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Structural Integrity – Historical developments through millennia

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Abstract

In this contribution, historical aspects through millennia of structural integrity development are presented, starting from the Great Pyramids in antient Egypt. Special attention is paid to the history of bridges, made of wood and stone in antient and medieval time, then from different kinds of iron and steel following the first Industrial revolution and finally by concrete, be it reinforced or pre-stresses, in modern times. The focus of this contribution is on bridges restoration, reconstruction and preservation as part of the world heritage. Two case studies are described, the old stone bridge in Mostar (Bosnia and Herzegovina) and a historical iron bridge in Transylvania (Romania). In the second case structural integrity analysis was performed in the form of Engineering Critical Assessment, to provide a solution for retrofitting the historical riveted steel bridge. This paper is dedicated to the memory of Prof. Stojan Sedmak (1929-2014), one of the fathers of the fracture mechanics in Southeast Europe. Motivation for our research is the paper published 12 years ago on the significance and applicability of structural integrity assessment, Sedmak et al (2012), which was based on the presentation at the Tenth Meeting "New Trends in Fatigue and Fracture" (NT2F10) in Metz, France, 2010.

Keywords: structural integrity; bridges; Engineering Critical Assessment; Failure Assessment Diagram

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1. Introduction

Great pyramids in Egypt are certainly the best starting point to illustrate men's ingenuity in sense of structural integrity, Sedmak et al (2012), Sedmak et al (2020). They were built earlier than 4.5 thousand years. With its 146.6 m the Great Pyramid was the tallest man-made structure in the world until the 1880-ies, when the Washington monument (USA), Cologne Cathedral (Germany) and Eiffel Tower (France) were built. According to official estimates, 2.300.000

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stone blocks with an average weight of 2.5 ton were used, total weigh being about 5.75 Mtons. Great pyramid of Giza (Egypt) is still an integral object, constructed for unlimited life, exposed only to its own weight load and environment. Anyhow, one should also notice that more than 2 centuries of development were needed for such a remarkable achievement, since the first attempts were not successful ones, e.g., Sakkara pyramids (Egypt) (2750 BC) made of soil, which could not sustain its own weight.

Many centuries have passed in the meantime, with other remarkable achievements (Roman pantheon, Hagia Sophia (Turkey), Eiffel tower, Empire state building (USA), Sedmak et al (2020)) leading to another great achievement in the sense of structural integrity – the world tallest building, Burj Khalifa (United Arab Emirates), being the closest ever to fulfil old dream of reaching the stars.

Here, special attention is paid to the history of bridges, made of wood and stone in antient and medieval time, from different kinds of iron and steel following the first Industrial revolution and finally by concrete, be it reinforced or pre-stresses, in modern times, with a focus on their restoration, reconstruction and preservation as being part of the world heritage. Two case studies are described, the old stone bridge in Mostar (Bosnia Herzegovina) and a historical iron bridge in Transylvania (Romania). In the second case a structural integrity analysis was performed in the form of Engineering Critical Assessment, Radu et al (2022), Jeremić et al (2021), Kačmarčić et al (2021), Kirin et al (2020), Mijatović et al (2019), Arsić et al (2021), Radu et al (2020), Radu et al (2018), Neggaz et al (2020), Sedmak et al (2020), Golubović et al (2018), Sedmak et al (2010), Zaidi et al (2022), to provide a solution for retrofitting the historical riveted steel bridge by using the fracture mechanics' approach.

2. Methods: overview of Bridges construction history and selection of case studies

Bridges often show ingenuity of their builders since they are rarely simple structures from design and structural integrity point of view. The first bridges were made of stone and wood, the simplest ones being wooden boulders placed over a stream. The oldest stone bridge still in use, (https://www.oldest.org/structures/bridges/), often called Caravan Bridge, dated from 850 BC, was built in Izmir (Turkey), to cross River Meles, Fig. 1. One can see that so-called Roman arch was actually used even before the Roman Empire.

