомобилей в сфере строительного производства. По этой причине достаточно проблематичным является выбор потребителем автосамосвалов из линейки машин, идентичных по выходным показателям эксплуатационных свойств. Часто он базируется на индивидуальных субъективных предпочтениях потребителя и не всегда оказывается обоснованным. Поэтому разработка методического аппарата, обеспечивающего объективность выбора модели, является актуальной. **Цель исследования:** Разработка научно-методического аппарата для сравнительной оценки строительных автосамосвалов одного класса грузоподъемности, но различного конструктивного исполнения. **Методы:** Сравнительная оценка образцов проводилась путем сопоставления обобщенных показателей качества машин, определяемых коэффициентами их технического уровня. В качестве научных методов получения исходных данных для оценки использовались информационный поиск, статистическая обработка информационных материалов, экспертные исследования и математическое моделирование. **Результаты:** Проведенная на основе предложенной методики сравнительная квалиметрическая оценка технического уровня самосвалов различного конструктивного исполнения дает основание признать, что использование седельного автопоезда в условиях дорожного строительства будет предпочтительнее, чем машины рамной конструкции. Это обусловлено тем, что седельный автопоезд с самосвальным полуприцепом обладает более высокой маршевой подвижностью, маневренностью и проходимостью. **Выводы:** Предложенная методика сравнительной оценки технического уровня позволяет, основываясь на анализе наиболее значимых показателей эксплуатационных свойств, повысить объективность выбора самосвальной техники для дорожно-строительных работ.

Ключевые слова

Дорожно-строительное производство, автосамосвал, эксплуатационные свойства, технический уровень, сравнительная оценка.

POTENTIAL FOR IMPROVING THE PROCEDURE OF INSPECTING ROAD TRAFFIC ACCIDENT BLACK SPOTS

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Abstract

Introduction: This study proves that the procedure of inspecting road traffic accident black spots (RTA BS) needs improvement. This improvement is to involve the tools and insights associated with the targeted program approach, as well as a road infrastructure indicator system, and information technology tools. The creation of a road infrastructure indicator system and its comprehensive application, coupled with analytical methods and accident prediction system methods, enables the assessment of measures aimed at reducing the number of RTAs. Accounting for information technology tools and systems (such as the digital traffic safety inquiries desk) is also necessary if traffic safety is to be organized and maintained in a systemic way. **Purpose of the study**: The study is aimed at finding a new approach to improving the procedure of inspecting RTA black spots. **Methods**: In the course of the study, we use systemic analysis, analytical methods, traffic safety evaluation based on defining the safety and accident coefficients and revealing RTA black spots, probability theory methods, research results processing, and IT computational methods. **Results**: We provide a rationale for a comprehensive approach to inspecting RTA black spots within the “traffic participant – vehicle – road – external environment” system. We also demonstrate how a group of parameters can be used for studying the systemic indicators of road infrastructure, in the context of the parameters’ characteristics, as well as the conditions of their use. We determine the capabilities of analytical methods, as well as accident prediction methods, in the context of finding an approach to improving the procedure of inspecting RTA black spots. We propose applying a comprehensive approach to the improvement of the RTA BS inspection procedure.

Keywords

Road, road traffic accidents, road traffic safety, RTA black spot, inspection.

Introduction

Improvement of traffic safety and its systemic management is the top public policy priority, primarily because addressing this issue will help safeguard human lives and health. To reaffirm its commitment to this mission, Russia introduced Federal Law No. 196-FZ “On Road Traffic Safety” dd. December 10, 1995 (State Duma of the Russian Federation, 1995). The law, which defines road traffic safety as “activities aimed at preventing the causes of road accidents and mitigating the consequences of road accidents”, has prompted the deployment of the targeted program approach (TPA), which now serves as the main principle of traffic safety measures. We interpret road traffic safety as a comprehensive and systemic set of activities. If the approach to traffic safety is randomized or non-systemic, it will not yield any viable results.

The systemic approach includes in-depth research and improvement of each element within the commonly used system: Driver – Vehicle – Road – Environment (DVRE). However, we believe that this system requires an adjustment: Traffic Participant – Vehicle – Road – External Environment (TP-V-R-EE). This is necessitated by some of Russia’s current official guidelines, which are aimed at reducing the number of road accidents and constitute TPA tools relevant to the following: behavior studies of TP (drivers (D), pedestrians (P), underage pedestrians (P_U), vehicle passengers (P_V)); analysis of vehicle (V) technical condition and use; improvement of the road infrastructure and management of traffic within the external environment (R, EE); studies of interactions between the external environment (EE) factors and TP, vehicles (V), and road (R); development of a road traffic accident (RTA) victim aid and rescue system and a road traffic safety (RTS) management (Fig. 1).

The systemic approach has been used in the global practice of ensuring RTS for a long time. It takes into account multiple internal and external factors that affect the tasks and their functions (Kravchenko and Oleshchenko, 2018). The need for studying the multi-factor method also serves as a rationale for developing a special approach to RTS improvement within the TP-V-R-EE system — specifically, a comprehensive approach to examining high-risk road sections that may potentially become RTA black spots; this approach should also account for the specific features of the road infrastructure.

