Enhanced Fatigue Life Prediction in Ancient Riveted Metallic Railway Bridges

Cláudio S. Horas[1], João Silva[1], José Correia[1], Abílio M.P. Jesus[2], Rui Calçada[1]

[1]*Department of Civil Engineering, CONSTRUCT - LESE, Faculty of Engineering, University of Porto*
Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
claudiohoras@fe.up.pt, up201705111@edu.fe.up.pt, jcorreia@fe.up.pt, ruiabc@fe.up.pt
[2]*Department of Mechanical Engineering, INEGI, Faculty of Engineering, University of Porto*
Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
ajesus@fe.up.pt

Abstract. The majority of transport investments funded by the European Union are aimed at improving the capacity of railway infrastructure in order to meet challenging environmental targets, which will culminate in achieving carbon neutrality by 2050. In this framework, existing railway bridges are relevant and should be preserved in service for as long as possible according to a sustainability perspective. In this paper, fatigue damage assessment is addressed, as this phenomenon has been proven to threaten the structural integrity of metallic railway bridges, affecting severely riveted details in particular. For this type of connection, very limited guidance is given in standards and codes concerning global methods based on S-N curves for nominal stresses, and unreliable results may be obtained, limiting the accurate fatigue check. Thus, a multiscale approach using submodelling techniques leveraged by modal superposition principles can be considered to calculate local fatigue parameters, allowing to compute the remaining life for the crack initiation and crack propagation phases, in line with the properties of the load transfer mechanism. From global to local assessment, relevant differences in results are found.

Keywords: railway bridges; fatigue prediction; local fatigue approaches; local methods; modal superposition.

1 Introduction

Nowadays, environmental concerns have a significant influence on the global political agenda, in particular when it comes to policies related to collective mobility. In 2019, the European Commission introduced the Green Deal, prioritising trains to transport passengers and goods over appropriate distances [1]. Naturally, this shift requires the expansion of the railway network's capacity and the enhancement of infrastructure assets. To minimize direct costs, it becomes imperative to extend the service life of existing metallic bridges, accommodating the foreseen increase in traffic demands. Among the primary threats to the structural integrity, fatigue phenomena play a pivotal role and have a historical record of shortening bridge lifespans [2].

When the fatigue awareness was getting consolidated, a relevant number of riveted metallic railway bridges was already in service, and no specific safety checks were conducted in the respective design. Therefore, these structures are particular susceptible to fatigue loading, and their integrity should be verified for the current and expected traffic scenarios. In Figure 1, the historical evolution on joining techniques is confronted with the development in knowledge about fatigue phenomenon, with an evident gap being chronologically identified until the publication of the first normative documents addressing fatigue (around 1950s) [3]. Historically, the dominant line of fatigue research has been adapting existing S-N curves for nominal stresses, originally derived for welded details, for the assessment of riveted ones. In the last years, considering the development of computational capabilities, the implementation of local methods have been explored, allowing to account for the real characteristics of the existing load transfer mechanism. In Figure 2, these two lines of research are systematised.

Still in the 19th century, Wohler presented the basis of S-N relations currently proposed to model the resistance side in global fatigue methods, which dominate the methodologies suggested in the current normative documents [4–6], linking a given nominal stress range to the respective total fatigue life expressed in number of cycles (crack initiation+crack propagation), and incorporating the local stress raiser effects to level up the analysis scale. Nevertheless, such global approaches may lead to inaccurate fatigue predictions, not reflecting the diversity of geometrical and material properties existing in real riveted details. Thus, relating a certain detail to a given curve for nominal stresses involves an inherent degree of uncertainty that may lead to unreliable predictions.

