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Residual life of a historic riveted steel bridge - engineering critical assessment approach

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Abstract

Sustainability has become an increasingly important component of requirements for the rehabilitation of bridge structures. Responsible use of our limited natural resources is essential for future generations, so the whole bridge rehabilitation process must be taken into account, in terms of structural integrity. The environmental impact for these types of structures is major – demolition and reconsideration of e.g. reinforced concrete structure being examples of poor management of resources and energy. On the existing roads and railways network steel bridges with more than 100 years in service lifetime are numerous. The in-service safety assessment of these structures is a complex problem. This article emphasizes the importance of rehabilitating the structure of existing steel bridges, considering the historical monument character of these structures, as well as the reuse of existing structures, part of sustainable development. The paper is presenting a study case for an historical riveted steel bridge build in the beginning of twentieth century, with an assessment method considering the structural integrity by means of fracture mechanics.

Keywords: historical steel bridges, structural integrity, fracture mechanics.

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1. Introduction

Nowadays, considering the sustainability requirement, the establishing the remaining in-service life of existing steel structures, is one of the most important matter. The re-use of existing steel structures is an actual concept strongly correlated with sustainability. When old structures are not more able to fulfil the present needs, the re-use concept can give them a second life regarding the sustainable concept of development.

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Nomenclature

a	half flaw length for through-thickness flaw, flaw height for surface flaw or half height for embedded flaw
a_0	initial crack length
a_{cr}	final crack length resulted in base of an assessment with Failure Assessment Diagrams
B	section thickness in plane of flaw
C	Paris material constant
D	the accumulated damage
da/dN	crack growth rate (mm/cycle)
m	Paris exponent
N	number of cycles
γ_{Ff}	safety factor for the loads/action forces
$\Delta\sigma_D$	threshold value of the fatigue resistance based on the considered detail.
$\Delta\sigma_i$	stress blocks in the in-service time period
W	plate width in plane of flaw
ΔK	stress intensity factor (SIF) range
ECA	Engineering critical assessment

The re-use of existing (old) structures must be conceived in accordance with all the interested factors, in order to assure safety and efficiency; the chosen technical solution must also comply with others criteria such as structural robustness, economics and easy execution (Radu et al. 2017).

When bridges reach the end of their design life, deconstruction is necessary (figure 1). Assessment of existing bridges is correlated to environmental sustainability. It means the selective dismantling of the structure, as the bridge can no longer be maintained in operation. The structure can be re-used after renewal or reconstruction and materials resulted from demolition can be then recycled.

Strengthening of the structure is the most environmentally and economically efficient option, practically giving the bridge a new life. Sustainability and energy efficiency are important building policy goals. Construction and re-use criteria should be both ecologically compatible and be economically acceptable and socio-culturally appropriate.

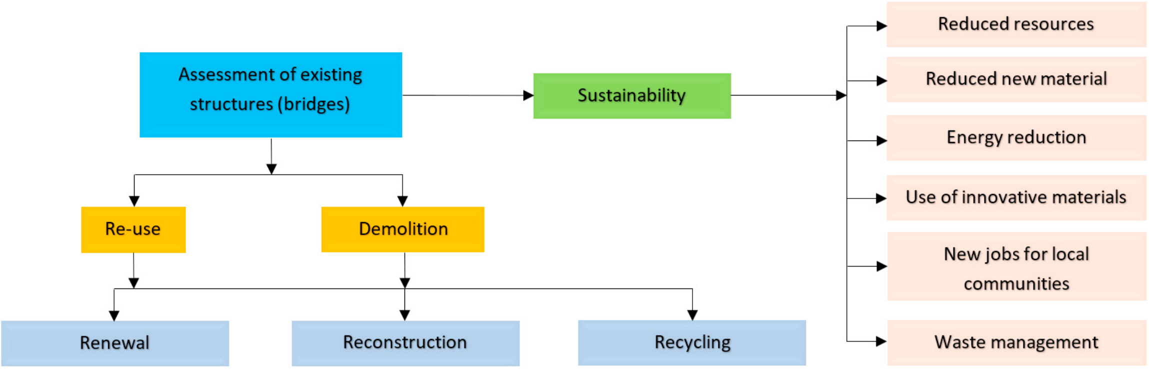


Fig. 1. Corelation between the assessment of the existing steel bridges and sustainability

