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A NEW TYPE OF HOLLOW-SHALLOW STEEL AND CONCRETE COMPOSITE FLOOR BEAM

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Abstract

Recently in Vietnam, steel-concrete composite structures especially composite beams are widely constructed in high-rise buildings. To apply broader in construction field mainly in secondary beam systems, the new type of slim-floor composite beam is proposed to aim at reducing the cost, saving the raw material, and decreasing the overall floor depth for sustainable development orientation. This type of floor beam structure consists of built-up hollow-shallow steel beam mandatory connected with cast in situ concrete slab through the openings at both side of web along the beam. The shear connection level of composite beam is depended on not only the friction at the connected surface between hollow steel section and concrete but also the shear resistance of concrete dowels, which go through the openings. The paper deals with an innovative shape of cross-section and design philosophy of composite beam according to EN 1994-1-1.

Keywords: hollow-shallow section; slim-floor beams; shallow floor-beams; composite beams; floor-beam structures; composite structures.

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1. Introduction

In the building construction filed, the definition of "composite structure" is typically related to the use of structural steel and concrete worked together as a single structure. The aim is to archive the significant advantages of both materials and eliminate or at least reduce the weak points of each separate material. The benefit of applying composite structure in floor beam systems could be listed as higher moment resistance, greater bending stiffness, shorter and more effective in construction manner [1], besides the composite beam still has some weaknesses as low fire resistance, large beam-floor structure depth, more cost for headed-shear stud connectors and on-site construction. Therefore, since 1990, many types of shallow floor systems are invented to overcome such problems including the Slimflor [2–4], Asymmetric Slimflor Beams (ASBs) [2–4], Composite Slim Floor Beams (CoSFB) [5] presented by ArcelorMittal, DELTABEAM [2, 6] developed by Peikko Group, Ultra Shallow Floor Beam (USFB) [2, 3] presented by Westok and some shallow floor with different steel section e.g., iTECH [2, 7], TEC [8], SCSC [9], TT [10], NW [11] and RH [12]. Typically, the steel sections of these composite beams are partial embedded in concrete slab to reduce the total floor-beam height, increase the fire resistance and make use of concrete dowel connectors instead of headed-shear studs to increase shear connection level.

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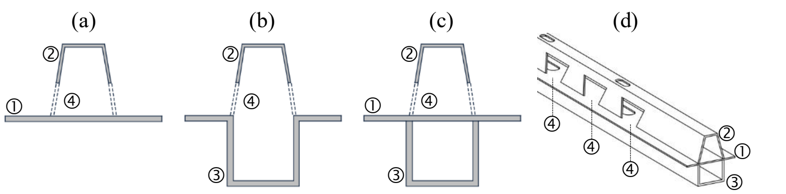
Recently in Vietnam, conventional steel-concrete composite structures especially composite beams are mostly constructed in high-rise buildings. To apply broader in construction field mainly as secondary beam systems in multi-storey building, the new concept of slim-floor composite beam is proposed to aim at reducing the overall cost, decreasing on-site works and minimizing the overall floor depth for sustainable development orientation. The raw material for steel beam could be saved by using tailor-made section that is generally based on load combinations. This type of floor beam structure consists of built-up hollow-shallow steel beam mandatory connected with cast in situ concrete slab through the openings at both side of web along the beam. The shear connection level of composite beam is depended on not only the friction at the connected surface between hollow steel section and concrete but also the shear resistance of concrete dowels, which go through the openings. The paper deals with an innovative shape of cross-section and design philosophy of composite beam according to EN 1994-1-1 [13].

2. Structural concept

For the domestic market, the proposed structural concept should be archived the key advantages of common shallow floor system involving headed-studs-free, fire resistance capable, combination either profiled steel decking or monolithic slab and satisfied the manufacturing steel beam and cast-in-place concrete process (Fig. 1).

Figure 1. The manufacturing steel beam and cast-in-place concrete process

Based on the mentioned general requirements of shallow floor system, the manufacturing steel beam and cast-in-place concrete process, the raw materials and also the manufacturing ability of national steel structure factories, the new shape of cross-section is illustrated in Fig. 2.



