

Strength of sinusoidally corrugated web beams with web openings

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Abstract

Creating openings in the webs of steel I-section beams has been a common method of incorporating services within the floor–ceiling zone of buildings. In the literature, the web opening problem was dealt with only for steel beams with plane web plates and the effect of an opening on a corrugated web was not considered. The present paper deals mainly with the effect of web openings on the shear strength/stability of sinusoidally corrugated web beams. A general purpose finite element program (ABAQUS) was used. Simply supported corrugated web beams of 2m length and with rectangular 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 dimensions of the openings and the corrugation parameters such as the amplitude of the sine wave and corrugation density. 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 shear resistance.

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. Studies on the behaviour of beams and girders with corrugated webs were conducted by researchers mainly in the United States, Europe and Japan. In these regions of the world, these beams have also been manufactured and exploited both in building and bridge constructions.

Using web openings in steel floor beams results in simplified layout and installation of building services. In addition, the overall depth of the floor construction zone is reduced accordingly. The size and shape of a web opening may differ according to the sizes and shapes of e.g. water pipes or air ducts used. Dimensions of up to 75% of the floor depth may be required for increasing installation sizes [2]. The effect of the presence of web openings on the load carrying capacity of steel beams with flat web plates has been studied by a number of researchers. Based on the results of these studies a number of design recommendations were prepared which are now available in the literature for both steel and composite beams [3-7].

In the literature, the web opening problem was dealt with only for steel beams with plane web plates and the effect of an opening on a corrugated web was not considered. The present paper deals mainly with the effect of web openings on the shear strength/stability of sinusoidally corrugated web beams. A general purpose finite element (FE) program (ABAQUS) was used for this purpose. Simply supported corrugated web beams of 2m length and with rectangular web openings at quarter span points were analyzed using ABAQUS. Various cases were considered including the dimensions of the openings (depth / height ratios for the rectangular openings) and the corrugation parameters such as the amplitude of the sine wave. Models without web openings were also analyzed and all cases were examined in terms of the effect of varying web opening dimensions and corrugation density on ultimate shear resistance and load-deformation characteristics of the beams.

Resistance of a sinusoidally corrugated section to EC3-1.5

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 [8]. In these rules for corrugated web beams, web openings are not included. The rules are given for two types of corrugation forms namely; trapezoidal and sinusoidal. Limit states considered for the design of a corrugated beam is similar to those considered for a typical 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 χ_c 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 whereas local buckling is more localized over a single sine wave or the flat plate wall of a trapezoidal wave. Shear resistance of a sinusoidally corrugated steel web is given as;

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

in which χ_c is given as the smallest value of the following expressions for local and global buckling of the web,

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

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

Numerical parametric study described below includes finite element models of corrugated web beams with and without web openings. The abovementioned design guidance is used to compare with the FE predictions of the models without web openings.

A numerical parametric study was carried out on simply supported I-beams with sinusoidally corrugated webs. Numerical modelling of the beams was carried out using ABAQUS [1], 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 dimensions and corrugation density. The modelling assumptions including the geometry, material and boundary conditions are presented below.

Description of the FE models

A typical finite element model adopted for corrugated web beams is given in Fig. 1. A type of four-node doubly curved shell element (S4R) which is available in ABAQUS (2005) was employed in the models. A typical model is composed of upper and lower flanges of 12mm x 200mm in size, representing a plate 200mm wide and 12mm thick, a 2mm x 500mm corrugated web which is a thin sheet of steel plate having 2mm thickness and 500mm height, two end cover plates and a central stiffener plate 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.2 to form the final FE model. Web opening is created on one side of the web and the centre of the opening is located at quarter span point i.e. for the 2000mm long beam, 500mm away from the left cover plate. The depth, d , of the rectangular opening is kept constant ($d=200\text{mm}$) and width is varied from 100mm to 500mm with 100mm increments. In this manner, five different models were developed. Assuming three different corrugation densities, which is explained schematically in Fig.2, 15 models were achieved. Considering also the models without openings, 3 more models with 3 different corrugation densities were added which eventually resulted in 18 models in total.

