Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 37 (2022) 771–778

Structural Integrity Procedia

www.elsevier.com/locate/procedia

ICSI 2021 The 4th International Conference on Structural Integrity

Solution for consolidation and retrofitting a historical steel bridge

Dorin Radu[a,]*, Radu Băncilă[b], Dorel Bolduş[b], Simon Sedmak[c], Mihajlo Aranđelović[c]

[a]*Faculty of Civil Engineering, Transilvania University of Brașov, Romania*
[b]*Faculty of Civil Engineering, Politehnica University of Timişoara, Romania*
[c]*Innovation Center of the Faculty of Mechanical Engineering, Belgrade, Serbia*

Abstract

Sustainable development is a fundamental goal of the European Union and seeks to meet the needs of the present, without compromising the future. The rehabilitation of historic steel constructions and old steel bridges in service, is part of the maintenance and conservation of existing heritage, thus considering a sustainable development concept, while constituting an act of culture.

In present time, in Romania there are a relatively small number of steel bridges older than 100 years, especially in Transylvania region; they can be considered "*witnesses of the past*". Two important aspects are highlighted: consolidation costs are lower than for a new structure and the retrofitted bridge can receive a new, modern functional role that fits functionally into the landscape. The paper is presenting a study case for an existing steel bridge build in the beginning of twentieth century (around year 1925). There are presented solution for consolidation of the bridge and retrofitting, taken into account fatigue design and structural integrity assessment. Critical flaws values were determined for each case type using the failure assessment diagrams. These values are used as limit values for fatigue analysis based on fracture mechanics principles, to determine the number of cycles for a crack to extend from initial to critical dimension, i.e. failure. For the assessment was used the code cyclic loading 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).

Keywords: Structural integrity; Steel structures, Hystorical steel bridges

---

* Corresponding author. Tel.: +40268 548228; fax: +40268 548378.
E-mail address: dorin.radu@unitbv.ro

10.1016/j.prostr.2022.02.008

1. Introduction

In mechanical engineering application, following fracture mechanics approach, the stress and the flaw (e.g. crack) are considered as the input data prior to the design. Following manufacturing, the service lifetime estimation and the inspection intervals can be known.

In civil engineering structures under low or high cycle fatigue loading, only the stress is considered as an input data for the design. Taken into account the service lifetime requirement (from the give normative/standard) and following the requirements of EN1993-1-9, EN1993-10, the structural design can be achieved. The manufacture/erection of the structure is done respecting the conditions imposed by EN 1090-2. The main issue in this process is the absence of the defect – the flaw appears only at the inspection (visual or NDT), done in accordance with the preset intervals.

Nomenclature

a	half flaw length for through-thickness 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
da/dN	crack growth rate (mm/cycle)
K_I	the stress intensity factor (SIF)
K_{mat}	the fracture toughness
m	Paris exponent
N	number of cycles
P_b	primary bending stress
P_m	primary membrane stress
Q	secondary stress
Q_b	residual bending stress
Q_{tb}	thermal bending stress
Q_{tm}	thermal membrane stress
Q_m	residual membrane stress
σ_{max}	the maximum tensile stress
$(Y\cdot\sigma)_P$	contribution of the main stresses
$(Y\cdot\sigma)_S$	contribution of the secondary stresses
W	plate width in plane of flaw
ΔK	stress intensity factor (SIF) range
FEM	Finite element method
ECA	Engineering critical assessment

For new structures, the EN 1993-1-9 prescribes the design methods of the fatigue resistance for elements and joints under cyclic loads, in function of the number of the stress ranges cycles, the fatigue being divided in two categories: Fatigue at a reduced number of cycles – low cycle fatigue (LCF) and fatigue at high number of cycles – high cycle fatigue (HCF). The LCF mechanism is determined by cyclic plastic deformations, the number of cycles being reduced (up to 10^4). Instead, the HCF mechanism is taken place in elastic domain. The stress concentration factors (constructive details) and the stress ranges are the main parameters which are to be considered in the design. The transition between LCF and HCF is determined by the stress level, i.e. the transition between the plastic and elastic deformations, depending on the ductility of the material. The normative EN 1993-1-9 establish a limit for the stress ranges at $1{,}5\cdot f_y$, thus for HCF, the number of cycles is considered as following relation:

$$N \geq 2 \cdot 10^6 \left(\frac{\Delta\sigma_c}{1.5 \cdot f_y}\right) \qquad (1)$$

