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Fatigue Cracks in the 60-year-old steel Structure of the Bridge

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ABSTRACT

The paper shows the fatigue cracks that appeared in the steel girders under the orthotropic plate inside the bridge structure. During decades of exploitation, fatigue cracks developed both in the base material and in the welded joints of the steel girders. Frequent stress cycles due to increased traffic and occasional overloads caused the cracks to propagate over time. Fatigue cracks propagation shortens the life of the steel structure and drastically affects the structural integrity of the bridge. As an effective tool in the detection and evaluation of fatigue cracks in steel bridges, NDT (non-destructive testing) methods occupy a significant place. Non-destructive field methods used for the purpose of fatigue crack detection were magnetic particle testing and penetrant testing. The non-destructive metallographic method of the replica was used to assess the type of crack, and the examination of the taken replicas was carried out in the laboratory using light optical microscopy. Timely detection and repair of fatigue cracks in steel bridge components are key maintenance activities that can prevent potential failure. The paper lists some of the methods that were used for stop the propagation of fatigue cracks. The aim of the paper is to show some of the "in-situ" methods of identification and repair of fatigue cracks in the steel structure of the bridge after 60 years in service.

Key words: *fatigue cracks, steel bridge, "in situ" testing, repair methods*

1. INTRODUCTION

Steel bridge structures are used all over the world, including Europe, in various structural projects and with different applications such as railway bridges, highway bridges and pedestrian bridges [1]. From the beginning of the 20th century to the present, key events have been recorded that have influenced the modern practice of design and testing of steel bridges for fatigue and failure [2]. The modern approach to material fatigue assumes the presence of any discontinuity created either during the manufacturing process or as a consequence of drilling, cutting, or welding [3]. The most common causes of failure of steel bridge components are fatigue, corrosion, impact loads, overloading, errors in either design or construction, as well as untimely and improper bridge maintenance [4]. Fatigue failure is defined in modern literature as the process of crack propagation due to the application of cyclically repeated loads. Microscopic cracks that appear at points of stress concentration gradually grow until they reach the critical section of the component, resulting in final fracture. While sustained stresses govern fracture, cyclical stresses govern both fatigue and fracture. Sustained stresses include the load accumulated during the construction of the bridge. Welded bridge components contain residual/sustained stresses that significantly affect the propagation of fatigue cracks. After 60 years of service, fatigue cracks in steel bridge components are usually caused by forces caused by distortion, or by increasing transport loads, as well as by cyclic stresses that are below the lower yield point of the material. Periodic inspections of the bridge provide an opportunity to ensure the detection of cracks in the initial stage and prevent them from reaching a critical size [5]. When a single crack is found

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on a bridge component, it can be assumed that other similar bridge components will show similar cracks. The appearance of cracks requires conducting a detailed inspection of the bridge in search of other possible cracks as well as planning their rehabilitation. The inspection is first performed visually, and then some of the integrated non-destructive testing (NDT) methods are used, such as: penetrant testing (PT), magnetic particle testing (MT), ultrasonic testing (UT), eddy current testing (ET) and infrared thermography (IR) [6]. The bridge that is the subject of research, built in 1976, is a key steel structure across the Danube. The total length of the bridge is 1424.4 m and the steel structure over the river is 1231 m. On both sides of the bridge there are access concrete structures, length 96.7 m. The steel structure of the bridge consists of three continuous girder structures over 13 columns, namely:

- approach structure between pillars S1 and S6, span 5×89.6m,
- the main structure across the river between pillars S6 and S9, spanning 108.8+171.2+108.8 m,
- approach structure between pillars S9 and S13, span 4×97.6 m. The main girder of all three steel structures from pillars S1 to S13 has a box section, with a 12.0m wide orthotropic road plate.

2. THE CRACKS DETECTION TECHNIQUES

Detecting cracks in painted or rusted structures can sometimes be an unwieldy and very difficult process. The best tool for detecting cracks is the inspector's keen eye. The cyclic opening and closing of the cracks cause the fracture surfaces to rub against each other, creating a fine steel powder that oxidizes over time. The oxidized powder leads to rust, and over time, the accumulated corrosion products begin to leak from the crack. This phenomenon offers easy and quick visual detection and location of cracks, but is not recommended as the sole means of detection. Fig. 1 shows the detection of cracks due to discoloration and rust spots.