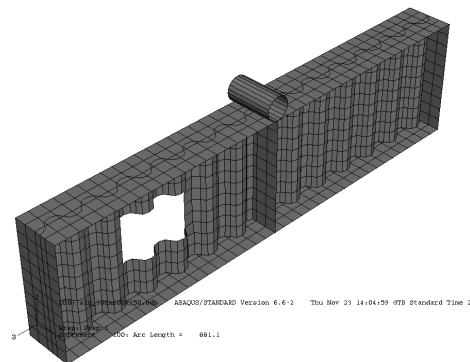
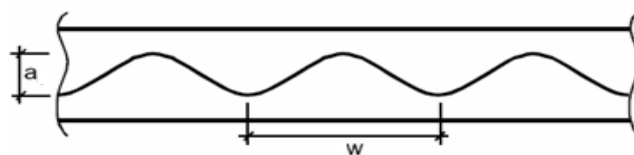


Figure 1. Typical FE model adopted for the analysis of sinusoidally corrugated web beams with rectangular web openings.



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

Boundary conditions were applied to either ends of the model 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 was 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 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 [1], 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.

Results of the Parametric Study

Key results obtained from the non-linear analysis of the above described FE corrugated web beam models are given in Table 1. Models are designated by their corrugation density and the rectangular web opening dimensions. For example, "a/w:50/75/Opening x/d:0.5" stands for the model with a rectangular opening of $x=100$ mm wide and $d=200$ mm deep (constant) and hence making $x/d=0.5$. The corrugation geometry (a/w) is as described previously in Fig. 2. FE predicted ultimate load values are presented in Table 1 alongside the FE shear resistance of the web and shear resistance of web to EC3 1.5 Annex D [8]. The FE predicted web shear strength is equivalent to half of the maximum load achieved on the load-displacement curve. For example for the "a/w:50/75/ No opening" model FE predicted ultimate load is 277 kN and hence shear resistance of the web is 138.5 kN.

It is observed that for all the models there is a decrease in the web shear resistance as the opening size increases. The relationship between the opening size and web shear resistance is given in Fig. 3 for three different corrugation density (a/w) values. For these three cases similar trends are observed; an approximately linear decrease in shear resistance for finer corrugations ($a/w=50/75$ and $a/w=50/150$) and a more polynomial type decrease for the courser corrugation ($a/w=50/300$).

In Table 1, characteristic shear resistance values as predicted by EC3 1.5 Annex D [8] are compared with those predicted by ABAQUS for un-perforated corrugated web models. For the corrugation densities considered, no reduction due to local or global buckling of the corrugated web is made since according to EC3 [8] the webs are suggested to be non-slender. The value given in Table 1 (136.3 kN) therefore corresponds to shear yielding strength of the webs which is a function of the height and thickness of the web and yield strength of the web

material which are common for all the models. It is noted that FE shear resistance predictions are very close to those of EC3. This shows that reasonable assumptions were made for the FE modelling of the corrugated web beams.