On the existing roads and railways network steel bridges with more than 100 years in service lifetime are numerous. The in-service safety assessment of these structures is a complex problem with an interdisciplinary approach. A first step was the applying of Palmgren-Langer-Miner relation for linear damage cumulation criteria (Miner 1945). Then the applying of fracture mechanics principles was a step forward – evaluation of the existing structures by means of engineering critical assessment (ECA) (Radu et al. 2022), as one option in the scope of broader approach, structural integrity assessment, (Neggaz et al. 2020, Kačmarčik et al. 2021, Pilic et al, 2019, Mijatovic et al. 2019).

2. Fatigue life of the existing steel road bridges

The procedure for fatigue life assessment of the existing steel bridges has four levels (EN 1993-1-9): 1) a general checking for fatigue; 2) a fatigue checking under service loads; 3) a further checking using fracture mechanics principles and 4) an in-depth checking - applying fracture mechanics based on values obtain on site.

Level 1 – Fatigue checking

$$\gamma_{Ff} \cdot max\Delta\sigma \leq \frac{\Delta\sigma_D}{\gamma_{Mf}} \tag{1}$$

where: γ_{Ff} is the safety factor for the loads/action forces (usually taken 1.00), γ_{Mf} is the safety factor of the material (according with EC3 equals between 1.00 and 1.35) and $max\Delta\sigma$ is the maximum stress block induced by the convoy.

This checking is overconservative, considering that the $max\Delta\sigma$ appears relatively rare. Usually, the level 1 is considered together with level 2 checking.

Level 2 – Fatigue checking under service loads

$$D = \sum \frac{n_i}{N_i} \leq 1 \tag{2}$$

where n_i is the number of the $\Delta\sigma_i$ stress blocks in the in-service time period (stress spectrum) and N_i is the maximum number of cycles of intensity $\gamma_{Ff}\Delta\sigma_i$ for the considered detail, respectively following Wöhler curves reduced with γ_{Mf}.

If the condition (2) is not fulfilled due to the fact that the in-service loads history could not have been obtain, or if D > 1.00 (overconservative D > 0.80), then it is recommended a fracture mechanics assessment (EN 1993-1-9). If following the visual inspection if the structure, there are discovered crack like flaws or other type of defects, it is mandatory to adopt a fracture mechanics assessment (level 3 or 4).

Level 3 – using fracture mechanics

The assessment method of the structural elements with cracks was developed on the modelling possibility with known laws for crack increasing dimension process in fatigue loading. This method is based on the BS 7910/2013 (BS7910/2013) being adapted for the case of steel road bridges.

In order to have a crack propagation and extension, it is needed that conditions (3-4) are fulfilled.

$$K_{max} \leq \frac{K_c}{\gamma_{Mf}} \tag{3}$$

$$(\Delta K)_{max} \leq \frac{(\Delta K)_c}{\gamma_{Mf}} \tag{4}$$

where stress intensity factor K_{max} is calculated with the following relation:

$$K_{max} = \sqrt{\pi \cdot a} \cdot \sigma_{max} \cdot y(a) \tag{5}$$

where a is the length of the crack-like flaw.