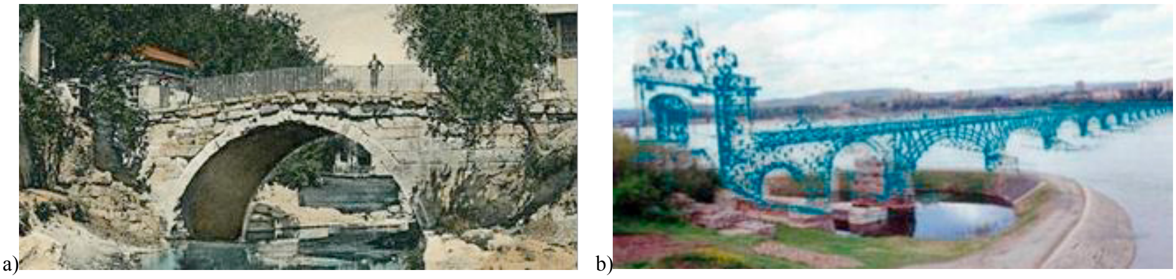

Fig. 1. (a) The oldest stone bridge – Caravan bridge in Izmir; (b) holographic presentation of Trajan's bridge over Danube.

The first bridge with a significant span was antient Roman bridge over the Danube, being a remarkable achievement in the early II century A.D, during Trajan reign. It was a segmental arch bridge, as shown in holographic projects in Fig. 1b, with total length 1135 m, representing one of the greatest achievements of antient Roman engineering, Fernandez et al (2023). Wooden arches with span 38 m, set on twenty brick masonry pillars, mortar, and pozzolana cement, were used, Fernandez et al (2023), O'Connor et al (1993), Ulrich et al (2007), Griggs et al (2007). In IV century it was surpassed in length by the legendary Constantine's Bridge (actually its existence is not proved yet), with total length 2,437 m, built in the same way at the lower Danube, using stone piers and wooden arches. Since wooden construction could not survive for a long time, both bridges were destroyed before the end of the IV century.

Another important achievement was from the XVI century, when the old bridge in Mostar, Fig. 2a, was built by Mimar Hayruddin to replace wooden bridge (https://en.wikipedia.org/wiki/Stari_Most), Andrejević et al (1990), Goodwin et al (1971). Other than the inscription on the bridge (1557-1566), nothing is preserved in writing. It was the widest man-made arch in the world at the time, with the span 30 m, made from mortar with egg whites. From the structural integrity point of view, it was a bit of a mystery how the bridge could sustain its own estimated weight, before young scientists, Aleksandar Vesic, from the University of Belgrade, proved in his D.Sc. thesis that the bridge was hollow and thus much lighter than previously thought Vesić et al (1956). Anyhow, longer spans and larger bridges required use of metal, starting with the first Industrial revolution Sedmak et al (2012), Sedmak et al (2020) , and different type of concrete later on, with total length over 100 Km. The old stone bridge is presented here as an excellent example how historical constructions should be preserved and even rebuilt after their destruction, as explained in the following text. The other case study is the road steel bridge in Romania, almost 100 years old, with a solution for consolidation and retrofitting, taking into account structural integrity assessment, which might be considered as the basis for other similar bridges.

3. Results

3.1 Case study 1 – old stone bridge in Mostar

The old stone bridge replaced even older wooden suspension bridge of dubious stability. Little is known about the construction of the bridge, since all that has been preserved is the name of the builder, Mimar Hayruddin. Upon its completion it was the widest man-made arch in the world. The 17th Century Ottoman explorer Evliya Çelebi wrote that the bridge "*is like a rainbow arch soaring up to the skies, extending from one cliff to the other... I, a poor and miserable slave of Allah, have passed through 16 countries, but I have never seen such a high bridge. It is thrown from rock to rock as high as the sky*." Muravljov et al (2011). Significant works was done in 1953-1955 to preserve the bridge from further damage, Muravljov et al (2011), as shown schematically in Fig. 2b and 2c.

