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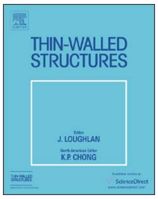

Full length article

Interaction of buckling modes in railway plate girder steel bridges

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ABSTRACT

This paper investigates, for the first time, the behaviour and design of railway double track open timber floor plate girder deck steel bridges under combined buckling modes including web distortional buckling. A 3-D finite element model has been developed for the railway bridges, which accounted for the bridge geometries, initial geometric imperfections, material nonlinearities of the bridge components, bridge boundary conditions, interactions among bridge components and bridge bracing systems. Most of the aforementioned parameters are not incorporated in current design codes of railway bridges, which are credited to this study. The simply supported bridges investigated had a span of 30 m, a width of 7.2 m and a depth of 3.12 m. The bridge components comprising main plate girders, stringers, cross girders, connections, bracing members, stiffeners, bearings, and field splices were designed following the design rules specified in the European Code for steel bridges. The live load acting on the bridge was Load Model 71, which represents the static effect of vertical loading due to normal rail traffic as specified in the European Code. The finite element model of the double track bridge was developed depending on additional finite element models, developed by the author, for small and full-scale plate girder steel bridge tests previously reported in the literature. Ultimate loads, load-mid-span deflection relationships, failure modes, stress contours of the double track bridge as well as of the small and full-scale tests were predicted from the finite element analysis and compared well against test results. Parametric studies were performed on the railway bridges highlighting the effects on the structural behaviour and ultimate loads carried by the bridges owing to the change in the bridge geometries, slenderness and steel strength. The paper presents a complete piece of work regarding the finite element analysis and design of railway steel bridges, which can be used for further parametric studies, finite element analyses and investigations of the bridges under different loading and boundary conditions. The parametric study has shown that the presence of web distortional buckling causes a considerable decrease in the ultimate load of the steel bridges. It is also shown that the use of high strength steel offers a considerable increase in the ultimate loads of less slender steel bridges. The study has also shown that the design rules, loading and recommendations specified in the European Code provide accurate and conservative estimations for the design of railway steel bridges, except for the bridges failing mainly by web distortional buckling.

1. Introduction

Numerous numerical investigations were reported in the literature highlighting the structural performance of different types of steel bridges subjected to different loadings and different boundary conditions. The numerical investigations proposed finite element models, for the bridges and the bridge components, which were developed to provide accurate analyses and better understanding for the behaviour and stability of different bridges. Earls and Shah [1] presented a combined experimental and numerical investigation on high performance steel I-shaped bridge girders. The investigations were assessed against the American bridge specification (AASHTO) provisions for cross sectional compactness and adequate bracing. The study showed that the specifications may be inadequate owing to intense interactions between local and global buckling modes in the high performance steel I-shaped bridge girders. An alternate bracing requirement was proposed by the authors for use with high performance steel bridge girders. Shanmugam et al. [2] presented a combined experimental and numerical study on the ultimate load behaviour of plate girders curved in plan. The investigated girders were medium-sized girders built using rolled steel plates and were tested to failure. The girders were supported at the ends and subjected to a concentrated load applied at the mid span. The numerical investigation employed the elasto-plastic finite element method and the results were compared with that

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Nomenclature

b_f	Flange width
COV	Coefficient of variation
E	Young's modulus of steel
f_y	Yield stress of steel
f_u	Ultimate stress of steel
h_w	Web height
L	Length
LTB	Lateral torsional buckling failure mode
$M_{\mathrm{b,Rd}}$	Bending moment resistance considering lateral torsional buckling
M_{cr}	Critical bending moment
$M_{\mathrm{D+L+\Phi}}$	Moment due to dead and live load with dynamic effect
l_u	Lateral unsupported length
P	Load
P_{FE}	Failure load from finite element analysis
P_{Test}	Failure load from tests
$Q_{\mathrm{D+L+\Phi}}$	Shear due to dead and live load with dynamic effect
SB	Buckling due to shear stresses
t_w	Web thickness of specimen
t_f	Flange thickness of specimen
V_{Ed}	Design shear force
$V_{\mathrm{b,Rd}}$	Design shear resistance
δ_{FE}	Mid-span deflection at failure from finite element analysis
δ_{Test}	Mid-span deflection at failure from tests
σ	Stress
ε	Strain
σ_{true}	True stress
ε_{true}^{pl}	Plastic true strain
Φ	Dynamic factor

measured experimentally. The study indicated that the load-carrying capacity decreases with the increase in curvature. Geometrical imperfections were imposed in terms of the buckled shape of the web plates at the elastic stage. Floor beams of orthotropic plated bridge decks were investigated by Corte and Bogaert [3]. The beams have generally elements with a low slenderness, especially in the case of railway bridges. This is attributed to combined flexural and shear deformations. The shear deformations can be considerably large to be neglected.

