

DOI: 10.32703/2415-7422-2023-13-2-419-455

UDC 621.791:624.21/.8:93:94

Oleh Strelko

State University of Infrastructure and Technologies

9, Kyrylivska Street, Kyiv, Ukraine, 04071

E-mail: olehstrelko@duit.edu.ua

<http://orcid.org/0000-0003-3173-3373>

On the history of the construction of metal bridges in the 20th century using welding technology

Abstract. *The history of bridge construction is an important part of historical knowledge. Developments in bridge construction technology reflect not only engineering advances, but also social, economic and cultural aspects of society. Engineers and scientists faced unique challenges when designing and building bridges depending on the technological level of the era, available materials and the needs of society. This process may reflect technological progress, changes in transportation needs, and cultural and social changes. The purpose of this article is to briefly review key moments and stages in the history of metal bridge construction using welding technology in the 20th century. The history of the development of the construction of metal bridges using welding goes back a little over 100 years. The short period from the construction of the first welded bridges to their first disasters led to the need to analyze the possible causes of these destructions. As the analysis performed showed, catastrophic destruction most often occurred under the influence of several factors, as well as a combination of external adverse influences and the internal “unpreparedness” of the structure for them. The above examples indicate that an irrational choice of steel could be both an independent cause causing brittle failure of structures, and an aggravating factor in the presence of structural violations, thermal stresses and welding defects. Over the years, bridge manufacturing technologies have been improved in different countries, and new steels and materials for their welding have been developed. Thanks to the use of carbon, low-alloy and alloy steel, designers abandoned the brutal “railroad-type” beam trusses and today metal bridges with graceful and beautiful silhouettes powerfully stride across the water surface, mountains and valleys. They became real attractions of megacities and country landscapes, and builders were able to successfully solve numerous technical and economic problems. An important contribution to the development of global bridge construction using welding technologies was made by the team of the Institute of Electric Welding of the Academy of Sciences of the Ukrainian SSR under the leadership of Academician Evgeny Oskarovich Paton. The team of the Institute of Electric*



Welding of the Academy of Sciences of the Ukrainian SSR, introducing welding into bridge construction, carefully checked the results and monitored the behavior of structures. A new grade of steel was created that was resistant to the formation of brittle and fatigue cracks, its welding technology was developed, a technology for installation welding of vertical sheets with forced formation of a seam was developed, and suitable welding materials were selected. At the time of construction in 1953, the Kyiv Evgeny Paton Bridge across the Dnipro River was the largest all-welded bridge in Europe, all seams of which, including assembly ones, were made for the first time using automatic and semi-automatic welding. In addition, the presence of large similar blocks in the design of the Evgeny Paton Bridge made it possible to mechanize assembly and welding operations and organize an in-line method for their production at the factory and installation, which improved the quality of welding work and reduced its labor intensity.

Keywords: *history of bridge construction; history of metal bridges; welding history; Evgeny Paton Kyiv Bridge; Historical Welded Structure Award; Institute of Electric Welding of the Academy of Sciences of the Ukrainian SSR*

Introduction.

One of the main goals of history as a science is to study the past on the basis of documentary evidence, archaeological finds and other sources. Historians strive to reconstruct the events, trends, and cultural characteristics of different time periods based on available information. It is important to note that historians adhere to certain methodologies and standards of evidence to ensure the integrity of their research. Comparison and analysis of various sources help historians build a more complete and objective understanding of the past. Historical facts and dates are subject to reinterpretation and debate in the light of new research and discoveries, and historians often revise their interpretations and conclusions based on new evidence. This process makes history a dynamic and constantly evolving field.

The history of bridge construction is also an important part of historical knowledge. Developments in bridge construction technology reflect not only engineering advances, but also social, economic and cultural aspects of society. Engineers and scientists faced unique challenges when designing and building bridges depending on the technological level of the era, available materials and the needs of society. This process may reflect technological progress, changes in transportation needs, and cultural and social changes.

Studying the history of bridge construction allows to understand how different civilizations dealt with technical problems, what engineering solutions they created, and how these solutions influenced the development of society. It also highlights the importance of engineering and construction achievements in human history.

The history of the construction of metal bridges is an exciting period in the development of engineering and construction art. An analysis of scientific research

devoted to the history of the construction of metal bridges allows to identify several main areas of this work:

1. Evolution of metal bridge construction technology (Pescatore & Borgeot, 2008; Armisen, 2019). This direction is devoted to the study of the history of the development of technologies and methods for constructing metal bridges from their initial introduction to modern trends.

2. The role of metal bridges in infrastructure development (Liegner, Kormos, & Papp, 2015; Statyvka, Kyrychenko, Strelko, & Berdnychenko, 2021; Vůjtěch, Ryjáček, & Matos, 2023). This direction is devoted to the analysis of the impact of the construction of metal bridges on the development of transport infrastructure, urban planning and economics in different regions and eras.

3. Architectural and engineering solutions for metal bridges (Bartlett, Graham, & Camiletti, 2009; Arwade, Schafer, B. W., Schafer, D. F., & Schafer, S. T., 2015; Schueremans, Porcher, Rossi, Wouters, & Verstrynghe, 2018). This direction is devoted to the study of the history of the various styles, designs and technical solutions used in the construction of metal bridges, and their impact on the overall landscape.

4. Historical metal bridges as cultural heritage (Bernabeu-Larena, Martín-Caro, Hernández-Lamas, & Plana, 2023).). This direction is devoted to assessing the role and significance of historical metal bridges as part of the cultural heritage and architectural monuments.

5. Problems of maintenance and restoration (Rymsza, Mistewicz, & Tucholski, 2017). This direction is devoted to the study of the challenges and technical aspects associated with the maintenance and restoration of ancient metal bridges, taking into account their preservation for many years.

This work belongs to the first direction. Its purpose is to briefly review key moments and stages in the history of metal bridge construction using welding technology in the 20th century.

Idea, Methodology and Sources of Research.

The author of this article became interested in the topic of constructing metal bridges using welding in connection with well-known information about the 70th anniversary of the Evgeny Oskarovich Paton Bridge in Kyiv in Ukraine. The Paton Bridge was put into operation on November 5, 1953 (Lobanov, Kyrian, & Shumitsky, 2003).

Evgeny Paton Bridge is truly unique. This is an undeniable fact and was specifically recognized in 1995 by the American Welding Society (AWS) with the Extraordinary Welding Awards in the Historical Welded Structure Award category (see Figure 1) (American Welding Society, 2023, p. 52). The AWS website states that (American Welding Society, n.d.): “Nominations for the Historical Welded Structure Award may be submitted by any AWS member for consideration by the Committee of Past Presidents. Nominations for historical recognition are valid for two years, and structures must be at least 35 years old.”

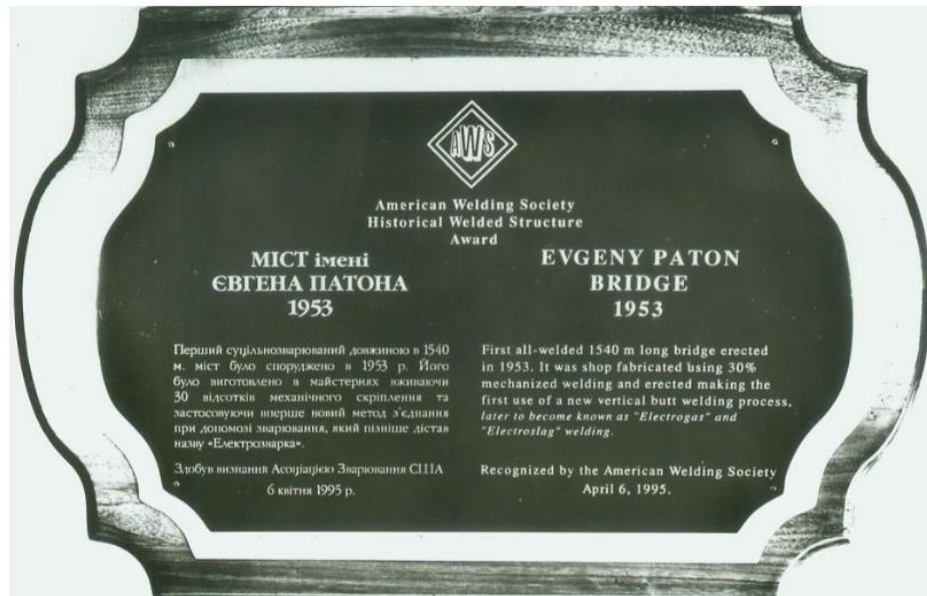


Figure 1. Memorial sign about the Evgeny Paton Bridge Extraordinary Welding Awards in 1995 (Lobanov, Kyrian, & Shumitsky, 2003).

It is worth noting that the Extraordinary Welding Awards were created to recognize and promote the science, technology and applications of welding (American Welding Society, n.d.). The Extraordinary Welding Awards was intended to encourage members of the welding community to recognize their heritage in metal joining; and to convey to the public the fact that the combination of metals has played and continues to play an important role in everyday life. The purpose of the Extraordinary Welding Awards is to recognize the excellence of welding in construction, fabrication and manufacturing, and to recognize those welded structures whose purpose is significant in or influences the history of the world.

As of this writing in 2023, only 42 objects or inventions have been awarded the Extraordinary Welding Awards in two categories: The Historical Welded Structure Award and the Outstanding Development in Welded Fabrication Award (American Welding Society, 2023, p. 52–53). Among them: Tokyo Tower (1997); U.S. Pentagon (2000); Pratt & Whitney F119 Engine (2001); Hoover Dam Penstock Power Plant System (2002); One World Trade Center (2015); Mars Curiosity Rover (2016); Panama Canal (2019).

Evgeny Paton Bridge was awarded the Extraordinary Welding Awards when the award was first presented in 1995, along with three other winners Sludwia River Bridge, Mr. Charlie (Morgan City, LA) and Soviet Combat Tank (American Welding Society, 2023, p. 52). This once again emphasizes the importance of the achievements of welding technologies in the manufacture of the Evgeny Paton Bridge structure.

As can be seen in Figure 1, the AWS award was awarded to the Evgeny Paton Bridge, as the first all-welded bridge, 1540 m long, built in 1953, using new welding processes in the manufacture of vertical butt welds, later called "Electrogas" and

"Electroslag" welding And also for the use of less than 30% mechanical connections in the manufacture of bridge structural elements in factory workshops (Lobanov, Kyrian, & Shumitsky, 2003).

It was in this part of the study that the author had the largest number of questions that required answers supported by documentary evidence of historical documents.

First of all, this concerned terminology. Namely, the use of the term "first". When the Evgeny Paton Bridge was discussed in the Extraordinary Welding Awards, it referred to the "First All-Welded Bridge." First in the world? The first in Europe? The first one this long? The first all-welded one of this length? The first one at the time of construction (put into operation) in 1953?

Finding answers to these questions turned out to be not so simple. The more the author delved into the history of the research question, the more inconsistencies and points there were that required a thorough and verified analysis, as well as a search for verified and reliable information.

For example. In various sources you can find information about Evgeny Paton Bridge, which differs in the degree of "primacy".

The article (Mezenin, 1977) claims that Evgeny Paton Bridge is "the largest all-welded bridge in Europe".

Evgeny Paton Bridge is presented as "the world's first all-welded bridge" in articles (Shumitsky, 1997, p. 240; Korsun, Buyak, & Matsyuk, 2019).

The well-known scientist in the field of bridge construction, Anatoly Viktorovich Perel'muter, proposed an option (Perel'muter, 2012): "The largest all-welded bridge in Europe at the time of construction, for the first time all seams, including assembly ones, were made using automatic welding".

The article (Lobanov, 2014) claims that Evgeny Paton Bridge is "the largest all-welded transport structure in the world at that time".

In articles (Poznyakov, Dyadin, Davydov, & Dmitrienko, 2021; Lobanov, Dyadin, Davydov, & Lytvynenko, 2021) about the Evgeny Paton Bridge, the bridge is shown as "the world's first all-welded road bridge".

Shymanovskiy, Shalinskyy, and Baran (2021), claim that the Evgeny Paton Bridge is "the world's first all-welded bridge with the girder system of such a length".

So, many sources contain the statement that at the time of its construction, Evgeny Paton Bridge was one of the largest all-welded bridges in the world, which for the first time had all seams, including installation ones, made using automatic welding. Today, a large number of overwater bridges are built using this technology, which combines welding and bridge construction. However, in those days, electric welding was still rarely used in bridge construction. And numerous sources reported from time to time that welded bridges were destroyed and fell in different places on the planet. But what could have caused this destruction? What allowed Ukrainian welders to erect such a complex structure without avoiding the mistakes of their predecessors? What does the term "all-welded bridge" mean, and how does it differ from simply a "welded bridge" or "a bridge built using welding technology"? How is welding used in bridge

construction? What kind of materials were used at different times in the construction of metal bridges? How relevant is welding technology to modern bridge construction?