① Flat plate ② Trapezoidal shaped plate ③ U-shaped plate ④ Inverted trapezoid openings

Figure 2. The cross-section and 3D model of proposed steel beam

There are three possible options to compound the shallow-hollow section of steel beam: (a) welding cold-formed trapezoidal shape plate with flat plate; (b) welding cold-formed trapezoidal shape plate with cold-formed U-shaped plate and (c) both cold-formed trapezoidal shape plate and cold-formed U-shaped plate are welded to flat plate. In all options, the inverted trapezoidal openings go with metal decking trough are perforated along the web of hollow section in order to concrete could be filled inside the hollow steel section. At both sides, the wings that are belonged to the flat or U-shaped plate are extended to support the metal decking or semi-precast slabs. The new shallow-hollow floor system is created after concrete hardening. Then, the concrete parts or dowel connectors go through the openings play a role in longitudinal slip prevention like shear connectors. The composite action is identified through the bond, friction at the contact surface and longitudinal shear resistance of concrete dowels. The 3D model of new composite hollow-shallow floor beam is illustrated in Fig. 3.

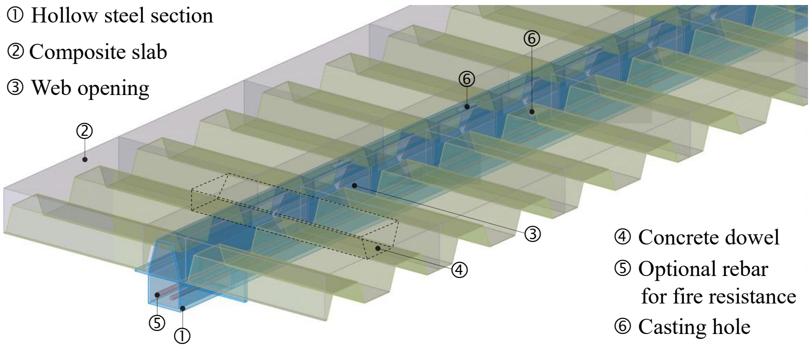


Figure 3. The 3D model of new composite hollow-shallow floor beam

3. Proposed design method in composite stage

The simply supported composite hollow-shallow floor beam is designed under simplified assumptions by Ultimate Limit State (ULS) and Serviceability Limit State (SLS), which are mentioned in EN 1994-1-1 [13]. For design composite beam under ULS and SLS, the plastic and elastic analysis are applied respectively. To obtain the maximum of cost effectiveness, the thickness of concrete above the deck ribs is selected so that the compression resultant force of concrete is greater than tension resultant force of structural steel. Therefore, in this paper the plastic moment resistance equations are only formulated in the case plastic neutral axis (P.N.A) in the concrete zone above the deck ribs. Moreover, the cross-sectional dimensions of hollow steel beam are selected so that the section classification is class 1 or 2. The geometrical dimension symbols of steel beam are presented in Fig. 4.

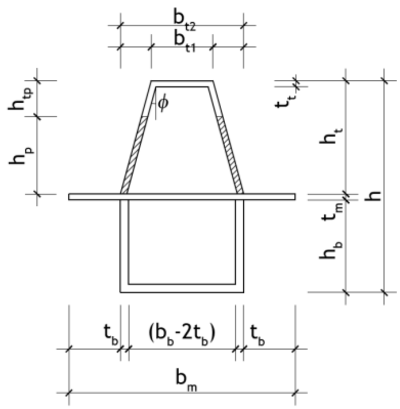


Figure 4. The geometrical dimension symbols of hollow-shallow steel beam

3.1. Theoretical strengths

To reduce the complexity of the formula establishment, the height of openings at both side and along the beam are equal to the decking height (h_p); the confinement effect of filled concrete inside the hollow steel section is ignored. All the common symbols are taken as description in the EN 1994-1-1 [13].

The effective breadth of slab (b_{eff}) of Slimflor type was not mentioned in the design norm [13]. In the guide of design and construction of composite slabs and beams by SCI [4], the authors addressed the determination method for b_{eff} which is basically the same as that for a conventional composite beam.

