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PARAMETRIC STUDY IN SHEAR BUCKLING CAPACITY OF SINUSOIDAL CORRUGATED STEEL WEB

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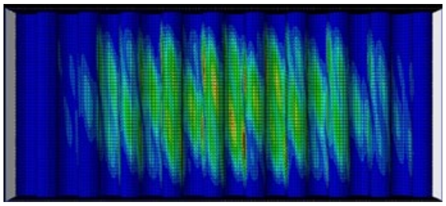
Graphical abstract



Abstract

Sinusoidal corrugated steel web has gradually gained attention over trapezoidal corrugated steel web. The design of shear buckling capacity for the trapezoidal corrugated web is governed by interactive buckling which normally has the lowest value among global, local and interactive failures. It was discovered in some studies that the shear buckling in a sinusoidal section is found to be governed by either local or global failures, where there is a lack of study in this area. The purpose of this study is to determine the effect of web thickness, web height, and sinusoidal radius on the shear buckling capacity and buckling mode in the sinusoidal corrugated steel web. Finite element analysis was conducted on 150 specimens with different radius of sinusoidal corrugated web, web height and web thickness to investigate their influence to the shear buckling capacity of the sections. The result shows that the increase in web thickness has been shown to increase the shear buckling capacity linearly. The increase in web height and radius of corrugated web reduce the shear buckling capacity of the beam exponentially. The results from finite element analysis are compared with an analytical equation from existing literature. It is found that the equation gives a conservative prediction of the shear capacity, however, could be used for a radius greater than 150 mm.

Keywords: Shear buckling, corrugated steel web, finite element analysis.

1.0 INTRODUCTION

The wide flanged corrugated steel web has been extensively researched in the last decade. Studies for such sections have been carried out on high-grade steel and applied in bridge designs around the world such as Ilverich Bridge in Germany and Ilsun Bridge in South Korea [1]. Due to the accordion effect, the corrugated steel web is assumed to only carry the shear load by distributing the stress evenly across the whole height while the flange effectively resists only bending moment [2]. The corrugated shape is adopted to increase its shear stability, hence reducing the need for stiffeners in the web. Due to the thin web, the beams are prone to buckling shear failure, especially at a low shear-span ratio. There are three types of failures found in the trapezoidal corrugated web section, namely local buckling, interactive buckling, and global buckling. Local buckling is the failure of a single flat panel while global buckling involved several flat panels. Interactive buckling failure, which has the lowest value among the three failures, always governed the shear buckling strength of the sections [3].

Most of the testing and numerical analysis of the corrugated steel web have been conducted on the trapezoidal-shaped web, due to its ease of fabrication. Wang et al. (2019) [4] performed experimental testing on trapezoidal corrugated steel girders with vertical and horizontal stiffeners to increase its buckling capacity. This study is numerically modelled in the research by He et al. (2019) [5]. The calculation of shear capacity using the equations by Hassanein and Kharoob (2013) [6] and Leblouba et al. (2017) [7] were found to be accurate for typical corrugated web, while underestimated for the corrugated web with stiffener. Wang et al. (2019) [8] tested the composite beam with a trapezoidal corrugated steel plate and different shear-span ratios under cyclic loading. It is found that beams with low shear-span ratio exhibit brittle shear buckling in the web and is not suitable for energy dissipator. Zhou et al. (2019) [9] investigated the bending, shear, and buckling behaviors of prismatic and non-prismatic beams with corrugated steel web using numerical analysis. It is found that the beams exhibit global shear buckling, with higher shear buckling stress in the non-prismatic shape. Several studies have been conducted on the application of corrugated steel plate in other structural members such as shear wall [10], steel arch panels [11], sandwich plates [12].

With respect to that, a sinusoidally corrugated web has been proposed to improve the shear buckling capacity of wide flange members [13]. Jiao et al. (2017) [14] found that there was a significant increase in buckling load when the web is changed from flat to sinusoidal shape. Other studies have been conducted on the lateral-torsional buckling capacity of sinusoidally corrugated webs using numerical analysis [15-17]. Nikoomanesh, and M. A. Goudarzi (2020) [18] also determined the shear buckling capacity of the sinusoidally corrugated web based on finite element analysis and experimental work. Most of the available formulae to calculate the elastic shear buckling capacity of the sinusoidal corrugated web are extracted from the trapezoidal corrugated web, which does not include important parameters such as the radius of the sinusoidal shape web.

