

INVESTIGATION OF RATIONAL DEPTH OF CASTELLATED STEEL I-BEAMS

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Abstract. There are many methods to calculate castellated steel beams; however, neither of these methods determines the rational cross-section selection. Selecting the rational cross-section induces a significant reduction in the quantity of steel. A new algorithm for selecting the rational dimensions of the castellated beams is presented in this paper. In future works it may be adopted and used for design. 12 m long beams, web thickness 6–12 mm and web depth 500–1000 mm are analysed in this paper. Opening size used varies from half of the web depth to the total web depth minus 100 mm. The chosen cross-sectional area of two flanges is equal to the cross-sectional area of the web. The thickness of the flanges is twice as big as the thickness of the web. The finite element method was used for geometrical and physical non-linear analysis of the castellated beams under a uniformly distributed load. The upper flanges of the beams are restrained out of the plane. The results are presented in relevant charts.

Keywords: castellated steel beam, perforation, perforation form, diameter of perforation, rational depth, finite element method, ultimate load.

1. Introduction

The bigger the area of the flange, the more rational the beam is (Čižas 1993). Thus, the flanges cross-section should be as big as possible to get a beam similar to the castellated beams (Fig. 1).



Fig. 1. View on test specimen of plate girder with web openings

The perforated beams have a wide range of applications ranging from commercial and industrial buildings to parking garages. They have a scene of beauty as well. These beams are well acceptable for big spans. Perforated beams have a structural advantage because it is possible

to pass through the web openings of the beam different kinds of communications (Liu and Chung 2003), which allow to save the effective height of the room and which is very important in multi-storey buildings. Advanced analysis of castellated beams generally has a verification character, i. e. the calculation, whether a beam with certain dimensions can carry the load or not, is carried out. In addition, there are tables used to select different types of castellated beams according to the load applied and the span. As a result of accurate analysis by finite element method, the design of castellated beams has become easier. A problem arises how to determine the rational dimensions of castellated beams, such as perforation diameter, the distance between perforations, web thickness, effective depth, etc. Therefore, it is very important to develop a method for selecting the rational parameters of castellated beams.

The beams used nowadays are not only made of rolled sections, but also built up using steel plates (Shanmugam *et al.* 2002; Hagen 2004). They are called steel plate girders with web openings. Using such beams allows one to dispose all cross-sectional dimensions and find the rational ones.

According to the experimental data, 8 failure modes of castellated beams are known (Mohebbkhan 2004; Megharief 1997; Zirakian and Showkati 2006):

1. Flexural mechanism;
2. Lateral torsional buckling;
3. Distortional buckling;
4. Web post buckling due to shear force;
5. Web post buckling due to compression force;

6. Vierendeel or shear mechanism;
7. Rupture of welded joints;
8. Ultimate deflecting.

2. Scope and aim of the investigation

Numerous researchers have quite well investigated the calculation methods for load carrying capacity of castellated beams. Quite a few theories are known (which can be trusted and used) for calculating castellated beams. Some of them are based on calculating the stresses in characteristic points such as in the corners of the openings and flanges, local stability of the web posts and local stability of tee sections over openings, etc. (Eurocode 3 1998; Biriulev *et al.* 1990; SNiP II-23-81* 1990).

The most difficult part is to find the rational depth of the beams which depends on many things. It is very complicated to achieve this due to mathematical difficulty in dealing with many unknowns and formulas. Using the finite element method, an analysis enables us to avoid such problems as mentioned above.

The main aim of this paper is:

1. to create charts $p = f(d)$ and $RF = f(d)$, where d – diameter of the perforation, p – uniform load [kN/m], RF – rational factor;
2. to analyse the charts mentioned above (how p and RF depend on the perforation diameter d , thickness of the web t_w and web depth h_w);
3. to present a new algorithm for selecting the rational dimensions of beams.

The modes of failure of castellated beams is not taken into account in this paper. The aim of the analysis performed by finite element method is to obtain only the ultimate load and the rational factor.

The next formula allows for calculation of the value of the rational factor:

$$RF = \frac{pL}{m}, \quad (1)$$

where RF – rational factor; p – uniform load [kN/m]; L – length of the beam [m]; m – weight of the beam [kN].

