Integrated Methodology for Fatigue Life Prediction of Existing Metallic Railway Bridges

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Abstract. In general, bridges are large structures modelled at the global scale in order to avoid computational limitations. The fatigue assessment of these structures using such a type of modelling is not possible based on local mechanical quantities due to the inherent difference between the size of bridges and the local nature of fatigue phenomena. Currently, the most important standards propose S-N relations for nominal stresses to overcome this multiscale problem, requiring an inherent approximation between the local characteristics of the investigated detail and those at the basis of a relatable S-N curve, which may be particularly conservative for complex connections of bridges in service with ancient construction technologies. Aiming to reduce unnecessary safety margins, local fatigue approaches based on submodeling techniques leveraged by modal superposition principles are proposed to implement local methods using fatigue quantities evaluated considering the real response of the mechanism of loading transference. A complementary relation can then be established between the global conservative normative approaches, applied to identify the fatigue-critical details, and such local fatigue approaches, defined as advanced calculations stages. Therefore, an integrated methodology for fatigue life prediction of existing metallic railway bridges is proposed, suggesting different phases of analyses at multiple scales. A real case study is investigated to demonstrate the added value of this multiphase calculation strategy.

Keywords: railway bridges; fatigue assessment; local fatigue approaches; submodelling relations; modal superposition.

1 Introduction

Environmental concerns are currently influencing the political agenda worldwide, with particular relevance for the collective mobility policies. In the European context, the Green Deal was proposed by the European Commission in 2019, defining the train as the preferred mode of transport for people and goods over appropriate distances [1]. Naturally, this transition process requires the expansion of the capacity of the railway network, increasing the stock of infrastructure. In order to limit the direct costs, existing metallic bridges should be kept in service for longer periods of time, supporting higher traffic demands. Among the main threats to the respective structural integrity, fatigue phenomena are critical, and have historically reduced the service life of bridges [2].

The fatigue assessment of large structures is limited by geometrical challenges derived from the multiscale problem related to the difference between the length of the structural systems and local areas affected by the fatigue damage process (km or m vs. mm or below, respectively). Currently, international standards propose global methods based on S-N curve for nominal stresses to overcome such constraints, including in the definition of these fatigue resistance boundaries the influence of certain local stress raisers associated with given local geometrical, material and contact properties. For such a reason, the fatigue analysis of an existing detail requires a mandatory approximation of the real characteristics of the mechanism of loading transference to those underlying the definition of a certain relatable S-N relation, which may lead to excessively conservative margins with a relevant impact on the remaining fatigue life calculation. The implementation of local fatigue approaches based on submodelling relations leveraged by modal superposition principles is then critical to numerically analyse the local response of a certain existing connection as close as possible to the real one. Such a calculation phase can be assumed as an advanced assessment, applicable to the fatigue-critical details screened using global conservative normative methods, following a multilevel philosophy from the global to the local scale. In this framework, an integrated methodology for fatigue life prediction of existing metallic railway bridges is proposed, assuming experimental data to increase the reliability of the structural calculations (see Figure 1).

