Determination of stresses in welded connections of railway bridges with the finite element method and global-local approach

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Abstract. Due to the cyclic loading in railway steel bridges and the high vehicle weight per axle, the welded joints are subjected to stress concentration points that induce fatigue damage that could lead to the collapse of the structure. Therefore, it may be necessary to use more accurate methods to obtain the stresses and a true value of the service life of the structure. In some cases, the evaluation of stresses by means of a refined finite element model may lead to more precise results than usual global approaches. Therefore, this paper proposes a global-local methodology to obtain the stress history in a bridge span with the passage of the cargo vehicle, using the commercial software Ansys and Python routines to post-process the results. The global model is developed with a coarse mesh, and its displacements are applied to a local model with a refined mesh. It was shown that, for the proposed problem, a linear static analysis can be carried out, hence, a moving load is passed through the global model and then the stress history in the local model is obtained via superposition.

Keywords: finite element model, railway bridges, global-local methodology, hot spot stress, fatigue

1 Introduction

In structures subjected to cyclic loading, particularly railway bridges, where those fluctuations are very large, fatigue failure may occur. If an adequate method for assessing stress concentrations is not adopted, it is not possible to adequately predict fatigue behavior and evaluate the structure's fatigue life. In fact, fatigue is the main cause of collapse in metallic bridges, accounting for over 38% of failures (Kuhn et al. [1]). Some techniques can be used for fatigue assessment, among which the nominal stress method is the most used. In this global approach, simple cross-sectional stresses that don't fully account for geometric discontinuities are calculated and compared to code limits.

In more complex geometries, however, a more precise local approach is needed. In this case, particular geometric features of the structure may be taken into account, but a numerical model considering the studied detail is needed to assess stress concentrations that may accentuate fatigue issues in the structure. This approach is dependent on numerical models with fine meshes, which, in the context of a bridge are unfeasible for the whole structure. In this case, a global-local approach may be used. A global model that captures the structural behavior is developed. This model may have a coarser mesh and not fully represent all the details of the proposed structure. Its results are then used to feed a local model, where all the relevant characteristics of the proposed structural detail are modeled, allowing for a determination of precise stress-history data that can be used in fatigue analysis. From this refined model, the hot-spot stress (that includes effects of stress concentrations and welding) may be calculated using reference interpolation functions. For example, for calculation of "type b" hot spot stresses, according to Hobbacher [2], a quadratic interpolation may be used to determine the stress according to eq. (1):

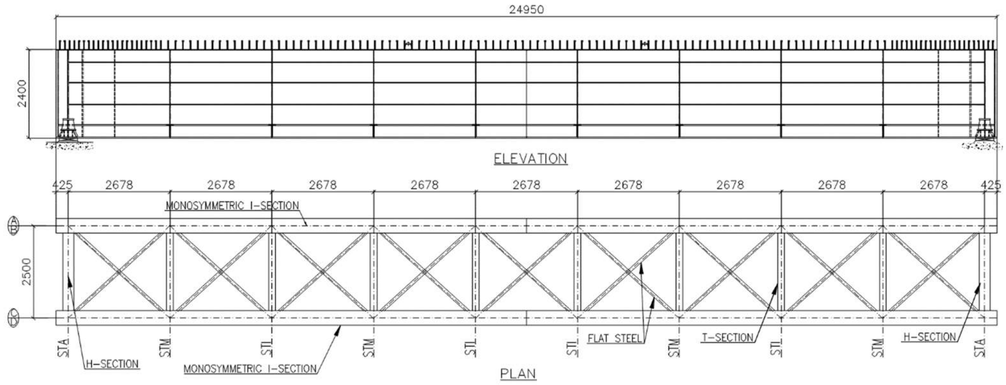
$$\sigma_{hs} = 3 \times \sigma_{4m} - 3 \times \sigma_{8mm} + \sigma_{12mm} \quad (1)$$

Where σ_{hs} is the hot spot stress and σ_{4mm}, σ_{8mm} and σ_{12mm} are the stresses at 4, 8 and 12 mm from the weld toe.

