

TRANSVERSE LOAD CARRYING CAPACITY OF SINUSOIDALLY CORRUGATED STEEL WEBS WITH WEB OPENINGS

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ABSTRACT

A study on the behavior and design of corrugated web steel beams with and without web openings is presented. In the literature, the web opening problem in steel beams was dealt with mostly for steel beams with plane web plates and research on the effect of an opening on a corrugated web was found out to be very limited. The present study deals mainly with the effect of web openings on the transverse load carrying capacity of steel beams with sinusoidally corrugated webs. A general purpose finite element program (ABAQUS) was used. Simply supported corrugated web beams of 2m length and with circular web openings at quarter span points were considered. These points are generally considered to be the optimum locations of web openings for steel beams. Various cases were analyzed including the size of the openings and the corrugation density which is a function of the magnitude and length of the sine wave. Models without web holes were also analyzed and compared with other cases which were all together examined in terms of load-deformation characteristics and ultimate web shear resistance.

Keywords: Sinusoidally corrugated web, web opening, web shear resistance, finite element analysis

INTRODUCTION

Steel corrugated web beams are fabricated girders with a thin-walled, corrugated web and wide steel plate flanges. Owing to its profiled form, corrugated web exhibits an enhanced shear stability and hence eliminate the need for transverse stiffeners or thicker web plates. In this respect, it is an innovative design where the amount of web material is optimized through the inherent stability provided by profiling of the web. The profiling of the web generally avoids failure of the beam due to loss of stability before the web ultimate load is reached by web yielding.

One of the first studies on the shear buckling behavior of corrugated plates has been carried out by Easley *et al.* (1969). In that study the global shear buckling strength of corrugated webs was proposed to be calculated by treating the corrugated web as an orthotropic flat web. Literature survey on steel corrugated webs have revealed that research interest in the topic has grown notably in the last two decades. With this respect, in the 1990s numerous theoretical and experimental research on the buckling behaviour and strength of corrugated steel webs or plate panels have been performed by Hamilton (1993), Yoda *et al.* (1994), Cafolla (1995), Elgaaly *et al.* (1996), Luo *et al.* (1996), El-Metwally (1998) and in the first decade of the 21st century various other aspects of

structural behaviour of corrugated steel webs have been studied theoretically and experimentally by Yamazaki (2001), Chan *et al.* (2002), Shiratoni *et al.* (2003), Gil *et al.* (2004), Khalid *et al.* (2004), Sayed-Ahmed (2005), Gil *et al.* (2005), Abbas *et al.* (2006), Ibrahim *et al.* (2006), Driver *et al.* (2006), Abbas *et al.* (2007), Yi *et al.* (2008) and Moon *et al.* (2009). These studies generally incorporate investigations into the elastic buckling and ultimate resistance of the profiled thin webs under predominant shear action. The failure mechanisms of steel beams with corrugated webs under shear, bending and compressive patch loads are the main topics of investigations undertaken by most of the above researchers. In particular, the nature of interactive shear buckling between local and global modes was studied by Yi *et al.* (2008). Studies on geometric parameters have been extensively carried out by Gil *et al.* (2004). The behaviour and design of steel girders with corrugated webs with emphasis on bridge applications was considered by Yoda *et al.* (1994), Cafolla (1995), Shiratoni *et al.* (2003), Ibrahim *et al.* (2006) and Driver *et al.* (2006). Lateral torsional buckling of steel I-girders with corrugated webs were numerically studied by Sayed-Ahmed (2005) and Moon *et al.* (2009).

In practical applications, two forms which are adopted for web corrugation are trapezoidal and sinusoidal forms, the former being the most preferred. Probably in line with that preference in real life applications, the above mentioned research studies have mostly focused on the behaviour and design of web panels with trapezoidal corrugation form. However, it should be noted here that in parallel to the developments in welding technology and automation, fully automatic and computer-controlled fabrication of sinusoidally corrugated web beams has been made possible leading to an increased interest in the use of such beams both in building and bridge applications.

