Theoretical Investigation of Shear Buckling for Hybrid Steel Plate Girder with Corrugated Webs

Amr B. Saddek

Department of Civil Engineering, Beni Sueif University, Egypt

Abstract: The corrugated steel plate is a widely used structural element in many fields of application because of its numerous favorable properties. The corrugated web beam behaves, in which the bending moments and applied forces are transferred only via the flanges, while the transverse forces are only transferred through the corrugated web. In the other hand, hybrid girders are assembled with different types of steel for the flanges and the web of a steel plated I-shaped element, it can be arguably stated that hybrid girders yield a greater flexural capacity at a lower cost and weight compared to a homogeneous girder. This paper aim to estimating the critical load of simply supported hybrid I-girders with corrugated webs under pure shear. A parametric study using three-dimensional finite element model using ANSYS version 12.0 were performed to investigate the effect of compactness of flanges, slenderness ratio of web and initial imperfection of web on the behavior of finite element models under pure shear. The present study, conclude that in case of hybrid section the ultimate loads for girders with compact and non-compact flanges are much closed especially at high slenderness ratios. Also, the initial imperfections of web under 100% of web have small effect on results and constraining of compression flange lead to fixed juncture between flange and web of I-girders with corrugated webs. Finally, it was found that, the proposed equation based on southwell technique for estimating the critical loads, have a good agreement with other methods mentioned at review.

Key words: Finite element method • Nonlinear analysis • Eigen buckling • Critical shear stress • Ansys12

INTRODUCTION

Steel girders with trapezoidally corrugated webs are structural members with high load-carrying capacity in relation to the material usage. The main advantage is that the corrugated web provides a high shear capacity for very thin web plates. The girder’s flanges provide the flexural strength of the girder with no contribution from the corrugated web which provides the girder’s shear capacity. Furthermore, the use of thinner webs results in lower material cost, with an estimated cost savings of 10-30% in comparison with conventional fabricated sections with flat web and more than 30% compared with standard hot rolled universal beams [1-3]. Also corrugated-web in can offer various advantages in terms of the architecturedue to their being aesthetically more appealing, fabricationtime and cost and structural (improved rotation capacity) as well as seismic (high energy absorption capabilities) performances [4]. The disadvantages of the girder with corrugated webs can be mentioned: a higher manufacture to build up such elements; the automatic welding is difficult to be applied; the corrugated webs have no ability to sustain longitudinal stresses, so, the conventional assumption is to ignore its contribution to the bending moment resistance; the joints with other members are more complicated [5]. Failure of the web occurs by steel yielding, web buckling or interactively between them. Lateral torsion and local flange buckling of corrugated web girders represent another two possible failure criteria [6]. Divahar and Joanna [7] study how to increase the shear capacity of web of large steel plate girders, basis of the experiments conducted on the six cold-formed steel beams with plain and trapezoidally corrugated web. Divahar and Joanna [7] concluded that:

Corresponding Author: Amr B. Saddek, Department of Civil Engineering, Beni Sueif University, Egypt.
E-mail: amrbkr93@gmail.com.

284
The average load carrying capacity of cold-formed steel beams with 30° corrugated webs increases by 25% than the beam with plain web. But there is only a marginal increase in load carrying capacity of beam with 30° corrugated web than that of beam with 45° corrugated web.

Beams with plain web showed shear buckling of web, but the failure due to shear in web could be eliminated by using corrugated web.

The strain in the beams with corrugated web is more than that of the beams with plain web.

Limaye and Alandkar [8] deal with the determination of buckling strength of a plate girder considering rectangular corrugated web plate. The finite element analysis of a plate girder is carried out using ANSYS. The results obtained from analysis are then compared with the plate girder with plane web of uniform depth. Various parameters like buckling strength and weight are compared. It is concluded that the corrugated web plate has high buckling strength and sufficient reduction in weight with light gauge elements, than plate girder with plane web. Zhiquan Wen and Wenlong We [9] study the shear buckling mode and ultimate shear capacity of corrugated steel webs by nonlinear finite elements method taking into account, the influences of different factors, such as web thickness, the corrugation angle, the width of horizontal plate, the corrugation depth and height of corrugated steel web. Zhiquan Wen and Wenlong We [9] concluded that:

- When the web thicknesses increase, the ultimate shear buckling loads significantly increase.
- Overall, the ultimate shear buckling load of corrugated steel web decreases as horizontal plate width raises.
- With the same corrugation angle and horizontal plate width, the ultimate shear buckling load of corrugated steel web decreases as the corrugation depth increases.
- As the corrugation angle increases, the ultimate shear buckling load of corrugated steel web is slightly improved.