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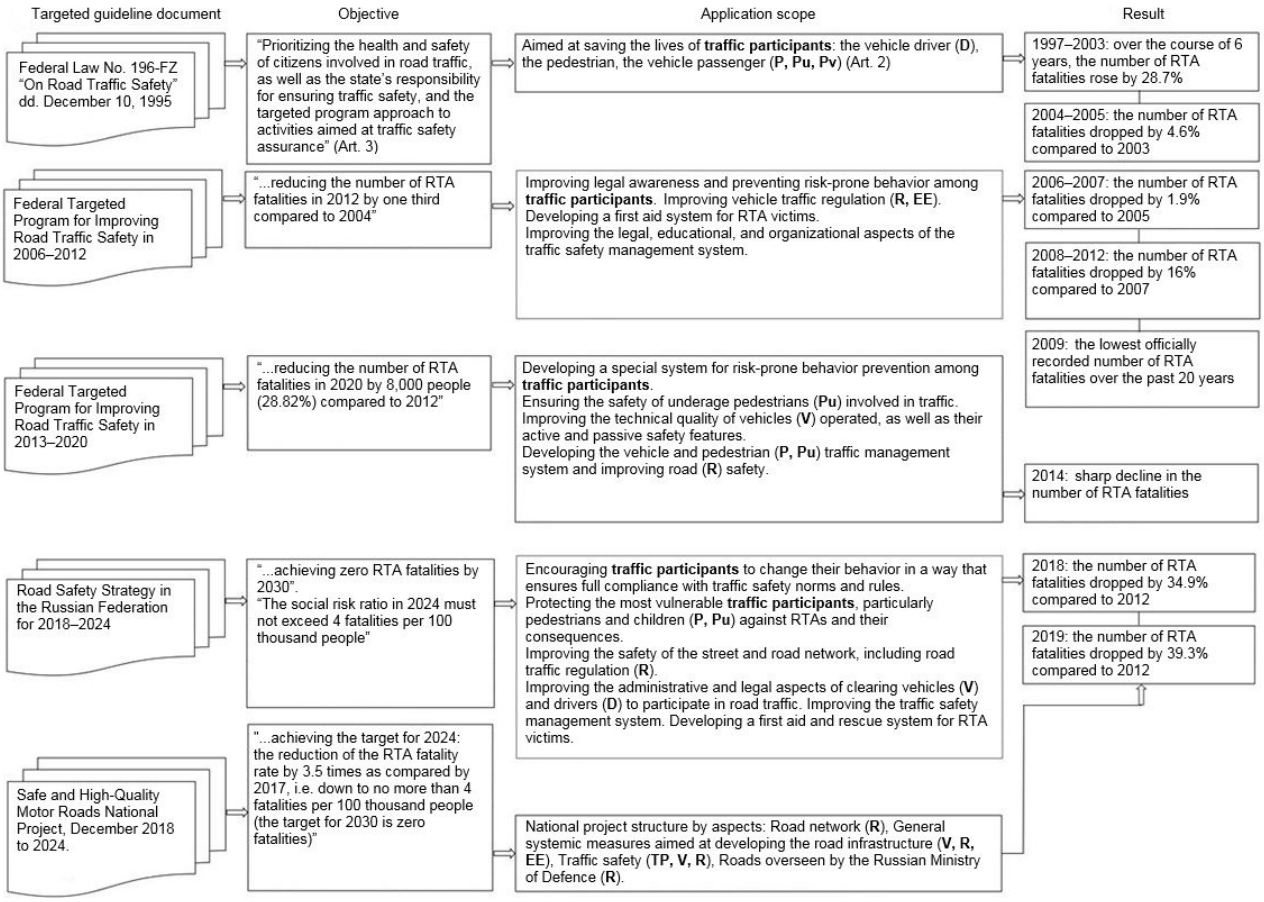

Figure 1. Targeted guidelines adopted in Russia for the purpose of reducing the road accident rate

Aside from the application of the TPA in a meaningful way that contributes to the positive dynamics of RTA reduction, the study of the system elements and RTS management is also furthered by distinguished authors, who have managed to obtain the following research and practical insights:

– systemic RTS organization and management (Kravchenko and Oleshchenko, 2015, 2018);

– methods of controlling traffic and pedestrian flows; groundwork for enhancing traffic light equipment with pre-signals that will facilitate traffic flow coordination; a new approach to the introduction of the left-turning section of signal control (Korchagin et al., 2015; Zhigadlo and Dubynina, 2018);

– new information on the specific ways in which the driver (D) changes vehicle (V) steering safety; discovery of reasons behind traffic safety violations (Evtjukov and Repin, 2015; Evtiukov et al., 2018);

– a scientific and educational approach to determining vehicle (V) service life; developed optimization algorithms for the vehicle (V) maintenance and repair system (Domke and Zhestkova, 2011; Kapitanov et al., 2018);

– results of studying the transport and operating conditions of roads (R), including the determination of a dynamic pattern in braking and adhesion characteristics of vehicle (V) wheels on the road surface at the stage of road operation and reconstruction (Brannolte et al., 2017; Novikov et al., 2019);

– methods of analyzing RTA and creating RTA models for the purpose of RTS improvement (Brannolte et al., 2017; Evtjukov and Repin, 2015; Kurakina, 2014);

– guidelines for conducting RTA expert analysis and improving the assessment methods and methods of examining vehicles involved in RTAs (including the technical condition of the vehicle (V) and road (R)), RTA BS study insights and suggestions for efficient RTS assurance (Evtyukov and Vasilyev, 2012; Kurakina, 2014, 2018; Kurakina et al., 2018, Novikov et al., 2019; Rajczyk et al., 2018).

However, the insights above were, to a certain extent, localized to very specific fields. Therefore, they do not provide tools for comprehensive qualitative assessment of the procedure of studying RTA BS as a system. This dictates a need for a systemic approach to improving the

RTA BS inspection procedure. The inspection is not only a set of state analyses and measures targeting the TP-V-R-EE system but also the result of those measures, namely the reduction of the target parameter (RTA fatalities). The main goal of RTA BS inspection is a comprehensive study on the parameters that describe the condition of TP-V-R-EE system elements through analytical, scientific and methodological, computational, and diagnostic means.