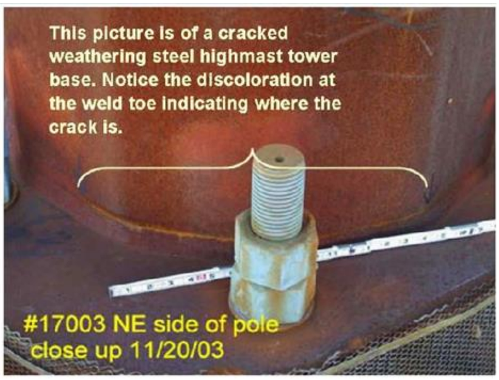

Fig. 1 *The detection of cracks due to discoloration [6]*

In this study, two key and commonly used non-destructive methods for detecting cracks in steel components, penetrant testing (PT) and magnetic particle testing (MT), were applied to detect fatigue cracks. After a preliminary assessment of the crack using the aforementioned methods, a surface replication metallographic method was used to determine the type of crack.

The surface replication method was used to determine the type of crack. A surface replication technique known as "in situ" metallography allows examination of the microstructure of the material without the need to cut the component. Field metallographic replication is a non-destructive process for reproducing the surface microstructure of a sample as a negative relief on plastic film. This technique involves applying a softened replica to a previously prepared test surface. Once the solvent has evaporated, the replica/plastic film containing the negative topographic image is removed from the surface and then examined under a microscope [7]. A schematic representation of the plastic replica technique is shown in Fig. 2.

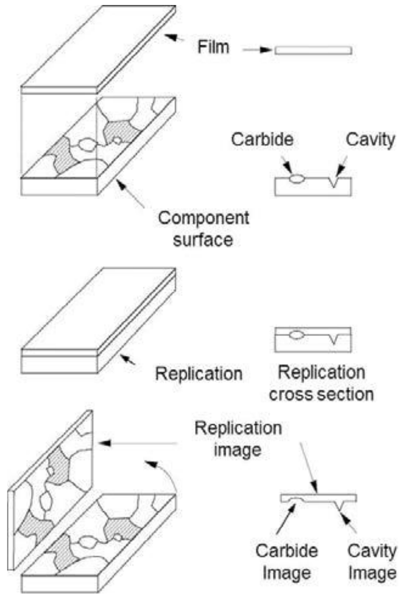

Fig. 2 *Schematic representation of the plastic replica technique [8]*

Crack determination is a vital step in root cause failure analysis, providing the essential evidence needed to identify why a component failed rather than just how it failed. Slow-growing cracks caused by repeated loading, which usually show smooth zones near initiation and rougher zones at final fracture, indicate a fatigue type of crack.

The cause of possible component failure can be determined by the type of crack. Different types of cracks and their propagation in steel components are shown schematically in Fig. 3 [9].

3. EXPERIMENTAL METHODS AND RESULTS

3.1 Basic material of steel girders

All the basic material from which the supports inside the bridge structure under the orthotropic plate are made is steel S355J0. Table 1 shows the chemical composition of steel S355J0 according to the European standard EN 10025-2 [10].

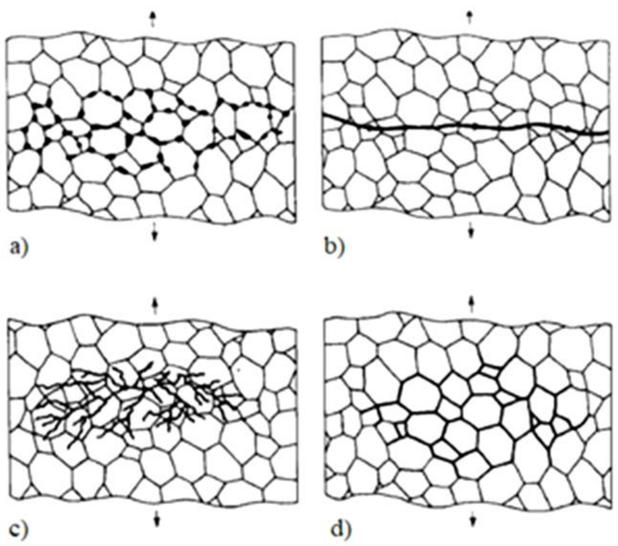

Fig. 3 *Propagation of different crack types: (a) Creep, (b) Fatigue, (c) Stress corrosion and (d) Intergranular corrosion [9]*

Table 1 - *Chemical composition (wt.%) of steel S355J0*

Element	by mass (%)
Carbon (C)	⩽ 0.22
Silicon (Si)	⩽ 0.55
Manganese (Mn)	⩽ 1.6
Phosphorus (P)	⩽ 0.035
Sulfur (S)	⩽ 0.035
Nitrogen (N)	⩽ 0.012
Copper (Cu)	⩽ 0.55
Aluminium (Al)	0.020 (minimum)

3.2 Mechanical properties of steel S355J0

S355J0 is an unalloyed, carbon-manganese steel characterized by good weldability, high toughness at 0°C (min. 27 Joules) and high tensile strength for thicknesses below 100 mm (470-630 MPa). The minimum yield strength of 355 MPa decreases with increasing thickness to 275 MPa for thicknesses greater than 250 mm. Steel S355J0 is suitable for use in constructions that are exposed to high-cycle fatigue in service, but has moderate resistance to fatigue crack growth. Experimental data have shown that the chemical composition of this steel has a primary influence on fatigue in relation to the structure of the material [11].

