Journal of Constructional Steel Research 102 (2014) 59–71

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Analysis of local elastic shear buckling of trapezoidal corrugated steel webs

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ARTICLE INFO

Article history:
Received 15 January 2014
Accepted 7 June 2014
Available online 17 July 2014

Keywords:
Corrugated steel webs
Shear buckling
Shear buckling coefficient
Finite element analysis

ABSTRACT

The local elastic shear buckling strength of trapezoidal corrugated steel webs is investigated using finite element (FE) and theoretical analyses. The local elastic shear buckling strength is represented by the local elastic shear buckling coefficient, which is obtained from FE analysis. Although inelastic buckling will control the shear strength of most practical corrugated webs, the local elastic shear buckling coefficient is an important parameter in the shear strength calculation. This study shows that the fold width ratio, defined as the longitudinal fold width over the inclined fold width, has a significant influence on the local elastic shear buckling strength as the fold width ratio varies from 1.0 to 2.0. It is shown that the commonly-used local elastic shear buckling coefficient underestimates the local shear buckling strength by a considerable margin when the fold width ratio is greater than 1.0. It is also shown that the local elastic shear buckling coefficient is sensitive to the fold height-to-width aspect ratio, the fold width-to-thickness ratio, and the web corrugation angle, but is insensitive to the flange-thickness-to-web-thickness ratio when it varies from 5 to 15. Based on regression of FE analysis results, a formula is proposed to improve the calculation of the local shear buckling strength, in which parameters such as fold width ratio, fold aspect ratio, fold width-to-thickness ratio, and corrugation angle are taken into account.

1. Introduction

Steel I-shaped girders with corrugated webs (i.e., corrugated web girders (CWGs)) have been used in buildings and bridges due to their notable advantages [1,2]. A corrugated web permits a thin web plate to be used without the need for transverse stiffeners, resulting in lighter and potentially more economical girders. In addition, a corrugated web does not carry any significant normal stress, so it does not suffer from bend buckling [1,3]. This paper focuses on the shear strength of CWGs with trapezoidal corrugations (Fig. 1), which consist of longitudinal folds (parallel to the longitudinal axis of the girder) and inclined folds (inclined to the longitudinal axis).

Two shear buckling modes, *local* buckling and *global* buckling, have been observed in laboratory tests of trapezoidal corrugated steel webs. Classical thin plate buckling theory [4] has been used to estimate the *local* elastic shear buckling strength, and orthotropic plate theory has been used to estimate the *global* elastic shear buckling strength [5]. Based on experimental and analytical results considering both local and global buckling, a formula to estimate the lower bound shear strength was given by Driver et al. [6]. Interaction formulae, considering local buckling and global buckling have been proposed by Bergfelt and Leiva [7], Abbas [1], Sause and Braxtan [8], El-Metwally [9], and Yi et al. [10]. In most cases, the proposed shear strength formulae have included material yielding to account for inelastic buckling.

Although inelastic buckling will control the shear strength of most practical corrugated webs, it is well known that the local elastic shear buckling coefficient k_L is an important parameter in a practical shear strength calculation. Theoretical results [3,4] indicate that for an infinitely long web fold (i.e., as the web height h_w in Fig. 1 tends toward infinity), k_L lies between 5.34 (assuming the fold has simply supported edges) and 8.98 (assuming the fold has fixed edges). However, the boundary conditions of an individual web fold provided by the flanges and adjacent folds are neither simple nor fixed, which makes it difficult to accurately estimate the value of k_L. In addition, k_L may be affected by other aspects of the corrugated web geometry, including the fold height-to-width aspect ratio (h_w/b in Fig. 1) and the corrugation angle (α in Fig. 1). The present study considers these aspects of the fold geometry and boundary conditions, but gives special attention to the relationship between k_L and the fold width ratio β ($\beta = b/c$ in Fig. 1). In previous research, k_L was estimated by assuming that the long edges of the folds (along the lines between the folds) are simply supported. When the adjacent folds have the same width (i.e., $\beta = 1.0$) and the same thickness, this assumption may be reasonable, since all folds have the same local elastic shear buckling strength. When adjacent folds have different widths, however, the local buckling of the fold with the larger width (e.g., the longitudinal fold) will be restrained by the adjacent folds (e.g., the inclined folds), so that a larger value of k_L can be expected.

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http://dx.doi.org/10.1016/j.jcsr.2014.06.006

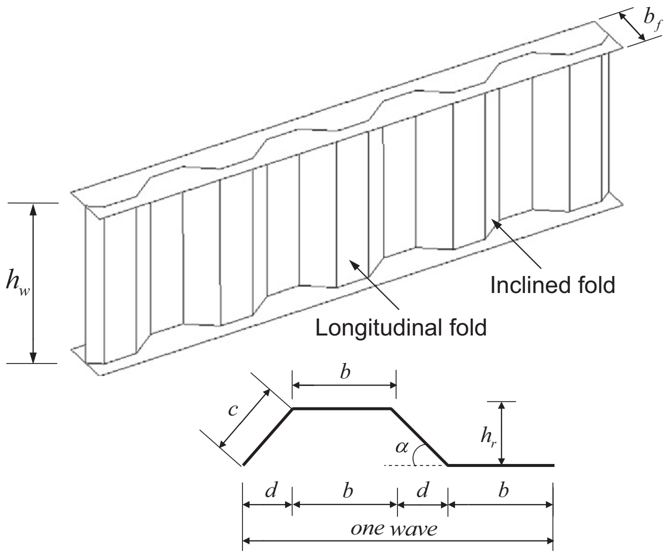

Fig. 1. I-shaped girder with trapezoidal corrugated web (CWG).