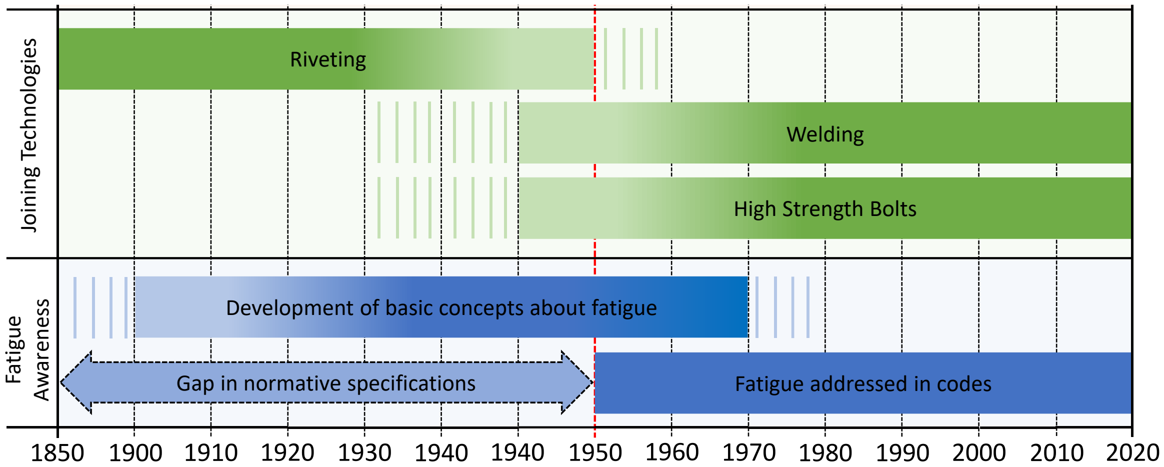


Figure 1. Evolution of steel bridge construction and fatigue knowledge

As alternative, after establishing validated submodelling techniques, relating the global and local scales, the fatigue analysis may be lowered to the mm dimension or below. Several local methods for assessment of the crack initiation [7, 8] have been proposed, mostly for uniaxial conditions, while Linear Elastic Fracture Mechanic (LEFM) based methods have been considered for the evaluation of crack propagation [9, 10].