The present paper deals mainly with the effect of web openings on the transverse load carrying capacity of steel beams with sinusoidally corrugated webs. In the literature, the web opening problem in steel beams was dealt with mostly for steel beams with plane web plates and research studies on the effect of an opening on a corrugated web was found out to be very limited. Also currently no design guidance is available for corrugated steel webs with web openings. Limited research on the topic includes two studies by Lindner *et al.* (1994) and very recently by Romeijn *et al.* (2009). In Lindner *et al.* (1994), an investigation was carried out, at the Technical University of Berlin, into girders with trapezoidally corrugated web plates with cut outs. The study is focused on the local buckling behaviour of these girders with web openings. In their paper, Romeijn *et al.* (2009) present a basic parametric study on steel girders with trapezoidally corrugated webs having cut outs. Finite element analysis is used to investigate the effect of cut outs in corrugated webs. Openings were considered on the flat plate parts of the trapezoidal web and the effect of various geometric parameters on the behaviour was investigated in the framework of a parametric study.

In this study, using a general purpose finite element (FE) program (ABAQUS), a numerical parametric study was carried out for simply supported corrugated web beams of 2m length and with web openings at quarter span points. These points are generally considered to be the optimum locations of web openings for steel beams (Lawson, 1987). Within the parametric study, various cases were considered including the opening size and the corrugation density expressed as a function of the magnitude and length of the sine wave. Models without web openings were also analyzed and results compared with estimations of the currently available design guidance. Cases with web openings were examined in terms of the effect of varying web opening size and corrugation density on ultimate shear resistance and load-deformation characteristics of the beams.

DESIGN OF SINUSOIDALLY CORRUGATED WEB STEEL BEAMS

Rules for calculating the design resistance of steel members with corrugated webs are given in Annex D of Eurocode 3 Part 1.5-Plated Structural Elements (2003). In these rules for corrugated web beams, web openings are not included. The rules are given for the above mentioned two types of corrugation forms (trapezoidal and sinusoidal). Limit states considered for the design of a

corrugated web beam is, in general, similar to those considered for a steel plate girder with a flat web plate.

In Annex D of EC3-1.5, bending resistance of a corrugated beam is given as the minimum of the tension or compression flange resistances multiplied by the section height and no contribution of the web is taken into account. On the other hand, shear action is assumed to be carried by the web alone. The shear resistance of the corrugated web is calculated as the product of the shear resistance of a flat plate web and a reduction factor which is the smallest of the reduction factors for local and global buckling of the corrugated web. Web global buckling represents a diagonal tension field type of buckling of the web whereas local buckling is more localized over a single sine wave or the flat plate wall of a trapezoidal wave. Design shear resistance of a sinusoidally corrugated steel web is given as;

$$V_{Rd} = \chi_c \frac{f_y}{\gamma_{M1} \sqrt{3}} h_w t_w \quad (1)$$

in which χ_c is the reduction factor which accounts for strength reductions for web shear buckling and is given as the smallest value of the following expressions for local and global buckling of the web,

$$\chi_{c,l} = \frac{1.15}{0.9 + \bar{\lambda}_{c,l}} \leq 1.0 \quad \text{and} \quad \chi_{c,g} = \frac{1.5}{0.5 + \bar{\lambda}_{c,g}^2} \leq 1.0 \quad (2)$$

The web reference slendernesses, $\bar{\lambda}_{c,l}$ and $\bar{\lambda}_{c,g}$ which are expressed as a function of yield strength and elastic critical shear buckling stresses for local and global web buckling ($\tau_{cr,l}$ and $\tau_{cr,g}$) are given in Equation 3 below.

$$\bar{\lambda}_{c,l} = \sqrt{\frac{f_y}{\tau_{cr,l} \sqrt{3}}} \quad \text{and} \quad \bar{\lambda}_{c,g} = \sqrt{\frac{f_y}{\tau_{cr,g} \sqrt{3}}} \quad (3)$$

For sinusoidally corrugated webs global shear buckling is generally the dominant mode of failure particularly for practical geometries. In comparison to trapezoidally corrugated webs, the sinusoidal corrugation has the advantage over trapezoidal profiling of eliminating local buckling of the flat plate strips. In the EC3 approach, the global shear buckling resistance is calculated based on the assumption that the corrugated web behaves as an orthotropic plate with rigidities D_x and D_z in the web longitudinal and transverse directions, respectively. These rigidities are used to calculate the web reference slenderness, $\bar{\lambda}_{c,g}$, values which lead to the calculation of the reduction factor for global shear buckling. Elastic critical global web shear buckling stress is given as in Equation 4 and in Equation 5 critical buckling stress for local shear buckling is given.

$$\tau_{cr,g} = \frac{32.4}{t_w h_w^2} \sqrt{D_x D_z}^3 \quad (4)$$

$$\tau_{cr,l} = \left(5.34 + \frac{as}{2h_w t_w} \right) \frac{\pi^2 E}{12(1-\nu^2)} \frac{2t_w}{s} \quad (5)$$

As stated above the rules in Annex D of EC3-Part 1.5 are given for corrugated webs without web openings and hence in this study design guidance is only used to compare with the FE predictions for the models without web openings.

