

THE DEMIDOV IRONWORKS IN NEVYANSK (URAL MOUNTAINS) – IRON STRUCTURES IN BUILDING FROM THE FIRST HALF OF THE 18TH CENTURY

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Keywords

Russian iron industry, bloomery iron, cast iron, reinforced cast beam, iron roof truss

Abstract

Although the use of single wrought or cast iron structural elements such as tie rods, plates or columns goes back to the ancient world and became more and more common in the 17th and 18th centuries, the roof structures erected in Paris at the Théâtre Français (1786–90) and the Salon Carré du Louvre (1789) are commonly regarded as the first examples of complete iron roof trusses in the history of construction. However, an earlier, larger application of an iron truss has been found in Russia dating from the first half of the 18th century.

Considering the dominant role of Russian iron production in the 18th century, this is hardly surprising. The “golden age of Russian iron” goes back to the strategic decision of Peter the Great, at the end of the 17th century, to push forward the foundation of iron-making plants in connection with pre-industrial “works towns” in the Ural Mountains. Within a few decades, the Urals became the centre of Russian iron production, with plants often equipped with larger and better tools and machinery than in Europe. Nevyansk, 90 km north of Yekaterinburg, was the first of these new plant towns. Founded by the state in 1699 but transferred into private hands (Nikita Demidov) in 1702, Nevyansk, the “grandfather of the Ural plant towns”, became one of the most important factories – not only in the Urals, but also in Europe in terms of both the quantity and quality of the metal produced.

From the structural point of view, the 58 m high “Leaning Tower” of Nevyansk and its porch are of central interest. Work on these began in 1722 and they are still standing today. Whereas the tower contains an impressive array of cast and wrought iron elements, including composite girders made of both materials, the porch is covered by a delicate roof truss built entirely of wrought iron; it spans about 9 m and reaches a height of 7.50 m. This essay analyses these iron structures in the context of the iron industry in the Urals in the 18th century.

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INTRODUCTION – BUILDING WITH IRON IN THE PRE-INDUSTRIAL AGE

The history of construction has an essentially consolidated image of the evolution of the manufacture and use of iron loadbearing members in the building industry, see, for example, (Sutherland 1997, XVI) and many other publications. Evidence of wrought iron cramps, straps and tie rods has been found in many stone and timber structures from ancient times right through to the Renaissance and Baroque. The first complete wrought iron reinforcement systems (Louvre Colonnades, 1667–74) were seen as early as the 17th century, the popularity of cast iron grew from the mid-18th century onwards following the development of coke smelting (Iron Bridge, Coalbrookdale, 1776–79) and, finally, the first complete wrought iron suspended floor and roof structures appeared towards the end of the 18th century. The roof structures erected in Paris at the Théâtre Français (1786–90) and the Salon Carré du Louvre (1789) are commonly regarded as the first examples of complete iron roof trusses in the history of construction.

Considering all this, it is not uninteresting to discover that a large wrought iron roof structure was built in the Ural Mountains in the first half of the 18th century. It spans over the porch to the “Leaning Tower” of Nevyansk, an imposing campanile that was built on the premises of the local ironworks starting in 1722. With its numerous iron components, not just the roof, but the tower itself is worth the attention of the construction historian (Figs. 1 and 2).

This paper describes these unique testimonials from the very first developments in the “structural language of iron” against the backdrop of the “golden age of Russian iron” in the 18th century. The investigation and analysis are based on survey carried out on site, studies of historical and contemporary literature and structural calculations.



Figure 1: Tower and porch (Lorenz 2013)



Figure 2: Porch roof structure (Heres 2012)

THE 18TH CENTURY – THE “GOLDEN AGE OF RUSSIAN IRON”

Up until now, Russian *iron construction* in the 18th century has hardly featured in research projects. Even standard Soviet and Russian publications hardly make any reference to it (e.g. Vazilev 1964, Chernyshev 2007), and those few references have hardly attracted any international attention; exceptions are the well-known and enthusiastic reviews of John G. James with their many valuable references (James 1983, 2013). On the other hand, *iron production* in the 18th century was and still is very popular among researchers investigating the history of both the metallurgy (e.g. Baklanov 1936, Alekseyev and Gavrilov 2008) and the architecture and urban planning aspects (e.g. Alferov 1960, Lotareva 2011). In addition, there are some highly enlightening contemporary descriptions of the ironworks in the Ural Mountains. Particularly worthy of note here is the report of Wilhelm von Henning (1676–1750), a German who worked for the Russians since 1713 establishing and modernizing numerous ironworks (Hennin 1735).

