Historical Overview of Infilled Shell Structures in Construction Practice

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Abstract. The evolution of engineering solutions related to the use of closed shells in construction is shown. Examples of formation of structures from shells with filler are given depending on the historical stage of development of construction technologies. The reasons why the considered structure entered the practice of engineering design are displayed. Versions of combination of infilled shells in structure are shown, as well as examples of built structures and advantages of used structures from infilled shells.

1. Introduction
Like most types of structures, shells in industry and construction appeared and began to be used as the most optimal and less costly solution to specific engineering problems. The positive effect of using curvilinear elements in the formation of openings in the walls, overlapping of spans of premises and the construction of crossings over obstacles was noticed in ancient times, as evidenced by the arched structures, domes and vaults of ancient structures. Among the numerous examples of such structures, one can mention ancient engineering and religious buildings, in which vaults and domes replaced the post-beam floor system.

For a long time, it was the need to overlap large spans and spaces of rooms without additional supports that was the main reason for expanding the scope, improving design solutions and developing the technology for erecting shell structures. Due to this need, associated with an increase of overlapping spaces, and, as a result, an increase of internal forces in the structure, the supporting structures themselves were modified, acquiring a shape that is increasingly close to optimal.

The widespread use of shells has always been and is constrained by the complexity of the design justification of structures and the resulting difficulties in ensuring their reliability and durability. With the development of calculation methods and with the advent of automated computing technology, shells erected with the aim of overlapping spaces have taken a dominant position among the design solutions of these engineering problems, possessing, in addition to the basic required performance characteristics, also high aesthetic appeal. Significant impulse in the use of shells occurred in the late 19th - early 20th centuries thanks to the research and extensive practical activities of the famous Russian scientist and engineer V.G. Shukhov. Currently, almost any unique structure contains one or more shells of various shapes.

Another direction of the use of shells in the construction of structures is caused by their ability to effectively perceive tensile and compressive forces at a relatively low material cost. This property has led to the use of shells for the perception of loads from various media (bulk, liquid, gaseous). Casings have long been used as storage facilities for grain, flour, root crops and other agricultural products, as
well as reservoirs for storing water, and subsequently for storing oil, gas and other products of the oil industry.

2. Overview of infilled shell structures

Shell structures in construction are favored by their ability to provide confinement and resist loads with relatively low material cost. This led to the extensive use of shells for receiving loads from various media in the form of granular solids, liquid, and gas. Shells have long been handled as storage of agricultural products (such as grain, flour, and root crops), water, oil, gas, and other products of petroleum industry. The first theoretically and experimentally substantiated solutions for calculating loads from granulated solids on the inner surfaces of silos were proposed by the German engineer Janssen (reference year) at the end of the 19th century.

Due to the rapid growth of urban agglomerations recently, the relative volume of underground construction is constantly increasing. Shells remain the primary constructive solution for receiving loads from the soil masses during the construction of many massive structures. Since the middle of the 20th century there have been also projects that used shells as foundation elements. The history of using shell infill as a part of the structure originates in the practice of constructing retaining structures where shell receives the pressure of the backfill. The shape of the enclosure contributes to the reduction of internal forces in the structure.

The use of infill in hollow building structures as a structural material is associated primarily with the construction of massive berthing facilities. There is evidence of the use of massive wooden hollow cones at the end of the 18th century during the expansion of the port of Cherbourg (France), transported by their own buoyancy to the place of work and flooded due to their own weight as their cavity was filled with a large stone [1]. For example, crib waterfront structures were built in the Northern Seas harbors during the XIX century (reference, year). Due to the presence of sufficient forest reserves, the shell was made of cribwork in the form of timber blocking logs, and the internal cavity of the cribwork was filled with coarse-grained soil (Ошибка! Источник ссылки не найден.1а).