NUMERICAL PARAMETRIC STUDY

A numerical parametric study was carried out on simply supported I-beams with sinusoidally corrugated webs. Numerical modeling of the beams was carried out using ABAQUS (2007), a general-purpose finite element program. This program can cater for problems ranging from relatively simple linear analyses to non-linear analyses which require consideration of various manufacturing distortions and material non-linearities. A parametric study was performed for a number of models with varying web opening size and corrugation density. The modeling assumptions including the geometry, material, loading and boundary conditions are presented below.

Description of the FE models

In the numerical parametric study two web heights were considered namely $h_w=500\text{mm}$ and $h_w=1000\text{mm}$ beams. Typical finite element models adopted for the corrugated web beams is shown in Fig. 1. The behaviour of beams with varying web corrugation and web opening cases was studied mainly by using the $h_w=500\text{mm}$ beams and the $h_w=1000\text{mm}$ beams were used to assess the effect of design web slenderness (as given in EC3-Part 1.5) on the capacity of beams with web openings. A type of four-node doubly curved shell element (S4R) which is available in ABAQUS (2007) was employed in the models. A typical model is composed of upper and lower flanges of $12\text{mm} \times 200\text{mm}$ in size, representing a plate 200mm wide and 12mm thick, a $2\text{mm} \times 500$ (and 1000) mm corrugated web which is a thin sheet of steel plate having 2mm thickness and $500\text{mm}/1000\text{mm}$ height, two end cover plates and a central stiffener plate (with plate thickness, $t=20\text{mm}$) above which point load is applied via a rigid circular shell in contact with the surface of the upper flange plate. These parts are assembled as in Fig.1 to form the final FE model. Interaction among the parts was defined by using the TIE option available under ABAQUS constraints options.

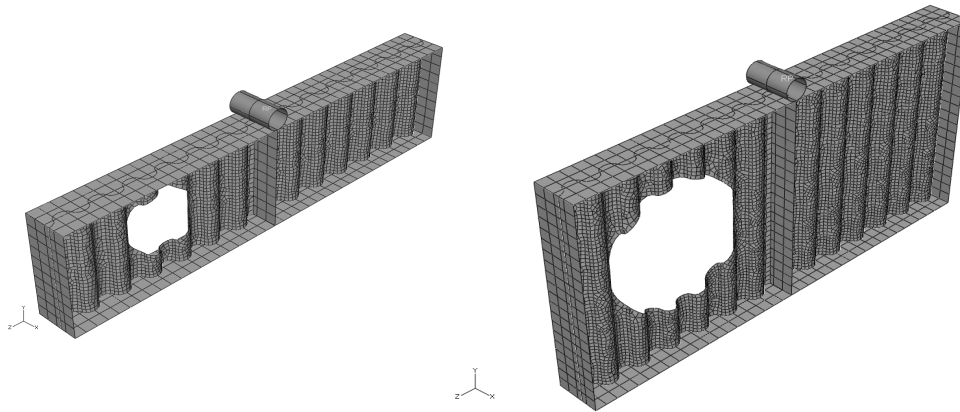
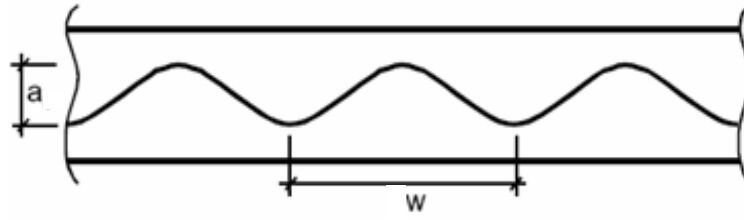


Figure1. Typical FE models adopted for the analysis of sinusoidally corrugated web beams with web openings

For the webs three different corrugation densities were assumed. As schematically explained in Fig. 2 the corrugation density is defined as the ratio of the magnitude of the sine wave, a , to the corrugation length, w . In the models the wave magnitude, a , was kept constant ($a=50\text{mm}$) and three different corrugation lengths ($w=75\text{mm}$, 150mm , 300mm) were used giving three different corrugation densities ($a/w=50/75$, $a/w=50/150$ and $a/w=50/300$). The corrugation densities adopted in this study represent practical geometries, the middle $a/w=50/150$ density web being the most commonly produced size for sinusoidally corrugated steel webs.



