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Analysis of dynamic and fatigue effects in an old metallic riveted bridge

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ABSTRACT

The fatigue behaviour of steel railway bridges is a complex phenomenon. On the one side, the Engineer must face the problem of dynamic amplification of the loads and their randomness, on the other side, the fatigue resistance is highly dependent on the load itself, since for different stress levels the material can sustain different number of cycles. This complexity makes the identification of the critical elements for structural safety a difficult task. In this context, and in the framework of the European research project FADLESS, the Laboratory of Vibrations and Monitoring (ViBest) of FEUP has conducted extensive research concerning the evaluation of dynamic effects and fatigue analysis of an old riveted railway bridge. Owing to the importance of this phenomenon, complementary numerical and experimental approaches have been used to assess fatigue effects. This article describes the main steps taken towards the goal of evaluating the dynamic behaviour and the fatigue life of this structure.

1. Introduction

Historically, the economic development has been always associated with the construction of railway lines, or with subsequent increase of traffic, vehicle axle loads and speed. Therefore, old railway metallic bridges, in many cases with more than one hundred years, have been required over the years to carry heavier vehicles and endure higher velocities than allowed by the original design. In addition, the cumulated degradation due to corrosion and fatigue contributes to an increased concern for their safety [1].

Owing to economic, cultural and environmental reasons, replacing every bridge at the end of the original design life has not proved to be sustainable. Additionally, society increasingly requires an optimised use of resources balanced with a deep sense of cultural and patrimonial preservation. This means that many structures, and particularly railway bridges, are considered historic landmarks and must therefore be preserved. These considerations make it clear that it is very important to correctly determine the structural behaviour of these structures, thereby making use of the latest scientific knowledge, in order to assess their fitness for further use.

In this context, since it is responsible for 80% to 90% of failures in steel structures [2], fatigue has emerged as one of the major concerns associated with old metallic railway bridges. Fisher et al. [3,4] showed that the majority of fatigue cracks are caused by distortion of member cross sections, local vibration and out-of-plane bending of webs. Numerical approaches, using local finite element models, nowadays allow one to study the realistic behaviour of structures of this kind with appropriate consideration of vibration-induced distortion and fatigue [5].

Furthermore, the evaluation of such phenomenon benefits from the implementation of monitoring campaigns, since they reduce the uncertainties associated with the variables of the problem [6]. For instance, in [7], the use of continuous dynamic monitoring made possible to detect damage by evaluating the variation of modal parameters as a function of time after appropriate removal of effects of environmental and operational factors. Particularly in the domain of railway bridges, Reference [8] presents a case where monitoring was used successfully for strain and acceleration measurements leading to the enhanced fatigue assessment of a steel bridge in Sweden.

In this context, the Laboratory of Vibrations and Structural Monitoring (*ViBest*) of FEUP has developed an extensive research concerning the evaluation of dynamic effects and fatigue analysis of the Portuguese metallic railway bridge of Trezói. In particular, strain measurement campaigns were conducted to evaluate the stress patterns in the main structural elements and stresses in the critical details for fatigue analysis, with the final goal of adding a contribution to the understanding of localised fatigue vibration effects.

This paper describes the experimental and numerical studies developed and presents the results achieved with MatLab routines developed to process the data. Preliminary studies included the development of an ambient vibration test and a global fatigue assessment using a beam FEM that was "tuned" to fit the identified bridge dynamic properties. This provided crucial information for the construction of more detailed local FEM models, as well as for the design of the continuous dynamic

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monitoring system. Subsequently, dynamic analyses were conducted using real train characteristics to understand the importance of local modes in the fatigue calculations. Finally, the results obtained from the field measurement campaigns were used to calculate a more accurate fatigue residual life of this bridge.

2. Description of the bridge

The Trezói Bridge (Fig. 1) is located in the international "Beira Alta" route that links Portugal to Spain, at the km 62 north of Mortágua in the village of Trezói. The bridge was constructed as part of a project to replace existing bridges in the "Beira Alta" route, carried out during the decade of 50, and was opened to traffic in August 1956. The project was funded by the Marshall Plan, and the conception, manufacture and mounting, together with 6 other bridges of larger span of the same line, was of the responsibility of the German House Fried Krupp.