According to the calculations, the charts $p = f(d)$ and $RF = f(d)$ have been drawn, where d – diameter of the perforation (Fig. 2). Charts were prepared for beams with web thickness of 6 – 12 mm, every 1 mm and with web depth 500 – 1000 mm, every 10 mm. The beams with maximum rational factor, as well as beams that carried the maximum load may be found on these charts.

3. Description of the problem

Simply supported perforated beams with hexagonal form of perforations were analysed (Fig. 2).

The main beam parameters taken for the analysis are as follows:

1. Length $L = 12$ m.
2. Web depth $h_w = 500 - 1000$ mm, every 10 mm.
3. Web thickness $t_w = 6 - 12$ mm, every 1 mm.
4. Flange thickness t_f equal to double thickness of the web.

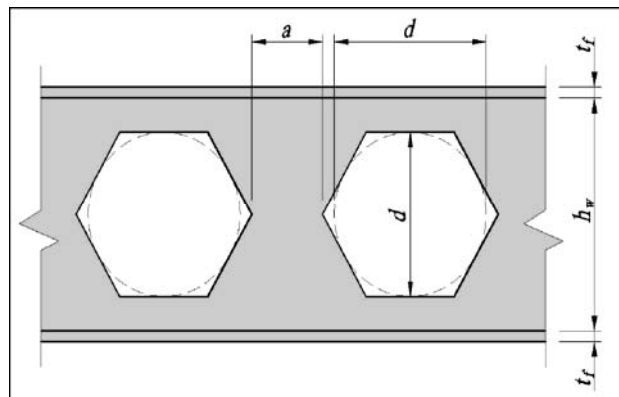


Fig. 2. Geometry of beam's web with hexagonal form of perforation

5. Thickness of the end stiffeners $t_s = 10$ mm.
6. Cross-sectional area of two flanges equal to the cross-sectional area of the web.
7. Diameter of perforations $h_w/2 - h_w - 100$ mm, every 10 mm.
8. Distance between the edges of perforations $a = 15$ cm.
9. Given an integer number of perforations, the distance from the end of the beam to the edge of the first perforation is minimal, but not less than 250 mm.
10. The uniformly distributed load per unit of the span length.
11. The upper flange restrained out of plane.
12. Analysis – geometrically and physically nonlinear.
13. Steel grade S355.
14. Form of perforation is a hexagon circumscribed about the circle.

All values of these parameters were selected because they are most common in practical use. Of course, some of them may be changed, especially those mentioned in clauses 1, 4, 6, and 8.

4. Finite element modelling

Calculations are performed using finite element programme *COSMOSM*. It is quite popular. It was applied to estimate the effects of soft defects on such difficult structures as cylindrical tanks (Rasiulis *et al.* 2006). *SHELL3T* was used as a type of finite elements. In order to simulate the structural behaviour of castellated steel beams with hexagonal web openings, a finite element model is established as follows:

- With material non-linearity incorporated into the finite element model. A bi-linear stress-strain curve is adopted in the material modelling of steel, as shown in Fig. 3.
- Moreover, with geometric non-linearity incorporated into the finite element model, large deformation in the model may be accurately predicted, allowing load redistribution in the web across the opening after initial yielding.

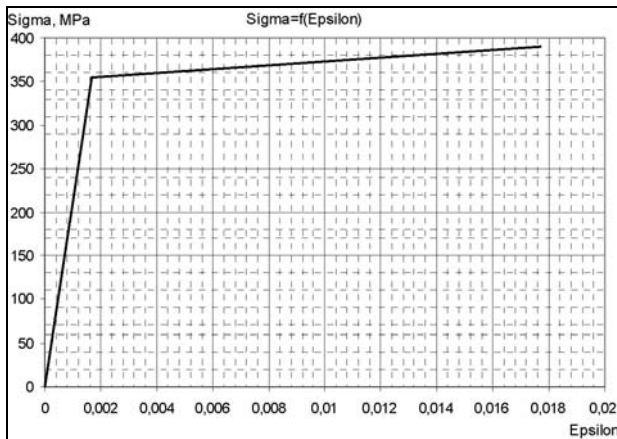


Fig. 3. Bi-linear stress-strain curve of material

Fig. 4 illustrates the finite element model, where the flanges and the web of a steel beam are discretised with three-noded shell elements.

