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EVALUATION OF DAMAGE OF ALL-WELDED LONGITUDINAL MAIN BEAMS OF THE E.O. PATON BRIDGE ACROSS THE DNIPRO RIVER

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The problem of general evaluation of technical condition of main longitudinal beams of the E.O. Paton Bridge was considered based on the results of selective non-destructive testing of truss elements. It is shown that the main cause of damage to the elements of the main beams is corrosion of the nodal welded joints in the places of debris accumulation. High quality of welded butt joints made by automatic and semi-automatic submerged arc welding was noted. 10 Ref., 18 Figures.

Keywords: E.O. Paton Bridge, main beams, welded joint, corrosion, non-destructive testing, technical diagnostics, automatic and semi-automatic welding, damage to welded joints

The E.O. Paton Bridge across the Dnipro River in Kyiv has been in operation since 1953. It is the world's first all-welded road bridge which entered the annals of the world bridge construction. Prior to the commissioning of this structure, all bridges had riveted joints of elements. Single attempts in building welded bridges had so far failed. That fact was first of all associated with a sharp drop in the load-carrying capacity of welded joints during manufacture of large-sized metal structures. The main cause for such a drop was a simple replacement of riveted joints on welded ones without taking into account the stressed state of welded elements and imperfection of welding technologies developed at the time, which led to crack formation both during manufacture (shop and site welding), as well as during operation of welded structures.

Brittle fractures of welded structures in the 1940s began to bear a mass character, the majority of which had a number of features:

- fracture nuclei were usually located at the places of welded joints;
- fracturing occurred at very low operating loads and relatively high temperatures;
- a number of partial fractures of welded structures significantly increased.

Thus, from the 2500 Liberty ships built during World War II, 145 broke in half and 700 were severely damaged. Many bridges and other structures followed the same pattern [1, 2].

Such kind of fractures very strongly stimulated the development of investigations in the field of welded joints and largely determined their direction. A significant contribution to the development of investigations on the load-carrying capacity of welded joints was made by the Laboratory of Electric Welding, which was a part of the All-Ukrainian Academy of Sciences in Kyiv, which later in 1934 was transformed into the Electric Welding Institute of the AS of the UkrSSR.

The experience gained at the Electric Welding Institute in the manufacture of metal structures allowed using the technologies of mechanized submerged arc welding, which were advanced at that time and proved themselves well during the Second World War at enterprises that manufactured hulls of armored vehicles. At that time, E.O. Paton changed the concept of the bridge construction and proposed to make it all-welded applying automatic welding. This approach caused a necessity in the development of new designing solutions for span structures, steel for their manufacture and automatic welding equipment.

As far as welding technologies were still imperfect at that time and could not provide a full evaluation of properties of welded joints, taking into account thermodynamic cycle of welding and residual stresses, the technologies of automatic welding proposed by E.O. Paton significantly improved the quality and strength of welded joints. Namely these welding technologies were taken as a basis and used in the manufacture of metal structures of the E.O. Paton Bridge in the shop conditions, as well as during their assembly on the construction site [3–6]. Among the significant advantages proposed by E.O. Paton over the ap-

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Figure 1. Welding of longitudinal stiffeners and girth welds of the truss [3]

proaches to the construction of steel bridges existing at that time, the following should be noted:

- maximum use of automatic and semi-automatic submerged arc welding at the plant that manufactured structures and at the erection site (Figures 1, 2);
- assembly of large-block elements at the plant that manufactured structures (Figure 1);
- assembly of erection joints to one-type butts of continuous trusses of double-T cross-section (Figure 3), which significantly simplified the assembly of trusses and reduced the time of welding works by using automatic and semi-automatic submerged arc welding;
- development of a special design of the erection joint of trusses with an insert in a vertical wall and an upper flange and a sequence of their joints by means of automatic submerged welding of girths with extension of a weld on additional laths (Figures 2, 3).
- maximum reduction in the use of manual arc welding with coated electrodes;
- development of low-carbon M16C steel, low-sensitive to thermodeformed welding cycle;
- development of new electrode wires and fluxes;
- development of new equipment for automatic and semi-automatic submerged arc welding in a wide range of technological modes of its use in industry.

The complex of these solutions provided the necessary reliability and quality of nodal welded joints of bridge structures (more detailed information can be found in [6]). That is why in 1995 the bridge was recognized by the American Welding Association as an outstanding welded structure of the twentieth century.

The total length of the bridge is 1542.2 m, it consists of 24 spans. The construction of the bridge began from the left bank of the Dnipro River.