The formula to identify the value of b_{eff} for simple span L with studs free is mentioned in (1).

$$b_{eff} = \min(L/8; B_1/2) + \min(L/8; B_2/2) \tag{1}$$

where: B_1 and B_2 respectively are taken as the distance from the center to center of design beam and adjacent beams.

a. Case 1, the P.N.A lies within the concrete slab above the steel beam

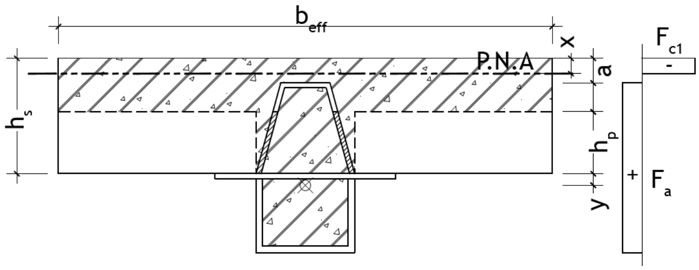


Figure 5. The P.N.A lies within the concrete slab above the steel beam

The compression resultant force of the concrete zone above the P.N.A, F_{c1} and the tension resultant force of the steel beam F_a are given as:

$$\begin{aligned} F_{c1} &= x \cdot b_{eff} \cdot (0.85 \cdot f_{ck}/\gamma_c) \\ F_a &= A_a \cdot \left(f_y \big/ \gamma_M \right) \end{aligned} \tag{2}$$

Based on the force equilibrium in horizontal, the depth of P.N.A from the top fiber of composite section x is obtained by:

$$x = \frac{A_a \cdot \left(f_y \big/ \gamma_M \right)}{b_{eff} \cdot (0.85 \cdot f_{ck}/\gamma_c)} \leq a \tag{3}$$

Taking the moment about the center of compression zone, the plastic moment resistance is taken:

$$M^+_{pl,Rd} = A_a \cdot \left(f_y \big/ \gamma_M \right) \cdot \left(y + \frac{t_m}{2} + h_s - \frac{x}{2} \right) \tag{4}$$

b. Case 2, the P.N.A lies within the top flange of steel beam

In this case, a part of the upper flange of the hollow steel section is under compression and the compression resultant force is called F_{a1}. The compression resultant force of the concrete above the steel section and the tension resultant force of the rest area of steel section respectively are given as F_c and F_{a2}.

$$F_{al} = b_{t1} \cdot (x - a) \cdot \frac{f_y}{\gamma_M} \text{ and } F_c = a \cdot b_{eff} \cdot \frac{0.85 \cdot f_{ck}}{\gamma_c} \tag{5}$$

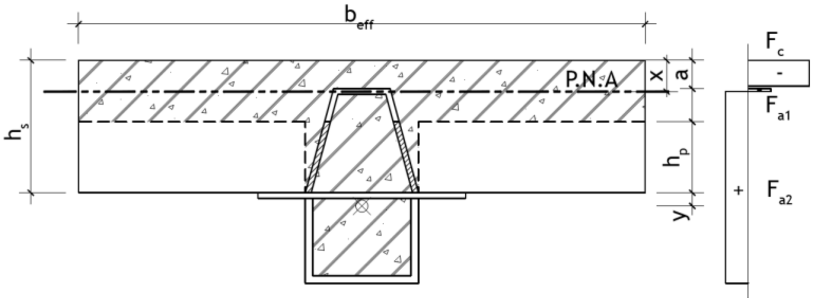


Figure 6. The P.N.A lies within the concrete slab above the steel beam

Equating tensile and compressive force and plus the value F_{a1} in both sides:

$$a \cdot b_{eff} \cdot \frac{0.85 \cdot f_{ck}}{\gamma_c} + 2 \cdot b_{t1} \cdot (x - a) \cdot \frac{f_y}{\gamma_M} = F_a \tag{6}$$

The distance x from top of composite section to P.N.A is obtained by:

$$x = \frac{(F_a - F_c) \cdot \gamma_M}{2 \cdot b_{t1} \cdot f_y} + a \tag{7}$$

The plastic moment resistance is given by:

$$M^+_{pl,Rd} = A_a \cdot \frac{f_y}{\gamma_M} \cdot \left(y + \frac{t_m}{2} + h_s - \frac{a}{2}\right) - 2 \cdot b_{t1} \cdot (x - a) \cdot \frac{f_y}{\gamma_M} \cdot \left(x - \frac{a}{2}\right) \tag{8}$$

