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# Transverse load carrying capacity of sinusoidally corrugated steel web beams with web openings

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**Abstract.** The present paper presents a study on the behavior and design of corrugated web steel beams with and without web openings. 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 2 m 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.

## 1. 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 notebaly 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 and Edlund (1996), El-Metwally

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(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, 2005), Khalid, *et al*. (2004), Sayed-Ahmed (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). Buckling and post buckling behaviour of rectangular corrugated board panels simply supported and subjected to compression load was investigated numerically in Biancolini, *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 sinosoidally 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 and Huang (1994) and very recently by Romeijn, *et al*. (2009). In Lindner and Huang.(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 2 m 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.

## 2. 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;

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

in which $h_w$, $t_w$ are the web height and web plate thickness and $f_y$ is the material yield strength. Other geometrical properties regarding the sinusoidal form are described in Fig. 1. In Eq. (1), $\chi_c$ 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,

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

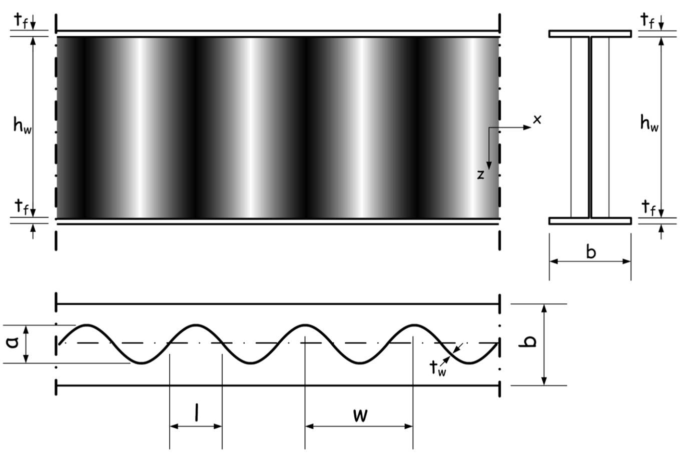



Fig. 1. Geometry of a sinusoidally corrugated web beam

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 Eq. (3) below.

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

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 rigidites 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 Eq. (4) and in Eq. (5) critical buckling stress for local shear buckling is given.

$$\tau_{cr,g} = \frac{32.4}{t_w h_w^2}\sqrt[4]{D_x D_z^3} \tag{4}$$

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

Plate rigidities in the longitudinal, $x$, and transverse, $z$, directions are given as;

$$D_x = \frac{E.t^3}{12(1-\nu^2)}\frac{l}{s} \tag{6}$$

$$D_z = \frac{E.I_z}{l} \tag{7}$$

in which $l$ is the length of one corrugation in the longitudinal direction, $s$ is the unfolded length of one corrugation or the length of the arc of one-half a wave of corrugation. $I_z$ is the second moment of area of one corrugation of length $l$, see Fig. 1. Also $a$ (given in (5)) is the corrugation magnitude as shown in Fig. 1.

The calculation of the unfolded length, $s$, and the second moment of area $I_z$ is made by using the following equations given in Timoshenko(1959),

$$s = l\left(1 + \frac{\pi^2 a^2}{16 l^2}\right) \tag{8}$$

$$I_z = \frac{a^2 t_w}{8}\left[1 - \frac{0.81}{1 + 2.5\left(\frac{a}{4l}\right)^2}\right] \tag{9}$$

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.

## 3. 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.

### 3.1. Description of the FE models

In the numerical parametric study two web heights were considered namely $h_w = 500$ mm and $h_w = 1000$ mm beams. Typical finite element models adopted for the corrugated web beams is shown in Fig. 2. The behaviour of beams with varying web corrugation and web opening cases was studied mainly by using the $h_w = 500$ mm beams and the $h_w = 1000$ 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 mm × 200 mm in size, representing a plate 200 mm wide and 12 mm thick, a 2 mm × 500 (and 1000) mm corrugated web