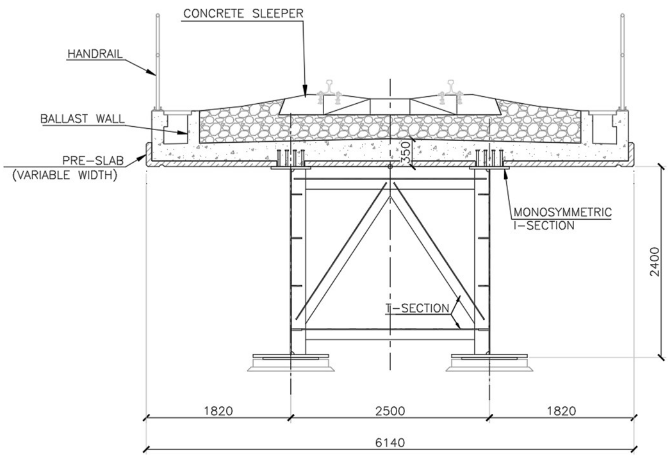
This approach has been successfully used multiple times for evaluating fatigue damage in high-speed passenger train railway bridges in Europe [3-6] but in Brazil a very different reality is present. The compositions have much higher loads by axle, their speeds are much smaller and the railway's irregularity pattern is very different. In this context, the present work discusses the modeling of a heavy-haul composite steel-concrete railway bridge using the global-local approach towards the determination of the hot-spot stress due to the passage of a composition for fatigue analysis.

2 Global model

The object of study of this work is a cargo railway bridge that is used for slow speed, heavy-haul trains. The bridge has 22 simply supported spans with 25 meters each and is composed by two composite steel-concrete girders with monosymmetric I-section, and bracing structure composed by T, H and flat steel profiles. The bridge deck is composed by pre-slab and slab with variable cross section. Figure 1 shows the main characteristics of the bridge structure. The global model has been developed in a parameterized manner within the commercial software ANSYS Mechanical APDL v2020R1 [7], utilizing shell and beam elements. To represent the bracing system, the BEAM188 element (with 2 nodes and 6 degrees of freedom per node) was used. The girders and the ribs were modeled with SHELL181 elements, with 4 nodes and 6 degrees of freedom. As illustrated in Fig. 1b, the bridge deck is composed of pre-slab, slab with variable width cross-section, ballast, concrete sleeper, handrail, rail and other elements that constitute the railway substructure. However, in a simplified way, the slab was represented by shell elements (SHELL181) with constant thickness of 35 cm, furthermore, the remaining nonstructural elements have been represented by an additional mass of 648 kg/m² on the slab.



a) Plan and elevation of the bridge



b) Intermediary cross section (STI)

c) Schematic 3D

Figure 1. Geometry characteristics of the bridge, with measures in mm

The material utilized for the shell and beam elements that compose the bridge superstructure, such as girders and the bracing system, has been steel with a longitudinal elasticity modulus (E) of 200 GPa, a Poisson's ratio (ν) of 0.3 and density (ρ) of 7850 kg/m³. The material utilized for shell elements that represents the slab, is concrete with E=33.1 GPa, ν=0.2 and ρ=2500 kg/m³.

The boundary conditions were applied to the end of the girders, in the bottom flange of the I profile, restricting the translations (UX, UY and/or UZ), as illustrated in Fig. 2, representing the superstructure connections with the bridge support devices in the concrete columns. Moreover, as it is a composite steel-concrete structure, node coupling between corresponding top flange and slab positions was conducted as a simplification to simulate the shear connection between the structural elements. This allowed for the consideration of full shear interaction between profile and slab.

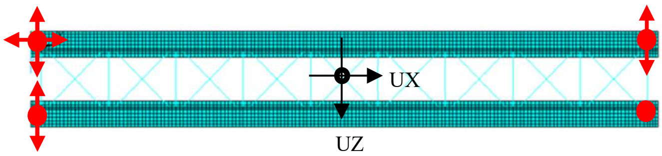


Figure 2. Boundary conditions of the railway bridge

To determine the ideal size of elements in the global model, a mesh study was proposed. From the modal analysis of the structure, the modes and vibration frequencies were obtained by considering shell elements with a refined mesh (e=2.5 cm) up to a coarse mesh (e=100 cm). The results of the vibration frequencies and node number of the analyzed structure are illustrated in Fig. 3. The modal analysis indicates that, for the shell elements in the global model, the mesh size of 15 cm is sufficient due to the lower frequency variability shown in the graphic. Therefore, this mesh can be adopted in the global model. Moreover, some local vibration modes to the beam elements representing the bracings were noted, and from of a similar analysis, a mesh size of 5 cm for the beam elements was proposed.

