The 2020 World Congress on
Advances in Civil, Environmental, & Materials Research (ACEM20)
25-28, August, 2020, GECE, Seoul, Korea

Enhancing railway bridge design rules using nonlinear finite element modelling

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ABSTRACT

Over the past two decades, there have been significant published investigations highlighting smart advanced nonlinear Finite Element (FE) Modelling of steel bridges. The nonlinear analyses have provided enormous databases detailing the structural performance of various bridge constructions at different load conditions as well as at ambient and elevated temperatures. Yet, to author's best knowledge, design rules are updated at years' time period, with some currently used international design guides have not been updated over the past decade. With experimental investigations remain costly and time consuming, particularly under fire conditions, nonlinear FE models have significantly dynamically improved. This paper highlights an approach on how nonlinear FE modelling can improve design guides of different steel bridges with a detailed case study presented. The case study presented is for a double track open-timber floor plate girder deck railway steel bridge. The approach is aimed to enhance current design guides through incorporating latest investigations in the field of steel bridge constructions. It has been shown that, nonlinear FE modelling can investigate full-scale bridges with actual geometries and layouts, wide range of material properties, wide range of initial local and overall imperfections and unlimited range of cross-section geometries. Also, it has been shown that FE modelling can detail the stress propagation at service and ultimate limit states, which is used for optimum design of sections of bridge components. In addition, FE modelling can predict the load-strain and load-deformation relationships at different load levels as well as at ultimate limit states, which are quite useful for the safety checks for limiting deflections and deformations. Furthermore, once the FE model is verified at ambient temperature, the model can be used to conduct complicated analyses regarding the structural performance of the full-scale bridge under fire conditions.

1. INTRODUCTION

Designing of steel, steel-concrete composite bridges and metal structures was the

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subject of extensive investigations available in the literature, with recent reviews of main investigations were presented by the author in (Ellobody 2014) and (Ellobody et al. 2014). Examples of the investigations, (Lin and Yoda 2017), (Bartlett 2016), (Pipinato 2015), (Kim 2014) and (Lebet, et al. 2013), have highlighted different aspects of design and problems associated with planning, design, inspection, construction, and maintenance of steel and steel-concrete composite bridges. On the other hand, considerable FE advanced nonlinear analyses were found in the literature highlighting developed FE models, as presented by (Chen and Duan 2014), (Karbhari 2014), (Jeffrey and Franklin 2016) and (Beg et al. 2012), investigating the behaviour of steel and steel-concrete composite bridges. Over the past two decades, FE software have been strengthened with latest numerical techniques that provide accurate solutions, in reasonable calculation times, for sophisticated analyses of the bridges. However, up-to-date, there are limited detailed books found in the literature addressing combining FE analysis with design of steel and steel-concrete composite bridges, which is previously published by (Ellobody 2014). The reference has provided a complete piece of work on the design guides, FE modelling and case studies of steel and steel-concrete composite bridges.

Advanced smart nonlinear FE modelling is complicated due to the material nonlinearities of the bridge components, connections, buckling of steel members, concrete cracking in case of composite bridges, loading and boundary conditions. The aforementioned issues can considerably compensate the lack, expensive and time-consuming experimental data and tests on this form of construction. Therefore, this paper presents how the FE modeling can be further beneficial in enhancing current design rules of steel and steel-concrete composite bridges with a case study presented. Design rules specified in the American Specifications AASHTO (2005), AASHTO (2012) and AREMA (2011), British Standards BS 5400–3 (2004) and European Code EC3 (2006) and EC4 (2005) were based on many assumptions, limitations and empirical equations. As an example of the shortcomings in current codes of practice for steel-concrete composite bridges is that, up-to-date, there is no design provisions to consider the actual load-slip characteristic curve of the shear connectors used in composite bridges, which results in partial degree of composite action behaviour. Another example of the shortcomings is the inclusion of initial local and overall imperfection and buckling modes in the calculation of bridge compression members. This paper presents a case study of a double track open-timber floor plate girder deck railway steel bridge with companion FE analyses that paved the way to an approach of combining advanced smart FE modelling with design to enhance current design rules of steel bridges.