Table 1. Key results from the non-linear parametric study

Model	Ultimate load, FE (kN)	Shear resistance of web, FE (kN)	Shear resistance of un-perforated web to EC3 [8] (kN)	Shear resistance (FE / EC3)
a/w:50/75/ No opening	277.00	138.50	136.3	1.02
a/w:50/75/Opening x/d:0.5	231.00	115.50	N.A	---
a/w:50/75/Opening x/d:1.0	203.00	101.50	N.A	---
a/w:50/75/Opening x/d:1.5	185.97	92.98	N.A	---
a/w:50/75/Opening x/d:2.0	176.28	88.14	N.A	---
a/w:50/75/Opening x/d:2.5	159.00	79.50	N.A	---
a/w:50/150/ No opening	271.00	135.50	136.3	0.99
a/w:50/150/Opening x/d:0.5	218.00	109.00	N.A	---
a/w:50/150/Opening x/d:1.0	188.00	94.00	N.A	---
a/w:50/150/Opening x/d:1.5	173.00	86.50	N.A	---
a/w:50/150/Opening x/d:2.0	164.00	82.00	N.A	---
a/w:50/150/Opening x/d:2.5	148.00	74.00	N.A	---
a/w:50/300/ No opening	251.00	125.50	136.3	0.93
a/w:50/300/Opening x/d:0.5	185.00	92.50	N.A	---
a/w:50/300/Opening x/d:1.0	164.00	82.00	N.A	---
a/w:50/300/Opening x/d:1.5	151.00	75.50	N.A	---
a/w:50/300/Opening x/d:2.0	144.00	72.00	N.A	---
a/w:50/300/Opening x/d:2.5	138.00	69.00	N.A	---

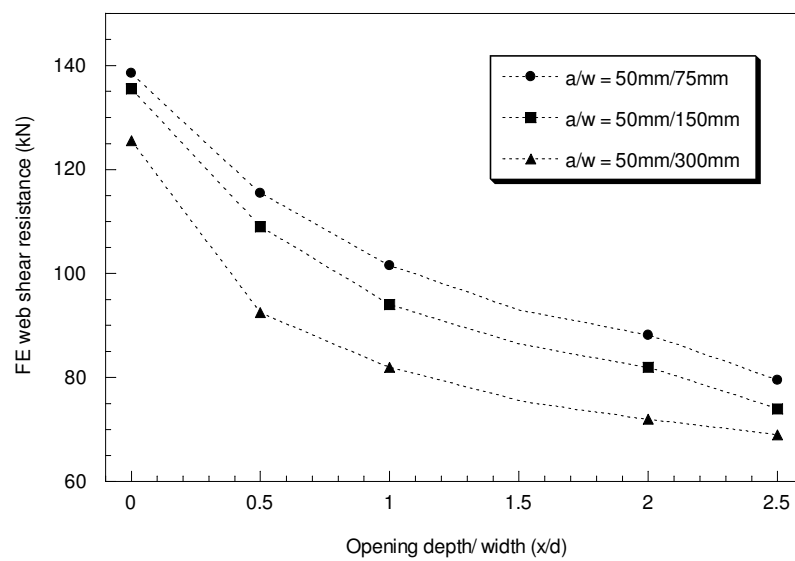


Figure 3. FE web shear resistance versus web opening size relationships for different corrugation densities

Fig. 4 shows non-linear response curves obtained from FE parametric study. 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.

For the models with $a/w=50/75$ and $a/w=50/150$, very similar load deflection characteristics are observed. The behaviour for these corrugation densities is very similar to the material response, i.e. there exists a well defined transition point from the elastic to non-elastic region as the applied load is increased. In contrast, the models with $a/w=50/300$ exhibit 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 interactive buckling. The interaction results in a buckling strength lower than which would be obtained if independent modes are considered separately. Therefore the relatively lower ultimate loads achieved for the $a/w=50/300$ models may be attributable to a possible interaction between local and global web buckling.

Fig. 5 presents deformed shapes at ultimate load for three different corrugation densities ($h/d=2.0$). 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 no noticeable web buckling, whereas for models with $a/w=50/300$ a significant web buckling is observed on the un-perforated side of the web. This type of buckling is considered to be the possible reason for sudden drop in stiffness after the attainment of the ultimate load.

Irrespective of the corrugation density, all the corrugated beams with web openings exhibited a Vierendeel type mechanism in the opening region as shown in Fig.6. This type of behaviour is caused by the transferring of lateral shear force across the web opening resulting in the formation of four plastic hinges in corner regions above and below the opening.