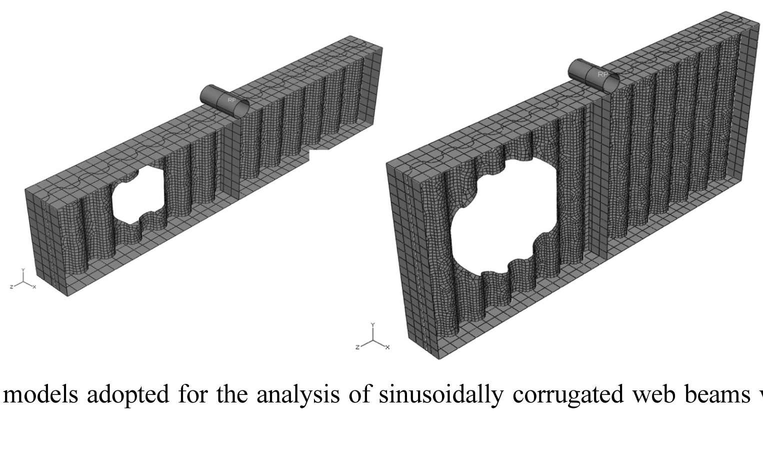


Fig. 2 Typical FE models adopted for the analysis of sinusoidally corrugated web beams with web openings

which is a thin sheet of steel plate having 2mm thickness and 500 mm/1000 mm height, two end cover plates and a central stiffener plate (with plate thickness, $t = 20$ 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. 2 to form the final FE model. Interaction among the parts was defined by using the TIE option available under ABAQUS constraints options. This option provides a surface-based tie constraint and is used to make the translational and rotational motion as well as all other active degrees of freedom equal for a pair of surfaces. Nodes are tied where the surfaces are close to one another (e.g. in this case where plate edges meet neighboring plate surfaces).

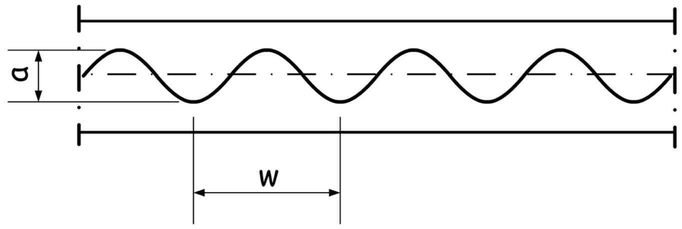
For the webs three different corrugation densities were assumed. As schematically explained in Fig. 3 the corrugation density is defined as the ratio of the magnitude of the sine wave, $a$, to the corrugation length, $w$. In the models the wave magnitude, $a$, was kept constant ($a = 50$ mm) and three different corrugation lengths ($w = 75$ mm, 150 mm, 300 mm) 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.

In the models, web opening is created on one side of the web (Fig. 2) and the centre of the opening is located at quarter span point i.e. for the 2000 mm long beam, 500 mm 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 $h_w = 500$ mm and $h_w = 1000$ mm. For example, for $h_w = 500$ and $d/h_w = 0.2$, a circular opening with a 100 mm diameter is used.

Boundary conditions were applied to either ends of the 2 m 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.

### *3.2. 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




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

Fig. 3 Corrugation densities adopted for FE modelling of the sinusoidally corrugated webs 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 $h_w = 500$ mm and $h_w = 1000$ 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 $h_w = 500$ mm and 12 models for $h_w = 1000$ mm beams).

## 4. Results of the parametric study

### 4.1 Non-linear behaviour of corrugated web beams with web openings

Fig. 4 shows non-linear response curves for the beam models with no web openings for three different corrugation densities. 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

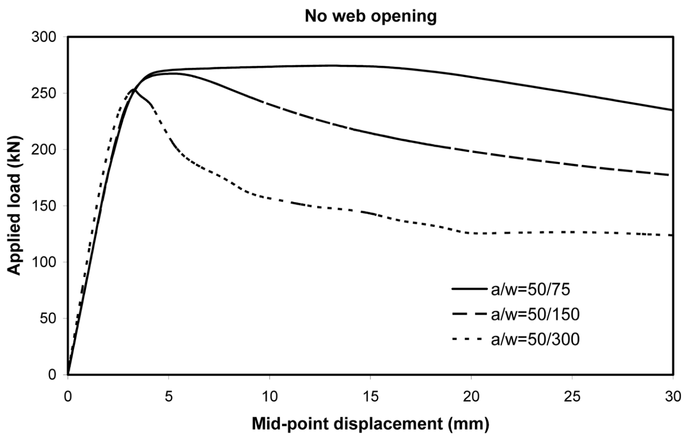



Fig. 4 Non-linear response curves for the beam models with no web openings for three different corrugation densities ($h_w = 500$ mm)