2. DESIGN OF A DOUBLE TRACK STEEL BRIDGE CASE STUDY

2.1 General

To show the effectiveness of combining design with FE modelling in enhancing design rules, a case study was considered. The case study presented in this paper is a bridge designed and detailed by the author in (Ellobody 2014). The bridge is a double track open-timber floor plate girder deck railway steel bridge, with the general layout shown in Fig. 1(a). The bridge is simply supported having a length of 31 m and a width of 7.2 m as shown in Fig. 1(a). The bridge was designed according to the design rules specified in (EC3 2006). The steel material of construction of the double track bridge conformed to standard steel grade EN 10025-2 (S 275) having a yield stress of 275 MPa and an ultimate strength of 430 MPa. The bridge has upper and lower wind bracings of K-shaped truss members as well as cross bracings of X-shaped truss members as shown in Fig. 1 (a). In addition, the bridge has lateral shock (nosing force) bracing for the stringers as well as braking force bracing at the level of upper wind bracing as shown in Fig. 1(b). The lateral shock bracing eliminates bending moments around the vertical axis of the stringers, while braking force bracing eliminates bending moments around the vertical axis of the cross-girder. The plate girder web is stiffened by vertical stiffeners, to safeguard against shear stresses and web buckling, spaced at a constant distance of 1.667 m. The expected live loads on the bridge conform to Load Model 71, which represents the static effect of vertical loading due to normal rail traffic as specified in (EC3 2006). The bolts used in connections and field splices are M27 high strength pretensioned bolts of Grade 8.8.

