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TOPOLOGICAL INTERLOCKING AS A PRINCIPLE OF ENGINEERING DESIGN IN CONSRUCTION OF MARINE AND COASTAL STRUCTURES

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As a discussion contribution, a new concept for solving problems of bank protection structures based on topological interlocking is presented, which opens up a way to obtaining new segmented or modular designs of building elements and structures. The relevance of the modular design principle based on the use of natural laws of harmonization of artificially created forms is justified. In this concept, the idea of Platonic solids is further developed in a quest for new types of harmony and practical technological and engineering design applications at macro scale. The ever growing capabilities of modern building materials and technologies make it possible to create new construction systems on the basis of the modular principle, one of the most interesting forms of which is topological interlocking. This innovative principle of engineering design and its many advantages are considered in relation to bank protection structures. Variants of new promising designs based on topological interlocking are presented.

***Keywords*:** bank protection structures, topological interlocking, hybrid materials

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Introduction. The total length of the coastline of Russia, washed by the seas and oceans, is about 40 thousand km. Due to the destruction of shores and their absorption by the World Ocean, this figure is constantly growing. The issue of reinforcing and protecting shores is especially acute in coastal cities and settlements where this problem is always topical and poses serious environmental challenges. Thus, at the beginning of the current century, the construction of a flood protection complex was completed in St. Petersburg, which, along with the real protection of the city, brought about a host of problems associated with a change in the ecosystem of the Gulf of Finland aquatic area due to a disruption in circulation of natural water flows. The organization of additional culverts in some parts of the dam during the final stage of construction did not lead to a significant improvement in the environmental situation. Today, a single and obvious solution to the problem is the expensive draining of wetlands of the Gulf of Finland and the attendant land reclamation.

However, what can be done in St. Petersburg is unlikely to be feasible in other coastal areas, such as the Krasnodar Krai on the Azov Sea with wetlands and a huge water area with an average depth of less than 2 m and silt thickness of more than 50 m. The development of these coastal areas requires a special approach and consideration of ecological features. Traditional continuous filling with small rocks is unacceptable in this case, and a new concept of solving shore-strengthening problems is needed. A similar situation applies to the northern coast of the Caspian Sea, as well as to a significant part of the southern shore of Lake Ladoga.

It is important to understand that in the near future, due to global warming and the raising level of the World Ocean, considerable efforts and costs will be required to fortify the sea shores, the total length of which worldwide is more than 1 million km. In the light of the above, the search for effective bank protection structures based on the newest materials and technologies is timely and relevant.

Currently, work in this direction is being carried out at the Department of Materials and Technology of Artworks Manufacturing of the Saint-Petersburg Mining University in cooperation with the Laboratory of Hybrid Nanostructured Materials of the National University of Science and Technology «MISiS» and the Department of Architecture and Design of the Sochi State University. A new concept of construction has been developed, whose essence is the modular principle of design and a technology of step-by-step laying of load-bearing elements of dams or bank reinforcement

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structures, such as breakwaters and tetrapods, made of hybrid high-strength heavy concrete with organic coating, which are interconnected by topological interlocking. An example of the geometry of the building blocks, which makes it possible to implement the modular design of bank protection structures, is shown in Fig.1.

This approach is in line with modern design methods, which originate in the field of interdisciplinary research aimed at harmonizing the artificially created forms and are increasingly moving towards the use of natural laws.

Discussion. One of the features of modern development in the scientific domain is, along with the transition to nanoscale structures, rapprochement between and interpenetration of the inorganic matter and the organic world of living nature. The principles of biomimetics are increasingly being used in the design of materials and engineering structures. Turning to a holistic picture of the world has become a natural trend in science that opens a new stage in the materials research and development. This is how nanobiotechnologies and new classes of composite materials, including hybrid nanomaterials, have come to being.

The concept of hybrid materials in scientific discourse has emerged due to the research of Australian scientists in the field of morphology of topologically interlocking, or self-wedging, materials [9, 15]. The principles of topological interlocking developed by them are ideally suited for creating hybrid materials by combining dissimilar (sometimes even incompatible) materials into an integrated structure, in any proportions. In Russia, the study and development of hybrid materials commenced relatively recently. As part of the implementation of a Russian Government grant, a specialized laboratory under the leadership of one of the authors of this article, engaged in the development of composite hybrid materials, was set up at NUST «MISIS». It was there that a new term, "archimats" was coined to designate materials with a special inner architecture, which also defines interlocking blocks of small size, from which a macro scale structure can be formed and shaped [2]. Within a short period of time the laboratory managed to obtain convincing results demonstrating to the research community the advantages of «non-monolithic» structure of hybrid materials, which open up a wide pathway to further research in this field.

