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Fatigue evaluation of a composite railway bridge based on fracture mechanics through global–local dynamic analysis

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ABSTRACT

An enhanced fatigue assessment of critical welded details in a steel–concrete composite railway bridge was carried out by fatigue crack propagation analysis based on linear elastic fracture mechanics (LEFM). The most fatigue critical connections concerned in this study were identified by the preliminary fatigue assessment based on the *S-N* method in the previous research of the authors Zhou et al. (2013) . Three-dimensional crack models of the critical connections were incorporated into the global–local finite element model of the bridge. The stress intensity factor (SIF) histories of the cracks were calculated through dynamic analysis of the bridge due to the high-speed train passages, which validated the applicability and the accuracy of the empirical SIF formulas for the concerned bridge details. The fatigue crack growth curve, represented by crack size versus number of train passages, was obtained through crack propagation analysis based on the Paris law and LEFM, and fatigue propagation life was predicted for each critical connection. The proposed crack propagation analysis method provides a general and alternative approach to evaluate the fatigue life of welded details in steel bridges.

1. Introduction

In the current design codes for steel structures, such as Eurocode 3 [2], BS 5400 [3] and AASHTO [4] etc., the prevalent fatigue design and assessment method is based on the detail category specified *S-N* curve and the Palmgren–Miner [5–6] cumulative damage rule. If the necessary test data in the form of fatigue strength curves are available for the specific detail categories, it is simple and efficient to use the nominal stress based *S-N* method to conduct fatigue design and assessment of a steel bridge. However, in reality, *S-N* curves are only available for a limited number of structural details, which are given by the classification tables in the design codes [2–4]. Complex structural details that are excluded from the code specified fatigue categories, or multi-axial stress conditions that cause difficulties in determination of the nominal stresses, invalidate the applicability of the nominal stress based *S-N* method. Furthermore, weld defects, such as welding cracks, incomplete penetrations, inclusions, undercuts, etc., are unavoidable in welded details of steel bridges. The traditional *S-N* method is inapplicable to evaluate the effect of a specific defect on the fatigue life, while linear elastic fracture mechanics (LEFM) [7–8] can be used to deal with fatigue crack propagation analysis of cracked welded details.

When a fatigue crack is detected in a steel bridge in service, the remaining fatigue life of the cracked detail needs to be estimated. The LEFM based approaches are able to provide knowledge about crack size and crack growth rate under actual service loads. With this information, it can be decided that either the crack propagates slowly so that enough time is available before retrofitting or the crack propagation is accelerated and the time for repair, retrofitting or replacement is short. Furthermore, the crack propagation information predicted by the LEFM approaches also helps to set up a plan for regular inspection and suitable repair measures before the crack grows to a critical size. The application of the LEFM in fatigue crack propagation analysis becomes more and more widely accepted [9–14]. Most of the researches on the LEFM based fatigue crack propagation analyses were concentrated on the local structural details and the solutions for the stress intensity factor (SIF) around the crack front [9–10], while only a few efforts [13–14] were made to determine the surrounding stress or deformation histories of the local details which drive the crack propagation, and even few studies deal with the localized crack growth model within a global bridge structure. In reality, fatigue crack propagation will change the stiffness and the stress state of the local structural detail which will further affect the crack growth behavior in turn. This interaction problem requires a global–local cracked model of the structure to implement crack propagation analysis, or an isolated local cracked model whose boundary conditions are not affected by local changes in stiffness due to crack propagation.

In the present study, an enhanced fatigue assessment of the critical welded connections in a steel–concrete composite railway bridge, the

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Sesia viaduct, was performed by the LEFM based crack propagation analysis through dynamic simulations of the global–local bridge model. The main purpose of this study is to predict the fatigue crack propagation life of the most fatigue-vulnerable welded connections in the bridge, as well as to compare the fatigue life estimated by the LEFM approach and the nominal stress based *S-N* method in the previous research [1]. In the previous study of the authors [1], a global finite element (FE) model of the Sesia viaduct was built and validated by the in-situ dynamic test results including modal identifications and strain measurements [15]. The dynamic stress histories of the concerned structural details generated by the global FE model of the bridge due to a high-speed train passage were used to calculate the fatigue damage based on the *S-N* method and then, the most fatigue critical welded connections were identified. As a continuation, in this study, the most fatigue critical connections were built with brick elements, which were incorporated into the global FE model. This FE model is termed as the global–local model of the bridge in the following paragraphs. The SIF histories of the cracks in the critical connections were obtained by global–local dynamic analyses of the bridge, which were used to validate the empirical SIF formulas for the pertinent connections. Then, the fatigue propagation life of each critical connection was predicted using a standard Paris crack growth model based on the validated SIF equations.