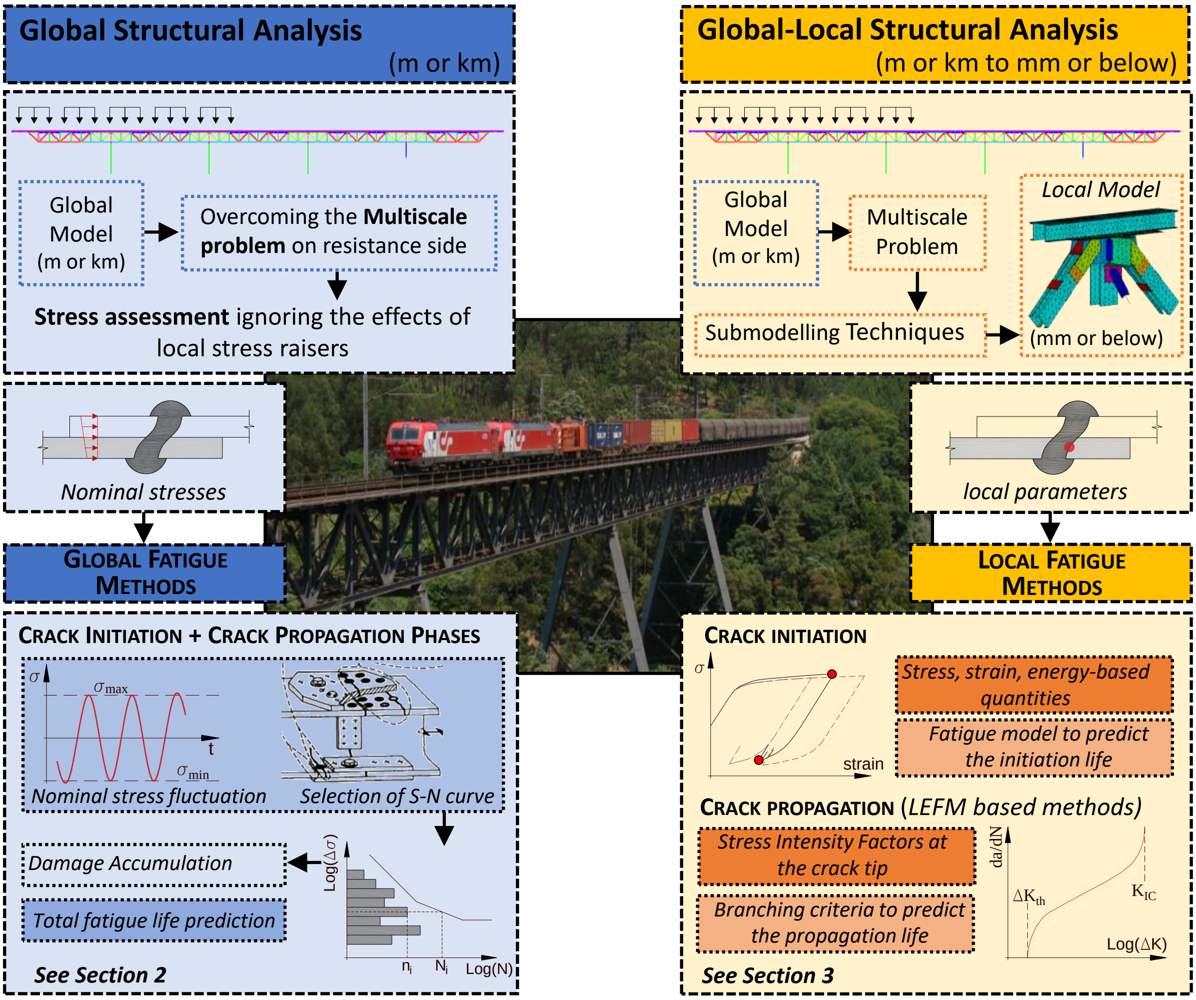


Figure 2. Fatigue assessment approaches originated by lines of investigation

In the next sections, global and local methods applicable to practical tasks of engineering are addressed, presenting relevant data based on the case-study of the Várzeas Bridge, located in Portugal in the railway line of Beira-Alta. This structure is 65 years old and is approaching the limit of service life, with the accurate assessment of fatigue damage being critical to extend the safe operation characterized by an important freight traffic.

2 Global Fatigue Methods

As mentioned, the main international codes propose global methods based on nominal stresses for fatigue damage calculation, incorporating on the resistance side the geometrical and material properties of the mechanism of load transfer. Such an approach is intended to overcome the multiscale problem inherent to the fatigue analysis, which rises from the difference of scales between the global size of the bridge and the very local dimension of the areas affected by fatigue damage (km or m vs. mm or below, respectively, as in Figure 2). Nevertheless, limited guidance is given for fatigue assessment on riveted details, which impacts on the accuracy when one is evaluating the safety of this type of connection. Historically, this research line has been focused in expressing the fatigue resistance with few curves for an extensive variability of geometries and material parameters, which leads to conservative lower boundaries for fatigue assessment (Figure 3).

