EARLY PREFABRICATED IRON-RIBBED DOMES: ST. ISAAC'S CATHEDRAL IN ST. PETERSBURG, RUSSIA, 1838–1841

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Keywords

Development of structural form, Iron architecture, St. Isaac's Cathedral in St. Petersburg, August Ricard de Montferrand, Charles Baird, William Handyside.

Abstract

One of the major architectural icons in Petersburg's historic center, St. Isaac's Cathedral (1818–1858) has to date fully preserved the ingenious iron structure of its dome (1838–1841). Essentially dealt with in available publications and research papers, it has mostly remained the least studied aspect of this architectural monument (e.g. Nikitin 1939; Shuisky 2005; Montferrand 2009a,b). This paper represents an attempt to lay the foundation for a comprehensive analysis and appreciation of St. Isaac's dome as a unique monument of construction history and an attempt to prove the advantages of cast-iron in dome structures of early industrial time.

The design planning and construction of St. Isaac's iron dome were carried out by the architect Auguste de Montferrand in very close collaboration with the largest private metallurgical enterprise in Petersburg, the iron works of Charles Baird. The prototype for St. Isaac's dome was that of St. Paul's Cathedral in London (1697–1710). The latter's massive conical stone structure was transformed into a "hybrid" ribbed dome structure of prefabricated cast and wrought iron, filled with brickwork made up of hollow clay pots. In 1845, the architect of St. Isaac's Cathedral published an album containing elaborate documentation of all the architectural and technical details of his largest work project in Petersburg (Montferrand 1845). Owing to this publication, the Cathedral soon thereafter became widely known in professional circles, which in particular is reflected in the well-known fact that St. Isaac's structural design concept directly influenced that of the dome of the U.S. Capitol building in Washington, D.C. (1855–1866), which represents an independent variation of the ribbed iron dome (Bannister 1948).

Generally speaking the cast-iron domes of the 19th century have proved to be a kind of *cul-de-sac* in the further structural development of early dome structures and were consequently replaced by lighter structures of wrought iron and steel with three-dimensional static work (e.g. Schwedler-Type). Nevertheless, all the well-known examples of cast-iron domes, first and foremost the Halle au Blé in Paris (1809–1813), St. Isaac's Cathedral (1838–1841), St. Nicholas' Church in Potsdam (1845–1850, lost in 1945) and the Capitol building in Washington, illustrate the search for innovative solutions for adapting the new materials of the industrial era to the largely traditional architectural functions and forms at that time.

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Figure 1, 2: St. Isaac's Cathedral: aerial view from the South-East, 1976 (Museum St. Isaac's Cathedral); interior view of the iron dome and its conical part, 2008 (Bernhard Heres)

FROM MASONRY TO IRON – A PARADIGM CHANGE IN CHURCH DOME DESIGN

Beginning in 1818, the work of designing and constructing St. Isaac's Cathedral was entrusted to the architect Auguste de Montferrand, who arrived in Petersburg from Paris in 1816 (Montferrand 2009a,b). The complexity of the architectural task facing Montferrand was further magnified by the need to incorporate into the new building the pillars of the older structure built by his predecessor (1766–1806, Antonio Rinaldi). The first draft design (1818), which had been subjected to criticism, and the second, revised, version (1825), which differed with regard to architectural composition, invariably considered the possibility of a brick dome with a wooden ribbed top (fig. 3). Its structure reflected the traditional solutions characteristic of classical construction, for example, the dome of the church of the Hôtel des Invalides (Jules Hardouin-Mansart, 1676–1708), with which Montferrand was obviously acquainted.