This steel riveted bridge has three spans; their lengths are 48 m for the central span and 39 m for the other two. The total length of the bridge is 126 m. The two inverted Warren truss girders that constitute the metallic deck of the bridge are 5.68 m in height. The girder panels are 6.50 m wide in the central span and 6.00 m in the end spans. Two trapezoidal shape trusses acting as columns and two granite masonry abutments transmit the loads carried by the structure to the foundation. The bridge has a constant width of 4.40 m throughout its length.

The cross girders, as well as the stringers resting on them, were built using "I-shaped" sections. The cross girders are 71 cm in height and are connected to the lateral vertical elements with riveted plates as shown in Fig. 3. The chords and diagonals of the truss girders are formed by double "U-shape" sections.

The bearing supports of the superstructure are metallic and allow free rotations in the structure plane. At the east support the longitudinal displacements are constrained, while at the west support deformations caused by longitudinal horizontal forces (thermal actions, braking, etc.) are allowed.

The stringers are aligned with the rails which is a fortunate conception option since a misaligned rail normally induces secondary stresses in the web of the stringers.

3. Numerical modelling of the dynamic behaviour

3.1. Numerical modelling of the global dynamic behaviour

A first numerical study was conducted based on a simple FE model using the software SOLVIA [9] to evaluate the dynamic behaviour of the bridge using a discretisation of the structure in 3D beam and truss elements (Fig. 4). Due to the relatively low computational effort required by this model, it was possible to make a first calculation of natural frequencies and modal shapes, and to run simulations of train crossing, introducing also the train–bridge interaction effect, and using the resulting nominal stresses to obtain a preliminary fatigue assessment.

Fig. 1. The Trezói bridge.

The deck and the lateral exterior elements of the columns were simulated with beam elements, while truss elements were used to represent the inner members that form a triangular geometry of the columns. The connection of these columns to the bridge deck is hinged, since there are mechanical devices that allow free rotation in the vertical longitudinal plane of the bridge. Several point masses were distributed along the deck and the columns to simulate the metallic connections, rivets and wood sleepers. The same elasticity modulus of 200 GPa was adopted for the deck and for the columns.

The bearings of the deck at the abutments allow the rotation in the vertical plane. Longitudinal movement is allowed in the east bearing and constrained in the west bearing. However, for low levels of excitation, as is the case during ambient vibration tests, the behaviour of these supports can be different, since friction forces can prevent displacements or rotations. As a consequence, for comparison with the frequencies and modal configurations obtained experimentally, restraining of the longitudinal displacements in both supports was introduced.

Due to localised vibration effects detected in these analyses, more detailed models were further developed.

3.2. Numerical modelling of local dynamic behaviour

The finite element model developed in the previous stage using beam elements was subsequently enhanced in order to capture local vibration modes that are not captured by the beam FEM. In Fig. 5 the mesh of this new model is schematically represented. As observed in this figure, the cross-girder above the column, the two adjacent cross-girders, the stringers, diagonals, top and bottom chords and vertical elements that are connected with the vertical column are simulated with 4-noded shell elements. The contact and friction between the individual parts of the connections as well as the rivets were not taken into account. The same modelling was made for the structural elements connected to the extremity supports. The rails and sleepers were not simulated and the corresponding masses were idealized as point masses located at the centre of gravity of these elements.

In these two regions, all secondary elements were conveniently discretised in order to characterise the real behaviour of these structural details. A special attention was given to the joints of the cross girders in order to capture local vibration modes, the effect of secondary bending moments and eventual distortion. The stringers that support the rails were also discretised with shell elements, so that the connection between the flange of these elements and the flange of the cross girders was correctly modelled in order to capture distortion effects.

"Rigid links" were introduced between the nodes connecting the bar elements with the corresponding shell elements that constitute the top and bottom chords, to simulate accurately the continuity between structural joints.

This model was also calibrated using the results from the initial ambient vibration test. The global vibration modes were compared and some slight modifications were made in terms of mass distribution and boundary conditions in order to achieve greater agreement between the calculated and identified modal shapes and frequencies.

With this model it was thus possible to calculate stresses that are enhanced due to geometric effects.

3.3. Evaluation of traffic induced effects

Numerical simulations were conducted in order to evaluate the structural response due to trains crossing. The calculations made, including the interaction effect between the bridge and the train, led to the conclusion that for this specific structure the effects due to the inertia of the vehicle are much inferior to the effects of its weight. In this case, the phenomenon of energy transfer between the bridge and the suspension of the vehicles showed to be of negligible importance for the range of circulation velocities that are possible and allowed in this bridge. To reach those conclusions, two methodologies were