This paper focuses on the parameters that affect the elastic shear buckling capacity of the sinusoidally corrugated web, and its failure mechanism. Parametric study based on the verified model is carried out using ABAQUS software by considering a few variables namely web height, thickness, and the sinusoidal radius. Finally, the result from finite element analysis is compared to the available equation modified for the trapezoidal section.

2.0 METHODOLOGY

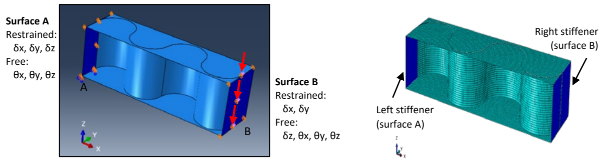
Finite element analysis is conducted using ABAQUS 6.11 (2011) [19] capable of performing linear and non-linear analysis. All specimens are modelled in 3D with non-linear material and geometrical properties.

Finite Element Model

The yield strength used for the steel is 300 MPa, with the modulus of elasticity of 200GPa and Poisson's ratio of 0.3. The steel is modelled as bi-linear, with a failure strain of 0.1.

The stiffeners are modelled as a rigid body, with no motion allowed. The thickness of both flanges and stiffeners are fixed at 30 mm throughout this study. To accurately simulate the shear buckling capacity of the members, the out-of-plane motion is restrained to prevent any failure due to torsion. Surface A (left stiffener in Figure 1(a)) is set to be pinned, while surface B is restrained in translation in x and y directions only. A shear load is assigned at the edge of the web along surface B, and the structural assembly is shown in Figure 1(a).

A 4 node shell element with reduced integration (S4R) is found to be able to provide an accurate result with shorter computation time using first-order interpolation, with a mesh size of 20 mm x 20 mm based on the mesh convergence study. Figure 1(b) shows the meshed assembly for the specimen, where the stiffeners (shown in blue) are being assigned as a rigid body.



(a) (b)

Figure 1 The assembly of model with (a) boundary conditions and applied load, and (b) appropriate meshing of the specimen

Parametric Study

A comprehensive parametric study was conducted based on different ranges of sinusoidal radius, web height, and thickness, which were found to be the main parameters affecting the buckling load of the structure. The variation of parameters used is shown in Table 1. In total, 150 specimens have been modelled based on the different combinations of the three parameters shown. For all models, the minimum flange width of 400 mm is used, with thickness of 30 mm. The amplitude and wave length of the corrugated web is R and 4R respectively.

Table 1 Variation of Web Parameters for Parametric Study

Sinusoidal radius, R (mm)	50, 100, 150, 200, 250, 300
Thickness (mm)	1, 2, 3, 4, 5
Height (mm)	500, 800, 1000, 1200, 1500

Elastic Shear Buckling of Sinusoidally Corrugated Steel Webs

Elastic shear buckling strength is the minimum value among local, global and interactive shear buckling. The design curve for shear buckling is given as in Equation (1) [20].

$$\frac{\tau_{cr}}{\tau_y} = \begin{cases} 1 & \text{for } \lambda_s < 0.6 \\ 1 - 0.614(\lambda_s - 0.6) & \text{for } 0.6 \leq \lambda_s < \sqrt{2} \\ \dfrac{1}{{\lambda_s}^2} & \text{for } \lambda_s \geq \sqrt{2} \end{cases} \tag{1}$$

where τ_{cr} and τ_y are the critical buckling and yield strength respectively, and λ_s is given in Equation (2).

$$\lambda_s = \sqrt{\frac{\tau_y}{\tau^e_{cr,B}}} \tag{2}$$

The shear buckling parameter, λ_s, indicates the type of failure of the beam. When λ_s is less than 0.6, yielding will govern the behaviour while a value larger than $\sqrt{2}$ indicates elastic shear buckling. An intermediate value will result in inelastic buckling, which is not covered in this research.

To ease the calculation in sinusoidal corrugated web beam, Eldib (2009) [13] has proposed Equation (3) which included the parameters affecting the shear buckling capacity of the sinusoidally corrugated web.

$$\left(\frac{1}{\tau^e{}_{cr,B}}\right)^{0.5} = 0.002124 \left(\frac{R h_w}{{t_w}^2}\right)^{0.3145} \tag{3}$$

R, h_w, and t_w are the radius, height, and thickness of the corrugation respectively. This regression formula considers the radius of the corrugation web which was not included in equations by previous researchers.