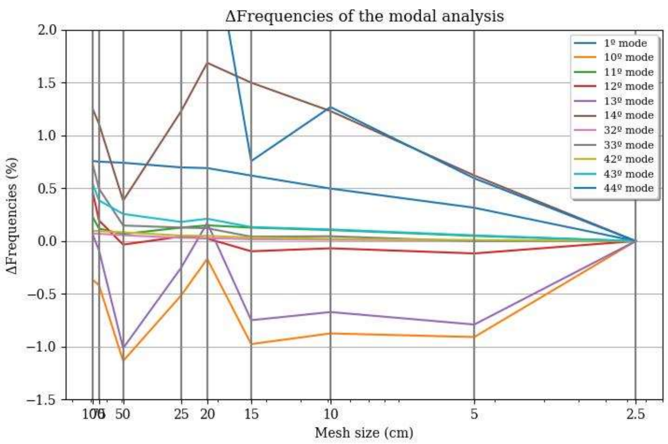


Figure 3. Variation of frequencies of the modal analysis per mesh size

For the global model analysis, the vehicle used to assess the stresses in the bridge is composed by 3 Dash 9 locomotives type with 238 kN/axle and 258 GDE wagons type with 275 kN/axle. Figure 4 illustrates locomotive and wagon details.

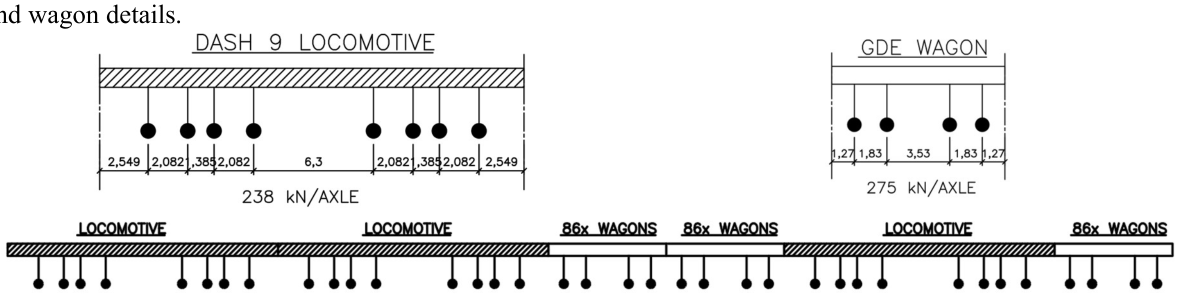


Figure 4. Rail vehicle composition

Regarding the analysis type, one may conduct either a static or a dynamic analysis for the global model. According to the EN 1991-2:2003 [8], for the given bridge, as the vehicle speed is lower than 200 km/h, the bridge is simply supported and the first natural frequency is within the limits established by the code, a dynamic analysis is not required. For the sake of the given paper, though, both static and dynamic analyses were conducted to assess the influence of considering the dynamic response in the model. A simplified vehicle was proposed, composed of two locomotives followed by 30 wagons (with the same weights per axle from Fig 4). The vehicle speed was taken as 50 km/h. For the dynamic analysis, Newmark's algorithm was used, with time steps of $\Delta_t = 0.0125$s and a damping coefficient of 0.5%. The results for midspan deflection along time for both the static and the dynamic analyses are presented in Fig. 5. It is noticeable that, despite the computational cost of a dynamic analysis, only minor changes in displacements are observed for the selected speed. Therefore, further on in this paper, only static analyses will be conducted.

