Engineering Structures 74 (2014) 157–169

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Shear buckling behavior of tapered bridge girders with steel corrugated webs

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ARTICLE INFO

Article history:
Received 22 November 2013
Revised 6 May 2014
Accepted 6 May 2014
Available online 6 June 2014

Keywords:
Tapered corrugated steel webs
Critical shear strength
Shear strength
Local buckling
Global buckling
Interactive buckling

ABSTRACT

The existing literature on bridge girders with steel corrugated webs (BGCWs) is focused on prismatic girders; i.e. with constant depth. To the authors' best knowledge, no work has been done on the shear stability of *tapered* BGCWs although they have been increasingly used in bridges in recent years. Research presented in this paper focuses, first, on the critical shear buckling stress (τ_{cr}) of the corrugated webs of tapered BGCWs. This is made by carrying out elastic bifurcation buckling analyses using ABAQUS software on isolated corrugated webs with simple and fixed boundary conditions. Webs in different typologies of tapered girders with steel corrugated webs are considered. The corrugation dimensions of the considered corrugated webs are taken typical of those used in Shinkai and Matsnoki bridges. Opposite to prismatic corrugated webs which may buckle globally, it is found that the tapered corrugated webs buckle interactively without nothing buckling globally. It is additionally found that predicting τ_{cr} values for tapered webs based on prismatic web calculations are not accurate. Therefore, critical buckling stresses of the tapered webs based on the prismatic ones with different equation for each typology are proposed. The paper is, then, extended to investigate the nonlinear shear strengths of the BGCWs. The available design shear strength formulas for prismatic girders are compared with the FE shear strengths of the tapered BGCWs. Based on these comparisons, design strengths for the different cases of the tapered BGCWs are suggested. An illustrative example is given at the end to explain the application of the proposed predictions.

1. Introduction

Girders with steel corrugated webs have been used as structural members in Bridges. The Maupré Bridge in France and the Hondani Bridge in Japan, shown in Fig. 1, are two examples of structures fabricated from such girders [1]. Currently, bridge girders with steel corrugated webs (BGCWs) represent a very attractive structural form that is now benefiting from extensive success in different countries. A trapezoidally corrugated steel plate is composed of a series of longitudinal and inclined sub-panels, as can be seen in Fig. 2. Because of their significant out-of-plane stiffness, corrugated web plates have much higher buckling strengths compared with flat web plates. Therefore, the necessity of using stiffeners is eliminated by using them as the girder web and the required web thickness is reduced [2–6]. Additionally, the flexural strength of such girders is entirely provided by their flanges while the shear strength is provided by their webs. This is attributed to the negligible axial stiffness of the corrugated webs in the longitudinal directions of the girders which is known as the accordion effect [7,8]. Consequently, there is no interaction between shear and flexural behaviors. For that reason, it is widely accepted to assume a constant shear stress in the corrugated webs of such girders and then to quantify it in terms of the average shear stress, as follows:

$$\tau = \frac{V}{t_w h_w} \tag{1}$$

where V is the vertical shear force of the girder, h_w represents the web depth and t_w stands for the web thickness. However, the shear buckling mechanism in steel corrugated webs is classified into *local*, *global* or *interactive* buckling. Several investigations [2–8] have studied the interaction between local and global buckling in corrugated webs using the following generalized form of the interactive buckling stress:

$$\tau_{cr,I} = \frac{\tau_{cr,L} . \tau_{cr,G}}{\left((\tau_{cr,L})^n + (\tau_{cr,G})^n \right)^{\frac{1}{n}}} \tag{2}$$

Abbreviation: BGCWs, bridge girders with steel corrugated webs.

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http://dx.doi.org/10.1016/j.engstruct.2014.05.021
0141-0296/

Nomenclature

Roman letters

a	shear span
b	width of horizontal fold
c	width of inclined fold
d	horizontal projection dimension of the inclined fold
D_x	transverse bending stiffness per unit length of the corrugated web
D_y	longitudinal bending stiffness per unit length of the corrugated web
E	Young's modulus of elasticity of the steel material
f_y	yield strength of the steel material
f_u	ultimate strength of the steel material
h_w	web depth
h_{wo}	minimum depth of tapered corrugated web
h_{w1}	maximum depth of tapered corrugated web
h_r	depth of the corrugation cross-section
I_y	moment of inertia of the corrugated web as presented in Eq. 7
k_G	global shear buckling coefficient
k_L	local shear buckling coefficient
n	order of interactive buckling strength
q	length of one corrugation wave in the horizontal projection
s	actual length of one corrugation wave
t_w	web thickness
t_f	flange thickness
V	vertical shear force of the girder
$V_{ul,FE}$	FE ultimate shear strength
w	maximum fold width (maximum of flat panel width b and inclined panel width c)

