Design of castellated and cellular beam according to TCVN 5575

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Abstract

This article introduces the structural and calculation requirements for steel beams with openings in the web, including: irregular hexagonal or oval openings, special cases are castellated (regular hexagonal) and cellular (round) openings. Calculation requirements, including verified the strength and deflection of the beam. Performing a numerical example for a beam with a opening in the web by zigzag cutting the web of the I-shaped steel beam, then butt-welding the cut part to form a regular hexagonal opening. The calculation steps show the implementation sequence, from material selection, load calculation, bending verified strength, verified buckling and deflection. Through numerical examples, to clarify the steps of designing steel web beams according to Vietnam's standard Design of steel structure TCVN 5575 (draft version 2023).

Key words: *castellated beam, cellular beam, I section, design, TCVN 5575 ((draft version 2023)*

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1. Introduction

Steel structures in general and steel beams in particular are widely used in civil and industrial engineering projects, including steel beams with openings in web beam. The openings in the beam's web have a very diverse shape, they can be square, rectangular, regular (castellated) or irregular hexagonal, circular (cellular) or oval. Square or rectangular openings are often created locally at several locations along the beam length, with hexagonal (castellated) or circular (cellular) or oval openings are often created continuously along the beam length. It can be seen that the main advantage of perforated steel beams is that they allow technical pipes of electrical, water or air conditioning and ventilation systems to pass through the beam's web, so it does not require much height space house for the technical system below the floor, to improve the efficiency of the building's usable space. At the same time, the web of the perforated web beam is made from a solid steel plate that is cut zigzag and then welded head-on at the cut part to create a steel plate with openings in the desired shape. This steel plate with openings has a height greater than the height original solid steel plate height, which means more efficient use of section height.

The problem of designing castellated and cellular steel beam structures to meet the requirements for resistance, stability as well as deflection requirements is a matter of concern. Recently, Vietnam's new standard design of steel structure TCVN 5575 (draft version 2023) [1] replaced the current standard TCVN 5575:2012 [2]. Standard TCVN 5575 is compiled based on the Russian Federation Standard of the same name SP 16.13330.2017 [5], updated with revisions 1 to 5 from 2018 to 2022, in addition to adding many contents of SP 294.1325800.2017 [7]. In addition, the standards of some advanced countries also mention the type of castellated and cellular beam members, such as the American Standard (AISC) [4], and recently the draft European standard (FprEN 1993-1-13) [5].

Accordingly, this article will introduce in detail the structural requirements and calculation of castellated and cellular steel beam components according to the conditions of resistance, stability and deflection, and design regulations mentioned in TCVN 5575. Limited to irregular hexagonal and oval opening shapes (regular hexagonal (castellated) or round (cellular) opening shapes are special cases of the two shapes mentioned above).

2. Design of castellated and cellular beam

2.1. Definition

Beams with opening in web are also known as castellated or cellular beams, they are designed with rolled I-shaped steel (with a cross-sectional height not less than 200 mm) made of steel with a yield limit of up to 440 MPa.

The expansion level of rolled steel (the ratio of the height of the expanded beam to the original I-shaped height) is taken to be no greater than 1.5.

The weld connection of the web should be made with a butt weld through the thickness.

2.2. Calculate

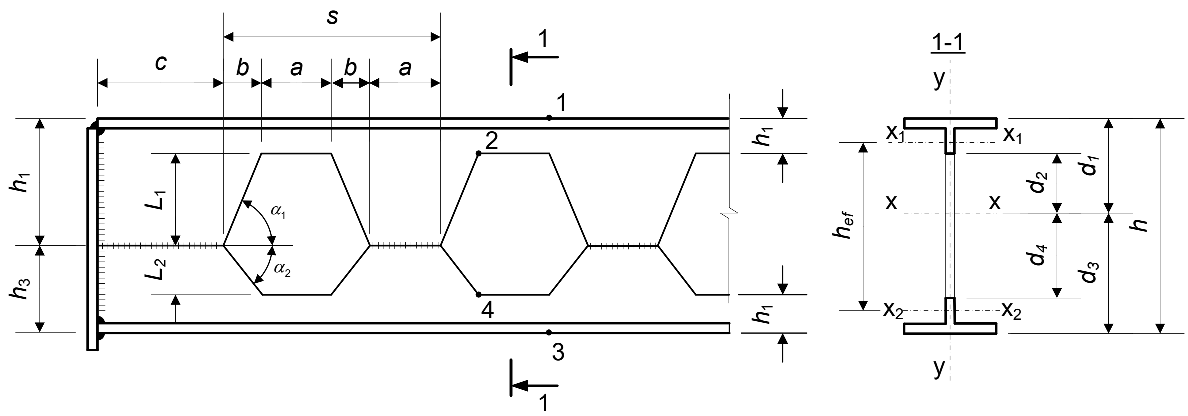
a) Calculation of resistance

Calculation of Flexural Strength in plane of beam (Fig 1) is carried out according to the formulas:

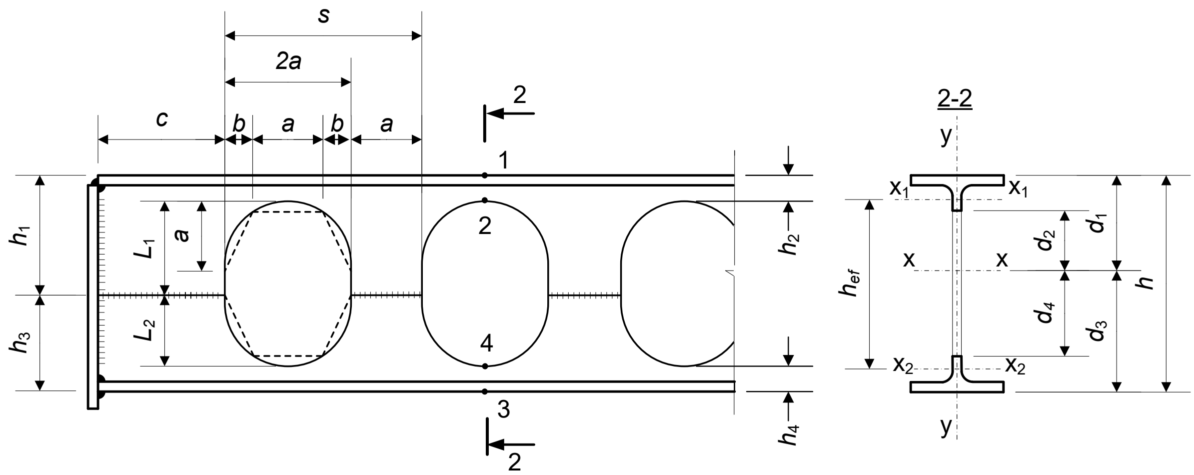
- For points at the corners of the openings, nearest to the flanges of the T:

$$\frac{1}{f_{ud}\gamma_c}\cdot\left(\frac{M}{W_x}+\frac{Va}{4W_{min}}\right)\leq 1 \qquad (1)$$

- For the nearest points located on the upper side of the T flanges above the openings:



a) castellated (regular hexagonal) openings



b) cellular (round) openings

Figure 1. Diagram of the openings in beam's web [1]

$$\frac{1}{f_{yd}\gamma_c}\cdot\left(\frac{M}{W_x}+\frac{V_1 a}{4W_{max}}\right)\le 1 \qquad (2)$$

$$\frac{V_s s}{t_w\, a\, h_{ef}\, f_v\, \gamma_c}\le 1 \qquad (3)$$

where:

M is the bending moment in the beam;

t_w is the web thickness;

V is the shear force in the beam;

V_s is the shear force in the beam section at distance (c + s – 0.5a) from the support (see Fig 1);

W_x is the section modulus of the I-beam developed at the opening section (actual cross-section) with respect to the x–x axis (when calculating the cross-section according to point 2: $W_x = I_x/d_2$; when calculating the cross-section according to point 4: $W_x = I_x/d_4$ where d_2, d_4 are the distances from the center of the section to points 2 and 4 respectively);

W_{max}, W_{min} are the largest and smallest section modulus of the T-section.

When determining the bearing capacity of the opening web beam at points 2 and 4:

$$\frac{\gamma_u}{f_{ud}\gamma_c}\cdot\left(\frac{Md_2}{I_x}+\frac{V_1 a}{2W_{1,min}}+\frac{N}{A_n}\right)\le 1 \qquad (4a)$$

$$\frac{\gamma_u}{f_{ud}\gamma_c}\cdot\left(\frac{Md_4}{I_x}+\frac{V_2 a}{2W_{2,min}}+\frac{N}{A_n}\right)\le 1 \qquad (4b)$$

where:

M is the bending moment in the beam;

V_1, V_2 are the shear forces under by the upper and lower T sections;

N is the longitudinal force in the beam;

I_x is the moment of inertia of the I section developed at the opening beam section (gross section) with respect to the x–x axis;

A_n is the area of the I section developed at the beam section with openings (gross section);

$W_{1,min}$, $W_{2,min}$ are the smallest section moduli of the upper and lower T-sections, respectively;

a is the lintel width of the web beam;

d_2, d_4 are the distances from the centroid of the section to points 2 and 4 respectively.