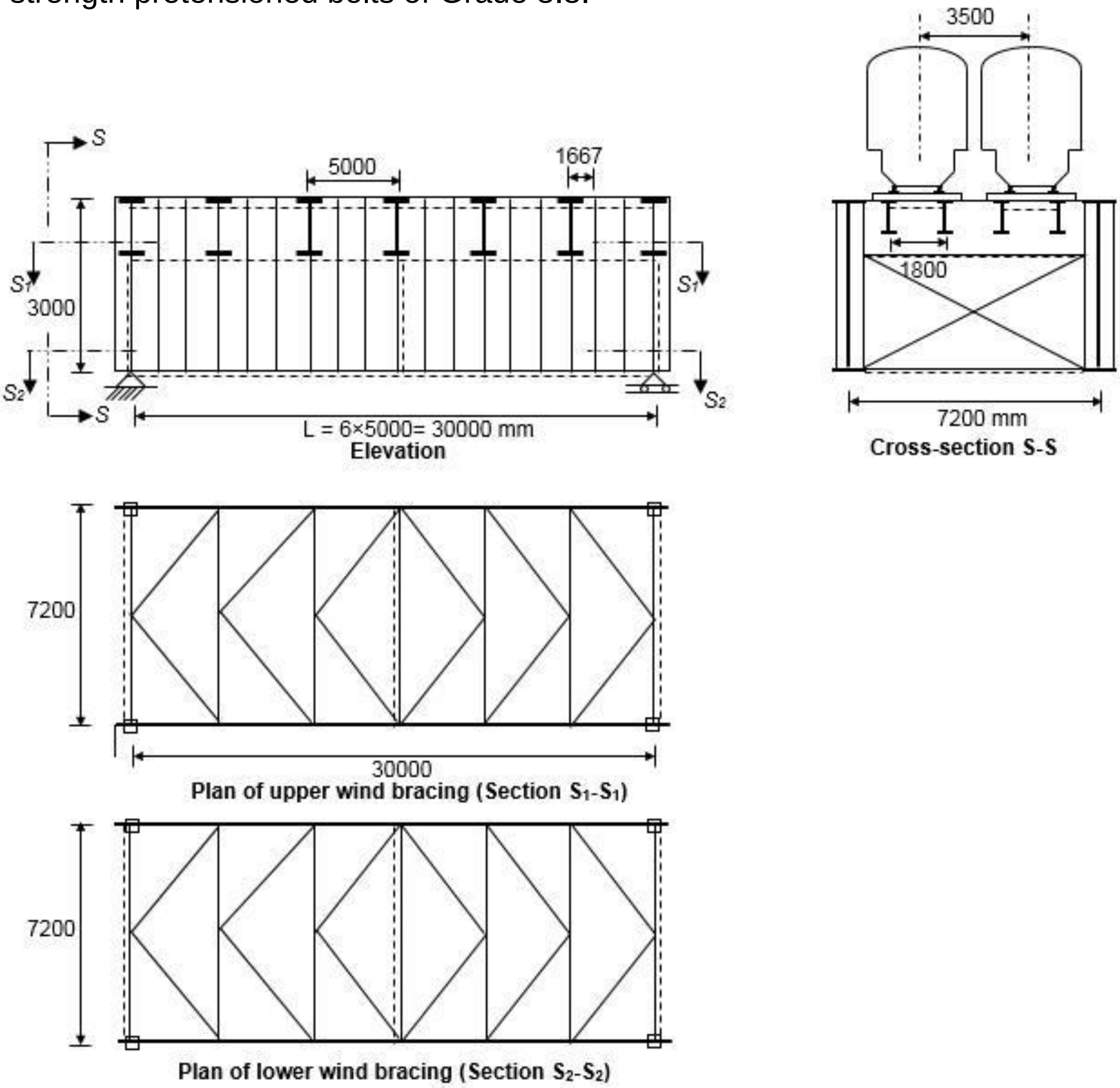

Fig. 1(a) General layout of a double track open-timber floor plate girder deck railway steel bridge detailed by the author in (Ellobody 2014)

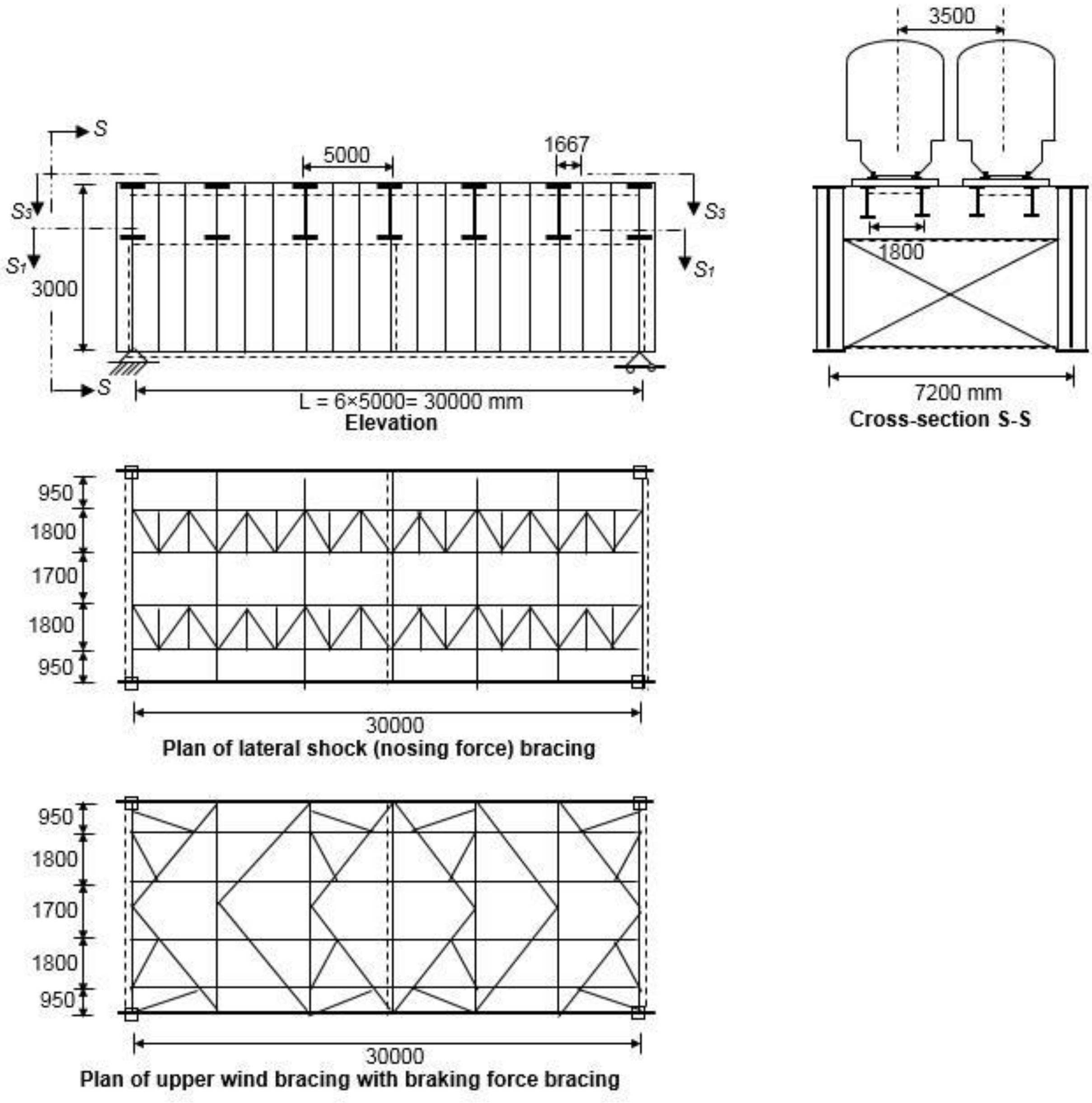

Fig. 1(b) General layout of the double track plate girder railway steel bridge detailed in (Ellobody 2014)