In 2015, the Saint-Petersburg Mining University embarked on a study of the feasibility of practical application of the principles of topological interlocking in the construction of bank protection structures in Sochi. For this purpose, scientific contacts were established with the NUST «MISiS» laboratory and Sochi State University, which resulted in joint publications [5].

It is well-known that a landmark of any seaside city is the individuality and uniqueness of its se facade. In this respect, as yet Sochi does not meet the expectations one has of it as the main resort of the country. Therefore, a common task of architects, designers and builders is speedy elimination of this shortcoming. It was decided to start with the most aesthetically annoying and, at the same time, very significant bank protection elements and structures, such as breakwaters and tetrapods. With the help of computer modeling based on the modular design principle [6], there has been performed calculations and selection of the inner structure of the material, the optimal shapes and sizes of the studied objects for testing and their practical application in non-monolithic, «mosaic» form making

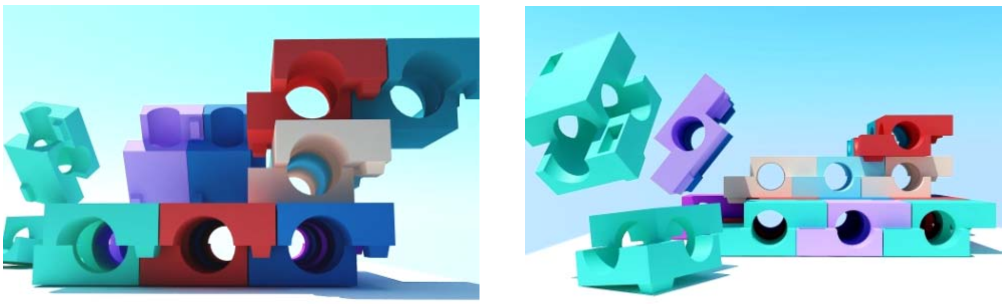

Fig.1. An example of modular elements for application in bank protection structures

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them to real macro size archimats. A methodology for manufacturing small-scale prototypes of coastal fortifications with various designs has been developed, and their laboratory and bench tests have been conducted.

At some point, by mutual agreement of the researchers involved in the project, the term «interlocking» was replaced with the term «self-wedging» proposed by Alexey Kanel-Belov, which most accurately reflects the essence of the principle of assembly of the individual blocks into a structure. Let us recall the essence of the block «self-wedging» principle. It was previously reported [15] that an important feature of the new class of composite materials is their non-monolithic structure and their being ensembles of individual elements – self-wedging or interlocking blocks that can have different shapes, including tetrahedrons, cubes, or other members of the family of the so-called Platonic solids [15] (Fig.2). Their peculiarity consists in the fact that they are convex polyhedra and that the contact between them is implemented on their flat faces. Self-wedging occurs due to their shape and mutual arrangement in space. No binding elements or glue is required for that. This is where they radically differ from the blocks shown in Fig.1, which are connected according to the «LEGO» principle.

Another type of self-wedging elements are the so-called osteomorphic blocks, the connection of which occurs due to their concavo-convex contact surfaces [9] (Fig.3). At the same time, the geometry of the blocks is such that after their assembly none of the «bricks» can be extracted from the resulting structure. Due to the mosaic nature of the material, the overall resistance to fracture increases. The product remains solid and does not lose its serviceability under loads, even if part of the blocks are destroyed, and the «tolerance» of the structure to local damages is very high [9]. As an example, a sheet of glass with a length of 2 m, which in the usual monolithic state has a deflection of not more than 10 %, being made of self-wedging elements, can be bent into a pipe with a diameter of 63.6 cm [2].

As mentioned above, the principle of topological interlocking provides the possibility to create a vast variety of different hybrid materials. One of the variants of such a hybrid is shown in Fig.4 [9].