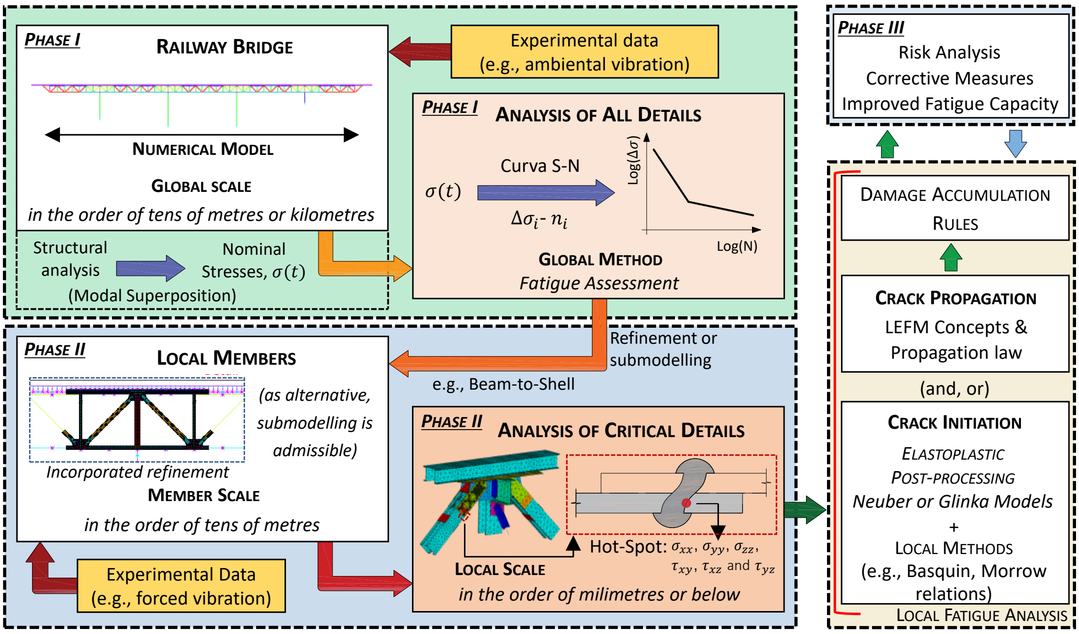


Figure 1. Workflow for the proposed integrated methodology for fatigue life prediction of existing metallic railway bridges (global-local assessment)

In Figure 1, the multiphase workflow for fatigue assessment is outlined, with the aim of fully investigating the details of existing metallic railway bridges. The organisation of this integrated methodology may be adapted to different normative specifications, but the Eurocodes are used as reference in this work. In Phase I, the linear damage accumulation method suggested in EN1993-1-9 [3] is adopted to identify the fatigue-critical details, inherently assuming a certain conservative margin, since the catalogue of S-N curves is limited and the derivation of new fatigue resistance boundaries of this type for each case would be unaffordable. After defining the connections with fatigue damage indices above the limit, Phase II is applied based on local fatigue approaches to refine the structural calculations using submodelling relations to lower the modelling to the local scale detail, with these being leveraged by modal superposition principles to increase the computational efficiency [4,5]. The implementation of such a calculation strategy overcomes the multiscale problem, allowing the evaluation of local quantities as a function of the existing mechanism of loading transference to apply local fatigue methods. From these results, an update of the fatigue classification should be carried out, and the details still classified as critical have to be analysed in the scope of Phase III, in which corrective measures may be designed using the numerical and analytical tools developed in the previous Phase II, depending on a risk analysis according to the importance of each detail for the integrity of the structural system. At the end of the multiphase assessment consisting of three sequentially dependent phases, the bridge management authority obtains reliable information to assume a reasonable decision on the remaining service life of the structure, under certain traffic scenarios.

2 Methods

As in EN1991-2 [6], quasi-static or dynamic analyses may be carried out in the scope of Phase I, allowing one to calculate nominal stress values defined as input loading for a given appropriate S-N curve. If dynamic calculations are mandatory, the system of equations that defines the response of the structural system under moving loads may be decoupled into independent equations for each degree of freedom, as follows:

$$\ddot{Y}_j(t) + 2w_j.\xi_j.\dot{Y}_j(t) + w_j{}^2.Y_j(t) = f_j(t) \quad (1)$$

where, $Y_j(t)$ and $f_j(t)$ are column matrices of modal coordinates and modal nodal forces, respectively, both related to the N degrees of freedom (Nx1 of dimension). In addition, w_j is j^{th} modal frequency and ξ_j is the modal damping coefficient associated with the same modal shape. Applying the modal superposition concepts, any mechanical quantity not directly influenced by local contacts may be computed according to:

$$\psi(t) = \psi_{sw} + \sum_j \psi_j \,.\, Y_j\,(t) \quad (2)$$

in which, ψ is a fatigue parameter of interest, ψ_{sw} the respective permanent share and ψ_j is the modal quantity related to the j^{th} modal shape. In Phase II, when the fatigue phenomenon is not affected by local nonlinear contacts, equation (2) may be considered to compute local quantities (e.g., stresses or stress intensity factors), with the submodelling relation established in the modal space adopting modal boundary conditions, $BDCOs_j$. On the other hand, when hot-spots are affected by nonlinear contacts related to rivets or bolts, the analysis has to be performed by imposing on the local model the railway loading defined by $BDCOs(t)$, with this being calculated as follows:

$$BDCOs(t) = BDCOs_{sw} + \sum_j BDCOs_j \,.\, Y_j\,(t) \quad (3)$$

where, $BDCOs$ are the displacement fields obtained in the global model at the boundaries of a given submodel, which defines the railway loading to be input to such a local model in the time domain, requiring a static analysis for each time step, t, assuming that the inertia field generated in the submodel is negligible when compared to the elastic one derived from the imposed boundary displacement fields. From these calculations, the local fatigue parameters of interest can be calculated. For either equations (2) or (3), the appropriate amplification factors, φ' and φ'', should be properly considered as in the applicable normative specifications [6].

For crack initiation assessment, analytical elastoplastic post-processing may be necessary when the elastic stresses are higher than the yielding limit, and the models suggested by Neuber [7] or Glinka [8] may be combined with the Ramberg-Osgood [9] proposal to calculate accurate elastoplastic values for localised and confined plasticity [4,5]. For crack propagation analysis, local behaviour in the elastic regime is expected, with Linear Elastic Fracture Mechanics principles being implemented to investigate the progression of a given crack [10,11].

3 Results

The proposed integrated methodology was applied to analyse the remaining fatigue life of the Várzeas Bridge located in Portugal and built in 1958, but already compose of typical modern steel grades (S355 and S235). This riveted structure is 281 m in length, composed of two inverted Warren trusses connected by cross-girders, supporting a ballastless railway track (see Figure 2). These structural members are the most important for the load carrying capacity of the bridge, and the respective fatigue safety is critical to ensure the structural integrity in order to extend the service life under increasing traffic demands.

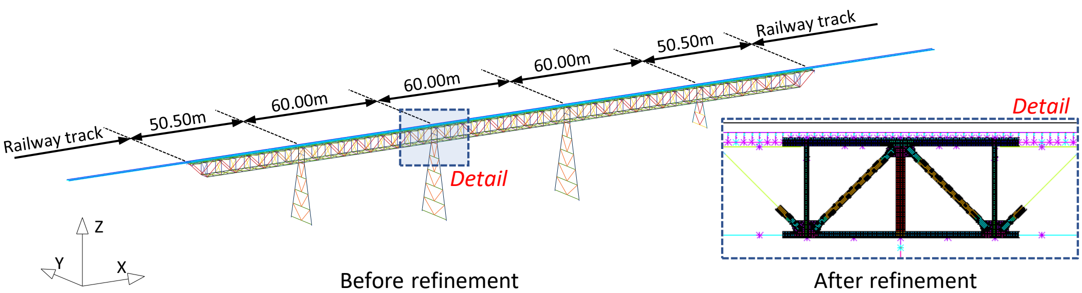
a) partial view of the bridge b) partial view of the balastless track

Figure 2. Várzeas Bridge: site photos [12,13]