3.3 Experimental methods for fatigue crack detection

3.3.1 Magnetic particle testing (MT)

The MT method is effective for detecting surface and subsurface defects to a depth of about 2-4 mm. The MT method includes several standard steps such as: cleaning of the test surface, magnetization, application of magnetic particles, followed by examination of the surface under appropriate lighting that improves the visibility of cracks or other discontinuities. The final step of the MT method is demagnetization, i.e. removal of magnetic particles and cleaning of the examined surface.

In this study, a Uniflux UF 230A yoked magnet, a powerful AC handheld magnet, was used for magnetic particle crack testing. The test was conducted in accordance with EN ISO 17638 [12]. The ambient temperature during the test was 20 °C. A fatigue crack in the heat affected zone of a steel girder under an orthotropic plate, detected by the MT method, is shown in Fig. 4.

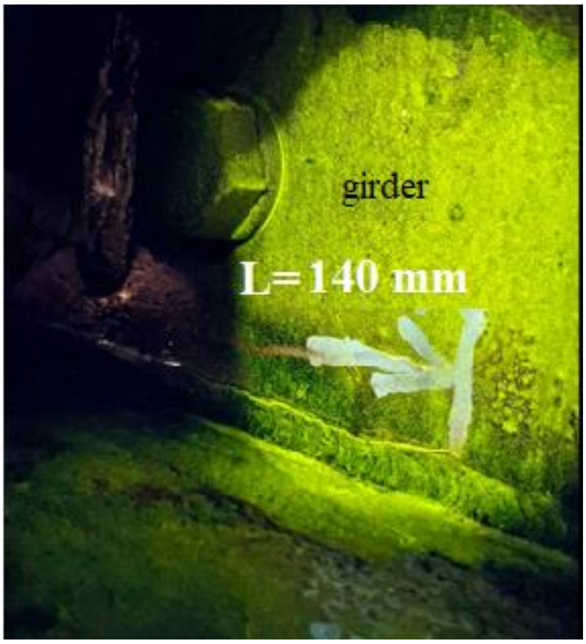

Fig. 4 *A fatigue crack in the heat affected zone of a steel girder under an orthotropic plate*

3.3.2 Penetrant testing (PT)

The PT method is used to detect cracks or surface irregularities in both welded joints and the base material of the structure. Penetrant, which is usually red, is applied onto the previously degreased and cleaned surface. After a penetration time of usually 60-90 seconds, the penetrant is removed from the surface with a dry cloth. The next step, after drying the penetrant, is the application of the developer which is usually white in color. The developer draws the red penetrant dye out of the crack, which becomes easily visible on the white painted metal surface.

In this case, the test surface was cleaned using an aerosol spray based on alcohol brand HELLING U87. HELLING U88 penetrant and HELLING U89 developer were used for fatigue crack testing. The dye needed about 15 minutes to develop. Testing was performed in accordance with EN ISO 3452-1 standard [13]. A fatigue crack in the weld metal of a steel girder under an orthotropic plate, detected by red penetrant, is shown in Fig. 5.

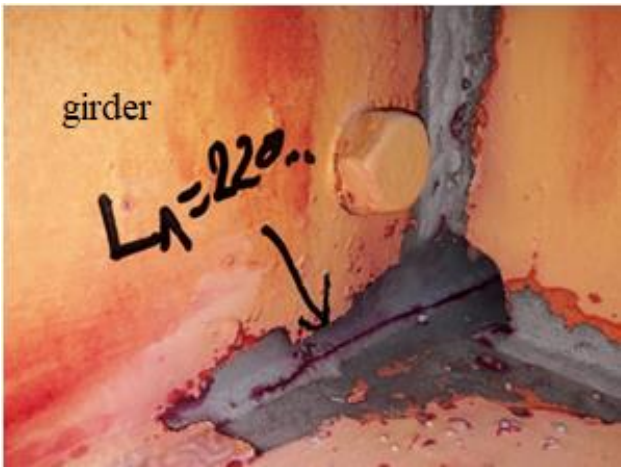

Fig. 5 *A fatigue crack in the weld metal of a steel girder under an orthotropic plate*