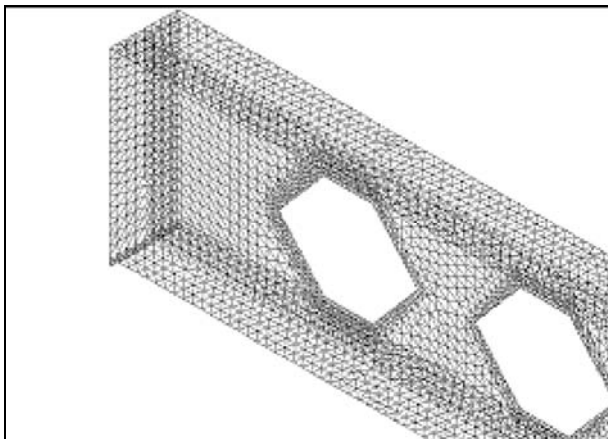


Fig. 4. Finite element model with hexagonal form of perforation

A hexagonal opening is formed in the web with refined mesh configuration. After sensitivity studies on the density of the finite element mesh, it was found that the size of a finite element may be about 5 cm. The size of a finite element around the opening chosen is about 1,5 cm. The calculations were made with iterations as the analysis was geometrically and physically non-linear. Arc-length algorithm was for calculations. This algorithm was not chosen accidentally. Other calculation methods were not suitable, because when a beam buckles, an increase in displacements at the plane is observed, where the load is almost the same. The calculations stopped when the maximum stress or strain values were reached, when the node's displacement exceeded $L/250$ or it started to increase very rapidly without sufficient load changing. Since the geometrical and physical analysis was carried out, the values of stresses, nodal displacements and buckling load may be received from the results of a single calculation.

5. Results obtained from the finite element method analysis

It is possible to determine by finite element method the calculations of the ultimate load p , which the beam can carry and the rational factor RF the bigger which is the more rational the material of the beam is used. The calculations were performed for a wide range of beams. When the length of the beam L was 12 m, the web depth h_w altered from 500 to 1000 mm, every 10 mm. The diameter of perforation at each depth also altered from $h_w/2$ to $h_w - 100$ mm, every 10 mm. The chosen distance between perforations was a fixed one of 150 mm; therefore the number of perforations changed with the diameter of perforations. The calculations were carried for the beams of such dimensions with the web thickness t_w of 6–12 mm. The total number of beams was 10 255.

However, due to a large number of results only some of them are presented herein.

5.1. Results of analysis of ultimate load

Due to a big amount of data, below are given the charts $p = f(d)$ (Fig. 5) only for web thicknesses of 6, 9, 12 mm, and with web depth 500–980 mm, every 40 mm. The charts of Fig. 5 are used to make charts for Fig. 6 (according to formula (1)) and to better conceive ultimate loads which the beams can carry. To see the load changes in different charts, we take the same scale of ordinates.

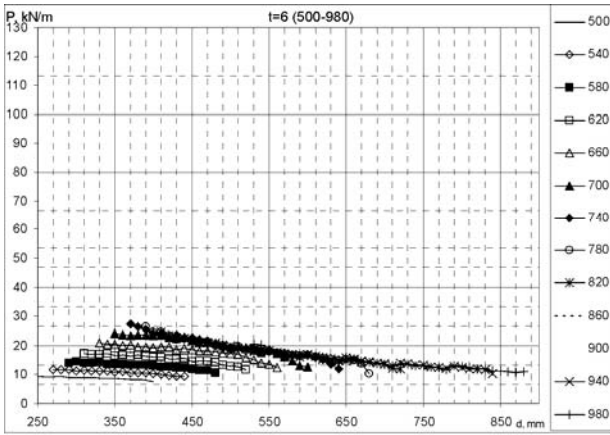
It is seen in the charts above, that the increase of ultimate load depends more on the depth of the web than on its thickness. When the thickness is 6 mm and the web depth increases, the ultimate load remains almost the same. This happens due to local stability of the web. When web thickness increases, the influence of the web depth is larger. In addition, when the diameter d of perforation increases, the ultimate load decreases. The bigger is the ultimate load, the more it declines when d increases. We can see from the charts, that the highest load is carried by a castellated beam with the thickest and highest web.

