Historical Aspects of Development of Metall Structures and Application Thereof in Buildings and Facilities

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Abstract: Brief history of development of metal structures and application thereof in various buildings and facilities starting from the 12th century and up to now is presented herein. “The metal structures” notion includes structural form, manufacturing technology and ways of installation. Evolution step in making metal structures is defined both by public needs therein and level and capabilities of technical facilities: development of metal industry, engineering technology, metalworking, construction machinery and science. Proceeding from this, five periods in metal structures evolution may be singled out. Development of industry and construction is shown to result in vast variety of metal structures to be applied nowadays in different buildings and constructions especially in significant spans, heights and loads. Therewith wide scientific R&D in engineering design with application of modern high-power PCs and CAD complexes, in particular, enable to efficiently upgrade and vary the structural form of facilities with less materials and resources expenses. In-depth and comprehensive analysis of centuries-old evolution of metals application in construction and implementation of investigation results in teaching high-skilled builders and architects of today will enable to efficiently provide staffing for successful solving of state challenges of hi-tech and social development of the Russian Federation.

1. Introduction

Industrial and civil construction is one of main building economics sector. For the last years when erecting industrial facilities and low-rise administration buildings the steel structures are given preference which is stipulated by certain reasons. First, iron ore reserves are vast and annual output thereof is increasing every year [1]. According to expert estimates the ore reserves will last for 250 years. Second, steel structures are much lighter (and it is related to resource saving) as compared with the reinforced concrete ones, and they may be erected for a short period of time even in winters. Third, the structures made of steel and with overdue service life or the damaged ones may be remelted and recovered.

Steel Construction Development Association (SCDA) was set up in Russia in 2015 that is raising technological potential for applying steel structures in the construction. As of the beginning of 2019 the number of the Association participants is 84 companies, the leading Russian metallurgical manufacturing companies (EVRAZ, Severstal, OMK, NLMK), research institutes, engineering companies, construction companies and other organizations. For the 4 years the Association revised and
issued the new sets of rules for steel structural design, significantly reviewed technical standards and design procedures, much attention is paid to fire resistance and corrosion of steel. One of main tasks is application of BIM-technologies in design of buildings made of metal structures.

Today there are not many BIM-programs enabling qualitative calculations with the Russian standards realized therein, such as SCAD Office, Lira-CAD related to CAE (Computer-aided engineering), for making calculations with finite element models [2, 3]. These programs calculate rod-based building models very quickly and with good quality, however, modeling of joint connections takes much time, in this case the international IDEA StatiCa software is better to be used [4].

After the calculations and analysis of sections of basic load-bearing structures of the building the design documentation may be prepared with the use of Renga Structures, Advance Steel or Tekla Structures included to CAD (Computer-aided design) [5].

2. Steps of the structural elements development

Application of steel structures greatly enables to get architectural expressiveness to new facilities [6]:

- the form of bionic elements of metal structures makes the form of either building or structure identical to the one made by nature for many centuries;
- great metal strength enables to apply small and aesthetic in size thin-walled sections;
- application of visually open plate elements enables to clearly present the structural role thereof;
- “lightness” of structural elements is demonstrated by application of grate or truss elements;
- extended cable-stayed solutions of the structures enable to efficiently apply steel and realize long span structures [7, 8];
- plasticity of steel enables to get bent and bent-up elements [9];
- structural mechanics principles are visually demonstrated by joints between steel structures;
- paint coatings of metal is available in various color spectrum.

The history of steel structures in our country includes five historical steps.

The first step (XII-XVII cc) started in Russia with application of the simplest structures in temples. Girders and fasteners to be rigidly connected with the masonries were used here. Elements for the first structures were forged from refined iron. To fix girders with masonries the eye rings were made that were embedded to masonries, and the girders were connected to eye rings by dowels. All elements forged from refined iron were made of cast iron accompanied by filtration-refining as to get forgeable iron [10]. Historical evidence of applying these girders and fasteners is the Cathedral of the Assumption (Vladimir, 1158), the Pokrovsky Cathedral (Saint Basil's Cathedral, Moscow, 1560) (Fig.1, 2).

![Figure 1. The Cathedral of the Assumption in Vladimir.](image-url)
The second step (XVII-XVIII cc) was marked by applying steel in arched structures of spiritual facilities [11]. As a rule, sections of elements were like square beams. Connection between such elements were on locks by forge welding, and such joints were of good quality for that time, and such temples are still used without substitution of the original steel structures. One of prominent examples is the 18m span in Trinity Lavra of St. Sergius in Zagorsk (Fig.3) built in 1698.

The third step (XVIII–XIX cc) started from rapid development of the first metallurgical shops due to mastering of new forms of casting, making of bars of any form and section, and metalware. During this period people start making cast iron bridges and then use for both industrial and civil buildings therefrom. Connections between the bridge elements were basically made on locks. Due to the fact that the cast iron was considered to be the expensive material, the preference was given to masonry arch bridges till the end of XVIII c. The problem with such bridges was small spans due to which the ships could not navigate under them. When the first blast furnaces were built the iron cast self-costs decreased. Soon the first cast iron bridge was made in the Shropshire county of England, near Coalbrookdale, thereby the Severn river (1779) became navigable. The bridge span was 30.6m, while its weight reaches 384t (Fig.4.).