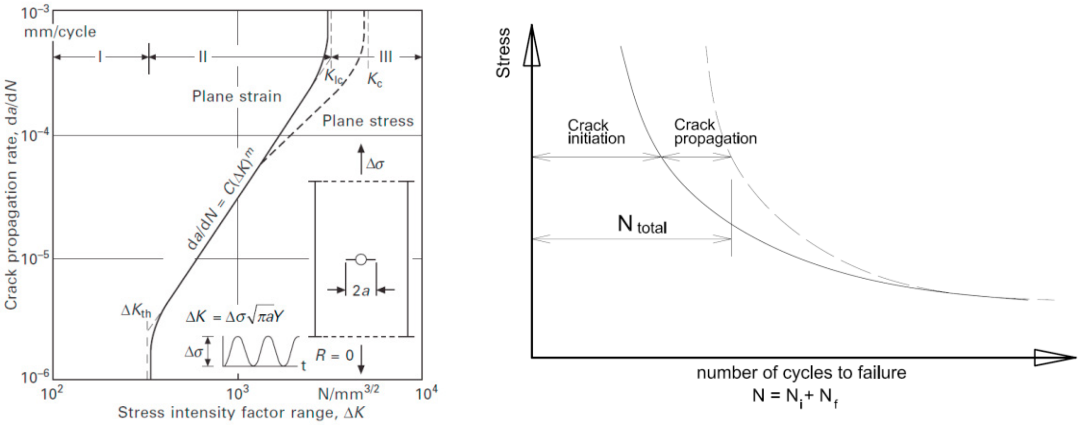
The crack propagation rate can be calculated following Paris law for crack growth (zone II in figure 2).

$$\frac{da}{dN} = C(\Delta K^m - \Delta K_{th}^m) \tag{6}$$

In relation (6) *C* and *m* are the material constants (determined by tests) and ΔK depends on the flaw geometry and stress level:

$$\Delta K = \sqrt{\pi \cdot a} \cdot \Delta\sigma \cdot Y(a) \tag{7}$$

In relation (6), ΔK_{th} represents the threshold value beneath which the crack will not advance (Paris curve – zone I) where K_c is the fracture thoughness of the material and ΔK_c is the critical stress intensity block. If the condition (3) is not fulfilled, the level 4 should be adopted.



(a) (b)

Fig. 2. (a) Paris law for extension of a crack; (b) number of cycles in the crack growth process (Hobbacher 2009)

Level 4 of checking – Applying fracture mechanics based on values obtain on site

The measurements refer to material properties parameters (stress intensity factor and crack propagation speed parameters) and to the real values of the structure stresses based on loading events.

3. Determining the in-service safety of the existing steel bridges based on fracture mechanics principles

The methodology presented in the previous chapter, needed for determining the acceptability of the assessed flaws (cracks) in the steel structures/steel bridges, is followed by a fatigue assessment of the elements containing cracks. This phase is imposed due to the fact that steel road bridges are subject to cyclic loads. Discovered and assessed defects (cracks) which initially were considered acceptable, may increase up to the failure of a component, and in the lack of redundancy, the entire structure may be subject to failure. In these conditions, it is important to know the time period in which the structure can operate in safety conditions without failure / collapse.

Fatigue crack growth calculation methodology is based on the crack type flaw dimension increasing in a cycle loading and determining the number of cycles N from the initial crack a_0 to the critical crack dimension a_{cr}. The analysis is using all the fracture assessment data (geometry of the flaw/crack, fracture mechanics parameters, flow critical dimension, etc.).

3.1. Case study – 1925 rivetted steel bridge

The bridge is a rivetted type, build around year 1925 in Transylvania and from the geometry point of view, having a parabolic truss main beam structure, with a span of L = 27.00 m and a width of 6.25 m (road for only 5.25 m). The structure is similar to other bridges built in the same period: heavy deck (with pavers) consisting of Zores profiles arranged on a network of beams consisting of stringers and cross girders with a bracing system ensuring the spatial stability of the structure. The elements are made of composed cross section – L type profiles with additional steel plates (figure 3).

Regarding the fracture mechanics material properties, following Charpy test and SINTAP procedure (Zerbst et al 2007 and Bannister 1998) the needed data were determined, including the material fracture toughness, K_{mat} = 71.8 MPa·m$^{1/2}$.