These methods are following large scale fatigue tests and numerical simulations which include also the geometrical and structural imperfections which may appear in the manufacturing process or erection itself. The rules are applicable for steels for which the manufacturing is respecting the EN-1090-2 standard.

For existing structures, there is no possibility to check the manufacturing process and Engineering Critical Assessment is a solution for determining the service lifetime limit.

The paper is presenting a study case for an existing steel bridge build in the beginning of twentieth century (around year 1925). There are presented solution for consolidation of the bridge and retrofitting, taken into account fatigue design and structural integrity assessment. Critical flaws values were determined for each case type using the failure assessment diagrams. These values are used as limit values for fatigue analysis based on fracture mechanics principles, to determine the number of cycles for a crack to extend from initial to critical dimension, i.e. failure, Grbović et al. (2019).

2. Case study – beginning of 20th century historical bridge

The study is carried out following the need of the municipality to assess in-service reliability for an existing historical bridge, taken into account a solution for consolidation and retrofitting. It was proposed an assessment for the existing structure in order to evaluate implications of flaws on structural integrity and life.

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 descending diagonals with a span of L = 27.86m and a width of 6.25m (road for only 5.30m). 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 1).

Fig. 1. Existing structure – view and joints details

Regarding the fracture mechanics material properties, following Charpy test and SINTAP procedure (Zerbst et al. 2007 and Bannister et al. 1988) the needed data were determined, including the material fracture toughness, $K_{mat} = 71.8\ MPa{\cdot}m^{1/2}$.

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 (crack like type)
- fatigue assessment

2.1. Structural analysis of the existing and retrofitted structure

The existing and the new structure was analyzed by means of Finite Element Modelling. The results are presented in table 1.

