ON THE SUSTAINABLE RESTORATION DESIGN OF A HISTORICAL STEEL RAILWAY BRIDGE

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Keywords: Fatigue; Restoration design; Riveted joints; Steel railway bridges; Sustainable bridges

ABSTRACT

This paper presents a methodology applied for the restoration design of the old steel truss Echedoros River Railway Bridge. Such an intervention can be characterized as sustainable if the design considerations include the assessment of the remaining fatigue life, the estimation of the future traffic demands and the evaluation of the total cost of the project. The certification of the design criteria used in the present study, i.e. loads and resistance assessments is mainly based on the Guidelines entitled 'Sustainable Bridges', which have been recently produced by the European Commission. The Echedoros River Railway Bridge due to its position used for decades to be one of the most important structures of the railway network in the northern part of Greece. The bridge been classified as a historic structure, was completely reconstructed in 1946 after the 2nd World War in its present form that consists of two spans with one concrete support in the middle of the river and two main truss girders with riveted connections for each opening. In the present work a finite element analysis model of the whole bridge and several partial finite element analysis models of critical details have been studied using ANSYS software including solutions for critical traffic, earthquake and fatigue loading combinations. With this framework the field conditions of the most representative details have been simulated taking into consideration different local deficiencies and possible failures. As a result an evaluation of extreme stress areas on gusset plates and a more representative stress distribution among the connecting rivets has been obtained. The restoration of the old steel-truss railway bridge with riveted connections is mainly limited by its strength against fatigue and influenced by the ultimate strength of its structural members. So, the proposed methodology leads to a more accurate and robust restoration design.

1 INTRODUCTION

An intervention can be characterized as sustainable if the design considerations include the assessment of the remaining fatigue life, the estimation of the future traffic demands and the evaluation of the total cost of the project. The certification of the design criteria used in the present study, i.e. loads and resistance assessments is mainly based on the Guidelines entitled 'Sustainable Bridges', which have been recently developed by the European Commission. In the present work a finite element analysis model of the overall bridge and partial finite element analysis models of critical details have been studied using ANSYS software. Within this framework the field conditions of the most representative details have been simulated taking into consideration different local deficiencies and possible failures.

2 SUSTAINABLE RESTORATION DESIGN

2.1 General Description of the Historic Bridge

The historic Railway Echedoros River Bridge due to its position was used for decades to be one of the most important structures of the railway network in the northern part of Greece as shown in Figure 1. This bridge classified as a historic structure, was completely reconstructed in 1946 after the 2nd World War in its present form with a total opening of $L = 121,00m$ that consists of two steel parts with particular length $l_i = 60.00m$ each supported by strong concrete piers at the supports [6], [10]. Each span consists of two main steel girders as shown in Figures 1 and 2 with truss elements and riveted connections. The bridge is constructed in a prefabrication process mainly with the assembling technique of riveting.

Figure 1. Internal view of the old steel truss Railway Bridge

2.2 Structural form of the old bridge

The steel truss supporting the bridge is made up primarily of I & H- beams and composed channel columns (riveted channels made by 2 located opposite U beams and 2 plates (flanges)) and additional secondary members of angle sections, hollow sections, square bars etc. The general structural condition of the whole bridge seems to be in good condition but with some corrosion problems to be identified in the details, joints and partial structural elements as shown in Figures 1 and 2. The two main truss girders of the each opening are transversally interconnected in a satisfactory level between them downward by the deck and a truss bracing structure and upward by a strong truss bracing structure too. One additional disadvantage of the structural system except fatigue remaining life of the bridge is that the bridge resists the crash (traffic) loads undertaken from the track directly to the truss members without any ballast bed. Additionally, due to the age of the bridge and the construction of a new railway line in the same region, no inspections and maintenance process were carried out in the last years. Thus the general condition of the whole bridge, as well as of the significant details such as the riveted nodes and the gusset plates seems to be with some corrosion problems but in a sustainable level after the necessary repair works.

Figure 2. View of a main truss-deck riveted join of the bridge

On the basis of several research projects, studies and guidelines about the material properties of historical steelworks [4], [7] and the help of the Carnegie Steel Company's Standard specifications [2] together with an in-site detailed investigation, the mechanical properties of the existing steel bridge have been evaluated and herein presented.