the lowest corrugation density (a/w = 50/300) exhibits a much more sudden loss of strength 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 residual strength. It is noted here that the curves given in Fig. 4 are for the $h_w$ = 0.5 m models and very similar behaviour is obtained for the $h_w$ = 1.0 m models.

Fig. 5 presents response curves (applied load versus vertical mid-displacement) separately for each corrugation density and with varying web opening sizes as described earlier. 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.

Fig. 6 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. 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 strength after the attainment of the ultimate load (as observed on the load-deflection response curves for these models). Finally Fig. 7 shows deformed shapes for the beam models with a constant corrugation density of a/w=50/150 but with varying web opening sizes after the attainment of ultimate load. Similar deformed shapes are achieved for all the models except that a noticeable local bucking of the corrugated web around the smallest size opening is observed.

### *4.2. Parametric assessment of the FE ultimate strengths for models with varying opening sizes and beam depths*

Ultimate shear resistance values obtained from the non-linear FE analysis for the models are given in Table 1 together with the predictions of EC3 1.5 Annex D (2003) for the corrugated beams with no web opening. The models given in this table include the above mentioned 6 beam models with no web opening and 24 models with quarter span circular web openings both for $h_w$ = 500 mm and $h_w$ = 1000 mm beams with three different corrugation densities. Models are designated by their corrugation density and web opening sizes.

Considering both the corrugation densities and web heights chosen for the models, the model geometries fall within a practical range both in terms of production and structural application. An assessment of these geometries (both for $h_w$ = 500 mm and $h_w$ = 1000 mm beams) according to the previously explained EC3 slenderness limits for local and global shear buckling of the web suggests that the webs are more of compact type and hence no reduction in shear resistance is required due to elastic shear buckling. In other words, for the web dimensions ($h_w$, $a$, $w$) chosen, global and local shear