Russia's great interest in the history of the iron industry in the Urals can be attributed to the fact that the region is intrinsic to the history of metallurgy – the consequences of which are still in evidence today as almost all the towns and cities of this region have their roots in this history. It was primarily iron from the Urals that helped 18th century Russia to become not only the world's largest pig iron producer (Tab. 1), but also allowed it to supply most of the world's markets. For example, Great Britain imported a total of 59 905 t of iron in 1793, some 36 662 t of which came from Russia (Alekseyev & Gavrilov 2008).

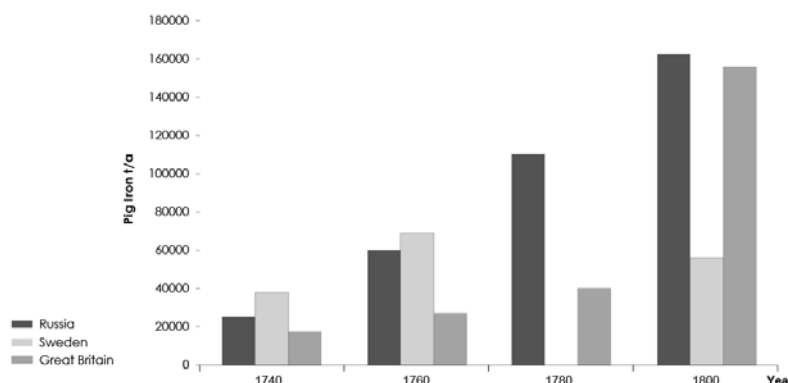


Table 1: Pig iron production (t/a) in Russia, Sweden and Great Britain (according to Alekseyev and Gavrilov 2008)

The origins of the remarkable development of Russian ironworks can be found in Tsar Peter the Great's (1672–1725) efforts to modernize the military. In view of the foreseeable war with Sweden (hitherto the greatest supplier of iron) over Russian access to the Baltic Sea, the tsar gave the order to build several Russian ironworks in 1698. Initially, the Urals formed the focus, but following the first setbacks in the Great Northern War (1700–20), the construction of ironworks in Karelia and around St. Petersburg was accelerated.

The number of ironworks in the Urals grew constantly. Whereas there were just nine plants in 1710, their number had increased to 79 by the middle of the 18th century and reached a zenith in 1780 with a total of 140 works (Baklanov 1936). The region offered the best conditions for operating the plants: high-quality ores were easily obtained from open-cast mines, the seemingly endless forests provided the charcoal and numerous smaller, slow-flowing rivers served as power supplies for the waterwheels driving the bellows, hammers and mechanical tools.

During the first three decades in particular, many works were founded by the state. The state tried to promote the manufacture and processing of copper, silver and gold as well as iron by

carrying out constant surveys to discover ore deposits and by recruiting skilled workers. Some of these initially state-owned factories were transferred to private owners shortly after being founded on condition that they supplied certain quantities to the military every year. Most of the private owners were friends of the tsar; some of the powerful Russian aristocratic families, such as the Stroganovs, participated with success.

IRONWORKS IN THE URALS – STRUCTURE AND PRODUCTION

All the ironworks were built according to a similar plan. It began with the site of the works, with the governing criteria being the proximity of ore deposits and a topography that was beneficial for damming a river. The most time-consuming part of the project was then building the dam itself, which could reach quite a size; lengths of up to 1 km, widths of 40 m at the crest and heights of 8 m were not unusual (Alexeyev & Gavrilov 2008, 343).