The right-bank part of the bridge consists of ten spans, which are overlapped by two all-welded five-

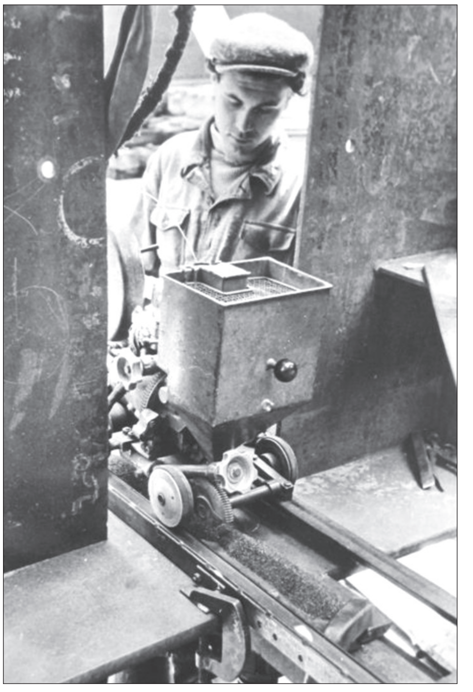

Figure 2. Example of applying automatic submerged arc welding of the lower girth while joining trusses of the main beams [4]

span continuous structures — (5×58) + (5×58) m (further indicated as 1–5S and 2–5S).

The middle part of the bridge over the navigable region of the river has six spans, which are overlapped by continuous all-welded structures — 58 + 4×87 + 58 (m) (further indicated as 6S).

The left-bank part of the bridge has 8 spans of 58 m each and is overlapped by two four-span continuous welded structures — (4×58) + (4×58) m (further indicated as 1–4S and 2–4S).

In the cross-section, each structure has four main longitudinal beams of double-T section, consisting of a vertical wall with 3600 mm height and 14 mm thickness and girths of different thickness, varying from 30

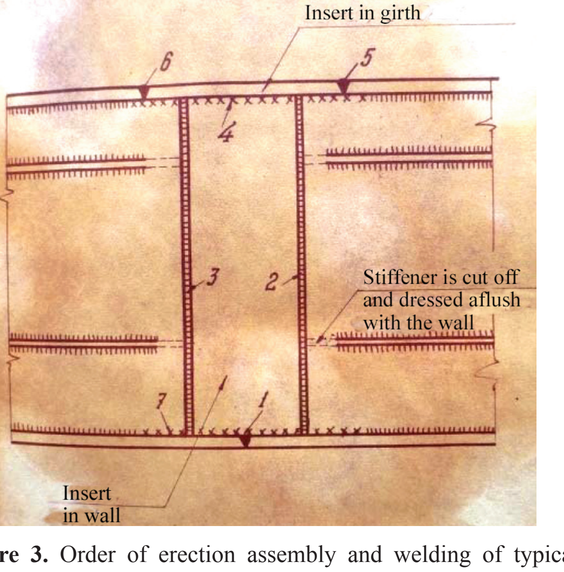

Figure 3. Order of erection assembly and welding of typical bridge trusses [4]

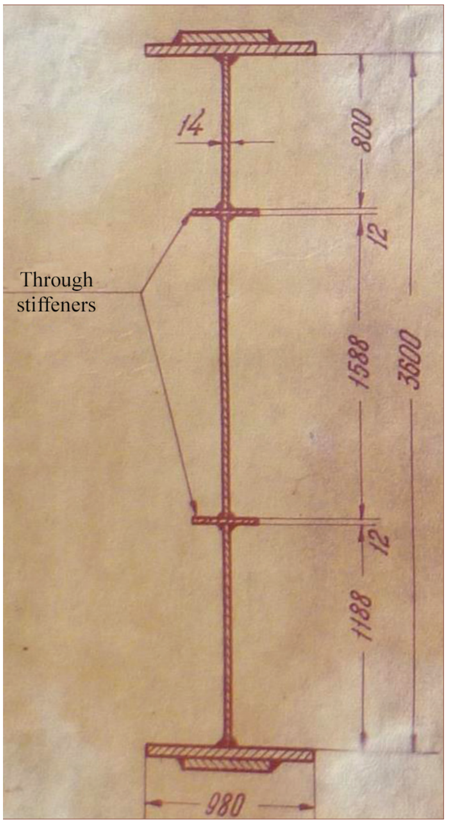

Figure 4. Cross-section of the truss of the main longitudinal beams of four- and five-span structures of the bridge [4]

to 80 mm, with a width of up to 1000 mm (Figure 4). The stability of the beam wall is additionally provided by vertical stiffeners mounted with a step of 7.25 m.

In six-span structures, the height of the wall above the intermediate supports is increased to 6200 mm due to built on haunches.

The main longitudinal beams are composed of trusses, which are butt-welded using automatic submerged arc welding during erection of metal structures. A number of trusses in each of the four-span main longitudinal beams is 9 pcs, in the five-span main beams there are 11 pcs, and in the six-span main beams there are 21 pcs. The trusses are made of low-carbon steel of M16C grade.

The E.O. Paton Bridge across the Dnipro River in Kyiv was designed based on the conditions that the designed traffic intensity should be 10 thou cars per day. During a long-term operation of the bridge, the load on its load-carrying elements gradually increased, which is associated both with an increase in the traffic intensity per day (currently it has increased by almost 10 times — during «peak» hours — up to 85 thou per day), as well as with an increase in car weight [7]. As a result of laying pipes of the heat pipeline and increasing the thickness of the asphalt concrete pavement, the constant loads on the bridge also increased. Taking that into account, in 1994–1998 the transverse beams of the bridge, which are located near the expansion joints, were reinforced, and additional stiffeners were mounted on some regions of vertical walls of the main beam trusses [7].