If we want to find the dimensions of the beam carrying the highest load, we have to find out when stresses exceed the strength of the beam material when deflections do not exceed their ultimate values and stability is ensured. If we want to find the dimensions of the beam which would be rational, additionally the web of the beam should be the thinnest or the beam should fail due to all modes at the same time.

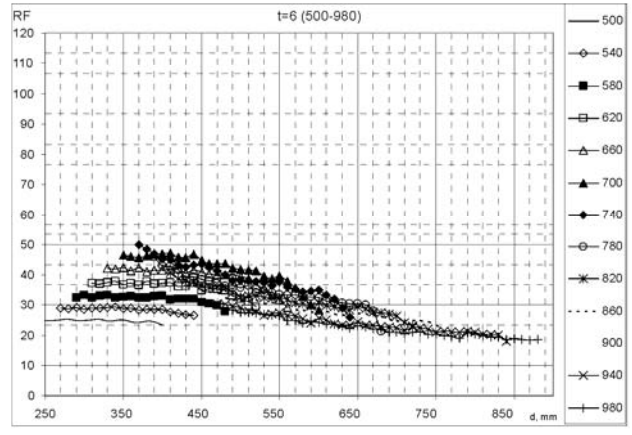
5.2. Results of analysis of rational factor

Due to a of big amount of data, bellow are given the charts $RF = f(d)$ only for web thicknesses of 6, 9, 12 mm, and with web depth of 500–980 mm, every 40 mm (Fig. 6).

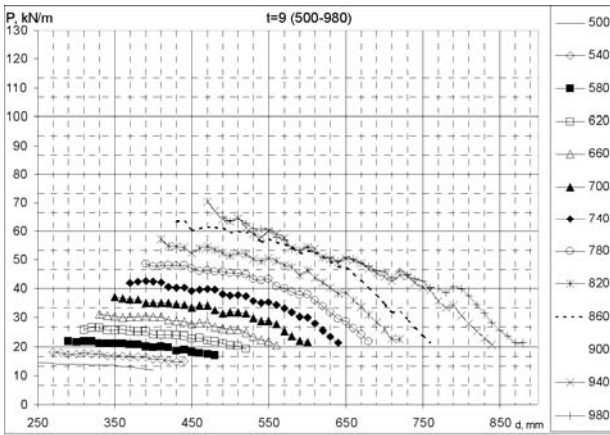
To see the load changes in different charts, we take the same scale of ordinates.



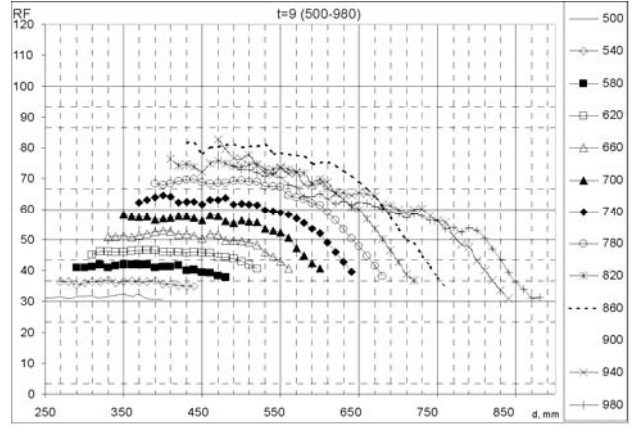
a)



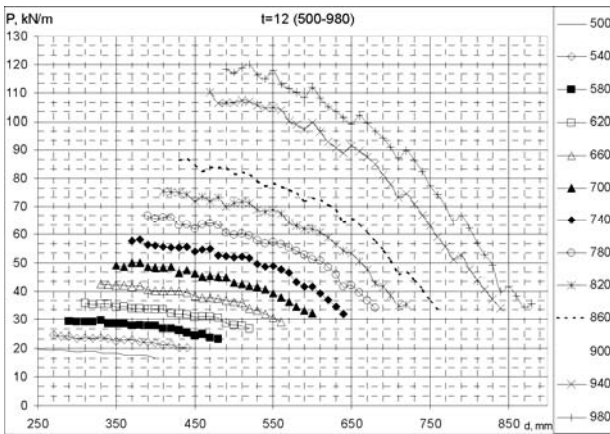
a)