2.2 Design of the bridge components

The stringers (UB 533×210×92), cross-girders (UB 914×305×253) and main plate girders (web plate of 3000×16, two top flange plates 600×30 and 560×30 as well as two bottom flange plates 600×30 and 560×30) were designed according to (EC3 2006) as detailed in (Ellobody 2014). Curtailment of the flange plates of the main plate girder, main plate girder fillet welds, lateral torsional buckling of the plate girder compression flange, plate girder web stiffeners, load-bearing stiffeners at supports, stringer bracing, wind bracings, stringer-cross girder connection, cross-girder main plate girder connection, field splices, roller and hinged bearings were all designed according EC3 as detailed in (Ellobody 2014). Fig. 2 shows the main bridge components.

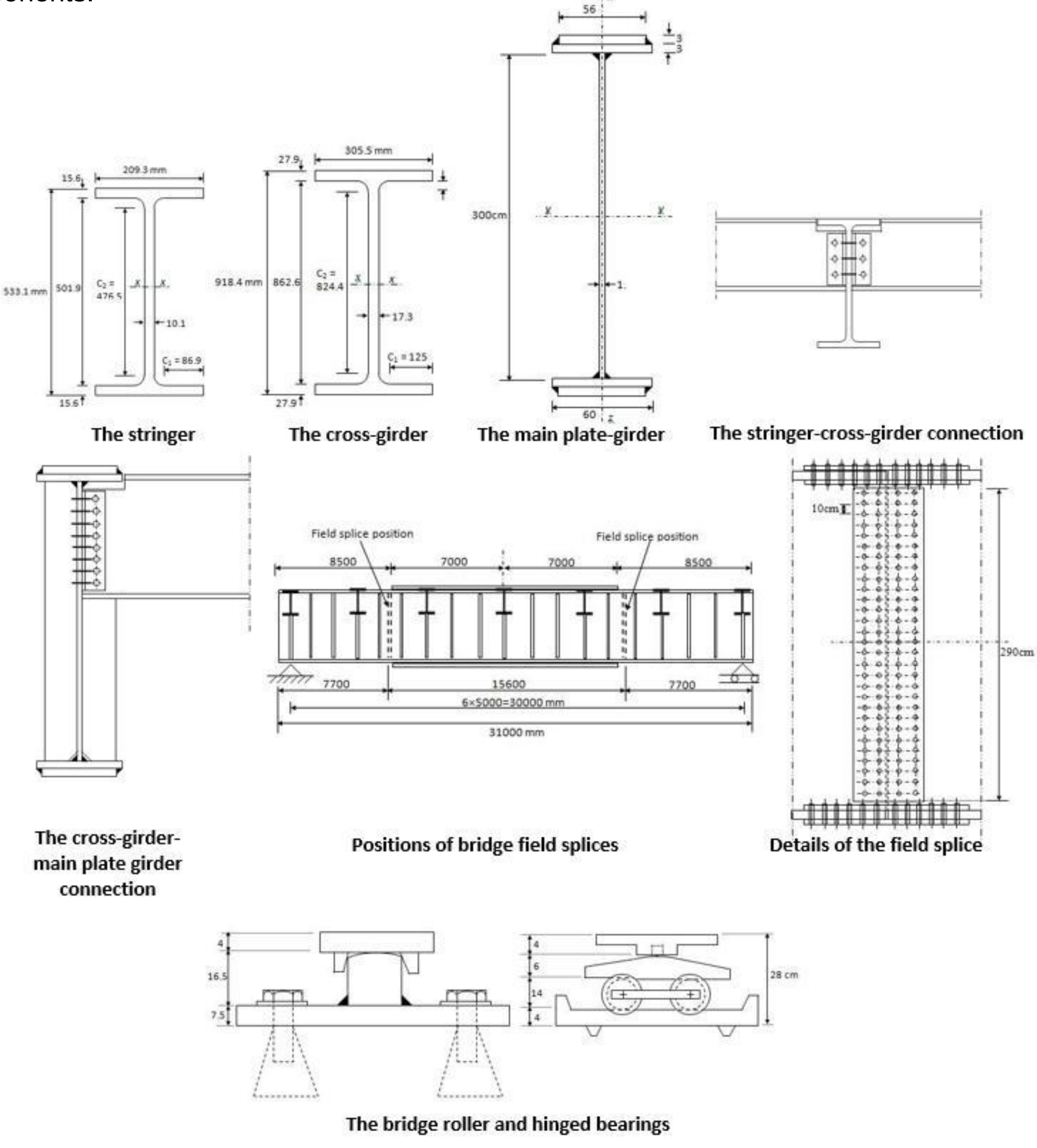

Fig. 2 The investigated double track railway bridge components detailed in (Ellobody 2014)

3. NONLINEAR FE MODELLING OF THE BRIDGE

3.1 General

The double track open-timber floor plate girder deck railway steel bridge was modelled using FE method as detailed by the author in (Ellobody 2014). The developed

FE model was used to provide detailed data that complement available data in the field, assess the accuracy of the design rules and propose more accurate design equations. In addition, the models can be extended to investigate the structural performance of the bridge under different load conditions, different boundary conditions as we as at ambient and fire conditions. To model the full-scale double track open-timber floor plate girder railway steel bridge, the FE program (ABAQUS 2011) was used.

3.2 FE modelling of the bridge

The developed FE model the double track open-timber floor plate girder deck railway steel bridge has accounted for the bridge geometry, initial geometric imperfections and nonlinear material properties of the steel used. Four-node doubly curved shell elements with reduced integration (S4R) was used to model the flanges and webs of the stringers, cross-girders and main plate girders. The element was also used to model the stiffeners of the web of the main plate girders. The bracing members were modelled using structural 2-D truss elements (T2D2) available in the (ABAQUS 2011) element library. The bolts connecting the cross girders to the main girders as well as the bolts connecting the stringers to the cross girders were modelled using JOINTC joint elements, available in the (ABAQUS 2011) element library, having stiffnesses in two directions, which simulated the simply