Until 2019, the main longitudinal beams of the bridge were inspected only visually without the use of instrumental and physical methods of testing, which did not allow obtaining more detailed information on the actual technical condition of metal structures [7, 8]. Thus, according to the results of inspection of the bridge, performed at the end of 2018 by the specialists of LLC «V.M. Shimanovsky Ukrainian Institute of Steel Construction», it was pointed out that on the walls of the main beams of the structure in the locations of expansion welds, the formation of a layer of corrosion products was observed. Considering and analyzing the results of investigations, V.M. Shimanovsky Ukrainian Institute of Steel Construction came to the conclusion that the E.O. Paton Bridge is in an emergrency situation and urgently needs major repairs with a partial replacement of its structural elements. This issue was repeatedly discussed at the meetings in the Kyiv City State Administration and «Kyivavtodor», on the results of which a decision was made on the reconstruction of the bridge and a need for a more detailed inspection of its structural elements. In 2019, the works on evaluation of general technical condition of the bridge were entrusted to LLC «V.M. Shimanovsky Ukrainian Institute of Steel Construction» with the involvement of specialists of the E.O. Paton Electric Welding Institute of the NAS of Ukraine in terms of inspection of the main longitudinal beams of the bridge.

Inspection of the technical condition of the main beams of the bridge structures was performed in 2020. A part of the results of the investigations conducted by the experts of the PWI is given in [9]. The investigations were conducted in the following areas:

- selective ultrasonic testing of butt shop and erection welded joints of beams and base metal of beam elements for the presence of delamination;
- thickness measurement of the main elements of the main beams at the access points;
- selective magnetic control of fillet and butt welded joints.

The choice of such testing methods was determined based on the results of the previous inspection of the main longitudinal beams of the bridge located between the 2nd and 3rd supports, which was performed by the specialists of the PWI (in July 2019), taking into account data [10]. 100 % visual inspection of welded jonts was also completed. According to the results of the previous inspection, the main areas of investigations were determined, which can be divided into three components:

Figure 5. Example of testing butt vertical welds of the joining insert

● detection of a possible fatigue damage of welded joints after a long-term operation;

● evaluation of integrity of the base metal from which the elements of trusses are made;

● evaluation of the sizes of a corrosion damage of the elements of trusses and welded joints of the main beams.

The main attention during the selective ultrasonic testing of butt welds was paid to the places where defects were detected during the erection and manufacture of truss elements [3, 4, 9], and to the maximum stressed areas. At a total length of erection and shop welded joints of about 110 km, 150 m of welded joints were inspected, 50 % of which amounted to erection welds at the places of joining trusses (Figures 2, 3, 5, 6).

Considering that the ultrasonic method of testing does not provide a reliable control of surface and near-surface layers in a welded joint, the magnetic method of testing was additionally applied. Magnetic control was performed in different places of span structures on 124 sections of welded joints with a total area of 40.0 m^2. Taking into account the more complex conditions of erection, more attention was paid to erection welded joints using the method of magnetic control. All places where non-destructive testing was performed were entered into the operation charts of testing, which were linked to the numbers of trusses from which the longitudinal beam was made and the numbers of supports between which it was located.

Visual inspection of welded joints and analysis of the results of ultrasonic and magnetic control of erection and shop welds of span structures indicate that welded joints of the main beams are in satisfactory condition. Fatigue cracks in welded joints after a long-term operation were not formed. Even those

Figure 6. Example of testing butt weld in the upper girth of the joining insert

defects that were detected already at the stage of construction of the bridge, did not propagate in the process of a long-term operation (Figure 7).

The obtained testing results once again confirm that the proposed designing solutions for a large-block assembly and the principle of maximum use of automatic and semi-automatic submerged arc welding laid at the plant and erection area allowed providing a guaranteed high quality of welded joints. A significant role in achieving these results belongs also to the developed equipment and proposed advanced technologies for welding and assembly of large-block elements (trusses)).

Checking the integrity of the base metal of the main beams by a non-destructive method of testing was associated with the fact that in the manufacture of trusses of the main longitudinal beams in some cases local places with delamination in the metal of horizontal stiffeners were detected. In some cases, when delaminations detected during the manufacture and erection did not reach welded joints, such areas were not repaired [3]. In these places, to evaluate the probable further growth of delamination, 7 m^2 of metal sur-

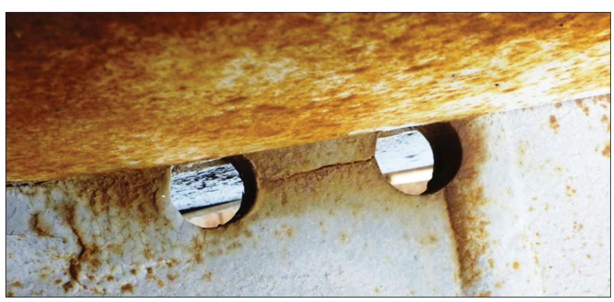

Figure 7. Example of absence of growth of a defect left during erection (ends of the crack were arrested by drilling method) [4]

Figure 8. Area of debris accumulation and condition of inspection passages on the inner side of the end beam of the five-span structure

face was selectively inspected. The areas of the base metal of different thicknesses were inspected, which were directly adjacent to the welded joints, in which delamination was detected during erection. In none of the tested places the propagation of delamination to other areas was detected.