The phases of the study are taken into account the existing and the proposed structure as following:

- structural analysis of the existing bridge
- structural analysis of the proposed solution - retrofitted bridge
- Engineering Critical Assessment considering discovered flaws
- fatigue assessment

Due to bridge condition and the lack of maintenance, the most frequent flaw type discovered after visual inspected the structure, was the surface type flaw (figure 3 and 4).

Fig. 3. Existing structure – views and joints details

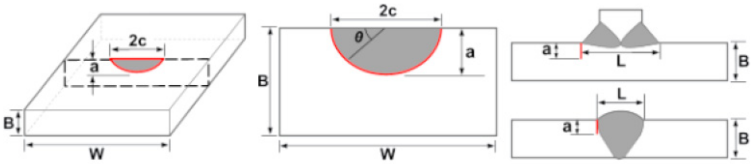


Fig. 4. Surface flaws – geometry.

In this way, an assessment was needed in order to evaluate the importance of the discovered flaws in the behaviour of the whole structure. Being a non-redundant type structure, the existing of flaws/crack like type flaws, was an important matter for overall behaviour of the structure and for the decision for keeping in service the bridge.

The input data for geometry includes type of geometry, type of flaw, weld profile, maximum misalignment, wall thickness *B*, width or length *W*, radius, flaw height *a*, and flaw length *2c* (figure 4). Stress Intensity Factor (SIF) and reference stress solution depend on the type of flaw and geometry.

The assessment is summarized in following steps (Radu et al. 2022): the determination of the cyclic stress range; the determination of the flaw normal to maximum principal stress; the defining of the flaw dimensions; the determination of the crack growth limit.

Considering the real case assessment level 2 – Failure Assessment Diagrams - FAD-2 (BS7910/2013) there were done assessments on different flaws type and flaws position (table 2), with surface flaws (SF), the dimensions and the FAD 2 results are presented in table 2.

Table 1. Description of the flaws.

Case no.	Name	Description of the flaw
Case 1	FP-SF-1	Surface flaw nearby the rivet - diagonal
Case 2	FP-SF-2	Surface flaw in the lower chord
Case 3	FP-SF-3	Surface flaw in the upper chord
Case 4	FP-SF-4	Surface flaw in the longitudinal girder
Case 5	FP-SF-5	Surface flaw in the transversal girder

Table 2. Failure Assessment Diagrams results.

Case	B	W	2a	a	2c	L_r	K_r
	mm	*mm*	*mm*	*mm*	*mm*		
FP-SF-1	12	80		3	10	0.8330	0.4183
FP-SF-2	15	300		5	30	0.7429	0.3899
FP-SF-3	10	300		5	10	0.7125	0.2808
FP-SF-4	15	200		5	30	0.7644	0.3965
FP-SF-5	15	120		5	20	1.026	0.5153

Five types of flaws were assessed – flat plate surface type flaws in the first diagonal of the main truss beam, in the lower chord of the truss, in the upper chord, in the longitudinal and transversal girder (table 1 and 2). For this assessment, cyclic loading was used (EN 1991-2), as a block independent iterative solver – applying the specified stress ranges sequentially line by line, repeating the entire cyclic loading - entire group of cycles for a number of blocks, one block representing all the applied cycles of stress ranges, (Grbović et al 2019, Arsić et al 2021, Jeremić et al 2021). It resulted in the number of cycles until reaching the critical flaw dimension (length or height). A comparison was made between groups of flaws, in order to detect and underline the most critical flaws in term of fast crack growth and number of cycles until reaching the critical dimensions – remaining in service life time. Thus, the FP-SF5 resulted the most critical type one – from a_0 = 5 mm surface flaw (of 20 mm length) in the transversal girder, the flaw will extend to a critical crack value of 9.2 mm in 24 years (figure 5 & 6).