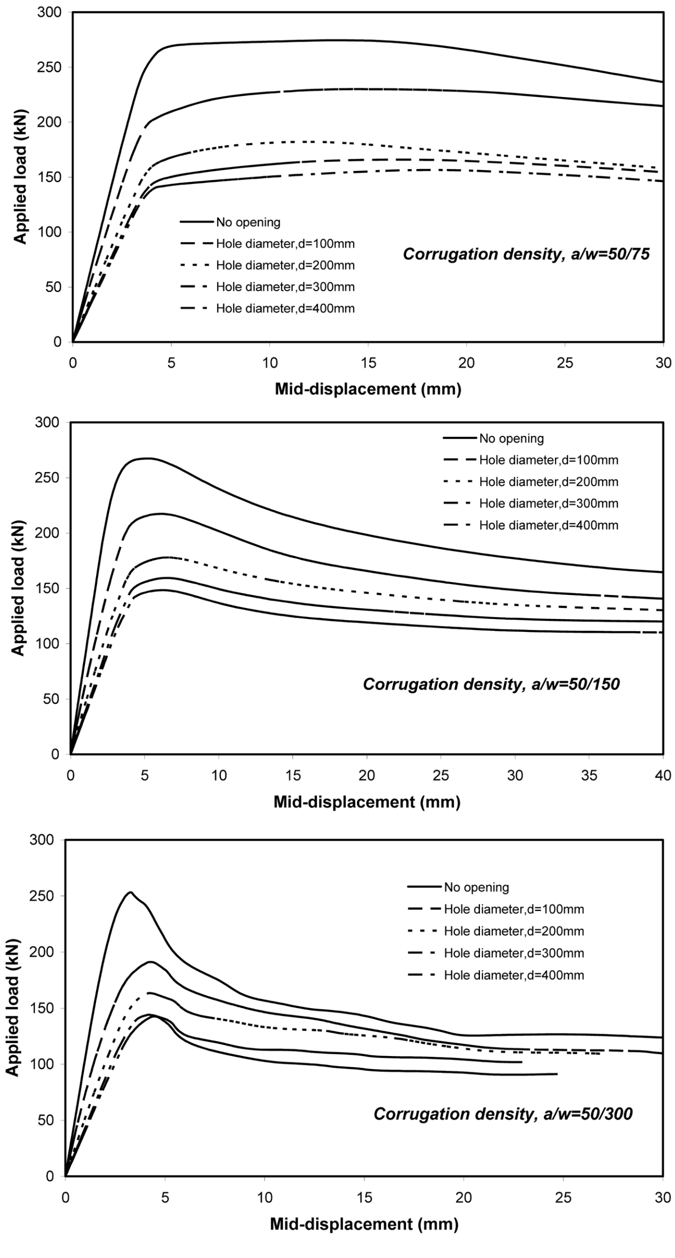



Fig. 5 Non-linear response curves obtained from FE parametric study ($h_w$ = 500 mm)

buckling reduction factors $\chi_{c,g}$ and $\chi_{c,l}$ are not calculated to be smaller than 1. Therefore the expected mode of failure for the finite element models is shear yielding followed by inelastic shear buckling of the web. With this respect, the EC3 1.5 Annex D prediction for shear resistance for these compact webs (with no opening) is simply the web cross-sectional area (thickness *x* web height) multiplied by the shear yield strength of the web material. In Table 1, web shear resistance values as calculated in this way are compared with those predicted by FE for corrugated web models with no web opening. It is

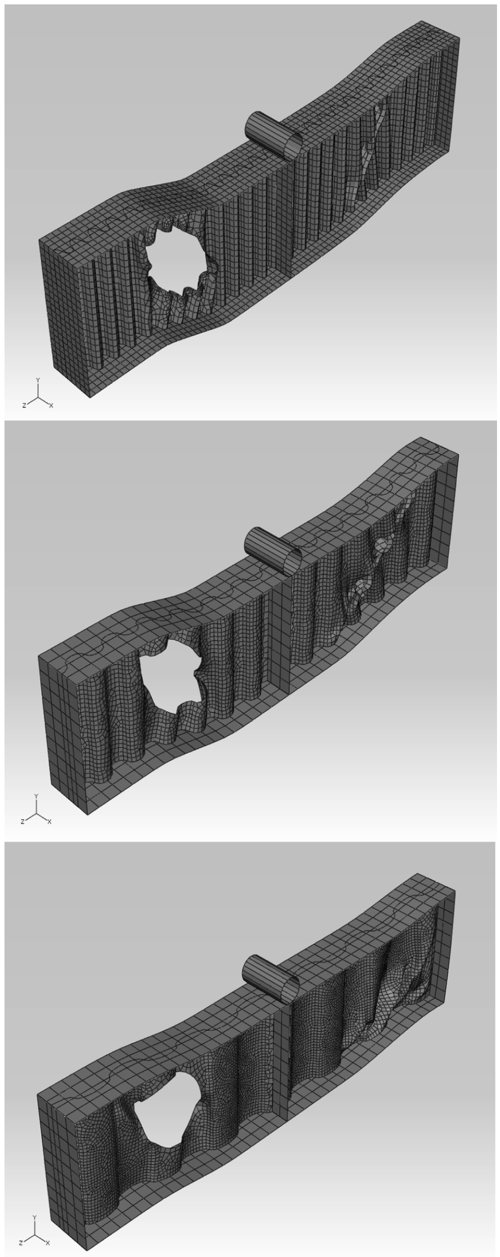


Fig. 6 Deformed shapes for three different corrugation densities at ultimate load ($d/h_w = 0.6$)

observed that FE shear resistance predictions are very close to those of EC3. It is noted again that there is no design rule for predicting the strength of corrugated webs with web openings and hence there are no design estimations that could be used to compare with the FE predicted strength values of the models with web openings.