When designing horizontal stiffeners, their welding-on to the vertical wall of the truss without a full penetration was provided (Figure 4), which significantly reduced the residual stresses over the thickness of the metal and, as a result, considerably lowered the risk of propagating this defect.

In general, the results of carried out investigations showed that in the process of long-term operation, fatigue cracks were not formed in the welded joints of the metal structures of the main beams and these joints are in satisfactory condition.

According to the preliminary conclusions from the obtained results of selective technical diagnostics of the main longitudinal beams [9], the main cause that can significantly reduce the further service life of the bridge is corrosion. During the period of operation, the metal of the main beams has suffered some loss

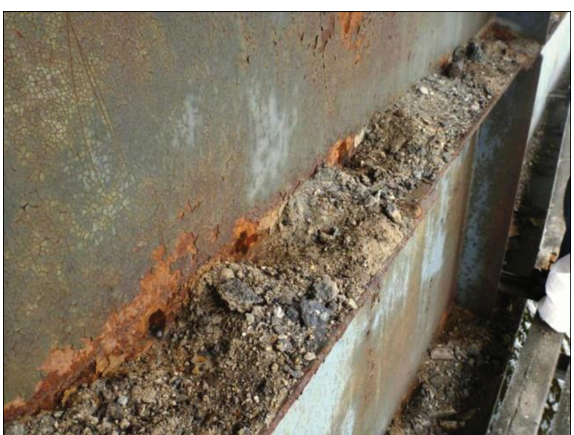

Figure 9. Area of debris accumulation on the outer side of the end beam of the five-span structure

Figure 10. Area of debris accumulation in the supporting part of the four-span structure

of thickness from corrosion. This was especially observed in the areas of large debris accumulation on the lower horizontal stiffeners, the lower girths of the end beams and at the ends of the supports of the span structures (Figures 8–10).

To specify and determine the most typical damages of the main beam elements and related factors during the inspection of span strucutres with the help of thickness measurements, a number on of which the end beams (No.1, No.4) was significantly higher than on the beams No.2 and No.3. An increased number of measurements was caused by a limited access to the tested elements as a result of an unsatisfactory con-

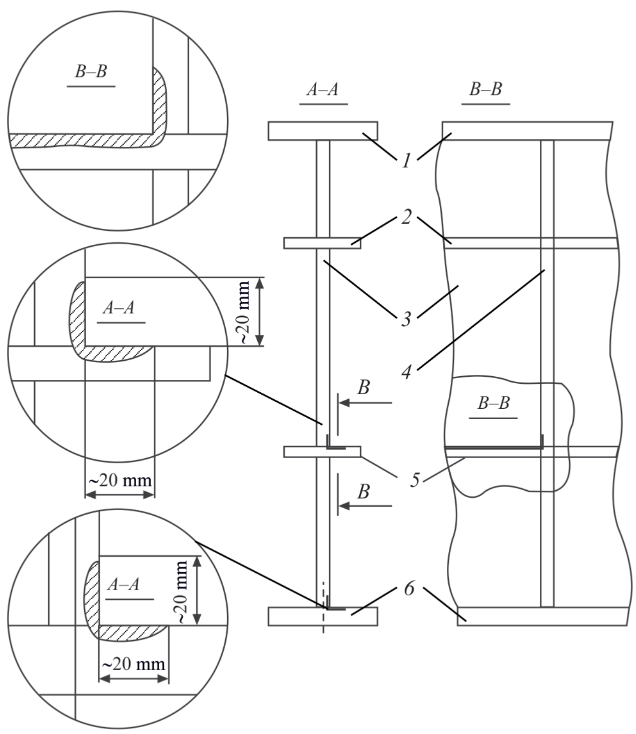

Figure 11. Typical corrosion damages of welded joints of truss elements of the main beams: *1* — upper flange; *2* — upper horizontal stiffener; *3* — wall; *4* — vertical stiffener; *5* — lower horizontal stiffener; *6* — lower flange