Fatimah De’nan et al. [10] developed three-dimensional finite element model using LUSAS 14.3 to study on the effect of the triangular steel beam web profile (T WP) in shear buckling behavior of different thickness compared to that of the normal flat beam (FW). All specimens are cantilever beam which are fixed at one ends. The flange is constant with variable web thickness. Eigenvalue buckling analysis was used in analyzing the buckling load of the flat plate model and triangular web profile (T WP). Results showed that the web thickness gave a significant impact on the shear buckling of the T WP. In addition, the corrugation thickness of web was also effective in increasing the shear buckling capacity of the profile. On the basis of experimental and numerical studies of shear behavior for corrugated web girders, it can be found that shear buckling of corrugated webs is often classified as either local buckling (Fig. 1a) or global buckling (Fig. 1c). The interactive shear buckling mode (Fig. 1b) is attributed to the interaction between local and global shear buckling mode. Generally, local buckling is considered to be controlled by the slenderness of the individual folds of the web and global buckling is considered to be controlled by the slenderness of the entire web [11]. He [12] carried out parametric analysis on the shear strength of corrugated web girders by pertinent FE Models and compared with other researcher’s works, found that:

- The web initial geometric imperfection can be simulated by consistent mode imperfection through the first order mode of eigen value buckling analysis if the measured out-of-plane displacements were not obtained.
- When the corrugation is dense, global buckling of the whole web is in control. As the corrugation becomes coarse, the capacity of web will be controlled by local buckling of single folds.
- With the increase of corrugation depth, the buckling mode changes from global buckling to a more localized buckling mode.
- The ultimate shear capacity increases with the thickness and strength of the web.

Karthi and Nandakumar [13] present a parametric study on the strength of corrugated plates with varying parameters viz., thickness, angle of corrugation and aspect ratio for various boundary conditions, linear elastic analyses. Equations for maximum principal stress and maximum deflection for corrugated sheets subjected to various loadings with simply supported boundary condition are made available in non-dimensional parameters based on the multivariable regression method.
Because of this characteristic, the corrugated steel webs fail due to shear buckling or yielding. Three different shear buckling modes (local; global; and interactive) are possible, depending on the geometric characteristics of corrugated steel webs. Fig. 4 shows the geometric notations of the corrugated steel webs used in this study. The shear stress which causes an element of corrugated web to yield when it is subjected to pure shear stress state can be determined using von mises yield criterion with $f_y$ being the yield strength of the steel as:

$$\tau_y = \frac{f_y}{\sqrt{3}}$$  \hspace{1cm} (1)

where: $f_y$ is the yield strength of the steel.

Two buckling modes are associated with corrugated steel web; local and global buckling.

**Local Buckling Mode:** Local buckling occurs when a flat sub-plate between vertical edges has a large width to thickness ratio as shown in Fig. 5. Corresponds to the instability of a steel panel simply supported between two folds, corrugated web in this mode of failure acts as a series of flat plate sub panels that mutually support each other along their vertical (longer) edges and are supported by the flanges at their horizontal (shorter) edges. These flat plate sub panels are subjected to shear, the elastic buckling stress considering these plate as isotropic plates is given by Galambos [20].
Fig. 4: Corrugated plates with trapezoidal corrugation profiles

Fig. 5: Local buckling mode

Global Buckling Mode: In the case of dense corrugations, global buckling becomes the dominant failure mode. Global shear buckling is characterized by the formation of diagonal buckles through the entire web similarly to a flat plate web as shown in Fig. 6. It is characterized by diagonal buckling over several corrugation panels. This failure mode is typical for dense corrugation. When global buckling occurs, the buckling stress can be calculated using the orthotropic-plate buckling theory. The global elastic buckling stress can be calculated from Galambos [20]:

\[
\tau_{cr,g} = k_g \frac{D_x^{0.25} D_y^{0.75}}{th_w^2}
\]

where; \( k_g \) is global shear buckling coefficient depends solely on the web top and bottom constrains: \( k_g = 36 \) for steel flanges and = 68.4 for composite flanges [21]. The factors \( D_x \) and \( D_y \) are the flexural stiffness per unit corrugation about the \( x \)-and \( y \)-axes respectively. These factors are defined for trapezoidal corrugation profile as follows:

\[
D_x = \frac{E}{b} + \frac{E}{b+d} \left( \frac{bt_w (dtan \alpha)^3}{4} + \frac{t_w (dtan \alpha)^3}{12sin \alpha} \right)
\]

\[
D_y = \frac{cEt_w^3}{s \cdot 12} = \frac{(b+d)}{b+dsec \alpha} \frac{Et_w^3}{12}
\]

where; \( I \) is the second moment of area of "wavelength" of the web, \( c = \) the wave projection length, \( s = \) the actual wave length, \( t_w = \) the web thickness, \( b = \) the panel width, \( d = \) the horizontal projection of the inclined panel width, \( \alpha = \) the corrugation angle and \( d tan \alpha = \) the corrugation depth.

Interaction Between Failure Modes: The interactive shear buckling mode is attributed to the interaction between local and global shear buckling modes and governs the shear buckling strength as shown in Fig. 7. The following equation can be used to calculate the interaction between the buckling modes described earlier; which based on the experimental analyses performed by Bergfelt and Leiva-Aravena [22], the critical stress due to the interaction between local and global buckling modes (\( \tau_{cr, i} \)) had given as,

\[
\tau_{cr, i} = \frac{1}{\tau_{cr, l}} + \frac{1}{\tau_{cr, g}}
\]
This equation doesn't consider the steel yielding failure criterion and its interaction with the other buckling failure criteria. If the critical shear stress calculated from any mode exceeds \((0.8\tau_y)\) inelastic buckling will occur and the following equation can be used \([20, 21]\) to calculate the inelastic critical stress \(\sigma_{cr, in}\), in both local and global buckling modes:

For \(\tau_{cr, l} > 0.8\tau_y\):

\[
\sigma_{cr, l} = \sqrt{0.8\tau_{cr, l}\tau_y}
\]

where \(\tau_{cr, l} \leq \tau_y\)

(10)

For \(\tau^{ext} > 0.8\tau_y\):

\[
\sigma_{cr, g} = \sqrt{0.8\tau_{cr, g}\tau_y}
\]

where \(\tau_{cr, g} \leq \tau_y\)

(11)

Methodology and Research Strategy: The present study addresses the linear elastic buckling analysis and non-linear analysis of steel girders with trapezoidally corrugated webs, for estimating critical load and critical shear stresses using finite element technique for which ANSYS software is employed. Models have been studied, considering parameters such as, web thickness, corrugation angle, flange compactness and initial imperfection. The proposed equation for estimating critical load of plate girder with flat web has a good agreement with other methods presented by Venkataramaiah and Roorda [14] and Galambos [20], especially at high slenderness ratios for webs.

Theoretical Approach

Finite Element Analysis of the Girder: Analysis of corrugated steel web to ultimate shear buckling load and buckling mode with the linear theory of small deflection just gets the branch points of buckling load. The elastic branch points of corrugated steel webs can be obtained by buckling analysis of ideal structures, while the actual structure inevitably exists initial defects and such defects may induce corrugated steel webs to shift from the ideal branch points of buckling modes to the extreme branch points of buckling modes. From this perspective, in order to more realistically reflect the actual structure stress state, the only way to analyze the structure is to use the nonlinear theory of large deflection, considering the material nonlinearity and geometric nonlinearity in the whole process, as shown in Figs. 8. ANSYS is a finite element based software to simulate the combined geometric and materials nonlinear response. To analyze and get the precise results of any structure in ANSYS, software required some inputs like material property, element type, boundary conditions, proper meshing etc.

Element Types and Material Properties: The models are built with two-dimensional ANSYS shell elements (Shell 93), by incorporating all the nodes, element, material properties, dimensions and boundary conditions. The element has six degrees of freedom at each node: translations in the nodal x, y and z directions and rotations about the nodal x, y and z axes. The deformation shapes are quadratic in both in-plane directions. The element has plasticity, stress stiffening, large deflection and large strain capabilities. In addition, this element is well suited for modeling the buckling of steel plates. The Bi-linear isotropic hardening model with Von-Mises yield criterion was employed for modeling the non-linear behavior of steel. The stress–strain curve used in FEA for flanges and web steel are shown in Fig. 9.