The construction work, which began in 1825, was accompanied by further discussions regarding the architectural and technical aspects of the design for St. Isaac's Cathedral and proceeded rather slowly. In this connection, a proposal to speed up the work and complete the building sent by Montferrand to the construction commission at the beginning of 1838 (RGIA 1311-1-1002, 12) was completely natural, if not somewhat belated. The content of the proposal, compared with previous designs, was amazingly pivotal. In order to complete the building, he proposed the "metal construction method", which involved the installation of an iron attic floor over the entire building and the design of the main dome on the basis of prefabricated cast-iron metal structures (fig. 4, 5). The note drawn up by Montferrand on the "new approach for constructing St. Isaac's Cathedral" included the following provisions:

– a cast-iron dome weighs three times less than the traditional stone dome (the weight of an iron dome was estimated at 163,000 puds (2,679 tons), the weight of a brick or marble dome at up to 454,440 puds (7,443 tons), facilitates the equal weight transfer on the tambour and protects the lower part of the structure (the brickwork) against cracking;

– the proposed structure cannot cause damage to the architecture "because the properties of the material used in erecting the structure are not as important as its size and proportions" and the appearance of a iron dome on St. Isaac's Cathedral will bear further witness to "the success of the arts in Russia since the introduction of such an approach will accord it primacy in the utilization of iron structures in such prominent buildings”;

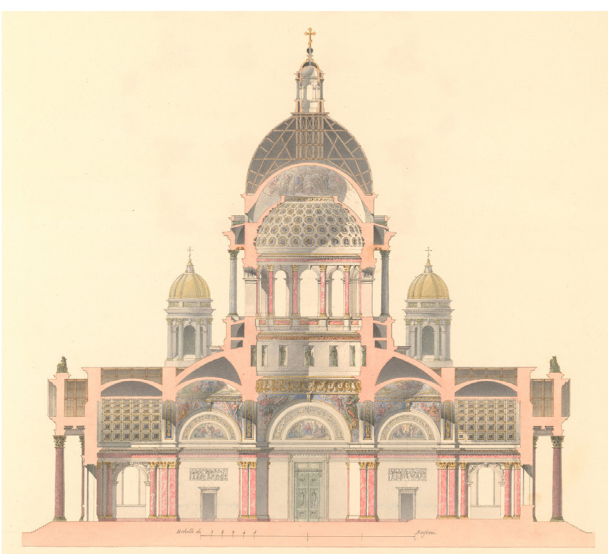
– the cost estimates for completing the building will amount to 7 million rubles (in paper money), whereas the cost of installing a metal dome will be only 500,000 rubles. The dome and the building (without the architectural finishing of the interior) in this case can be completed in 1841.

Montferrand’s proposals were accepted without discussion or objections. Owing to the heavy workload of the main producer of iron structures in St. Petersburg at that time, the Aleksandrovsky state-owned factory, in manufacturing the metal structures for the reconstruction of the Winter Palace after the disastrousness fire of 1837, the construction commission decided to consign the cast-iron, iron and copper production work for St. Isaac’s to the Baird Works (with the remark “since there is no competition to it in this matter”).

In order to understand the reasons for the variation of the dome structure to be erected (fig. 3-4), Montferrand’s description of the design work in process, which bears witness to his profound interest in the technical aspects of contemporary architecture (Montferrand 1845, 55–61), is more helpful than the preserved documents (RGIA 512-2; 1311-1). Analyzing well-known sacred buildings, above all St. Peter’s Cathedral in Rome, which he visited in 1806, Montferrand points out their basic flaw – the formation of cracks in the dome and the pendentive masonry vaults of stone structures. He evidently considered iron, a new material at the time, as an alternative to vault masonry since he was probably acquainted with iron from his experience in France (the Halle au Blé, 1806–1813) and subsequent observations made by French colleagues. In his album, Montferrand refers to the opinion expressed by Navier, which he obviously shared, that a metal structure that has a simple and monumental form can be considered a monument on an equal footing with a stone edifice (Montferrand 1845, 56).