3.3.3 Replication metallography

The NDT replica method included taking replicas (imprints) from the previously prepared surface on steel girders, from the zones that contained the cracks. A 4% alcoholic solution of nitric acid was used as a reagent for microstructure development. The analysis of the taken replicas was performed in the metallographic laboratory on a light optical microscope manufactured by Carl Zeiss, according to the ISO 3057 standard [14]. The cracks propagation (L1=150 mm and L2=80 mm) from the edges of the opening formed during the manufacturing process is shown in Fig. 6.

Fig. 6 *The cracks propagation (L1=150 mm and L2=80 mm) from the edges of the opening formed during the manufacturing process*

Microscopic analysis of the replica, which represents the negative of the actual microstructure, was performed at a magnification of 100 times. Fatigue cracks in the ferritic-pearlite microstructure of the steel girder, taken by the replica, are shown in Fig. 7.

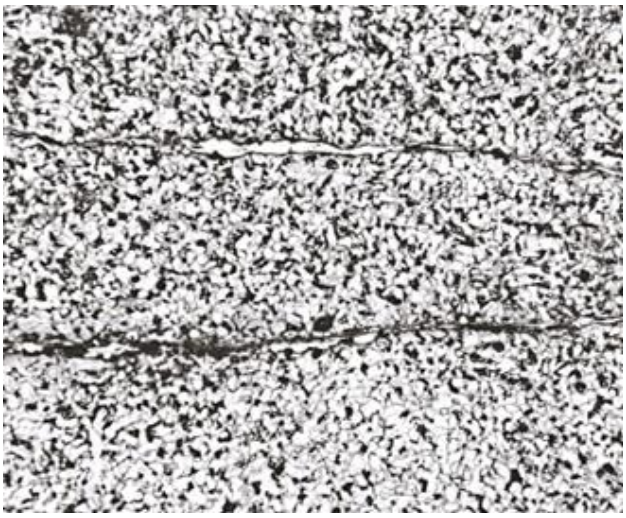

Fig. 7 *Fatigue cracks in the ferritic-pearlite microstructure of the steel girder. 4% nital. Original magnification: 100x*

4. REPAIR METHOD

To stop further crack propagation, rehabilitation is required, while to improve fatigue resistance and prevent possible component failure, reconstruction is required. The choice of methods for the repair of cracks and the reconstruction of components subject to fatigue depends on the availability of the contractor's equipment, as well as on the operational skills of the working personnel.

According to the American Association of State Highway and Transportation Officials (AASHTO), repair and reconstruction methods are classified into three groups: surface treatment, crack repair by depth and reduction of the cause of failure by weld modification [15].

The experimental test results from this study enable timely detection of bridge structural damage and provide cost-effective maintenance, while ensuring structural reliability and safety.

The most economical and commonly used method of repairing fatigue cracks is to drill holes, usually 50.8 to 101.6 mm in diameter [10]. The diameter of the hole must be large enough to prevent crack propagation without compromising the strength of the component or joint. A hole is placed at the top of the crack to remove the sharp notch and prevent further crack propagation. The holes can be drilled with an annular cutter or twist bit depending on the hole diameter. Flame cutting of the holes is not permitted as this may lead to the formation of new fatigue cracks. Proper centering of the drill ensures that the tip of the crack is removed, as shown in Fig. 8. Sharp edges created by drilling must be ground to a smooth state.

4.1 "Stop hole" drilling

In order to slow down or completely prevent crack growth, stop holes were drilled at the tips of the identified cracks. This method proved to be a very effective and very economical field method in case of rehabilitation of this bridge. Repair of fatigue cracks directly protects against sudden failure of the steel structure. Fig. 9 shows stopping the propagation of fatigue cracks by drilling holes at end in both the base material and the weld, according to the recommendations shown in Fig. 8.