2.3 Restoration of the bridge against future traffic demands

The investigation of the re-operation of the railway line in this region includes the assessment of the remaining life of the bridge and its bearing capacity about traffic demands after the necessary repair works. That means it is an investigation on the sustainability of the bridge, which includes the meaning of the historic structure in its initial form and the total budget of the necessary interventions. The certification of the design criteria is mainly based on the Guidelines entitled 'Sustainable Bridges', [4], [11] which have been recently prepared by the European Commission; the present study constitutes an opportunity for a best practice application of them.

3 STRUCTURAL ANALYSIS OF THE OLD BRIDGE

3.1 Section properties and design stresses of the structural models

In order to define realistic safety factors for the bridge, the corresponding structural behavior at the various limit states such as the Ultimate Limit State ULS, the Serviceability Limit State SLS and the Fatigue Limit State have been considered. The Ultimate tensile strength of the studied old steel is estimated by a value of $f_u = 385N/mm^2$ and the corresponding Yield strength or elastic limit by a value of $f_y = 240N/mm^2$. Moreover, it is often necessary to identify the structural condition of an old bridge like this by on-site and laboratory testing to identify the properties of the structural components that are used in the analytical and computer models. The corresponding normal and sticking stiffness of the rivet is computed taking into account an average value of $100N/mm^2$ for the prestress of rivets that had been applied between the connected plates of a structural detail. Due to the parameters influencing the prestress [1] such as the fabrication quality of the bridge, a possible bandwidth of rivet prestress from $50N/mm^2$ to $200N/mm^2$ is taken into account with normal or abnormal distribution onto the connection plate. Moreover, due to the fact that the studied material is old steel, a recommended value of $\gamma_{M_i} = 1{,}1$ is used for the corresponding material resistance factor.

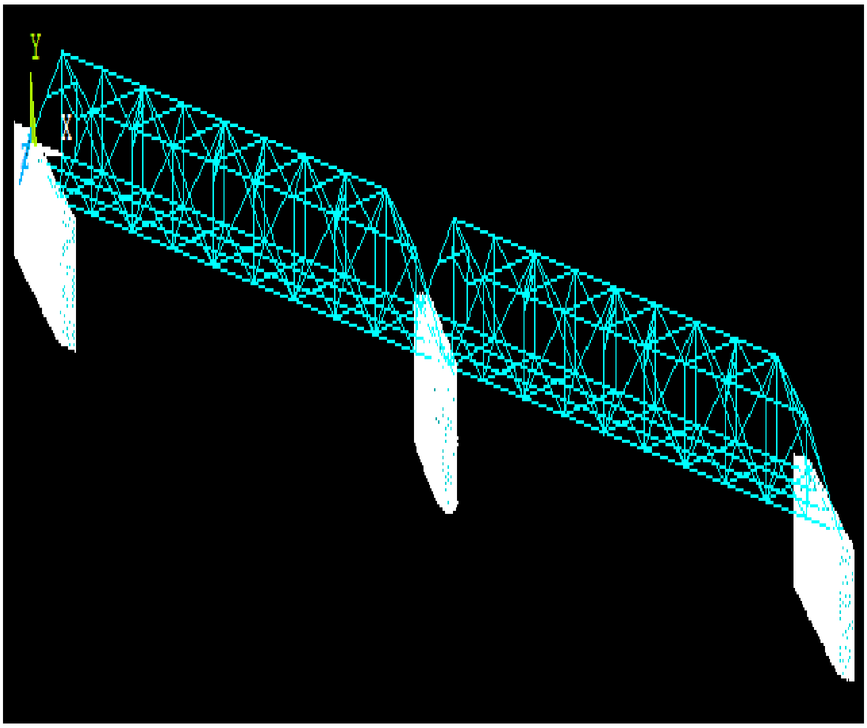

Figure 3. 3-D frame FEM for the whole bridge

3.2 Finite element Analysis

In the present work a 3-Dimensional finite element analysis model of the whole bridge as shown in Figure 3 and a more accurate 3-Dimensional finite element analysis model, in order to investigate the critical connection detail of the main beam and to detect any weaknesses in both sections and rivets shown in Figure 4, have been studied using ANSYS software. The load models that are used here for a combined response of the structure are actions due to railway operations defined in 6.2 of EN-1991-2 [5].