In Montferrand‘s opinion, the sole example ensuring structural stability and relative lightness and security was the dome of St. Paul’s Cathedral in London (1676–1710). Stability was achieved in that case by successfully determining the geometry of the conical dome with its top according to a catenary line. In the design for the dome of St. Isaac’s, the structural principle of St. Paul’s dome was transformed through the new materials of the age of industrialization – cast iron and wrought

Figure 3, 4: St. Isaac’s Cathedral with masonry and wooden dome, 1818/1825/1828 (Montferrand 1828, table 4); design conversion to iron dome structure, 1838 (Montferrand 1845, table 26)



iron bricked in with hollow pots (Donaldson 1849, 11). Such an approach, in Montferrand's view, made it possible to solve the basic problem of cracking in masonry domes and pendentives, which was the "incurable disease" of traditional dome structures ("une maladie incurable qui ronge, ruine et détruit l'édifice bien avant le temps assigné pour sa décadence").

CAST-IRON INSTEAD OF WROUGHT IRON – A MORE STABLE DOME STRUCTURE

It should be pointed out that the first proposal for a metal dome for the construction of St. Isaac's Cathedral was done as early as 1823. A certain Mr. Loginov submitted "a draft design for a dome on the basis of iron" in order to prevent cracking as a result of uneven settlement. Under the guidance of Augustin de Betancourt, the commission declined the proposal (RGIA 1311-1-212, 4).

According to Montferrand's description, his iron structure of St. Isaac's dome (1838) represented "a system of three domes": the internal spherical and conical domes (often referred to as parabolic) with an interior span of 22.75 m and the external one with an outer diameter of 25.4 m. The two internal domes had a load-bearing function, each consisting of 24 ribs assembled from the cast-iron perforated elements of various sections. The lower row of elements was firmly attached to a support ring and embedded in the tambour masonry – roller supports were not provided. The ribs of the basic conical dome (24.86 m in height) consist of 4 sections that are tightly bound together by horizontal rings (fig. 5).

