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Integrated Methodology for Fatigue Assessment of Existing Metallic Railway Bridges

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Abstract

Bridges are typically large structures whose numerical modelling is focused on the global scale, mainly due to computational constraints. Using such models, the evaluation of fatigue phenomena is not possible based on local mechanical quantities, with the difference between the dimension of the structure and the local nature of the damage being a multiscale problem. Presently, S-N relations for nominal stresses are assumed to overcome this issue, but the mechanism of loading transference may not be correctly represented and conservative approximations are in general adopted to analyse existing bridges. In order to reduce the assumed safety margins, hierarchical modelling strategies should be implemented to allow the fatigue assessment based on local methods using fatigue parameters evaluated according to the properties of the real structural response. At the local scale, the geometrical, material and contact characteristics may be modelled using submodelling relations potentiated by modal superposition principles to improve the computational efficiency. Thus, an integrated methodology is proposed, combining global and local methods, each with a specific range of application. Aiming at demonstrating the capabilities of the suggested multiphase calculation strategy, a real case study is investigated.

Keywords: fatigue assessment, existing bridges, local methods, hierarchical models.

1 Introduction

Railway bridges are subjected to complex loadings that may give origin to fatigue damage over the years, with relevant consequences for structural integrity.

Considering the expected increase in the traffic demand due to sustainable and ecological mobility policies, the development of methodologies involving advanced analysis tools to extend the remaining service life of these bridges has been set as the main priority [1].

Fatigue assessment of large structures is highly limited by geometrical challenges, with the accurate numerical evaluation of dynamic local responses leading to complex multiscale problems associated with high computational costs, making fatigue analysis using local methods extremely difficult. Currently, the difference between the global scale and the local nature of fatigue damage is overcome using S-N curves for nominal stresses, but this approach has relevant drawbacks that limit the respective application to existing bridges without assuming important conservative margins. Thus, an integrated methodology with different phases of fatigue analysis should be proposed, adopting global methods to define the critical connections, followed by local approaches to refine the assessment of those details, both calculation stages validated with experimental information about the structure (see Figure 1).

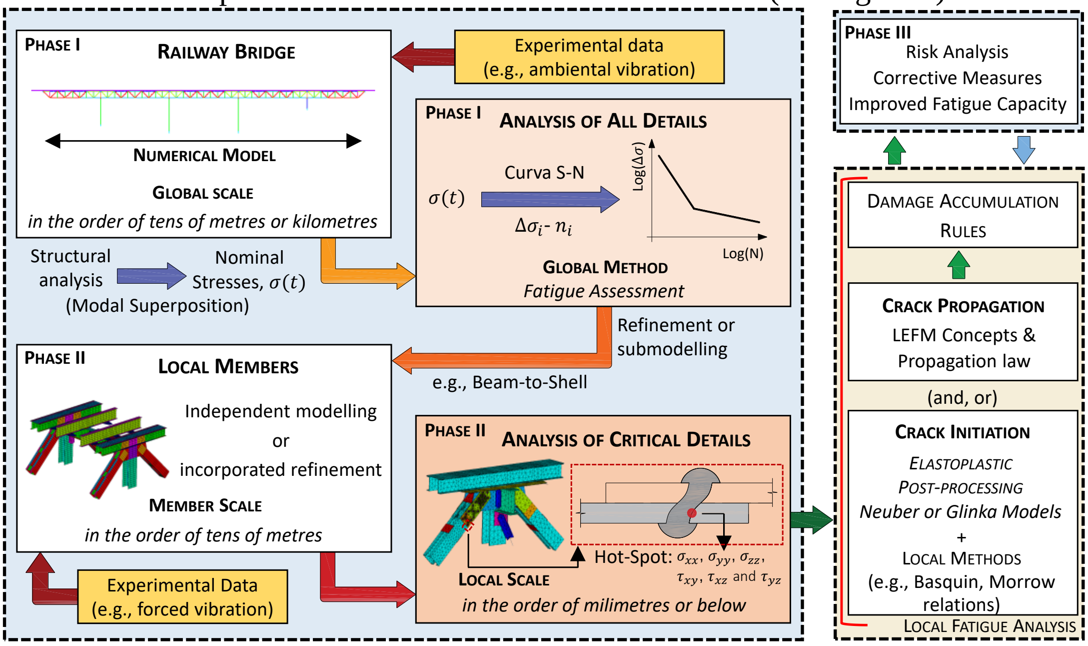


Figure 1: Integrated methodology for fatigue life prediction of existing metallic railway bridges