When determining the bearing capacity of the castellated and cellular beam at points 1 and 3:

$$\frac{1}{f_{yd}\gamma_c}\cdot\left(\frac{Md_1}{I_x}+\frac{V_1 a}{2W_{1,min}}+\frac{N}{A_n}\right)\le 1 \qquad (5c)$$

$$\frac{1}{f_{yd}\gamma_c}\cdot\left(\frac{Md_3}{I_x}+\frac{V_2 a}{2W_{2,min}}+\frac{N}{A_n}\right)\le 1 \qquad (5d)$$

where:

M is the bending moment in the beam;

V_1, V_2 are the shear forces under by the upper and lower T sections;

N is the longitudinal force in the beam;

I_x is the moment of inertia of the I beam developed at the opening beam section (gross section) with respect to the x–x axis;

An is the area of the I section developed at the beam section with openings (gross section);

$W_{1,min}$, $W_{2,min}$ are the smallest section moduli of the upper and lower T-sections, respectively;

a is the lintel width of the web beam;

d_1, d_3 are the distances from the centroid of the section to points 1 and 3 respectively.

b) Calculation of buckling

Calculations of beam buckling are performed according to 8.4.1 in TCVN 5575:2023; then the geometric characteristics of the beam are calculated for the opening section. The stability of the beam is considered guaranteed if it meets the requirements in 8.4.4 and 8.4.5 in TCVN 5575:2023.

At the support sections, if the abdomen has h_{ef}/t_w>40, it needs to be stiffened with rigid ribs and is calculated according to 8.5.17 in TCVN 5575:2023; Then the bearing cross section needs to be c ≥ 250 mm (see Fig 1).

The web beam in the upper area must be checked for stability according to the formula:

$$\tau \le \tau_{cr} \qquad (5e)$$

The shear stress at the lintel of the web beam is calculated according to the formula:

$$\tau = \frac{Vs}{t_w a h_{ef}} \qquad (5f)$$

where:

V is the shear force at the cross-section of the lintel under consideration;

t_w is the web thickness;

a is the lintel width of the beam web;

s is the opening pitch of the beam web;

h_{ef} is the distance between the centroids of the T section.

The critical shear stress is calculated according to the formula:

$$\tau_{cr} = \frac{4\left(\alpha-\frac{\pi}{2}\right)^2\sigma_{cr}}{3tg\left(\alpha-\frac{\pi}{2}\right)} \le f_v\gamma_c \qquad (4g)$$

where:

α is the opening angle of the beam web (see Fig 1);

σ_{cr} is the critical normal stress, calculated according to the formula:

$$\sigma_{cr} = \varphi f_{yd}\gamma_c \qquad (4h)$$

where:

is the stability coefficient, determined according to 7.1.3 when slenderness, where L =L_1 + L_2 is the opening height of the beam web (see Fig. 1).

When calculating the castellated beam or cellular beam, in the lintel area, use the geometric dimensions of a regular hexagon inscribed in a circle with diameter 2a (see Fig 1b).

Concentrated loads should only be placed on beam sections that are not placed openings.

The web height of the compression T-section needs to satisfy the requirements in 7.3.2 in TCVN 5575:2023, in which in formula (28) take $\bar{\lambda} = 1{,}4$.

c) Caculation of deflection

Determining the deflection of a hexagonal opening web beam with opening height d = 0.667h and ratio L/h_{ef} ≥ 12 (where L is the beam span) should be carried out according to the formula:

$$f_{perf} = f\cdot\left(1+\frac{1{,}3\pi^2 dA_f\alpha(\eta)\left(1+\frac{2}{\eta}\right)}{t_w L^2}\right) \qquad (5)$$

where:

$$f = \frac{5qL^4}{384EI_m}$$

is the beam deflection calculated according to bending theory (including I_m);