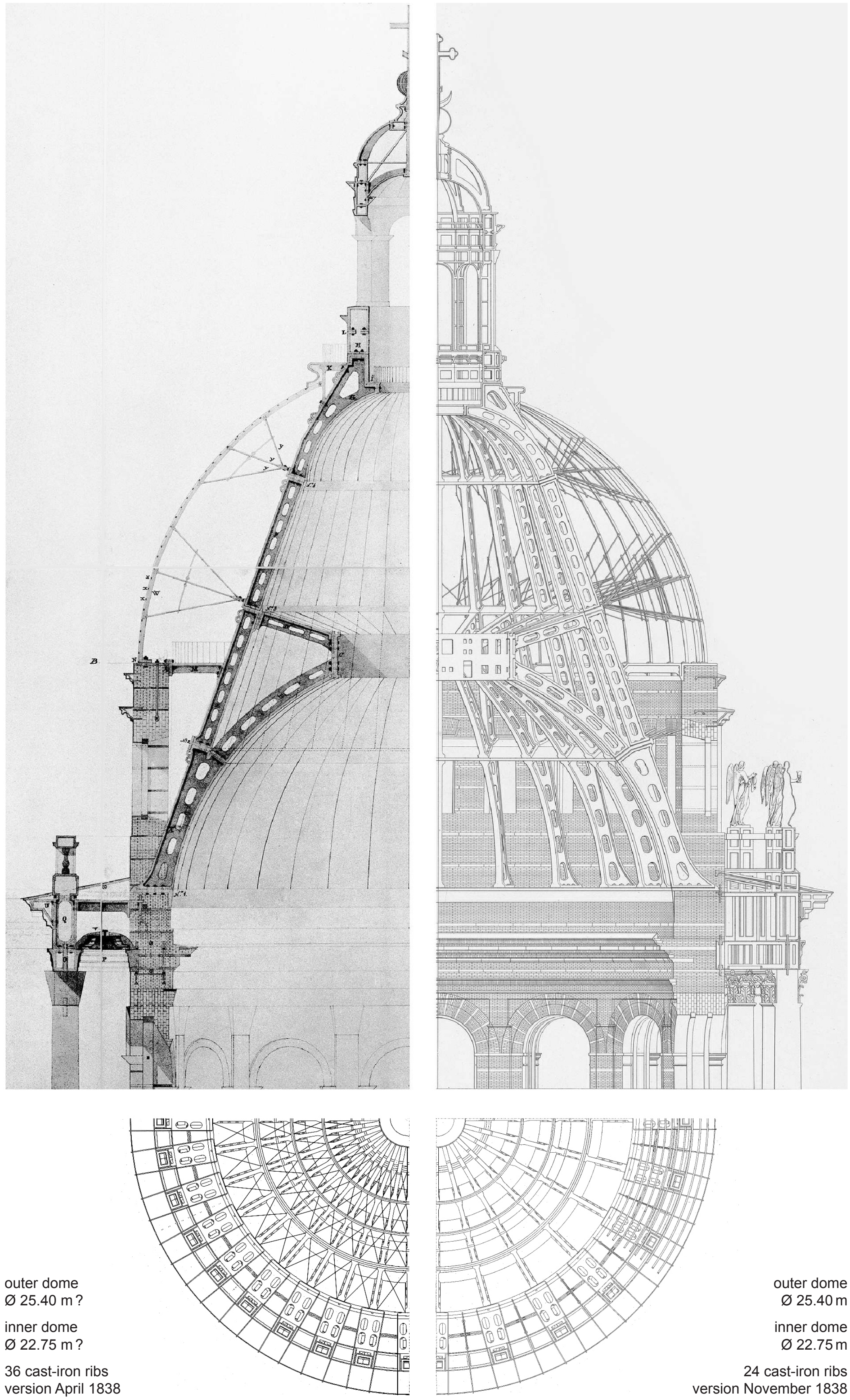
The obvious intent in the design of the metal dome of St. Isaac's Cathedral (1838) to use compressed cast-iron elements was possibly connected with an unsuccessful attempt to utilize flat wrought iron in constructing the dome of the Trinity Cathedral in Petersburg (1828–1835, V. P. Stasov, Matthew Clark). The light iron dome initially used here was destroyed by the first windstorm (1834). An alternative dome structure proposed the same year by the engineer Pierre-Dominique Bazaine with internal truss-reel underpinning owing to mistrust of the stability of large span structures made of pliant flat-bar iron was not accepted (Montferrand took part in the discussion of that case). As a result, Bazaine drew up a design with a rather massive wooden dome, which was erected in 1835 (Fedorov 1996, 45–52).

The use of cast-iron evidently also made it possible to overcome such a shortage of flat-bar iron profiles as a difficulty to withstand of transverse loads. All the groups of the structural elements of St. Isaac's dome have a different form of sections with flanges (fig. 9), which substantially increase the stability of both the separate elements and the dome as a whole. The developed sections of the elements of St. Isaac's dome possibly also corrected structural defects found in other early Petersburg buildings, such as the flat-iron arches of the General Staff archive building (1819–1823, K. I. Rossi, Matthew Clark) (Handyside 1847, 221).

IMPROVING AND OPTIMIZING THE IRON DOME DESIGN, APRIL – NOVEMBER 1838

As the construction correspondence indicates, several months after the approval of the design for the iron dome it underwent a number of structural changes. On 19 April 1838, Montferrand submitted a report asserting the need to manufacture one sazhen (2.13 m) high wooden model of the dome structure. In September 1838, after examining the completed model Montferrand reported that the number of ribs in the iron dome could be reduced from 36 to 24 (RGIA 1311-1-1003a/1, 64). This decision was meant to improve the structural design, ensure more practical

Figure 5: St. Isaac's iron dome structure: comparison of the approved (left) and implemented (right) variations, April to November 1838 (NTB RGUPS, FM 16-15, and Montferrand 1845, tables 44 and 45).