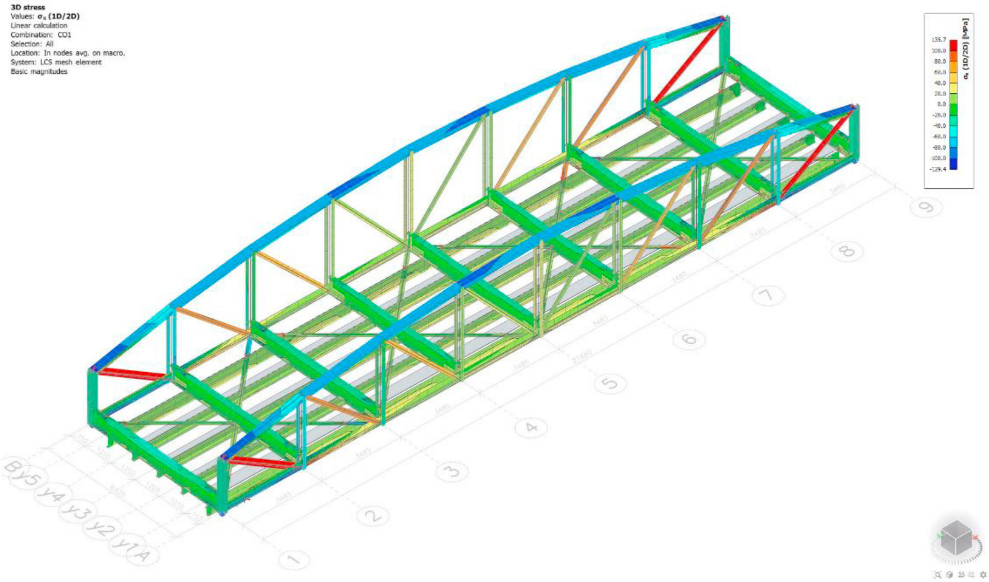

Fig. 2. Analysis results of the existing structure

Regarding the retrofitted structure, it was proposed a solution in order maintain the bridge in service (after the retrofitting), and to avoid traffic restrictions, the future bridge being able to withstand the loads of LM1 type convoy according with Eurocode EN 1991-2:2004. Thus, the existing deck structure is maintained, in the middle of the deck a new deck structures appears, containing a main beam box girder type of 600mm width and 1800mm height with thickness variable from 10mm to 15mm S355 steel type, and new transversal beams connected to the existing beams through an end plate bolted type connection (figure 3). In this way can be assured a two lanes traffic (approximately 4,20m width for each way) without restrictions.

Table 1. Existing and proposed structure - Stress values following FEM analysis

Element	Existing structure	New structure
	σ (*MPa*)	
Main truss beam - lower chord	183.2	162.2
Main truss beam - upper chord	115.5	102.3
Main truss beam - diagonal 1	135.5	112.1
Main truss beam - diagonal 2	115.2	95.2
Main truss beam - diagonal 3	85.5	55.5
Main truss beam - diagonal 4	60.2	35.2
Deck transversal beam	115.1	285.3
Deck secondary beam	85.2	115.2
Deck main beam	-	291.8

Following the FEM analysis it resulted values of the stresses for each structural element. For the existing structure truss beam, the maximum stress appears in the first diagonal (as expected) and in deck cross girders. Considering the new structure (retrofitted), compared with the existing one, the stresses are reduced with approximately 15%. As one can see the new carrier beam (box girder type) is having a high stress ratio ~82% of yielding strength. The results are confirming that the proposed solution is a valid one.

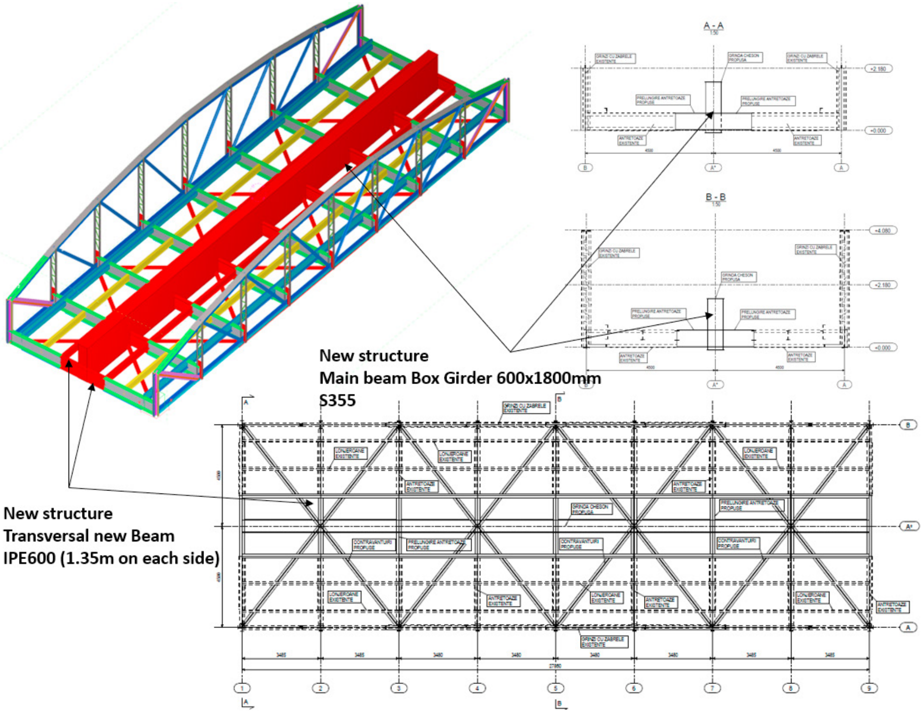

Fig. 3. Proposed structure – consolidation and retrofitting

2.2. Engineering Critical Assessment considering possible discovered flaws

An Engineering Critical Assessment (ECA) is an analysis, based on fracture mechanics principles, of whether or not a given flaw is safe from brittle fracture, fatigue, creep or plastic collapse under specified loading conditions. In the presented case, the ECA is used during operation, to assess flaws found in service (Kirin et al. 2020) and to make decisions as to whether they can safely remain, or whether down-rating/repair are necessary.