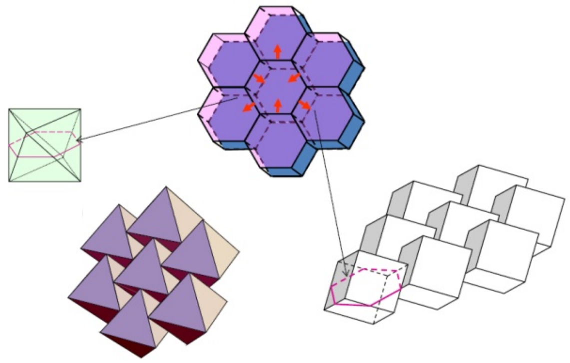

Fig.2. Examples of interlocking of Platonic solids [3]

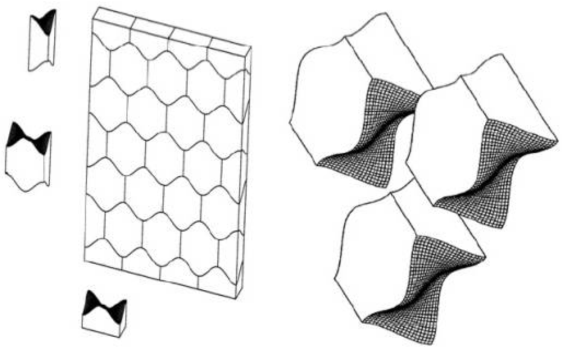

Fig.3. Assembly of osteomorphic units [9]

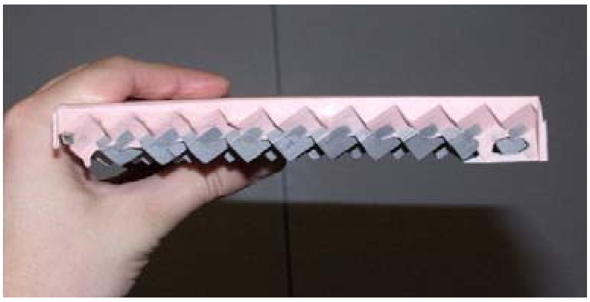

Fig.4. Hybrid structure made of topologically interlocked metallic cubes with flexible polymer base [9]

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Fig.5. Examples of plane segmentation into geometrically simple shapes

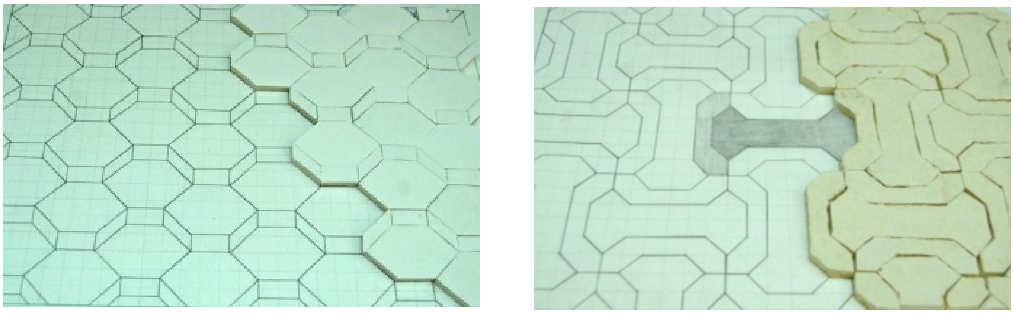

Fig.6. Building volumetric structure from interlocking units by transforming the tesselation of the initial plane when shifting to parallel planes along their common normal

Undoubtedly, obtaining the described advantages of hybrid materials at the macro level requires the use of special techniques and design solutions for constructing the inner space and the body of the product. The knowledge of just the Euclidean geometry is not enough for that. When developing a design and calculating specific products, especially the load-bearing elements of hydraulic structures, it is necessary to take into account all types of external influences on the structure during its operation, and its spatial location relative to the main load directions. It can safely be said that such work will always be unique, since the conditions and the environment for a given structure in each particular case are unique. Since the problems of bank protection structures are of a global nature, today it is extremely urgent to formulate new concepts for their solution.

One of the key points of our new concept is the modular design principle [1, 3]. Volumetric elements are generated by transforming a flat modular grid when shifting to parallel planes along their common normal. The mathematical principles of such transformation, leading to a three-dimensional structure of self-wedging blocks, were formulated in [12]. For a formal design search, a plane tessellation can be formed from simple geometric shapes or their combinations (Fig.5). The evolution of the elementary planar modules used in this work when shifting in a direction perpendicular to the initial plane is illustrated in Fig.6.