100.20,0 m
85.08,5
83.36,5
82.48,5
77.98,0
72.12,5
70.46,0
69.27,0
65.40,0
58.50,0

Level marks of the dome refer to the right cross section

outer dome
Ø 25.40 m ?
inner dome
Ø 22.75 m ?
36 cast-iron ribs
version April 1838

outer dome
Ø 25.40 m
inner dome
Ø 22.75 m
24 cast-iron ribs
version November 1838

linkage between dome elements and "provide more light" without detriment to the dome's durability. The sole weight of the dome decreased thereby by 584 tons. After considering Montferrand's submission and design model, the construction commission adopted a final decision to reduce the number of ribs at the end of October 1838.

The construction concept in the initial design version for a new metal dome (April 1838) is found in both the preserved design (NTB RGUPS, FM 16-15; RGIA, 512-2-200). The concept underlying the completed alternative design is found in Montferrand's album (Montferrand 1845, tables 44, 45). A comparison of the two versions indicates that, contrary to Montferrand's assessment, the design for a brief period underwent a number of serious structural changes (fig. 5). In addition to the reduction in the number of ribs, they included, inter alia, lessening the height of the dome (ca. 1.5 m), changing the contour of the last section of the conic dome (the catenary line), removal of braces between the ribs, adding flanges in certain sections, completely changing the structure of the lantern and the colonnade entablature (prefabricated cast-iron elements), and also increasing the thickness of the tambour's brickwork.

It should be pointed out that the "hybrid" iron-pottery structure of St. Isaac's dome took into account and further developed the experience of European building practice with regard to the use of iron and ceramic structures ("constructions en poteries et fer") summarized in the first publication of the French architect Charles Eck (Eck 1836). Hollow ceramic pots were bricked in between the cast-iron ribs and were heat-insulated by means of a cork layer with a cement coating (fig. 7-8). They formed a solid internal layer with a complex configuration, which provided thermal insulation for the cast-iron ribs and the interior space of the Cathedral and also helped to collect condensed moisture. It remains unclear whether the combination of the cast-iron with the ceramic hollow pots was already provided for in the initial version of the structural design or appeared at a later date.

MANUFACTURING AND ASSEMBLY OF THE DOME – THE BAIRD IRON WORKS

Montferrand's collaboration with Petersburg's largest private metallurgical factory, the Charles Baird Iron Works (founded in 1792) continued throughout the entire period of the construction of St. Isaac's Cathedral. In the 1820s, the Baird Works filled individual orders to manufacture machines for lifting and move of building materials, monolithic stone blocks and columns. Subsequently, its work included orders to manufacture the bronze bases and capitals of columns and, from 1834 through 1838, the wrought iron braces to reinforce the stone work of the gables and secure the tops of columns. In 1838, the Baird Works became the principal manufacturer of all the metal structures (cast-iron, iron, bronze and gold plating) of St. Isaac's Cathedral.

The factory's previous experience, which basically related to ship construction and manufacture of steam engines (Tower 1867) helps to explain a specific characteristic of the dome's individual details (e.g. the mounting of the stamped plates of the exterior dome shell, fig.2). In addition to its basic profile of mechanical engineering, the Baird Works also had experience in producing cast-iron and iron bridge structures. In 1806/07, Charles Baird built a cast-iron arched bridge (with a span of 19.20 m) at the entrance to the site of his factory, the first such structure in Petersburg. Subsequently, the Baird Works manufactured the support structures (iron chains and cast-iron frames) for five chain bridges in Petersburg (1823/24 and 1825/26, Fedorov 2000, 115–226).

The largest orders relating to architectural engineering carried out by the Baird Works involved the work of erecting the Alexander Column (1829–1834) and St. Isaac's Cathedral, both in accordance with Montferrand's design plans. The Works' chief engineer William Handyside (Handyside 1850, 86) took part in these activities.

In manufacturing the dome, the iron used by the Baird Works (as well as the Aleksandrovsky Iron Foundry) was acquired from the Demidov factories in the Urals through Petersburg wholesale merchants (RGIA 502-1-189, 25). On the basis of this evidence, it can be assumed that Ural iron were utilized in the dome as well as most of the iron structures in Petersburg in those years.