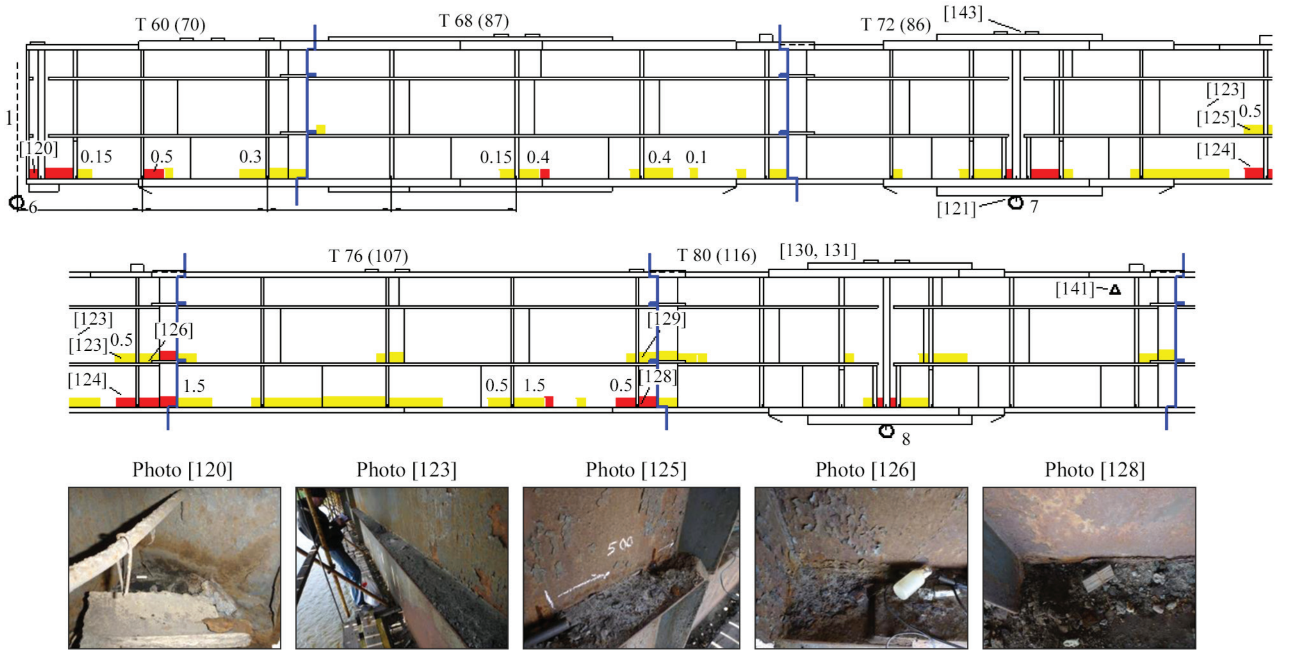

Figure 12. Fragment of tabulated results of testing elements of the beam No.1 of the five-span structure located between the 6-9 support

dition of the inspection passages and a large debris accumulation on the end beams of the structures.

In selective testing of thickness of the truss elements in places of debris accumulation, 12640 measurements were carried out. In total, 16876 measurements of thickness were carried out during a partial inspection of the main longitudinal beams of the span structures, which were entered in the operation charts of the testing (168 truss charts) with a record of the section, where testing was carried out and on the generalized schemes of span structures. The most typical places of corrosion damages of welded assemblies of the main beams of the bridge are presented in Figure 11.

As an example, Figures 12, 13 present the sections with detected corrosion damages and a delamination of the main beams of span structures.

On the given fragments, the following symbols are used (Figures 12, 13): T is a truss; the areas where the