The works buildings were erected directly adjacent to the dam alongside flowing water, which was distributed through the buildings via wooden channels. Arranged according to their need for water, first of all came the blast-furnaces (mostly fed via a bridge from the dam), then the fineries with their hearths and forge hammers, the vertical mills, stamp mills and – depending on the facilities at the plant – further units such as sawmill, anchor forge, steel casting foundry, copper smelter or other mechanical and metalworking shops. Warehouses, offices, houses, churches and other public amenities completed the picture of these “works towns”; a detailed overview of, for example, Yekaterinburg (Fig. 3) can be found in (Baklanov 1935). During the first decades of this development in particular, the towns were frequently protected by extensive fortifications. The “opening-up” of Siberia that had been going on since the time of Ivan the Terrible (1530–84) was without doubt a colonization process stretching over centuries in which the Russians made this “Wild East” their own. It was important to protect the towns against attacks by the indigenous peoples or vagabonds.

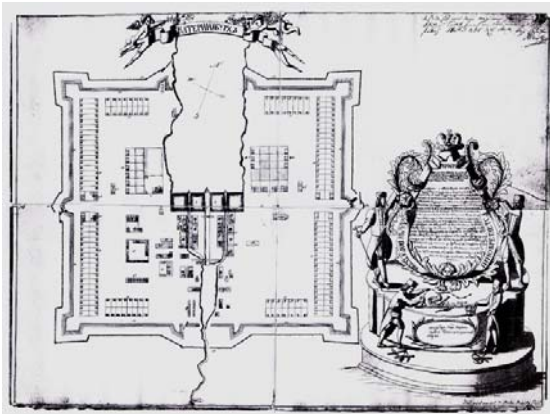


Figure 3: Yekaterinburg in 1729 (Lotareva 2010)

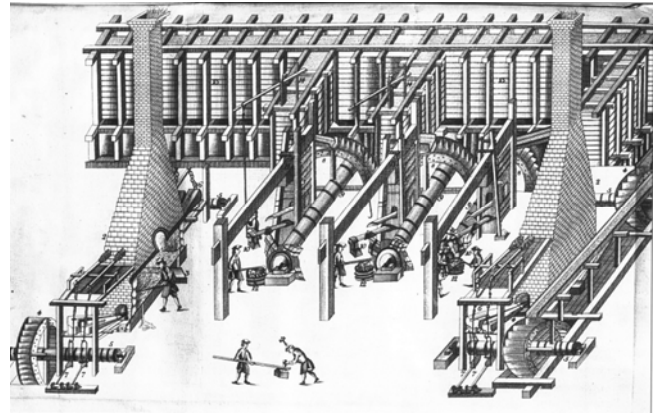


Figure 4: Refinery around 1750 (Saimogov 2011)

In the main, peasants were conscripted to carry out the simple jobs. In lieu of various taxes, they helped to build dams and mine ores, produce and transport charcoal; the peasants were joined by others banished to the region and local convicts. By contrast, skilled workers for the blast-furnaces and fineries were frequently recruited from central Russia or abroad. Also present were soldiers whose job was to protect the works and catch runaway peasants.

The Russian blast-furnaces equipped with water-powered bellows were among the most efficient in Europe. After tapping, the pig iron was cast into readily transportable pieces and the further processing to form iron bars was then carried out in the finery with bloomeries and their associated forge hammers arranged in pairs (Fig. 4). The blooms were produced according to the “old German method”: a certain amount of pig iron plus slag sand was placed in the hearth, covered with charcoal and then melted with the help of a powerful air supply; the oxides in the slag reduced the carbon content. The ensuing doughy bloom was then compacted under the hammer and the slag pressed out. The method had to be varied or even repeated depending on the quality of the pig iron until the bloom could be divided and beaten out into bars. One master and his three workers needed a day to produce and process one bloom weighing up to 160 kg (Alekseyev & Gavrillov 2008; Karsten 1841).

This method continued virtually unchanged until well into the 19th century; at best, any new developments were only taken up very hesitantly. And it was precisely for this reason that the demand for Russian iron on the world market collapsed dramatically around 1800. Productivity in Great Britain had in the meantime increased substantially due to the introduction of innovations such as the use of coal, the puddling method or the use of steam-driven machinery – and that brought down prices considerably.

The Russian state reacted to this by forcing through comprehensive new plans for the works, but that did not begin until the 1820s. Investment focused on technical innovations such as blowing engines using cylinders or new blast-furnaces, and the puddling method became widespread in the 1840s. Admittedly, Russia did not start using coal until the 1870s, in the Donets Basin in the Ukraine.