The vertical volumetric construction is carried out taking into account the contacts between the formed blocks on their sides. In this way, the conditions under which the modules «arrest» each other are created. Thus, original composites with a pre-conceived structure can be formed, in which gravitational characteristics of the interacting individual modular elements (blocks) transform the motif specified in the initial plane into a self-wedged spatial structure [4]. The segmentation, or tessellation, of a plane can be carried out in various ways. Thus, tessellation into squares or regular hexagons leads to a layer of interlocked Platonic solids [12]. The possibilities of other tessellation options, including a Penrose mosaic, were investigated in [17].

Thus, the spatial search based of geometric modularity becomes a strictly formalized design process. One can say that in this case the form arises in the design process [6]. Since the motifs of tessellations of the initial plane allow for a huge number of variations, this technique makes it possible to introduce new parameters and a variety of plastic forms in the architectural design practice [11, 16, 17].

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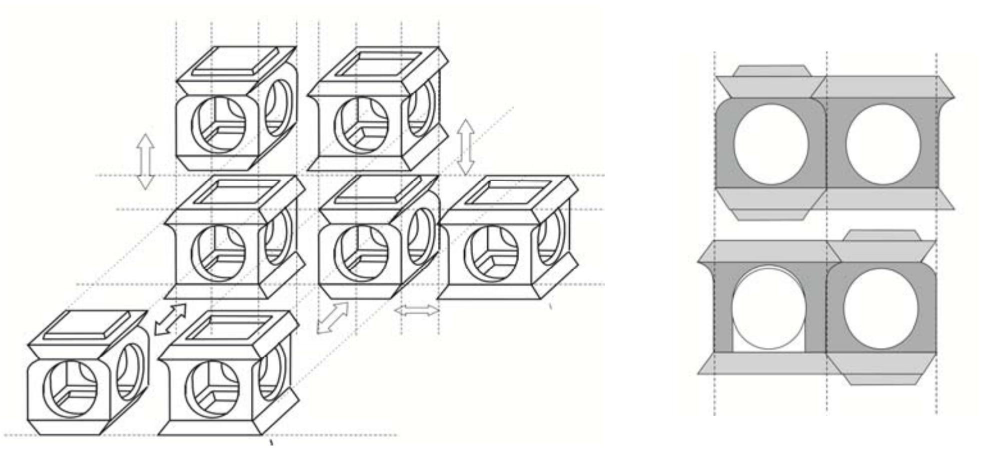

Fig.7. An example of elementary units enabling self-wedging

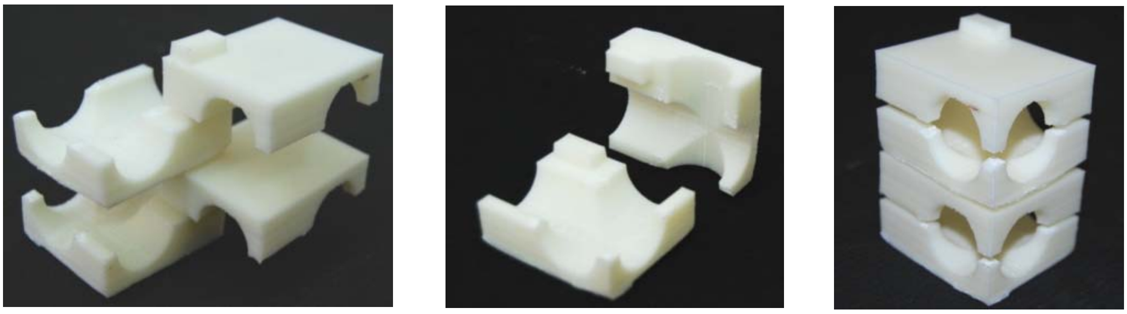

Fig.8. An example of modular blocks for bank protection structures manufactured by 3D printing

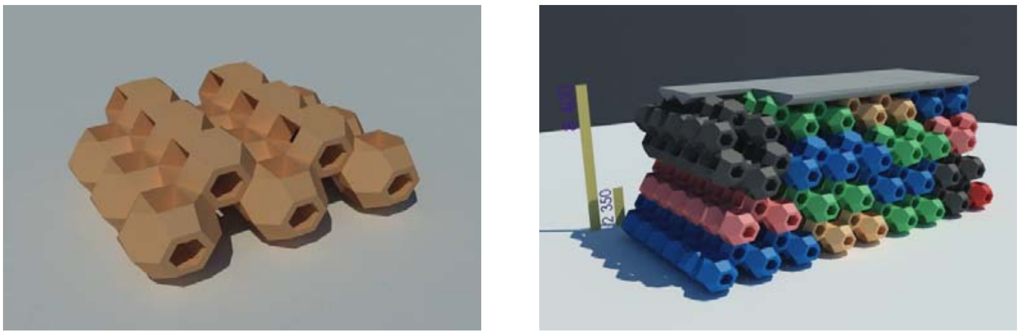

Fig.9. Design of modular block assembly providing free circulation of water flows