The search for answers to these and many other questions formed the basis of this study. During its preparation, a historical and chronological analysis of numerous engineering and scientific studies in the field of bridge construction, construction technologies, materials science and architecture was carried out. This made it possible to offer our own version of the stages in the history of the construction of metal bridges using welding technology in the 20th century.

Results and Discussion.

What materials were used at different times in the construction of metal bridges?

Metal bridges were not known in ancient times. There are only indications that in ancient China and India, around the 1st century AD, iron chains were used for suspension bridges (Bender, 1872; Sedmak, Ković, & Kirin, 2022;).

Any bridge, as we know, consists of one or more spans covered in one way or another. If the spanning parts are suspended from the abutments using a rope or chains, then such a bridge is called a suspension bridge. If the span is covered with wooden beams or wooden trusses (lattice structures of various shapes), or stone slabs, then the bridge is called a beam bridge. Finally, an arched bridge is a bridge in which an arch is thrown across each span, that is, a vault resting on the abutments with its heels. Of course, there are many transitional forms between these main types of bridges. Arch bridges were the highest achievements of ancient bridge construction. Suspension and beam bridges usually had wooden spanning parts. The stone slab could not be suspended, and it was inconvenient to use it as a beam, since it could only cover a very narrow span. The vault retains its strength even with a large span.

Metal bridges could not be developed in ancient times because metallurgy was still at a very low level. Iron was extracted directly from the ore in small pieces in so-called raw furnaces and forged by hand. This took a lot of time and labor. In those days they did not yet know how to cast iron. Therefore, all castings were made of bronze, and large castings could not be made then. After the collapse of the Roman Empire, bridge construction was in decline.

In the 15th century, metallurgy began to develop significantly. In addition to the great successes of bronze foundry, which already produced complex castings (bells, cannons), the production and use of cast iron was mastered. Cast iron was smelted in special high furnaces with increased blast, called blast furnaces. Iron began to be extracted mainly from cast iron in the so-called limit (fresh) forges. These forges were much more productive than cheese forges. Bellows blowers, large forging hammers, drilling machines, etc. began to be driven by water wheels. That is why advanced designers of that period were able not only to improve the types of stone and wooden bridges in every possible way, but also to raise the question of metal bridges.

This idea was first put forward by the Venetian Fausto Veranzio (or Verantius), who lived in the first quarter of the 17th century (Gazzola, 2015, p. 2; Blažević, 2017). At that time, Venice was still a powerful trading republic, although its period of greatest prosperity had passed. Various complex arts and crafts were developed in Venice and the lands under its control. In his work “*Machinae Novae*” (1615 or 1616) (Veranzio, 1968), Veranzio devotes a lot of space to the construction of bridges (Figure 2–4).

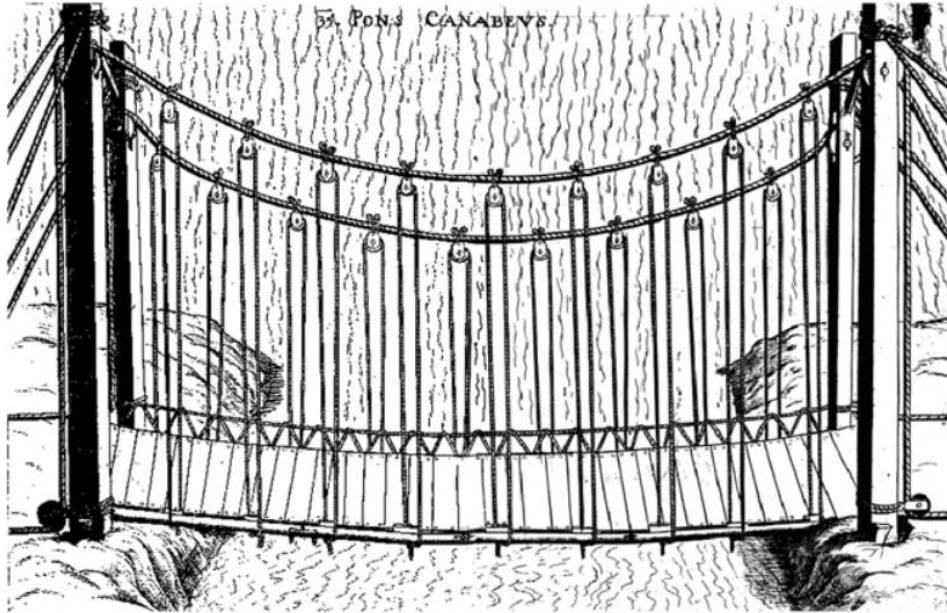


Figure 2. Picture of the Pons Canabeus by Fausto Veranzio (Gazzola, 2015, p. 3).

He puts forward the idea of building a bronze bridge (Pons Arevs) of an interesting design see Figure 3.

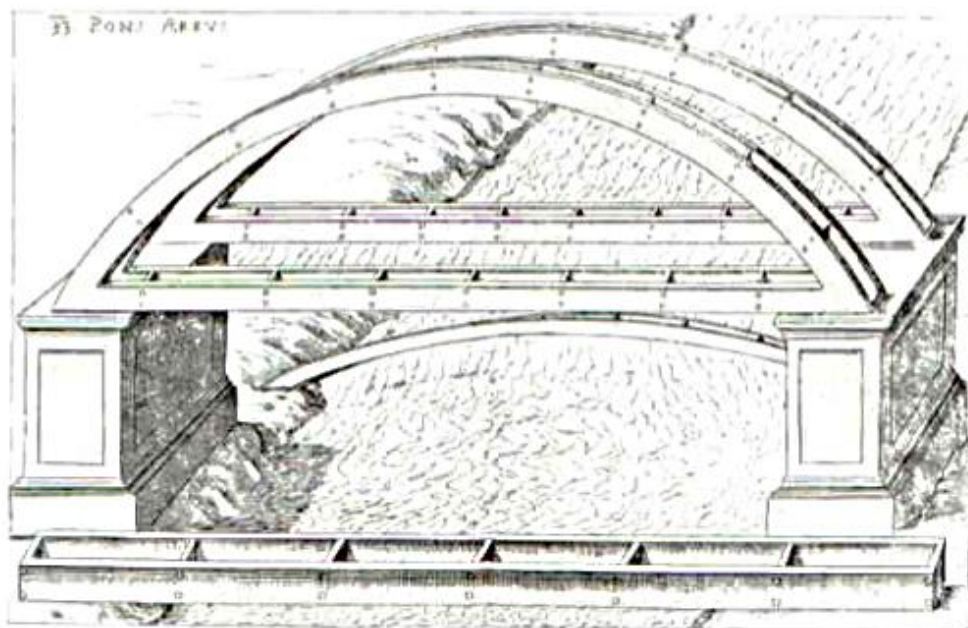


Figure 3. Picture of the Pons Arevs by Fausto Veranzio (Radić, Puž, & Šavor, (2013).

Each of the arches has the appearance of a “bow with a string” or, in geometric language, an arc with a chord, and consists of two bronze, flat arches connected to each other (Figure 3). By its type, such a bridge is transitional from arch to beam. In fact, here the arch is pulled together by a lower, as they say, “belt” and acts on the support in almost the same way as an ordinary truss. Veranzio's main mistake was that he chose bronze as a building material. He not only could not imagine steel castings, but even, apparently, was little familiar with iron foundry, which had already reached a significant level in some countries. Veranzio believed that the bridge's trusses should be cast in bronze, and argued that such a bridge would be cheaper than a stone bridge of equal size. However, bronze, due to its fragility, could not fulfill the tasks that Veranzio assigned to it. A bronze bridge of significant size would collapse on its own. Veranzio's project had only the significance that it prompted later architects to seek materials for bridges.

Even more interesting is another bridge project, which in the text of Veranzio's book is called “Ferrevs” (“Iron”) (Veranzio, 1968). “We call this bridge,” writes Veranzio, “iron, because it is suspended on many iron chains on two towers built along the banks of the river”. The bridge deck, i.e. the part along which the path is laid consists of links, apparently of metal (not specified in Veranzio), covered with transverse boards. The links of the canvas are doubly suspended: firstly, to the supporting chains by iron pendants; secondly, additional chains to the towers (Figure 4). Both of Veranzio's projects remained unrealized.

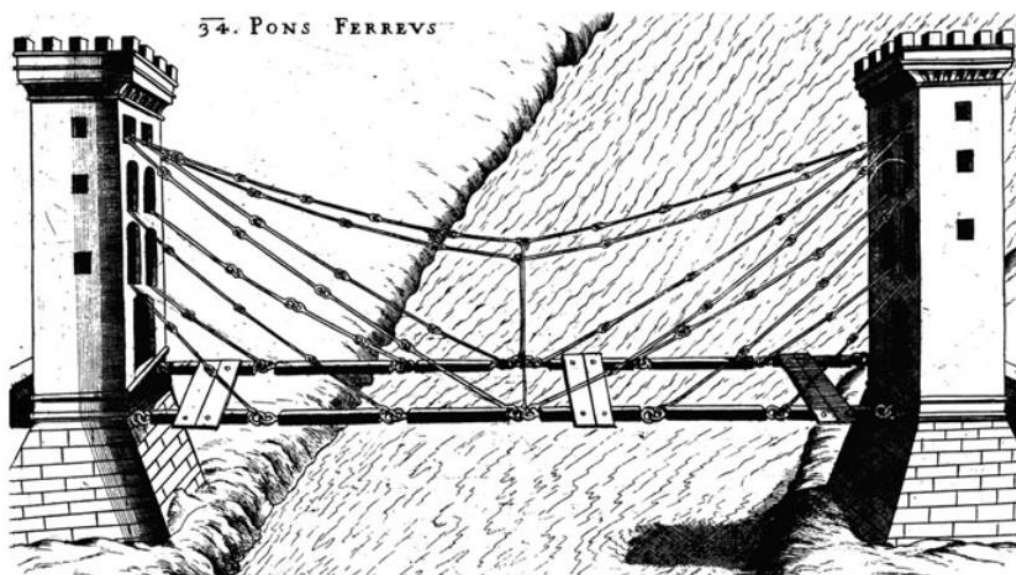


Figure 4. Picture of the Pons Ferreus by Fausto Veranzio (Gazzola, 2015, p. 3).

The first real metal bridge was built in the central industrial region of England, in the county of Shropshire across the river. River Severn (Sedmak, Ković, & Kirin, 2022). On one side of the river was the famous Coalbrookdale works of Abraham

Darby II and Reynolds. On the other are the factories of John Wilkinson. All these names have glorified themselves in the history of technology. Abraham Darby I converted blast furnace smelting to coke in 1709, thereby opening a new chapter in iron foundry (Johnson, n.d.). Reynolds was the first to build a horse track with cast iron rails. John Wilkinson was the largest English metallurgist of that time. The most advanced machines and production methods were introduced at his factories. In particular, Wilkinson was the first to use steam engines for blowers, drilling machines, etc.

As industry grew around the gorge, so did the need for a strong, durable bridge to transport goods across the river. In 1773, Thomas Farnolls Pritchard, an architect from Shrewsbury, came up with a bold idea (English Heritage, n. d.). Combining engineering expertise with new iron casting techniques, he proposed the world's first iron bridge, which would link the parishes of Madley and Benthall across one of the busiest rivers in the country. Pritchard's designs were approved by Act of Parliament and construction began in 1777. Abraham Darby III with Reynolds and Wilkinson jointly created the first metal bridge, which was built from 1777 to 1779 (Siviero & Martini, 2020). The bridge was in the form of a semicircular arch of five parallel cast-iron chords and a 100-foot cross-braced span to support a level mainline 14 feet wide, located 55 feet above the water. Each edge was cast in halves, 70 feet long and weighing 38 tons (Figure 5). They were brought from a nearby foundry on barges, placed in place using a pulley system and connected in the middle with cast iron bolts.



Figure 5. The Cast Iron Bridge near Coalbrookdale (Williams, 1780).

At the same time, the cast iron frames from which the bridge arch was made had a tapering wedge-shaped shape, in imitation of the shape of the stones from which the arched stone bridge arches were erected (Figure 6). Subsequently, the shore supports leaned forward slightly and raised the arch in the central part, but this in no way affected its strength. The coastal abutments of the Coalbrookdale Bridge and the approaches to it were made of brick. Soon a new city grew up near the bridge, called Iron Bridge. The radical new structure, which officially opened on New Year's Day 1781, used a total of 384 tons of iron, costing around 6,000 GBP – significantly more than the original estimate of 3,200 GBP. But if Abraham Darby had wanted to build such a bridge today, he would have to raise in the region of £1.5 million (The Ironbridge Gorge Museum Trust, n. d.). The bridge stands to this day as a monument to the skill of the builders and the efficiency of cast iron. It became a UNESCO World Heritage Site in 1986 and remains an iconic element of Britain's industrial past .