In Table 1, it is observed that for all the models there is a decrease in the web shear resistance as the

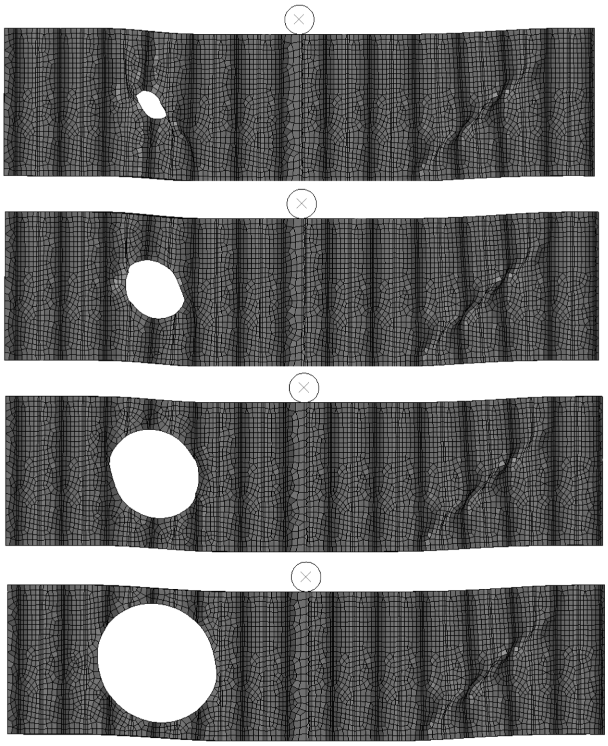


Fig. 7 Deformed shapes for a constant (a/w = 50/150) corrugation density and varying opening sizes at ultimate load

Table 1 Ultimate shear resistances obtained from the non-linear parametric study

| Model | FE (kN) Shear res. of web | | EC3 (kN) Shear res. of web | | (FE / EC3) | |
|---|---|---|---|---|---|---|
| | $h_w$ = 0.5 m | $h_w$ = 1.0 m | $h_w$ = 0.5 m | $h_w$ = 1.0 m | $h_w$ = 0.5 m | $h_w$ = 1.0 m |
| a/w:50/75 No opening | *137.50* | *275.30* | *136.3* | *272.6* | *1.02* | *1.01* |
| a/w:50/75_$d/h_w$:0.2 | 115.01 | 177.19 | N.A | N.A | --- | --- |
| a/w:50/75_$d/h_w$:0.4 | 94.5.00 | 149.93 | N.A | N.A | --- | --- |
| a/w:50/75_$d/h_w$:0.6 | 82.90 | 141.752 | N.A | N.A | --- | --- |
| a/w:50/75_$d/h_w$:0.8 | 78.00 | 136.3 | N.A | N.A | --- | --- |
| a/w:50/150 No opening | *133.70* | *267.15* | *136.3* | *272.6* | *0.98* | *0.98* |
| a/w:50/150_$d/h_w$:0.2 | 108.15 | 166.286 | N.A | N.A | --- | --- |
| a/w:50/150_$d/h_w$:0.4 | 89.00 | 144.478 | N.A | N.A | --- | --- |
| a/w:50/150_$d/h_w$:0.6 | 80.00 | 136.3 | N.A | N.A | --- | --- |
| a/w:50/150_$d/h_w$:0.8 | 74.40 | 133.574 | N.A | N.A | --- | --- |
| a/w:50/300 No opening | *129.00* | *258.97* | *136.3* | *272.6* | *0.94* | *0.95* |
| a/w:50/300_$d/h_w$:0.2 | 95.00 | 163.56 | N.A | N.A | --- | --- |
| a/w:50/300_$d/h_w$:0.4 | 81.50 | 139.026 | N.A | N.A | --- | --- |
| a/w:50/300_$d/h_w$:0.6 | 72.20 | 133.574 | N.A | N.A | --- | |
| a/w:50/300_$d/h_w$:0.8 | 71.00 | 130.848 | N.A | N.A | --- | --- |