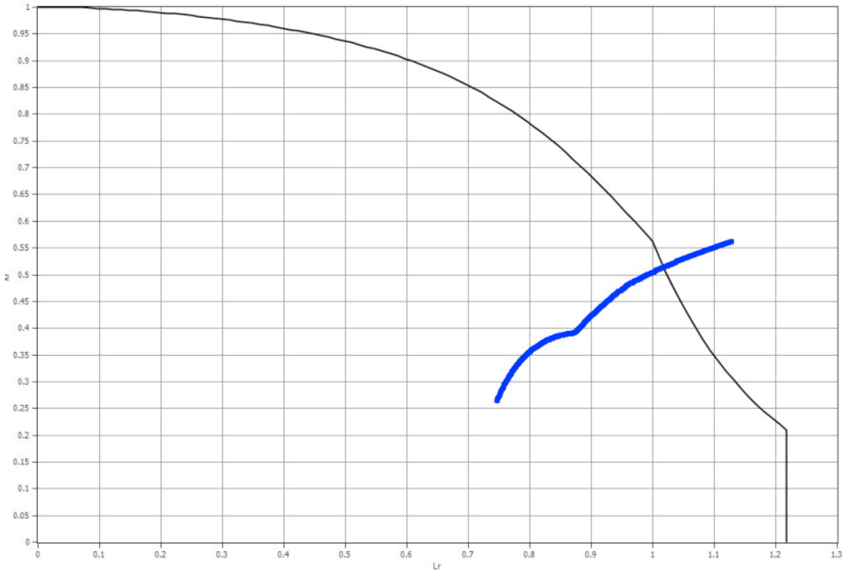


Fig. 5. FP-SF-5 results. Sensitivity Parameter Flaw Height a = 9.2 mm.

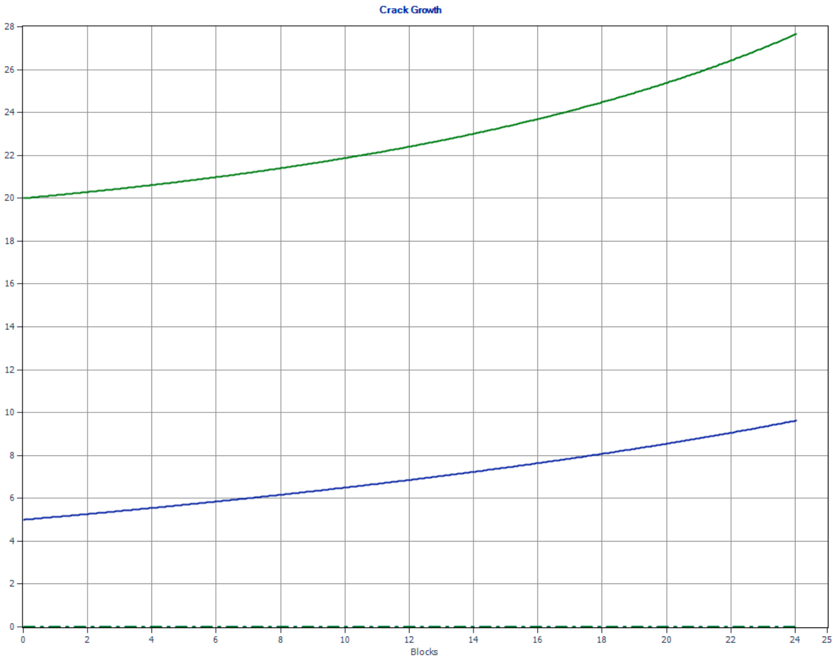


Fig. 6. FP-SF-5 results. Flaw will extend to a critical crack value of 9.2 mm in 24 years (blocks=years).

4. Conclusions

The paper presented a study case – a 1925 historical rivetted steel bridge in Transylvania region, which is assessed by means of fracture mechanics, following surface discovered flaws.

The algorithm of the evaluation methodology can be applied in other existing bridges, especially the historical ones, in order to assess the implications of the flaws (Kirin 2020, Sedmak 2022, Zaidi 2022). The evaluation can be made for different types of flaws from crack like type, edge or through thickness type, up to embedded or surface flaw ones.

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