supported end boundary conditions. In order to choose the FE mesh that provides accurate results with minimum computational time, convergence studies were conducted. It was found that approximately 153×260 mm (length by width of S4R element) ratio provided adequate accuracy in modelling the webs of the main plate girders while a finer mesh of approximately 75×260 mm was used in the flanges of the main plate girders, see Fig. 3.
Also, it was found that approximately 153×251 mm ratio provided adequate accuracy in modelling the webs of the cross girders while a finer mesh of approximately 76×251 mm was used in the flanges of the cross girders, see Fig. 3. Finally, it is found that approximately 153×260 mm ratio provided adequate accuracy in modelling the webs of the stringers while a finer mesh of approximately 96×260 mm was used in the flanges of the stringers, see Fig. 3. The hinged support of the bridge attached to the main plate girders was prevented from displacement in the horizontal direction (direction 1-1) and the vertical direction (direction 3-3). On the other hand, the roller support of the bridge was prevented from displacement in the vertical direction only (direction 3-3). More details regarding the FE modelling of the bridge can be found in (Ellobody 2014). Further to developing of the FE model, the model was used to analyse the bridge under investigation. Fig. 3 shows summary of the results obtained using the FE model. The non-linear geometry was included to deal with the large displacement analysis. The stress-strain curve for the structural steel given in the (EC3 2006) was adopted in this study with the yield and tensile stresses of 275 and 430 MPa, respectively.
The material behaviour provided by (ABAQUS 2011) allows a nonlinear stress-strain curve to be used. The first part of the nonlinear curve represents the elastic part up to the proportional limit stress with Young's modulus of (E) 200GPa and Poisson's ratio of 0.3 were used in the finite element model. Since the buckling analysis involves large in-elastic strains, the nominal (engineering) static stress-strain curves were converted to true stress and logarithmic plastic true strain curves. An Eigenvalue buckling analysis was performed for the whole bridge to model initial geometric imperfections of the

bridge. The developed FE model was used to predict the buckling mode used as a basis for the nonlinear load-displacement analysis, the deformed shape at failure, load-displacement relationship and stress contours at failure, as shown in Fig. 3.