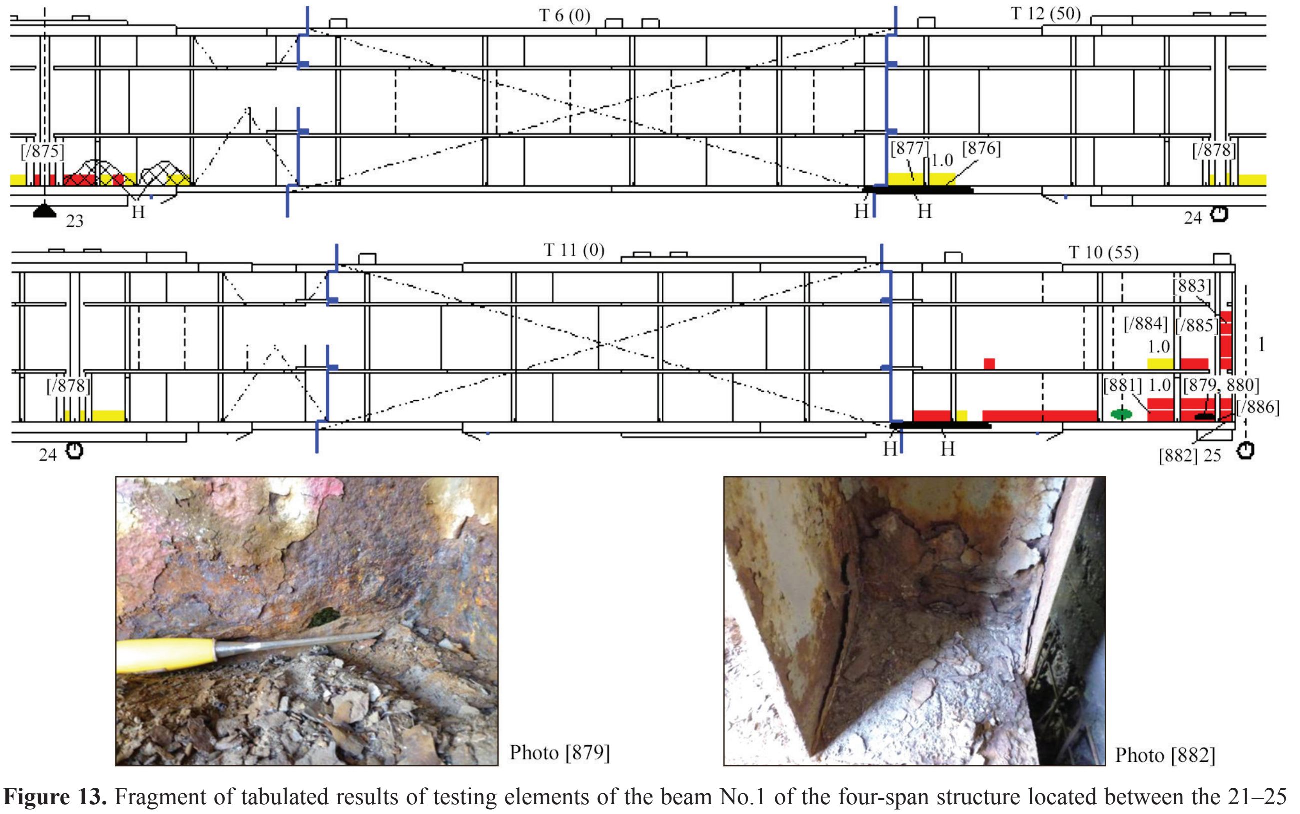

Figure 13. Fragment of tabulated results of testing elements of the beam No.1 of the four-span structure located between the 21–25 support

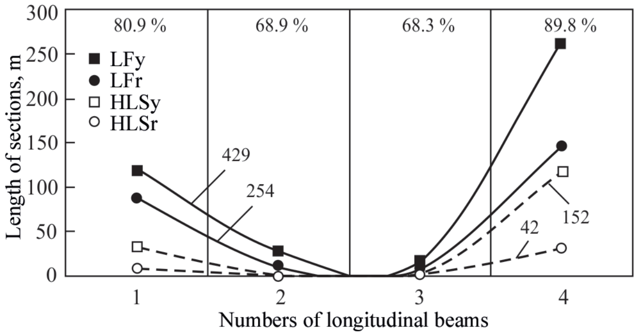

Figure 14. Total length of detected corrosion damages of the main longitudinal beams in the welding assemblies of the following elements: middle wall of the truss to the lower horizontal stiffener — HLS (y, r); lower wall to the lower flange of the truss — LF (y, r) (marks «y» and «r» characterize the depth of corrosion damages from 2.0 to 4.0 mm and more than 4.0 mm, respectively)

loss of metal from corrosion is in the range from 2 to 4 mm are yellow and red where it is more than 4 mm. A number above the color indicates the approximate length of the corresponding area along the truss. A separate square of yellow or red colour corresponds to a length of about 100 mm. If the area is separated by structural elements, such as for example vertical stiffeners or welded sheet joints, then a number above the color is not marked. Nonmetallic inclusions are green. The boundaries of trusses are marked in blue. Movable and immovable supports are respectively — ○ 22 △ 23. In square brackets, the numbers of photos of some sections are given. The sections that were not subjected to a selective testing are marked with dotted intersection. Defects are marked in black according to the data of LLC «V.N. Shimanovsky Ukrainian Institute of Steel Construction», given in the report compiled based on the results of the inspection of the bridge in 2018.

According to the results of selective measurements of the thickness of truss elements and the carried out analysis [9], it was determined that as a result of rainwater and moisture, formed by melting snow (containing salts), leaking through expansion welds of a reinforced concrete slab on the metal structures of the main beams, the metal in some regions of trusses suffered significant local corrosion damages. In some cases, the thickness of the metal as a result of corrosion in the lower girths, lower horizontal stiffeners and in the lower part of the walls of the main beams decreased significantly (in some cases by 40–50 %).

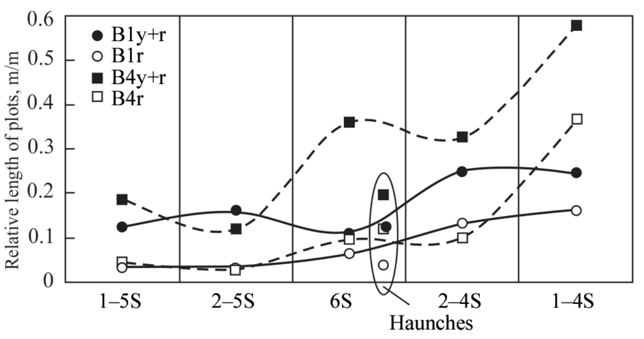

Figure 15. Relative length of detected sections damaged by corrosion in the welding-on assembly of the lower wall to the lower flange of the truss for the structures 1–5S; 2–5S; 6S; 2–4S; 1–4S of the end beams No.1 and No.4 to the controlled length of the structures (B1y+r is the total length of damages with a depth of more than 2.0 mm of the beam No.1; BБ1r is the total length of damages with a depth of more than 4.0 mm of the beam No.1; B4y+r is the total length of damages with a depth of more than 2.0 mm of the beam No.4; B4r is the total length of damages with a depth of more than 4.0 mm of the beam No.4)

The smallest depth of corrosion damages was observed near the expansion joints in the trusses of the middle main beams No.2 and No.3, where debris was absent (Figure 14). In addition to the sections of the main beams No.2 and No.3, located near the expansion joints, other elements of these beams are in satisfactory condition.