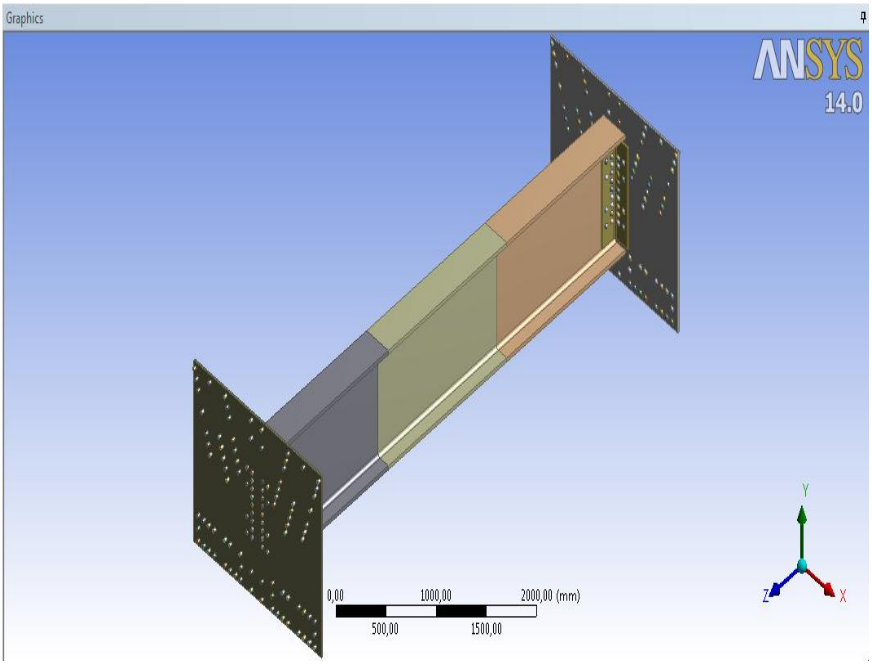

Figure 4. 3-D solid FEM for a critical connection detail

The most representative actions are the characteristic values of Load Model 71, SW/0 and SW/2 respectively [9] and their distribution in the case of a 1 track railway bridge, multiplied by a) the line classification factor $a_{LC} = 1{,}00$ (specified in the guidelines for sustainable bridges [4]) and b) the maximum dynamic factor for track with standard maintenance, is taken (Table 6.2(5.6), EN-1991-2). Especially for the 3-D structural model and for each one of the two girders of the bridge, pin boundary conditions for both bearings at one end and rolled in one direction boundary conditions for both bearings at the other end are introduced. Within this framework the field conditions of the most representative details have been simulated taking into consideration different local deficiencies and possible failures. As a result, an evaluation of extreme stress areas on gusset plates and a more representative stress distribution among the connecting rivets has been obtained. The load models that are used here for a combined response of the structure are actions due to railway operations defined in 6.2 of EN-1991-2 [5]. The most representative actions are the characteristic values of Load Model 71, SW/0 and SW/2 respectively [9] and their distribution in the case of a 1 track railway bridge, multiplied by a) the line classification factor $a_{LC} = 1{,}00$ (specified in the guidelines for sustainable bridges [4]) and b) the maximum dynamic factor for track with standard maintenance, is taken (Table 6.2(5.6), EN-1991-2). The calculated natural frequency of the deck satisfies the design procedures $n_o^{lower} < n_O = 4{,}33Hz < n_o^{upper}$. Moreover, actions due to eccentricities of vertical loads, traction and braking forces in the longitudinal direction, wind forces etc, have been formulated and evaluated into the loading combinations.