3.0 RESULTS AND DISCUSSION

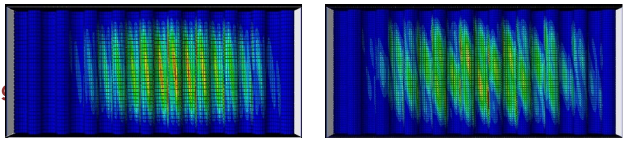
The model developed has been validated using the analysis by Aggarwal et al. (2018) [21] for four trapezoidal beams with the width of 120 mm, height of 1200 mm and thicknesses ranging from 1 to 3 mm. Similar geometric and material properties of the beams have been modelled and loaded to obtain its shear buckling capacity. The capacities obtained from this finite element analysis for the various sections yield less than 1% difference to the validation models, showing the modelling methods are considered accurate and therefore used in this analysis.

The 150 specimens of sinusoidal corrugated web beam have been modelled in ABAQUS with varying sinusoidal radius, web thickness, and height. From the analysis result, the critical shear buckling load for some of the models exceeds the yielding stress of the materials, especially for thicknesses of 4 and 5 mm. This indicated that the section would fail in material yielding before the buckling load is reached. For these beams, the shear buckling parameter, λ_s, calculated using Equation (2) has a value of less than 0.6.

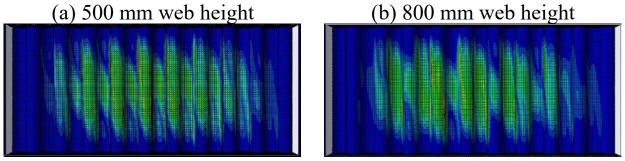
In all of the specimens analyzed, the three modes of failure namely local, interactive and global buckling have been observed. The local buckling happens at a larger sinusoidal radius, while global and interactive shear buckling failures tend to happen in sinusoidal corrugated web beams with a radius of less than 150 mm. In the following sections, the effects of web height, radius, and thickness on the shear buckling capacity and failure modes are discussed.

Effect of Web Height

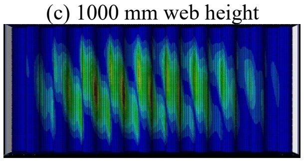
Figure 2 shows the changes of failure mode as the height of the section increases, for a constant web radius of 50 mm and web thickness of 1 mm. The stress is shown to be concentrated within a panel, with high shear angle, showing interactive shear buckling at lower web height. However, as the height increases, the failure is shown to be extended through several panels, exhibiting global shear buckling mode. The increase in height increases the slenderness of the section. This reduces the shear buckling capacity of the section considerably, hence is typically avoided in the design of such beams.



(a) 500 mm web height (b) 800 mm web height



(c) 1000 mm web height (d) 1200 mm web height



(e) 1500 mm web height

Figure 2 Shear buckling in sinusoidally corrugated beam with varying web height and constant web radius (50 mm) and thickness (1 mm)

Figure 3 shows the results of 25 sinusoidal web beams with a thickness of 1 mm and varying web height and sinusoidal radius. From the figure, it can be observed that the increase in the web height reduces the elastic shear buckling capacity of the sinusoidal corrugated web non-linearly. A more abrupt reduction in capacity is observed for beams with a lower sinusoidal radius (100 to 200 mm). This is because, at lower web height, the beam fails in global shear failure, while at greater web height, the failure changes to interactive buckling. In comparison, beams with large sinusoidal radius fail in local shear buckling at a much lower load, and this failure remains as the height increases. This trend remains similar for other thicknesses, depending on the type of failure it exhibits at lower web height. This shows that as the slenderness of the web section increases, the buckling capacity reduces hence controlling the section capacity.

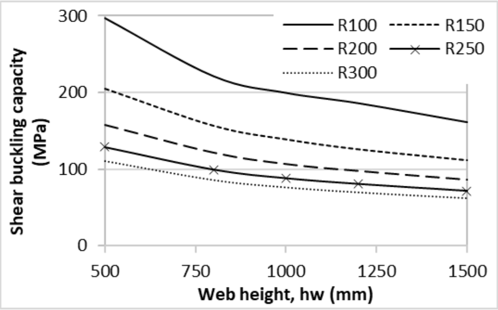
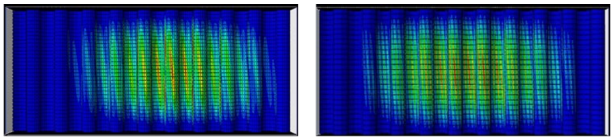


