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SIMPLIFIED DESIGN METHOD AND PARAMETRIC STUDY OF COMPOSITE CELLULAR BEAM

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Abstract

Nowadays, with the development of cutting and welding technologies, steel beams with regular circular openings, called cellular beams, have been widely used for construction. The cellular beams could be designed either as steel beam or composite beam when headed shear connectors connect concrete slab to top flange of steel beam. This paper presents a procedure to design cellular composite beams according to EN 1994-1-1. In addition, a parametric study is carried out to evaluate the influence of circular opening geometry to ultimate load and failure mode of a series of cellular composite beams. As a result, an optimal dimension of cellular beam is proposed.

Keywords: steel - concrete composite beam; cellular beam; web opening; Vierendeel mechanism.

1. Introduction

The initial idea was to create single web openings in steel beam in order to pass heating, ventilation and air conditioning (HVAC) system through the web of beam. Since the first decade of the twentieth century, the improved automation in fabrication has resulted in the use of castellated beams and cellular beams. In comparison with traditional steel beam, castellated beams and cellular beams have more advantages such as light weight and long span capability. One of its great advantages is the ability to run utilities directly through the web openings. By integrating the HVAC system into the floor structure, the clear height of floor will be increased.

Castellated and cellular beams are defined as steel beams with repeating hexagonal openings and circular openings. They can be produced from either hot-rolled profiles or steel plates (Fig. 1). The manufacturing process of castellated and cellular beams are the same. In comparison with castellated beams, cellular beams are preferable to use because the circular openings are suitable to pass conduits through. Moreover, the circular shape of openings will minimize the stress concentration around the openings.

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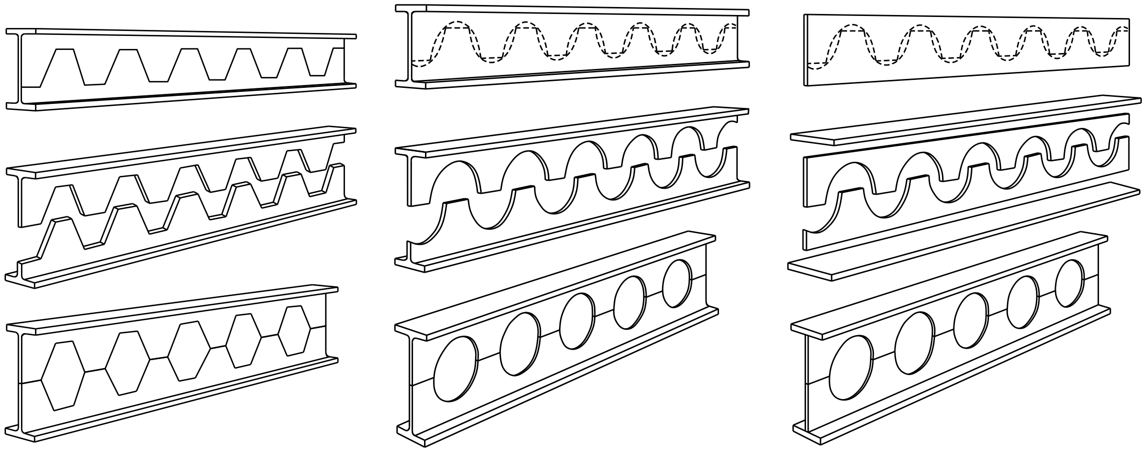

(a) Castellated beam from hot-rolled profile

(b) Cellular beam from hot-rolled profile

(c) Cellular beam from steel plates

Figure 1. Manufacturing of castellated and cellular beams

Castellated or cellular composite beams typically consist of concrete slabs which are connected to the top flange of steel beams through headed shear studs. This type of structure combines the advantages of concrete compressive strength and steel tensile strength under sagging moment.

Design guidance for composite beam with large web openings is published in [1, 2]. These publications apply only to isolated openings in beams of symmetric cross-section. The Steel Construction Institute (SCI) publication P100 [3] introduces design method for symmetric cross-section cellular beams. SCI publication P355 [4] extends the guidance in SCI P068 for both hot-rolled and welded sections. This publication covers the design of simply supported composite beams for the symmetric and asymmetric sections. The American Institute of Steel Construction (AISC) Design Guide 31 [5] introduces design method of castellated and cellular beams for both of non-composite and composite cases. The design methods in [4, 5] are based on the same theory as described in [6] but there are slight differences among them because they were developed by different parties. The behavior of cellular beam is still being investigated [7–9]. The use of cellular beams in Vietnam is limited due to the shortage of steel profiles in local market and the lack of a design guide.