opening size increases. For the considered web heights of $h_w = 0.5$ m and $h_w = 1.0$ m, the relationship between the opening size and web shear resistance is given in Figs. 8 and 9, respectively, for three different corrugation density (a/w) values. It is observed in these relationships that for increasing opening sizes, a gradual decrease in web resistance is noted for $h_w = 500$ mm models while for $h_w = 1000$ mm models a sudden decrease is noted for the first $d/h_w = 0.2$ opening size and for the rest of the increasing opening sizes the relationship is nearly horizontal. Also, for a particular opening size the difference in FE predicted resistances among the three corrugation densities seems to be less pronounced for the $h_w = 1000$ mm models. For example, for the opening size of $d/h_w = 0.2$, the difference between resistances obtained for the a/w = 50/75 and a/w = 50/300 corrugation densities is 18 % for $h_w = 500$ mm web model whereas for the $h_w = 1000$ mm model this difference is around 9%.

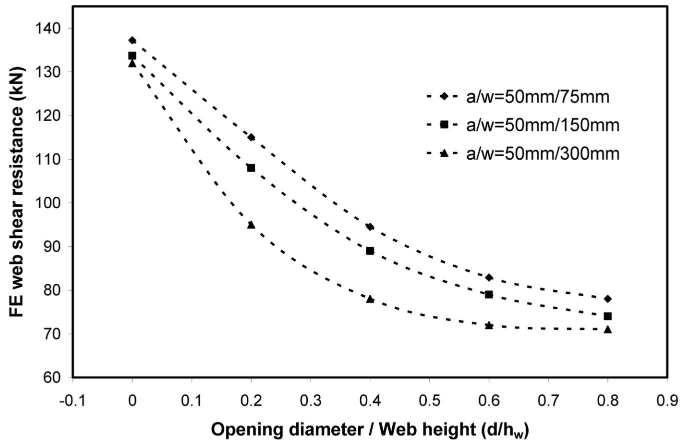



Fig. 8 FE web shear resistance versus web opening size relationships for different corrugation densities ($h_{web} = 500$ mm)

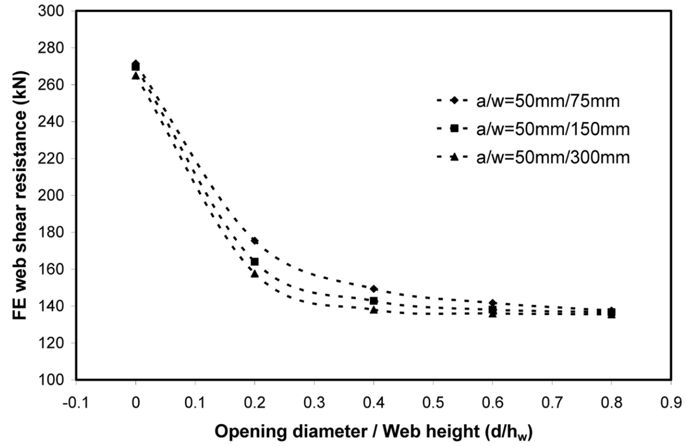



Fig. 9 FE web shear resistance versus web opening size relationships for different corrugation densities ($h_{web} = 1000$ mm)

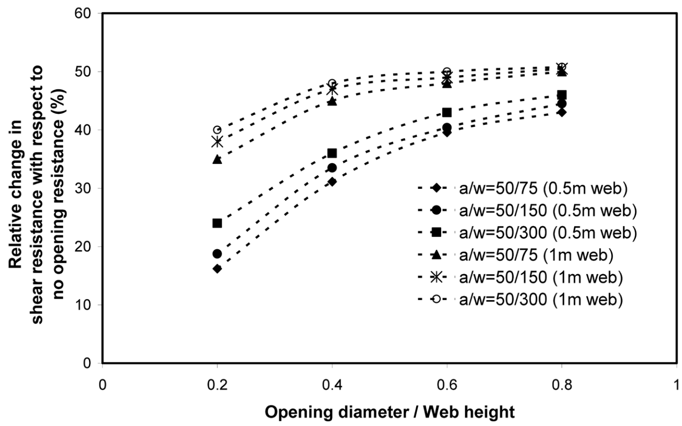



Fig. 10 Relative percentage changes in shear resistance of models with respect to the resistances obtained for models with no web opening