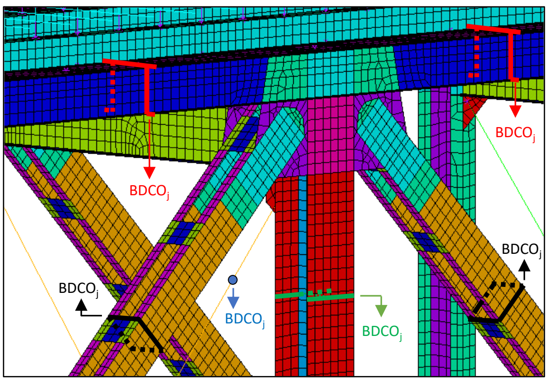
In Phase I, the global model of the bridge was conceived based on existing information complemented by data gathered after *in situ* visual inspections (see Figure 3 a), before refinement). Two ambient vibration tests were performed to identify the modal properties related to the global behaviour and those of the structural subsystem associated with the ballastless railway track, with these results considered as input to an optimisation process based on the implementation of a genetic algorithm [12,13] (as foreseen in Figure 1). 2286 riveted connections were identified and properly investigated, with 942 details classified as principal ones. The fatigue resistance of all connections was considered adopting the S-N curve for the category 71 ($\Delta\sigma_c$=71 MPa, m_1=3 and m_2=5), as proposed in the literature due to the absence of guidelines for riveted details in EN1993-1-9 [3]. Despite the geometrical differences in the riveted lengths of the connections, no distinction can be made in terms of fatigue strength due to the limitation of the available catalogue of S-N curves. Also, due to the lack of reliable data to define the real traffic scenario, the heavy traffic mix suggested in EN1991-2 [6] was considered, but it must be noted that past, present and future admissible traffic scenarios should have a relevant influence on fatigue damage.

After analysing all riveted connections, only 100 out of 2286 were classified as fatigue-critical, mostly related to the cross-girders or the diagonals [12], which shows the usefulness of Phase I to rationally limit the number of details to be investigated locally in Phase II. The type of detail connecting the diagonals to the gusset plates presented the higher fatigue damage indices, with the lowest fatigue life equal to 56 years and 6 months, meaning that if the adopted normative traffic scenario had been in circulation since the construction of the bridge, fatigue failures could be expected in the short term. Therefore, the diagonal-to-gusset plate connection, located at x=109.30 m and part of the node at x=110.50 m, was representatively analysed at a lower scale.

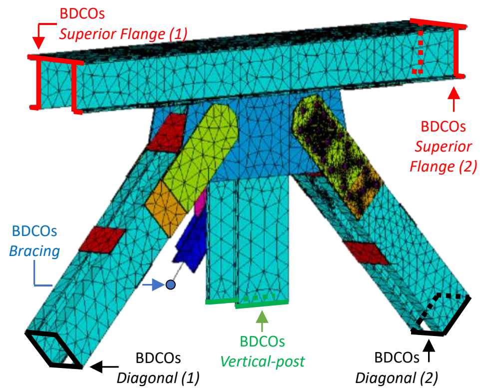
Subsequently, in Phase II, the multiscale relation between the submodel of interest and the global one was defined in the time domain, with the latter refined at the length of interest (see Figure 3a)). Following equation (3), the modal superposition of boundary conditions was carried out, and the $BDCOs(t)$ were properly amplified according to EN1991-2 [6] being then imposed to the submodel (see Figure 3 b) and c)). In the latter, all normal and friction contacts associated with the 44 rivets and 4 strengthening plates were modelled using contact pair elements CONTA174-TARG170 available in ANSYS [14].