THE DEMIDOV IRONWORKS IN NEVYANSK

The construction of the Nevyansk Works began in 1699, directly after Peter the Great had issued a decree to set up ironworks in the Ural Mountains. More than 1600 workers, mostly peasants, built the 216 m long x 32 m wide dam. The 10 m high blast-furnaces, the finery with two hearths and hammers plus other works buildings followed quickly. It was in December 1701 that – for the first time in the Urals – the blast-furnace could be tapped for the first time and a little later the first iron refined. Since then, the plant in Nevyansk has been regarded as the nucleus of the iron industry in the Urals.



Figure 5: Nevyansk in 1735 (Hennin 1735).

Lower right the dam and the ironworks, in the centre the manor house and to the left of that the campanile. The workers' houses are in the background to left and right.

Not long after (1702), the tsar gave this works and a number of other plants to his friend Nikita Demidov, an armourer from Tula, the former centre of Russian iron and weapons production to the south of Moscow. In return for supplying a certain quantity of iron products every year, this works was now able to operate and develop on its own account. In the following years, Nikita Demidov, later his son Akinfiy, founded or acquired further works on a regular basis and expanded the business until it became an industrial empire. Demidov began exporting iron as early as 1719, and 20 years later the 3369 t exported by the Demidov works accounted for about 60% of all Russian iron exports. Demidov iron bars, marketed under the name “Old Sable”, enjoyed an outstanding reputation throughout Europe, not just in Russia. Modern metallurgical analyses of samples from Nevyansk have confirmed the properties that in some respects match those of today’s structural steels (Rodionov et al. 2009, 2010).

THE LEANING TOWER – AN IRON CONSTRUCTION “SHOWPIECE”

It was Nikita who began building a magnificent ensemble in the early 1720s. The intention was to express in architecture how important the parent plant had become. The heart of the ensemble, besides the new manor house, was to be a campanile rising above the whole complex. Work on the tower began in 1722, but very soon afterwards the poor subsoil led to considerable difficulties due to the uneven settlement (Slukin & Gorodetskaja 2012); the shaft of the tower began to tilt towards the south-west.

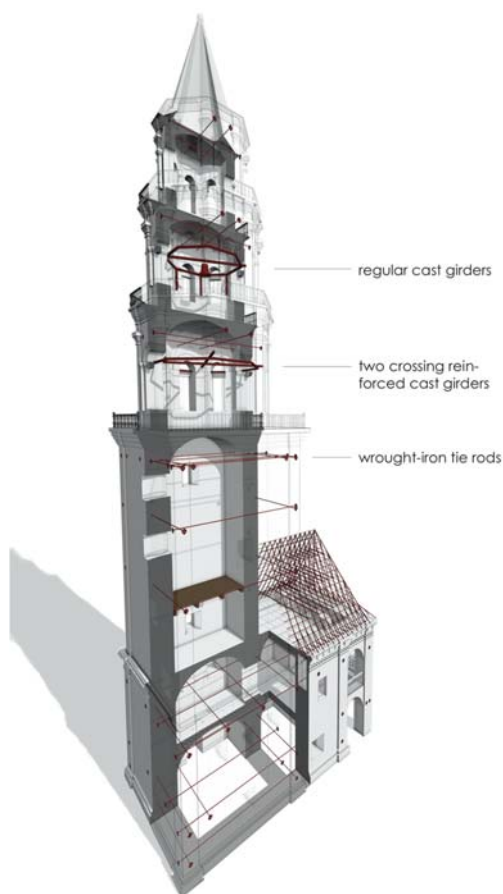


Figure 6: Iron loadbearing members in the tower (computer image by Mark Gielen, BTU CS, 2015)



Figure 7: Tie rod showing forging (Lorenz 2012)

Figure 8: Composite beam (Heres 2012)

Despite various corrective measures, building work had to be abandoned in the year of Nikita's death, 1725. Seven years later, however, his son, Akinfi, set about completing the structure. The work involved not only the octagonal upper part of the tower, including belfry and bells, but also the strengthening of the existing bottom part. This second phase of construction must have been completed quickly – Henning's travelogue of 1735 already shows the finished tower (Fig. 5).