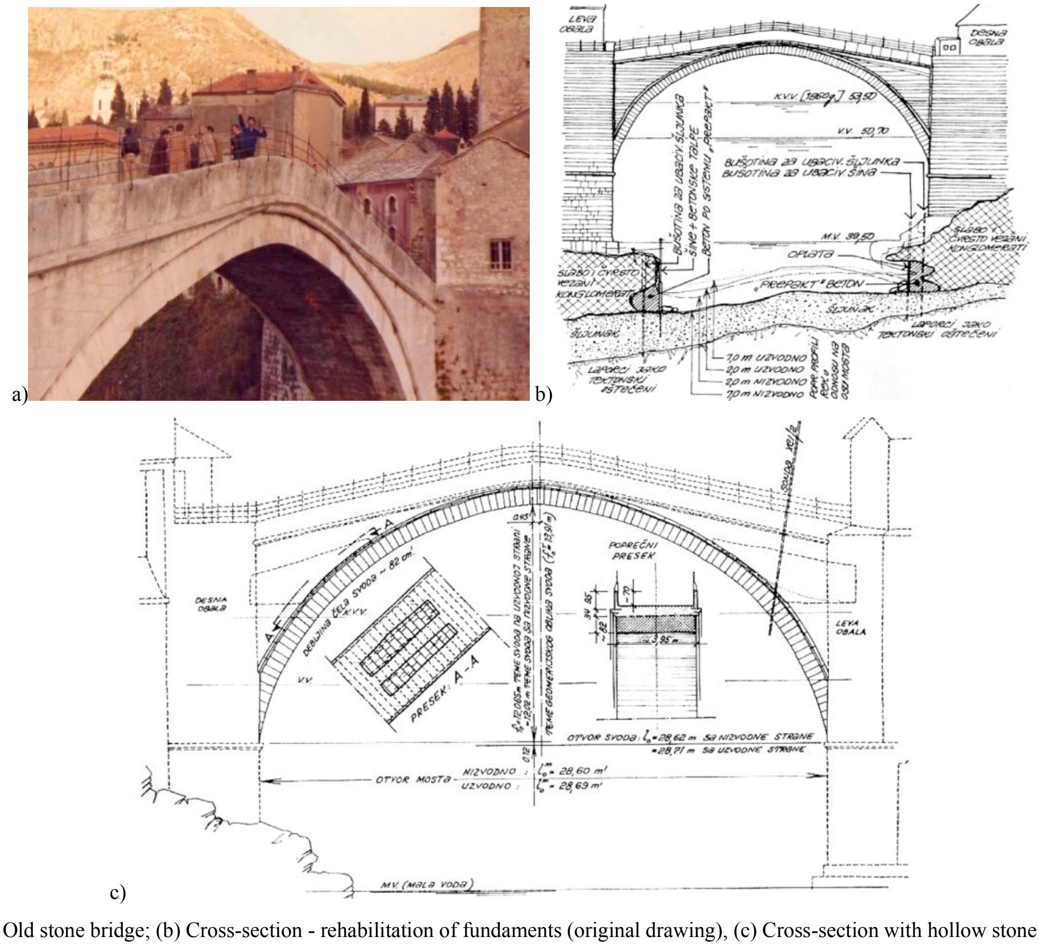

Fig. 2. (a) Old stone bridge; (b) Cross-section - rehabilitation of fundaments (original drawing), (c) Cross-section with hollow stones (original)

The most important work performed during 1953-1955 was on the rehabilitation of the foundations in order "to really secure the building for many years", Muravljov et al (2011). To this end, the project provided for the closing of the cavities on the side of the river with combined steel-wooden formwork (later replaced with reinforced concrete slabs), and then for the concreting to be carried out underwater in those underlain areas. This was made according to a special procedure, whereby the first was inserted gravel of a certain granulation was placed in the areas for concreting, and then it was bound by means of injection. Together with other procedures, this is an excellent example of successful restoration and preservation works.