The greatest loss of metal thickness as a result of corrosion was found in the trusses of the end main beams No.1 and No.4 (Figures 14, 15). The main cause for such a damage was the presence of debris on the lower horizontal stiffener and the lower girth of these beams, which retains moisture (Figures 8–13).

The maximum corrosion damages to the elements were detected in trusses T10 and T15 of the four-span structure of the main beam No.1 and trusses T1 and T3 of the four-span structure of the main beam No.4. In these trusses deep corrosion damages (rust-through in some places, Figure 13), which need urgent repair.

It should be noted that during the works, the specialists of the PWI were provided with a limited access to the testing elements of longitudinal main beams in connection with a general unsatisfactory condition of the inspection passages and also with the debris accumulation on the end beams, which allowed performing only a partial inspection.

Thus, Figure 16, *a*, *b* shows a dependence of the detected corrosion-damaged areas of the inspected structures, where in the top of the diagram the percentage of the performed testing on the structures is indicated.

Taking into account the limited access to the structural elements, it is possible to evaluate to some extent the «expected» length of damaged sections of the structures on other beams. As an example, Figure 17 shows the predicted (expected) length of corrosion-damaged areas of strucutres in the places of welding the lower girth to the wall of the main beams No.1 and No.2.

In this case, when evaluating the expected length of corrosion damages to the beams B1 and B2, a linear extrapolation between the found damaged sections and the controlled length was used. This approach provides only an approximate evaluation of possible damages, but can be useful when planning future repair works. A more accurate evaluation of damages

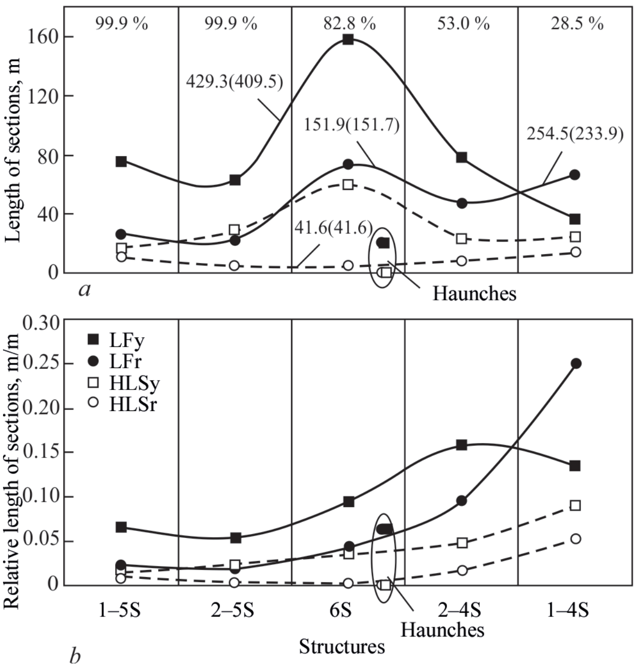

Figure 16. Length of detected sections damaged by corrosion of structures and percentage of performed testing (percentage of testing is indicated above) (*a*) and the relative length of detected sections damaged by corrosion of structures to the controlled length (*b*). The numbers indicate the total length, taking into account the data on haunches (in parentheses — without haunches)

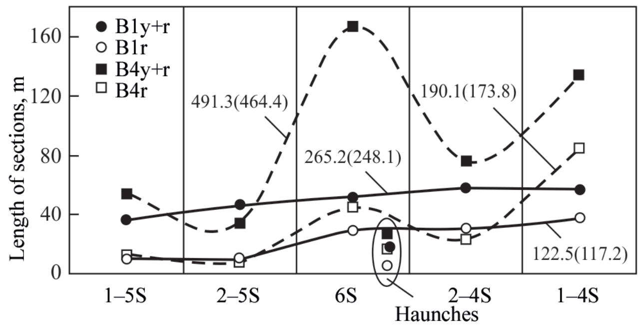

Figure 17. Example of predicting length of of detected sections damaged by corrosion in the welding-on assembly of the lower wall to the lower flange of the truss for the structures 1–5S; 2–5S; 6S; 2–4S; 1–4S of the end beams No.1 and No.4 (designation of curves as in Figure 15)

requires other approaches using probable methods. Thus, Figure 18 shows diagrams of distribution of detected damages to the trusses in the assemblies of welding-in the lower girt to the lower wall between the supports for the main beams No.1 and No.4. From the analysis of the results of this diagram it was found that the sections of detected damages are chaotic. The only similar pattern is an increase in damages along the boundaries of the structures.