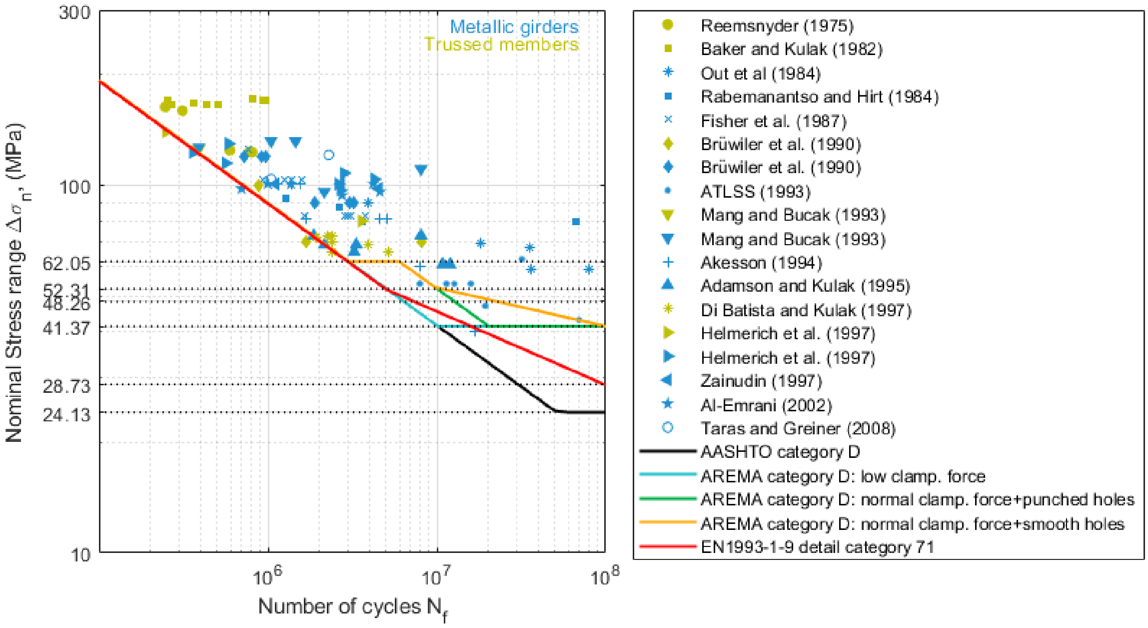


Figure 3. Fatigue test results of riveted details (real scale specimens) (adapted from [11])

In Figure 3, fatigue tests performed in relevant works performed in this research approach are outlined and compared to the S-N curves proposed in AASHTO [4], AREMA [5] and EN1993-1-1 [6]. Regarding the latter, it should be noted that no specific guidance if given for riveted connections, but several authors have been recommend the respective use as a lower bound for fatigue resistance of this type of detail.

The scattered results show that a single boundary to represent a large group of different connections may be too conservative to compute the total fatigue life. Some researchers have proposed to group some geometries in function of the local characteristics [12], as for welded or bolted connections, but others have concluded that the wide range of local responses may not allow grouping them into categories effectively [13]. Also, the S-N formulations does not allow considering several aspects that relevantly influence the local response, e.g. yield stress of materials and bearing ratio, stress ratio (R), hole preparation and specimen state.

In the analysis of the Várzeas Bridge (see the complete fatigue analysis of the bridge in [14, 15]), the implementation of the linear accumulation method proposed in EN1993-1-9 [6] allowed identifying the most fatigue-critical details, with one of the lowest fatigue lives being calculated for the riveted connection between the diagonal and the gusset plate (see Figure 4). For example, for the details at x=109.30 m, a limited fatigue life equal to 63 years and 11 months was computed for the normative heavy traffic mix [6], considering the resistance side modelled by the S-N curve detail category 71 proposed in EN1993-1-9 [6].