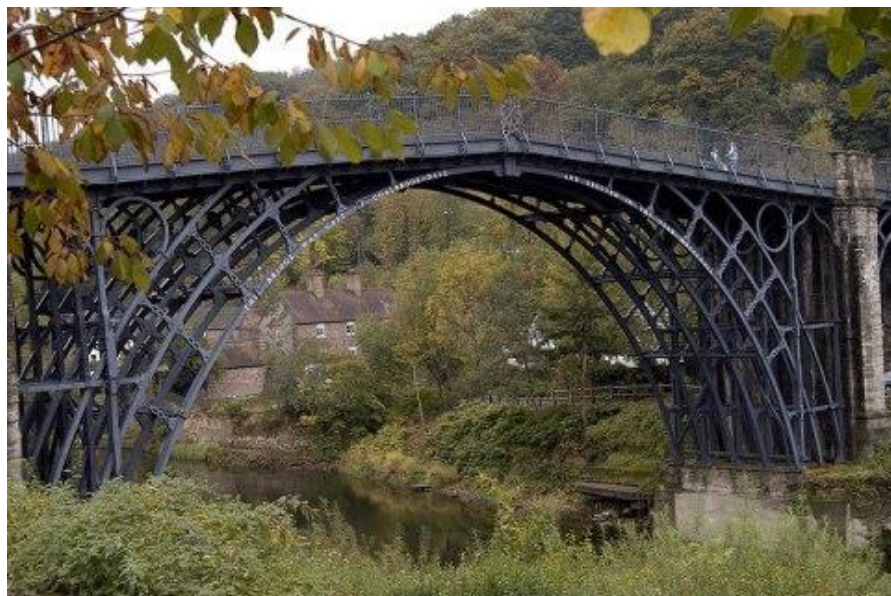


Figure 6. Ironbridge. “Birthplace of the Industrial Revolution” and UNESCO World Heritage Site. (Johnson, n. d.).

Bridge design in the mid-19th century was largely limited to trusses, and wood gradually gave way to iron. The Bavarian Karl Friedrich von Wiebeking (1762–1842) built flat-arch bridges from bolted planks so effectively that his peers credited him with the system's origins, but trusses and iron still dominated (Kahlow, 1995; Booth, 2017; Holzer & Knobling, 2020). Wrought iron's tensile strength, fire resistance, and other beneficial features made the metal the best material for building bridges, especially railroad bridges. While laying the Stockton–Darlington railway, George Stephenson experimented with a small iron bridge in County Durham in 1825 (Kozak-Holland & Procter, 2020; Groote, Ciccarelli, & Giuntini, 2021). The 50-foot long bridge had four lens-shaped spans in a combination of arches and suspended forms, convex at both the top and bottom. There were vertical posts, but no diagonal braces. In 1859, Isambard

Kingdom Brunel built a unique the Royal Albert Bridge over the Tamar River in Saltash (Fougères, 2022). He followed the same principles, but his bridge was much larger and improved by adding diagonal braces. Ten years later, another lenticular bridge was built over the Elbe River in Hamburg, Germany (Mehrtens, 1900a) (Figure 7). However, most builders relied on diagonals to take advantage of the stability inherent in triangles, the only polygons that do not change shape under stress. All designers, whether they realized it or not, acted in accordance with the principles that Simon Stevin formulated back in 1586, defining the “triangle of forces” (Van Dyck, 2020).

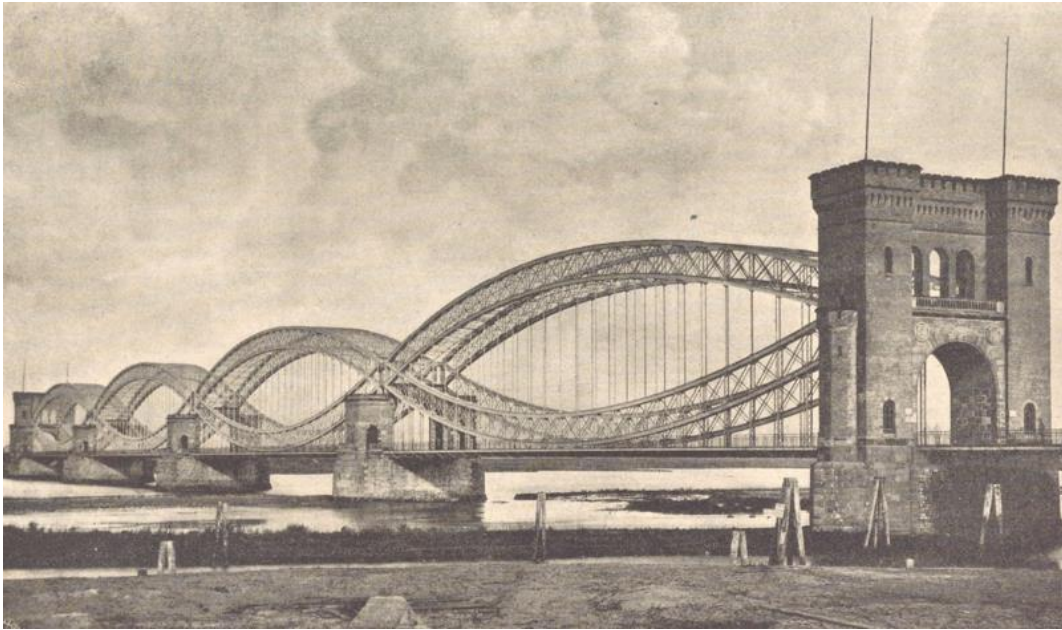


Figure 7. Railway-bridge over Elbe in Hamburg, built 1868–1872 (Mehrtens, 1900b).

Among the large steel bridges built with the rise of railroads in the second half of the 19th century, three were truly outstanding. All three bridges were different in concept and design. James B. Eads chose an arch design for his Mississippi Bridge, opened in the St. Louis area in 1874 (Grimes & Castro, 2020). For the famous Brooklyn Bridge, engineers John A. Roebling and his brother Washington A. Roebling chose a suspension structure that they had succeeded in Niagara (Witcher, 2022). John Fowler and Benjamin Baker, who built the bridge over the Firth of Forth in Scotland, preferred a cantilever design (Rosie, 2018). All builders had experience in underwater work. All three bridges are still in use.

Beginning of the use of welding in bridge construction.

In russian-language Internet sources, the primacy in the use of welding in bridge construction is often mistakenly attributed to Viktor Petrovich Vologdin. His 25-meter bridge was built in Vladivostok in 1928 (Perel'muter, 2012). Various Russian-speaking authors from time to time attribute primacy to this bridge, either in the USSR, then in

Europe, or in the world (Ban'kovskij, 1988; Turmov, 2004; Shevchenko, 2004; Chigarev, Litvinov, 2011; Perel'muter, 2012).

In fact, in 1928, Vologdin built the first all-welded viaduct in the USSR (PrimaMedia.ru, 2023). Four factory welders welded its 25-meter span in 20 days, saving 25% of metal compared to a riveted structure. Later, an urban myth arose in Vladivostok, as if the Kazan Bridge on the Egersheld, thrown across the last meters of the Trans-Siberian Railway, was the very brainchild of Vologdin. In fact, welders under his leadership produced an openwork metal structure of a completely different type and purpose; it has not survived to this day. "The bridge was intended for conveyors and pedestrians between two warehouses on Egerschöld, separated by a road," recalled one of the first graduates of the Far Eastern Politechnical Institute Welding Department, Candidate of Technical Sciences Ivan Dmitriev.

In the 1920s, bridge designers began preliminary research into the specifics of welding technology and its advantages and disadvantages (Fraser & Roberts, 1994). However, they were in no hurry to fully introduce welding into bridge construction (Figure 8). And instead of building new all-welded spans, they experimented with strengthening existing bridges. The first structure to be reinforced in this manner by welding was the Chicago Great Western Railroad's swing bridge over the Missouri River at Leavenworth, Kansas. Considered too light for modern locomotives of the time. The bridge was reinforced at critical points over a two-month period in 1927.



Figure 8. The article "Electric welding reduces cost of strengthening bridge" in the journal "Railway Engineering and Maintenance" (Railway Engineering and Maintenance, 1927).

The first welded bridge ever built was a pedestrian bridge, erected in 1921 between two buildings of the General Electric plant in Schenectady, New York (McKibben, 1929). In 1921, the Williams Bridge Company of Syracuse, New York, constructed a footbridge over the Delaware & Hudson Railroad tracks at the General Electric plant in Schenectady (Spivey, 2001). This single 35' span, the first all-welded bridge in the U.S. and , began a decade of experimentation with electric arc welding for bridge repair and construction. Until the advent of shielded welding electrodes, which reduced inclusions of slag and therefore improved the ductility of welds, bridge engineers avoided butt welds. They therefore initially kept to the truss form, using fillet welds to join members to the same splice and gusset plates found on those of riveted construction. Footbridges were a more fertile ground for experimentation with welding because they carried lighter loads and were subject to less stringent requirements.

However, the first of any significance was a 53-feet double-girder railroad a bridge constructed using arc welding by the Westinghouse Electric and Manufacturing Company over Thompson Run in Turtle Creek, Pennsylvania (Bissell, 1928). Opened for service on November 5, 1927, the bridge carried railroad traffic between the company's Linhart Works and East Pittsburgh Works (Hess & Hybben, 1989). Interested in promoting virtually any new technology related to electricity, Westinghouse was a leading proponent of electric arc welding. The Turtle Creek Bridge demonstrated what Westinghouse engineer A. G. Bissell called the company's "confidence in arc-welded structures" (Bissell, 1928).

In 1928, Westinghouse also sponsored the construction of the nation's second all-welded railroad bridge as a means of providing access to its plant in Chicopee Falls, Massachusetts (Hess & Hybben, 1989). This, too, was arc welding. To obtain comparative data on welding and riveting costs, Westinghouse based the 134-feet single-span structure directly on the Warren riveted truss originally intended for the site, "the only impediment to a true comparison was the replacement of rolled sections with the precast sections shown in riveted construction". The welded bridge even used regular gussets to connect the panels (Figure 9). Upon completion, Westinghouse claimed "substantial" cost savings: "The welded structure used about two-thirds the amount of steel required for its riveted counterpart, saving most of the joint materials and eliminating holes in tension members and floor stringer continuity" (Fish, 1933).

Highway engineers soon followed the railroads' lead: in 1929, the first all-welded steel highway bridge was built (Fraser & Roberts, 1994). Designed by professor of the Lwow Technical University Stefan Bryla in 1927, the 88-feet truss spans the Słudwia River near Łowicz, Poland (Bryla, 1930). According to design engineer Stefan Bryla, arc welding saved about 21 percent in materials, although the total cost of the project was roughly equivalent to riveted construction – as a result of the need to include the cost of welding equipment in the final accounting.

The construction of a number of welded road bridges followed in the 1930s. Although American civil engineers were reluctant to experiment with the new technology, their European colleagues did not hesitate. "The arc welding process,"

wrote Kansas engineer LaMotte Grover in 1934, “has been used quite extensively for the construction of new steel bridges in foreign countries, but it appears to have been indifferent to most American civil engineers” Grover, L. (1934). However, several welded bridges were built in this country during the second half of the decade, including the 397-foot Rancocas River Bridge in New Jersey (Davis, 1935).