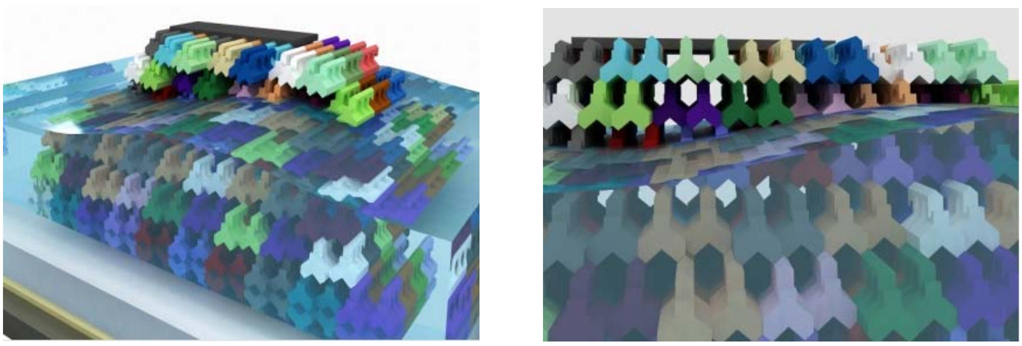

Fig.10. An assembly of modular blocks interleaved with soft polymer materials

Fig. 7 presents schematic and volumetric images of modular assemblies of self-wedging elements [4]. (We note, however, that their geometry does not fall under the definition of topological interlocking elements given in [13]).

The rapid development of 3D printing technologies greatly expands the possibilities of innovative design, notably with respect to bank protection structures. By way of example, Fig. 8 shows modules designed and 3D-printed, which are aimed at solving problems of bank protection.

The interlocking features of blocks enables the creation of spatial structures that ensure free circulation of water flows in the underwater part of bank protection structures. Figure 9 presents one of the design options for the modular assembly of units, which, in addition to the main load-bearing function, provide free circulation of water flows in all directions and the possibility of laying various communications and their maintenance inside the structure.

Another feature of the new concept is the use of hybrid heavy concrete in combination with organic polymer coatings in manufacturing and assembly of modular blocks. It is suggested to use concretes based on magnesia cements, which have a unique ability to harden in seawater. The density of these concretes depends on the type of filler and reaches 4000 kg/m^3 for concrete with magnetite filler, and 5000 kg/m^3 for cast-iron shot or metallurgical scrub.

Improvement of concrete parameters such as compression strength (up to 200 MPa), waterproofness, frost-resistance and, as a result, durability is provided by treatment of concrete with monomers and polymers of organic origin.

Coating of modular blocks with soft polymers will ensure their efficient assembly and reliability in operation (Fig.10). In [10], an increase of load-bearing capacity and fracture resistance of assemblies of rigid osteomorphic blocks with soft interlayers was demonstrated. Further improvements in structures of self-wedging blocks by armoring are possible. In particular, it is of interest to reinforce assemblies from osteomorphic blocks with rods of materials with shape memory [13]. This provides the possibility to control the shape and rigidity of the assembly through external stimuli, for example, by passing an electric current through reinforcing rods.

Conclusion. In recent years, foreign architects and builders have appreciated the possibility of topological self-interlocking as the principle of engineering design [11, 16, 17], in particular, for the creation of marine bank protection structures. Developments in this direction are just beginning to unfold. Of course, the introduction of such an approach in the creation of real large structures will require comprehensive laboratory-scale testing and a critical evaluation of the eligibility of transferring their results to real life conditions. However, in the opinion of the authors, topological interlocking, combined with the use of the latest materials and technologies, has undisputable potential, which justifies investments in this kind of research. Through this publication the authors hope to draw the attention of the engineering community to new technological solutions in creating bank protection structures, which are offered by the described innovative principle of engineering design.

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