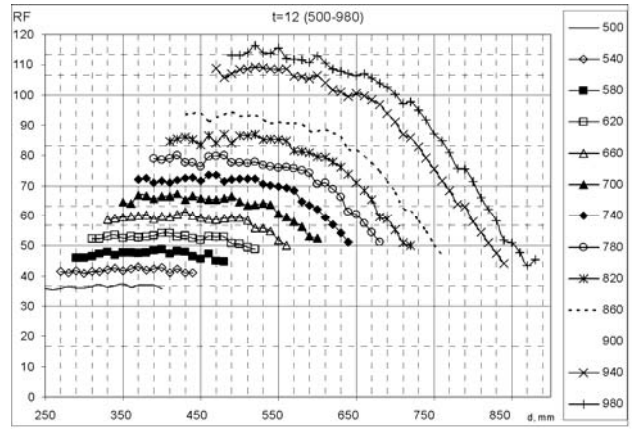
b)



b)



c)



c)

Fig. 5. Dependence of p versus d : a) for $t_w = 6$ mm; b) for $t_w = 9$ mm; c) for $t_w = 12$ mm

Fig. 6. Dependence of RF versus d : a) for $t_w = 6$ mm; b) for $t_w = 9$ mm; c) for $t_w = 12$ mm

It is seen in the charts above that the bigger is the web thickness, the bigger is the rational factor. It is also noted that if the depth of the web is increasing, the rational factor increases not necessarily. This happens because the web slenderness increase and causes the web-post buckling. In this case, the steel strength is not fully used.

When the web depth is not very big (500–700 mm), the perforation diameter has a negligible influence on the rational factor. The bigger the web depth, the higher the influence of perforation diameter on the rational factor, i. e. the bigger the perforation diameter, the smaller the rational factor is.

6. Selective analysis for a castellated beam with a rational section

The selection of the beam could look as follows:

1. Some data which limiting the web depth and some perforation dimensions are given;
2. According to these data, maximum value of RF may be found (Fig. 6).
3. If h_w and d are known, the beam weight may be found very easily.
4. If the length and weight of the beam are known, the load p [kN/m] may be found very easily.
5. If the load distributed per square meter g [kN/m²] is given, the rational beams' spacing b may be found according to formula $p = gb$.

For example:

The first step:

We have $h_w = 800$ mm, $d = 450$ mm.

The second step:

Finding from charts maximum RF (Fig. 6):

For $t_w = 6$ mm, $RF = 38$.

For $t_w = 7$ mm, $RF = 54$.

For $t_w = 8$ mm, $RF = 68$.

For $t_w = 9$ mm, $RF = 72$.

For $t_w = 10$ mm, $RF = 74$.

For $t_w = 11$ mm, $RF = 77$.

For $t_w = 12$ mm, $RF = 80$.

Due to a big amount of data, not all values of RF given above are presented in Fig. 6.

$$RF_{\max} = 80.$$

The third step:

Finding the beam weight:

$$m = (3t_w h_w L - N t_w A_{\text{opening}}) \rho,$$

where:

$$A_{\text{opening}} = 0.866d^2 - \text{area of the opening,}$$

$$\rho = 78.5 \text{ kN/m}^3.$$

So:

$$m = \left(3 \cdot 0.012 \cdot 0.8 \cdot 12 - 17 \cdot 0.012 \cdot (0.866 \cdot 0.45^2) \right) \cdot 78.5 = 24.32 \text{ kN.}$$

The fourth step:

According to formula (1):

$$p = \frac{RFm}{L} = \frac{80 \cdot 23.42}{12} = 156.13 \text{ kN/m.}$$

The fifth step:

We have $g = 8$ kPa.

So:

Rational beams' spacing will be

$$b = \frac{p}{g} = \frac{156.13}{8} = 19.5 \text{ m.}$$

If the spacing of the beams is too big due to other factors, the selected rational factor may be smaller. Another method for selecting rational dimensions of a beam should be applied.