For an analysis of a known flaw, the following information is needed:

- size, position and orientation of flaw,
- stresses acting on the region containing the flaw,
- toughness and tensile properties of the region containing the flaw,

The analysis is carried out in accordance with the British Standard procedure BS 7910:2013 based on Charpy energy and the FEM structural analysis stresses.

Considering the crack propagation curve as a double logarithmic (Paris law), it can be easily noticed that most of the crack growth period takes place during phase II, thus the entire crack extension process can be described with:

$$da/dN = C \cdot \Delta K^m \tag{2}$$

where

$$\Delta K = K_{Ic} - K_{min} = Y(\sigma_{max} - \sigma_{min})\sqrt{\pi a} \tag{3}$$

If the values of σ_{max} and σ_{min} are known, the correction factor Y can be calculated, the C and m material constants can be experimentally determined, and fatigue crack growth can be simulated, based on a procedure which contains the following steps:

The crack growth da_1 corresponds to dN = 1 load cycle is calculated according with the following relation:

$$da_1 = C \cdot \Delta K^m \tag{4}$$

In this phase the following input data is needed: stresses σ_{max} and σ_{min}, material constants C and m, initial crack dimension a_0 and geometry of element;

Based on da_1 increment, the crack dimension resulted in the first loading cycle is calculated with the relation:

$$a_1 = a_0 + da_1 \tag{5}$$

The following condition is checked:

$$a_1 < a_{cr} \tag{6}$$

If condition (6) is fulfilled, one should proceed to the next step;

This procedure is repeated until:

$$a_i = a_{cr} \tag{7}$$

The number of stress cycles *N*, for which condition (7) is fulfilled, represents the remaining life of structural element.

The presented procedure can be applied for assessing the acceptability of flaws in relation to their effects on fatigue strength, or for the estimation of tolerable flaw sizes based on fitness-for-service. Fracture mechanics principles are used to describe the behaviour of planar flaws whilst the assessment of non-planar flaws is based on experimental *S-N* data. The assessment is summarized in following steps (Radu et al. 2018): the determination of the cyclic stress range from P_m, k_{tm}, P_b, k_{tb}, Q; the determination of the flaw normal to maximum principal stress; the defining of the flaw dimensions; the determination of the crack growth limit.

Table 2. Description of the flaws

Case no.	Name	Flaw type	Description of the flaw
Case 1	(TTF-1)	through thickness flaw	Crack in area nearby the rivet – Main truss beam - lower chord
Case 2	(TTF-2)	through thickness flaw	Crack in area nearby the rivet – Main truss beam - upper chord
Case 3	(TTF-3)	through thickness flaw	Crack in area nearby the rivet – Main truss beam – Diagonal 1
Case 4	(TTF-4)	through thickness flaw	Crack in area nearby the rivet – Deck transversal beam
Case 5	(TTF-5)	through thickness flaw	Crack in area nearby the rivet – Deck longitudinal beam
Case 6	(EF-1)	edge flaw	Crack in area nearby the rivet – Main truss beam - lower chord
Case 7	(EF-2)	edge flaw	Crack in area nearby the rivet – Main truss beam - upper chord
Case 8	(EF-3)	edge flaw	Crack in area nearby the rivet – Main truss beam – Diagonal 1
Case 9	(EF-4)	edge flaw	Crack in area nearby the rivet – Deck transversal beam
Case 10	(EF-5)	edge flaw	Crack in area nearby the rivet – Deck longitudinal beam

The general fatigue assessment of structural elements with cracks is based on Paris law for crack growth modelling. This assessment procedure, as previously shown, is chosen considering that the relation between da/dN and ΔK is a sigmoidal curve in a graph of log da/dN function of ΔK.