The old stone bridge was destroyed 1993 during the war in Bosnia and Hercegovina, (https://en.wikipedia.org/wiki/Stari_Most#:~:text=Stari%20Most%20(Serbo%2DCroatian%3A,two%20parts%20of%20the%20city). In October 1998, UNESCO established an international committee of experts to oversee the design and reconst-ruction work, Amaly et al (2004). It was decided to build a bridge as similar as possible to the original, using the same technology and materials, Amaly et al (2004), providing one option how to rehabilitate important heritage structures.

3.2 Case study 2 – historical bridge in Transylvania

Road steel bridge in Transylvania was built almost 100 years ago (around 1925), Fig. 3a. Solution for consolidation and retrofitting of the bridge is presented here, taking into account structural integrity assessment. Critical values of crack-like flaws were determined for each case type using the Failure Assessment Diagram (FAD). These values are used as limit values for fatigue assessment based on fracture mechanics principles, to determine the number of cycles for a crack to extend from initial to critical dimension, i.e., failure, being nowadays standard procedure for remaining life evaluation, Golubović et al (2018). Here, we present Structural analysis of the existing bridge, Structural analysis of the proposed solution - retrofitted bridge, Engineering Critical Assessment considering most common possible discovered flaws (crack like type) and Fatigue assessment. The bridge is a riveted type, Fig. b, and has a parabolic truss main beam structure, with descending diagonals and an opening of L = 27.86 m, Fig. 3c. Figure 3d presents a few cross-sectional cuts. In order to strengthen the supporting structure, the new one is proposed, with a transversal beam, with main beam box girder 600x1800 mm, S355, as shown in Fig. 4.

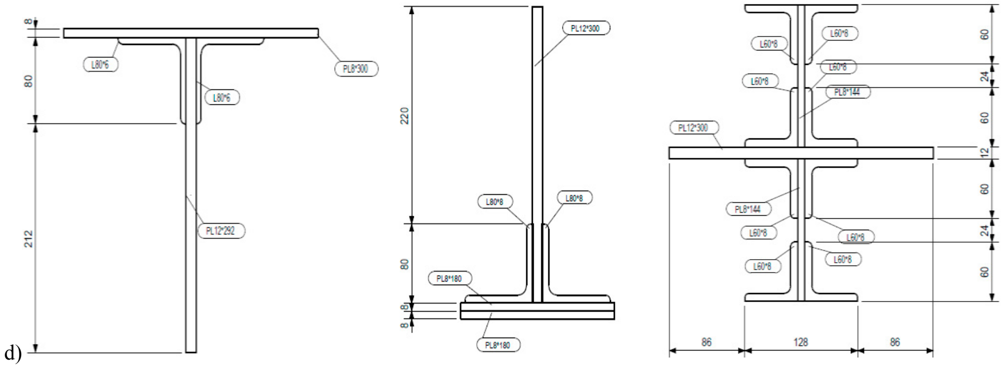

Fig. 3. (a) Historical bridge in Transylvania; (b) riveted joints (c) scheme of supporting structure, (d) cross-sections