The existing regulatory framework reflects the inspection procedure, but the officially recommended procedure of RTA BS study does not cover the entire set of relevant factors, all the more so as RTA BS represent a system, and, therefore, call for a comprehensive systemic organization. The results of analyzing a large set of statistical data show that the overwhelming majority of RTAs in black spots are caused by traffic safety violations; nonetheless, the road infrastructure, coupled together with external environmental conditions, does make its own contribution to creating a hazardous situation, thus increasing RTA risk or making RTA consequences more severe. The regulatory framework that we referenced above limits the opportunities for studying and analyzing the causes of RTAs in black spots, which calls for a better and more efficient RTA BS inspection methodology.

Subject, tasks, and methods

The subject of this study is RTA black spots.

The tasks of the study are as follows:

- assessing the need for studying a complete set of RTA causes and factors in black spots;
- creating the elements of a comprehensive approach to improving the RTA BS inspection procedure.

In order to complete these tasks, we used analytical methods that were based on analyzing links, vectors, and timescales, as well as RTS assessment methods that were based on determining the safety and accident coefficients and pinpointing the RTA black spots, probability theory methods, study result processing, and the computational methods of information technology.

Results and discussion

Order of the Federal Road Agency (Rosavtodor) No. 105-r dd. January 31, 2017 “On the Introduction of Amendments in Industrial Road Guidance Document ODM 218.6.015-2015 ‘Recommendations for Accounting and Analysis of Road Accidents on the Roads of the Russian Federation’, recommended for application according to Order of the Federal Road Agency No. 853-r dd. 12.05.2015”, defines a “black spot” as a road/street section not exceeding 1000 m outside a populated area and 200 m within a populated area, or a road/street intersection, where three and more RTAs of the same type or five and more RTAs resulting in injuries or fatalities (regardless of type) occurred during the reporting year. ODM 218.6.015-2015 and ODM 218.4.004-2009 “Guidelines on Preventing and Eliminating Road Traffic Accident Black Spots During Road Use” can be used as sources of recommendations for analyzing RTA BS. They lack a coherent procedure for inspecting RTA BS and the relevant objects that could have revealed the links and interaction vectors within the TP-V-R-EE system relevant to the black spot of each specific RTA, while also accounting for the complete set of causes and factors.

Studying the full set of RTA causes and factors in black spots is essential for an appropriate assessment of the RTS level in black spots and efficient RTS measures. In order to achieve this, we must account for the parameter groups created, and analyze them in the context of the parameters’ characteristics, as well as the conditions of using the parameters in the studies of systemic indicators of the road infrastructure. Furthermore, we must refer to road accident prediction methods (Kurakina et al., 2020). An RTA BS is referred to as stable if the annual number of accidents in the relevant road section does not fluctuate by more than one or two. If the above statement is true, this points to certain persistent factors that affect the road section; these include, first and foremost, the parameters of the road infrastructure in the actual RTA BS, as well as their disadvantageous combination with the road infrastructure parameters in adjacent road sections. We are proposing a new, comprehensive approach to improving the RTA BS inspection procedure (Fig. 2), based on the following: the RTS state analysis, the TPA impact, the statistical data on accident rates within the TP-V-R-EE system, the factors and causes of hazardous traffic conditions, the developed algorithms of road infrastructure studies, RTA BS, information technologies and communication links, prediction methods, and study result processing.

Notably, the development of information systems and technologies has had an impact on building efficient communication links between TP and the executive authorities responsible for improving traffic safety. For instance, in Saint Petersburg, TP are making an active contribution to the development of the street and road network (SRN); during their active use of certain SRN segments, they spot their flaws and report them via the digital inquiries desk of the city Administration.

The aforementioned collaboration has allowed us to include the “digital traffic safety inquiries desk” block into our comprehensive approach; however, it may also be used as a separate element.

The practical application of research results (Evtiukov and Vasilyev, 2012; Kurakina, 2014; Kurakina et al., 2017) has resulted in greater expert evaluation quality and accuracy, while also allowing for a downward shift of the RTA BS target value. Our analysis of road accident rate statistics, as well as the key systemic indicators that we have singled out within the road infrastructure (Kurakina et al., 2020) allow for an assessment of RTS measures’ efficiency.

The comprehensive approach to improving the RTA BS inspection procedure in the TP-V-R-EE system covers the following:

– assessment of the accident hazard scope by means of statistically processing the number of RTAs that resulted in injuries, and the severity of these injuries, and contrasting the target values and indicators against the reference years and similar periods;

– evaluation and assessment of the TPA and the key principles of achieving accident reduction in Russia over the previous year;

– the inclusion of: tools that help achieve the TPA goals, the TPA scope, and the road infrastructure indicator