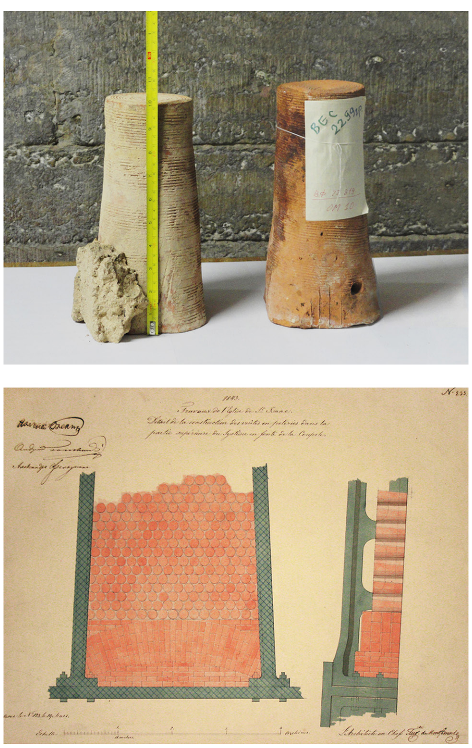
The designing of the wooden scaffolding for installing the dome and stacking the pottery filling constituted an independent part of the work of erecting the dome (RGIA 1311-1-1060, 102). The design plan was submitted to the commission in November 1838, and detailed drawings in Montferrand's album depict the structures involved in that work (fig. 6).

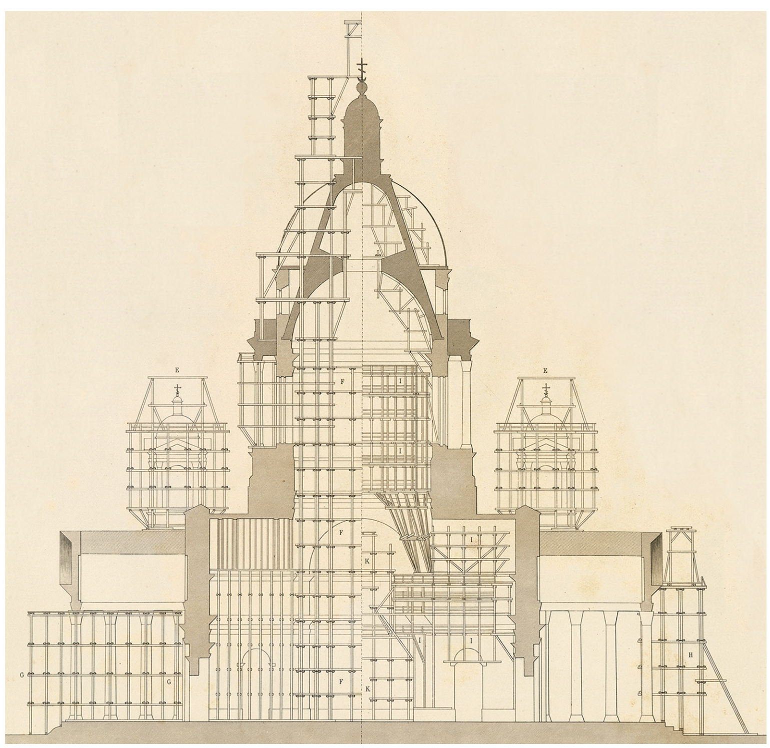
AN "EMPIRICAL" STRUCTURE AND ITS STATIC EVALUATION

Owing to the lack of references to calculations, the St. Isaac iron dome can be grouped among the large number of "empirical" metal structures manufactured at the beginning of industrialization by the producing factory primarily on the basis of its own metallurgical experience. This is confirmed by references to the facts that, except for dome model, all its parts were manufactured at the Baird Works in accordance with the drawings implemented there on a scale of 1:48. In his summary documentation Montferrand stated e. g. that Baird had made "the sole substantive change" in the construction design – reducing the number of ribs from 36 to 24, which made it possible to lighten the dome without decreasing its durability (Montferrand 1845, 60).