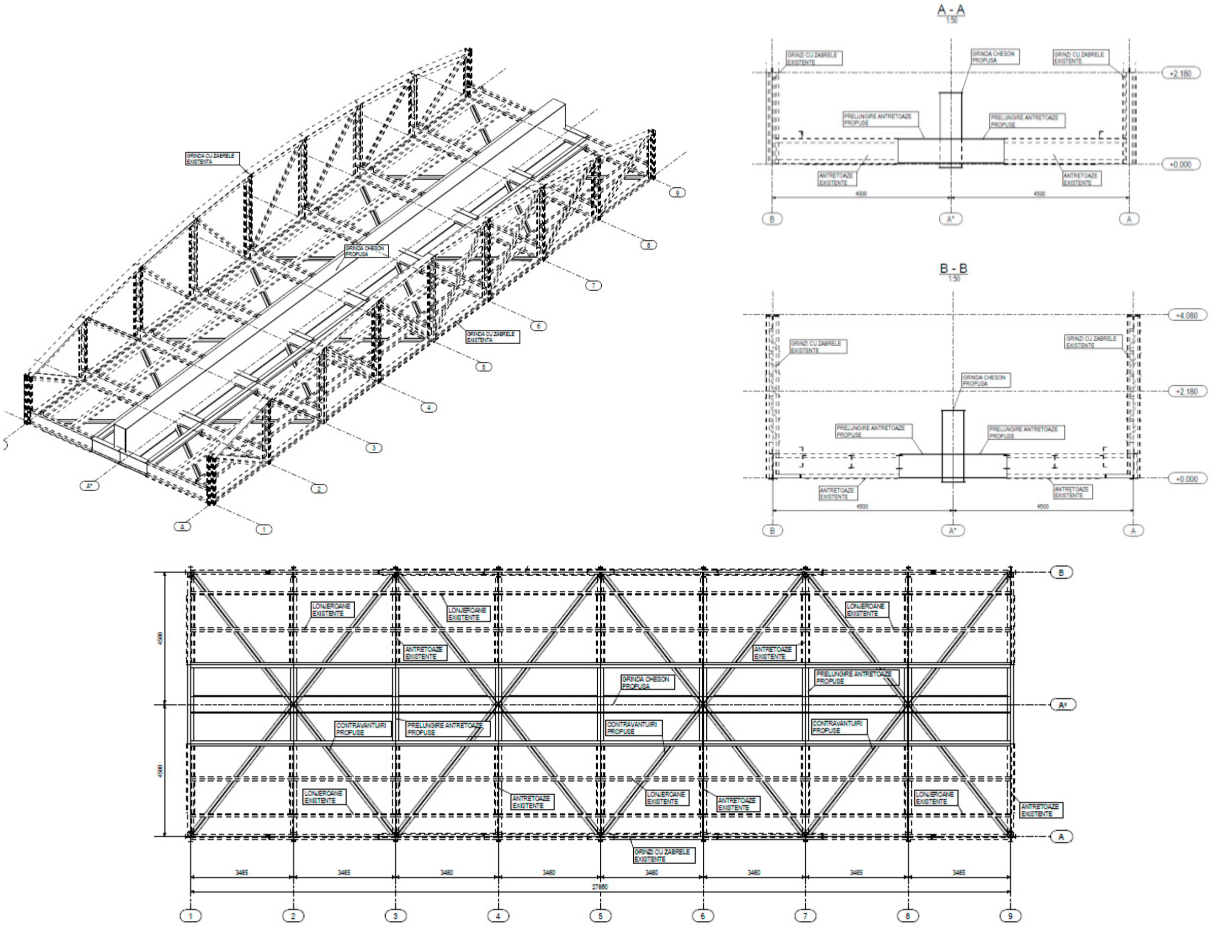

Figure 4. Proposed new structure with a transversal beam.

Finite element analysis was used for both existing and proposed rehabilitated structure in order to determine the stresses in the elements, as shown in Fig. 5a for the existing structure, and in Fig. 5b for the proposed one.

Comparison between stresses in the existing structure ("old") and proposed one ("new") is shown in Table 1. One can see that the highest stress value the existing structure (183.2 MPa) is reduced to 162.2 MPa in the new one, whereas the maximum stress is shifted to the deck main beam (291.8 MPa), which should be made of much stronger material than the original one (e.g., S355 steel type).