Af is the area of the T-shaped flang above the opening, calculated by the formula:

$$A_f = t_f b_f + t_w\left(0{,}5(h-d)-t_f\right) \qquad (6)$$

$\eta = 2/(s/a-1)$ relative clearance distance between openings, where a is the clearance distance between adjacent openings at the neutral axis level and s is the opening pitch (see Fig 1);

$\alpha(\eta)$ is a function of η :

$$\alpha(\eta) = -2{,}43\eta^2 + 4{,}54\eta + 0{,}586 \qquad (7)$$

The moment of inertia of section Im is calculated according to the formula:

$$I_m = \frac{b_f t_f (h-t_f)^2}{2} + \frac{t_w (h-2t_f)^3}{12} - \frac{t_w d^3}{24} \qquad (8)$$

3. Design example

3.1. Calculated data

Given: Castellated roof beam with I section constructed from shaped H section. Simple beam with span L = 18.0

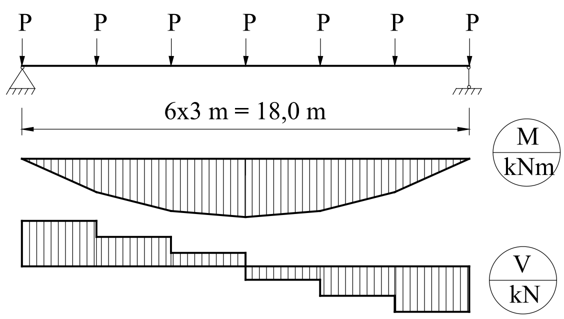


Fig 2. Load arrangement and diagram of internal forces M and V

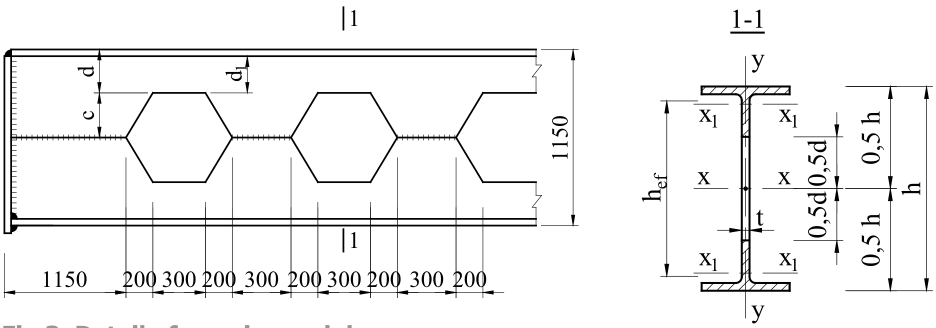


Fig 3. Detail of opening web beam

m, subjected to concentrated load from secondary beams placed 3.0 m spacing. The concentrated load distributed uniformly on the beam is 39 kN/m (q0 = 31.2 kN/m). The bending moment M and shear force V diagrams are shown in Fig 2 [3].

3.2. Solution:

Step 1. Determine beam cross-section and zigzag cutting diagram of web I section

Use H section. Steel material – HSGS 490 (according to Table B.9 in TCVN 5575:2023); For thickness up to 16mm, f_{yd} = 27.14 kN/cm^2; f_v = 15.74 kN/cm^2; f_{ud} = 46.67 kN/cm^2; For thickness up to 40mm, f_{yd} = 26.19 kN/cm^2. For beam head stiffeners, S235 steel is used.

Maximum bending moment caused by design load:

$$M_{max} = \frac{qL^2}{8} = \frac{39 \times 18^2}{8} = 1579,5\text{kN.m}$$

Required section modulus:

$$W_{req} = \frac{M_{max}}{f_{yd}\gamma_c} = \frac{1579,5 \times 100}{26,19 \times 1} = 6031\text{cm}^3$$

Choose the initial H section H800×300×14×22 according to TCVN 7571-16:2017. Dimensions section h_0 = 792mm; b = 300mm; t_f = 22mm; t_w = 14mm; R = 18mm. Cross-sectional area A = 239.5cm^2; I_x = 248000cm^4; W_x = 6270cm^3. The mass of 1 m is 188 kg long.