This paper aims to present a simplified design method for cellular composite beams (CCB) according to EN 1994-1-1 [10]. The design method is summarized in a practical procedure. Additionally, a parametric study is performed to evaluate the influence of the cellular beam geometry to ultimate load and failure mode of a series of CCBs. As a result, an optimal geometric dimension of cellular beam is proposed. This study particularly focuses on CCB fabricated from steel plates. Castellated and cellular beams fabricated from hot-rolled profile are not considered in this paper.

2. Design theory for cellular composite beams

The various modes of failure that may occur at or around large web openings are illustrated in Fig. 2 [4]. Some modes of failure are due to local effects around single large openings, whereas others arise due to the failure of the web-post between closely spaced openings. The principal modes of failure are following: global bending failure, pure shear failure, Vierendeel bending failure and web-post failure.

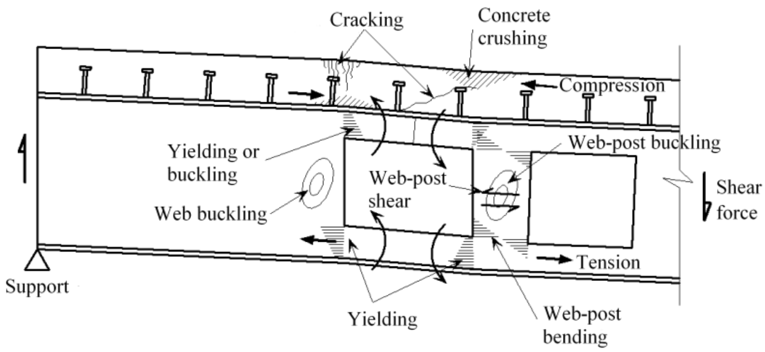

Figure 2. Modes of failure at large closely spaced openings

2.1. Global bending

In case of a composite beam with a single rectangular opening, its sagging moment is resisted by tension force in the bottom Tee of steel section and by compression force in the concrete slab. When the compression force in the concrete slab is smaller than tension force in the bottom Tee, compression force will be developed in the top Tee. Top Tee is assumed not to subject to tension force. For circular openings, it may be treated as an equivalent rectangular opening with effective length and height are taken as: $l_e = 0.45h_0$ and $h_e = 0.9h_0$ where h_0 is the diameter of openings (Fig. 3).

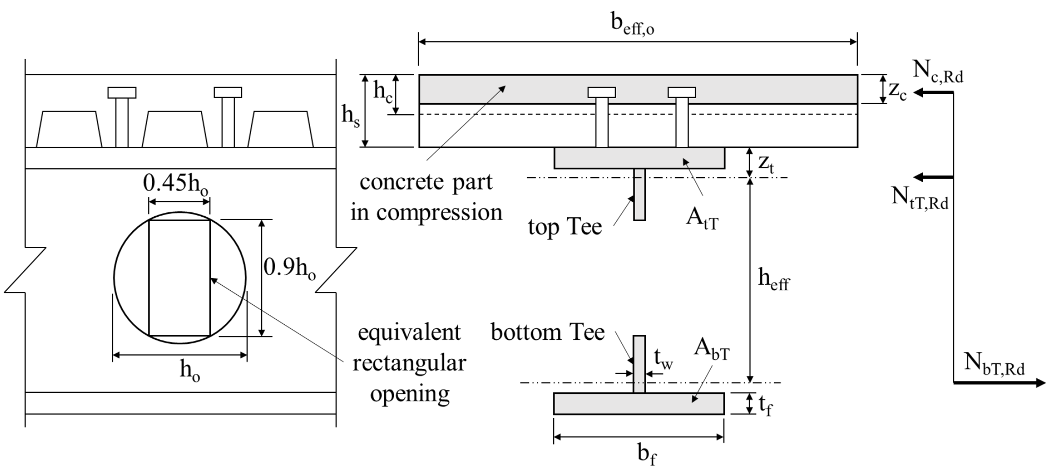

Figure 3. Forces at opening section

The tensile resistance of the bottom Tee is given by:

$$N_{bT,Rd} = A_{bT} f_y \big/ \gamma_{M0} \tag{1}$$

where A_{bT} is the cross sectional area of bottom Tee; f_y is the yield strength of steel and γ_{M0} is the partial factor for resistance of structural steel.