The development of production in monolithic and prefabricated reinforced concrete structures led to the emergence of box caisson gravity structures (figure 1b). Such structures are produced monolithic (when erecting cofferdams cutting-off water), or in the form of thin-walled reinforced concrete floating boxes transported to the placement location, submerged and filled with coarse-grained soil. With the emergence of design methods, manufacturability and capability of building structures of high-strength steel grades, reinforced concrete and some types of plastic, as well as theoretically substantiated methods and techniques for protecting structures from corrosion and other aggressive environmental impacts and the proportion of shell material in the total volume of the structure became less, the required shell thickness reduced, freeing space for the infill in the structure.
Figure 1. Examples of using the infill as a part of a massive structure; (a) protective works in Kronstadt, XVIII-XIX centuries. (Russia); (b) the construction of box caissons for a pier in the city of Korsakov (Jap. Otomari, 1920-1925) (photo from the collection of the Sapporo city library).

Since the middle of the 20th century, the examples of thin-walled shells application and thin-walled shells of various shapes have occurred. They were utilized more actively where the volume of filler material could reach 95% of the total volume of the structure.

Thin-walled shells with infill are relative newcomers. "Industrial" use of shells with infill as the core support of the structure is considered to begin with the construction of hydraulic engineering facilities. The first structure of the kind was implemented in the port of Le Havre City in France from 1947 to 1949 [2, 3] (figure 2)

Figure 2. Scheme of the Pasquier Herman embankment in the port of Le Havre City (France); (a) - cross section of the embankment; (b) – shells section in plan; 1 — reinforced concrete shell, 2 — decking (dimensions in m).
Since the 1960s, reinforced concrete shells with thinner walls have been used (wharves in the port of Dunkirk, France (figure 3), and the traditional construction technology of subsidence wells (dry masonry, in the pit) has been used to place them on the foundation soil.

Since the beginning of the 1970s, monolithic and prefabricated structures of reinforced concrete shells in various configurations have been widely used in the construction of various hydraulic structures all round the world. They have been used in the construction of oil berths, berths for unloading coal, mooring dolphins, piers, moles, breakwaters and other facilities in the ports of Marseille Fos, La Pallice, Le Havre (France), Cadiz (Spain), Quebec (Canada), Kalundborg, Hanstholm (Denmark), Brighton (United Kingdom), Kobe (Japan), Rio de Janeiro (Brazil), as well as in the territory of republics forming the USSR, in the cities of Riga, Klaipeda, Astrakhan, Sevastopol, St. Petersburg, Baku, Novorossiysk and other places [3].

![Figure 3](image_url)

**Figure 3.** Embankment scheme in the port of Dunkirk (France); (a) - cross section; (b) - the view of shells in plan; 1 - reinforced concrete shell, 2 - shells cantilevers under the decking, 3 - decking (dimensions in m).

The first examples of the multi-cell massive filled structures use can also be considered a mole in the port of La Pallice and the embankment in the port of Le Havre built in France in 1970 (figure 4). The use of multi-layered shells system made it possible to reduce the mass and overall dimensions of individual shells, provided the necessary stability of the entire structure.
Figure 4. Examples of shell layouts as part of structures: schemes of the plan and section of mole in the port of La Pallice; 1 - reinforced concrete shell, 2 - baseplates, 3 - decking, 4,5 - shell cantilevers (dimensions in m).

Since the beginning of the twentieth century, there have been examples of using the so-called cellular structures assembled by driving a steel sheet pile in accordance with the outline specified in the plan and filling the formed cavities with local soil. The structures of cells were formed as an alternative to thin sheet-pile walls, as building conditions and structure’s bearing forces frequently went beyond the limits of thin walls. Initially, such structures were used to create temporary crossbars for lifting sunken ships (figure 5), forming coastal strip and solving other problems of the river hydraulic engineering construction [4, 5]. One of the first known cases of eliminating levees and thin walls in favor of arranging closed cells is constructing a cofferdam at Black Rock Harbor, Buffalo, N.Y., USA in 1908 [6].