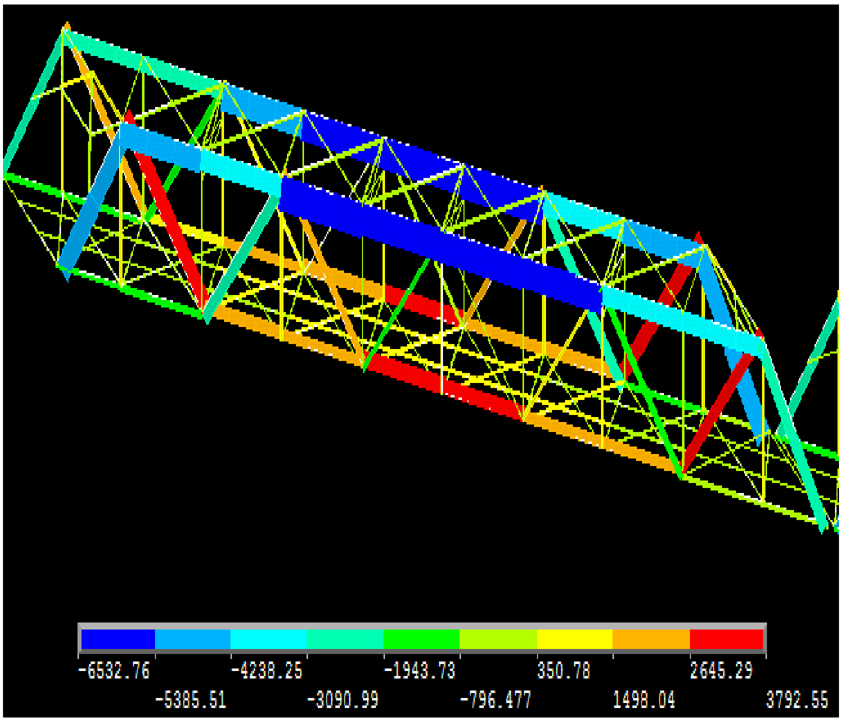

Figure 5. Calculated axial forces in the steel truss girder for the critical load combination

Evidently, each one of the main structural steel members of the bridge as it is showed in Figure 5 satisfies the representative resistance check which is one of the sustainability criteria for the restoration design of the bridge. Figure 6 histogram, summarize the satisfactory finding resistance checks for several different and complex structural members, since they have different cross sections leading to different bearing capacities.

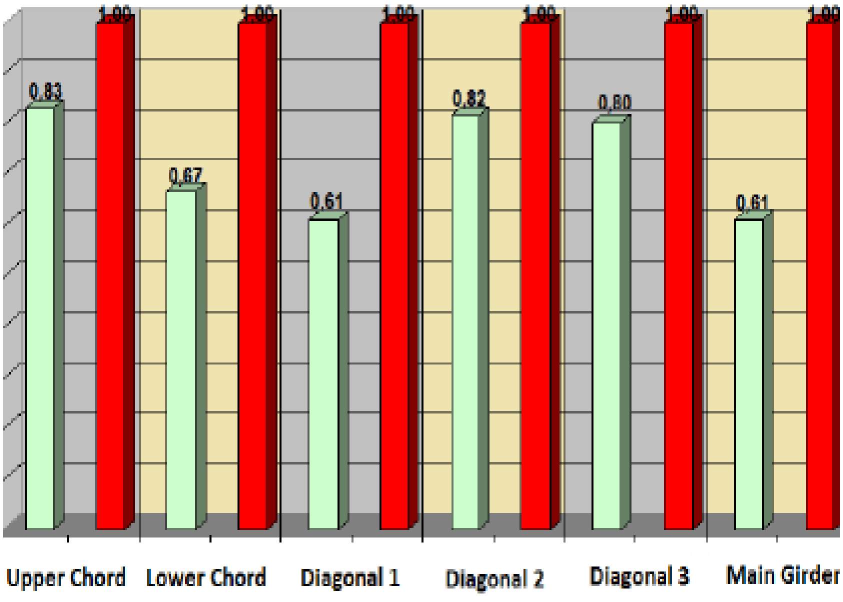

Figure 6. Histogram of the resistance check for critical structural steel members of the bridge

As it is already mentioned, the 3-D solid FEM for a critical connection detail used for the study of a characteristic riveted joint leading to a thorough analysis under the LM71 load combination (Figure 7). As a result, the weakest parts of the connection were located and subsequently, the bearing capacity of every rivet as well as of the gusset plate was assessed.