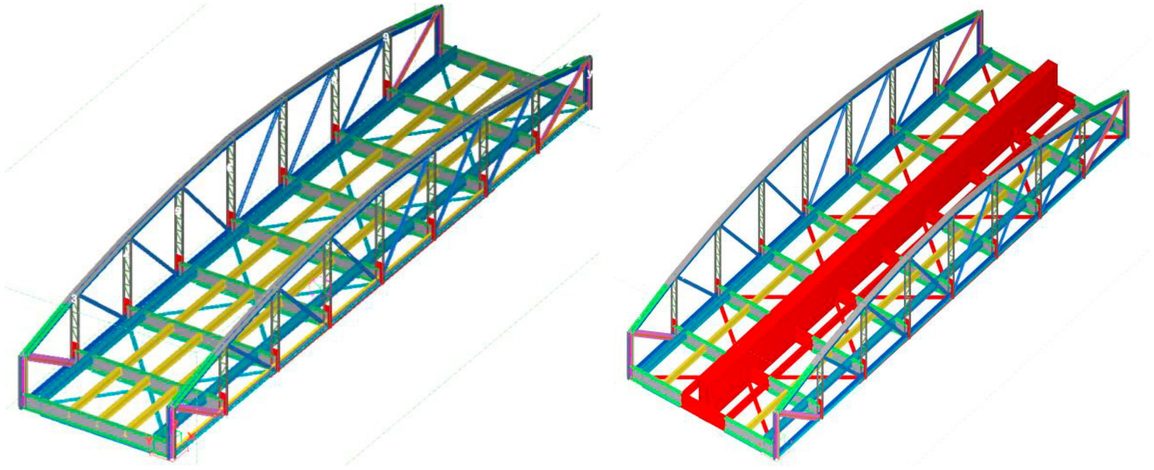

Figure 5. Stresses in a) Existing structure, b) Proposed new structure with a transversal beam.

Table 1. Stresses in “new” and “old” structure

Stresses - FEM analysis	**New structure**	**Existing structure**
Element	σ [MPa]	σ [MPa]
Main truss beam - lower chord	162.2	183.2
Main truss beam - upper chord	102.3	115.5
Main truss beam - diagonal 1	112.1	135.5
Main truss beam - diagonal 2	95.2	115.2
Main truss beam - diagonal 3	55.5	85.5
Main truss beam - diagonal 4	35.2	60.2
Deck transversal beam	285.3	115.1
Deck secondary beam	115.2	85.2
Deck main beam	291.8	N/A

3.2.1 Assessment of defects using ECA

An Engineering Critical Assessment (ECA) can be used during design, to assist in the choice of used details, during fabrication, to assess the significance of known defects which are unacceptable according to standards/fabrication codes and during operation/service, to assess flaws found in service and to make decisions as to whether they can safely remain, or whether down-rating/repair are necessary. In the first phase ECA determines the acceptability of the detected cracks in the structural element, while in the second one fatigue life is assessed for the elements containing cracks based on loading events history.

Starting point in static analysis is the Failure Assessment Diagram (FAD), levels 1-3, Radu et al (2022). Here, the level 2 is used to determine the stress distribution in the proximity of the flaws, represented by membrane – P_m, P_b, and bending stress components, Q_m and Q_b, Radu et al (2022) Then, the fracture ratio K_r is determined by equation (1):

$$K_r = K_I / K_{mat} \qquad (1)$$

where K_I is the stress intensity factor, and K_{mat} material property, typically the fracture toughness, K_{Ic}. Using the following formula for stress intensity factor

$$K_I = (Y\sigma)\cdot(\pi a)^{1/2} \qquad (2).$$

K_r can be calculated, if K_{mat} is known. Thereby, Y is geometry factor, σ is remote stress, *a* is crack length. Finally, the stress ratio L_r is determined according to equation (3):

$$L_r = \sigma_{ref} / \sigma_Y \qquad (3),$$

where σ_{ref} is the net stress in the crack cross-section, and σ_Y is the yield stress. The points of assessment are then represented graphically in (K_r, L_r) coordinates in the FAD level 2. In the case of existing structure, an edge crack-like flaw is considered as the most dangerous, Fig. 6a, with dimensions B=25 mm, W=120 mm, $2a_0$=30 mm.