a) global model: linear and shell elements, before and after refinement



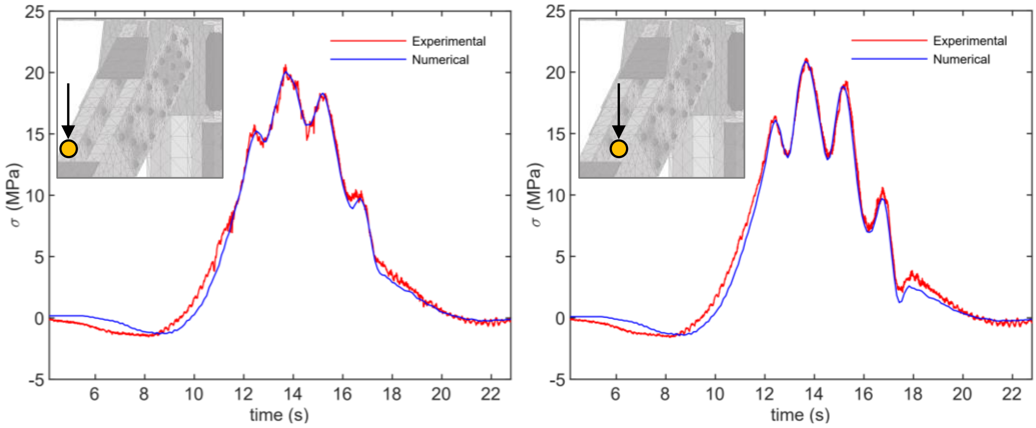
b) global model, after refinement



c) local model

Figure 3. Várzeas Bridge: developed numerical models [12,13]

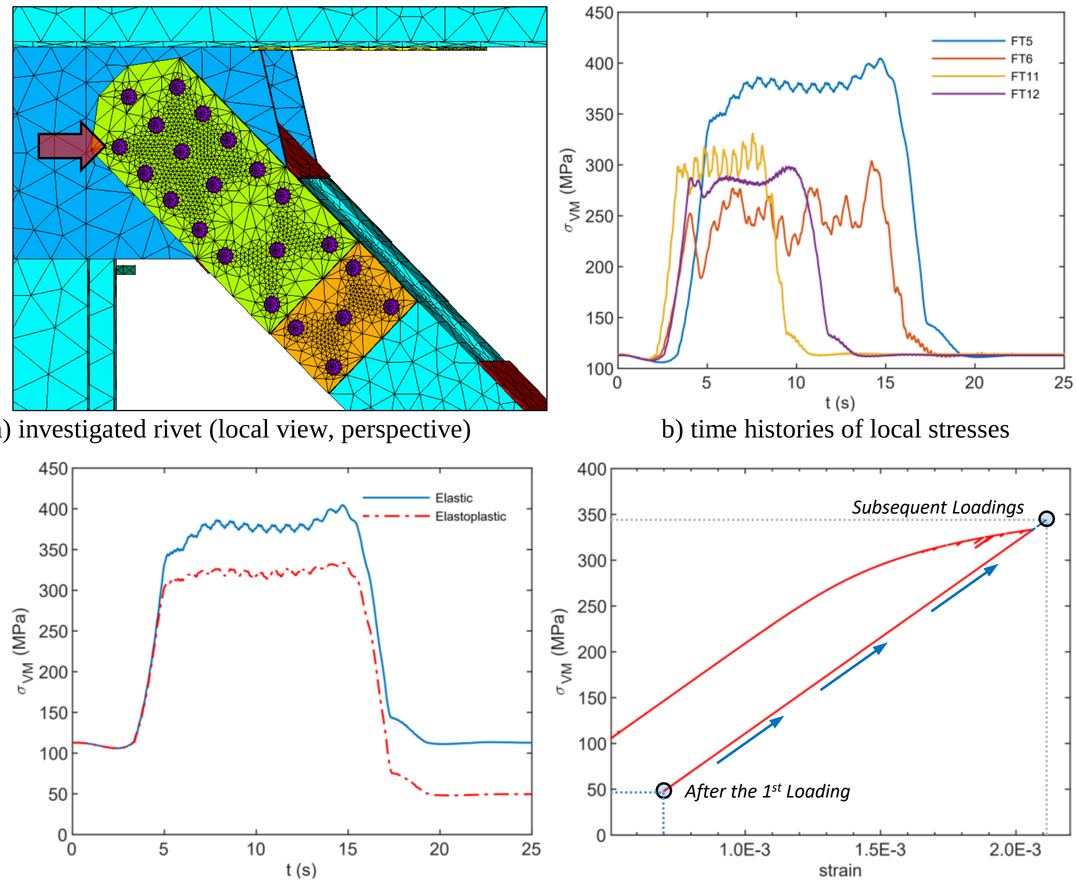
The numerically established submodelling relation was validated using stress results evaluated *in situ*, following the installation of strain gauges close to the riveted detail of interest. For the passage of a train with known axle loads and wheelbases, running at 53.34 km/h, and assuming an elastic response at the member scale (see Figure 1), the experimental stress results were computed from the strain ones, which allowed these experimental values to be compared with the numerical ones evaluated in the submodel (Figure 4).