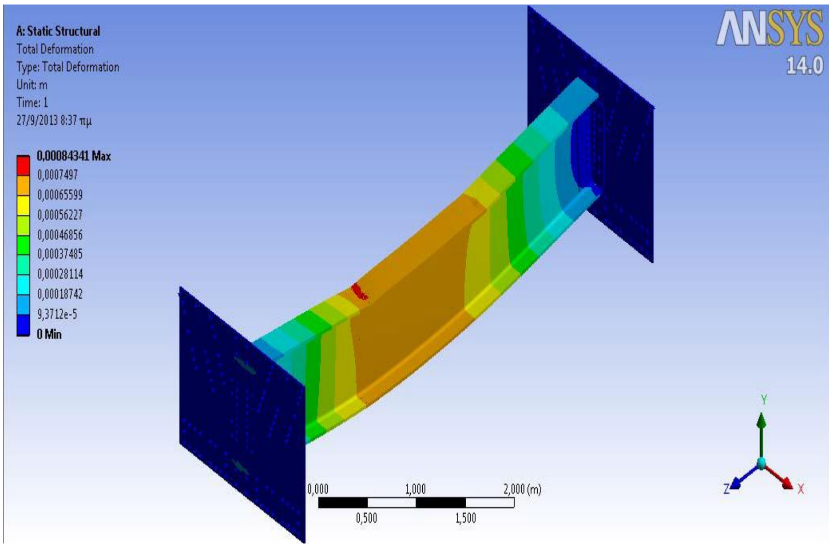

Figure 7. Stress distribution for the critical connection detail

4 FATIGUE ANALYSIS

4.1 Fatigue limit state

Fatigue failures can occur in a specific component of the bridge due to the repeated loading at levels lower than the design load (for a single load application) [3]. Fatigue is often critical at the details of joints, but because of the riveted connections of the composite steel structural members (channels, H-sections etc.) of the truss girders, critical details that belong to these members must be taken into consideration. For steel bridges, the safety verification according Eurocodes 1 & 3, is carried out by ensuring that the following fatigue design criteria are satisfied:

$$\gamma_{Ff} \cdot \lambda \cdot \Phi_2 \cdot \Delta\sigma_E \leq \Delta\sigma_C / \gamma_{Mf} \quad (1)$$

In the left part of the form (1) the parameters for the design stress range are: the partial safety factor for fatigue loading γ_{Ff} that depends on the known reliability of the safety concept and the possibility of failure; the damage equivalent factor for fatigue $\lambda = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 \leq \lambda_{max}$ expressed as a function of the parameters of loaded length/type of loading (λ_1), of the traffic volume (λ_2), of the design life (λ_3) and of the number of trucks supported by the members (λ_4); Φ_2 is the dynamic factor for meticulously maintained truck and $\Delta\sigma_E$ is the stress range due to design train loads being placed in the most unfavourable place for the element under consideration.

Table 1. Cumulative damage assessment for a critical inside gusset plate

No of train **Types** (light traffic mix)	$\Delta\sigma_i$ (Mpa)	N_i (cycles)	n_i (cycles)	n_i / N_i
1	18.32	8.36×10^7	3.65×10^5	0.004
2	13.77	3.49×10^8	1.82×10^5	0.000
3	34.75	3.97×10^6	7.30×10^4	0.018
4	15.95	1.67×10^8	6.93×10^6	0.042
$D_d = \sum(n_i / N_i) \leq 1$				0.063

Figure 8. Degree of depletion for each member type

Respectively in the right part of the form (1) the parameters for the allowable stress range are: $\Delta\sigma_C$ is the reference value of the fatigue strength to be taken by the S/N curves corresponding to the detail category for nominal stress ranges $\Delta\sigma_c = 71 N/mm^2$ at $2 \cdot 10^6$ cycles and γ_{Mf} is the partial safety factor for fatigue strength. For this riveted structure the nominal stress has been calculated on the net cross-section (gross cross-section minus section of rivet holes in the critical section). The cumulative damage assessment for variable amplitude loading, which is the case of a traffic mix such as "light traffic mix" depending on the assumption that the structure carries light traffic, is based on Palmgren-Miner rule $D_d = \Sigma(\mathrm{n_i} / N_i)$, where N_i is the number of cycles of stress range to cause failure for the relevant detail category, n_i is the number of cycles of $\Delta\sigma_i$ during the required design life and $\Delta\sigma_i$ is the nominal stress range. The service trains for light traffic mix are of Types 1,2,5 & 9 where details of theirs loading distribution and the evaluation in the light traffic mix variable loading is defined in Annex D of EN-1991-2.

Table 2. Cumulative damage assessment for a critical complex detail

No of train **Types** (light traffic mix)	$\Delta\sigma_i$ (Mpa)	N_i (cycles)	n_i (cycles)	n_i / N_i
1	38.24	3.36×10^6	3.65×10^5	0.108
2	28.56	1.10×10^7	1.82×10^5	0.016
3	120.91	2.60×10^5	7.30×10^4	0.279
4	33.25	2.32×10^7	6.93×10^6	0.298
$D_d = \sum(n_i / N_i) \leq 1$				0.701

For each group of structural details of the bridge a procedure as described above is carried out in Tables (as shown in Tables 1 and 2) where the partial safety factor for actions was taken $\gamma_{\mathrm{Ff}} = 1{,}35$ and the safety factor for resistance $\gamma_{\mathrm{Mf}} = 1{,}15$. The successful results of the cumulative damage assessment lead to sustainability of the restoration design.