Check deflection due to standard load qc = 31,2 kN/m:

$$\frac{f}{L} = \frac{5q^cL^3}{384EI_x} = \frac{5 \times 31,2 \times 18^3 \times 10^6}{384 \times 2,06 \times 10^6 \times 248000} = \frac{1}{216}$$

$$> \left[\frac{f}{L}\right] = \frac{1}{250}$$

Seeing that using a section beam H800×300×14×22 does not satisfy the allowable deflection, measures to increase stiffness are needed (increasing the beam height by using a openings web beam). The level of rolled steel development is required to be no greater than 1.5. Take height h = 115cm.

Choose the initial H section zigzag cutting method so that the secondary beam placed on the beam section is not weakened by the opening (3 m beam spacing requires even cutting steps s). Choose a opening pitch of 1 m (there are three openings within the beam spacing limit), i.e. 3×2×(b+e) = 3000mm or (b+e) = 500mm.

Suppose e = 300mm, b = 200mm. At the end of each 3m interval, arrange only two openings (Fig 3). Arrange welds of beam sections at mid-height. Take the beam end plate and weld it to the beam end.

Step 2. Determine the parameters of the opening beam section

Area of T flange:

$$A_T = \frac{A - ct_w}{2} = \frac{239,5 - 35,8 \times 1,4}{2} = 94,69\text{cm}^2;$$

c = 115 – 79,2 = 35,8cm.

Wing equivelence thickness:

$$t_f = \frac{A - h_0 t_w}{2(b - t_w)} = \frac{239,5 - 79,2 \times 1,4}{2 \times (30 - 1,4)} = 2,25 \text{ cm.}$$

T section height:

$$d = \frac{79,2 - 35,8}{2} = 21,7 \text{ cm; } d_1 = 19,45 \text{ cm.}$$

Step 3. Check the local buckling of the T section web

Check by condition:

$$\bar{\lambda}_w = (h_{ef} / t_w)\sqrt{f_{yd} / E} \le \bar{\lambda}_{uw}$$

The limited equivelence slenderness $\bar{\lambda}_{uw}$ is determined according to formula (28) in Table 9 in TCVN 5575:2023:

$$\bar{\lambda}_{uw} = \left(0,40 + 0,07\bar{\lambda}\right)\left(1 + 0,25\sqrt{2 - b_f / h_{ef}}\right) =$$

$$\left(0,40 + 0,07 \times 1,4\right) \times \left(1 + 0,25\sqrt{2 - 30/19,45}\right) = 0,58,$$

trong đó $\bar{\lambda}$ = 1,4 according to 15.13.5 in TCVN 5575:2023.

Equivelence slenderness of the web:

$$\bar{\lambda}_w = (19,45/1,4) \times \sqrt{271,4/\left(2,06 \times 10^5\right)} = 0,504 < 0,58.$$

Thus, the T section web ensures local buckling.

Step 4. Check beam section resistance

Flange cross-sectional area:

$$A_f = bt_f = 30 \times 2,25 = 67,5 \text{ cm}^2.$$

Modulus of section of the upper T flange with respect to the lower edge:

$$S_T = A_f\left(d_1 + \frac{t_f}{2}\right) + \frac{t_w d_1^2}{2}$$

$$= 67,5 \times \left(19,45 + \frac{2,25}{2}\right) + \frac{1,4 \times 19,45^2}{2} = 1654\text{cm}^3$$

Moment of inertia of the T section about the bottom edge:

$$I_{T,1} = A_f\left(d_1^2 + d_1 t_f + \frac{t_f^2}{3}\right) + \frac{t_w d_1^3}{3} =$$

$$= 67,5 \times \left(19,45^2 + 19,45 \times 2,25 + \frac{2,25^2}{3} \right) + \frac{1,4 \times 19,45^3}{3}$$

= 32037 cm^4.

The centroid section on the distance:

z = ST/AT = 1654/94,69 = 17,5 cm.

Moment of inertia of the T section about the central axis:

$$I_T = \left| I_{T,1} - zS_T \right| = \left| 32037 - 17,5 \times 1654 \right| = 3092 \text{ cm}^4.$$

Section modulus of T section flange:

$$W_{T,max} = \frac{I_T}{d - z} = \frac{3092}{21,7 - 17,5} = 736,2 \text{ cm}^3;$$

$$W_{T,min} = \frac{I_T}{z} = \frac{3092}{17,5} = 176,7 \text{ cm}^3.$$

The lever arm of the force pair acting in the flange:

f = 2(c+z) = 2×(35,8+17,5) = 106,6cm.