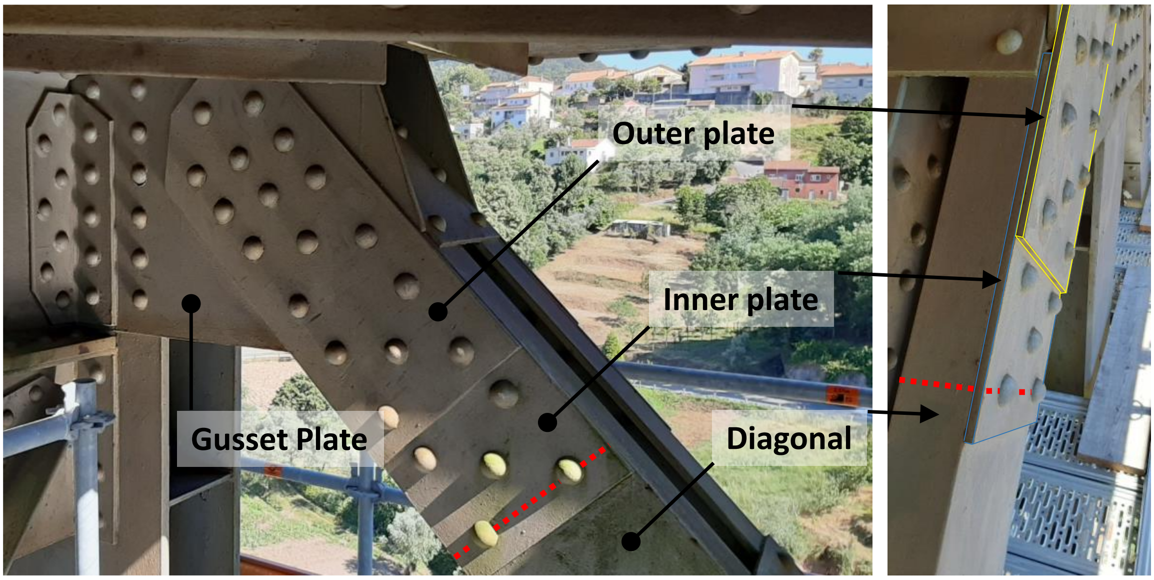


Figure 4. Riveted detail between the diagonal and the gusset plate at x=109.30 m

After, experimental fatigue test on double shear details were performed using steel extracted from the Bridge, and an S-N limit was proposed, also considering other results available in the literature (Figure 5).

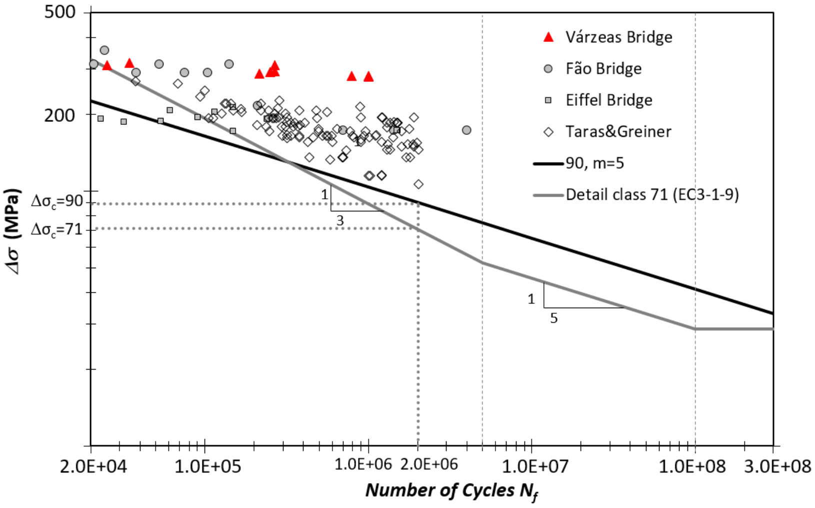


Figure 5. S-N results for several bridges materials (bi-log representation)

From this experimental test, an S-N curve was derived with characteristic stress range of 90 MPa ($\Delta\sigma_c$) and a single slope m equal to 5, and compared to the detail category 71 ($\Delta\sigma_c$=71 MPa and double slope m_1=3 and m_2=5) being less conservative for the high cycle fatigue regime, which is relevant for railway bridges. Assuming this new fatigue limit, the fatigue life for the same detail and loading was calculated equal to 135 years and 8 months, meaning a significant increase in fatigue life in the absence of initial defects.

In Table 1, the results are summarised. The variation in the outcomes by changing the assumed S-N curve shows the importance of accurately model the resistance side, with the normative boundary being too conservative, which limits the calculation of the remaining fatigue life for the existing bridges stock. Nevertheless, even the experimental S-N curve does not account for certain properties of the riveted length, such as the group effects associated to response of the mechanical fasteners. Thus, the implementation of local fatigue methods was explored to assess fatigue damage entirely according to the geometrical and material characteristics of the riveted connections and related mechanism of load transfer.

Table 1. Damage for 100 years (D_{100}), according to different S-N curves

S-N curve properties	D_{100}	Fatigue life (years, months)
$\Delta\sigma_c$=71 MPa, m_1=3 and m_2=5	1.563	63 yrs, 11 mos
$\Delta\sigma_c$=90 MPa, m=5	0.737	135 yrs, 8 mos

As has been shown, the application of global methods can lead to an incorrect prediction of the remaining fatigue life, but they were adopted on the basis of a compromise related to computational efficiency. However, the development of computational capabilities has made it possible to apply and explore local methods.