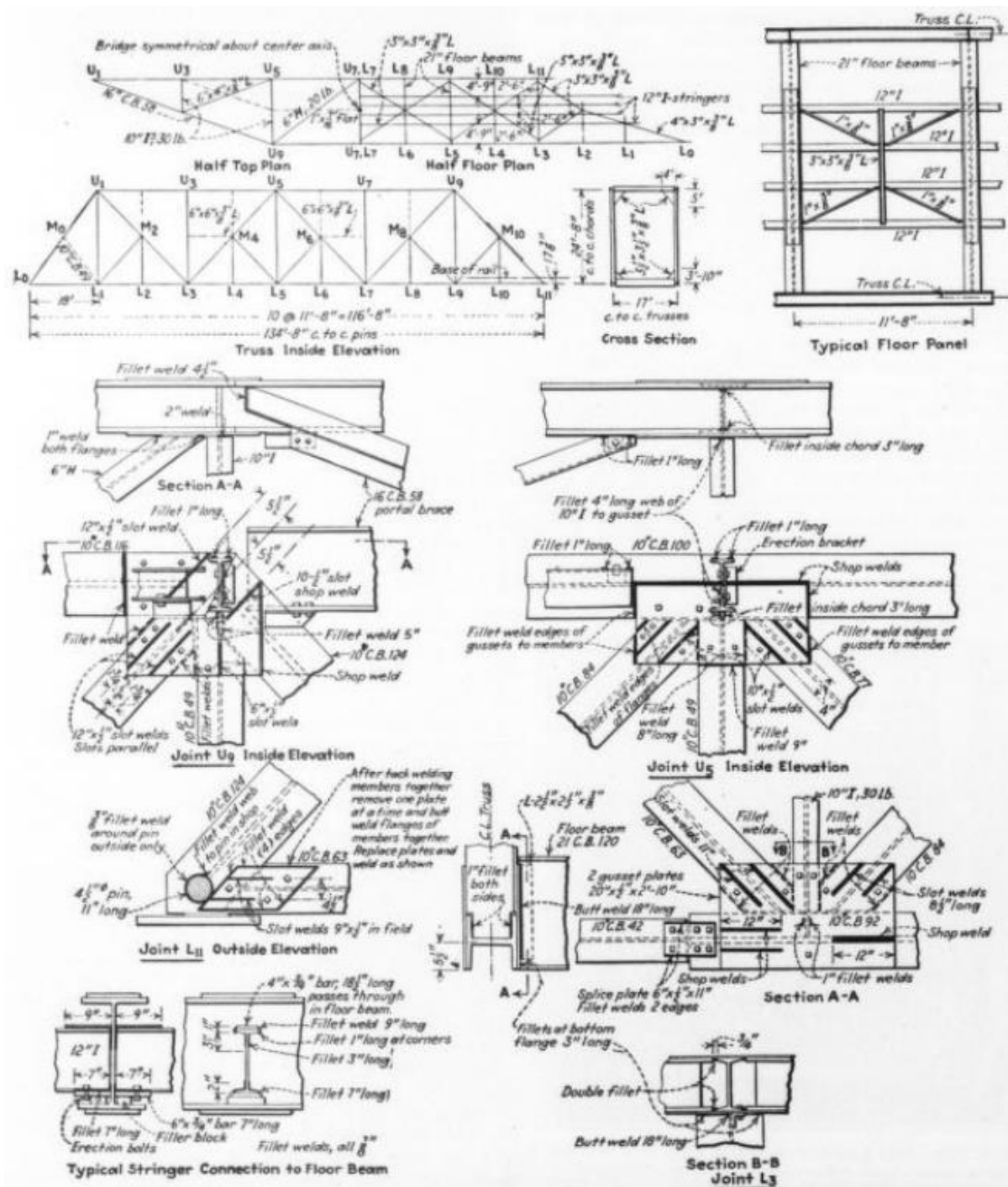


Figure 9. Details of arc-welded Through-Truss Railway Bridge, Chicopee Falls, Massachusetts (Fish, 1933).

In the 1930s, other welded bridges were also built. Thus, in 1934, the first all-welded drawbridge was built in the UK in Middlesbrough (Figure 10).

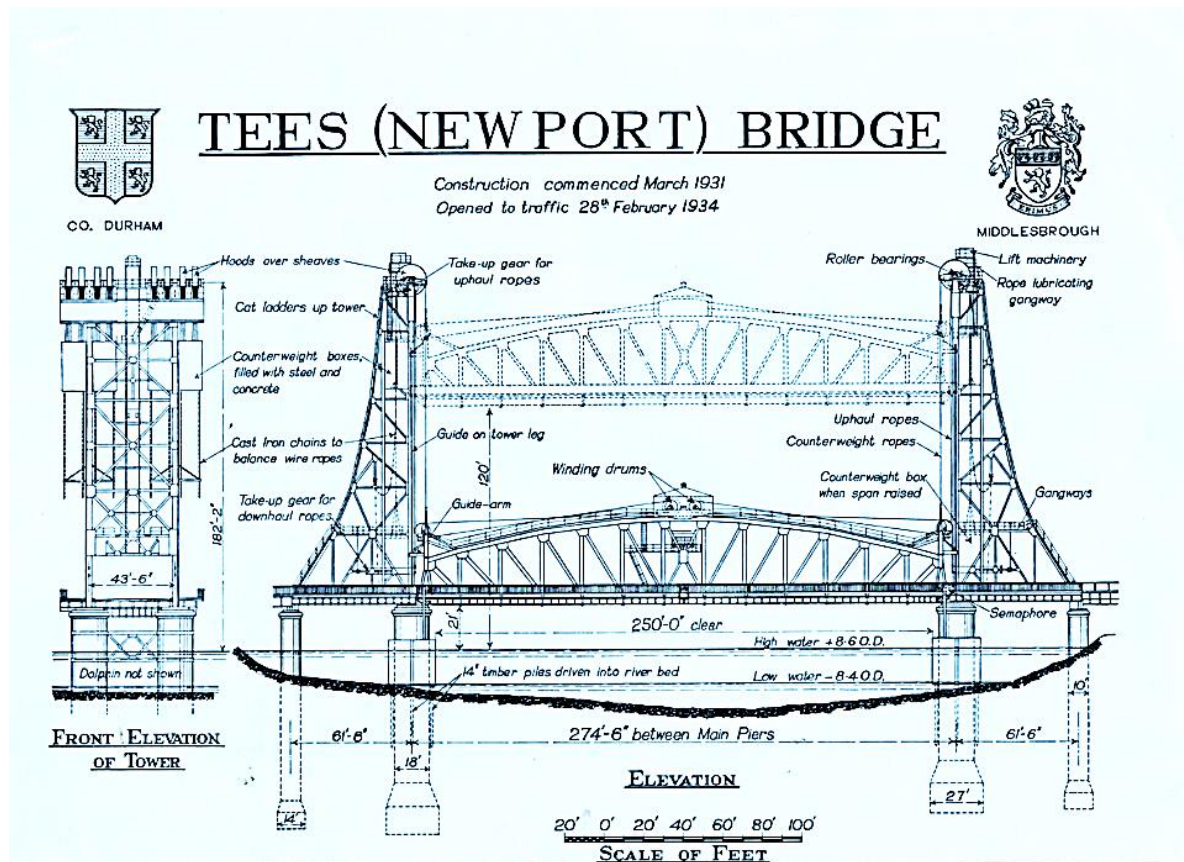


Figure 10. Dorman Long and Newport Bridge. (Tees Valley Museums, n. d.).

The Tees Newport Bridge was the first large vertical lift bridge in Europe, and opened by Prince Albert (later King George VI) on 28 February, 1934 (Figure 10). The bridge connects Middlesbrough to the borough of Stockton-on-Tees and was designed to lift up to 37 m to allow ships to pass under. The bridge was built by the Middlesbrough-based Dorman Long and Co Ltd. (Co-Curate, n. d.). Newport Bridge was a vertical lift bridge, the first of its kind to be built in the UK (Tees Valley Museums, n. d.). It was built specifically so that the main part of the bridge could be lifted to allow ships to pass under it, and then lowered again for people and vehicles to cross. Total length 4,920 feet (1499 m). Weight 8,000 tons. The bridge was fitted with two electric motors and a petrol engine in the event of a power failure. It only took a minute and a half for the bridge to be raised or lowered (Figure 11). It was possible for the bridge to be raised and lowered manually with a winch system, but this would have taken eight hours to do. During its working lifetime between 1934 and 1990, Newport Bridge was raised and lowered twice a day. On average 800 ships a year would pass under it. Gradually the number of ships sailing up the River Tees declined and the bridge was lifted a final time on 18th November 1990.

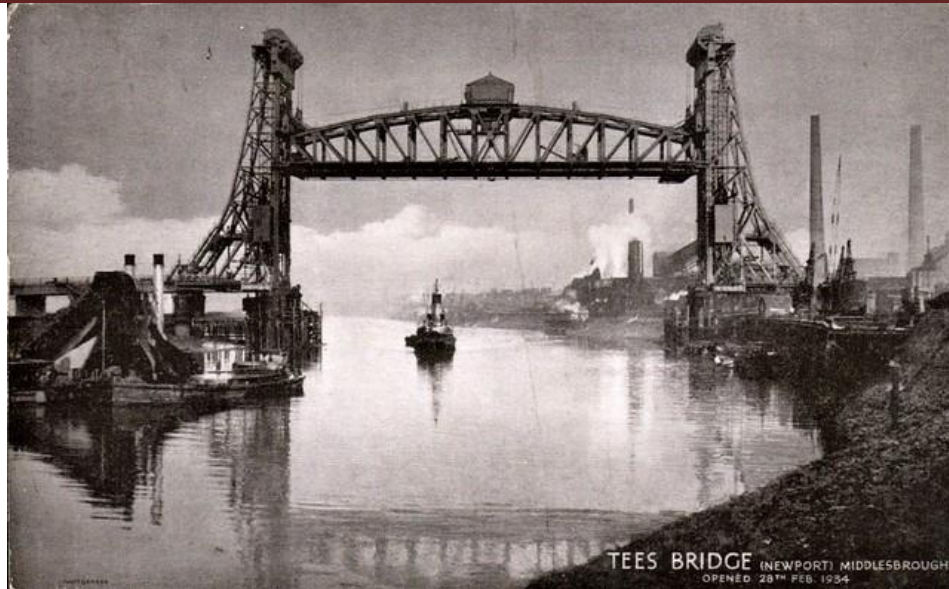


Figure 11. Tees Bridge, Newport. Middlesbrough. (Crombie, 2019).

In the late 40s in the USA, Professor Edward Ashton, who began work on creating an all-welded bridge even before the war, designed an all-welded bridge across the Iowa River (Figure 12). This bridge, called the Benton Street Bridge, had a five-span continuous girder span with a total length of approximately 175 m (Figure 13). The bridge project was completed in 1947, it began operation in 1949 and served well until 1989 – until it was replaced by a wider new bridge (Kallee, n. d.).



Figure 12. View showing welders at work on both the north and south girders, with the old bridge in the background, looking northwest , around 10 May 1949 (Kallee, n. d.).



Figure 13. View of the bridge from the west bank of the Iowa River (Kallee, n. d.).

Crossing the Iowa River in the south-central section of Iowa City, the Benton Street Bridge is an all-welded, continuous, five-span, deck, plate-girder highway bridge. Although all-welded bridges appeared in the United States as early as the 1920s, welding was not widely advocated for new bridge construction until immediately after World War II, when a number of state highway departments began preparing all-welded, deck, plate-girder plans. Designed in 1947 and erected in 1949, the Benton Street Bridge introduced all-welded bridge construction to the State of Iowa, and was nationally recognized as one of the most notable examples of the new genre. An early champion of welding, the bridge's designer, Edward (Ned) L. Ashton, had previously engineered several major Mississippi River crossings, and would subsequently be responsible for the world's first welded aluminum highway bridge, completed in Des Moines, Iowa in 1958. Ashton has justifiably been called "the most distinguished bridge engineer in the history of Iowa" (Kallee, n. d.).

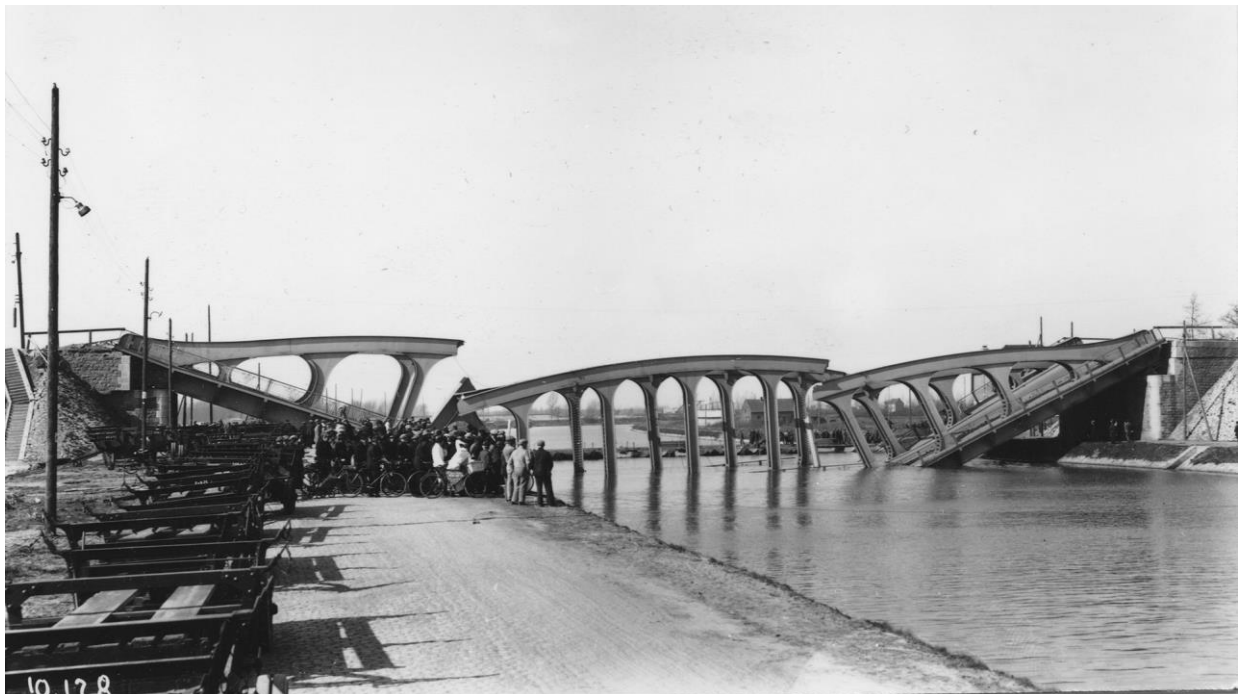
So, it can be said that by the beginning of World War II, traffic was carried out on more than a thousand bridges built using arc welding around the world. But this rapid adoption of welding in steel structures came with many challenges that were probably overlooked in the euphoria surrounding bridge construction. Welded bridges in different countries have begun to collapse (Alencar, de Jesus, da Silva, & Calçada, 2019).