Boundary Conditions, Meshing and Initial Imperfection: In the construction of the model some conditions were taken into consideration as the connection between the corrugated web and flanges. The modeled were considered to behave as simply supported beam. The simply supported beams have been modeled using no warping restrained boundary conditions. As shown in Fig. 10, all the nodes of the two ends are free to translate in all directions and/or rotate about all axes except the node at the mid height of the web which represents the practical simple connection and can be described as follows:
Fig. 8: Type of buckling problem

Fig. 9: Stress-strain curve of steel

Fig. 10: Boundary conditions of F.E. models
Displacement in Y-axis, X-axis and Z-axis direction (v) is prevented.
- Rotation about Y-axis and Z-axis is free (Out of plane bending free).
- Rotation about X-axis is prevented (twisting prevented).

The mesh sensitivity analysis is carried out, as will be shown in verification of models. All plate girders are provided for the entire height of the web and are braced against out-of-plane translation in an idealized way in order to reduce the number of parameters observed in the current study. All the elements comprising the plate girder mesh with a ratio not exceeding 1:20, this limit is recommended for the finite element program. The finite element models for plate girder with trapezoidal webs are shown in Fig. 11. Imperfections are added by using eigenvectors that result from an eigen value buckling analysis. The eigenvector determined is the closest estimate of the actual mode of buckling. The imperfections added should be small when compared to a typical thickness of the beam being analyzed. The imperfections remove the sharp discontinuity in the load-deflection response. The UPGEOM command in the ANSYS program adds displacements from a previous analysis and updates the geometry to the deformed configuration. In the cases of the first buckling mode and sine wave shapes both the positive and negative scaling factor can be applied.

**Verification of the Finite Element Model:** Elastic-plastic modeling of material stress-strain properties is used in this validation study. Prior to start the main model, the accuracy of the finite element study is controlled by the mesh refinement. Therefore, coarse and fine meshes were considered for a sample of plate girder models with and without, of initial imperfections. The mesh density is relative, i.e., the fine mesh is 30 percent more dense than the course mesh. The different in peak stress was only 0.7% so the coarser mesh was used to save computational time. Fig. 12 shows the finite element models for shell element. Z axis represents the longitudinal direction and X represents the lateral direction (cross sectional area). The constraints are against X, Y, Z for simulating hinged support and against Y, Z for simulating roller support as shown in Fig. 13. Fig. 14 shows that, the maximum deflection is 0.001891 with percentage error equal 1.6% compared with the theoretical solution as followed:

\[
\delta = \frac{pl^3}{4EI_t} + \frac{kPL}{4GA}
\]

\[
\delta = 0.001857 \text{cm}
\]
Fig. 12: Finite element model using shell element

Fig. 13: End conditions for shell element model

Fig. 14: Nodal displacement data for nodes at Y direction
Setup of Current Work: The analytical model used to performing the current study consist of a simply supported symmetric girder subjected to two point load at third points as shown in Fig. 15. The bearing and transverse stiffeners are present along the longitudinal axis of the finite element models on both sides of the web. The support bearing stiffeners are provided as 18mm thick and bearing stiffener is provided at the point load with the same thickness. The stiffener dimensions remain constant throughout the entire study. All stiffeners are provided for the entire height of the web and are braced against out-of-plane translation in an idealized way in order to reduce lateral torsional buckling of compression flange. This idealized bracing is achieved by specifying rigid supports at the top and bottom of the stiffeners orthogonal to the longitudinal axis. To include the initial imperfection of the component plates, a simulation of buckling shape by sine wave is performed by small concentrated force in the mid height of panels then the geometry of girder is update to the desire value of initial imperfection. To investigate the effect of large displacements on the behavior, a nonlinear geometric analysis was performed a bilinear elasto-plastic response of the material was considered.

Variations of Parameters used in the Theoretical Analysis: In order to investigate the effect of the different properties of the cross section on calculating the critical load of the plate girder with corrugated web, many cases were consider in the analysis as follows:

- Seven cases of web thickness given as follows:
  - a- $t_w=0.6cm$
  - b- $t_w=0.55cm$
  - c- $t_w=0.5cm$
  - d- $t_w=0.45cm$
  - e- $t_w=0.4cm$
  - f- $t_w=0.35cm$
  - g- $t_w=0.3cm$

- Two cases of flanges configuration as compact flange and non-compact flanges according to ECP [23]. Those are:
  - a- Compact flange $b_f=30cm$, $t_f=3cm$
  - b- Non-Compact $b_f=30cm$, $t_f=2cm$