Considering the real case assessment level 2 – FAD-2 (Hobbacher et al. 2009), there were done assessments on different flaws type and flaws position (table 2), with through thickness flaws (TTF), surface flaws (SF), long surface flaws (LSF), buried flaws (BF) and edge flaw (EF). The dimensions and the FAD 2 results are presented in table 3.

2.3. Fatigue assessment

Following the structural analysis and the load spectrum for a given time, the distribution of the loads was rearranged following a probability density function (PDF) using Weibull distribution. Following Rainflow algorithm, the results were processed and determined the block of stresses with stress ranges $\Delta\sigma_i$ and the appearance frequency (ni).

Table 3. Dimension of the flaws and FAD-2 results

Case	B	W	2a	a	2c	p	r_0	h	t_w	L_r	K_r
	mm	mm	mm	mm	mm	mm	mm	mm	mm		
FP-TTF-1	16	200	30							0.8318	0.6755
FP-TTF-2	32.63	200	30							0.8318	0.6755
FP-TTF-3	200	32.63	10							1.0195	0.4085
FP-TTF-4	25	200	30							0.8318	0.6755
FP-TTF-5	25	120	30							0.9427	0.6930
FP-SF-1	16	200		5	30					0.8330	0.4183
FP-SF-2	32.63	200		5	30					0.7429	0.3899
FP-SF-3	200	32.63		5	10					0.7125	0.2808
FP-SF-4	25	200		5	30					0.7644	0.3965
FP-SF-5	25	120		5	30					0.7644	0.3984
FP-LSF-1	16	200		2						1.0284	0.6580
FP-LSF-2	32.63	200		5						0.8350	0.4893
FP-LSF-3	200	32.63		5						0.9427	0.5787
FP-LSF-4	25	200		5						0.8838	0.5280
FP-LSF-5	25	120		5						0.8838	0.5280
FP-BF-1	16	200	5		30	3				1.1888	0.4075
FP-BF-2	32.63	200	5		30	3				0.8504	0.4075
FP-BF-3	200	32.63	5		10	3				0.7290	0.2679
FP-BF-4	25	200	5		30	3				0.9379	0.4075
FP-BF-5	25	120	5		30	3				0.9379	0.4140
FP-EF-1	16	200		15						0.7644	0.7688
FP-EF-2	32.63	200		15						0.7644	0.7688
FP-EF-3	200	32.63		15						1.3086	1.6678
FP-EF-4	25	200		15						0.7644	0.7688
FP-EF-5	25	120		15						0.8080	0.8139

Five types of flaws were assessed – only for the cross girders. For the assessment was used the code cyclic loading 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). It resulted 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 (figure 4).

As one can see, the flat plate – long surface flaw is the most critical flaw, considering the service lifetime of only 1.9 years (number of blocks) until the crack is extended to a critical flaw of 5.36mm depth. Also the FP-BF (flat plate buried flaw) type is critical, considering the reaching of the critical crack dimension of 6.28mm in 7.45 years.

3. Conclusions

It was studied a solution for retrofitting an existing historical riveted steel bridge considering also 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 (LM1-Eurocode). Thus, the current deck is maintained in combination with a new deck in the central area consisting