*Corrugation density = a/w
 $a=50\text{mm}$, assumed constant
 Three values assumed for w ; 75mm, 150mm and 300mm*

Figure 2. Corrugation densities adopted for FE modelling of the sinusoidally corrugated webs

In the models, web opening is created on one side of the web (Fig. 1) and the centre of the opening is located at quarter span point i.e. for the 2000mm long beam, 500mm from the left cover plate. As for the geometry of the web openings circular openings were used. Within the parametric study, four different opening sizes were considered which is expressed as the ratio of the opening diameter, d , to web height, h_w (d/h_w). Four values of d/h_w (0.2, 0.4, 0.6 and 0.8) were adopted both for $h_w=500\text{mm}$ and $h_w=1000\text{mm}$. For example, for $h_w=500$ and $d/h_w=0.2$, a circular opening with a 100mm diameter is used.

Boundary conditions were applied to either ends of the 2m long beam models at lower flange surface nodes by restraining appropriate degrees of freedom so as to simulate the simply supported condition. An elastic-perfectly plastic material model was assumed with a yield strength value of 235 MPa, modulus of elasticity $E=200000$ MPa and Poisson's ratio 0.3.

Non-linear FE Analysis

The non-linear response and ultimate strength of the models as described above were examined through finite element analysis. The FE program used in this study (ABAQUS) uses Newton's method to solve the nonlinear equilibrium equations. In this method, the solution is obtained as a series of increments, with iterations to obtain equilibrium within each increment. Following this method, non-linear static analyses were carried out for the beams in the parametric study. In order to model the possible unstable response due to buckling of the corrugated webs the Riks method was employed which provides solutions regardless of whether the response is stable or unstable. The Riks method uses the load magnitude as an additional unknown and solves simultaneously for loads and displacements.

Using the output variable identifiers as outlined in ABAQUS (2007), output data were requested for the generation of load-displacement curves. Load output was obtained by extracting the incremental point load values applied at the reference node of the circular rigid shell. On the other hand, corresponding nodal displacements were extracted from the mid-bottom node directly underneath the lower flange, in the direction of bending.

The numerical parametric study of corrugated web beams as described above includes the analysis of mainly 30 finite element models. Out of these 30 models 6 are beam models with no web opening for both $h_w=500\text{mm}$ and $h_w=1000\text{mm}$ beams with three different corrugation densities. 24 models include web openings with differing sizes of circular openings as defined above and located at quarter beam span (12 models for $h_w=500\text{mm}$ and 12 models for $h_w=1000\text{mm}$ beams).

Results of the Parametric Study

Figure 3 presents response curves (applied load versus vertical mid-displacement) separately for each corrugation density and with no web opening cases and with varying web opening sizes as described earlier. It is observed that all three cases exhibit similar behaviour within the elastic region. Close initial stiffness and ultimate load levels were achieved for all three densities. However, the behaviour changes within the post-elastic region. For the model with the highest corrugation density ($a/w=50/75$), the behaviour resembles a material response curve with an elastic region followed by a horizontal plateau which represents a stable behaviour. On the other hand the model with the lowest corrugation density ($a/w=50/300$) exhibits a much more sudden loss of stiffness after the attainment of the ultimate load. This type of load-deflection response is generally regarded as an evidence of an instability failure due to interactive buckling. The interaction results in a strength lower than which would be obtained if independent modes are considered separately. In comparison to the ultimate loads obtained for the $a/w=50/75$ and $a/w=50/150$ models, relatively lower ultimate loads were achieved for the $a/w=50/300$ models. This may, therefore, be attributable to a possible interaction between local and global web buckling. The model with web corrugation density of $a/w=50/150$ exhibits a behaviour in the form of almost in between those of the highest and lowest density models. Therefore as the corrugation density increases a trend is noted for the behaviour of the models in the post-elastic region, the higher the density the lower the post-ultimate stiffness. It is noted here that the curves given in Fig.3 are for the $h_w=0.5\text{m}$ models and very similar behaviour is obtained for the $h_w=1.0\text{m}$ models. For a particular web corrugation density response curves for varying web opening sizes were obtained to be in similar forms as described above for the no web opening cases. It is noted that for all the models considered, as the opening size increases both initial stiffness and ultimate load decreases. Hence, the greatest initial stiffness and ultimate load values were achieved for models with un-perforated webs.