Conclusions

The study presented in this paper has covered an investigation into the behaviour of sinusoidally corrugated web beams with rectangular web openings. A general purpose finite element program was used to model steel beams with varying web opening sizes and corrugation densities. Un-perforated web models were also considered to establish proper trends in the behaviour. The effect of increasing the opening size on shear strength of the corrugated web is significant. The corrugation density on the other hand appears to effect the overall load-deflection response. Courser corrugations cause an apparent difference in the post ultimate behaviour. A sudden drop in post-ultimate load was observed for the models with course corrugations. Ultimate web shear strengths predicted for the models with un-perforated webs were found to be in reasonable agreement with the code estimations. The study presented herein is part of an ongoing research project on sinusoidally corrugated web beams and further research is planed to investigate the effect of the corrugation density, opening type and size on the Vierendeel mechanism behaviour that forms around the opening.

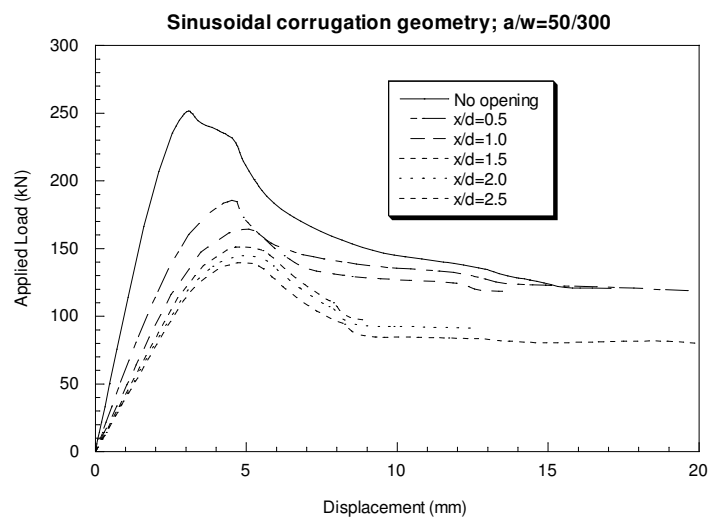
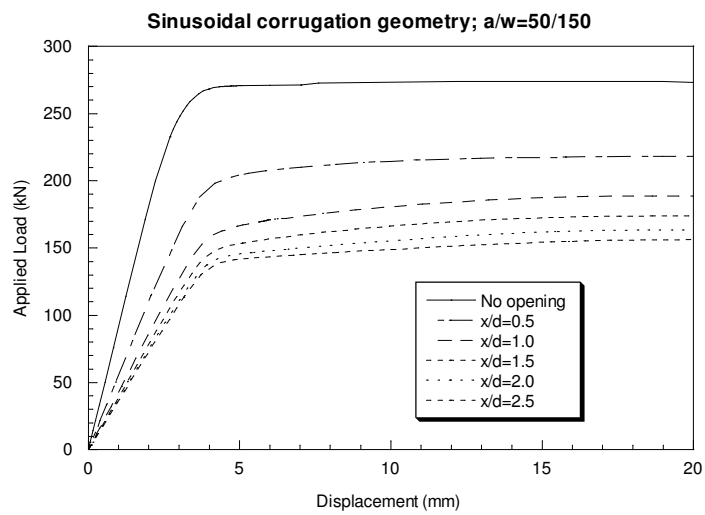
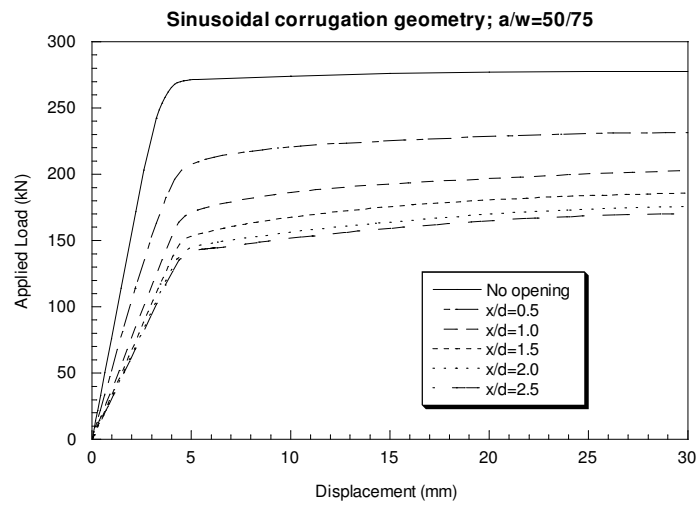