What were the main reasons for the destruction of metal welded bridges in the first half of the 20th century?

In March 1938, the Hasselt Bridge suffered a catastrophic failure (Figure 14).



a



b

Figure 14. Photographs of the Hasselt Bridge over the Albert Canal before destruction (a) and after the disaster (b) on March 14, 1938 (Schuermans, 2018).

This is generally considered the first brittle failure of a large all-welded structure (Espion, 2012) and received much attention at the time. The article by Espion (2012) analyzed the main causes of cracks and failures in welded bridges. Between 1932 and 1937, about 50 welded road bridges of the frame construction type invented by Vierendeel truss were built in Belgium to cross the Albert Canal or the Campine canals. These were the first significant applications of electric arc welding in Belgium, and they account for the majority of large welded bridges built in Belgium at that time. Of the 50 typical Vierendeel road bridges with a parabolic top belt: 25 over the Albert Canal, 23 over the Campine canals. and two in Dudzeel (near Bruges). Five of them were partially welded, and the remaining 45 were fully welded. Twelve steel fabrication contractors and three electrode suppliers were involved in the project: Arcos, Esab and Thermarc. A total of 70 welded bridges were built in Belgium in the late 1930s, of which 60 were considered "large", including 50 Vierendelle spans. By comparison, Germany had about 100 welded railway bridges built by 1935, and an impressive list of 800 welded road bridges and 300 welded railway bridges built by 1939 has been published.

An article by Petrova (2022) shows that in the winter of 1940, cracking problems were reported on at least eight other large welded bridges of the same design. The most notorious cases are damage to bridges in the city of Herental and in the city of Kaulil (Figure 15). These bridges were not completely destroyed, but, as in the case of the Hasselt Bridge, they received cracks in the lower truss: in both cases the air temperature was about -14°C .

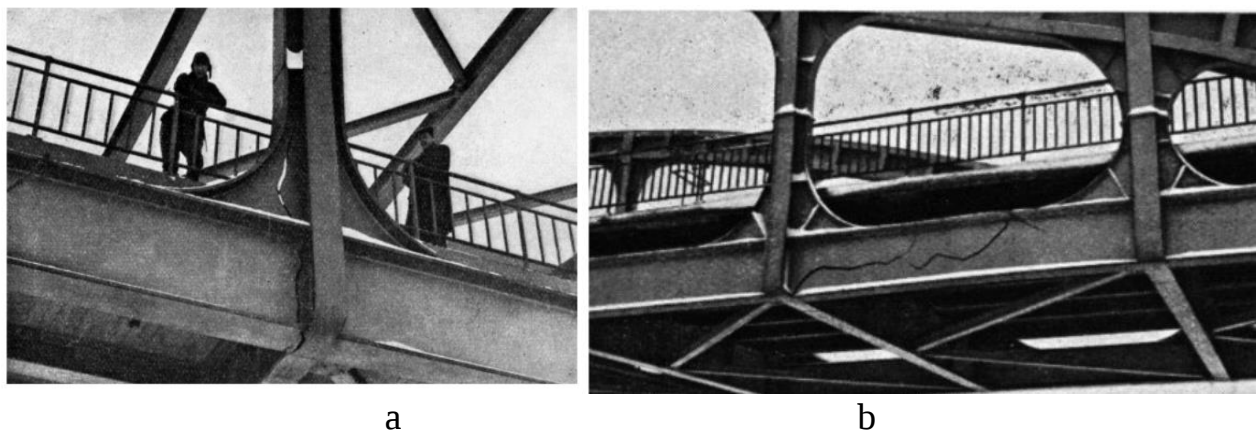


Figure 15. Photographs of bridges in Belgium with cracks: (a) Cracks in Herenthals-Oolen Bridge, 1940; (b) Cracks in Kaulille Bridge, 1940 (Espion, 2012).

A generalized analysis of available sources based on the results of the investigation of these cases showed that for all these bridges, non-deoxidized "Thomas" steel of the St-42 grade was used, which contains an increased amount of phosphorus compared to open hearth steel (up to 0.079% P). Independent experts from Germany concluded (Busch & Reuleke, 1946) that the sensitivity of steel to cracks, caused, among other things, by welding defects, could be one of the reasons that

provoked or aggravated the destruction. They called for eliminating the use of undeoxidized steel for welded structures greater than 1.5 inches thick.

Disasters of welded bridges have occurred not only in Europe. The collapse of the Duplessis Bridge (1951, Canada) is a typical example of the action of metallurgical factors, namely, the increased content of carbon, oxygen and sulfur in the destroyed steel. The all-welded bridge across the Saint-Maurice River in Quebec collapsed three years after construction. Figure 16 shows a photo of the Duplessis Bridge collapse taken by Milt Loomis (Lambie, 2021).



Figure 16. Duplessis bridge collapse (Lambie, 2021).

On the frosty night of January 31, 1951 (at an air temperature of -34°C , four long spans of the bridge collapsed into the river (Figure 17) (South Clark, 2013). As a result of the disaster, 4 people died in their cars, which fell through the ice.

The local newspaper, The Lethbridge Herald, dated August 29, 1951, wrote (Lethbridge Herald, 1951): “defective and inferior steel blamed for the collapse of the 3,500,000 USD Duplessis Bridge.” A construction company spokesman told the newspaper that low quality boiling steel was used. These claims were made against steel plates used to strengthen cracked bridge beams a year before the accident. The plates fastening the damaged areas were ordered from boiling steel CSA S40 (ASTM A7), which, according to technical regulations, was only suitable for thin sheets. The thick plates (2.5 inches) had to be made of calm, deoxidized grade C steel. It was the

cold brittleness of the plates reinforcing the truss that led to the collapse of the bridge. Analysis of the destroyed plates showed high local concentrations of carbon (up to 0.4% C) and sulfur (up to 0.116% S), and discovered many string slag inclusions. In his book *Fractures and Life*, Brian Cotterell concludes (Cotterell, 2010, pp. 205–206): “Obviously, boiling steel was too brittle and almost guaranteed that the bridge would collapse.” He explains: “Molten steel contains dissolved oxygen and other gases that must be controlled during solidification. In boiling steel, the reaction of dissolved oxygen with carbon is accompanied by the formation of gaseous carbon monoxide, which leads to the formation of an ingot with gas bubbles... Boiling steels are the cheapest, but have a high brittle transition temperature... The Charpy impact load for the broken beams of the Duplessis Bridge was only 4–8 J at 38°C. Obviously, the steel rimmed was too fragile and almost guaranteed that the bridge would collapse.” Thus, the stresses were too great for a notch-sensitive material: in such a brittle material, any minor defect, combined with permanent stresses, could lead to catastrophic failure at low temperatures.

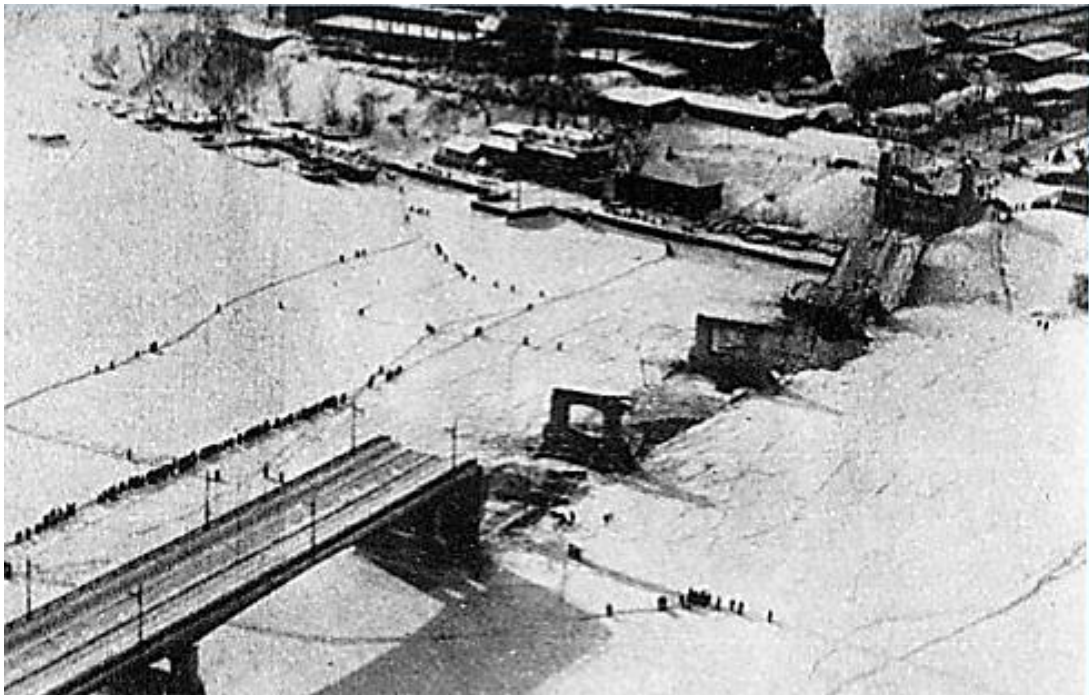


Figure 17. Two remaining spans of the Duplessis bridge in the foreground and four collapsed spans (South Clark, 2013).

As the analysis performed showed, catastrophic destruction most often occurred under the influence of several factors, as well as a combination of external adverse influences and the internal “unpreparedness” of the structure for them. The examples given indicate that an irrational choice of steel could be both an independent cause causing brittle failure of structures, and an aggravating factor in the presence of structural violations, thermal stresses and welding defects.

To the 70th anniversary of the history of the creation of the Evgeny Paton Bridge.

In the Electric Welding Laboratory at the All-Ukrainian Academy of Sciences (Kyiv, Ukraine), transformed in 1934 into the Electric Welding Institute of the Academy of Sciences of the Ukrainian Soviet Socialist Republic (Electric Welding Institute AS USSR), they began to purposefully study the load-bearing capacity of welded joints and structures (Malishevskij, 2003; Strelko, 2021). In this laboratory, organized and headed by academician Evgeny Oskarovich Paton, experimental studies were initially carried out by comparing the test results of identical welded and riveted joints of samples, beams and entire structures under static, variable and impact loading. The tests carried out made it possible to obtain the most visual and convincing evidence of the strength of welded joints and the advantages of welding technology. In these and other comparative tests, welded joints failed from fatigue not in the weld metal, but in the base metal in the joint zone. It became obvious that the main reason for their destruction is the concentration of stresses created by the shape of the joint and seams or technological welding defects.

It was also assumed that the insufficient strength and toughness of the weld metal, its lower homogeneity than the base metal, would reduce the resistance of structures to fatigue failure. In the late 1930s – early 1940s, work was carried out at the Electric Welding Institute AS USSR to find rational design and technological solutions that ensure the specified cyclic durability of welded joints and assemblies. The studies mainly concerned bridges, carriages and cranes. They convincingly showed that welded joints and assemblies can be reasonably used in critical structures that can withstand the effects of alternating stresses. The equal strength of butt joints with the “seam reinforcement” removed and the base metal under variable loads was proven.

The question of the construction of a road bridge across the river in Kyiv the Dnipro was raised before the World War II. At the same time, a technical design of a bridge with a ride on top and split through main trusses spanning spans 58 m long (in the floodplain part) and 87 m long (in the navigable part) was drawn up and approved. Since during this period the Electric Welding Institute AS USSR developed a method of automatic submerged arc welding, which made it possible to obtain high-quality seams, its director, Evgeny Oskarovich Paton, proposed manufacturing bridge spans using welding. The bridge design was based on large blocks and the maximum use of automatic and semi-automatic welding in the manufacture of bridge beams at the factory and during their direct installation.