Figure 3 also presents deformed shapes after the attainment of ultimate load for three different corrugation densities ($d/h_w=0.4$). Common failure modes were obtained in all the models with a Vierendeel type mechanism in the opening region and buckling of the corrugated web plate on the other side. These deformed shapes seem to support the above argument made regarding the load-deflection responses for different corrugation densities. Note that at ultimate load, deformed shapes for the models with $a/w=50/75$ and $a/w=50/150$ are similar with a noticeable formation of a diagonal web buckling, whereas for models with $a/w=50/300$ density, a mixture of diagonal and local web buckling (localized towards the right support) is observed on the un-perforated side of the web. For these models, this type of buckling is considered to be the possible reason for sudden drop in stiffness after the attainment of the ultimate load.

FE predicted percentage strength reductions for all the 24 models considered are presented in Figure 4 and Figure 5 in relation to strength reduction factor (χ_c) versus web slenderness ($\bar{\lambda}_c$) design curves as given in EC3 1.5. Strength factors for the 6 models without web opening (close to unity) are also shown in these figures (close agreement with design). The design curve given in Figure 4 is the global web shear buckling curve whereas in Figure 5 local web shear buckling design curve is given. Web reference slenderness values, $\bar{\lambda}_{c,l}$ and $\bar{\lambda}_{c,g}$, for the analyzed models, which are mainly functions of the web height and corrugation density, were calculated as given in EC3 1.5 Annex D (2003). Here it should be noted that the value of global web buckling slenderness is sensitive to web height (h_w) and on the other hand for local shear buckling slenderness it is the corrugation density which governs. With this respect, as shown in Figure 4, on the global web buckling design curve, in terms of global buckling slenderness the $h_w=0.5\text{m}$ and $h_w=1.0\text{m}$ models are well separated ($\bar{\lambda}_{c,g} \approx 0.31\text{--}0.33$

for $h_w=0.5\text{m}$ models and $\bar{\lambda}_{c,g} \approx 0.61\text{-}0.67$ for $h_w=1.0\text{m}$ models) whereas in terms of local web buckling slenderness as given in Figure 5 all the models are very closely spaced, $\bar{\lambda}_{c,l} \approx 0.05\text{-}0.08$ since the levels of sensitivity of the chosen corrugation density webs to local shear buckling are close. It is observed in these figures (particularly in Figure 4) that the effect of web opening is more pronounced for webs with higher global buckling reference slenderness values. However, as the opening size increases the effect of web slenderness seems be less significant. Close reduction factors are achieved, for example for opening size of $d/h_w=0.8$, for both web slenderness values.