3 Local Fatigue Methods

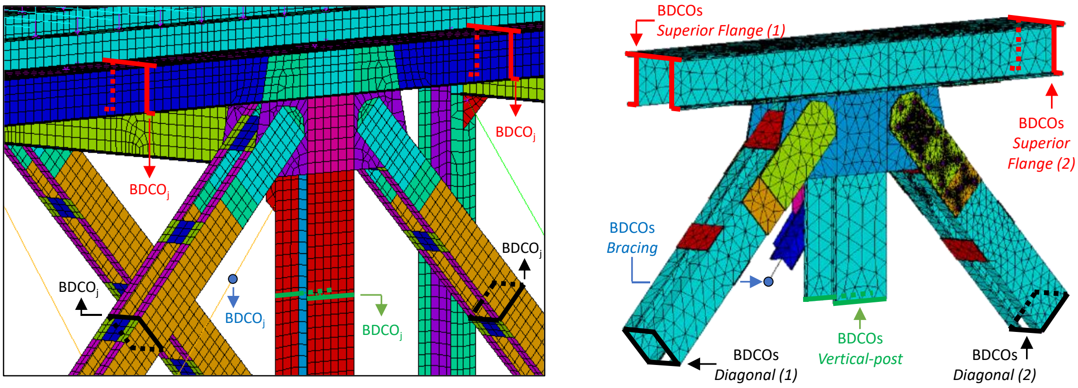
When it comes to modelling railway bridges, most of the global models are based on beam or shell finite elements in order to achieve reasonable computational efficiency. Although this approach allows the global behaviour to be accurately captured, it does not allow the local fatigue parameters to be calculated taking into account the local properties of the details at mm scale.

In this context, several authors have proposed different modelling scales to assess fatigue, namely: i) global or bridge scale, with all members modelled to evaluate nominal measures; ii) component or member scale, which allows a detailed analysis of stress and strain fields in a given connection; and iii) local or material scale, generally conceived with shell or volumetric finite elements, modelling all the geometrical and material characteristics of the load transfer mechanic to accurately compute local fatigue parameters. Combining the three modelling scales, the fatigue assessment can be performed.

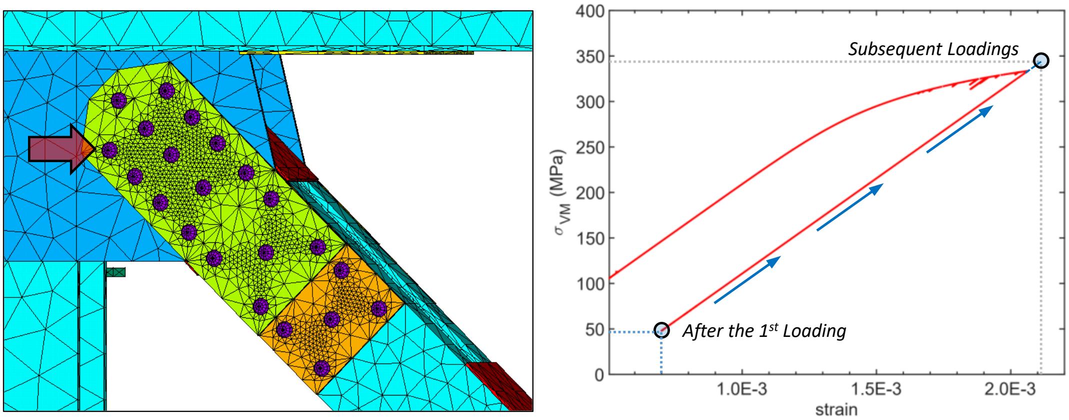
With the aim of improving fatigue calculations, Horas et al. [16, 17] proposed two local fatigue approaches that differ in the way they address local contacts, using submodelling techniques leveraged by modal superposition concepts. These principles imply the modelling to be material linear, and stress values above the yield require the implementation of an elastoplastic post-processing. The accuracy of these local fatigue approaches was verified for uniaxial and low level of multiaxiality, but alternative local models can be considered to address more complex stress states. The combination of Critical Plane Theory and Critical Distance Theory has been considered in other industrial fields [18], and the implementation of reliable submodelling allow exploring the respective application to details part of railway bridges.