In Figure 1, sequential implementation of three phases of fatigue assessment is suggested to analyse all connections of a certain existing metallic railway bridge. In Phase I, the linear damage accumulation method proposed in EN1993-1-9 [2] is admitted to identifying the fatigue-critical details, assuming a given level of conservatism due to the approximation between the characteristics of the mechanism of loading transference related to the S-N curve adopted for nominal stresses and the real local structural response. After identifying the connections with higher fatigue damage indexes, Phase II should be implemented by applying local approaches to refine the structural calculations with a basis on submodelling relations defined considering modal superposition principles, allowing accurately to evaluate local mechanical quantities to compute the fatigue life using local methods, overcoming the multiscale problem [3, 4]. An updated fatigue classification should be established, with the connections still defined as critical being investigated in Phase III, in which corrective measures should be designed in function of a risk analysis based on the importance of such details and magnitude of the respective damage. Once the three sequentially dependent phases of the calculations have been implemented, the bridge management authority should have data to decide about the remaining fatigue life of the structure, in the function of certain traffic scenarios.

2 Methods

According to EN1991-2 [5], quasi-static or dynamic calculations may be performed in Phase I, allowing one to obtain nominal stress measures to compute fatigue damage. When dynamic analyses are mandatory, the system of equations that defines the structural response may be decoupled into independent ones 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, respectively, the matrix of modal coordinates and the matrix of modal forces, both associated with the N degrees of freedom. Also, w_j is the frequency of mode j and ξ_j is the modal damping coefficient related to this modal shape. In general, any mechanical parameter may be computed superimposing a limited number of vibration modes according to:

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

in which, ψ is a certain fatigue quantity, ψ_{sw} the respective permanent portion and ψ_j is the modal quantity associated with the shape of mode j. In Phase II, this generic parameter may be defined as a local stress, strain or displacement field associated with a given submodelling relation. Concerning the last, the boundary conditions may be calculated as follows:

$$BDCO(t) = BDCO_{sw} + \sum_j BDCO_j\,.Y_j\,(t) \quad (3)$$

where, $BDCO$ is the displacement field evaluated in the global model at the boundaries of a certain submodel, allowing to define the loading to be imposed on such a local model in the time domain. When the fatigue phenomenon is not affected by local nonlinear contacts, equation (2) may be considered based on the modal superposition of local quantities (e.g., stresses or stress intensity factors). On the other hand, if the critical point is influenced by the structural performance of mechanical fasteners, the analysis should be carried out by imposing to the local model the railway loading defined by $BDCO(t)$, equation (3), performing one static analysis for each time step, t. From such calculations, the local fatigue parameters of interest may be defined. Also, for either equations (2) or (3), the applicable amplification factors should be properly considered, φ' and φ'' [5]. Concerning the initiation of cracks, analytical elastoplastic post-processing may be required if the magnitude of the elastic stress-strain relation is higher than the yielding, with the models suggested by Neuber [6] or Glinka [7] combined with the Ramberg-Osgood [8] proposal allowing to obtain accurate results for confined and localised plasticity [3, 4]. Regarding the crack propagation, a response in the elastic regime is expected, and Fracture Mechanics concepts should be implemented to investigate the progression of a certain crack [9, 10].

3 Results

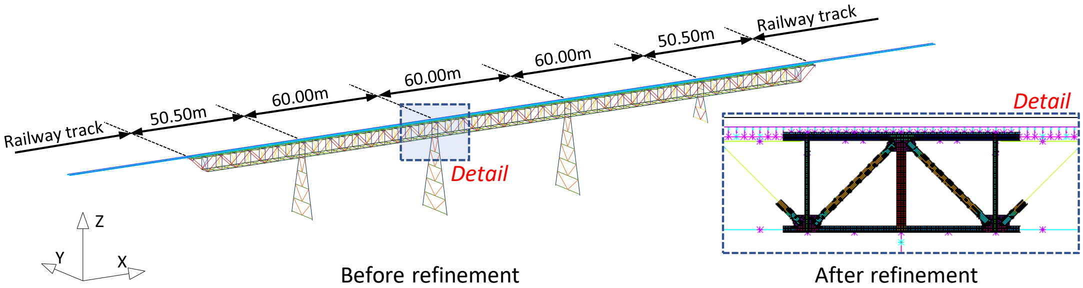
The integrated methodology was implemented to investigate a riveted structure in Portugal with 281 m and built in 1958. The Várzeas Bridge is composed of two inverted Warren trusses connected by cross-girders, supporting a ballastless railway track (Figure 2). Such structural members may be defined as the principal ones, with complex riveted connections between them, whose fatigue safety is critical to ensure the structural integrity for a certain period of life, under a given future traffic scenario.

