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Lateral-torsional buckling strength and behaviour of high-strength steel corrugated web girders for bridge construction

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ABSTRACT

Corrugated web plates have been used in recent years as the webs of steel girders in bridge constructions thanks for their advantages, especially their superior shear capacities relative to stiffened flat webs. Therefore, they have been extensively investigated under shear compared with their limited investigations on the bending behaviour which was exclusively concentrated on the girders formed from the conventional normal strength steels. On the other hand, the use of high-strength steels (HSSs) in bridges has been increased when large and column-free spaces are key design issues. This paper focuses on the lateral-torsional buckling (LTB) of bridge girders with corrugated webs (BGCWs) built up from HSSs. This is done by using the commercially available finite element (FE) analysis package ABAQUS which has been used to generate parametric studies addressing the different affecting parameters on the behaviour of these girders. Simply-supported girders subjected to uniform bending, representing the worst case in LTB which is used in developing the member capacity design rules in different standards, are used in developing the current nonlinear FE models. The recently suggested warping constants in literature are used to compare the critical buckling moments with the elastic FE predictions. Then, the design model included in the Eurocode 3 is compared with the nonlinear strengths of the girders. The comparisons show that it provides conservative outcomes; therefore a modified version of the design model is suggested by using another buckling curve.

1. Introduction

1.1. General

I-section plate girders with flat webs (IPGs) are currently main structural elements in numerous constructional areas [1]. They are mainly designed for their bending moments. So, they are generally formed from cross-sections of large depths and slender web plates. These slender web plates reduce the flexural strengths of the girders because of their weak out-of plane bending stiffness. To avoid such weak out-of plane bending stiffness of the flat web plates, transverse stiffeners are often used in the IPGs. This, however, causes a large increase in the girder's weight and increases the risk of the girder to fail by fatigue due to the welds used to attach the stiffeners to the flanges and the web. Recently, the use of corrugated webs has been found to raise the bending stiffness in the lateral direction of the girder without using stiffeners, leading to much less weight and higher fatigue resistance [2]. Accordingly, corrugated web girders have been used in bridges all over the world [3]. However, such girders, referred hereafter as BGCWs, were designed based on half-scale experiments [2]. To make use of these innovative girders, design models should be provided for different straining actions. Despite that, the literature survey [4] shows that most studies on the behaviour of the BGCWs were undertaken to study the shear, while the lateral-torsional buckling (LTB) behaviour of these girders attracted less number of investigations [5–11].

In a LTB mode, the cross-section of the girder suffers from a rigid-body lateral movement (u) and twisting (φ) as can be seen in Fig. 1 (taken from a previous investigation by authors [12]). Accordingly, the LTB depends principally on the unbraced length (L_b) of the compression flange. It is worth pointing out that the flexural capacity of an IPG failing by LTB is less than the moment producing the cross-sectional yielding ($M_{pl,R}$). Historically, in 1899, Prandtl [13] and Michell [14], independently, introduced a unified theory which considers both the flexural and torsional buckling behaviour of beams. Both investigated a narrow rectangular cross-sectional beam subjected to transverse loading. Their solution [13,14] was in the form of a second-order differential equation in u and φ as can be revised in Ref. [15]. Later on, the valuable contributions mainly by Timoshenko [16,17] led to the

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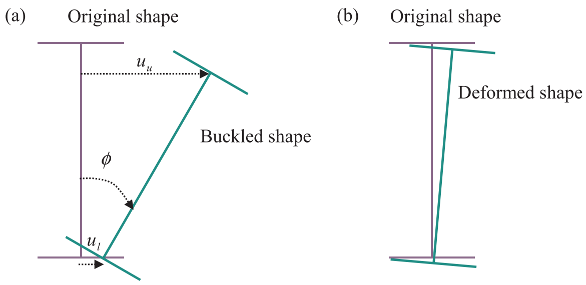

Fig. 1. Typical buckled/deformed and original shapes for an I-section girder from: (a) elastic and (b) inelastic analyses [11]; u_u and u_l are the lateral displacement of the upper and lower flanges, respectively.

development of the general theory of the LTB of I-section members by including the effects of warping torsion which dominates the response of thin-walled open sections [18]. In his solution [19], the elastic critical buckling moment, which can be resisted by a simply-supported perfect doubly-symmetric I-section girder subjected to a uniform bending moment before LTB occurs, was given as:

$$M_{cr,LTB} = \frac{\pi}{L}\sqrt{EI_y GJ\left(1 + \frac{\pi^2}{L^2}\frac{EC_w}{GJ}\right)} \tag{1}$$

where:

L is the unbraced length, EI_y is the minor-axis flexural rigidity, GJ is the torsional rigidity, and EC_w is the warping rigidity given by:

$$GJ = \frac{E}{2(1+\upsilon)}\sum\frac{bt^3}{3} \tag{2}$$

$$EC_w = E\frac{t_f b_f{}^3 (h_w + t_f)^2}{24} \tag{3}$$

where E is the Young's modulus, G is the shear modulus, υ is the Poisson's ratio, b_f is the flange width, t_f is flange thickness and h_w is the web height of the IPG.

1.2. Lateral torsional buckling of corrugated web girders

For the case of BGCWs, Sause et al. [6] recommended to use the existing LTB equations for IPGs without considering the increased torsional stiffness of corrugated web girders until research demonstrates that BGCWs have an increased inelastic LTB resistance compared with IPGs, despite that Lindner [5] found such relative increase in the BGCWs LTB strengths. More recently, it has been found that BGCWs, indeed, own increased LTB resistance compared with IPGs [8,9,11]. This has been attributed merely to the increase in the warping constant of the cross-section [8,9]. Accordingly, new formulae for the warping constant, for the case of the BGCWs, were proposed in literature [5,8,9]. However, the warping constant proposed by Lindner [5] was found to increase quadratically with the length of the girder (L), as noticed by Larsson and Persson [18]. Accordingly, this warping constant was ignored in this investigation because a sectional constant should merely depend on the cross-sectional geometrical details, and not on the girder's unbraced length. It is worth pointing out that the studies on the increased LTB strength of the BGCWs were all dealing with those girders formed from normal-strength steel (NSS) [5,8,9].

1.3. High-strength steels (HSSs) in bridge construction

Recently, it has been recognised that utilising high-strength steels (HSSs) in bridges [20] and buildings [21] provides various structural benefits, such as increasing the spans (i.e. providing column-free spaces) without the use of substantially thick steel plates. This enables the use of smaller cross-section sizes for the supporting structural elements which results in significant cost savings. Accordingly, a lot of bridges have been constructed worldwide by using HSSs [22], specially the steel with yield strength of 460 MPa, with the Ilverich Bridge in Germany being an example. Additionally, the demonstration bridge with corrugated webs shown in Fig. 2, which was designed by Pennsylvania Department of Transportation (PennDOT) and opened for service in July of 2005 [23], was formed from HSSs. However, as can be noticed above, studying the LTB of BGCWs built up from HSSs has rarely been undertaken and existing researches using HSSs [6,20] have not shown the increased strength compared with the IPGs.

Fig. 2. HSS demonstration bridge with corrugated webs in Bradford County, USA [23].

1.4. Problem statement and scope of current paper

A recent study on the LTB of IPGs built up with HSSs by Bradford and Liu [24] has found that the design models in international specifications are not compliant with the ultimate moments of the girders. So, modifications have been applied to these design models, raising the importance of investigating the members formed from HSSs. More recently, Somodi and Kövesdi [25] investigated the flexure buckling of HSS members, from which the applicable column buckling curves for steel grades between S420 and S960 were upgraded, compared with NSSs, by using curves with smaller imperfection factors (α_{LT}) [26]. This is because the obtained buckling resistances for such steel grades were always higher than the appropriate EN 1993-1-1 [26] column buckling curve. This is mainly attributed to the fact that the residual stress amplitudes are much smaller for HSS structures compared to their yield stresses than those of the NSS members [27]. Based on above information, the investigation of the LTB behaviour of the BGCWs built up from HSSs becomes important to substitute the lack in their strength and behaviour.

This paper, accordingly, reports the investigation on such girders. This is made numerically by using the finite element (FE) analysis package ABAQUS [28]. Considering both the elastic and inelastic buckling analyses, simply-supported girders are currently modelled under the case of pure bending moment, which is the critical case of flexural loading. Available warping constants [8,9] are evaluated by using the critical bending moments ($M_{cr,FE}$) obtained numerically, and then the ultimate moments ($M_{ul,FE}$) are compared with the design model presented by the EC3 [26] for the case of conventional IPGs. Several conclusions, as well, are drawn from this investigation on the behaviour of the BGCWs. Despite that this investigation considers only bare steel girders; the findings are conservatively suitable for girder segments close to intermediate supports of composite bridge girders where the negative bending moment exists.