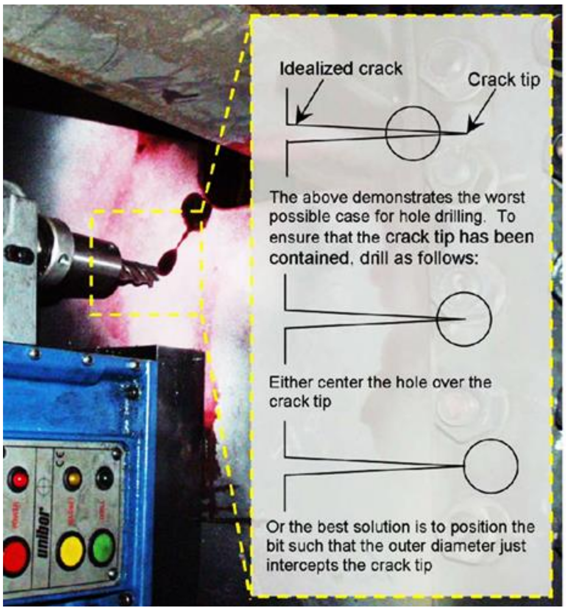

Fig. 8 *Correct placement of the drill bit and removal of the crack tip identified by red penetrant*

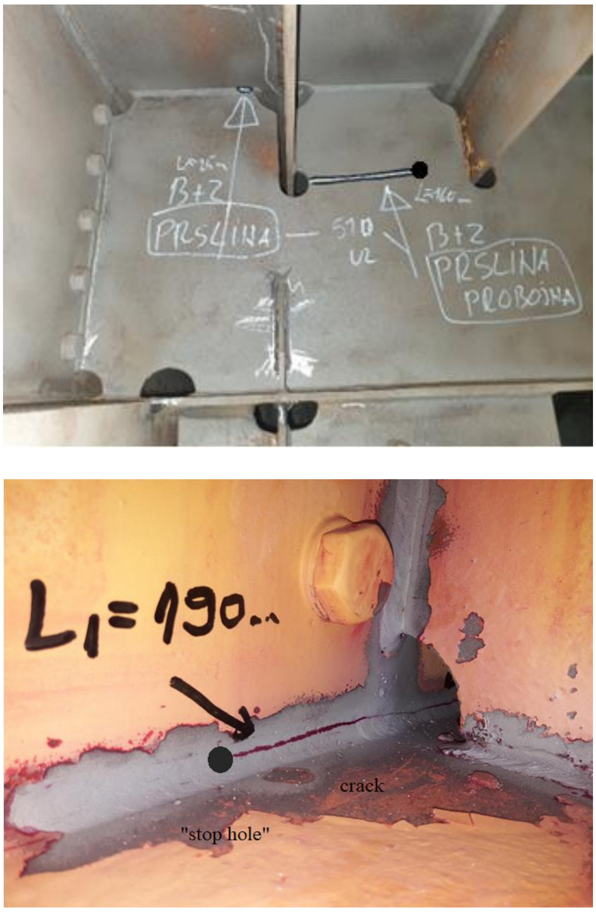

Fig. 9 *Stopping the propagation of fatigue cracks by drilling holes at the end: a) in the base material; b) in a welded joint.*

5. DISCUSSION

Most of the fatigue cracks in the investigated bridge structure were caused by increased traffic load. The bridge, which was built six decades ago, was not designed for today's volume and weight of freight vehicles.

The main goal of the applied NDT techniques was to identify fatique cracks that pose a risk to the bridge as they propagate over time under operational loads. For this reason, MT and PT techniques were chosen as cost-effective, fast techniques for fatigue crack detection. The test was conducted under conditions of normal traffic load on the bridge, which affected the opening of any cracks. In this case, the technical assessment of the condition of the bridge and the basis for further monitoring of the structure was based on the detection and identification of fatigue cracks.

The appearance of fatigue cracks in the main elements of the bridge structure, such as in this case the cross girder under the orthotropic plate, can pose a great risk to the safety of people on the bridge because failure can occur. The key importance of the test results from this study was the early detection of cracks in the steel structure of the bridge, as well as stopping their propagation, thereby increasing the overall public safety of the bridge.

Fatigue cracks were mostly repaired by drilling stop holes in both the base material and the welds, see Fig. 9. However, the repair of penetration cracks in welded joints required the previous removal of cracks by grooving, after which repair welding was performed. The repair welds were hammer peened to improve the fatigue resistance of the welds.

The theoretical assumption that fatigue cracks occur on similar details of a steel bridge, i.e. when a crack is identified on one detail, it is certain that other similar details will also have such cracks, was confirmed in this analysis [16].

6. CONCLUSIONS

The main findings of this study can be summarized as follows:

- Fatigue cracks in the cross member and welded joints were attributed to increased loading of the bridge structure.
- Based on the obtained results, it was recommended that the repaired fatigue cracks be periodically inspected at six-month intervals to monitor their propagation. In addition, further preventive measures were proposed to mitigate the risk of crack growth and ensure the long-term structural integrity of the bridge.

ACKNOWLEDGEMENTS

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