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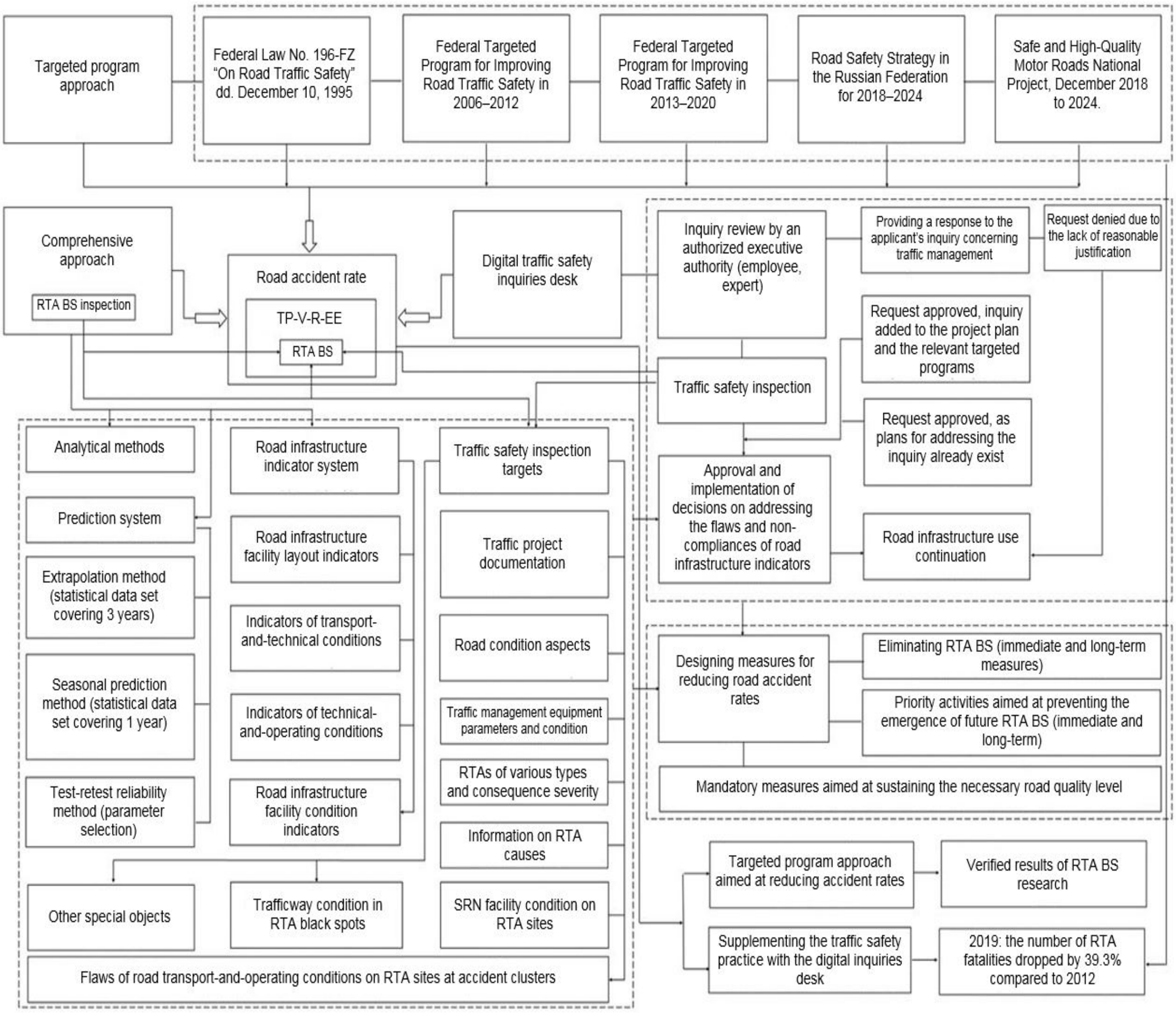

Figure 2. Comprehensive approach to the improvement of the RTA BS inspection procedure

system; the comprehensive application thereof, coupled with analytical methods and accident prediction system methods; possibly, also the inclusion of the digital inquiries desk at the organization responsible for traffic safety.

The efficiency of RTA BS inspection is defined by the following factors:

– the reference period for accident rate evaluation at the road sections analyzed;

– the use of scientific, analytical and computational methods for analyzing and processing the data on road infrastructure facilities' parameters;

– the use of diagnostic equipment for obtaining accurate data on road infrastructure facilities' parameters;

– the validity of regulatory documents establishing procedures for RTA BS inspection.

We recommend using two alternative criteria for selecting sets of RTS measures at RTA BS:

– whether or not the relevant measures have helped meet target accident rate reduction value at a minimal cost;

– whether or not the relevant measures have helped meet target minimal accident damage value at a minimal cost.

As for deploying the measures aimed at reducing accident rates in the conditions described, we recommend a step-by-step approach.

The results of efficiently applying the set of measures include: finding inconsistencies between the layout and features of the road infrastructure facilities and transport-and-technical / technical-and-operating conditions, on the one hand, and the current regulations and technical specifications, on the other hand; determining accident causes and factors relevant to black spots; designing impactful administrative solutions and measures for eliminating RTA BS (immediate and long-term) and priority activities aimed at preventing the emergence of future RTA BS (immediate and long-term); offering recommendations on mandatory measures aimed at sustaining the necessary road quality level, in line with the current regulations and technical specifications.

Conclusions

The organization of work to identify and eliminate RTA BS is a significant resource for reducing road accident rates and improving RTS. Studying a set of causes and fact causes and factors that define RTAs in black spots is founded on a qualitative assessment of the RTS level and accident trends in black spots, as well as on the opportunity to conduct a comprehensive study that accounts for the full set of RTA causes and factors. The use of a comprehensive approach to improving the RTA BS inspection procedure is a non-binding recommendation, and the inspection approaches that we have used highlight the potential for further improvement.