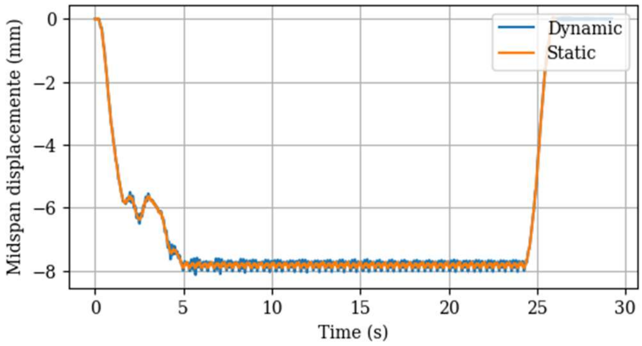
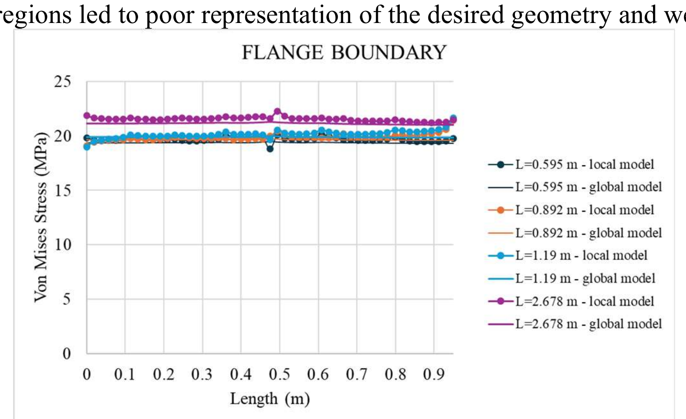


Figure 5. Midspan deflection along time

3 Local model

The local model was developed from the region in global model with maximum displacement, and the connection in the midspan was chosen. The selected joint is composed by a section of girder, ribs and bracing profiles. After definition the interest region, the o geometry of the joint was exported from a CAD software to ANSYS and the volume representing the connection was obtained. All joint elements are formed by solid element type SOLID186, with 20 nodes and 3 translational degrees of freedom per node.

To obtain the stress field in the connection, the displacements obtained from the global model are applied in the local model boundary. It should be noted that, in a global-local approach, the definition of the local model's boundary can be tricky. While a larger local domain may lead to more precise results, it also leads to greater computational costs. Therefore, a convergence test was realized to define the ideal boundary region for the local model. To do so, von Mises stresses of both local and global models were compared in the boundaries of four different local model lengths, as shown in the Fig. 6. If the local domain is not compatible with the global response, deviations between global and local stress results should occur. The figure shows that the stresses present good results in the proposed comparison even for the smallest chosen domain, so the 59,5 cm domain was adopted. Smaller regions led to poor representation of the desired geometry and were not considered.



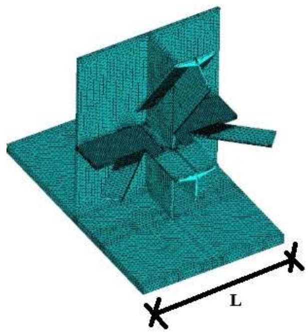
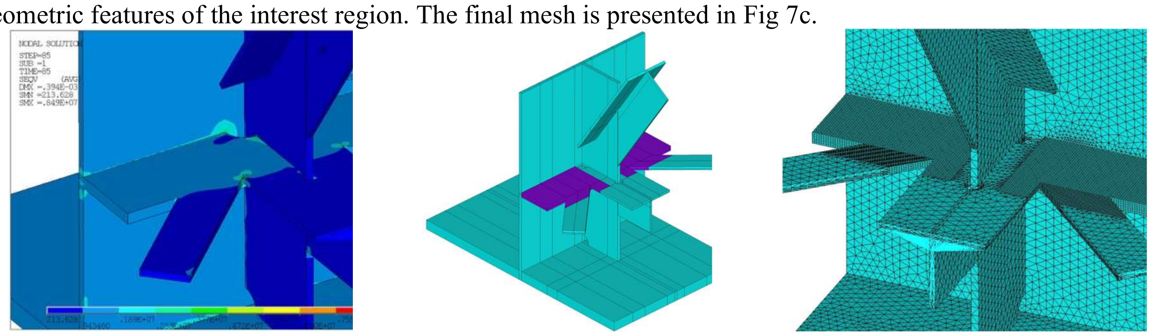