2. Global bridge model and fatigue critical connections

2.1. Sesia viaduct and dynamic experiments

The Sesia viaduct was constructed along a new Italian high-speed railway line connecting Torino with Milano, over the Sesia River near the city of Novara. It is a box-girder steel–concrete composite bridge and consists of seven simply supported spans, each approximately 46 m long, reaching a total length of 322 m. A general view of the bridge is given in Fig. 1. The double-box steel girder has 13 intermediate and 2 end cross frame diaphragms (see Fig. 2). The bottom steel box made of S355 steel was built by in-situ assembly of three segments, each roughly 15 m in length, connected by full penetration butt welding. The thickness of the lower flanges in segment C1 is 25 mm, which is smaller than that in segment C2, 30 mm. However, the thickness of the girder webs A, B and C in segment C1, 20 mm, is larger than that in segment C2, 18 mm. The top concrete slab cast in the field on prefabricated concrete elements is 13.6 m wide and 0.4 m thick, and is connected to the upper flanges of the steel box girder by shear studs. On the ballast, two tracks with UIC60 rails are supported by prestressed concrete sleepers at an interval of 0.6 m.

In order to evaluate the dynamic behavior, the actual train loads and the fatigue stress spectra of the bridge, preliminary dynamic experiments and long-term monitoring were carried out on the Sesia viaduct [15–17]. Due to the large scale of the bridge, in-situ measurements were concentrated on the second span from the Torino side. Besides, a small number of accelerometers were placed on the first and third spans to evaluate the dynamic interaction between two adjacent spans. The vertical and/or horizontal accelerations at 89 positions were measured with 33 accelerometers in several setups, where 7 fixed reference positions including 1 horizontal and 6 vertical acceleration measurements were adopted. A full description and arrangement of accelerometers can be found in Ref. [15]. Measurements were performed to obtain acceleration responses of the bridge due to ambient vibrations (excited by wind and traffic load of the adjacent highway) and high-speed train passages. With the vibration data, modal identification of the bridge (eigenfrequencies, damping ratios and mode shapes) was performed by the reference based stochastic subspace identification [18]. Based on the ambient vibration data, a total of 8 modes were identified for the second span, including the first and second bending modes, as well as the first and second torsional modes. According to the mode shapes of the adjacent spans, the identified modes of the second span could be subdivided into symmetrical and anti-symmetrical ones, which revealed that the neighboring spans were dynamically coupled through the ballast layer and the continuous rails. From the free vibration data immediately after the train left the second span, three symmetrical modes, i.e. the first and second bending modes and the first torsional mode, were extracted. Additionally, the first and second symmetrical bending modes were also identified through the vibration data during a train crossing the span. Thus, it was concluded that the train passage predominately excited the symmetrical modes. Detailed modal analysis results were described and discussed in Refs. [15,19].

The dynamic strains in the longitudinal direction were measured with the fiber optic strain sensors during a high-speed train passage. These sensors measured the relative displacement between a pair of points at a distance of 1.0 m on the steel box girder or 1.2 m on the concrete sleepers. A total of 16 sensors were installed at Cross Sections 1 and 5. A schematic plot of the strain sensor arrangement can be found in Ref. [1].

2.2. Global model of a single span and verification

Due to the large dimensions of the Sesia viaduct including seven spans, a FE model of the complete bridge would lead to expensive computational costs. As the seven simply supported spans are identical to each other, a single span model is sufficient and also efficient to estimate the fatigue damage of the bridge. Therefore, a detailed FE model of the second span (as shown in Fig. 3), was built using the general FE software ABAQUS [20], and appropriate boundary conditions were applied at the ends of rails and ballast to simulate the weak coupling between the adjacent spans. The steel box girder was modeled by four-node shell elements S4 and the bracings were simulated by beam elements B31 in combination with shell elements S4 at the end connections. Couplings of 6 degree of freedoms (DOFs) were adopted to join the endpoint of beam element with the edge of shell element, at a distance of 0.8 m from the bolt connections of the bracings. The preloaded high-strength bolt connections of the bracings and the gusset plates were assumed rigid and realized by the TIE option in ABAQUS [20], which is a surface-based constraint to make all DOFs equal for a pair of surfaces. The concrete deck and safety barrier were modeled by eight-node hexahedral brick elements C3D8. The shear studs were not explicitly modeled and the TIE constraints were used to connect the concrete deck to the upper flanges of the steel box girder. The ballast layer was assumed as a continuum and simulated by brick elements C3D8. The

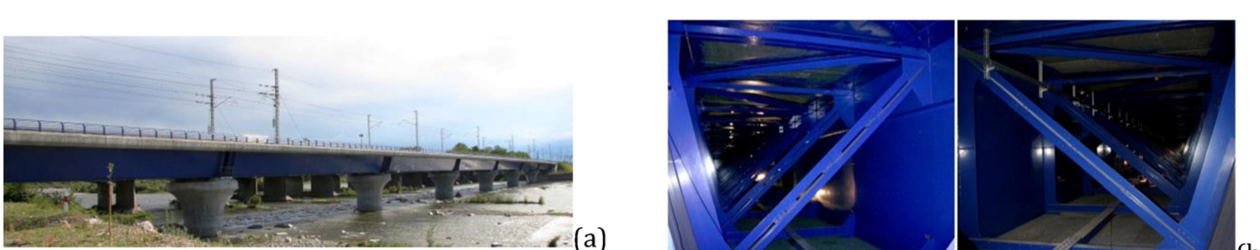

Fig. 1. Sesia viaduct: (a) general view of the spans and (b) interior view of the double-box girder.