Moment of inertia of beam cross-section according to opening:

$$I_{x,0} = 2I_T + \frac{A_T f^2}{2}$$

$$I_{x,0} = 2 \times 3092 + \frac{94,69 \times 106,6^2}{2} = 544192 \text{ cm}^4.$$

The section modulus of the I section expands with respect to the x-x axis:

$$W_x = \frac{2I_{x,0}}{h_{ef}} = \frac{2 \times 544192}{107} = 10172 \text{ cm}^3.$$

Check the bending moment resistance of the T flange at mid-span:

M_{max} = 1579,5 kN.m; V = 117,1 kN; N = 0 (see Fig 1).

Point located above the opening corners at a distance of 0.5h from the x-x axis:

$$\frac{1}{26,2 \times 1,0} \times \left(\frac{1579,5 \times 100}{10172} + \frac{117,1 \times 30}{4 \times 736,1} \right) = 0,64 < 1.$$

The point is located at the opening corners at a distance of 0.5d from the x-x axis:

$$\frac{1}{46,7 \times 1,0} \times \left(\frac{1579,5 \times 100}{10172} + \frac{117,1 \times 30}{4 \times 176,7} \right) = 0,44 < 1.$$

Check the bending strength of the T section at a quarter span (under the second force from the support):

$M_1/4$ = 1361,6 kN.m; $V_1/4$ = 234,2 kN.

Point located above the opening corners at a distance of 0.5h from the x-x axis:

$$\frac{1}{46,7 \times 1,0} \times \left(\frac{1361,6 \times 100}{10172} + \frac{234,2 \times 30}{4 \times 176,7} \right) = 0,50 < 1;$$

The point is located at the opening corners at a distance of 0.5d from the x-x axis:

$$\frac{1}{46,7 \times 1,0} \times \left(\frac{1361,6 \times 100}{10172} + \frac{234,2 \times 30}{4 \times 176,7} \right) = 0,50 < 1.$$

Check the bending strength of the T section flange at the beam support (on the first opening):

M_1,65 = (351,4-29,3)×1,65 = 531,46 kN.m;

V_1,65 = 322,08 kN.

The point is located at the opening corners at a distance of 0.5d from the x-x axis:

$$\frac{1}{46,7 \times 1,0} \times \left(\frac{531,46 \times 100}{10172} + \frac{322,08 \times 30}{4 \times 176,7} \right) = 0,40 < 1.$$

Thus, the bearing capacity of the bending moment T section is guaranteed.

Step 5. Check the local buckling of the beam web

Check beam web thickness according to standard requirements (Article 15.13.5 in TCVN 5575:2023).

$$\frac{h_{ef}}{t_w} = \frac{115 - 2 \times (2,2 + 1,8)}{1,4} = 76,4$$

(h_{ef} according to Figure 3);

$$2,5\sqrt{\frac{E}{f_{yd}}} = 2,5 \times \sqrt{\frac{2,06 \times 10^4}{27,14}} = 68,9 \quad (76,4 > 68,9).$$

Check the installation of horizontal stiffeners in the web section:

$$\bar{\lambda}_w = 76,4 \times \sqrt{\frac{271,4}{2,06 \times 10^5}} = 2,8 < 3,2,$$

horizontal stiffeners are only installed under concentrated loads (at the secondary beam position, i.e. 3 m away). Stiffeners sizes are taken according to standards:

Stiffeners width:

$$b_r \geq h_w / 30 + 25 \text{ mm} = 1250 / 30 + 25 = 66,7 \text{ mm}.$$

Take b_r = 70 mm.

Stiffeners thickness:

$$t_r \geq 2 \times 70 \times \sqrt{223,8 / \left(2,06 \times 10^5\right)} = 4,6 \text{ mm}.$$

Take t_r = 6 mm.

Beam head stiffener size:

Width of beam head stiffener (support stiffener):

$b_{ro} = b_f$ = 300mm (b_f is the beam flange width).

Thickness according to strength:

$$t_{ro} \geq \frac{V_{max}}{b_{ro} f_c \gamma_c} = \frac{351,4}{300 \times 34,3 \times 10^{-2}} = 3,4 \text{ mm}.$$

In addition, article 8.5.17 in TCVN 5575:2023 requires:

$$t_{ro} \geq 3 \times 150 \times \sqrt{223,8 / \left(2,06 \times 10^5\right)} = 14,8 \text{ mm}.$$

Take t_{ro} = 16mm.