Figure 5. Use of shells as lintels (cofferdams) - water area fencing at the site of a sunken ship.

The cofferdam structure contained seventy-seven square in plan sheet pile cells installed along closed path. During the construction, as a result of observing under-load operation of structures, the design solution was altered and the last four cells were made with walls rounded in plan.

The most typical outline of sheet pile cellular structures is circular in plan filled tube cell – shell (figure 6).
Figure 6. Steel sheet pile cylindrical shells (cells) (shore protection wall arrangement in Paducah, Kentucky) (a, b) - construction of shell structure and filling with soil.

The experience of research and cellular structures construction by embedding individual sheet pile elements created the conditions for the emergence of the “ready-made cell” technology [7, 8], when a pre-assembled cell of the desired shape is embedded in the soil using the necessary number of silent pile drivers simultaneously. The inability to embed into hard rocky soils caused, in turn, the emergence of solutions for single-sheet steel shells (figure 7).

Figure 7. Cylindrical steel shells; (a) - the process of installing steel sheet shells in Kozmino Bay (Russia); (b) - shell installation (Hong Kong, Hong Kong-Zhuhai-Macau Bridge project).

The first application examples of filled single-sheet steel shells made from solid sheet were registered in Japan and some other industrialized countries of Southeast Asia. In Russia, projects of single-sheet steel shells in hydraulic structures were developed on the proposal of some organizations (the Gidrospetsfundamentstroy trust and the Baltmorgidrostroy trust) [9]. Starting since the 1980s and to the present, both of the above main directions of forming single-sheet steel shells (single-sheet and formed by sheet pile embedding) remain relevant, each finds their own field of application and has certain advantages depending on the conditions of the construction site (geotechnical conditions, resource base of construction, size of the structure, etc.) [10].
3. Conclusion
A brief review of the design solutions history development for structures using infilled shells has been performed. It is shown that shells have been used in construction since ancient times; initially they found application when it was necessary to cover large areas in buildings, as well as spans in engineering communications structures. As the challenges of preserving large volumes of agricultural products, storing fuel and building materials arise, shells are endowed with the important function of retaining the inner filler as a preserved medium. The need for buried and underground structures creates conditions for the contact of the shells with the ground, which, along with the observed property of a sharp improvement in the performance of the shell as it is infilled with loose and cohesive material, leads to the appearance of shell structures in which the filler becomes not a conserved medium, but a part of the structure. The main advantages of the design are in its efficiency, as well as in the possibility of efforts redistribution in the filler during loading and in its versatility.

4. References
[1] O’Bannon P 2009 Working in the Dry: Cofferdams, In-River Construction, and the United States Army Corps of Engineers (Pittsburgh District Pittsburgh, Pennsylvania: U.S. Army Corps of Engineers) p 195
[2] Gurevich V 1969 River port hydraulic structures p 416
[3] Levachjov S 1978 Shells in hydraulic engineering construction (Moscow: Stroyizdat) p 168
[4] Fjodorov V, Titova V 1952 Metal sheet piling (Moscow) p 320
[5] Ovesen N 1962 Cellular cofferdams, calculation methods and model tests 14th ed. (Copenhagen: Denmark: Danish Geotechnical Institute)
[6] Mosher A 1992 Three-dimensional finite element analysis of sheet-pile cellular cofferdams (US: Army-Corps of Engineers) p 435
[7] Sirasi M 1978 Use of steel structures in port facilities constructed in Japan (Japan: Karamu) pp 51-56
[8] Takakadzu M 1978 Method of construction of fencing of steel sheet piles, previously assembled into large blocks, in the construction of ports (Japan: Kjensjeu-no kikajka) pp 27-31
[9] G.T.M 36.44.12.1-90 1992 Harbour hydraulic engineering and design using major diameter steel shells (Saint-Petersburg: VNIIGS) p 63
[10] Chernova T I et al 2014 Overview of Shells with Infill used in Geotechnical Engineering Applications pp 16-18