The compressive resistance of composite slab is the smaller value of concrete compressive resistance and shear resistance of headed stud connectors between the support and the center line of opening:

$$N_{c,Rd} = \min(0.85 f_{ck} b_{eff,0} h_c \big/ \gamma_c; n_{sc} P_{Rd}) \tag{2}$$

in which f_{ck} is the characteristic compressive cylinder strength of concrete; $b_{eff,0}$ is the effective slab width at opening which will be defined in Eq. (3); h_c is the depth of concrete above decking; γ_C is partial factor for concrete; n_{sc} is the number of shear connector; and P_{Rd} is the shear resistance of one shear connector.

The effective slab width for openings close to the support is less than at the mid-span. For a simply supported span beam with a sufficient available width of slab on both sides, the effective slab width at an opening, at a distance x from the support may be determined as following:

$$\begin{aligned} b_{eff,0} &= 3L/16 + x/4 \leq B \qquad &\text{if} \quad x \leq L/4 \\ b_{eff,0} &= L/4 \leq B \qquad &\text{if} \quad x > L/4 \end{aligned} \tag{3}$$

where L is the beams' span; B is the spacing of the beams.

In general, the maximum compression force developed in the top Tee section is given by:

$$N_{tT,Rd} = N_{bt,Rd} - N_{c,Rd} \leq A_{tT} f_y \big/ \gamma_{M0} \tag{4}$$

The plastic bending resistance of a composite beam at the centerline of an opening is given by:

$$M_{0,Rd} = N_{bT,Rd} \left(h_{eff} + z_t + h_s - 0.5 z_c \right) - N_{tT,Rd} \left(z_t + h_s - 0.5 z_c \right) \tag{5}$$

where h_{eff} is the effective depth of the steel section between centroid of the Tees; z_t is the depth of the centroid of the top Tee from the outer edge of the flange; h_s is the total depth of slab; z_c is the depth of concrete part in compression that may be determined by equations as shown in Table 1.

Table 1. Depth of concrete part in compression

Position of P.N.A	Condition	Depth of concrete part in compression	
P.N.A in slab	$N_{c,Rd} > N_{bT,Rd}$	$z_c = \dfrac{N_{bT,Rd}}{0.85 b_{eff,0} \left(f_{ck}/\gamma_c \right)} \leq h_c$	(6)
P.N.A in top Tee	$N_{c,Rd} < N_{bT,Rd}$	$z_c = h_c$	(7)

2.2. *Pure shear*

The vertical shear resistance of the composite section is the sum of the shear resistance of steel section and the shear resistance of the concrete slab. Normally, the shear resistance of concrete slab is much smaller than the shear resistance of steel section. Conservatively, the shear resistance of concrete slab can be ignored. For welded section, the shear area of the Tees consists of web and a part of flange as illustrated in Fig. 4. The design plastic shear resistance of steel section at opening positions is given as following:

$$V_{pl,Rd} = \left(A_{V,tT} + A_{V,bT} \right) \left(f_y \big/ \sqrt{3} \right) \big/ \gamma_{M0} \tag{8}$$

where $A_{V,tT}; A_{V,bT}$ are the shear area of top and bottom Tee.

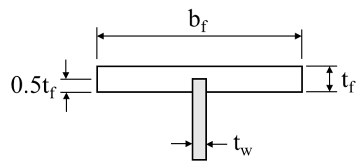

Figure 4. Shear area of welded section

2.3. Vierendeel bending

The Vierendeel bending resistance is the sum of the Vierendeel bending resistances of the Tees and the contribution of local composite action between the top Tee and the slab. The Vierendeel bending resistance must be greater than the design Vierendeel moment. This may be expressed as:

$$2M_{bT,NV,Rd} + 2M_{tT,NV,Rd} + M_{vc,Rd} \geq V_{Ed} l_e \tag{9}$$

where $M_{bT,NV,Rd}$; $M_{tT,NV,Rd}$ are the reduced Vierendeel bending resistances of the Tees in presence of axial and shear force; $M_{vc,Rd}$ is the local composite bending resistance. The magnitude of the local composite bending resistance depends on the number of shear connectors placed over the opening. It is conservative to ignore this component if the Vierendeel bending resistance of the Tees alone is adequate.