Check the buckling of the first zone from the bearing (with the highest load) according to the formula:

$t_{2\varphi} = 35,8 / 20 = 1,79$; φ = 60,8°; θ = 29,2°.

Units in radians θ = 29,2×π/180 = 0,5096; tgθ = 0,5589;

$$\tau_{cr} = \frac{4\theta^2}{3tg\theta}\sigma_{cr} = \frac{4}{3} \times \frac{0,5096^2}{0,5589}\sigma_{cr} = 0,6195\sigma_{cr};$$

$$\sigma_{cr} = \varphi f_{yd} \gamma_c;$$

$$L_0 = \frac{c}{\sin\varphi} = \frac{35,8}{0,873} = 41,0;$$

$$i = 0,289 t_w = 0,289 \times 1,35 = 0,39 \text{cm};$$

$\lambda = 105$, $\bar{\lambda} = 105 \times \sqrt{\dfrac{271,4}{2,06 \times 10^5}} = 3,81$;

according to Table D.1 in TCVN 5575:2023, there is $\varphi = 0,485$;

$\tau_{cr} = 0,6195 \times 13,2 = 8,18$ kN/cm^2;

$\tau_{cr} = 0,6195 \times 13,2 = 8,18$ kN/cm^2.

Gross shear stress in the first zone:

$$\tau = \frac{322,08}{1,35 \times 30} = 7,95\ kN/cm^2 < \tau_{cr}.$$

Step 6. Check overall buckling

Overall buckling is ensured by braces (auxiliary beams). In any case, this inspection is no different from that of conventional beams. Geometric characteristics need to be obtained for sections with openings.

Step 7. Check beam deflection

Check deflection according to formula (204) in TCVN 5575:2023:

$$f_{perf} = f\left(1 + \pi^2 1,3dA_f\alpha(\eta)\left(1 + \frac{2}{\eta}\right)\frac{1}{t_w L^2}\right);$$

$$f = \frac{5q_n L^4}{384EI_m} = \frac{5 \times 31,2 \times 18^4 \times 10^8}{384 \times 2,06 \times 10^6 \times 560138} = 3,70\ cm;$$

$A_f = t_f b_f + t_w(0,5(h - d) - t_f)$

= 2,25×30 + 1,4×[0,5×(115 - 76,7) – 2,25] = 91,2 cm^2;

d = 0,667h = 0,667×115 = 76,7 cm;

$$I_m = b_f t_f \frac{(h - t_f)^2}{2} + \frac{t_w (h - 2t_f)^3}{12} - \frac{t_w d^3}{24} = ;$$

According to formula (206) in TCVN 5575:2023:

α(η) = -2,432 + 4,54η + 0,586

= 2,43×0,862 + 4,54×0,86 + 0,586 = 2,69;

According to formula (208) in TCVN 5575:2023:

$$I_m = b_f t_f \frac{(h - t_f)^2}{2} + \frac{t_w (h - 2t_f)^3}{12} - \frac{t_w d^3}{24} =$$

$$= 30 \times 2,25 \times \frac{(115 - 2,25)^2}{2} + \frac{1,4 \times (115 - 2 \times 2,25)^3}{12} - \frac{1,4 \times 76,7^3}{24} = 560138cm^4$$

$$f_{perf} = 3,70 \times \left(1 + \pi^2 \times 1,3 \times 76,7 \times 91,2 \times 2,69 \times \left(1 + \frac{2}{0,86}\right) \times \frac{1}{1,4 \times 1800^2}\right)$$

= 3,70×(1 + 0,177) = 4,35 cm.

$$\frac{f_{perf}}{L} = \frac{4,35}{1800} = \frac{1}{414} < \left[\frac{f}{L}\right] = \frac{1}{250}.$$

Beams ensure deflection conditions.

Conclusion: The deployed I-beam cross section ensures the load bearing requirements.

Conclusions

- Calculation of steel beam members with opening in web mentioned in TCVN 5575 (draft version 2023) for the general case of irregular hexagonal openings, oval openings and special cases of beams with (castellated) regular hexagonal openings or (cellular) round openings. Accordingly, other advanced steel structure design standards have also been accessed, for example European standards (prEN 1993-1-13) [5] or US standards (AISC) [4].

- Vietnam's Steel Structure Design Standard TCVN 5575 (draft version 2023) has many new points compared to TCVN 5575:2012, and their content is quite extensive. Therefore, there needs to be further research into this standard in the future to properly understand and exploit all the contents mentioned in this standard./.

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