References to dome calculations by Lamé and Clapeyron to be founded in some publications relate in fact to their calculations of the vaults in the earlier version of the draft design of St. Isaac's Cathedral (Lamé, Clapeyron 1826). Similar indications that static of the cast-iron dome were provided by the military engineer Petr Karlovich Lomnovsky have not yet been confirmed through

Figure 6: Scaffolding for erecting the iron dome and installing the ceramic pots (Montferrand 1845, table 32-33).
Figure 7 (a, b): Ceramic pots and masonry in the ribbed dome structure: (a) placement (NTB RGUPS, FM 4-233), (b) view of the pots, 250 mm in height on bases of 100 and 135 mm, and weighing 2.20 to 2.60 kg, each (Fedorov)





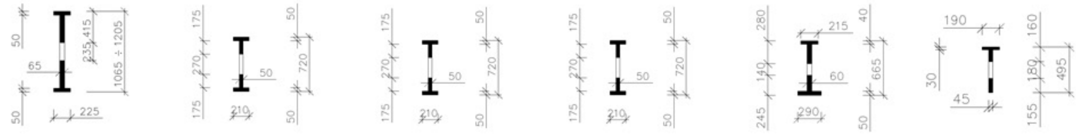
construction element	radial rib 1	radial rib 2	radial rib 3	radial rib 4	radial rib 5	radial bar
cross-section						
component length [m]	7,50	6,70	6,00	6,00	7,00	4,00
own weight [kNm]	5,43	3,70	3,31	4,83	3,76	1,17
capacity utilisation [%] cross-section check	20,00	23,20	11,10	16,60	16,20	no risk of buckling
capacity utilisation [%] flexural buckling	17,00	18,40	9,00	12,30	11,50	no risk of buckling

Figure 8: Cross-sections of the cast-iron dome elements and their capacity utilization (Chizhevsky 2009, Weidemüller)

documentary evidence. As the supervisory official of the commission on the construction of St. Isaac’s Cathedral (1827–1858), Lomnovsky signed most of the working design sketches, including those relating to the dome, from the end of the 1830s to the beginning of the 1840s.

Contemporary structural analysis of the dome (including that by Chizhevsky 2009) and the calculations conducted in the preparation of this paper (Weidemüller) indicate that the design and dimensions of the dome elements are fully in accordance with contemporary requirements regarding durability and stability (fig. 8-9). Despite well-known complexities, more exactly multivalence of static modeling of the historic structures, all available calculations of St. Isaac’s dome yields similar results. Judging from the sound condition of the dome, the non-uniform settlement of the support ring (tambour) predicted in the first decade following its erection did not lead to the appearance of critical seepage or increased loads, presumable also because of the high quality of the pile foundation (developed by Betancourt, Montferrand 2009a, 136).

CONCLUSION – ST. ISAAC’S IRON DOME IN CONSTRUCTION HISTORY CONTEXT

- Current research (proposed paper is a short resumé) make it possible to rank St. Isaac’s dome among the most well thought-out and independent examples of Russian early “empirical” iron structures, in a positive sense paradoxically located on the boundary of local and European engineering experience in the 1830s.