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

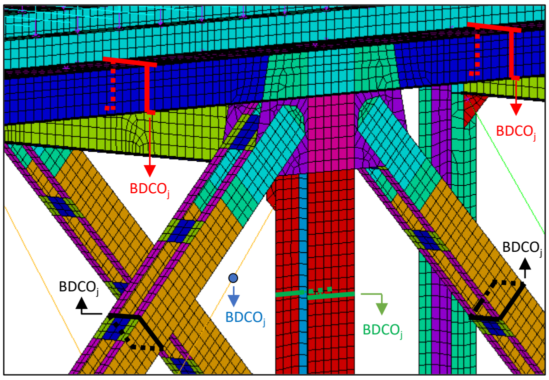
Figure 2: Várzeas Bridge: site photos

In Phase I, after the global model was conceived, 2286 riveted connections were investigated, considering the heavy traffic mix proposed in EN1991-2 [5], due to the lack of data about the real trains circulating on the bridge, and the S-N curve for the detail category 71 ($\Delta\sigma_c$=71 MPa, m_1=3 and m_2=5), as advised in the literature given the absence of guidelines for riveted connections in EN1993-1-9 [2]. The type of detail between the diagonals of the inverted Warren trusses and the gusset plates was identified as critical, with the lowest fatigue life equal to 56 years and 6 months if the admitted loading had been circulating on the bridge since its construction (lower than the age of the structure). Thus, the connection diagonal-to-gusset plate located at x=109.30 m, part of the node at x=110.50 m, was representatively investigated.

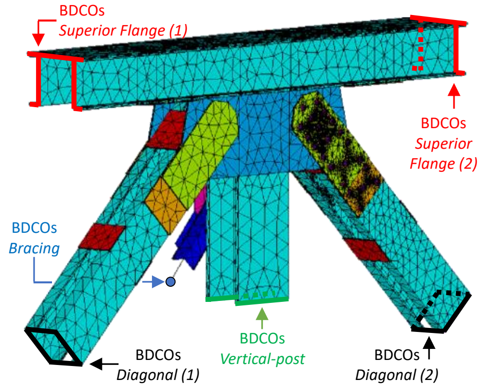
In Phase II, a submodelling relation was established between the local model and the global one, refined at the length of interest (Figure 3 a)). The modal superposition of boundary condition was performed according to equation (3), with $BDCO(t)$ properly amplified being imposed to the submodel (Figure 3 b) and c)), allowing one to define the local stresses at the hot-spots for crack initiation.