For the Várzeas Bridge case study, the fatigue assessment of the critical detail at x=109.30 m was carried out, as in section 2. A submodelling relation was implemented in the time domain and the heavy traffic mix was assumed to compute the local stresses at the hot-spot for the crack initiation, preliminarily identified at the rivet holes. In Figure 6 a), the shell refinement of the global model is presented, with the boundaries of the submodel properly identified, corresponding to those shown in Figure 6 b). After establishing a submodelling relation, properly validated [14, 15], the most loaded rivet was identified (Figure 6 c)), and an elastoplastic post-processing was implemented based on the Glinka model and Ramberg-Osgood proposal [15, 19]. As can be seen in Figure 6 d), the stress analysis was performed in terms of von Mises values to address the reduced multixiality, σ_{VM}, and after the first passage of the fatigue train nº5, a local and confined plasticity occur, lowering the permanent stress level (112.82 MPa to 48.04 MPa), which gives origin to a fatigue phenomenon entirely in the elastic regime with a maximum local stress equal to 346.75 MPa from a stress range of 297.71 MPa (48.04+297.71=346.75 MPa). Considering these results, the Basquin model was considered, and a fatigue life for crack initiation of 8421 years was computed (theoretical infinite fatigue life) [15].

Taking into account this prediction, it is clearly shown the impact of representing inadequately the fatigue resistance by assuming lower and conservative S-N boundaries. In the three fatigue calculations performed, different results were achieved, with the one recommended in the codes and literature being more restrictive for fatigue verification. From an assessment that identified the detail between the diagonal and the gusset plate as restrictive for the circulation on the bridge (see Figure 4), fatigue issues were dismissed as a threat for the existing riveted metallic railway bridge, in the absence of accidental or constructions flaws.



a) global model, after refinement b) local model



c) investigated rivet (local view, perspective) d) elastoplastic stress-strain diagram, train nº5

Figure 6. Submodelling relation and local results at the hot-spot (adapted from [19])

In short, the development of integrated and multiscale approaches to compute fatigue has high impact in terms of sustainably and economy, allowing to maximise the service life of current bridges.

4 Conclusions

Fatigue is a critical phenomenon for the degradation of the structural integrity of existing metallic railway bridges, and of particular concern for riveted details, since there is a gap between the massive use of this joining technique and the awareness of fatigue. From the results presented, the following conclusions can be stated:

1) The standards and codes in force suggest S-N curves for nominal stresses to perform the fatigue assessment of metallic railway bridges, according to a global analysis and incorporating local stress raisers on the resistance side. For riveted details, very limited guidance is given and few S-N curves are advised for a large variety of geometrical and material characteristics (see Figure 3).
2) The approximation between a given geometry and a relatable S-N curve from existing catalogues implies a certain degree of deviation in relation to the real properties of the mechanism of load transfer, which can lead to a non-representative fatigue assessment.
3) The experimental estimate of new S-N curves can be considered to improve the calculation of local damage using nominal stresses, which was prove in the current paper with a shift from the limited total fatigue life to a more reliable prediction (from 63 years and 11 months to 135 years and 8 months, respectively) (see Table 1).
4) The application of local fatigue methods allowed further refinement, showing that the initial predictions were too conservative and not in line with the real characteristics of the load transfer mechanism, and a theoretical infinite fatigue life was calculated in the absence of initial defects.
5) Local fatigue methods applied to aging metallic railway bridges, in particular to riveted ones, opens new possibilities for reliable fatigue assessment, allowing to maximize the service life of these structures, in

line with a greener philosophy.

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