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ПОТЕНЦИАЛ СОВЕРШЕНСТВОВАНИЯ МЕХАНИЗМА АУДИТА МЕСТ КОНЦЕНТРАЦИИ ДТП

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Аннотация

Обоснована необходимость совершенствования механизма аудита мест концентрации дорожно-транспортных происшествий (МК ДТП). Потенциал совершенствования заключается в приеме учета механизмов достижения результатов программно-целевого подхода и направления их реализации, системы индикаторов дорожной инфраструктуры, инструментов информационных технологий. Разработанная система индикаторов дорожной инфраструктуры в комплексном применении с аналитическими методами и методами системы прогнозирования аварийности позволяет оценить мероприятия, направленные на сокращение числа ДТП. Прием учета инструмента информационных технологий и систем - электронной приемной организации безопасности дорожного движения необходим для разработки системной организации и управления уровнем безопасности дорожного движения (БДД). **Цель исследования:** Разработка подхода к совершенствованию механизма аудита мест концентрации ДТП. **Методы**: Системный анализ, аналитические методы, методы оценки БДД на основе выявления коэффициентов безопасности и аварийности, выявления мест концентрации ДТП, методы теории вероятности и обработки результатов исследования, программно-вычислительные методы информационных технологий. **Результаты**: Обоснована эффективность комплексного подхода к исследованию мест концентрации ДТП в системе «участник дорожного движения – транспортное средство-дорога-внешняя среда». Обосновано применение группы показателей в системе их параметрических характеристик и условий использования для исследования системообразующих индикаторов дорожной инфраструктуры. Определены возможности аналитических методов, методов прогнозирования дорожной аварийности для разработки подхода к совершенствованию механизма аудита мест концентрации ДТП. Предложен комплексный подход совершенствования механизма аудита МК ДТП.

Ключевые слова

Автомобильная дорога, дорожно-транспортные происшествия, безопасность дорожного движения, место концентрации ДТП, аудит.

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IMPROVEMENT OF ANALYSIS AND DESIGN OF ROAD PAVEMENTS USING NEPHELINE SLUDGE

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Abstract

Introduction: Predicting possible and arising defects in pavement layers made of new construction materials is an important task in the operation of any transport infrastructure facility. **Purpose of the study**: The study is aimed at performing a literature review, regulatory and practical analysis of the road pavement structure operation, and analysis of the operation of cement-containing pavement layers. The obtained results will be applied to pavements made with the use of nepheline sludge in order to derive a general equation that will reveal insights into a model for the prediction of the structure service life depending on various factors. **Methods:** The methodological framework of this study is information on the theory and practice of predicting the service life of cement-containing pavement layers. The study is based on the existing and applicable equations of mathematical models. **Results**: We analyze the operation of pavement structures with respect to defects (macro and micro defects) formation as well as factors affecting the structure service life. Dependence of the strain capacity on the modulus of elasticity of sludge ground and the bending strength as well as dependence of the self-hardening coefficient on the structure service life are shown; factors affecting the structural durability are noted. An overview of the equation for the specific strain energy of structural bonds in a composite material is presented. We also derive a generalized equation of the service life of a structure taking into account a number of factors and set a task solved at the development of models that are the closest to real conditions.

Keywords

Nepheline sludge, prediction of the structure service life, road pavement, structural durability, self-healing, self-compaction, micro-cracks, slow strength gain.

Introduction

In the development of design and engineering solutions, specialists in design, construction and operating organizations that ensure the life cycle of roads shall objectively predict, foresee and control possible and arising deformations in the structure of road pavements by means of existing tools of mathematical modeling and other analysis methods. The majority of current methods, equations and models are insufficient since they do not completely take into account real parameters of the traffic flow and ever-changing weather conditions, as well as relevant parameters of moisture transfer and temperature behavior in the road bed – pavement structure system. As Nosov noted (1997), these parameters predetermine the destructive nature of cement-containing surfaces due to the gradual accumulation of microdamage. This is applicable both to the road surface, reinforced road foundation, and subgrade.

In another work (Nosov, 2013), the author emphasizes the objective nature of a solution to the task of determining the service life (T_{ser}) of the road pavement. The actual service life T_{ser} is less than the estimated one (T_{est}).

When new construction materials are used for pavements, including nepheline sludge (NS, alumina production waste) used in road foundations, it is important to predict (calculate) the T_{ser} value in pavement structure development. While in case of traditional pavements, it is possible to use T_{ser} for similar structures, then in order to calculate T_{ser} of pavement structures made using a new material, it is necessary to study test road sections, which is time-consuming and expensive. Therefore, it is required to calculate T_{ser} using empirical equations confirmed by laboratory tests that are similar to real processes.

Subject, tasks, and methods

The subject of the study is the self-healing ability (recombination) of nepheline sludge and its positive impact on the service life of road structures (Mukharryamov, 2017). The article solves the following tasks: analyzing the state of application of nepheline sludges in the road industry, taking into account their self-healing ability; deriving a generalized equation to predict the service life of road pavements made using nepheline sludges. In the course of the study, methods of planning univariate and multivariate theoretical experiments were used.

Results and discussion

When determining the strength characteristics of a road foundation made using sludge and subject to intense impact from vehicles, it is necessary to take into account the specifics of the behavior of a new type of foundation, its physical, mechanical, chemical and thermal properties. A typical road foundation has a heterogeneous structure. This is due to the fact that it consists of various construction materials (native soils, native rock materials, crushed stone of various sizes, gravel-sand mixtures, limestone, and others) that interact with each other through friction and cementation.

As opposed to lean concrete, sand-and-cement mix, and other cement-containing structural layers that are highly brittle and hard, a layer made using nepheline sludge is more elastic-plastic, characterized by high crack resistance at dynamic loads from vehicles, and hinders intense crack formation. Nepheline sludge has special physical and chemical characteristics: the crack resistance of rolled nepheline sludge whose brittleness varies from 0.2 to 0.8 is conditioned by its specific strain capacity (Mukharryamov, 2019a). This is due to the shock-absorbing effect of sludge grains that have significant microporosity (up to 30%) making it possible to diffuse concentrated stresses at the tip of a subcritical micro crack. The brittleness of nepheline sludge rarely reaches 1.0. The crack resistance of nepheline sludge is conditioned not by Griffith's energy criterion but by the strain capacity that controls the subcritical growth of main cracks (Kalashnikov et al. 1995).

$$D = \frac{R_{compression}}{E_{layer}^{sludge}} \quad (1)$$

where *D* is the strain capacity, [relative values],

$R_{compression}$ is the estimated value of tensile strength in bending of a reinforced material in a layer of the road structure or road bed, [MPa],

E_{layer}^{sludge} is the modulus of elasticity of sludge ground, [MPa].