The structure was obviously conceived as a "showpiece for iron architecture" – a fact impressively emphasized by the cast iron balustrades, floor tiles and door frames all over this building. Inside, we find a multitude of different iron loadbearing members (Fig. 6), e.g. shear connectors for ceiling vaulting and arches in the form of tie rods made from roughly square iron bars (Fig. 7); their ends are forged into eyes through which iron wedges are driven to force the cast iron anchor plates against the masonry. The many horizontal reinforcing elements in the masonry were executed similarly, and even the structure supporting the pavilion roof is possibly made from wrought iron.

There are both wrought iron bars and cast iron beams in the arched windows of the first octagonal level. Furthermore, at this level there are two approx. 6 m long beams spanning across the interior which are made from a composite of cast and wrought iron: each cast iron beam (190 x 145 mm) has a groove on its underside into which "reinforcement" in the form of a wrought iron bar (60 x 36 mm) has been inserted (Fig. 8). The carbon content of the cast iron is 3.75%, that of the wrought iron < 0.1%; this lower value proves that the material is "bloomery iron" produced in the bloomery (Korotun & Korotun 2006).

These beams are a striking demonstration of how the builders of the tower were fully aware of the properties and structural behaviour of the materials they were using. Even though it is still unclear as to what means were used to achieve the bond between the two components, it should be pointed out that these "composite beams" were conceived, produced and used in Nevyansk more than a century *before* the pioneering achievements, known as "reinforced castings", of William Barlow (1848: beams for the "Reading and Reigate Railway") and Robert Stephenson (1834: "bow-string girders" made of cast iron arches and malleable iron tie rods connecting the ends) (Sutherland 1963–64, 70–71). Space limitations allow us to mention another amazing innovation only briefly: two decades before the invention of the lightning conductor by Benjamin Franklin in 1752, the Nevyansk Tower already had one in the form of a hollow sphere with spikes. This "sun-ball" with a diameter of about 30 cm crowned the tower spire for more than 200 years, and after its repair in the middle of the 20th century became a museum piece.

THE TOWER'S PORCH – A ROOF STRUCTURE MADE OF WROUGHT IRON

No less interesting is the hipped roof to the porch on the north-east side of the tower. The steep pitch of almost 60°, indeed, 77° for the hips, is striking; with a span of just over 8.60 m, the roof rises 7.15 m. The present porch was obviously not built at the same time as the tower, but rather in the course of extending the porch in the early 1740s. Although Henning's generally very detailed drawing of the iron structure in 1735 (Fig. 5) already shows the tower with its belfry, the porch is only a small building with a rather nondescript pitched roof at a much lower angle.

Closely spaced rafters without purlins form the main structure (Fig. 9). These rest on cast iron wall plates, with sprockets protecting the top of the wall as far as the eaves. Most pairs of rafters are braced by three collars, one above the other, which gain additional support in the middle from a member suspended from the ridge. Collars are missing from four pairs of rafters,

presumably due to the spiral staircase at this position. The battens for attaching the roof covering are not – as we might expect – on top of the rafters, instead are in the form of short lengths of iron fitted between rafters.

The entire iron structure is made from simple flat iron bars (rafters and ridge hangers approx. 20 x 70 mm, collars and sprockets approx. 20 x 60 mm, battens approx. 10 x 45 mm). The dimensions show considerable scatter (the battens especially). Further, the original iron bars have prominent marks that allow us to deduce how they were produced and worked. For example, the flat iron bars were obviously flattened by hammering in a forge. In addition, on longer components we can clearly see where they were forged together from (shorter) semi-finished products. The detail at the base (Fig. 10) and the complex hip-jack rafter connections reveal the craftsmanship the builders needed to solve their tasks.

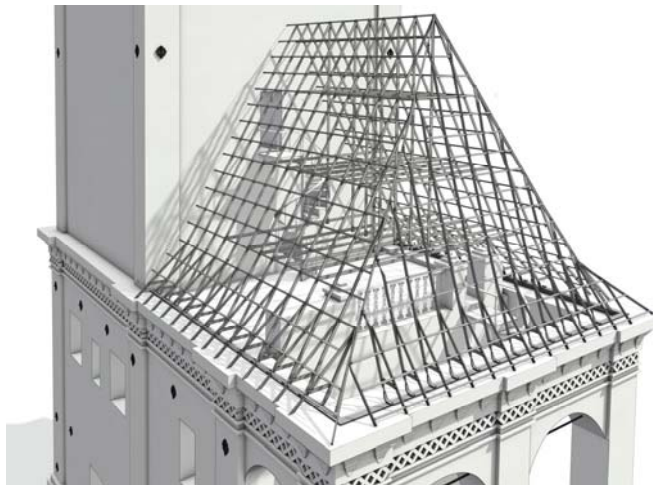


Figure 9: Iron roof structure to porch (computer image by Mark Gielen, BTU CS, 2015)