Another selection method is also possible. It may look as follows:

1. The load distributed per square meter g [kN/m²] and beams spacing b are given. According to formula $p = gb$, the load p may be found.
2. The diameter of the perforation d is limited.
3. According to the charts mentioned above (Fig. 6) and with known d , the maximal value of $[RF]_{\max}$, t_w , number of the perforations N , density of the steel ρ , by approximation method according to formula (2) h_w may be found:

$$h_w = \frac{0.433Nd^2}{L} + \frac{p}{2[RF]_{\max} t_w \rho}. \quad (2)$$

For example:

The first step:

We have $g = 8.0$ kPa, $b = 6.0$ m, $d = 450$ mm.

So:

$$p = gb = 8.0 \cdot 6.0 = 24.0 \text{ kN/m.}$$

The second step:

Finding from charts maximum RF :

For $t_w = 6$ mm, $RF = 45$.

For $t_w = 7$ mm, $RF = 58$.

For $t_w = 8$ mm, $RF = 72$.

For $t_w = 9$ mm, $RF = 86$.

For $t_w = 10$ mm, $RF = 90$.

For $t_w = 11$ mm, $RF = 94$.

For $t_w = 12$ mm, $RF = 96$.

Due to a big amount of data, not all values of RF given above are presented in Fig. 6.

The first iteration

$$[RF]_{\max} = 96,$$

$$t_w = 12 \text{ mm.}$$

According to formula (2):

$$h_w = 0.257 \text{ m.}$$

It does not match with the chart.

The second iteration

$$[RF]_{\max} = 45,$$

$$t_w = 6 \text{ mm.}$$

According to formula (2):

$$h_w = 0.690 \text{ m.}$$

It does match the chart.

Therefore, we can choose a beam with web depth of 690 mm and with web thickness of 6 mm.

It should be noted that the method proposed in this paper is intended only for selecting rational cross-sectional dimensions of a beam, but not for design. In order to use this method for design, we additionally have to use the partial safety factors whose influence the reliability of steel structures and was studied by Kala (2007).

7. Conclusions

An analysis of perforated beams with a hexagonal form of perforations by finite element method is accomplished in this paper. Some conclusions may be drawn:

1. A non-traditional method for selecting castellated beams has been proposed.
2. The proposed method may be adopted and used for design in future works.
3. The charts determining the behaviour of beam failure may be drawn.
4. Data received are only valid for beams with the condition mentioned above.
5. With some coefficients, the curves used in charts can be adopted for beams of different lengths.
6. It can be seen from calculation data that the higher the web, the more efficiently the beam material is used. However, the bigger the web slenderness, the more critical influence has local buckling on the beam's carrying capacity. That is why it is very important to find such dimensions of the beam which in the moment of failure would ensure maximal stresses in the section.

SIJŲ SU PERFORUOTĄJA SIENELE RACIONALIAUS AUKŠČIO TYRIMAS

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Santrauka

Yra ne viena sijų su perforuotąja sienele skaičiavimo teorija, tačiau nė viena iš jų nenurodo, kaip parinkti racionalius tokių sijų skerspjuvio matmenis. Jeigu sijos su perforuotąja sienele skerspjuvio matmenys būtų parinkti racionalūs, galima būtų sutaupyti nemažai plieno tokioms sijoms gaminti. Buvo analizuotos sijos, kurių ilgis 12 m ir sienelės storis 6–12 mm, o aukštis 500–1 000 mm. Perforacijos skersmuo buvo parinktas nuo pusės sienelės aukščio iki sienelės aukščio atėmus 100 mm. Dviejų lentynų plotas buvo parinktas lygus sienelės plotui, o lentynų storis lygus dviem sienelės storiams. Analizuotos sijos buvo dviatramės, apkrautos tolygiai išskirstytąja apkrova, jų viršutinės lentynos buvo suvaržytos iš plokštumos. Sijos skaičiuotos baigtinių elementų metodu geometriškai ir fiziškai netiesiškai. Išanalizavus šias sijas, skaičiavimo rezultatai buvo pateikti grafikų pavidalu.

Reikšminiai žodžiai: sija su perforuotąja sienele, perforacija, perforacijos forma, perforacijos skersmuo, racionalus aukštis, baigtinių elementų metodas, ribinė apkrova.

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