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



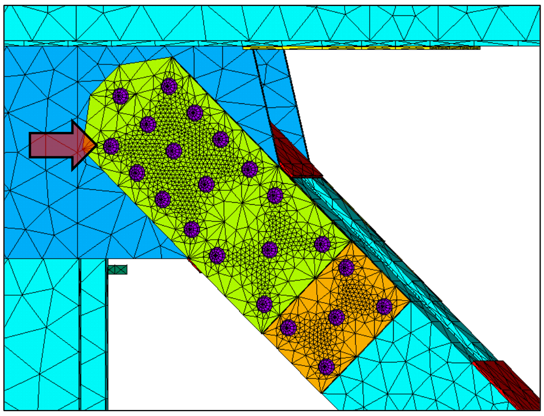
b) global model, after refinement



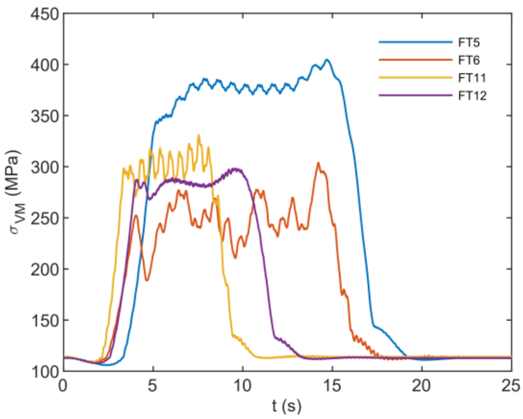
c) local model

Figure 3: Várzeas Bridge: developed numerical models

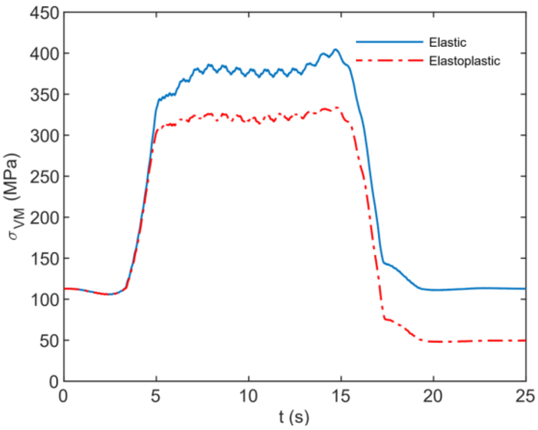
In Figure 4 a) and b), the results for the most critical rivet hole are presented. Taking into account that the von Mises local stress is higher than the yielding (355 MPa), analytical elastoplastic post-processing was implemented based on the Glinka model [7] (Figure 4 c) and d)).



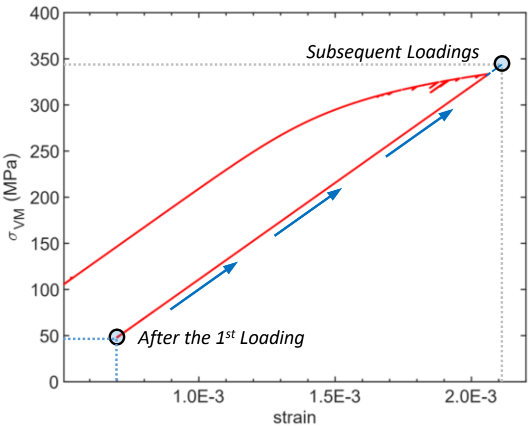
a) rivet C'13 (local view, perspective)



b) time histories of local stresses (C'13)



c) time histories of local stresses, FT5 (elastic and elastoplastic) (C'13)



d) stress-strain diagram, FT5 (elastoplastic) (C'13)

Figure 4: Time histories of the local con Mises stresses

Considering the plastic residual stress, all the train passages after the first one related to FT5 are in the elastic domain. Subsequently, applying the rainflow algorithm, the Basquin proposal was used to compute the fatigue damage, with this being accumulated depending on the characteristics of the traffic. Overall, a theoretical infinite fatigue life related to the crack initiation was defined, after a limited value was calculated by implementing a global normative methodology.

4 Conclusions and Contributions

The integrated methodology is proposed to investigate existing bridges built and designed using superseded standards, without specific safety verifications concerning fatigue phenomena. Several phases of analysis are suggested, supported by experimental data and information about the bridge. Adopting hierarchical modelling based on submodelling techniques potentiated by modal superposition principles to implement local fatigue methods, the multiphase methodology may be applied to a broad range of existing metallic railway bridges, overcoming the normative limitations of the current standards and guidelines mainly conceived to design new structures. After defining the fatigue-critical details using normative global methods, advanced calculations strategies may be implemented, allowing to consider numerical models that represent the respective real response of the local mechanism of loading transference, modelling accurately the local geometrical and contact properties. Also, the analytical elastoplastic post-processing addresses the localised and confined plasticity when necessary as demonstrated, with the accuracy of this approach already confirmed in previous works [3, 4].

For the investigated bridge, the results obtained from a reliable numerical replication of the local response led to an efficient implementation of a local notch method. The shift from the regime of finite life to the regime of theoretically infinite life associated with the initiation of cracks proves the importance of local fatigue calculations in the context of exploring entirely the safety margins of existing bridges. Also, preliminary calculations showed that about 50 years would be necessary for the progression of a certain pre-existing and non-detected defect until reaching the respective critical length, which proves the safety of the structure.

Overall, the implementation of advanced numerical analysis and local fatigue methods opens new perspectives to investigate a wide range of fatigue-critical details with different geometrical and material properties, overcoming the drawbacks associated with the limited catalogue of available S-N curves for nominal stresses. The proposed integrated methodology should establish a systematised process to analyse fatigue in the existing bridges part of the Portuguese and European stock, maintaining the same safety criteria and promoting the interoperability of the network.

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