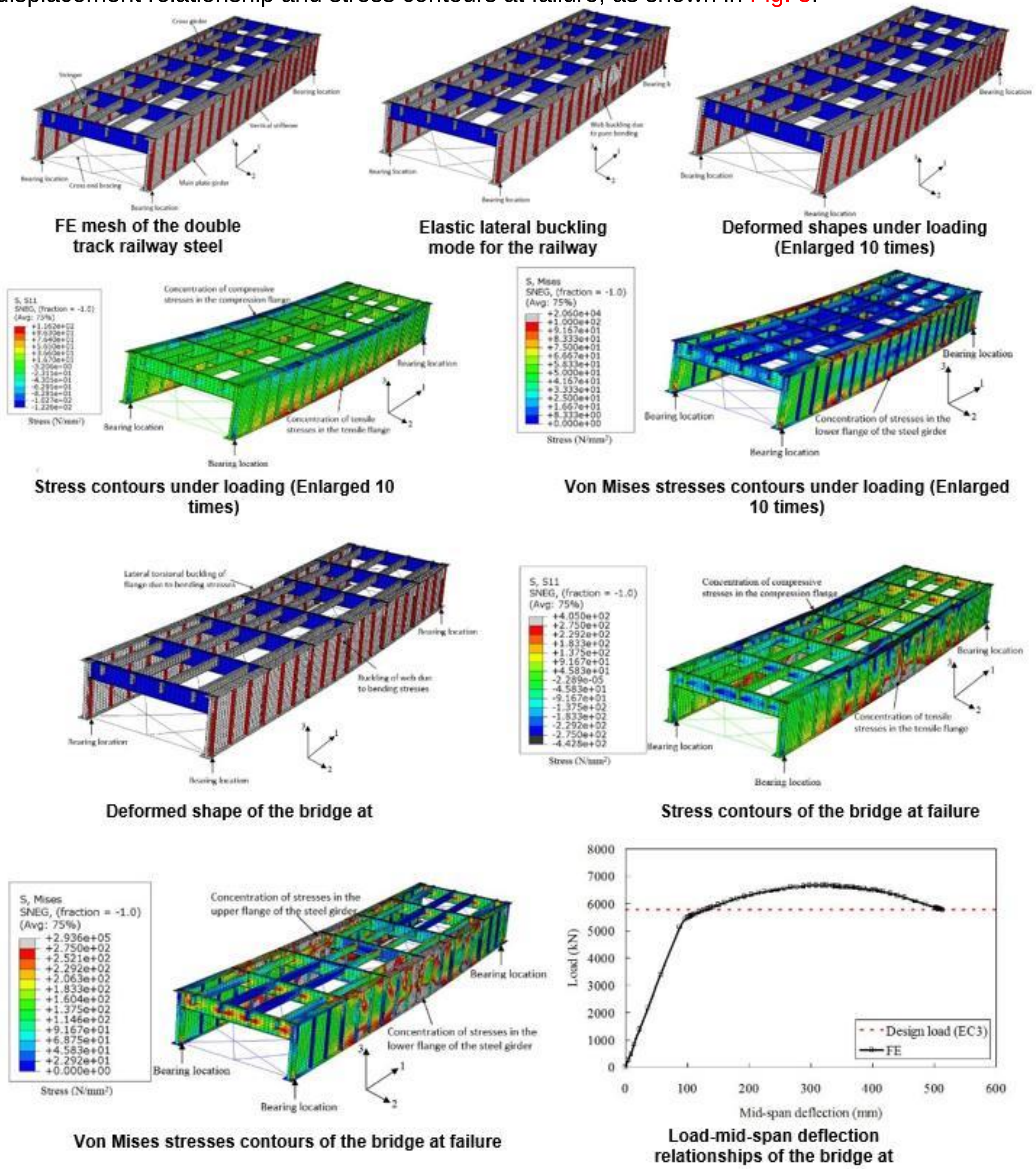

Fig. 3 FE modelling results of the double track railway bridge components detailed in (Ellobody 2014)

4. DISCUSSION OF HOW FE MODELLING CAN ENHANCE DESIGN RULES

Looking at the current design rules, it can be seen that the design rules were mainly developed based on small-scale tests of bridges as well as contain empirical equations used under limitations such as limits of stresses, limits of imperfections, limits of loads as well as limits for the cross-section geometries. Smart advanced nonlinear FE modelling can investigate full-scale bridges with actual geometries and layouts, wide range of material properties, wide range of initial local and overall imperfections and unlimited range of cross-section geometries. It is almost impossible for the current design guides to have full-scale tests covering all types of bridges under different loading and boundary conditions. In many occasions in the literature, researchers have found the design rules are either conservative or unconservative and it was concluded that there is a need to propose more accurate design equations. Also in many published occasions, researchers have proposed the extension of current design guides to accommodate a wider range than that specified by the standards.