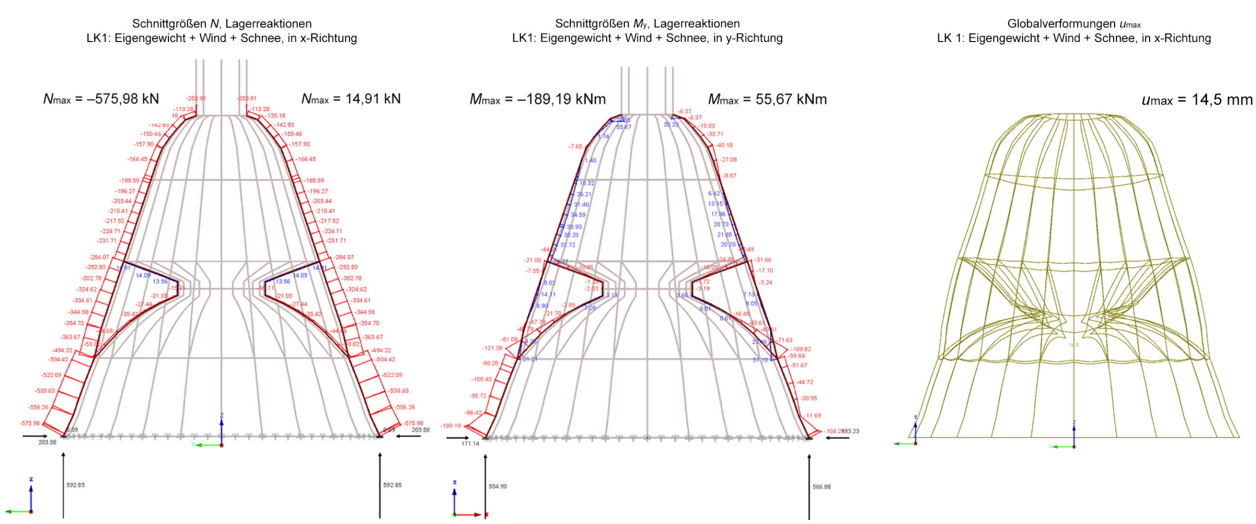
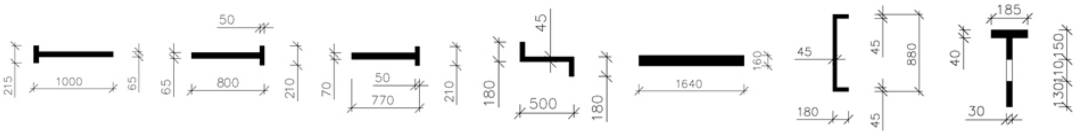


Figure 9: Stress and deformation analysis of the dome structure: normal stress, moments, deformation levels. (Modeling with bars firmly attached into support ring; Weidemüller)



construction element	ring 1	ring 2	ring 3	ring 4	support ring	inner ring	circular runway
cross-section							
component length [m]	62,00	46,50	34,00	9,40	76,50	21,40	2,80
own weight [kNm]	5,26	4,35	4,42	2,22	19,02	3,46	3,46
capacity utilisation [%] cross-section check	15,10	19,00	24,90	65,60	4,10	4,30	5,70
capacity utilisation [%] flexural buckling	no risk of buckling	no risk of buckling	no risk of buckling	no risk of buckling	no risk of buckling	no risk of buckling	9,90

- The erection of the dome was the result of the joint work carried out by a representative of the French architectural school, Auguste Ricard de Montferrand (1786–1858) and representatives of Scotland's metallurgical school, Charles Baird (1766–1843) and Francis Baird (1802–1864).
- One of the main factors contributing to the appearance of St. Isaac's dome and other structural innovations in Petersburg in the first third of the 19th century was the establishment of the *Institut des Voies de Communications* in 1809 by Augustin de Betancourt (1758–1824) and the presence over many years of a number of prominent representatives of the French engineering school. Montferrand, Betancourt and the Bairds were very closely linked through personal, social and commercial contacts.
- At the same time, design and manufacturing of the structurally complex cast-iron dome structure was tightly connected with the successful development of the Russian mining industry of the 18th century and the widespread production of iron material at numerous private (for example, Demidov's) and state-owned Ural plants. It led, in our view, to the emergence of the still little-known phenomenon of the early use of iron in Russian architectural and engineering practice (see also publication Lorenz/Heres).
- Beginning with the 1800s, it is possible to speak of the Petersburg context of metal architecture, one of whose signal achievements was the erection of the dome of St. Isaac's Cathedral.

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