Figure 10: Base detail showing wall plate (Heres 2012)

The material of the loadbearing structure differs from the bloomery iron of the forged anchors in the tower. The much higher carbon content of 0.5–0.6% shows it to be crude steel (*uklad* in Russian). The method of obtaining *uklad* was probably based on remelting bloomery iron; it was produced at the Nevyansk factory from the very moment of its foundation (Rodionov et al. 2009, 2010).

The main loadbearing members of the roof are still in place in their original condition. However, many smaller parts have been replaced in the course of various maintenance measures (the last around 1989). Parts replaced include some of the battens (the new ones with their accurate dimensions and good surface finishes being clearly distinguishable from the original battens), most of the original fasteners and the roof covering, where zinc sheets have long since replaced the original iron sheets. A survey revealed that, for example, on the eastern eaves side, about 22% of the parts are no longer original.

Without the roof covering, the entire iron structure weighs about 6.3 t. If we take into account that the sum of the (steep) roof surfaces is much greater than the plan area roofed over (approx. 9.65 x 9.20 m), the weight of the roof structure per unit area of floor is approx. 71 kg/m², which is not high. In view of the relative lightness of the roof structure, but also with regard to a number of visible deformations, the question of the structural behaviour arises: How does this delicate structure carry the applied loads (especially the wind loads in this case) and transfer them safely to the masonry of the porch?

Frank Batke has investigated the loadbearing behaviour in detail as part of his master’s thesis at BTU Cottbus (Batke 2015). The wind loads in his model were based on those given for this region in current Russian codes of practice (snow loads are not relevant), and he also took into account the local deformations already visible. Comparative calculations were carried out using both 2D and 3D systems allowing for possible stability failure, and the modelling of the connections between rafters and battens were varied in parametric studies. Using the strength parameters specified by (Rodionov et al. 2009, 103), which for the bloomery iron investigated results in yield stresses and ultimate strengths similar to those of modern structural steels, grade S 235 steel was used for simplicity. In combination with the dead loads, a distinction was made between the relevant loading cases “wind on eaves” and “wind on hip”.



Figure 11: A pair of rafters (with and without collars) subjected to dead and wind loads: utilization in terms of effective stress (according to Batke 2015)

In the transverse direction the collar system, also taking into account the low transverse stiffness of the flat sections – exhibits considerable reserves of strength (Fig. 11, left). The loads on the individual rafters are low because of their close spacing. Furthermore, the close spacing of the stiffening battens (despite the relatively “soft” connections) counteracts the buckling tendency. A study of the four pairs of rafters without collars underlines the latter’s importance (Fig. 11, right); the theoretical utilization is much higher, although not significantly higher than 100%.