In Fig. 10, relative percentage change in shear resistance of models with varying web opening sizes are presented (both for $h_w = 500$ mm and $h_w = 1000$ mm models) with respect to the resistances obtained for models with no web opening. It is observed in this Figure that, for the geometries considered in this 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. It is also noted that the percentage reduction values calculated for the two web heights tend to converge each other for increasing opening sizes. Obtaining closer percentage reduction values for the two different web heights with greater web opening sizes (e.g. $d/h_w = 0.8$) means that the effect of web opening becomes the dominant factor that controls resistance (or the effect of web height becomes less significant) and on the other hand for smaller opening sizes, for which the percentage reductions are not as close for the two web heights, it is probably a coupled effect of opening size and the web height (web slenderness) together that governs the behaviour. In other words, for the two cases with two different web heights, the contribution of web yielding and buckling to the strength reduction becomes less pronounced for greater web opening sizes and more pronounced for smaller ones. In the extreme case with no web opening, shear resistance for $h_w = 1.0$ m webs is twice that of webs with $h_w = 0.5$ m height.

### *4.3. Design considerations for sinusoidally corrugated steel web beams with web openings*

The above mentioned FE predicted percentage strength reductions for all the 24 models considered are presented in Fig. 11 and Fig. 12 in relation to strength reduction factor ($\chi_c$) 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 Fig. 11 is the global web shear buckling curve whereas in Fig. 12 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 Fig. 11, on the global web buckling design curve, in terms of global buckling slenderness the $h_w$= 0.5 m and $h_w$ = 1.0 m models are well separated ( $\bar{\lambda}_{c,g} \approx 0.31$-0.33

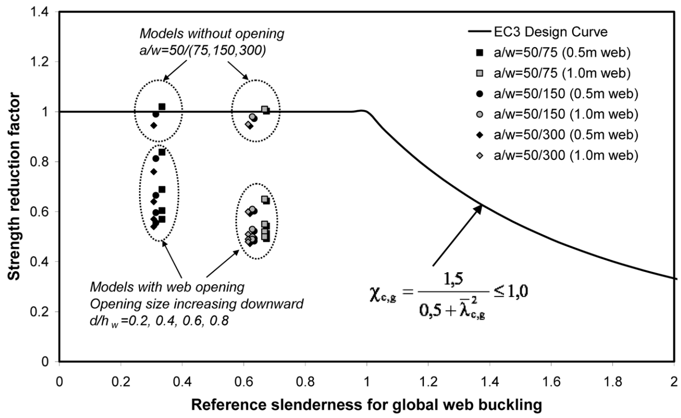



Fig. 11 FE predicted web shear strength reductions in relation to EC3 1.5 global web buckling design curve

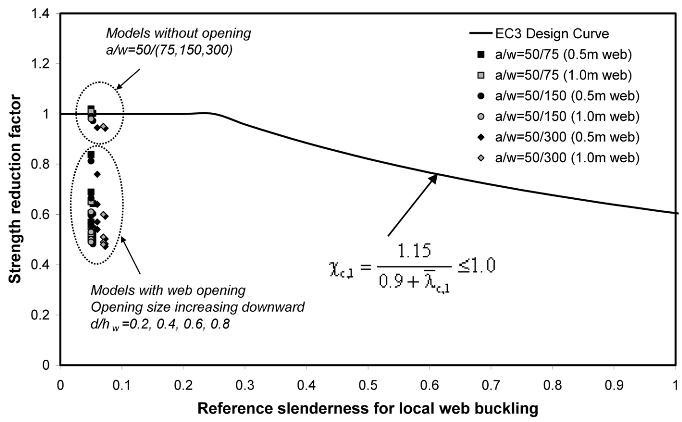



Fig. 12 FE predicted web shear strength reductions in relation to EC3 1.5 local web buckling design curve

for $h_w$ = 0.5 m models and $\bar{\lambda}_{c,g} \approx$0.61-0.67 for $h_w$ = 1.0 m models) whereas in terms of local web buckling slenderness as given in Fig. 12 all the models are very closely spaced, $\bar{\lambda}_{c,l} \approx$ 0.05-0.08 since the levels of sensitivity of the chosen corrugation density webs to local shear buckling are close. As also stated above in Fig. 10, it is observed in these figures (particularly in Fig. 11) 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.