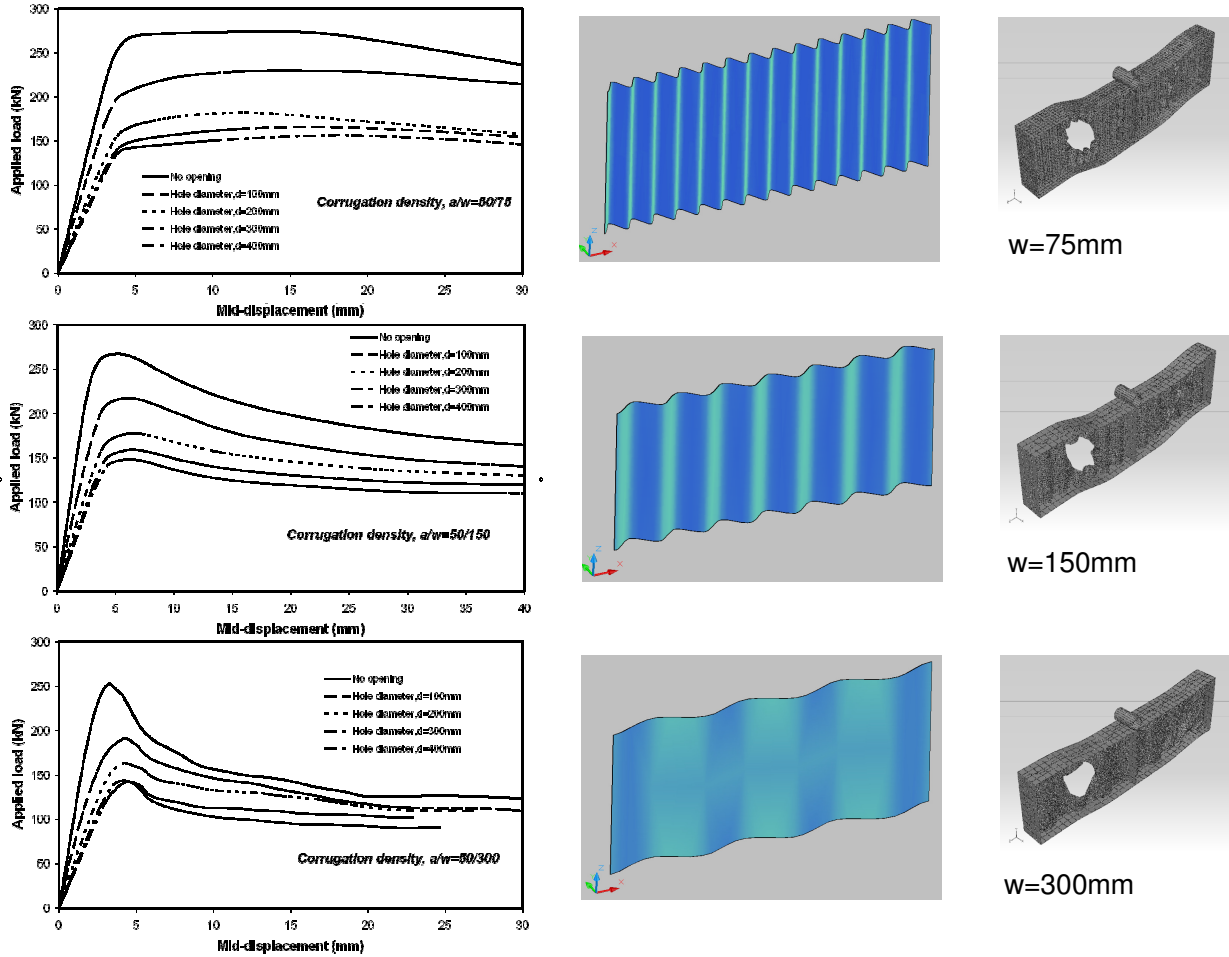


Figure 3. Non-linear response curves obtained from FE parametric study ($h_w=500\text{mm}$) and deformed shapes after the attainment of ultimate load for three different corrugation densities ($d/h_w=0.4$)

Note that on the buckling curves in Figure 4 and Figure 5, in terms of a FE predicted strength reduction versus web reference slenderness relationship, the models without web opening lie very close to the $\chi_{c,g} = 1$ and $\chi_{c,l} = 1$ plateau. In accordance with this fact and as also stated earlier the webs of the chosen model geometries are in the compact geometry region where web yielding is preceded by any type of buckling. In Figure 4 and Figure 5, it is observed that strength reductions due to buckling effects are considered for webs with $\bar{\lambda}_{c,g} > 1$ (for global) and / or $\bar{\lambda}_{c,l} > 0.25$ (for local). An investigation of various web geometries that would satisfy these conditions revealed that for the chosen corrugation densities, web heights greater than 2m become necessary. Actually, webs with $h_w > 2\text{m}$ are still not prone to local buckling since local buckling is not very sensitive to web heights but more to plate thickness and corrugation

densities. Such web heights or other corrugation densities were not considered in this study as they were deemed to be out of the practical range in terms of both production and structural application.