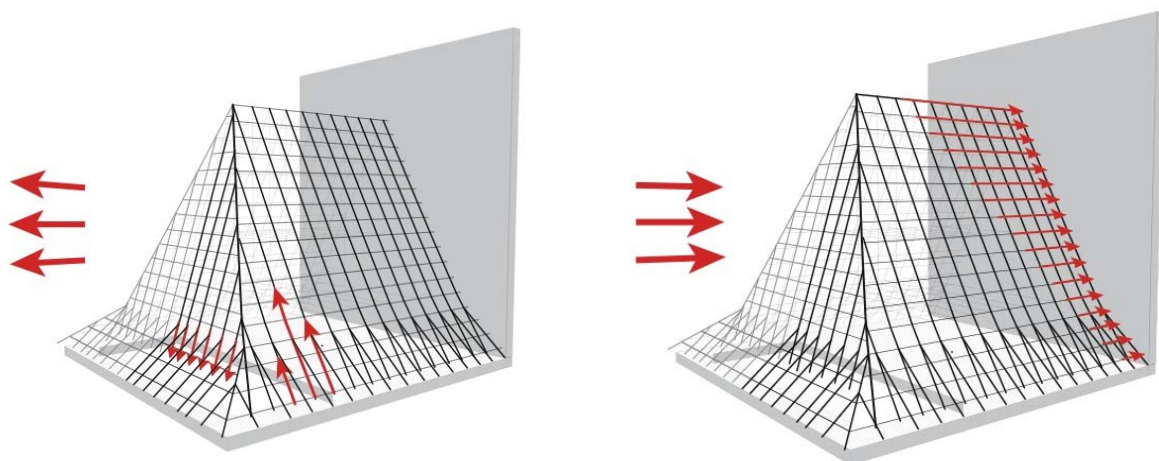


Figure 12: Structural behaviour in longitudinal direction under wind (suction, pressure; according to Batke 2015)

How the wind loads are carried in the longitudinal direction is also interesting (Fig. 12). The survey of the structure revealed that although the batten connections are good in compression, they are not necessarily good in tension. It was precisely this assumption that was then used as a basis for the 3D analysis. Accordingly, with wind pressure on the hip, the battens transfer the load directly into the tower, whereas suction loads, even when assuming hinged batten-rafter connections, are essentially carried in the front hip area.

CONCLUSIONS AND OUTLOOK

Whereas in the campanile we are amazed by the consequential composite make-up of the “reinforced beams” of cast and wrought iron, in the porch it is the delicate roof structure. According to our present state of knowledge, this is not only the oldest iron roof structure still standing, but perhaps the oldest iron roof structure ever built.

The forged flat sections, likewise the construction details (especially for the difficult three-dimensional connections at the hip), demonstrate quite clearly that this marks the start of structural steelwork. The roof structure can be seen as the first tentative steps in a new, as yet totally unknown design language that was still waiting to be developed. How was one to design or join together these semi-finished iron products when there were still no rules of any kind?

As in comparable phases in the history of construction, the evolution of a new design language began with the transformation of tried-and-tested prototypes borrowed from traditional forms of construction. In Nevyansk it is obvious that the loadbearing structure owes its origins to traditional timber construction; such steep, high timber roofs are typical of Russian houses and important buildings in the 17th century (Piljavski et al. 1984). Structurally, this roof form also leads to a significant decrease in the level of load on this iron version now being tried out because snow loads are hardly relevant on such a steep roof. For the remaining loads, the structural safety can be deduced from the intelligent, highly redundant concept, distributing the load over many closely spaced individual bars in both principal directions.

But maybe the designers in Nevyansk were also able to rely on iron role models already built. For example, Chernishev refers not only to the wide use of iron anchors and wall reinforcement in Russian churches and palaces, but also to the forged loadbearing structure of an onion dome 5.90 m in diameter and 7.85 m high that had been built back in the 1690s (Chernishev 2007). Iron rafters allegedly up to 15 m long used in the Church of the Resurrection in Zvenigorod (Ludvig & Vasilev 1964) have been assessed as dating from the same period. Incidentally, not unconnected with the Demidov dynasty, in 1779 “Demidov Church” in Tula was given a roof of braced iron rafters spanning an impressive 14 m.

Evidently, iron production in Russia during the 18th century, which was widespread and briefly the best the world, was based on primarily military objectives and had a higher priority than providing construction with a “scientific basis”, was also able to develop its own power of innovation in construction technology. A more detailed investigation for history of construction purposes, not only concerning Russian iron construction in the 18th century in general, but specifically the campanile at Nevyansk, has yet to be undertaken. Elementary questions still remain to be answered: Which construction phases can we discern? Who developed the structure and details for the iron structure? Which skills between “knowledge” and “ability” enabled the draft and detailed design? And, in the end, how was iron construction marketed and received? Further research is necessary here, also a systematic evaluation of the sources distributed over various Russian archives and a more accurate in situ survey using the methods of “building archaeology”. We hope to be able to do this in the near future.

ACKNOWLEDGMENTS

The authors wish to thank Evgeny Kurlayev (Russian Academy of Sciences, Yekaterinburg), Evgeny Volkov (architect in Yekaterinburg) and the staff of Nevyansk Ironworks Museum. Only through their dedicated support was it possible to carry out a survey of the roof structure in 2012 and 2013.

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