Looking at the FE modelling detailed in (Ellobody 2014) and presented briefly in this paper, it can be seen that the double track open-timber floor plate girder deck railway steel bridge was analysed using the FE model and a buckling analysis was conducted. The predicted Eigen Value buckling analysis, Fig. 3, was done for the full scale bridge with actual geometries and actual designed components. The current design rules provide only factors to be considered for the initial local and overall imperfections. However, the factors were proposed for individual components and not for the investigated full-scale bridge. Another example, the deformed shapes under the applied loads as well as at failure are not presented in any of the design rules. Once again, it is almost impossible for the design rules to present full-scale tests on different roadway and railway bridges constructed worldwide. However, with the use of smart advanced nonlinear FE modelling techniques and software, we can incorporate the deformations for different bridge categories in current design rules.

A third example, the plotted stress contours, see Fig. 3, that detail the stress propagation at service and ultimate limit states provide an important information into the developed stresses in cross-sections as well as maximum and minimum stressed fibres. The information can be used for optimum design of sections as well as for limiting the costs of self-weight. The stresses plotted at ultimate limit state cannot be obtained experimentally except through destructive tests of the whole full-scale bridge, which is quite costly and time consuming. All types of stresses can be plotted nowadays using commercially available software with an example is given by (ABAQUS 2011) in this paper. More details regarding the developed stresses and the process of developing the contours can be available in (Ellobody 2014). A fourth example, is that we can predict the load-strain and load-deformation relationships at different load levels as well as at ultimate limit states. These are quite useful for the safety checks for limiting deflections and deformations. Once again, these are quite useful information and cannot be obtained experimentally except for loading the whole bridge to failure. Incorporating the FE information into design guides will provide designers and practitioners with a useful insight on the structural performance of the full-scale bridge.

Finally, a clear example on how FE modelling can enhance currently used design rules for steel bridges is that once the FE model is verified at ambient temperature, the model can be used to conduct complicated analyses regarding the structural performance of the full-scale bridge under fire conditions as well as to study fire spread across the whole bridge. The bridge can be analysed for a wide range of fires ranging from long cool to short hot fires. The structural performance at elevated temperatures cannot be conducted experimentally except thorough full-scale bridge fire tests that are quite costly and time consuming for a single fire test. There have been extensive FE modelling data, detailing the structural behaviour of steel bridges at ambient and fire conditions over the past two decades, that need to be embedded in current design rules. The smart advanced nonlinear FE modelling data will significantly have a useful impact on enhancing current design rules for steel and steel bridges.

5. CONCLUSIONS

This paper has presented a case study highlighting the advantage of combining design with FE modelling to enhance current design rules. The case study investigated is for a double track open-timber floor plate girder deck railway steel bridge previously design and numerically modelled by the author. The presented FE modelling data have shown that the numerical results comprising Eigen Value buckling analyses, deformed shapes, stress contours and load-displacement relationships cannot be obtained experimentally except through conducting quite costly and time consuming full-scale tests. The FE data can considerably enhance current design rules and provide a quite useful insight regarding the structural performance at service and ultimate limit states. The approach of combining design with smart advanced nonlinear FE modelling not only can be used at ambient temperatures but also can be used under fire conditions. The approach can considerably strengthen current design rules and lead to more accurate guides for the structural performance of steel bridges. It has been shown that, nonlinear FE modelling can investigate full-scale bridges with actual geometries and layouts, wide range of material properties, wide range of initial local and overall imperfections and unlimited range of cross-section geometries. In addition, it has been shown that FE modelling can detail the stress propagation at service and ultimate limit states, which is used for optimum design of sections of bridge components. Furthermore, it has been shown, FE modelling can predict the load-strain and load-deformation relationships at different load levels as well as at ultimate limit states, which are quite useful for the safety checks for limiting deflections and deformations.

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