4.2 Evaluation of fatigue life

By the use of the general form (1) an estimation of the traffic loading per day in respect to several partial safety factors can be carried out for the anticipated service loading throughout the operational life (here is taken 100 years) of the structure.

Table3. Estimation of the fatigue life (T=100 years) of the steel truss bridge

Partial safety factor	γ_{Ff}	$\Delta\sigma_i$ (Mpa)	n_i (cycles)	Number of train (LM 71) per day
Damage tolerant concept / Low consequence	1.00	175.47	5.00×10^5	13.50
Damage tolerant concept / High consequence	1.15	149.48	3.00×10^5	8.20
Safe life concept / Low consequence	1.15	149.48	3.00×10^5	8.20
Safe life concept / High consequence	1.35	129.98	1.70×10^5	4.50

The results as shown in Table 3, correspond to different design proposes.

4.3 Fatigue life of the main girder connection

In this section the remaining life of the connection is evaluated and the most critical rivets in fatigue failure are identified under cyclic loading of the Load Model 71, using the ANSYS Workbench software and setting the fatigue parameters mentioned previously.

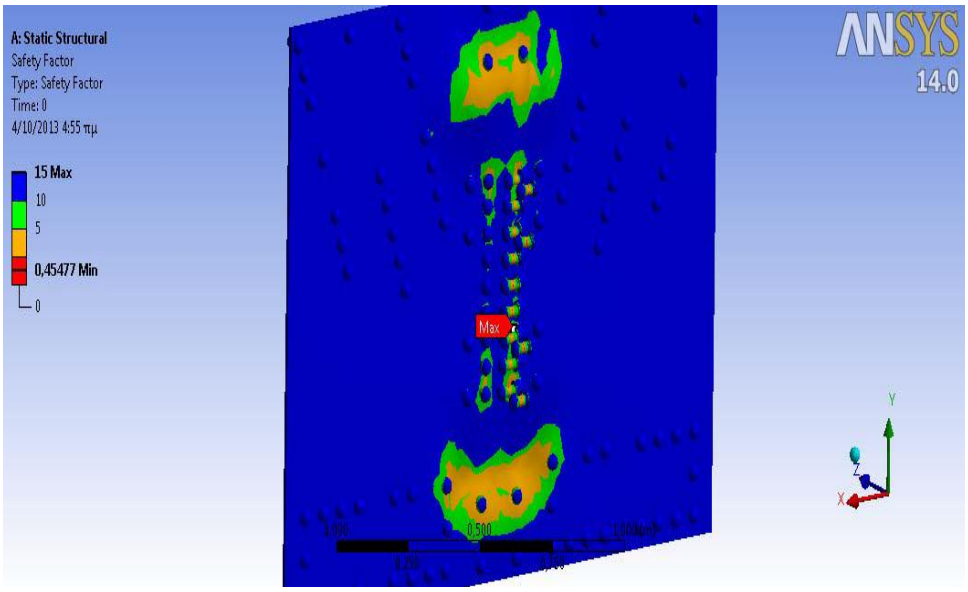

Figure 9. Design life safety factor of the connection

Consequently, the fatigue life of every component of the connection can be estimated separately, providing us with the ability to locate where and when the failure is going to appear. In addition, given a theoretical design life of the connection, the safety factor of each component is obtained, providing us with a wider image of the possible failure (Figure 9).

5 CONCLUSIONS

A restoration design methodology within the Eurocodes framework and the relevant guidelines on sustainable bridges produced by the European Commission for a typical old steel truss bridge has been herein proposed. Fatigue design as well as an evaluation methodology for a global or local structural analysis along with the Finite Element Method proposed to assess the stress field for the cyclic life of structural details have been also discussed and evaluated. The effects of various factors used for this problem have been studied in details and the results for various cases appears to be satisfactory and encouraging to be decided by the National authority for the restoration and re-use of old bridges. In any case a much more detailed research on the sustainability of the present railway bridge based on a detailed on-site inspection together with laboratory checks according guides like prEN1090-2 for riveted connections and materials must be performed in order to obtain information regarding its performance. To conclude with, it is worthy to be mentioned that by rehabilitating such a historic bridge like the one under investigation, the fabrication and preservation of this important structure is in details investigated and recorded [8].

ACKNOWLEDGMENTS

The cooperation and the encouragement of the Association of Friends of the Railway Museum of Thessaloniki for the conduct of this work are gratefully acknowledged.

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