The Vierendeel bending resistances of the Tees depend on the class of the composite section. Generally, the top flange may be treated as Class 2, or better, because of its attachment to the slab. The web of the Tee may be classified, depending on the ratio of the length of the opening to the outstand depth as presented in Table 2. For this classification, the effective length of equivalent rectangular opening may be taken as $l_{0,eff} = 0.7h_0$. The plastic stress distribution can be considered when the cross section of the Tees is Class 1 or 2. Where the web is Class 3 or 4, only the elastic stress distribution can be used.

Table 2. Classification of the web of the Tees

Class	Limit on depth of web h_w according to length of opening		
	$l_{0,eff} \leq 32\varepsilon t_w$	$32\varepsilon t_w \leq l_{0,eff} \leq 36\varepsilon t_w$	$l_{0,eff} > 36\varepsilon t_w$
2	(no limit)	$h_w \leq \dfrac{10\varepsilon t_w}{\sqrt{1-\left(32\varepsilon t_w / l_{o,eff}\right)^2}}$	
3	(no limit)		$h_w \leq \dfrac{14\varepsilon t_w}{\sqrt{1-\left(36\varepsilon t_w / l_{o,eff}\right)^2}}$
4	(no limit)		

2.4. Web-post resistance

The design forces for circular openings are shown in Fig. 5. The condition to check web-post shear and bending resistance can be expressed as following:

$$V_{wp,Rd} = \frac{(s_0 t_w) f_y / \sqrt{3}}{\gamma_{M0}} \geq V_{wp,Ed} = \min \begin{cases} \dfrac{V_{Ed} s}{\left(h_{eff} + z_t + h_s - 0.5h_c\right)} \\ \dfrac{V_{Ed} s - \Delta N_{cs,Rd} (z_t + h_s - 0.5h_c)}{h_{eff}} \end{cases} \tag{10}$$

$$M_{wp,Rd} = \left(s_0^2 t_w / 6\right) \left(f_y / \gamma_{M0}\right) \geq M_{wp,Ed} = \left(V_{Ed} - 2V_{b,Ed}\right) s/2 + V_{wp,Ed} e_0 - \Delta N_{cs} (z_t + h_s - 0.5h_c)/2 \tag{11}$$

where s_0 is the edge-to-edge spacing of adjacent openings; s is the center-to-center spacing of adjacent openings; e_0 is the eccentricity of center of opening above the centerline of the web; $\Delta N_{cs,Rd}$ is the increase in compression resistance of the slab due to shear connectors between the centerlines of the openings.