For example, a previous study by Sause and Braxtan [8] showed that when β is close to 1.0, close agreement was observed between test results and the calculated shear strength assuming $k_L = 5.34$, but when β is not close to 1.0, close agreement was not observed between test results and the calculated shear strength assuming $k_L = 5.34$.

The present study shows that k_L increases when β is not equal to 1.0, and that k_L is influenced by other geometric parameters. The study uses elastic finite element (FE) analysis of corrugated webs. By studying cases with carefully selected geometric parameters where local shear buckling dominates the shear buckling strength, the influence of global or interactive buckling on the shear buckling strength is minimized. Values of k_L are calculated for various values of β, h_w/b and other geometric parameters. The influence of the CWG flange thickness on local shear buckling of the web is considered. Finally a formula is proposed for estimating k_L.

2. Elastic shear buckling of trapezoidal corrugated steel webs

Local shear buckling is shown in Fig. 2. The theoretical local elastic shear buckling stress (i.e., strength) of a corrugated web, $\tau_{L,el}$, derived from classical plate buckling theory, can be expressed as [1,6]

$$\tau_{L,el} = k_L \frac{\pi^2 E}{12(1-\mu^2)(w/t_w)^2} \tag{1}$$

Table 1
Theoretical values of k_L for simply-supported web fold from [4].

h_w/w	3	4	5	6	Infinite
k_L	5.9	5.7	5.51	5.46	5.35

where w is the maximum fold width (the larger of the longitudinal fold width b and the inclined fold width c); t_w is the web thickness; E and μ are the elastic modulus and Poisson's ratio, respectively; and k_L is the local elastic shear buckling coefficient. When the fold edges are assumed to be simply supported, classical thin plate buckling theory [4] estimates $k_L = 5.35 + 4(w/h_w)^2$. Elgaaly et al. [3] estimate $k_L = 5.34 + 2.31(w/h_w)\text{-}3.44(w/h_w)^2 + 8.39(w/h_w)^3$ when the long edges are simply supported and the short edges are fixed by the flanges, and $k_L = 8.98 + 5.6(w/h_w)^2$ if all edges are fixed. For an infinitely long web fold (i.e., as h_w tends toward infinity), k_L lies between 5.34 and 8.98. The value of k_L used commonly in previous studies is the lower bound, 5.34. Theoretical values of k_L for a simply supported web fold corresponding to various values of h_w/w from [4] are given in Table 1.

Global shear buckling, shown in Fig. 3, can occur when the corrugations are relatively shallow. Based on an equation provided by Easley [5], Abbas [1] proposed Eqs. (2) and (3) to calculate the theoretical global elastic shear buckling stress (i.e., strength):

$$\tau_{G,el} = k_G \frac{E t_w^{1/2} b^{3/2}}{12 h_w^2} F(\alpha, \beta) \tag{2}$$

where k_G is the global elastic shear buckling coefficient which depends on the web geometry and boundary conditions and $F(\alpha, \beta)$ is a non-dimensional coefficient characterizing the web corrugation geometry:

$$F(\alpha, \beta) = \sqrt{\frac{(1+\beta)\sin^3\alpha}{\beta + \cos\alpha}} \cdot \left\{\frac{3\beta+1}{\beta^2(\beta+1)}\right\}^{3/4} \tag{3}$$

For an infinitely long web, Easely [5] suggests that k_G varies from 36 (assuming the web is simply supported by flanges) to 68.4 (assuming the web has fixed edges at the flanges). Similarly, Elgaaly et al. [3] suggest that k_G varies between 31.6 and 59, respectively. In the present study, $k_G = 36$ is used.

Interaction between local and global shear buckling has been considered in previous research, though the details of the interaction behavior have not been clearly explained. Formulae to account for this interaction have been proposed to express the theoretical interactive elastic shear buckling strength $\tau_{I,el}$, as follows:

$$\frac{1}{(\tau_{I,el})^n} = \frac{1}{(\tau_{L,el})^n} + \frac{1}{(\tau_{G,el})^n} \tag{4}$$

Bergfelt and Leiva [7] and Sause and Braxtan [8] proposed n = 1 and 3 for Eq. (4), respectively. In addition, Sause and Braxtan [8] and El-

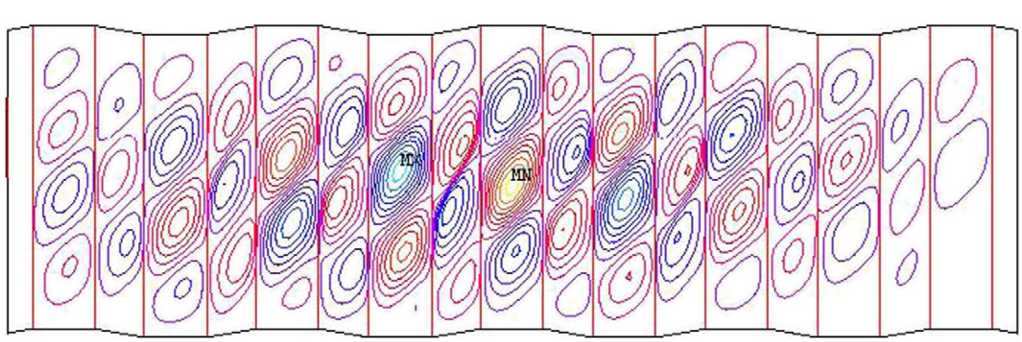

Fig. 2. Local shear buckling.