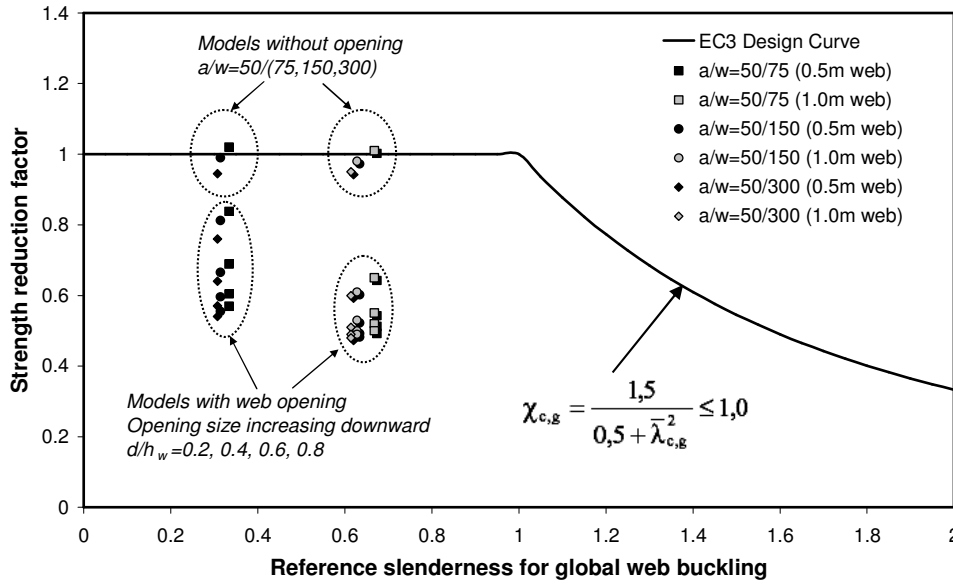


Figure 4. FE predicted web shear strength reductions in relation to EC3 1.5 global web buckling design curve

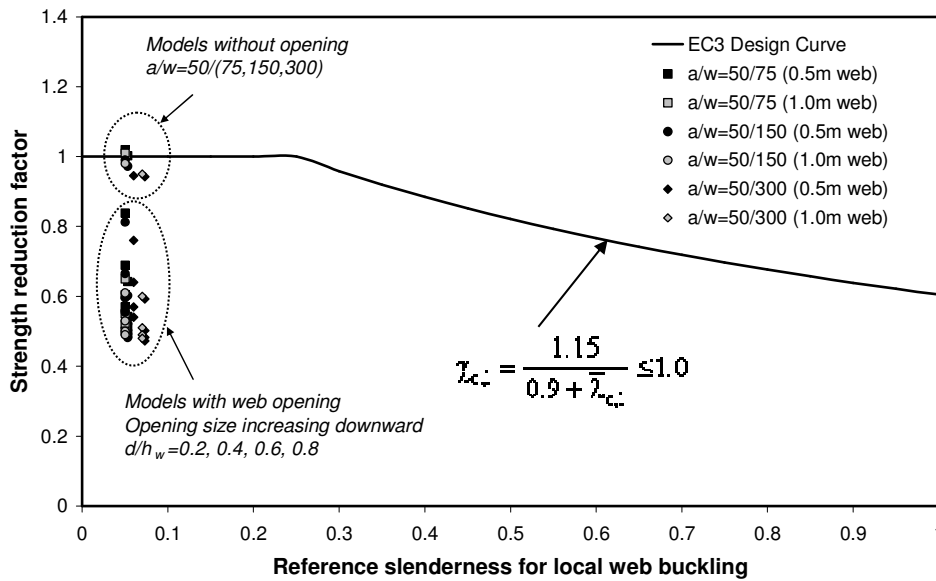


Figure 5. FE predicted web shear strength reductions in relation to EC3 1.5 local web buckling design curve

CONCLUSIONS

In this paper an investigation into the behaviour and design of sinusoidally corrugated steel web beams with web openings was carried out. A general purpose finite element analysis program was used to model steel beams with varying web opening sizes and corrugation

densities. Using this program, a numerical parametric study was carried out for simply supported corrugated steel web beams of 2m length and with web openings at quarter span points. Within the parametric study, various cases were considered including the web height ($h_w=0.5\text{m}$ and $h_w=1.0\text{m}$), opening size and the corrugation density expressed as a function of the magnitude and length of the sine wave. For each web height and web corrugation density, models without web opening were also analyzed. The chosen models represented practical geometries in terms of production and structural application. Three different corrugation densities were considered. For these densities, non-linear response curves (applied load – vertical mid-displacement) were produced for the models with and without web openings. A comparison of these curves has revealed that as the corrugation density increases a trend is noted for the behaviour of the models in the post-elastic region, the higher the density the lower the post-ultimate stiffness. In Annex D of EC3-1.5, design rules are available for sinusoidally corrugated steel beams without web opening. For the models without web openings, very close agreement was achieved between the design shear resistance calculated per these rules and the FE predicted ultimate shear resistance values. For the geometries considered in the study, introducing a web opening causes strength reductions between around 15% up to 50%. As the opening size increases, the percentage reduction values also increase. Comparing the effect of web opening on the shear resistance for different web heights or web reference slenderness values, as defined in EC3-1.5, it was found out that for greater web heights the effect is more pronounced however the difference of the effect for different web heights tends to diminish for higher web opening sizes.