The design forces for circular openings are shown in

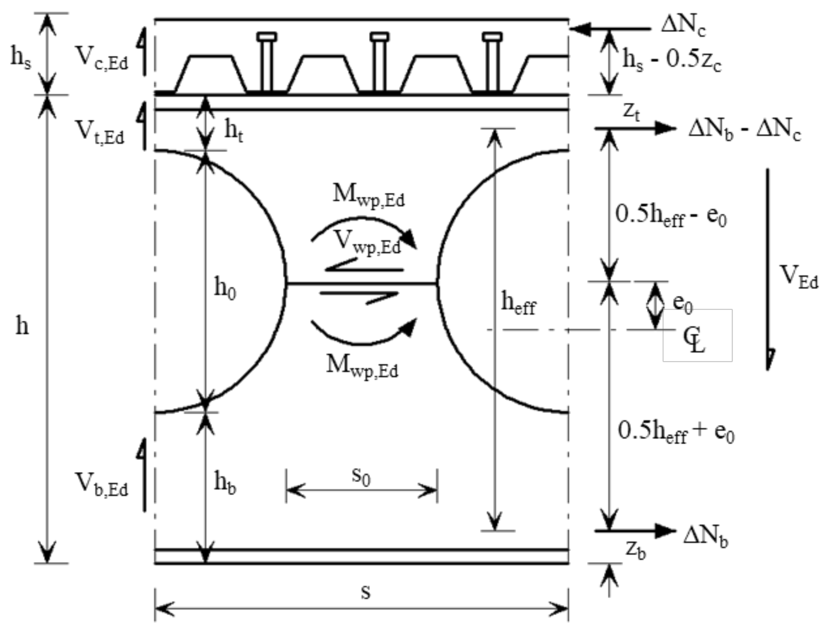

Figure 5. Forces in web-post between circular openings [4]

Because of the presence of the compression force, the web-post must be checked the buckling resistance. According to SCI P355, the buckling length of web-post is $l_w = 0.5\sqrt{\left(s_0^2 + h_0^2\right)}$. The buckling resistance is determined from buckling curve "*b*" based on EN 1993-1-1 Clause 6.3.1.2 [11]:

$$N_{wp,Rd} = \chi \frac{s_0 t_w f_y}{\gamma_{M1}} \geq N_{wp,Ed} = V_{wp,Ed} + \left|M_{wp,Ed}\right| / (h_0/2) \tag{12}$$

2.5. Serviceability limit state (SLS)

The total deflection of CCB must take account of the additional deflection due to the loss of flexural stiffness at the openings, the additional deflection due to Vierendeel bending effects and the reduction in overall stiffness. For a CCB, the total additional deflection may be calculated approximately from:

$$\delta_{add} = 0.47 n_0 \left(h_0/h\right)^2 (h/L) \tag{13}$$

in which n_0 is the number of openings along the beam; h is the depth of steel beam; L is the beam's span.

2.6. Geometric limitations

Table 3. Geometric limitations

Max. depth of opening	$h_0 \leq 0.8h$	Proposed by Lawson [4]
Min. depth of Tees	$h_T \geq t_f + 30mm$	
Max. ratio of depth of Tees	$0.5 \leq h_b/h_t \leq 3$	
Min. width of web-post	Low shear zone: $s_0 \geq 0.3h_0$ High shear zone: $s_0 \geq 0.4h_0$	
Min. width of end-post	$s_e \geq 0.5d_0$	
Spacing and depth of opening	$1.08 \leq s/h_0 \leq 1.5$ and $1.25 \leq h/h_0 \leq 1.75$	Proposed by Ward [3]

3. Design procedure

The presence of web openings introduces many additional failure modes which are not detected in normal beams. Design checks on the web posts and Tee sections are required. Additionally, shear deformations with the top and bottom Tees in the beams can be significant, thereby increasing the difficulty of deflection analysis. Based on design theory as mentioned above, a simplified design procedure is proposed and presented in flowchart as shown in Fig. 6.

4. Parametric study

SCI P100 [3] and SCI P355 [4] presented different geometric limitations for CCB. In addition, there is not any recommendation for the eccentricity of openings. It causes the difficulty in preliminary sizing of members. A parametric study is carried out to investigate the influence of the cellular beam geometry to ultimate load and failure mode of CCB. In total, 36 specimens of cellular composite beam with different dimensions of openings are analyzed. The geometrical characteristics of the investigated CCBs are shown in Fig. 7. The label of specimens is CCB/A/B/C in which: A is the ratio of diameter of openings to the total depth of steel beam (h_0/h), B is the ratio of spacing to diameter of openings (s/h_0) and C is the eccentricity of the center of openings above the centerline of the web e_0.

Constant data of all specimens: beam's span $L = 10,000$ mm; spacing of beams $B = 3,000$ mm; steel beam H550 × 200 × 10 × 12 grade S235; composite slab 120 mm thickness with concrete class C25/30; depth of decking profile $h_p = 60$ mm; headed stud connectors with diameter $d_s = 19$ mm; height $h_{sc} = 100$ mm; number of studs per rib $n_r = 02$; super dead load SDL = 1.5 kN/m^2; imposed load $LL = 3.5$ kN/m^2.

The results of the parametric study are summarized in Table 4. From this table, it can be noted that:

- The limit state of CCB is mostly global bending.