Greek letters

α	inclination angle of the inclined fold
γ	inclination angle of the upper or lower flange of the tapered girder
λ_s	shear buckling parameter of the corrugated webs
τ	average shear stress
τ_{cr}	critical shear buckling stress
$\tau_{cr,L}$	local critical shear buckling stress
$\tau_{cr,G}$	global critical shear buckling stress
$\tau_{cr,FE}$	FE critical shear stress
$\tau_{cr,I}$	interactive critical shear buckling stress
$\tau_{cr,FE,P}$	FE critical shear buckling stress of the reference prismatic web
$\tau_{cr,\mathrm{Prop}}$	currently proposed critical shear buckling stress
$\tau_{cr,I,1}$	critical shear buckling stress of Yi. et al. [2] with n = 1.0
$\tau_{cr,I,2}$	2nd-order interactive buckling stress according to Abbas et al. [17]
τ_y	shear yielding strength of the steel material
$\tau_{ul,FE}$	FE maximum shear stress values
$\tau_{ul,M}$	shear strength values according to Moon et al. [3]
$\tau_{ul,S}$	shear strength values according to Sause and Braxtan [11]
$\tau_{ul,\mathrm{Prop}}$	currently proposed ultimate shear stress ($\tau_{ul,M,\mathrm{mod}}$)
υ	Poisson's ratio of the steel material

where $\tau_{cr,L}$ is the local shear buckling stress and $\tau_{cr,G}$ is the global elastic buckling stress which are calculated from the following Eqs. (more details could be revised in Ref. [5]):

$$\tau_{cr,L} = k_L \frac{\pi^2 E}{12(1-\upsilon^2)}\left(\frac{t_w}{w}\right)^2 \quad (3)$$

$$\tau_{cr,G} = k_G \frac{D_x^{0.25} D_y^{0.75}}{t_w h_w^2} \quad (4)$$

where E is the Young's modulus of elasticity, υ is the Poisson's ratio, w is the maximum fold width (maximum of flat panel width b and inclined panel width c as shown in Fig. 2), t_w is the web thickness, k_L is the local shear buckling coefficient and k_G is the global buckling coefficient. The transverse bending stiffness per unit length of the corrugated web (D_x), the longitudinal bending stiffness per unit length of the corrugated web (D_y) and I_y are defined as:

$$D_x = \frac{q}{s} \cdot \frac{E t_w^3}{12} \quad (5)$$

$$D_y = \frac{E I_y}{q} \quad (6)$$

$$I_y = 2bt_w\left(\frac{h_r}{2}\right)^2 + \frac{t_w h_r^3}{6\sin\alpha} \quad (7)$$

As can be noticed in literature, the extensive investigation on the shear buckling of steel corrugated webs [2–8] concentrated merely on prismatic girders such as the Maupré Bridge seen in Fig. 1(a). On the other hand, there are no investigations, to the best of the authors' knowledge, into the shear response of tapered steel plate girders with corrugated webs (see Hondani Bridge in Fig. 1(b)). As can be seen in Fig. 1(b), the tapered alignment for Hondani Bridge is of parabolic shape.

2. Previous investigations by current authors

In their previous investigations on the shear behavior of BGCWs, prismatic girders were considered by the current authors. They investigated BGCWs [5], firstly, to find the proper boundary conditions at the juncture between the corrugated web and the flanges used in bridges. Elastic bifurcation buckling analyses were carried out using ABAQUS [9] for corrugated webs with simple (S) and fixed (F) boundary conditions at their junctures with the flanges. To validate the model, the critical shear buckling stresses of isolated flat steel web plates, obtained from *elastic bifurcation buckling analyses* [5], were compared to the elastic shear buckling stress (τ_{cr}) calculated using the classical *plate buckling theory*

(a) Prismatic bridge girders (b) Tapered bridge girders

Fig. 1. Bridge girders with corrugated webs; (a) Maupré Bridge and (b) Hondani Bridge.