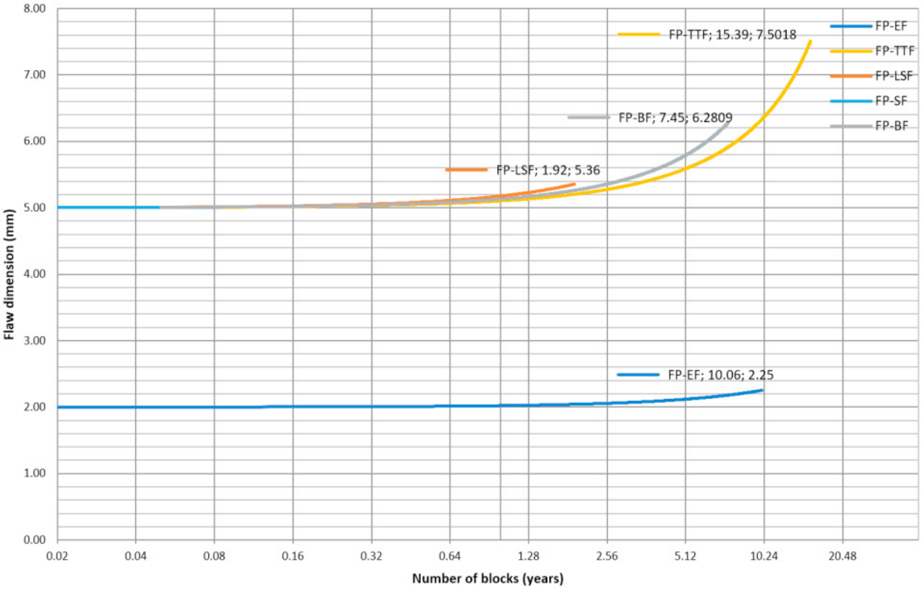

Fig. 4. Fatigue assessment of the different flaw cases – main deck beam

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 (cross girders) that join part of the existing spacers on the current truss beams, so as to result in two distinct traffic lanes (approximately 4.0-4.25m per each way), separated from each other by the newly added box girder beam.

Considering the existing structure age, it was needed to do an assessment to reveal the possible implication of the future possible discovered flaws.

It was done FAD-2 assessment in order to determine the critical dimensions of the flaws – dimensions needed for the fatigue assessment. The results are presenting the acceptability level for each type of flaw with comparative graphs, determining also the critical dimension of the flaw.

In the end, there are presented comparative graphs for structural element service lifetime, taken into account different types of flaws and locations.

References

*** Eurocode 3: Design of steel structures - Part 1-9: Fatigue

*** Eurocode 3: Design of steel structures - Part 1-10: Material toughness and through-thickness properties

*** EN-1090-2: Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures

Kirin, S., Sedmak, A., Zaidi, R., Grbović, A., Šarkočević Ž., Comparison of experimental, numerical and analytical risk assessment of oil drilling rig welded pipe based on fracture mechanics parameters, Engineering Failure Analysis, 10.1016/j.engfailanal.2020.104600

Grbović, A., Kastratović, G., Sedmak, A., Eldweib, K., Kirin, S., Determination of optimum wing spar cross section for maximum fatigue life, International Journal of Fatigue, 10.1016/j.ijfatigue.2019.06.019

Zerbst, U., Schodel M., Webster, St., Ainsworth, R., Fitness-for-Service Fracture Assessment of Structures Containing Cracks: A Workbook based on the European SINTAP FITNET procedure (Advances in Structural Integrity), Academic Press 2007

Bannister A.C., Structural Integrity Assessment Procedures for European Industry: SINTAP: Sub-task 3.3 Report: Final Issue Determination of Fracture Toughness from Charpy Impact Energy: Procedure and Validation, British Steel plc; 1998

*** Abaqus software guide

*** Eurocode EN 1991-2:2004 Actions on to the structures. Part 2. Traffic loads on the bridges.

*** BS 7910/2013, "Guide to methods for assessing the acceptability of flaws in metallic structures", BSI British Standards

Radu., D., Sedmak, A., Băncilă, R., Determining the crack acceptability in the welded joints of a wind loaded cylindrical steel shell structure, Engineering Failure Analysis, 2018, 10.1016/j.engfailanal.2018.04.032

Hobbacher, A., IIW Recommendations for fatigue design of welded joints and components, WRC Bulletin 520, Welding Research Council, New York, 2009, pp. 144.