a) strain gauge 1 b) strain gauge 2

Figure 4. Comparison of experimental and numerical stress values (submodel)

In Figure 4, the nominal stresses obtained *in situ* are compared with the numerical values for two strain gauges close to the fatigue-critical detail at x=109.30 m, whose location is identified representatively. A good agreement was achieved between the stress spectra, proving the reliability of the multiscale relation [13].



a) investigated rivet (local view, perspective) b) time histories of local stresses

c) time histories of local stresses, FT5 d) stress-strain diagram, FT5 (elastoplastic)

Figure 5. Time histories of the local von Mises stresses

After initial analyses, some degree of multiaxiality related to the local responses of interest at the hot-spots was identified. However, the stress-strain relation associated with the axial direction of the diagonal showed to be the dominant one. Assuming a conservative assumption to analyse the magnitude of the local stresses, the local von Mises stress values were computed by considering the average of the stress fields across the thickness of the most stressed member, adopting a reasonable approximation to evaluate the fatigue life of an edge crack propagating to the full width.

Concerning the fatigue assessment, in Figure 4 a) and b), the results at the critical point of the most stressed rivet hole are presented for the fatigue train type 5 (FT5), part of the normative heavy traffic mix considered. Since the von Mises local stress values are higher than the yielding (355 MPa), analytical elastoplastic post-processing was implemented based on the Glinka model [8] (see Figure 4 c) and d)). Taking into account the plastic residual stress developed that reduces the related permanent value, all the train passages after the first of FT5 are in the elastic domain, with a maximum von Mises stress equal to 346.75 MPa. Subsequently, applying the rainflow counting algorithm, the Basquin model [15] was assumed to compute the fatigue damage, which was accumulated linearly as a function of the traffic composition and volume. A theoretically infinite fatigue life related to the crack initiation was obtained, which means a shift in terms of the fatigue resistance regime considering the limited total fatigue life evaluated using the adopted global fatigue assessment method in Phase I. Given the results achieved, the implementation of Phase III was not necessary, and the bridge is considered safe for fatigue issues if the preservation conditions are maintained as at its early ages.

4 Conclusions and Contributions

The integrated methodology is proposed to investigate existing bridges built and designed using superseded standards, without specific safety checks regarding fatigue phenomena, in order to overcome the limitations of the current normative procedures. From the case study investigated, some main conclusions can be highlighted:

i) the implementation of the linear damage accumulation method in Phase I is conservative for investigating the fatigue life of details, but has proved to be useful for screening those with proneness for the development of important fatigue phenomena;
ii) in Phase II, the applied local fatigue approach reduces the conservative approximations by accurately considering the characteristics of the real mechanism of loading transference;
iii) the shift from the finite life regime to the theoretically infinite fatigue life related to crack initiation shows the importance of fully exploring the fatigue resistance of details, taking into account the real local geometrical, material and contact characteristics.
iv) by establishing submodelling relations, leveraged by modal superposition concepts to increase the efficiency of calculations, a reliable local scale structural assessment, more representative of the nature of fatigue damage, can be performed;
v) the progressive global-local fatigue calculation methodology is based on several numerical and analytical approaches that are critical tools for the bridge management authority to take enlightened decisions, also allowing to continuously follow the structural and fatigue behaviour in a health monitoring approach;
vi) the definition of statistical methodologies to define admissible assumptions for past, present and future traffic scenarios may be a relevant further development.

Overall, the integrated methodology for fatigue life prediction of existing metallic railway bridges opens new possibilities to accurately address a wide range of details with geometrical, material and contact properties not covered in the current applicable normative specifications. The suggested methodology establishes a systematised procedure to investigate fatigue in ageing bridges, ensuring the fatigue safety for certain periods of time, depending on the traffic in circulation. Extending the service life of existing bridges will have relevant environmental and economic impacts.

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