The construction of this bridge is the result of a collaboration between designers, scientists and builders from Ukrproektstalkonstruktziya, the Kyiv Bridge Construction Trust of the Ministry of Transport, the Electric Welding Institute AS USSR and Metal Structures Plant named after Babushkin (Dnipro, Ukraine).

The team of the Electric Welding Institute AS USSR, introducing welding into bridge construction, carefully checked the results and monitored the behavior of

structures. A new grade of steel was created that was resistant to the formation of brittle and fatigue cracks, its welding technology was developed, a technology for installation welding of vertical sheets with forced formation of a seam was developed, and suitable welding materials were selected.

On November 4, 1953, the Government Commission inspected in situ the constructed road bridge across the river Dnipro in Kyiv, got acquainted with the technical documentation and decided to accept the bridge into permanent operation from November 5, 1953 with the passage of all types of loads provided for by the project, without speed restrictions. The Government Commission gave the main work on the construction of the bridge an “excellent” rating.

On November 5, 1953, the Council of Ministers of the Ukrainian SSR, by its Resolution No. 2348, approved the act of the Government Commission on the acceptance into permanent operation of an all-welded road bridge across the river. The Dnipro in Kyiv and the opening of traffic on the bridge was scheduled for November 5, 1953 (Figure 18). Thus, ended the crucial and most difficult stage in the development of welded bridge construction.



Figure 18. Rally on the Paton Bridge on the day of its opening, view from the right bank of the Dnipro, November 5, 1953 (Central State Audiovisual and Electronic Archive, n. d.).

On December 18, 1953, by Decree of the Council of Ministers of the Ukrainian SSR No. 2644, the newly built bridge was named after Evgeny Paton.

In 1995, the American Welding Association built an all-welded bridge in Kyiv across the river the Dnipro is included in the list of outstanding engineering structures.

After 70 years of operation, the Evgeny Paton Bridge continues to operate reliably with the design load N-10 and a significantly increased traffic intensity (80 thousand vehicles per day with a design value of 10 thousand).

An analysis of numerous documents devoted to the design and construction of this bridge allowed to establish the following. The Kyiv welded road bridge named after Evgeny Paton is unique in a number of its characteristic features not only in Ukraine, but throughout the world (Figure 19).



Figure 19. View of the Evgeny Paton Bridge from the right bank of the Dnipro from the place where the monumental sculpture “Motherland” now stands. (Central State Audiovisual and Electronic Archive, 1956).

Its uniqueness lies in the fact that all connections in the bridge spans are made at the factory and installed by welding, i.e. the bridge is all-welded. If we take into account that it has a total length of 1,543 m and that about 10 thousand tons of steel were used for the spans, and the total length of the welds is 10,668 m, then we can say that it is still the largest all-welded bridge in the world (Kornienko & Litvinov, 2008). When manufacturing mounting elements at the factory and making assembly joints, they were carried out mainly using automatic and semi-automatic welding (Lobanov & Kyrian, 2013). Manual welding was used to perform less critical elements of the bridge (braces, transverse beams, etc.). When designing the bridge, the large-block principle was used, which allowed 97% of all factory seams of the main trusses and 88% of all

installation seams of the main trusses to be performed using automatic and semi-automatic welding. In addition, the presence of large blocks of the same type made it possible to mechanize assembly and welding operations and organize an in-line manufacturing method at the factory and installation, which improved the quality of welding work and reduced its labor intensity.

The bridge is rightly named after Evgeny Paton (Figure 20), and can be presented as ***the largest all-welded bridge in Europe at the time of construction, in which for the first time all seams, including assembly ones, were made using automatic and semi-automatic welding.***



Figure 20. Evgeny Paton Bridge with night architectural illumination and panorama of the Left Bank (Naumov, 2017).

The Evgeny Paton Bridge has never been closed for major repairs. To improve traffic safety, a semi-rigid decorative and artistic fence was installed on the Paton Bridge in 1968 (for the first time in the USSR) (Figure 21). It was carried out by a company from Donetsk, Remkommunelektrotrans.

In 2019, the bridge was declared unsafe; two outer lanes were closed to traffic due to danger. Design work is currently ongoing on the bridge, after which the first reconstruction in 70 years should begin.



Figure 21. Evgeny Paton Bridge across the Dnipro in Kyiv, 1960s. (Central State Audiovisual and Electronic Archive, n.d.).

How relevant is welding technology to modern bridge construction?

Touran and Ladick (1989) examined the financial aspects of welded bridge construction. Their research found that welding, including consumables, accounted for an average of 14% of the total module manufacturing cost, 38% for material costs, and 48% for additional labor costs.

The construction of metal bridges using welding continues in our time (Markashova, Berdnikova, Bernatskyi, Sydorets, & Bushma, 2019; Poznyakov, Markashova, Shelyagin, Zhdanov, Bernatskyi, Berdnikova, & Sydorets, 2019; Chandramohan, Roy, Taheri, Karpenko, Fang, & Lim, 2022). Welded bridges play an important role in modern infrastructure, ensuring safe and efficient transportation systems. The largest bridge in the world today (Guinness World Records, n.d.), the Danyang-Kunshan Viaduct (Figure 22), was also built in 2011 using welding technologies (iXBT.com, n.d.).

Nowadays, the undisputed favorite of all bridge builders in the world is steel, which has good mechanical properties under various operating conditions under load and is perfectly amenable to processing. It is carbon and low-alloy steels that are the most popular and cost-effective materials, widely used for the construction of small, medium and simply gigantic bridge structures of our time (Bazaras, Cesnavicius, Ilgakoityte-Bazariene, & Kersys, 2017; Lenner, Ryjacek, & Sýkora, 2020; Tkachenko, Tsegelnyk, Myntiuk, & Myntiuk, 2022).



Figure 22. Danyang-Kunshan Viaduct (iXBT.com, n.d.).

The use of high-strength and high-strength steels and the use of welded structures helps reduce metal consumption, so a steel bridge is often a cheaper and more practical alternative to other options.

Conclusions.

The history of the development of the construction of metal bridges using welding goes back a little over 100 years. The short period from the construction of the first welded bridges to their first disasters led to the need to analyze the possible causes of these destructions. As the analysis performed showed, catastrophic destruction most often occurred under the influence of several factors, as well as a combination of external adverse influences and the internal “unpreparedness” of the structure for them. The examples given indicate that an irrational choice of steel could be both an independent cause causing brittle failure of structures, and an aggravating factor in the presence of structural violations, thermal stresses and welding defects. Over the years, bridge manufacturing technologies have been improved in different countries, and new steels and materials for their welding have been developed.

Thanks to the use of carbon, low-alloy and alloy steel, designers abandoned the brutal “railroad-type” beam trusses and today metal bridges with graceful and beautiful silhouettes powerfully stride across the water surface, mountains and valleys. They became real attractions of megacities and country landscapes, and builders were able to successfully solve numerous technical and economic problems.

An important contribution to the development of global bridge construction using welding technologies was made by the team of the Institute of Electric Welding of the Academy of Sciences of the Ukrainian SSR under the leadership of Academician Evgeny Oskarovych Paton. The team of the Institute of Electric Welding of the

At the time of construction in 1953, the Kyiv Evgeny Paton Bridge across the Dnipro River was the largest all-welded bridge in Europe, all seams of which, including assembly ones, were made for the first time using automatic and semi-automatic welding. In addition, the presence of large similar blocks in the design of the Paton Bridge made it possible to mechanize assembly and welding operations and organize an in-line method for their production at the factory and installation, which increased the quality of welding work and reduced its labor intensity.

The author declare no conflict of interest.

Alencar, G., de Jesus, A., da Silva, J. G. S., & Calçada, R. (2019). Fatigue cracking of welded railway bridges: A review. *Engineering Failure Analysis*, 104, 154–176.
<https://doi.org/10.1016/j.engfailanal.2019.05.037>

American Welding Society. (2023). AWS National Awards Package 2022. Award Descriptions and Past Winners. Retrieved from <https://aws-p-001-delivery.sitecorecontenthub.cloud/api/public/content/a6a0971a52a6451397245c2cbfa695e9?v=fa3002b1>

American Welding Society. (n. d.). Extraordinary Welding Awards. American Welding Society. Retrieved from <https://www.aws.org/About/Awards/Outstanding-Achievement-Awards/>

Armisen, J. M. (2019). Puentes que me ayudaron a entender y diseñar. *Informes de la Construcción*, 71(553), e279. <http://dx.doi.org/10.3989/ic.67502> [in Spanish].

Arwade, S. R., Schafer, B. W., Schafer, D. F., & Schafer, S. T. (2015). Modern Examples of Structural Art in Metals. In *Structures Congress 2015* (pp. 714–729).
<https://doi.org/10.1061/9780784479117.062>

Ban'kovskij, L. (1988). *Sozidayushchee Plamya [Creative Flame]*. Perm: Perm Book Publishing House. Retrieved from
<https://books.google.co.uk/books/about/%D0%A1%D0%BE%D0%B7%D0%B8%D0%B4%D0%B0%D1%8E%D1%89%D0%B5%D0%B5%D0%BF%D0%>

- [BB%D0%B0%D0%BC%D1%8F.html?id=ptQMAQAAIAAJ&redir_esc=y](#) [in Russian].
- Bartlett, F. M., Graham, J. M., & Camiletti, J. (2009). 1870s innovation in London Canada's Blackfriars Bridge. *Proceedings of the Institution of Civil Engineers-Engineering History and Heritage*, 162(2), 111–117. <https://doi.org/10.1680/ehh.2009.162.2.111>
- Bazaras, Z., Cesnavicius, R., Ilgakojoyte-Bazariene, J., & Kersys, R. (2017). Investigation of the probabilistic low cycle fatigue design curves at stress cycling. *Mechanics*, 23(2), 176–181. Retrieved from <https://pdfs.semanticscholar.org/237e/2c710d299130436854ef6465bdea48a7c8a7.pdf>
- Bender, C. (1872). Historical sketch of the successive improvements in suspension bridges to the present time. *Transactions of the American Society of Civil Engineers*, 1(1), 27–44. <https://doi.org/10.1061/TACEAT.0000003>
- Bernabeu-Larena, J., Martín-Caro, J. A., Hernández-Lamas, P., & Plana, Á. G. (2023). Technical heritage of Madrid's bridges, Spain. *Proceedings of the Institution of Civil Engineers-Engineering History and Heritage*, 176(3), 113–126. <https://doi.org/10.1680/jenhh.23.00012>
- Bissell, A. G. (1928). An arc welded railroad bridge. *Journal of the American Welding Society*, 7(4), 42–46. Retrieved from https://archive.org/details/sim_welding-journal_1928-04_7_4/page/42/mode/2up?view=theater
- Blažević, Z. (2017). Faust Vrančić (1551–1617) and intellectual culture of his age. *Povijesni Prilozi*, 36(52), 53–66. <https://doi.org/10.22586/pp.v52i0.2> [in Croatian].
- Booth, L. G. (2017). The development of laminated timber arch structures in Bavaria, France, and England in the early nineteenth century. In *The Development of Timber as a Structural Material* (pp. 291–304). Abingdon: Routledge. Retrieved from https://books.google.com.ua/books?hl=uk&lr=&id=glPEAAQAQBAJ&oi=fnd&pg=PA291&dq=Wiebeking+Bridge&ots=ZZ8DMSwdhP&sig=P0ABiy2eSWkpAUUpu5QNhRudivMA&redir_esc=y#v=onepage&q=Wiebeking%20Bridge&f=false
- Bryla, S. (1930). The first arc-welded bridge in Europe. *The Journal of the American Welding Society*, 9(5), 71–74. Retrieved from https://archive.org/details/sim_welding-journal_1930-05_9_5/page/70/mode/2up?view=theater
- Busch, H., & Reuleke, W. (1946). Investigation of failures in a welded bridge. *Welding Journal*, 25(8), 463s–466s. Retrieved from https://archive.org/details/sim_welding-journal_1946_25_index/page/n5/mode/2up?view=theater