Note that on the buckling curves in Fig. 11 and Fig. 12, 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 Fig. 11 and Fig. 12, 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 2 m become necessary. Actually, webs with $h_w > 2$ 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.

### 4.4. The effect of introducing a ring stiffener into the web opening

Finally, to increase the shear resistance of corrugated webs with circular web openings a practical stiffening arrangement using a steel plate ring welded to the curved edges of the opening is proposed. In this way, local instability of the corrugated web plate around the opening is prevented or its effect on strength is reduced by utilizing the hoop-rigidity of the ring under differential compressive stresses. FE models with a circular web opening with diameter, $d = 400$ mm and a web corrugation density of a/w = 50/150 were used for the non-linear analysis of several alternative cases of ring-stiffening. Various plate thickness values were adopted for the ring stiffeners ($t = 2$ mm, $t = 6$ mm, $t = 12$ mm). Also a different ring model was produced by providing a lip around the exterior circumferential edge of the ring with a $t = 2$ mm plate thickness. The results of the analyzed models are presented in Fig. 13 in the form of applied load versus mid-displacement curves. Around 20% increase in the maximum applied load is achieved for the highly stiffened model with a ring plate thickness of 12 mm in comparison to that of the model with no stiffener. Also for the lipped ring stiffener case an increase of around 12% is noted. In Fig. 14, deformed shapes for two models, one with a flat other with a lipped ring stiffener, are shown. It is observed that the ring contributes to the resistance of the web by buckling inwards. These deformed shapes correspond to post-ultimate load levels at which, as can be observed in the deformed shapes, the corrugated web plate around the ring stiffener has also buckled.

## 5. 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

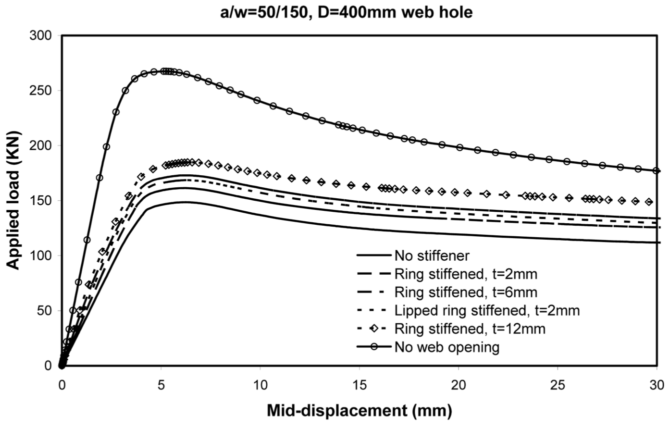



Fig. 13 Effect of ring stiffener on the resistance of corrugated web

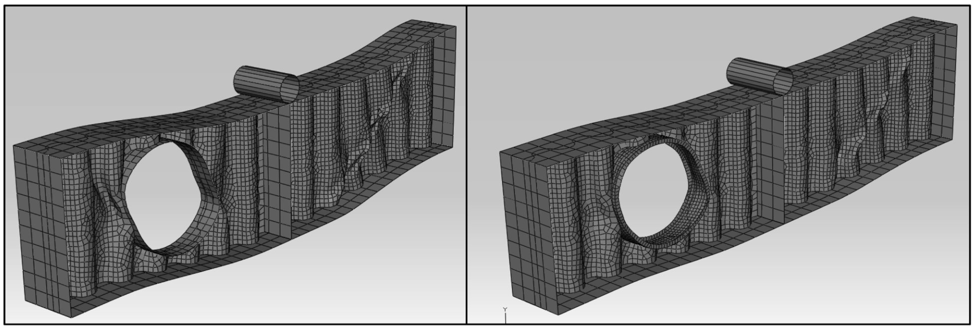


Fig. 14 Deformed shapes for models with web opening ring stiffeners with and without lips

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 2 m 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 m and $h_w$ = 1.0 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.

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