The behaviour of bridge girders made of high performance steel (HPS 70W) was evaluated by Felkel et al. [4]. The basis for the study was a three span replacement bridge utilizing HPS 70W girders within all negative moment regions. The study consisted of in-situ measurements, experimental tests and analytical investigations. Three half-scale specimens, were tested under monotonic and cyclic loading conditions. The findings of the study indicated that improved structural performance may be obtained when location of bracing was optimized and fabrication imperfection tolerances were minimized. Galvin and Dominguez [5] presented a theoretical and experimental research work on a cable-stayed bridge. Full-scale tests were carried out to measure the bridge dynamic response. The experimental program included the dynamic study for two different live load conditions, which are the bridge with one half of its lanes full of cars and the bridge empty of cars. Modal parameter estimations were made based on the acquired data. The traffic-structure interaction was also studied. Romeijn and Bouras [6] developed a finite element model of a tension-tie arch bridge to investigate the in-plane buckling length factor of the arches. The modelling of the tension-tie arch bridge, the bridges' properties and the solution procedure were described. Three different bridge geometries were modelled. Eldib [7] presented the shear buckling strength and design of curved corrugated steel webs for bridges considering material inelasticity. A finite element analysis was performed to study the geometric parameters affecting the shear buckling strength of curved corrugated steel webs for bridges. Based on the numerical results, a shear buckling parameter formula was proposed.

A new type of streamlined girder bridge with a thin-walled steel box girder was investigated by Zhang et al. [8]. The bridge had a large width-to-span ratio, which resulted in significant shear lag effects and causes non-uniform stress distribution in the three-cell thin-walled box girder, especially along the flanges of the girder. The authors investigated the effect of shear lag in thin-walled box girder bridges with large width-to-span ratios through both experimental and numerical investigations. A large-scale model was tested under different loading cases. The authors concluded that that the finite element analysis can be an effective method to predict properties of this class of bridges. Graciano et al. [9] studied the influence of initial geometric imperfections on the postbuckling behaviour of longitudinally stiffened plate girder webs subjected to patch loading. The authors performed a sensitivity analysis using two approaches (deterministic and probabilistic) in order to investigate the effect of varying imperfection shape and amplitude on both, the postbuckling response and ultimate strength of plate girders under patch loading. The material was considered to have a perfect elastoplastic behaviour. Displacement constraints were applied to these loaded nodes in the out-of-plane direction and all rotations were restrained.

Recently, Lin et al. [10] showed that, due to the increasing aging problems of old railway bridges, structural repair or maintenance technique has been the subject of recent investigations Rubber–latex mortar, Glass Fiber Reinforced Polymer plates and rapid hardening concrete can be integrated with the old steel railway bridge to increase its rigidity and reduce both stress levels and structure-borne sound levels of the old steel bridge. The study [10] investigated the mechanical performance of the renovated hybrid railway bridge. Material tests on aged structural steel, static loading test on the strengthened bridge, and impact hammer test on the old bridge before and after strengthening, were conducted to confirm the effects of present strengthening method. In addition, three-dimensional finite element models were developed to compare between the strengthened and the original steel bridge. It was shown that both experimental and numerical results indicated that the renovation method can greatly enhance the stiffness and reduce the stress levels of steel members, resulting in the extension of the service life of the old steel railway bridge. However, to date there is no detailed investigations on railway steel bridges combining the design and finite element modelling of the bridges, which is addressed in this study. The study will highlight for the first time that finite element modelling can complement design rules of railway steel bridges by incorporating initial geometric imperfections, actual geometries, loading and boundary conditions.

Interaction of buckling modes, including web distortional buckling, has been the subject of extensive experimental and numerical investigations highlighting the behaviour of doubly symmetric steel I-sections, with examples presented by Bradford [11–13], Zirakian [14,15] and Ellobody [16,17]. However, tests and numerical investigations on railway plate girder steel bridges under combined buckling are rarely found in the literature, which is addressed in this study. Finite element modelling could provide better understanding for interaction of lateral torsional and distortional buckling behaviour of railway steel bridges and compensate the lack in the tests on this form of construction. However, accurate finite element modelling of the behaviour of railway steel bridges under combined buckling modes is quite complicated due to the presence of the initial geometric imperfections, lateral buckling restraints, interactions among bridge components and loading conditions. Hence, to date, there is no detailed finite element model in the literature highlighting the interaction of buckling modes in railway steel bridges, which is highlighted in this study.