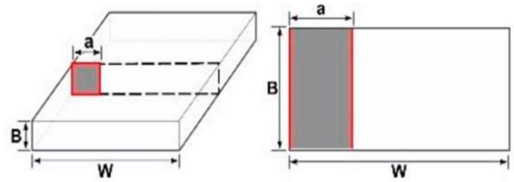

Figure 6. Geometry of an edge crack

Other data needed for the ECA is: σ_Y = 215 MPa; σ_m (ultimate tensile strength) = 375 MPa, K_{mat}=71.8 MPa·√m (SINTAP procedure), P_m = Primary stress – according to the structural analysis, P_b = 0, Q_m=0, Q_b=0. The point with coordinates (L_r, K_r) is shown in Fig. 7, together with 4 other points, considered elsewhere, Radu et al (2022). From this analysis one can find out the critical length of a through thickness flaw in area nearby the rivet (FP-TTF-5) to be less than assumed 30 mm, i.e., 28.408 mm.

3.2.2 Fatigue life assessment

The needed data are: Stress ranges, Limits of the crack growth (FAD), Fatigue crack grow law (one slope or two stages) and types and dimensions of the flaw, Radu et al (2022). Load spectrum for a given time is obtained from the distribution of the loads rearranged following a probability density function (PDF) using Weibull Distribution. Using Rainflow algorithm, the results were processed and was determined the block of stresses with stress ranges ($\Delta\sigma_i$) and the appearance frequency (n_i), Fig. 8.

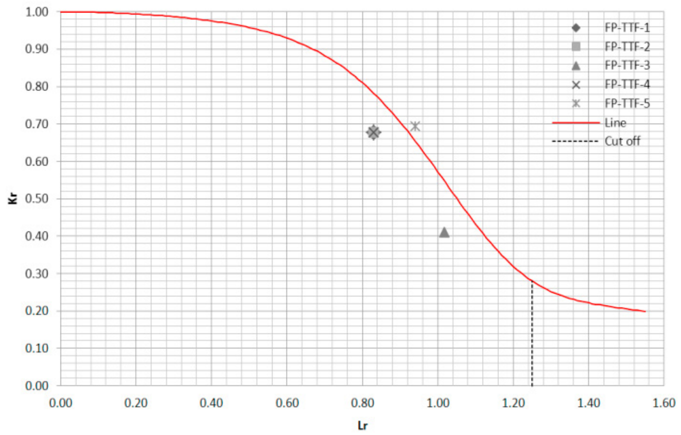

Figure 7. FAD, level 2, for the existing structure

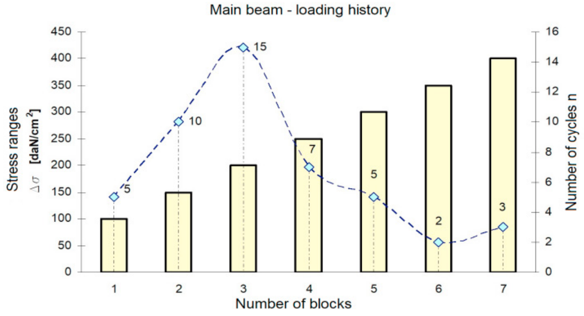

Figure 8. Stress range vs. number of blocks of different stress ranges

As in the case of static loading, 4 types of flaws were analysed and presented in Radu et al (2022), while here we present briefly the crack of initial length 5 mm to grow up to 7.5 mm, resulting in cca. 16 years of remaining life.

4. Discussion and conclusions

Solution for retrofitting an existing historical riveted steel bridge was considered using the fracture mechanics approach – Engineering Critical Assessment for the proposed structure.

The proposed solution maintains the bridge in operation and allows the unrestricted traffic of current convoys. Thus, the current deck is maintained in combination with a new deck in the central area consisting of a main beam (box girder type that takes up approximately ½ of the traffic loads), the beam of which are rigidly fixed the spacers that join part of the existing spacers on the current truss beams, so as to result in two distinct traffic lanes (approximately 4.0-4.25 m per each way), separated from each other by the newly added box girder beam.

It was shown that the critical crack length is 28.408 mm for static loading, whereas the remaining life for the crack of initial length of 5 mm, to grow up to 7.5 mm under typical amplitude loading, was estimated to 16 years.

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