- Central State Audiovisual and Electronic Archive. (n. d.). *Tsentralnyi Derzhavnyi Audiovizualnyi ta Elektronnyi Arkhiv [Central State Audiovisual and Electronic Archive]*. Retrieved from <https://tsdaea.archives.gov.ua> [in Ukrainian].
- Chandramohan, D. L., Roy, K., Taheri, H., Karpenko, M., Fang, Z., & Lim, J. B. P. (2022). A state of the art review of fillet welded joints. *Materials*, 15(24), 8743. <https://doi.org/10.3390/ma15248743>
- Chigarev, V. V., & Litvinov, A. P. (2011). Razvitie elektrodugovoj svarki [Development of electric arc welding]. *Visnyk Natsionalnoho Tekhnichnoho Universytetu «Kharkivskyi Politekhnychnyi Instytut». Zbirnyk Naukovykh Prats. Seriiia "Istoriia nauky i tekhniki" – Bulletin of the National Technical University "Kharkiv Polytechnic Institute". Collection of Scientific Works. "History of Science and Technology" Series*, (20), 176–181. <https://repository.kpi.kharkov.ua/handle/KhPI-Press/14062> [in Russian].
- Co-Curate. (n.d.). Tees Newport Bridge. Co-Curate. Retrieved from <https://co-curate.ncl.ac.uk/tees-newport-bridge/>.
- Cotterell, B. (2010). *Fractures and Life*. London: Imperial College Press. Retrieved from https://books.google.co.uk/books?hl=uk&lr=&id=nznICgAAQBAJ&oi=fnd&pg=PR9&dq=Cotterell+2010+Fractures+and+Life&ots=Nj4chYIycX&sig=SSJZg-AbAZJzEbR3F0KV9k6aqis&redir_esc=y#v=onepage&q=Cotterell%202010%20Fractures%20and%20Life&f=false
- Crombie, M. (2019, April 11). Middlesbrough. Tees Bridge, Newport. Opened 1934. Yorkshire. *Flickr*. Retrieved from <https://www.flickr.com/photos/147645911@N08/32644218697/>
- Davis, A .F. (1935). Largest all-welded bridge completed in New Jersey. *The Journal of the American Welding Society*, 14(8), 2–4. Retrieved from https://archive.org/details/sim_welding-journal_1935-08_14_8/page/2/mode/2up?view=theater
- English Heritage. (n. d.). History of Iron Bridge. *English Heritage*. Retrieved from <https://www.english-heritage.org.uk/visit/places/iron-bridge/history/>
- Espion, B. (2012). The Vierendeel bridges over the Albert Canal, Belgium—their significance in the story of brittle failures. *Steel Construction*, 5(4), 238–243. <https://doi.org/10.1002/stco.201210029>
- Fish, G. D. (1933). Arc-welded steel frame structures. *Engineering News-Record*, 101(4), 120–123. Retrieved from https://archive.org/details/sim_enr_1928-07-26_101_4/page/120/mode/2up?view=theater
- Fougères, D. (2022). Le pont Royal-Albert, 1875–1876: Histoire d’une Bérézina sur fond de rivalités ferroviaires. *Revue D’histoire de l’Amérique Française*, 75(3), 3–34. <https://doi.org/10.7202/1092169ar> [in French].
- Fraser, C. B. & Roberts, J. J. (1994). 86th Street Overpass. *Historic American Engineering Record*. Retrieved from <https://tile.loc.gov/storage-services/master/pnp/habshaer/ia/ia0400/ia0410/data/ia0410data.pdf>

- Gazzola, F. (2015). Brief History of Suspension Bridges. In: *Mathematical Models for Suspension Bridges. MS&A – Modeling, Simulation & Applications*, 15, 1–41. Cham: Springer. https://doi.org/10.1007/978-3-319-15434-3_1
- Grimes, N., & Castro, J. J. (2020). The less imperial path: the Mississippi Valley, US expansionism, and engineer James B. Eads' failure to build a ship railway. *The Historian*, 82(2), 156–181. <https://doi.org/10.1080/00182370.2020.1747842>
- Groote, P. D., Ciccarelli, C., & Giuntini, A. (2021). The history of rail transport. In R. Vickerman (Ed.), *International Encyclopedia of Transportation*, 5 (pp. 413–426). London: Elsevier. <https://doi.org/10.1016/B978-0-08-102671-7.10461-0>
- Grover, L. (1934). Arc welding for bridge construction. *Civil Engineering*, 4(7), 360–364. Retrieved from https://archive.org/details/sim_civil-engineering-1930_1934-07_4_7/page/360/mode/2up?view=theater
- Guinness World Records. Longest bridge. (n. d.). *Guinness World Records*. Retrieved from <https://www.guinnessworldrecords.com/world-records/longest-bridge>
- Hess, J. A. & Hybben, R. (1989). Benton Street Bridge. *Historic American Engineering Record*. Retrieved from <https://tile.loc.gov/storage-services/master/pnp/habshaer/ia/ia0100/ia0198/data/ia0198data.pdf>
- Holzer, S. M., & Knobling, C. (2020). The laminated arch in the first half of the 19th century: A status report from Switzerland. In *Iron, Steel and Buildings: Studies in the History of Construction. The Proceedings of the Seventh Annual Conference of the Construction History Society, Cambridge, United Kingdom, April 4–5, 2020* (pp. 389–404). Cambridge: Construction History Society. <https://doi.org/10.3929/ethz-b-000449543>
- iXBT.com. (n.d.). Most dlinoj 164 kilometra: kak vyglyadit neveroyatnyj kitajskij viaduk [A bridge 164 kilometers long: what the incredible Chinese viaduct looks like]. *iXBT.com*. Retrieved from <https://www.ixbt.com/live/offtopic/most-dlinoj-164-kilometra-kak-vyglyadit-everoyatnyy-kitayskiy-viaduk.html> [in Russian].
- Johnson, B. (n. d.). Ironbridge. “Birthplace of the Industrial Revolution” and UNESCO World Heritage Site. *Historic UK*. Retrieved from <https://www.historic-uk.com/HistoryMagazine/DestinationsUK/Ironbridge/>
- Kahlow, A. (1995). French influence on the development of applied mechanics in Germany in the nineteenth century. *History and Technology, an International Journal*, 12(2), 179–189. <https://doi.org/10.1080/07341519508581883>
- Kallee, St. (n. d.). Benton Street Bridge in Iowa. The First All-welded Steel Bridge in Iowa, and One of the First in the USA. *AluStir*. Retrieved from <https://www.alustir.com/english/did-you-know/benton-street-bridge/>
- Kornienko, A. N., & Litvinov, A. P. (2008). Transition to integrated development of welding production. *The Paton Welding Journal*, (3), 37–40. Retrieved from <https://patonpublishinghouse.com/tpwj/pdf/2008/tpwj200803all.pdf>
- Korsun, I. V., Buyak, B. B., & Matsyuk, V. M. (2019). Contribution of Ukrainian scientists to the development of technology. *Science and Innovation*, 15(6), 94–102. <https://doi.org/10.15407/scin15.06.099>

- Kozak-Holland, M., Procter, C. (2020). Chapter Case Study 1: The Stockton and Darlington Railway. In: *Managing Transformation Projects: Tracing Lessons from the Industrial to the Digital Revolution* (pp. 27–46). Cham: Palgrave Pivot. https://doi.org/10.1007/978-3-030-33035-4_3
- Lambie, G. (2021, January 31). Looking back on the Duplessis bridge collapse 70 years later. *The Sherbrooke Record*. Retrieved from <https://www.sherbrookerecord.com/looking-back-on-the-duplessis-bridge-collapse-70-years-later/>
- Lenner, R., Ryjacek, P., & Sýkora, M. (2020). Resistance models for semi-probabilistic assessment of historic steel bridges. In *1st IABSE Online Symposium Wroclaw 2020: Synergy of Culture and Civil Engineering – History and Challenges, Wroclaw, 7–9 October 2020*, (pp. 1061–1068). <https://doi.org/10.2749/wroclaw.2020.1061>
- Lethbridge Herald. (August 29, 1951). Poor quality steel blamed for bridge crash. *Lethbridge Herald*. Retrieved from <https://digitallibrary.uleth.ca/digital/collection/herald2/id/20998>
- Liegner, N., Kormos, G., & Papp, H. (2015). Solutions of omitting rail expansion joints in case of steel railway bridges with wooden sleepers. *Periodica Polytechnica Civil Engineering*, 59(4), 495–502. <https://doi.org/10.3311/PPci.8169>
- Lobanov, L. M. (2014). Do 60-richchia mostu imeni Ye. O. Patona [To the 60th anniversary of the bridge named after E. O. Paton]. *Budivelni Konstruktsii – Building Structures*, (81), 119–128. Retrieved from http://irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe?C21COM=2&I21DBN=UJRN&P21DBN=UJRN&IMAGE_FILE_DOWNLOAD=1&Image_file_name=PDF/buko_2014_81_1_6.pdf [in Ukrainian].
- Lobanov, L. M., & Kyrian, V. I. (2013). The E. O. Paton all-welded bridge is sixty years old. *The Paton Welding Journal*, (12), 33–38. Retrieved from <https://patonpublishinghouse.com/tpwj/pdf/2013/pdfarticles/12/7.pdf>
- Lobanov, L. M., Dyadin, V. P., Davydov, E. O., & Lytvynenko V. A. (2021). Vybir neruivnykh metodiv kontroliu shchodo otsinky tekhnichnoho stanu metalevykh konstruktsii holovnykh balok mostu im. Ye.O. Patona cherez r. Dnipro u m. Kyiv [Selection of nondestructive testing methods for evaluation of the technical condition of metal structures of the main beams of E.O. Paton bridge across the Dnipro in Kyiv]. *Tekhnichna Diahnostyka i Neruivnyi Kontrol – Technical Diagnostics and Non-Destructive Testing*, (4), pp. 47–53. <https://doi.org/10.37434/tdnk2021.04.05> [in Ukrainian].
- Lobanov, L. M., Kyrian, V. I., & Shumitsky, O. I. (2003). Fifty years of the E.O. Paton bridge. *The Paton Welding Journal*, (10–11), 12–20. Retrieved from <https://patonpublishinghouse.com/tpwj/pdf/2003/tpwj200310all.pdf>
- Malishevskij, I. (2003, October 31). Den' rozhdeniya mosta. 50 let tomu nazad v Kieve byl otkryt Most Patona. Birthday of the bridge. 50 years ago the Paton Bridge was opened in Kyiv. *Zerkalo Nedeli – Mirror of the Week*. Retrieved from

- https://zn.ua/SOCIUM/den_rozhdeniya_mosta_50_let_tomu_nazad_v_kieve_by_l_otkryt_most_patona.html [in Russian].
- Markashova, L., Berdnikova, O., Bernatskyi, A., Sydorets, V., & Bushma, O. (2019). Crack resistance of 14KhGN2MDAFB high-strength steel joints manufactured by laser welding. *IOP Conference Series: Earth and Environmental Science*, 224(1), 012013. <https://doi.org/10.1088/1755-1315/224/1/012013>
- McKibben, F. P. (1929). *Evidence that welding is being adopted for fabricating steel bridges and buildings*. Boston: General Electric Company. Retrieved from <https://archive.org/details/EvidenceThatWeldingIsBeingAdoptedForFabricatingSteelBridgesAnd/page/n1/mode/2up?view=theater>
- Mehrtens, G. C. (1900a). *A hundred years of German bridge building*. Berlin: Springer. Retrieved from https://archive.org/stream/hundredyearsofge00mehr/hundredyearsofge00mehr_djvu.txt
- Mehrtens, G. (1900b, May 1). *Eisenbahnbrücke über Elbe, Eisenkonstruktion mit Lohse-Trägern, erbaut 1868–1872. Der deutsche Brückenbau im XIX jahrhundert*. Retrieved from https://commons.wikimedia.org/wiki/File:HH-EisenbahnBr%C3%BCckeLohse_Mehrtens1900.png
- Mezenin, N. (1977). Bridges, welding, and metallurgy. *Metallurgist*, 21(12), 845–848. <https://doi.org/10.1007/BF01087567>
- Naumov, R. (2017, August 5). *Most Patona s Nochnoj Arhitekturnoj Podsvetkoj i Panorama Levogo Berega [Evgeny Paton Bridge with Night Architectural Illumination and Panorama of the Left Bank]*. Retrieved from https://ru.wikipedia.org/wiki/%D0%A4%D0%B0%D0%B9%D0%BB:%D0%9C%D1%96%D1%81%D1%82_%D0%9F%D0%B0%D1%82%D0%BE%D0%BD%D0%B0_%D0%B7_%D0%BD%D1%96%D1%87%D0%BD%D0%BE%D1%8E_%D0%B0%D1%80%D1%85%D1%96%D1%82%D0%B5%D0%BA%D1%82%D1%83%D1%80%D0%BD%D0%BE%D1%8E_%D0%BF%D1%96%D0%B4%D1%81%D0%B2%D1%96%D1%82%D0%BA%D0%BE%D1%8E_%D1%82%D0%B0_%D0%BF%D0%B0%D0%BD%D0%BE%D1%80%D0%B0%D0%BC%D0%B0_%D0%9B%D1%96%D0%B2%D0%BE%D0%B3%D0%BE_%D0%B1%D0%B5%D1%80%D0%B5%D0%B3%D0%B0.jpg
- Perel'muter, A. V. (2012). Pervyj cel'nosvarnoj most [The first all-welded bridge]. *Promyslove Budivnytstvo ta Inzhenerni Sporudy – Industrial Construction and Engineering Structures*, (1), 33–35. Retrieved from https://urdisc.com.ua/rl/info/1_12.pdf [in Russian].
- Pescatore, J.-P., & Borgeot, J.-H. (2008). Chapter 10. Welding Steel Structures. In R. Blondeau (Ed.), *Metallurgy and Mechanics of Welding: Processes and Industrial Applications*, (pp. 359–374). London, Hoboken, NJ: ISTE Ltd., John Wiley & Sons, Inc. <https://doi.org/10.1002/9780470611272.ch10>
- Petrova, L. G. (2022). Metallovedcheskaya ekspertiza razrushenij konstrukcij po prichine hladnolomkosti: istoricheskij obzor [Metallurgical examination of