- Ratio between flat part width of corrugation web to web height:
  - a- $b/hw=0.2$

- Angle of corrugation:
  - a- $\alpha=30^\circ$

- Initial imperfections of web equal to the following:
  - a- $w/t_w=1\%$
  - b- $w/t_w=40\%$
  - c- $w/t_w=100\%$

- Yield stress for web and flange:
  - a- $F_{y=web}=2.4 t/cm^2$
  - b- $F_{y=flange}=3.6 t/cm^2$

Effect of Flange Compactness on the Behavior of Plate Girder with Corrugated Web: The finite element analysis was performed for the different cases mentioned before to obtain the data of load-deflection relations for different girders. These data are used to evaluate effect of compactness of flanges on these structures; especially the most modes of failure are due to shear stresses, when compression flange is constrained against lateral displacement. Fig. 16 shows the relation between load and deflection at the mid span of such girders for both of compact and non-compact flanges for different slenderness ratios of the corrugated web. It can be clearly noticed from all these figures that the ultimate loads for girders with compact flanges are with small slight difference over the ultimate loads for girders with non-compact flanges. This is quite reasonable as the webs were with the low yield stresses and the different modes failures for all girders are in the zone of maximum shear as shown from Fig. 17. However, the load-deflection relationships lead to a suggestion, that using of non-compact flanges for hybrid plate girder with corrugated web, when constraining compression flanges against lateral displacement lead to economic sections.

Estimating of Critical Load: When a plated structure member is subjected to direct compression, bending, or shear stresses or to combinations of these stresses,
Fig. (16-a): Load deflection curve in case of $t_w=0.6\text{cm}$

Fig. (16-b): Load deflection curve in case of $t_w=0.55\text{cm}$

Fig. (16-c): Load deflection curve in case of $t_w=0.5\text{cm}$

Fig. (16-d): Load deflection curve in case of $t_w=0.45\text{cm}$
the plate component may buckle locally before the entire member fails. The problem of local buckling for plates can be approached by setting up the differential equations of equilibrium for the buckled form of the complete section, or by assuming deflection functions. Many different attempts were made to compute the critical load for plate element based on, that the strain energy stored in the plate equal to the total work done by the compressive forces during buckling.

**Estimating of Elastic Buckling Load for Plate Girder under Pure Shear using Method of Load Square Deflection Method:** The elastic critical buckling stress is estimated by using the load vs. lateral displacement squared method, as described by Venkataramaiah and Roorda [14] whereby a tangent to the curve is drawn in the post buckling range and the intersection point of this line with the vertical (load) axis gives the elastic buckling load, for the case of pure compression [24].

Fig. (16-e): Load deflection curve in case of \( t_w = 0.4\text{cm} \)

Fig. (16-f): Load deflection curve in case of \( t_w = 0.35\text{cm} \)

Fig. (16-g): Load deflection curve in case of \( t_w = 0.35\text{cm} \)
Fig. (17-a): Failure pattern for plate girder with non-compact flanges and web thickness 0.35cm

Fig. (17-b): Failure pattern for plate girder with compact flanges and web thickness 0.35cm

Fig. (17-c): Failure pattern for plate girder with non-compact flanges and web thickness 0.3cm
Fig. (17-d): Failure pattern for plate girder with compact flanges and web thickness 0.3cm

Fig. (18-a): Estimating of critical load for plate girder with web thickness 0.6cm

Fig. (18-b): Estimating of critical load for plate girder with web thickness 0.55cm
Fig. (18-c): Estimating of critical load for plate girder with web thickness 0.5cm

Fig. (18-d): Estimating of critical load for plate girder with web thickness 0.45cm

Fig. (18-e): Estimating of critical load for plate girder with web thickness 0.4cm

Fig. (18-f): Estimating of critical load for plate girder with web thickness 0.35cm
Fig. (18-g): Estimating of critical load for plate girder with web thickness 0.3cm

The post-buckling slope of the load versus maximum squared web deflection (P versus \( w^2 \)) was obtained by linear curve fitting in the post-buckling region [14]. Fig. 18 show the results generated from the application of this method for plate girder with corrugated web in case of compact and non-compact flanges and by considering variations in the web thickness. The extension of the slope for curve in the post buckling region well give the critical load at the point of intersection at Y-axis which, represent critical load.