Summarizing the results of the inspection of the main beams of the E.O. Paton Bridge across the Dnipro River in Kyiv, the following conclusions can be drawn.

1. Welded joints of truss elements of the main longitudinal beams are in satisfactory condition. In the course of a long operation, inadmissible defects and fatigue cracks were not formed in them.

2. As a result of leaking rainwater and water formed from melting snow (containing salts) on metal structures of the main beams, the metal of the end sections of the trusses adjacent to the expansion welds, suffered local but sometimes significant corrosion damages. As a result of corrosion, the thickness of the metal in the structural elements, namely of the lower girths, the lower horizontal stiffeners and in the lower

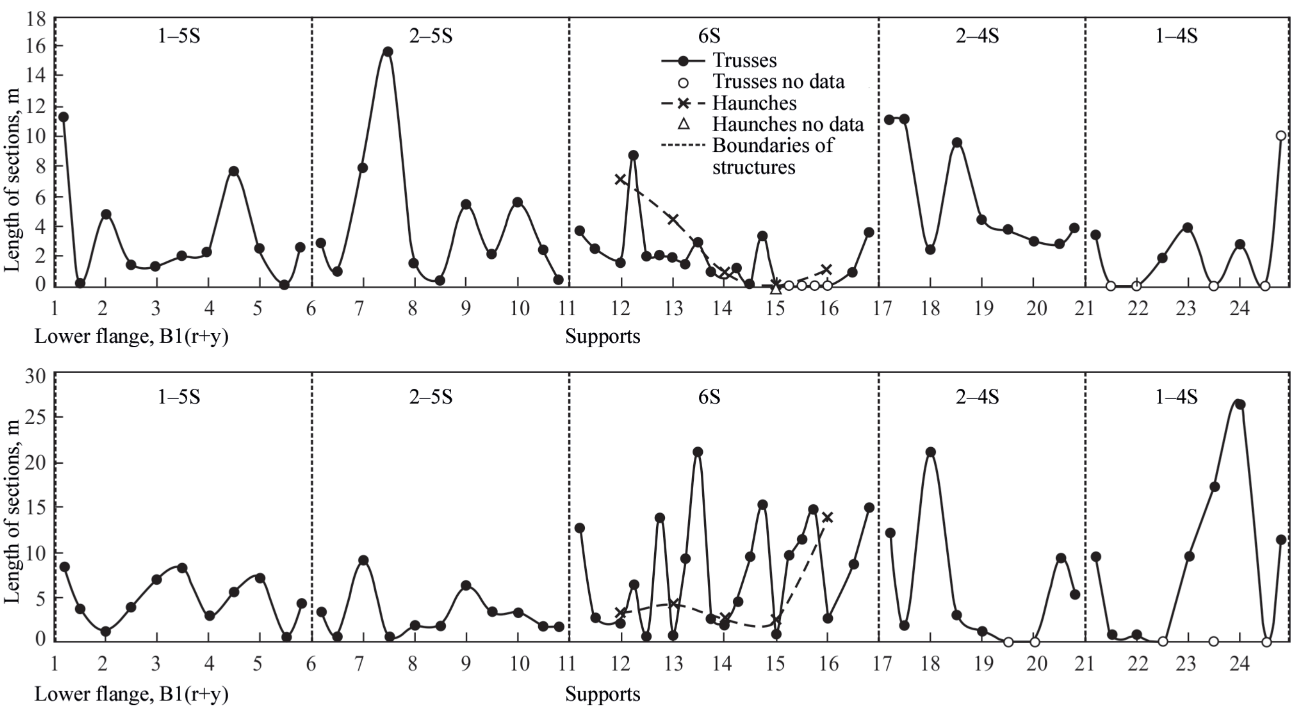

Figure 18. Distribution of detected damaged sections in the welding zone of the lower girth to the truss wall between the supports for the main beams No.1 and No.2 (designation as in Figures 15, 17)

part of the walls of the main beams significantly decreased. In some cases by 40–50 %.

3. The smallest corrosion damages are observed near the expansion welds in the trusses of the middle main beams No.2 and No.3, more intense are in the trusses of the end No.1 and No.4 main beams, which is caused by the debris accumulation on the lower horizontal stiffener and the lower girth of these beams, which retains moisture.

4. Local corrosion damages were formed on the lower flanges, lower horizontal stiffeners and parts of the truss walls of the end main beams No.1 and No.4 adjacent to them. The similar sections of the main beams No.2 and No.3 are in satisfactory condition.

5. The deepest corrosion damages (in some places through) were observed in the trusses T10 and T15 of the main beam No.1 and the trusses T1 and T3 of the main beam No.4. These trusses need urgent repairs.

6. Taking into account the current technical condition of the main beams of the E.O. Paton Bridge across the Dnipro River in Kyiv, on the condition that the works aimed at restoring their initial load-carrying capacity will be performed, the main beams can be used during reconstruction (restoration) of the bridge.

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