- structural failures due to cold brittleness: a historical review]. *Problemy Ekspertizy v Avtomobil'no-Dorozhnoj Otraski – Problems of Examination in the Automobile and Road Industry*, (2(3)), 29–46. Retrieved from https://disk.yandex.ru/i/es-Yxsv_EhO-MQ [in Russian].
- Poznyakov, V. D., Dyadin, V. P., Davydov, Y. O., & Dmitrienko, R. I. (2021). Evaluation of damage of all-welded longitudinal main beams of the E.O. Paton bridge across the Dnipro river. *The Paton Welding Journal*, (7), 30–38. <https://doi.org/10.37434/tpwj2021.07.06>
- Poznyakov, V. D., Markashova, L. I., Shelyagin, V. D., Zhdanov, S. L., Bernatskyi, A. V., Berdnikova, O. M., & Sydorets', V. M. (2019). Cold cracking resistance of butt joints in high-strength steels with different welding techniques. *Strength of Materials*, 51, 843–851. <https://doi.org/10.1007/s11223-020-00132-7>
- PrimaMedia.ru. (2023, July 27). Duga sud'by professora Vologdina [The arc of fate of Professor Vologdin]. *PrimaMedia.ru*. Retrieved from <https://primamedia.ru/news/1544555/?from=37> [in Russian].
- Radić, J., Puž, G., & Šavor, Z. (2013). Arch bridge development in Croatia in the international context. In *4th Chinese-Croatian Joint Colloquium* (pp 1–22). Retrieved from https://www.researchgate.net/profile/Goran-Puz-2/publication/262159643_ARCH_BRIDGE_DEVELOPMENT_IN_CROATIA_IN_THE_INTERNATIONAL_CONTEXT/links/00b7d536caaba719cd000000/ARCH-BRIDGE-DEVELOPMENT-IN-CROATIA-IN-THE-INTERNATIONAL-CONTEXT.pdf
- Railway Engineering and Maintenance. (1927). Electric welding reduces cost of strengthening bridge. *Railway Engineering and Maintenance*, 23(7), 279–281. Retrieved from https://archive.org/details/sim_railway-track-structures_1927-07_23_7/page/278/mode/2up?view=theater
- Rosie, G. (2018). Double Crossings: The Tangled Tale of the Forth Road Bridges. *Scottish Affairs*, 27(3), 342–360. <https://doi.org/10.3366/scot.2018.0247>
- Rymsza, B., Mistewicz, A., & Tucholski, Z. (2017). Kierbedź Bridge: A history of the first permanent bridge across the Vistula river in Warsaw, Poland. *Icon*, 23, 145–166. Retrieved from <https://www.jstor.org/stable/26454979>
- Schueremans, L., Porcher, H., Rossi, B., Wouters, I., & Verstrynghe, E. (2018). A study on the evolution in design and calculation of iron and steel structures over the mid 19th century in western and central Europe. *International Journal of Architectural Heritage*, 12(3), 320–333. <https://doi.org/10.1080/15583058.2017.1323244>
- Schuermans, D. (2018, March 5). Expo over de Kempische brug die in het water viel. *Bad Republic*. Retrieved from <https://www.badrepublic.be/lokaal/2018/03/expo-over-de-kempische-brug-die-in-het-water-viel/> [in Dutch].
- Sedmak, A., Ković, M., & Kirin, S. (2022). Structural Integrity-Historical Context. *Tehnički vjesnik*, 29(5), 1770–1776. <https://doi.org/10.17559/TV-20220321074430>

- Shevchenko, V. G. (2004). *Svarshchik Viktor Vologdin [Welder Viktor Vologdin]*. Vladivostok: Far Eastern State Technical University. Retrieved from <https://proza.ru/2010/12/28/899> [in Russian].
- Shumitsky, S. I. (1997). Welded structures and their optimization. *Welding and Surfacing Reviews*, 8(1), 239–47. Retrieved from https://books.google.com.ua/books?hl=uk&lr=&id=JDKUSCqRreQC&oi=fnd&pg=PA239&dq=Paton+Bridge+1953&ots=JGJyFz40Mu&sig=SAhnw16wRNE3ogWHvZlYtY3Govs&redir_esc=y#v=onepage&q=Paton%20Bridge%201953&f=false
- Shymanovskiy, O., Shalinskyi, V., & Baran, W. (2021). Peculiarities of reconstruction work as a result of possible terrorist attacks on out-of-class bridges. In Z. Zembaty, D. Beben, Z. Perkowski, A. Rak, G. Bosco, & P. Solanki (Eds.), *Environmental Challenges in Civil Engineering. ECCE 2020. Lecture Notes in Civil Engineering*, 122 (pp. 15–30). Cham: Springer. https://doi.org/10.1007/978-3-030-63879-5_2
- Siviero, E., & Martini, V. (2020). Bridges in the world heritage list between culture and technical development. In *1st IABSE Online Symposium Wroclaw 2020: Synergy of Culture and Civil Engineering – History and Challenges*, Wroclaw, 7–9 October 2020, (pp. 157–180). <https://doi.org/10.2749/wroclaw.2020.0153>
- South Clark, N. (2013). The Duplessis Bridge Collapse – January 31, 1951. *An Engineer's Aspect*. Retrieved from <http://anengineersaspect.blogspot.com/2013/04/the-duplessis-bridge-collapse-january.html>
- Spivey, J. M. (2001). Passerelle in Lincoln Park. *Historic American Engineering Record*. Retrieved from <https://historicbridges.org/illinois/lincolnpark/haer-il-155.htm>
- Statyvka, Y., Kyrychenko, H., Strelko, O., & Berdnychenko, Yu. (2021). Control of technological processes using a fuzzy controller of the system for management of cargo delivery by railway. *Acta Scientiarum Polonorum Administratio Locorum*, 20(3), 241–251. <https://doi.org/10.31648/aspal.6808>
- Strelko, O. (2021). Stages of development, improvement and application of equipment for welding in space, created with the participation of Ukrainian scientists. *Studia Historiae Scientiarum*, 20, 263–283. <https://doi.org/10.4467/2543702XSHS.21.010.14041>
- Tees Valley Museums. (n.d.). Dorman Long and Newport Bridge. *Tees Valley Museums*. Retrieved from <https://teesvalleymuseums.org/blog/post/newport-bridge/>
- The Ironbridge Gorge Museum Trust. (n. d.). The Iron Bridge. *The Ironbridge Gorge Museum Trust*. Retrieved from <https://www.ironbridge.org.uk/about-us/the-iron-bridge/>
- Tkachenko, D., Tsegelnyk, Ye., Myntiuk, S., & Myntiuk, V. (2022). Spectral methods application in problems of the thin-walled structures deformation. *Journal of Applied and Computational Mechanics*, 8(2), 641–654. <https://doi.org/10.22055/JACM.2021.38346.3207>

- Touran, A., & Ladick, D. R. (1989). Application of robotics in bridge deck fabrication. *Journal of construction engineering and management*, 115(1), 35–52. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1989\)115:1\(35\)](https://doi.org/10.1061/(ASCE)0733-9364(1989)115:1(35))
- Turmov, G. P. (2004). *Ognyom Svarki i Plamenem Serdca. Istoricheskij Oчерk [With the Fire of Welding and the Flame of the Heart. Historical Essay]*. Vladivostok: Far Eastern State Technical University [in Russian].
- Van Dyck, M. (2020). Causality and the Reduction to Art of Simon Stevin's Mechanics. In C. A. Davids, F. J. Dijksterhuis, I. H. Stamhuis, & R. H. Vermij (Eds.), *Rethinking Stevin, Stevin Rethinking* (pp. 155–181). Leiden, The Netherlands: Brill. https://doi.org/10.1163/9789004432918_008
- Veranzio, F. (1968). *Machinae Novae. Facsimile of the Printed Edition: Venetiis, [1615-1616?]*. Milano: Ferro.
- Vůjtěch, J., Ryjáček, P., & Matos, J. C. (2023). Dealing with defects and strengthening historical steel bridges. *Structural Engineering International*, 33(1), 195–205.
- Williams, W. (1780). *The Cast Iron Bridge near Coalbrookdale*. Retrieved from <https://comestepbackintime.files.wordpress.com/2013/04/5-iron-bridge-william-williams-painting.jpg>
- Witcher, T. R. (2022). Bridge of the Century. *Civil Engineering Magazine Archive*, 92(4), 26–29. Retrieved from <https://ascelibrary.org/doi/pdf/10.1061/ciegag.0001622>

Олег Стрелко

Державний університет інфраструктури та технологій, Україна

До питання історії будівництва металевих мостів у 20 столітті з використанням технології зварювання

Анотація. Історія будівництва мостів є важливою частиною історичного знання. Розвиток технології будівництва мостів відбиває як інженерні досягнення, так й соціальні, економічні та культурні аспекти суспільства. Інженери та вчені, проектуючи та будуючи мости, стикалися з унікальними викликами залежно від технологічного рівня епохи, доступних матеріалів та потреб суспільства. Цей процес може бути відображенням технологічного прогресу, змін у транспортних потребах, а також культурних та соціальних змін. Метою цієї статті є короткий огляд ключових моментів та етапів історії будівництва металевих мостів з використанням технології зварювання у 20 столітті. Історія розвитку будівництва металевих мостів із застосуванням зварювання налічує трохи більше 100 років. Невеликий період від будівництва перших зварних мостів, до перших катастроф, призвів до необхідності аналізу можливих причин цих руйнувань. Як показав виконаний аналіз, катастрофічні руйнування найчастіше відбувалися під дією кількох факторів, а також при поєднанні зовнішніх несприятливих впливів та внутрішньої «неготовності»

конструкції до них. Наведені приклади свідчать про те, що нераціональний вибір сталі може бути як самостійною причиною, що викликає крихке руйнування конструкцій, так і погіршуючим фактором за наявності конструктивних порушень, термічних напружень і дефектів зварювання. За ці роки у різних країнах було вдосконалено технології виготовлення мостів, розроблено нові сталі та матеріали для їх зварювання. Завдяки використанню вуглецевої, низьколегованої та легваної сталі проектувальники відмовилися від брутальних балкових ферм «залізничного типу» і сьогодні металеві мости з витонченими та красивими силуетами потужно крокують через водну гладь, гори та долини. Вони стали справжніми визначними пам'ятками мегаполісів та заміських ландшафтів, а будівельники змогли успішно вирішити численні технічні та економічні завдання. Важливий внесок у розвиток світового мостобудування із застосуванням технологій зварювання зробив колектив Інституту електрозварювання Академії наук УРСР під керівництвом академіка Євгена Оскаровича Патона. Колектив Інституту електрозварювання Академії наук УРСР, впроваджуючи зварювання у мостобудування, виконував ретельну перевірку результатів та вів спостереження за поведінкою конструкцій. Було створено нову марку сталі, стійку до утворення крихких і втомних тріщин, відпрацьовувалась технологія її зварювання, розроблялася технологія монтажного зварювання вертикальних листів із примусовим формуванням шва, підбиралися відповідні зварювальні матеріали. На момент побудови у 1953 році, київський Міст імені Євгена Патона через річку Дніпро був найбільшим у Європі цілнзварним мостом, усі шви якого, включаючи монтажні, вперше виконали за допомогою автоматичного та напівавтоматичного зварювання. Крім того, наявність великих однотипних блоків у конструкції Моста імені Євгена Патона дозволило механізувати складально-зварювальні операції та організувати потоковий метод їх виготовлення на заводі та монтажі, що підвищило якість зварювальних робіт та знизило їх трудомісткість.

Ключові слова: історія будівництва мостів; історія металевих мостів; історія зварювання; Київський Міст імені Євгена Патона; Нагорода за Історичні Зварні Конструкції; Інститут електрозварювання АН УРСР

Received 19.07.2023

Received in revised form 02.11.2023

Accepted 09.11.2023