Since the crack resistance of a layer depends on the strain capacity, it is required to introduce a coefficient that will record the loss of strength in a sludge ground layer after temperature shrinkage.

Sludge slowly gains strength, hardens gradually, and layers made with the use of sludge have a tendency towards recombination (self-healing). S. N. Zhurkov (Zhurkov, 1968) states that lean concrete, sand-and-cement mix, and other cement-containing structural layers do not possess an ability for self-healing after bond breaking, as opposed to structural layers made using nepheline sludge.

Self-hardening in time occurs due to the hydration of the main component of nepheline sludge — β-dicalcium silicate 2*($2CaO \cdot SiO_2$). Self-hardening is a self-induced increase in the strength of structural bonds in a solid material during its use (Federal Road Agency (Rosavtodor), 2015). Conventional local and other stone materials are cohesionless (discrete) materials that do not have structural bonds between the particles, do not resist tension and are destroyed under loading with irreversible displacement. Nepheline sludge is subject to the aggregation of smaller (less than 0.314 mm) grains with large grains. There are natural and structural bonds. Industrial Road Guidance Document ODM 218.3.043-2015 (Federal Road Agency (Rosavtodor), 2015) suggests introducing a special indicator — the predicted modulus of elasticity of the foundation material (E_{ft}).

$$E_{ft} = E_0 \cdot \alpha \quad (2)$$

where α is the self-hardening coefficient.

Using the value of the predicted modulus of elasticity of the foundation material (E_{ft}), the value of the design modulus of elasticity of the subgrade (E_{sub}) and design thickness (h_0), the predicted total modulus of elasticity of the road structure $E_{req}^{\min t}$ after self-hardening is determined according to Industrial Road Regulations ODN 218.046-01.

The relationship used for determining the self-hardening coefficient, given in the corresponding regulatory document (Federal Road Agency (Rosavtodor) 2015), is very important in the subsequent development of the ideas, equations and mathematical model of V. P. Nosov for the case of using nepheline sludge in the structural layer of road pavements.

$$\alpha = 0.3642 \cdot \ln(T_{ser}) + 1.37 \quad (3)$$

where T_{ser} is the service life of a road structure at the moment of self-hardening coefficient calculation.

Thus, it is obligatory to take into account the self-hardening coefficient (equations (2) and (3)) when presenting or supplementing the equation used to predict the service life of pavements using sludges.

Sludge represents a structure-forming material in the foundation layer made of a mix of crushed stone and local stone materials, where the upper part of the layer can resist shear and bear vertical loads. This leads to an increased service life of the whole pavement.

The above specifics of nepheline sludge used in layers of road structures should be taken into account when determining/clarifying/updating the service life of composite road structures (Mukharryamov, 2019b).

Before describing the model for the prediction of the service life of pavements with nepheline sludge, which will be used to make a hypothesis about the service life, it is necessary to find the sources that negatively affect the pavement structure in general and determine due to what factor the destruction occurs.

Factors that affect durability (*D*) and have a random impact on the structure as a whole are as follows:

1. heterogeneity of materials;
2. increased stresses in composite materials due to various origin of components, which leads to microdamage;
3. alternating moisturization/drying, freezing/defrosting; precipitations; air humidity;
4. solar radiation;
5. rapid changes in temperatures; air temperature;

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6. impact of osmotic pressure; cloud amount; wind speed;

7. highly scattered loads from vehicles.

When determining the service life of a pavement, it is necessary to take into account all the above factors to the maximum degree. The research conducted by V. P. Nosov and S. N. Zhurkov to derive the equation to calculate the pavement service life can be used as the basis for the model.

According to the theses and equation suggested by S.N. Zhurkov (1968), the relationship of durability t (time) and σ (stress) from T (temperature) is as follows:

$$t = \tau_0 \cdot \exp\cdot(\frac{V_0 - n\cdot\sigma}{R - T}) \quad (4)$$

where τ_0 is a constant, [~10–13],

R is the Boltzmann constant, [~1.38·10-16 erg/degree],

T is temperature (degrees),

n is the coefficient that characterizes the structure and homogeneity of the material (sludge ground layer, sludge-and-crushed stone layer) and is important for the consideration of special nepheline sludge properties,

V_0 is the potential barrier (energy that brings breakup of atomic bonds).

In a loaded body under the effect of tensile forces, the potential barrier V_0 will decrease, and the fluctuation energy will start gradually breaking up the structural bonds, creating micro-cracks. The specific strain energy, i.e. the energy to be spent in order to destroy the structure of a layer in the process of its deformation to a certain degree, can act as an indicator of the destruction of structural bonds (Zadneprovskiy, 2016). In terms of math, this indicator is expressed as the ratio between the energy and the volume where structural bonds are destroyed:

$$A_s = \frac{A}{V} = \sigma \cdot \varepsilon \quad (5)$$

where A_s is the specific strain energy,

A is the deformation energy,

V is the volume of the deformed layer,

σ is the ultimate stress,

ε is the relative strain.