REFERENCES

- ABAQUS (2007) Standard User's Manual, ABAQUS CAE Manual, Version 6.7-1.
- Easley JT, McFarland DE (1969) "Buckling of light-gage corrugated metal shear diaphragms" *Journal of the Structural Division*, ASCE;95:1497–516
- Hamilton RW. (1993) Behavior of welded girder with corrugated webs. Ph.D. thesis. University of Maine
- Yoda T, Ohura T, Sekii K. (1994) "Analysis of composite PC Box girders with corrugated steel webs" The Proceedings of 4th International conference on short and medium span bridges, pp. 1107–15.
- Cafolla J. (1995) Corrugated webs and lateral restraints in plate girders for bridges. Ph.D. thesis. University of Warwick
- Elgaaly M, Hamilton RW, Seshadri A (1996) "Shear strength of beam with corrugated webs" *Journal of Structural Engineering*, ASCE;122(4): 390–8.
- Luo R, Edlund B. (1996) "Shear capacity of plate girders with trapezoidally corrugated webs" *Thin Walled Structures*, 26(1):19–44.
- El-Metwally AS (1998) Prestressed composite girders with corrugated steel webs. Masters Thesis. Calgary (Alberta, Canada) University of Calgary.
- Yamazaki M. (2001) "Buckling strength of corrugated webs" Structural Engineering Research Paper, *JSCE* 47A.
- Chan C.L., Khalid Y.A., Sahari B.B., Hamouda A.M.S. (2002) "Finite element analysis of corrugated web beams under bending" *Journal of Constructional Steel Research* (58) 1391–1406

- Shiratori H, Ikeda H, Imai Y, Kano K. (2003) "Flexural shear behavior of composite bridge girder with corrugated steel webs around middle support" *JSCE Journal* 724(I-62):49–67.
- Gil H, Lee S, Lee H, Yoon T. (2004) "Study on elastic buckling strength of corrugated web" *Journal of Structural Engineering*, KSCE 24(1A) 192–202.
- Khalid Y.A., Chan C.L., Sahari B.B., Hamouda A.M.S. (2004) "Bending behaviour of corrugated web beams" *Journal of Materials Processing Technology* (150) 242–254
- Sayed-Ahmed EY. (2005) "Plate girders with corrugated steel webs" *AISC Engineering Journal*, First Quarter 1–13.
- Gil H, Lee S, Lee J, Lee HE (2005) "Shear buckling strength of trapezoidally corrugated steel webs for bridges" *J Transport Res Board*; CD11-S:473-80.
- Abbas HH, Sause R, Driver RG (2006) "Behavior of corrugated web I-girders under in-plane loading" *Journal of Structural Engineering*, ASCE;132(8):806-14.
- Ibrahim SA, El-Dakhakhni VW, Elgaaly M (2006) "Behavior of bridge girders with corrugated webs under monotonic and cyclic loading" *Engineering Structures*;28(14):1941-55.
- Driver RG, Abbas HH, Sause R (2006) Shear behavior of corrugated web bridge girder. *Journal of Structural Engineering*, ASCE;132(2):195-203.
- Abbas HH, Sause R, Driver RG (2007) Analysis of flange transverse bending of corrugated web I-girders under in-plane loads. *Journal of Structural Engineering*, ASCE;133(3): 347-55.
- Yi J, Gil H, Youm K, Lee HE. (2008) "Interactive shear buckling of trapezoidally corrugated webs" *Engineering Structures* 2008;30:1659-66.
- Moon J, Yi J, Choi BH, Lee HE (2009) "Lateral-torsional buckling of I-girder with corrugated webs under uniform bending" *Thin Walled Structures* 47 (1), 21-30
- Romeijn A, Sarkhosh R, Hoop H (2009) "Basic parametric study on corrugated web girders with cut outs" *Journal of Constructional Steel Research* 65: 395–407
- Lindner J, Huang B (1994). Trapezoidally web girder with cut out. Report no. VR 2105. Institute for Building Construction and Stability at Technical University of Berlin [in German].
- Lawson RM. (1987) Design for openings in the webs of composite beams. CIRIA Special Publication and SCI Publication 068, CIRIA/Steel Construction Institute.
- Eurocode 3 1993-1-5 (2003). Design of steel structures Part 1.5 : Plated structural elements