Figure 6. Stresses along the flanges in the boundary

In the mesh size analysis for the local model, an interest region with high stress concentration and prone to fatigue failure was defined and the model had two different mesh sizes: one, more refined, at this region of interest and another one, coarser, in the rest of the model. These regions are presented in Fig. 7a and 7b. A path for calculating the hot spot stresses was defined and a stress evaluation along this path was conducted. The results from Fig. 8a illustrates the stresses along this path for different mesh sizes. It is noticeable that all the proposed meshes lead to very similar results in the stress distribution along this path, except at the point where a singularity is expected. The hot-spot stress was calculated for each of the cases and is illustrated in Fig. 8b. There is very little difference between results, therefore the 4 mm mesh was adopted, as recommended by Hobbacher [2]. In the surrounding region, it was noted that virtually no change to the calculated hot spot stress occurs as the mesh is changed. A mesh size of 15 mm was adopted as it was the largest possible value that could properly represent all the geometric features of the interest region. The final mesh is presented in Fig 7c.

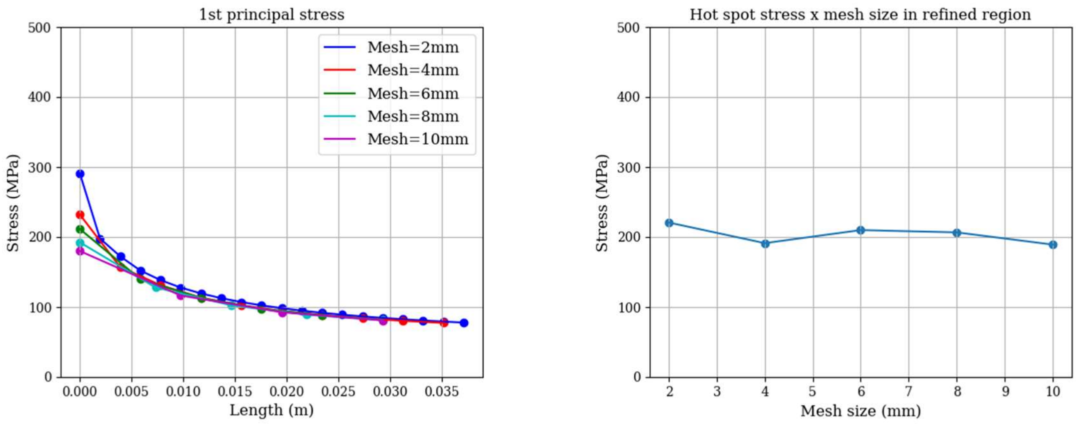


a) Stress distribution and hot spot

b) Connection geometry and region of finer mesh

c) Finite element mesh

Figure 7. Stresses along the flanges in the boundary



a) Stress along the bar section

b) Hot spot stress for differents mesh size

Figure 8. Stress concentration region

4 Global Local Approach

After the development of global and local models, the two of them must be coupled to perform the intended analysis. As it was shown, a static linear analysis is sufficient for the global model, indicating that superposition of results may be used in calculating the stress distribution at the connection. The results for the hot spot stress at the analyzed point were obtained as follows. Firstly, a moving-load analysis was conducted on the global model. A unitary load was passed through the bridge and the displacement field of the structure for each different position of the load was stored. Then, the positions of the boundary nodes of the local model were stored in an external file. For each of these nodes and for each position of the load in the global model, the displacements were stored and then imposed to the local model. This allowed for the determination of the local model stresses for each given position of the load. Then, the full train was considered in the analysis by superposition. For each instant of the passing of the vehicle, each axle had its position determined and then, the stresses corresponding to this position were assessed and added allowing for the determination of the stress history. A Python code was implemented for the post-processing (superposition) of the results.