Presumably, if the load decreases further, the time spent for the accumulation of structural failures and occurrence of this type of deformation will increase. In this case, the total specific energy spent for the destruction of the layer structure will consist of the sum of the energies spent at each change of temperature (the temperature factor that affects the pavement service life is taken into account):

$$A_s = \sum_1^n A_{si} = \sum_1^n \sigma_i \cdot \varepsilon_i \quad (6)$$

The above is in line with the concept of the "damage degree" introduced by V. P. Nosov (Nosov, 2013). In lean concrete, sand-and-cement mix, and other cement-containing layers, damage is accumulated gradually. This process results in micro-cracks. The length of micro-cracks grows until a certain moment when they become a single micro-crack. At the place of its origin, stresses increase. It is a so-called stress concentration, which accelerates the further growth. Crack development leads to pavement destruction. Such a process of the gradual accumulation of defects under the effect of alternating stresses is called cyclic fatigue of cement-containing layers of the pavement structure. In cement-containing layers, large cracks and cracks growing in width (when the process has ended) develop along a weakened section (with the maximum stress-strain state). It should be noted that in sludge, due to slow gain in strength, small cracks (when the process continues) reform concrete till its maximum strength, and destruction of concrete starts only after that.

The process of sludge strength gain due to the dynamic effect of the load and compaction together with the development of micro-cracks each time a vehicle passes the pavement leads to sludge activation and layer reformation (slow and gradual) until the formation of a finely grained sludge-and-concrete mix. Two processes occur in sludge after the paving and one-year operation:

1. gradual crack formation;
2. crack healing in parallel to the first process.

The above processes are directly reflected in the equation and model to calculate the pavement service life since the components of nepheline sludge activation and the factor of dampened crack growth will be taken into account.

In accordance with the theory suggested by V. P. Nosov (Nosov, 1980a, 1980b) and cyclic fatigue of cement-containing layers of the pavement structure, the level of the stressed state in a cycle (ρ) depends on the relationship between the maximum stress at single loading and the ultimate strength at single loading.

$$\rho = \frac{\sigma_{\max}}{R} \quad (7)$$

There is a stable correlation between the level of the stressed state and the number of cycles before the destruction of a sample (N):

$$N = F \cdot (\frac{\sigma_{\max}}{R}) = F \cdot \rho \quad (8)$$

where F is the coefficient characterizing the relationship.

The number of cycles depends on the load cycle characteristic, and the load cycle characteristic is the $\sigma_{min}/\sigma_{max}$ ratio in a cycle.

Stresses caused by loads from the movement of vehicles, which occur in structures, vary since the traffic flow consists of different vehicles with different carrying capacity, different axle loads, different position of the wheels relative to the road edge, different condition of the subgrade, road surface temperature, etc. This is why the value of tensile stresses in an arbitrarily fixed moment t is random, i.e. the function of stress changes in time is random.

In order to find N (the ultimate number of cycles of loads for a pavement that is in a stressed state characterized by an arbitrary random function), defects should be summed.

$$\alpha_i = \frac{1}{N_i} \quad (9)$$

where N_i is the cycle of load application (determined by means of the stress-cycle diagram), α_i is a single defect.

The process of layer (primarily, surface) destruction can be represented as a process of the accumulation of single defects caused by each cycle of application of axle loads from vehicles moving on the road (cumulative model by V. V. Bolotin) (Bolotin 1981).

The damage degree according to V. P. Nosov is as follows:

$$D = \sum_{i=1}^{C} \alpha_i \tag{10}$$

where C is the number of repeated loads for a certain period of time.

Therefore, at D<1, we observe pavement material behavior without destruction; at D=1, the material is damaged since the threshold value of N is reached.

Equations (9), (10) make it possible to predict the performance of road surfaces and foundations. The more $D(t)$ approaches 1, the faster the destruction of the road surface will be and the less residual performance the pavement structure will have at this point in time.

One of the conclusions made by a number of experts (Nosov, 2013) is as follows: the width of a cement-containing layer (slab) is the most important factor that predetermines cracking and T_{ser}. This should be taken into account when designing composite pavements.

Foreign authors suggest an equation that accurately determines the value of cracking (C), which directly depends on vehicles (the number of wheel loads with the load per wheel of 4.082 t) and the slab width:

$$C = 2.8 \cdot N \cdot H^6 \tag{11}$$

where N is the number of interactions between the pavement and the wheels,

H is the slab (layer) width, in inches (1 inch = 0.0254 m).

The foreign scientists derived this equation through a number of experiments and analysis of previous experience, but with different climate conditions. That is why, when this equation is used to calculate the pavement service life in Russia, it is necessary to introduce some adjusting factors or clarify the equation due to: I — heterogeneity of the materials and soils comprising the subgrade and pavement, II — variability of climate conditions during road operation, and III — traffic flow parameters, which lead to the fact that we have to predict T_{ser} on the basis of many formalities and assumptions (Nosov, 2013).

It would be insufficient to use traditional equations to determine the service life of road pavement in terms of its reliability since they do not completely take into account parameters of the structure, physical and mechanical properties of the materials and soils comprising the subgrade, and natural features of the road location.

In his paper on the analysis and consideration of the dynamic interaction between concrete road surfaces with the road foundation, V. A. Chernigov (Chernigov, 1963) presents an equation to determine the limit number of impacts:

$$\lg N = \left(R \cdot K_1 - \frac{6 \cdot P \cdot (0.0592 - 0.09284 \cdot \lg \frac{r}{L})}{H}\right) \cdot \frac{\lg N_0}{R \cdot (K_1 - K_2)} \tag{12}$$

where R is the ultimate tensile strength in bending, MPa;

K_1 is the endurance limit corresponding to one load cycle, K_1 = 0.45.;

P is the mass of the vehicle affecting a wheel, t;

r is the radius of a circle equivalent to the vehicle wheel imprint;

L is the elastic response, which is calculated using the following equation:

$$L = H \cdot \sqrt[3]{\frac{E}{6 \cdot E_0}} \tag{13}$$

N_0 is the base number of cycles when determining the endurance limit.

