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Shear analysis and design of high-strength steel corrugated web girders for bridge design

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ABSTRACT

Steel girders with corrugated web plates (BGCWs) have already been used in many bridges around the world because they own several advantages compared with traditional plate girders with flat webs. They have considerably high shear resistances and provide weight saving by reducing the web thickness and by eliminating the use of transversal stiffeners. However, these girders practically have been designed based on half-scale experimental tests. On the other hand, it has been recently recognised that high strength steels (HSSs) provide designers with the opportunity of creating more slender and weight efficient structures than would be possible if the normal strength steels (NSSs) have been used. To gain benefit from the advantages of both the BGCWs and the HSSs in one structure, this research work is carried out to investigate the BGCWs built with HSSs which have seldom been explored in literature despite being utilised in the Pennsylvania Demonstration Bridge with corrugated web, USA, which was opened for service in 2005. Finite element models, by using ABAQUS programme, have been used to accomplish this investigation. They are firstly verified by comparing their results with the existing test results in literature. Then, extensive nonlinear parametric studies are generated considering the corrugation dimensions used in the available constructed bridges. The strengths of the girders are compared with the available design models and the best model calculating the ultimate shear strength is highlighted. Additionally, from this investigation, an understanding for the real behaviour of the BGCWs built with HSSs is established.

1. Introduction

Recently, it has been recognised that using high-strength steels (HSSs) in buildings [1] and bridges [2] provides various structural benefits, such as avoiding the use of considerably thick steel plates. Such plates cause a lot of problems in the design stage, fabrication process, transportation of main systems to the sites and in the construction technologies used in civil and architectural heavy-steel structures. Accordingly, the current emphasis on the HSSs in literature, see for example Refs. [1–7], is attributed to the fact that they are widely utilised when reducing the weight of the structure is an important issue or when smaller load-carrying elements are required for architectural considerations. Just as an example in building construction, parts of the Skytree, which is an outstanding broadcasting, restaurant and observation high-rise tower in Tokyo, were constructed by using HSS of Grade 700 steel tubes [1]. Additionally, a lot of bridges have been constructed worldwide by using HSSs [8] with the Ilverich Bridge in Germany is shown as an example in Fig. 1(a). On the other hand, the stress-strain characteristics of HSSs, defined as those steels having nominal yield strength $f_y \geqslant 460$ MPa [6], are totally different from the characteristics of the widely used and investigated normal strength steels (NSSs). HSSs have gradual elastic portion without either a sharp yield point or a yield plateau. Additionally, they are characterised by a reduced strain hardening part and a high yield ratio (YR) which is often greater than 0.90. Therefore, the material behaviour is often modelled in numerical studies by elastic-perfect plastic bilinear curves [3,7]. Furthermore, research results [3–7] indicated that existing codified equations suggested for NSSs are not directly

Abbreviations: dof, degrees of freedom; BGCW, bridge girder with corrugated web; CWG, corrugated web girder; FE, finite element; HSS, high strength steel; IPG, plate girder with flat web; NSS, normal strength steel; PH, plastic hinge; YR, yield ratio.

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(a) Ilverich Bridge in Germany (b) Ilsun Bridge in South Korea

Fig. 1. Bridge plate girders: (a) plate girder built with S460 HSS and (b) plate girder with corrugated web.

applicable to HSSs. As may be noticed, the shear strength and behaviour of the web panels of HSSs plate girders showed typically the previous two main observations [7].

On the other hand, the use of corrugated plate profiles as the webs of girders in bridges, steel frames and buildings has been accelerated, thanks mainly for their significant shear stability. They also eliminate the need for the double-sided transverse stiffeners that have a principal influence on raising the shear strength of the I-section plate girders with flat webs. Accordingly, they provide relatively high strength-to-weight ratios [9–22]. Many examples of bridge girders in the world were built by using corrugated web girders; see Fig. 1(b) which represents the Ilsun Bridge in South Korea. However, the main difference in behaviour between the corrugated web girders compared with those formed from flat web plates is their negligible axial stiffness or what is so called the Accordion Effect [9–22]. This effect eliminates the interaction between shear and flexural behaviours, as the flexural strength of such beams is entirely carried by flanges, while the corrugated web becomes purely responsible for carrying the shear load. However, the literature [9–22] shows that the shear strength and behaviour of the girders with corrugated webs were extensively investigated considering the NSSs, while limited studies were devoted to investigate those corrugated web girders formed from HSSs [2,23].

This paper is, accordingly, emphasising on the fundamental shear strength and behaviour of bare plate girders with trapezoidally-corrugated webs (Fig. 2) used in bridge constructions (BGCWs) which are built with HSSs, with the main aim of combining the advantages of both the corrugated webs and the HSSs. Despite that these plate girders are compositely erected in bridges with concrete slabs, the design manuals often neglects the slabs in resisting the shear. Accordingly, this study provides slightly conservative results by neglecting the contribution of the concrete slabs in resisting the shear. Steel S460 is considered for this investigation. This is made through finite element (FE) analyses. Recently verified FE model [23] is used to generate parametric studies, considering a number of variables, by using ABAQUS software [24]. Currently, several conclusions have been delivered for the structural engineering community related to the shear behaviour of these girders, with the most suitable design model is provided at the end.

2. Review of shear buckling behaviour of NSS corrugated web girders

Before an investigation on the shear buckling behaviour of the BGCWs formed from HSSs could be made, it was important to start with a review of the current knowledge on those girders formed from NSSs. Accordingly, this section provides short up-to-date summary and critical review on the shear buckling behaviour of the CWGs formed from NSSs, raising the main differences in behaviour between them and those girders formed from flat webs.

2.1. Shear stress distribution in the corrugated webs

The above mentioned Accordion Effect [9–22] results in completely different shear buckling behaviour in the corrugated web girders (CWGs) compared with that appearing in the conventional plate girders with flat webs (IPGs). This is because, in the CWGs, the web carries insignificant longitudinal stresses from the bending moment and normal force affecting the girder, forcing the flexure to be effectively carried by the flanges. Therefore, it is widely accepted that the shear stress distribution is constant in the corrugated webs,

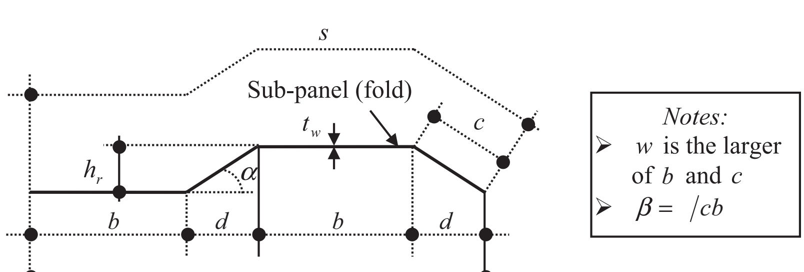

Fig. 2. Corrugation configuration and geometric notation.