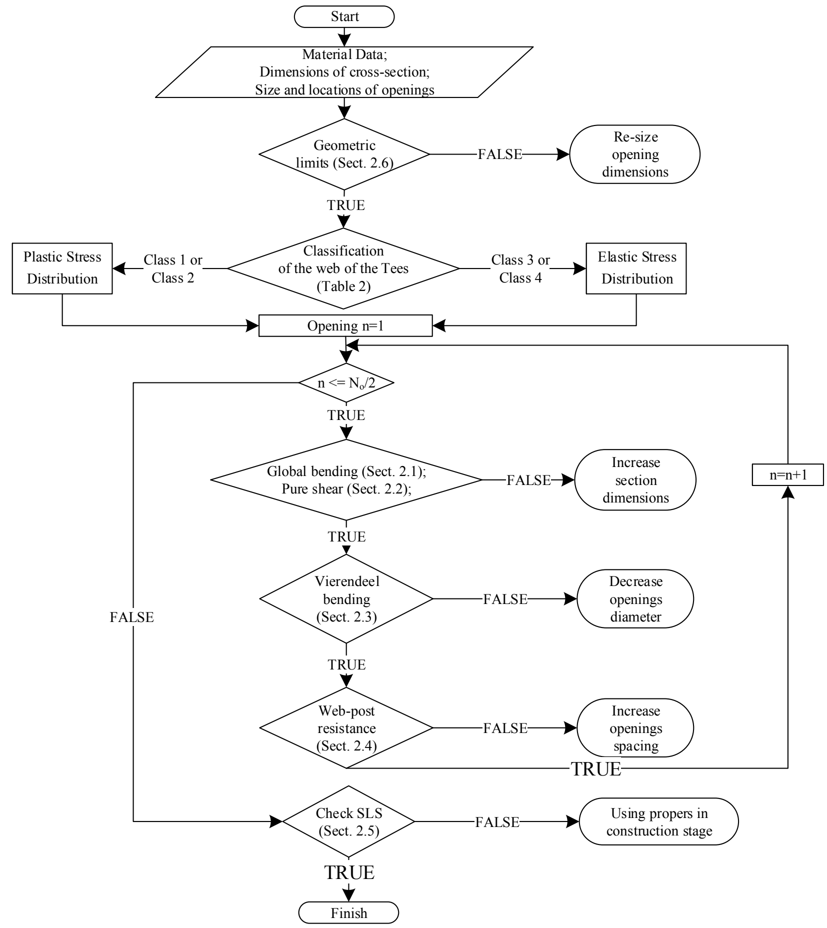

Figure 6. Flowchart of design procedure for CCB

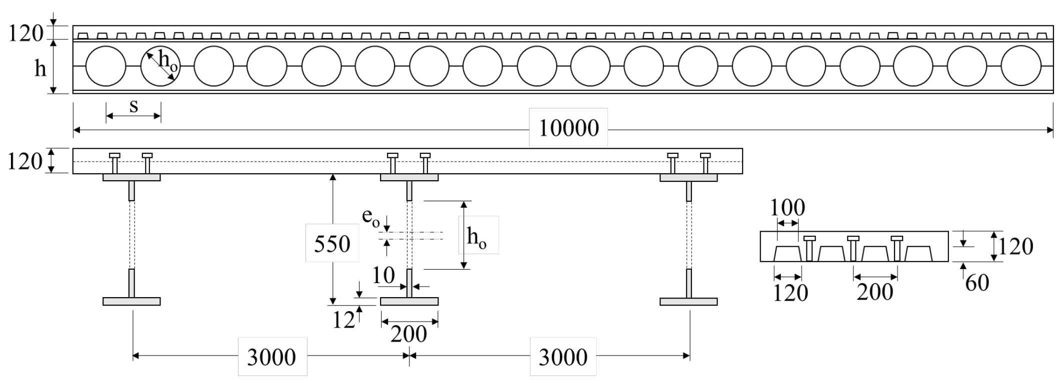

Figure 7. Geometrical characteristics of investigated CCBs

- Serviceability limit state is guaranteed in all specimens. It can be noticed that deflection is not the limit state that governed the design because of the greatly moment of inertia of composite section.
- Theoretically, when using the eccentricity of the openings, the area of bottom Tee is increased and the global bending resistance is increased accordingly. But the results in Table 4 show that: the

global bending resistance is slightly increased; meanwhile, the shear force at web-post is significantly increased. Therefore, it can be seen that: using the eccentricity of the openings is not effective in improving $M_{0,Rd}$.