Regarding the transfer of boundary conditions between the two models, two different approaches were needed. At some regions, the boundary of the local model is represented in the global domain by shell elements. In other regions, the representation at the global level is by means of beam elements. Two transfer techniques are then used. In the first one, named shell-to-solid, the corresponding data from the nodes of the local model is obtained by projecting the nodes to the mid-plane of the corresponding shell and interpolating their displacements from global nodal results by the shape functions of the corresponding elements. Any extra displacement due to cross-sectional rotation is also accounted for. This is automatically performed by the ANSYS package by means of the CBDOF command. For bracing elements, another technique was used. The application of displacements between the bar and solid elements is done by transferring the boundary conditions from the global model to the local model through a rigid bar placed in the connection region of interest in the local model. In the local model, the contour nodes of the corresponding elements are selected and a rigid element type MPC184 is created connecting the surrounding nodes and the centroid node of the solid element (pilot node). The rotation and translation displacements in the global model at the pilot node coordinate are saved in an external file, and the displacements are applied to the local model at the pilot node.

5 Results and discussion

After conclusion of the two numerical models and integration between results, the stress history for one composition was assessed. The superposition of the results led to the stress-history presented in Fig. 9. It is noticeable that the maximum hot spot stress was of approximately 75 MPa. Also, the stress history is composed of several small fluctuations in stress due to the change in wagons and one large peak (corresponding to the passage of the DASH-9 locomotive, which has a smaller distributed weight than the wagons. A detail of the graph on the passage of the wagons is also presented.

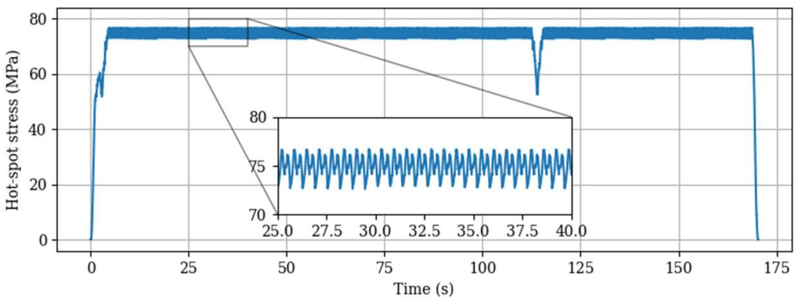


Figure 9. Hot spot stress the passage of a vehicle

It is noticeable that, overall, the stress amplitude in the load cycles is small (about 5 MPa). Such a low amplitude should not introduce any fatigue damage to the structure, as it is below the cut-off limit for this detail (of approximately 40 MPa). Only two load peaks (corresponding to the composition entering and leaving the bridge and to the passing of the middle locomotive) provoke damage in this scenario. Hence, the detail is not expected to present fatigue failure over the structure's life.

6 Conclusions

In the present paper, a global-local approach for stress determination in welded bridge connections was presented. The methodology comprised finite element models at two different levels, a global model, with coarse mesh, made of shell and beam elements that captures the global dynamic response of the bridge and a local model, made of solid elements, that is used for stress evaluation, importing displacements from the global model.

A few conclusions regarding the development of numerical models for this purpose can be taken. Firstly, for the given span and vehicle speed, it was noted that considering the dynamic behavior in the numerical analysis of the global model is unnecessary. This is in line with what is described in EN 1991-2:2003 [8] that defines specific parameters upon which the dynamic analysis is needed. Also, regarding the local model, it was shown that, for the chosen detail, the selection of a size for the local domain was not a critical factor. In fact, it was noted that the smallest of the domains that could properly represent all geometrical features of the connection was already suitable for the proposed model. Regarding mesh size of the local models, two domains were developed and, firstly, it was shown that a 4 mm mesh size was sufficient for calculating the hot-spot stresses, as prescribed in IIW [2] recommendations. Also, for regions that are further from the hot spot, a coarse mesh may be used without imparting any change to the stress calculations. In the proposed study, the coarsest mesh that could represent properly all geometric features of the connection was adopted to the external domain.

Lastly, regarding the assessment of stresses due to the passing of the composition, it was noted that no significant stresses are developed. In fact, the stress amplitude of high-cycle loading is below the cut-off limit for this detail, inducing no fatigue damage upon the passage of the composition.

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