Figure 2. Antechurch of the Pokrovsky Cathedral (Saint Basil's Cathedral).

Figure 3. 18m spans in the Refectory Church of the Trinity Lavra of St. Sergius in Zagorsk.
Figure 4. Cast iron bridge across the Severn river, England.

In the forth step (XIX–XX cc.) during rapid technological advance new casting technologies were improving all the time, with very many industrial enterprises, workshops and plants being opened. Puddling – a new step in the manufacture of iron at that time – was soon replaced by ore smelting in open-hearth shops. While making node connections a new solution was proposed, i.e. rivet connection. Node connections from rivets were made by using punch press. The metallurgy was rapidly developing and the leading workshops started thinking of manufacturing the standard rolled and moulded items. Application of heavy cast iron in building structures was fully stopped thereafter.

Metal structures were also used in bridge engineering that appeared due to railways making in the second part of the XIX century. One of the first such bridges was built in Luga river that was used for 90 years and destroyed during the Great Patriotic War (Fig.5). It was designed by engineer S.V. Kierbedź in 1852 thereby starting manufacture of the iron lattice girder (Town-type lattice girders).

Figure 5. The iron railroad bridge across the Luga river of the Saint Petersburg–Warsaw Railway.

Another example of bridges of that time is the 640m railroad bridge across the Belaya river in Ufa (1886-1888) (Fig.6).
Figure 6. Ufa railroad bridge.

The span of the slab of Haymarket in Saint-Petersburg was 25m long and very light although providing the required protection (Fig.7).

Figure 7. The construction of Haymarket in Saint-Petersburg, end of XIXc.

Later many facilities were erected taking the Haymarker as an example, e.g. Warehouses at the Spit of Nizhny Novgorod (Fig.8) built in 1896.

Figure 8. Warehouses at the Spit of Nizhny Novgorod.
Construction of arched-frame structures was evolved by talented Russian engineer Vladimir G. Shukhov. The Kyiv station building in Moscow is covered by a train shed built in 1914 by his design (Fig. 9).

![Train shed of Kyiv station, Moscow.](image)

The Eiffel Tower was being built in Paris in 1887-1889. The sightseeing of the whole France was planned to be demolished in 20 years after finishing the construction thereof, but due to rapid growth of radio and later of TV it was left as it was. The Tower height is 300.65m (324m with a new TV mast), with the weight thereof being 7.3t. It should be mentioned that the Tower oscillations due to the wind exceed no 15cm, it is rather the thermal forces that affect it more: dimensions of metal structures increase so because of the sun heating so that the upper point deviates for 18cm [12].

The fifth step (from 1920s to present) is connected with the development of casting technology with the application of alloy additives to significantly improving the steel physical properties [13]. Together with it there appeared an improved method for connecting elements by various kinds of welding, with the riveted connection being replaced by welding by the end of 1940s [14].

In the middle of the XX century all metal structures in the Soviet Union were calculated by more improved limit state method (the permissible stress method was used before), thereby enabling to make larger constructions therewith applying structures of less weight [5].

Large volume of construction and uniformity of structures contributed to standardizing of structural layout of buildings. Unification was reducing labor intensity for making and assembling metal structures [15]. The design school of the Soviet era adhered to the principle of steel saving.

In the background of the total development of steel structures the computers (electronic computing machines) became widely applied from the middle of the XX century, due to which there appeared the first CAD systems (computer aided engineering) enabling reducing the design period for various facilities [3].

Making of any facilities not only from steel structures is to be thoroughly analyzed [16, 17], so the architects systemized the criteria for form-making in architecture.

Kind of the material the facility is made of became the basis for many architects in realization of their ideas, e.g. Hi-Tech style appeared, with the metal being the principal material therein. Hi-tech is expressing quality, aesthetics and form of steel using metal items and structures.

Steel is known to be very strong in bending and in tension. Nowadays application of metal in the leading countries is almost 60-70% of total volume of the construction. The ability of taking any shapes is the advantage of this material as compared with the other ones.

Design concepts by V.G. Shukhov still widely applied speak to the genius of the engineering ideas of the Russian scientist, with these concepts realized in steel structures being highly appreciated.

The application of steel is considered at engineering of unique buildings and structures distinguished...
by the original architectural forms and therewith having various functions. E.g. the Bird’s Nest stadium in Beijing designed for use throughout the 2008 Summer Olympics (Fig.10) is the largest structure of steel having the most complicated engineering construction in the world. A new grade of steel differed by absence of various admixtures was used for the stadium construction, which to some extent complicated welding of steel elements. Another example of applying steel as the principal material is the Arganzuela bridge in Madrid connecting the old part of Arganzuela in Spain (Fig.11). The Hi-Tech representative, French architect Dominique Perrault designed modern and fantastic footbridge that became the local sightseeing attracting tourists.

Figure 10. The Bird's Nest stadium in Beijing, China.

Figure 11. Arganzuela footbridge in Madrid, Spain.

3. Results
Deep and thorough analysis of centuries-old development of metal application in the construction and using the results thereof in training current high-quality experts and architects will enable efficiently to provide human resources for intensive upgrading of the construction complex to successfully solve priority state tasks of high-technological and social development of the Russian Federation.

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