Table 4. Flowchart of design procedure for CCB

Specimen	h_0 (mm) (h_0/h)	s (mm) (s/h_0)	e_0 (mm)	Utilization ratio (%)	Critical limit state	Check
CCB/0.6/1.3/0	330 (0.6)	429 (1.3)	0	80	Global bending	Adequate
CCB/0.6/1.3/10			10	81	Web-post shear	
CCB/0.6/1.3/20			20	81	Web-post shear	
CCB/0.6/1.3/30			30	82	Web-post shear	
CCB/0.6/1.4/0	330 (0.6)	462 (1.4)	0	72	Global bending	
CCB/0.6/1.4/10			10	71	Global bending	
CCB/0.6/1.4/20			20	70	Global bending	
CCB/0.6/1.4/30			30	70	Global bending	
CCB/0.6/1.5/0	330 (0.6)	495 (1.5)	0	72	Global bending	
CCB/0.6/1.5/10			10	71	Global bending	
CCB/0.6/1.5/20			20	70	Global bending	
CCB/0.6/1.5/30			30	70	Global bending	
CCB/0.7/1.3/0	385 (0.7)	501 (1.3)	0	79	Web-post shear	
CCB/0.7/1.3/10			10	79	Web-post shear	
CCB/0.7/1.3/20			20	79	Web-post shear	
CCB/0.7/1.3/30			30	80	Web-post shear	
CCB/0.7/1.4/0	385 (0.7)	539 (1.4)	0	77	Global bending	
CCB/0.7/1.4/10			10	76	Global bending	
CCB/0.7/1.4/20			20	75	Global bending	
CCB/0.7/1.4/30			30	74	Global bending	
CCB/0.7/1.5/0	385 (0.7)	577 (1.5)	0	77	Global bending	
CCB/0.7/1.5/10			10	76	Global bending	
CCB/0.7/1.5/20			20	75	Global bending	
CCB/0.7/1.5/30			30	74	Global bending	
CCB/0.8/1.3/0	440 (0.8)	572 (1.3)	0	168	Vierendeel bending	Inadequate
CCB/0.8/1.3/10			10	167	Vierendeel bending	
CCB/0.8/1.3/20			20	-	Geometric limits	
CCB/0.8/1.3/30			30	-	Geometric limit	
CCB/0.8/1.3/0	440 (0.8)	616 (1.4)	0	172	Vierendeel bending	
CCB/0.8/1.4/10			10	171	Vierendeel bending	
CCB/0.8/1.4/20			20	-	Geometric limits	
CCB/0.8/1.4/30			30	-	Geometric limits	
CCB/0.8/1.5/0	440 (0.8)	660 (1.5)	0	169	Vierendeel bending	
CCB/0.8/1.5/10			10	167	Vierendeel bending	
CCB/0.8/1.5/20			20	-	Geometric limits	
CCB/0.8/1.5/30			30	-	Geometric limits	

- The optimal geometry for CCB is that with diameter of openings equals 0.6 times the total depth and spacing of adjacent openings is equal to 1.4 times the openings diameter.

- When the diameter of openings equals 0.7 times the total depth, the maximum utilization ratio is 80%. But when the diameter of opening reaches to 0.8 times the total depth, the utilization ratio exceeds 100% and the beam fails. Therefore, it is recommended that the diameter of openings should be less than or equal to approximatively 0.7 times the total depth.

5. Conclusion

A simplified design method for cellular composite beam based on EN 1994-1-1 was presented in this paper. A flowchart of design procedure for cellular composite beam was also provided. Engineers could apply the design procedure in practical design.

Finally, a parametric study of 36 specimens of composite cellular beam was conducted. The result shows that the use of composite cellular beam is efficient when the openings diameter equals from 0.6 to 0.7 times the total depth and the ratio of opening spacing to diameter ranges from 1.4 to 1.5. It is recommended that the ratio of opening diameter to total depth should not exceed 0.7.

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