Figure 4. Non-linear response curves obtained from FE parametric study

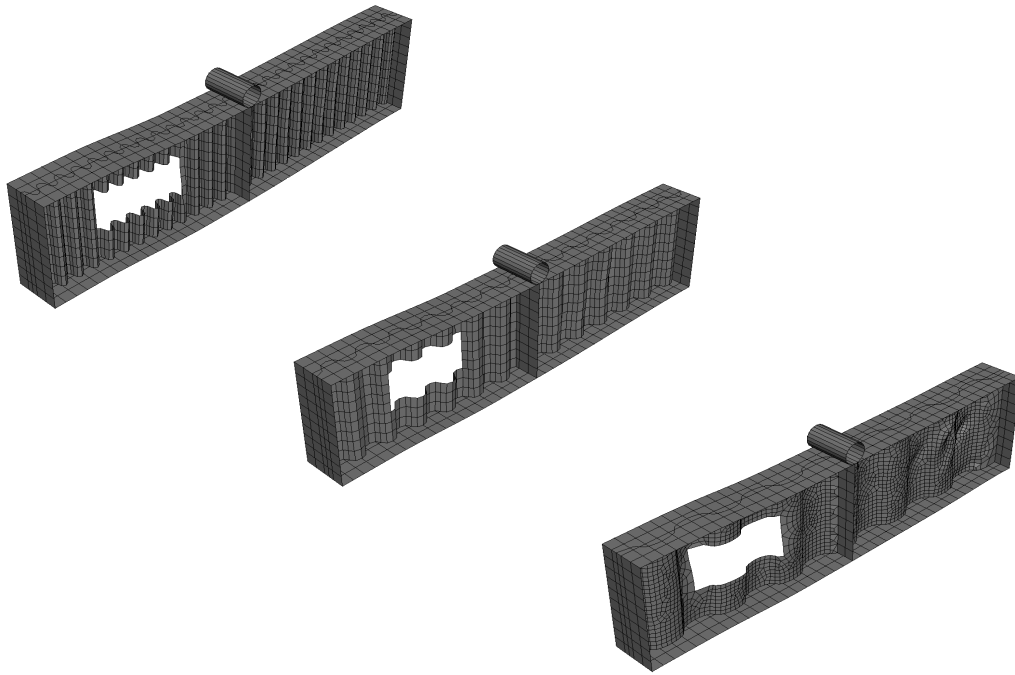


Figure 5. Deformed shapes for three different corrugation geometries at ultimate load ($h/d=2.0$)

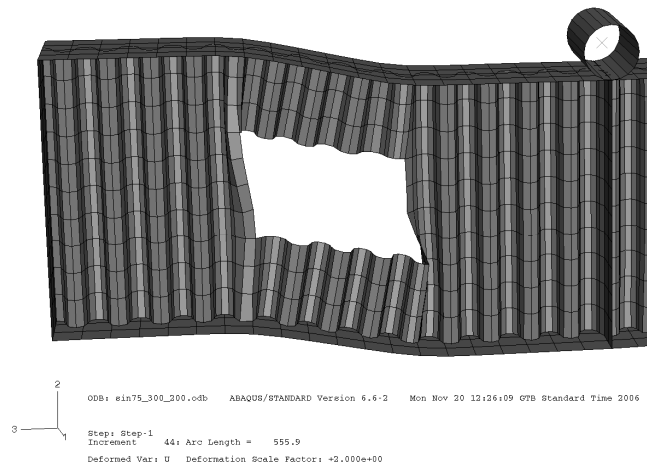


Figure 6. Typical Vierendeel mechanism observed in the web opening region

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