**Proposed Technique for Generating of the Algebraic Equations for Estimating the Critical Load for Web Plate in Shear:** A powerful tool for estimating the critical load and the imperfection magnitude for imperfect strut under pure compression from the experimental data “Load VS. Deflection” graphically, is due to Southwell [24]. A modified approach was made by Spencer and Walker [25] in order to extend the Southwell idea for the large plate deflection with small or large imperfections, the proposed technique using the so called Donnell and Walker [26] equation for plate deflection. In the present work a modified technique for estimating critical load for plates with initial imperfections under pure moment presented by Saddek [16] is introduced based on Southwell equation and Spencer technique at pure shear. The proposed equation could be in following formula;

\[
\frac{1}{E_t}\left((w^2 + (w_o)^2) - \frac{(w)^2}{(P)}\right) = \frac{(w)^2}{(P)}
\]  

(12)

This equation could give a satisfactory accurate relationship between the out of plan displacement and the applied load taking into account the initial imperfection of web panel under pure shear. Applying of Eq. (12) on the plate girder models with compact flanges and different initial imperfection (1%, 40% and 100%) (Fig. 19) can be constructed for different web thickness. These relationships were constructed for Eq. (12) by using the data from the finite element analysis. For each diagram, the best fit line was obtained from which the value of the critical load is found and typed on the top right of each drawing.

**Verification of Proposed Design Equations and Comparison with Results Obtained by Other Researcher:**

The previous analysis was intended to reproduce the critical load of plate girder under pure shear analytically from the finite element analysis data. A comparison of results is performed for the estimated critical load from these methods. Fig. 20 shows the critical load obtained from the following methods:

- Load square displacement method [16-19,24].
- Proposed equation.
- Galambos equation for long edge simply supported and short edges clamped [20].

It can be seen from the previous bar chart that:

- The difference between present equation and method of load square displacement method for estimating critical load equal 7%.
- Galambos equation (Eq. 12), are valid only for local buckling mode which was investigated from theoretical analysis (Fig. 17).
Fig. (19-a): Estimating of critical load for plate girder with web thickness 0.6cm

Fig. (19-b): Estimating of critical load for plate girder with web thickness 0.55cm

Fig. (19-c): Estimating of critical load for plate girder with web thickness 0.5cm

Fig. (19-d): Estimating of critical load for plate girder with web thickness 0.45cm
Fig. (19-e): Estimating of critical load for plate girder with web thickness 0.4cm

Fig. (19-f): Estimating of critical load for plate girder with web thickness 0.35cm

Fig. (19-g): Estimating of critical load for plate girder with web thickness 0.3cm
CONCLUSION

The current papers deals with estimating the critical load of simply supported I-girders with corrugated webs whose compression flange is adequately supported against lateral torsional buckling, by studying the panels under pure shear. For this reason the previous theoretical analysis were performed and the following conclusion may be attained:

- Many theoretical treatments which are applied or developed through the research provide reasonable tool for the estimation of the critical load, hence the critical load for plate girders regarding the panel of pure shear.
- The suggestion formula for the calculation of the critical load for such case can be used for plate girders provided that load-out of plane web deflection data could be collected. This is, of course, of practical importance when these data are obtained through non-destructive tests at any time of the structure lifetime. Another advantage of this method is the determination of the actual initial imperfection of the web.
- Also, if the structure cannot be tested, the load-out of plane displacements data from any finite element based program can be used for the determination of the critical shear load by using the suggestion formula.
- Using of non-compact flanges for hybrid plate girder with corrugated web, when constraining compression flanges against lateral displacement, lead to economic sections.

Nomenclature:

\[ L \] = span of plate girder.
\[ t_w \] = web thickness
\[ t_f \] = thickness of flange.
\[ i \] = width of inclined fold of corrugation.
\[ s \] = unfolded length of one corrugation.
\[ F_y-web \] = yield stress of web material.
\[ \tau_c \] = shear yield stress of web material.
\[ \tau_{o,g} \] = global shear buckling.
\[ h_w \] = web height.
\[ b_f \] = width of flange.
\[ b \] = width of horizontal fold of corrugation.
\[ c \] = horizontal length of one corrugation
\[ \alpha \] = angle of corrugation.
\[ F_y-flange \] = yield stress of flange material.
\[ \tau_{o,l} \] = local shear buckling.
\[ \tau_{o,s} \] = interactive shear buckling.

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