The widely-known equation, suggested by foreign scientists after a number of new experiments AASHO conducted in 1962, should be taken into account (Fenves et al., 1962). This equation empirically calculates the limit number of axle impacts on the layer N depending on the value of cracking C:

$$\lg N = 4.7 + 0.5 \cdot \lg C - 2.62 \cdot \lg\left(\frac{2 \cdot P}{0.454}\right) + 4.84 \cdot \frac{H}{254} \tag{14}$$

where P is the mass of the vehicle affecting a wheel, t;

C is the length of cracks relative to 100m^2 of the road surface, m;

H is the thickness of the road surface, cm.

The equation referenced by V. A. Kudryavtsev (Kudryavtsev et al., 1973) is also important. It takes into account the difference in temperatures at the top and the bottom of the road surface (different temperature stresses):

$$N = \frac{6 \cdot P \cdot (0.0592 - 0.0928 \cdot \lg \frac{r}{L})}{1.08 \cdot R \cdot H^2} - \frac{E \cdot \alpha \cdot \Delta T}{2.16 \cdot R \cdot (1 - \mu^2)} \cdot (C_x + \mu \cdot C_y) \tag{15}$$

where α is the coefficient for the longitudinal expansion of concrete (in our case, sludge ground / sludge-and-crushed stone mix foundation/surface);

ΔT is the difference between the temperatures at the top and the bottom of the slab (the same goes for sludge ground / sludge-and-crushed stone layer);

E, μ is the modulus of elasticity and Poisson's ratio for concrete / sludge ground / sludge-and-crushed stone layer;

C_x and C_y are the coefficients that depend on the ratio of the length and width of the slab and the elastic response.

This is why it is necessary to take into account processes affecting the pavement service life to develop

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a model to predict the service life of road pavement made using nepheline sludge.

It is reasonable to divide all the factors into the following three groups: traffic flow parameters, weather conditions' parameters, and structure parameters representing vector projections. Traffic flows have different speeds and different distances from each other. We introduce the following parameters: vehicle type, wheel arrangement, weight distribution on axles and wheels, pressure in tires, speed, lateral position, distance between vehicles.

Weather conditions include solar radiation, air temperature, cloud amount, precipitations, air humidity, wind. Structure parameters characterize the shape and size of the structure elements (road surface, road foundation, subgrade, road bed), as well as the properties of the materials and soils used in the structure. It should be emphasized that under the influence of weather conditions, the structure parameters change, and these changes are so important that stresses caused by vehicle loads can change manifold.

Heterogeneity of a pavement layer occurs due to technological mistakes (insufficient mix compaction, failure to comply with the time limits for curing the mix until compaction, maintaining a new layer after the paving, etc.).

Conclusions

A pavement layer made using nepheline sludge is characterized by specific strain capacity and crack resistance. Strength is gained slowly. Sludge ground layers of pavement structures have a self-healing advantage in comparison to cement-containing layers. These advantages of sludge ground layers increase the pavement service life in comparison to lean concrete, sand-and-cement mixes, and other cement-containing layers.

As a result, the service life remains an important indicator of road structure operation. It can be represented in the form of dependence from various factors (a general equation).

$$T_{ser} = f(n; n_1; T°C; W; P) \qquad (16)$$

where n is the homogeneity of the material,

n_1 is a change in stresses occurring in the structure during its operation taking into account the process of nepheline sludge self-healing,

$T°C$ is changes in the air temperature,

W is the water and temperature conditions of the structure;

P is the dynamic load from the traffic flow.

As for the impact of other factors on the pavement service life, further research of their application to sludge ground layers of pavement is needed.

The main purpose of this study is to address the matter of determining the pavement service life with account for the specifics of nepheline sludge as it is in the structure as a binder (matrix) for local stone materials.

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СОВЕРШЕНСТВОВАНИЕ РАСЧЕТА И КОНСТРУИРОВАНИЯ ДОРОЖНЫХ ОДЕЖД С ИСПОЛЬЗОВАНИЕМ НЕФЕЛИНОВОГО ШЛАМА

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Аннотация

Прогнозирование возможных и зарождающихся дефектов, в конструктивных слоях дорожных одежд, устроенных из новых строительных материалов, важная задача при эксплуатации любого объекта транспортной инфраструктуры. **Цель исследования**: Провести литературный, нормативный и практический анализ процесса работы конструкции дорожной одежды. Анализ работы цементосодержащих конструктивных слоев. Полученные результаты перенести на конструкции дорожных одежд, устроенных с применением нефелинового шлама для формирования формулы общего вида, которая дает понимание модели прогнозирования срока службы конструкции в зависимости от различных факторов. **Методы:** Методологическая основа данного исследования представляет из себя базу информации по положениям теории и практики развития прогнозирования сроков службы цементосодержащих слоев дорожных одежд. В исследовании за основу принимались уже существующие и применяемые формулы математических моделей. **Результаты**: Проанализирована работа конструкций дорожных одежд на предмет образования дефектов (макро- и микродефекты), а также на предмет влияющих факторов, на срок службы конструкции. Показана зависимость деформативности от модуля упругости шламогрунта и величины сопротивления растяжению при изгибе; приведена зависимость коэффициента самоупрочнения от срока службы конструкции; также отмечены факторы, влияющие на долговечность конструкции. Обзор формулы удельной энергии деформации структурных связей в композитном материале. Выведена обобщенная формула срока службы конструкции с учетом ряда влияющих факторов, а также поставлена основная задача, решаемая при разработке моделей более близких к реальным ситуациям.

Ключевые слова

Нефелиновый шлам, прогнозирование срока службы конструкции, дорожная одежда, долговечность конструкции, самозалечивание, самоуплотнение, микротрещины, медленный набор прочности.