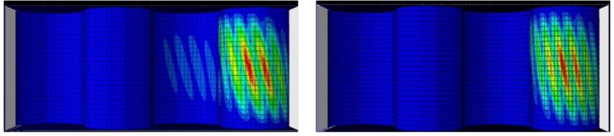
Figure 3 Shear buckling capacity versus web height for various sinusoidal radius, at web thickness of 1 mm

Effect of Web Sinusoidal Radius

Figure 4 shows that the buckling mode changes significantly from global to local buckling as the sinusoidal radius increases from 50 mm to 300 mm, while the web height and thickness remain constant at 50 mm and 1 mm respectively. The governing parameter for local buckling is the flat width of the panel (for trapezoidal corrugated shape), which is proportional to the sinusoidal radius of the corrugation. The critical shear buckling stress reduces from 297 MPa to 110 MPa as the sinusoidal radius increases from 50 mm to 300 mm. Among the three parameters, the sinusoidal radius is found to significantly affect the buckling mode. It is observed that the global and interactive shear buckling tends to govern the failure in a denser corrugation, while local shear buckling affected a larger sinusoidal radius.

In practical applications, the sinusoidal radius used for a primary structural element is greater than 200mm. Thus, the interactive shear buckling may not affect the section, provided that the beam has enough height of at least 500 mm.


(a) 50 mm sinusoidal radius (b) 100 mm sinusoidal radius


(c) 150 mm sinusoidal radius (d) 200 mm sinusoidal radius

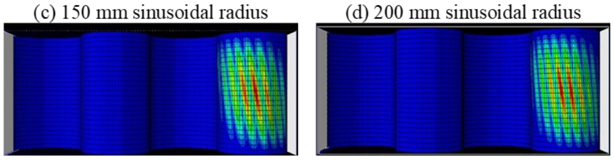

(e) 250 mm sinusoidal radius (f) 300 mm sinusoidal radius

Figure 4 Shear buckling in sinusoidally corrugated beam with varying radius and constant web height (500 mm) and thickness (1 mm)

The increase in radius of sinusoidal corrugated web reduces the shear buckling capacity exponentially as shown in Figure 5. No significant difference in trend is found as the thickness of the section varies. The increase in the sinusoidal radius enlarges the 'flat' area of the panel, making it more susceptible to local buckling.

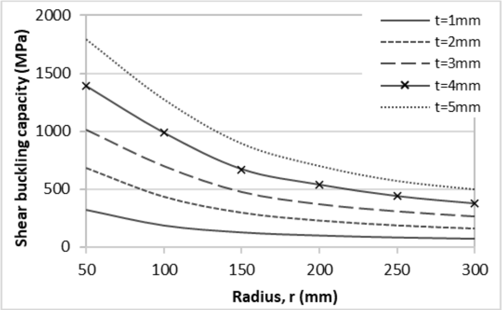
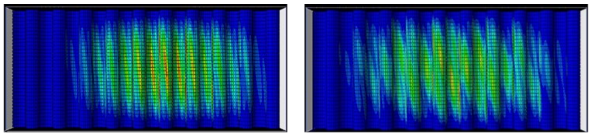
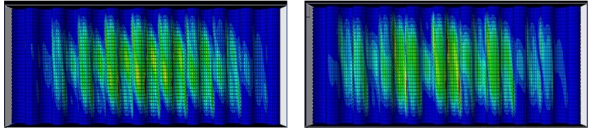


Figure 5 Shear buckling capacity versus web radius for various thickness, at web height of 1200 mm

Effect of Web Thickness

It is expected that the web thickness is directly proportionate with the buckling strength of the section, provided the sinusoidal radius and height remain constant. Figure 6 shows the result from the finite element analysis for a beam section with constant sinusoidal radius and web height of 50 mm and 500 mm respectively, and varying web thickness from 1 mm to 5 mm. It is generally observed that the failure remains as interactive buckling, with a more concentrated failure occurring at a larger thickness.


(a) 1 mm web thickness (b) 2 mm web thickness


(c) 3 mm web thickness (d) 4 mm web thickness

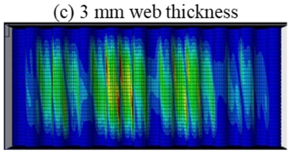

(e) 5 mm web thickness

Figure 6 Shear buckling in sinusoidally corrugated beam with varying web thickness and constant radius (50 mm) and web height (500 mm)

Figure 7 shows the variation of shear buckling capacity with respect to the increase in web thickness and height and constant radius of 250 mm. It is found that the elastic shear buckling capacity increases linearly with the increase of thickness, provided there are no major differences in the mode of failure. The trend is similar for all sections with similar web height. For a section with a sinusoidal radius of 250 mm and a height of 500 mm, the shear buckling load increases from 129 MPa to 910 MPa (7 times larger) as the web thickness increase from 1 mm to 5 mm. However, the strength will be limited by the yielding strength beyond 300 MPa. The shear buckling capacity of a section is dependent on its loaded area, where the increase of the thickness increases the area to resist the shear buckling load.

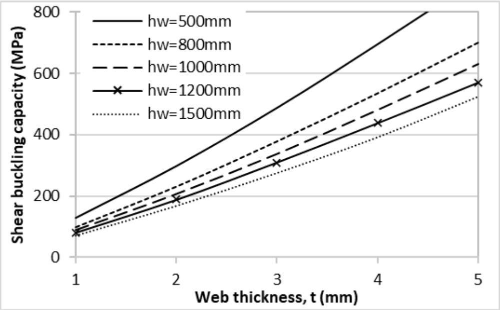


Figure 7 Shear buckling capacity versus web thickness for various web height, at a sinusoidal radius of 250 mm

Comparison with Existing Literature

Figure 8 compares the theoretical value calculated using Equation (3) with results from the finite element analysis for 1200 mm web height at various thicknesses. The graphs show similar trends of development in shear buckling capacity, where it is decreasing non-linearly as the sinusoidal radius increases. In general, the result from the finite element analysis yields a higher value of shear buckling capacity compared with Equation (3). This shows that the equation tends to be more conservative in estimating the shear buckling capacity. At a higher radius of 300 mm, however, the equation slightly overestimates the shear buckling capacity of the beam section. This could be due to the large nonlinearity that occur at a smaller radius due to higher shear buckling capacity beyond the material yield strength.

As shown in Figure 8, the results from Equation (3) compares well with the finite element analysis at sinusoidal radius beyond 150 mm. This trend is found to be similar, regardless of the thickness of the web. Though not shown, a similar trend is also observed for other web heights. It is thus to recommend that for the design of a section with a radius of more than 150 mm, Equation (3) can be used for the estimation. Some modifications of the equation should be made for beams with a sinusoidal radius of less than 150 mm. The finding of this research is applicable for sections with fairly small sinusoidal radius of less than 300 mm, and considerably slender with height of up to 1.5 m.

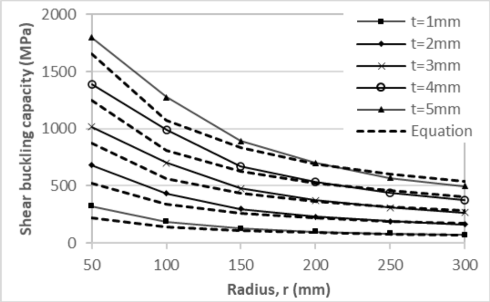


Figure 8 Comparison of Equation (3) with finite element result from this desk study (1200mm web height)

4.0 CONCLUSION

Finite element analysis has been conducted on 150 sinusoidally corrugated beams, with varying parameters namely the thickness and height of the web, and the sinusoidal radius. Based on the results, the following conclusions are made:

1) Global, interactive and local shear buckling failures have been observed in the sinusoidal corrugated beam sections investigated. The buckling mode is mainly governed by the geometric properties of the sinusoidal section. When the sinusoidal radius is more than 200 mm, local shear buckling usually governs and the buckling capacity reduces significantly. The increase of the radius of the section decreases the elastic shear buckling capacity.
2) The increase in web height reduces the elastic shear buckling capacity of the sections due to the increase in its slenderness. The rate of reduction in strength as the web height increases is very closely related to the type of failure it exhibits.
3) An increase in web thickness increases the elastic shear buckling capacity of the corrugated sections. The effect is significant in the sinusoidal section with a small radius and shorter web. The increase in web thickness is offset by the increase in web height.
4) Equation (3) proposed by Eldib (2009) [13] is not able to estimate accurately the elastic shear buckling capacity for the sinusoidal section with a radius of less than 150 mm. For a section with a radius of more than 150 mm, the equation shows an acceptable difference compared to the elastic shear buckling capacity with finite element analysis carried out in this study.

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