c. Case 3, the P.N.A lies within the web of steel beam and above the deck rib

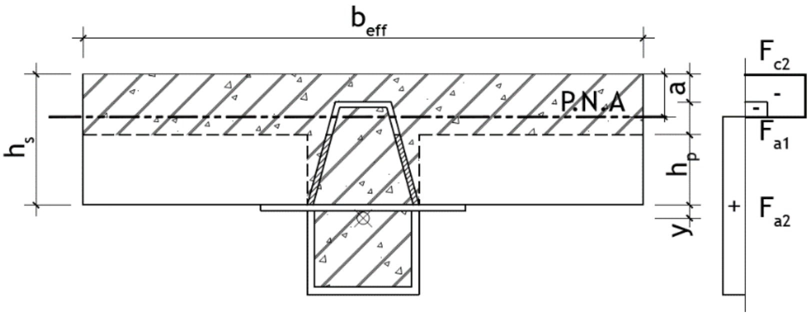


Figure 7. The P.N.A lies within the concrete slab above the deck rib

Not only the upper flange but also parts of web are under compression. Similar to case 2, the resultant force of compression and tension are:

$$\begin{aligned} F_{c2} &= 0.85 \cdot x \cdot b_{eff} \cdot (f_{ck}/\gamma_c) \\ F_{a1} &= ((b_{t1} - 2 \cdot t_t) + 2 \cdot (x - a)/\cos\phi) \cdot t_t \cdot \left(f_y / \gamma_M\right) \end{aligned} \tag{9}$$

The distance x from top of composite section to P.N.A is obtained by:

$$x = \frac{F_a - \dfrac{2 \cdot t_t \cdot f_y}{\gamma_M} \cdot \left(b_{t1} - 2 \cdot t_t - \dfrac{2 \cdot a}{\cos\phi}\right)}{\left(\dfrac{0.85 \cdot b_{eff} \cdot f_{ck}}{\gamma_c} + \dfrac{4 \cdot t_t \cdot f_y}{\cos\phi \cdot \gamma_M}\right)} \tag{10}$$

The plastic moment resistance is:

$$\begin{aligned}M^{+}_{pl,Rd} &= (b_b - 2\cdot t_b)\cdot\frac{f_y}{\gamma_M}\cdot\left(h - \frac{t_b}{2} + a - \frac{x}{2}\right) + 2\cdot h_b\cdot t_b\cdot\frac{f_y}{\gamma_M}\cdot\left(\frac{h_b}{2} + t_m + h_s - \frac{x}{2}\right)\\ &+ b_m\cdot t_m\cdot\frac{f_y}{\gamma_M}\cdot\left(\frac{t_m}{2} + h_s - \frac{x}{2}\right) + \frac{2\cdot t_b}{\cos\phi}\cdot\left(h_t + a + h_p - x\right)\cdot\frac{f_y}{\gamma_M}\cdot\left(\frac{h_t + a + h_p}{2}\right)\\ &- \frac{2\cdot t_t}{\cos\phi}\cdot(x-a)\cdot\frac{f_y}{\gamma_M}\cdot\left(\frac{a}{2}\right) - (b_{t1} - t_t)\cdot t_t\cdot\frac{f_y}{\gamma_M}\cdot\left(t_t + a - \frac{x}{2}\right)\end{aligned} \tag{11}$$

d. Vertical shear strength

Vertical shear is supposed that resisted by the only hollow steel beam, in which the web plays the main shear role. The vertical shear resistance is approximation as:

$$V_{pl,Rd} \approx 2\cdot\left(h_t - h_p\right)\cdot t_t/\cos\phi + 2\cdot h_b\cdot t_b\cdot\frac{f_y}{\sqrt{3}\cdot\gamma_M} \tag{12}$$

3.2. Bond and longitudinal shear resistance

In the EN 1994-1-1 [13], the bond strength (f_b) between structural steel and concrete is only mentioned in composite columns. It ranges from 0.2 MPa to 0.55 MPa for each type of composite column. In the report of TEC [8], the bond strength is adopted as 0.60 MPa. The bonds area is conservative taken as the outside area of top part which is embedded in the concrete slab excluding the openings area.

$$V_{Rd,bo} = \left(b_{t1}\cdot L + 2\cdot\left(\frac{h_t\cdot L}{\cos\phi} - n_o\cdot h_p\cdot\left(\frac{h_{p1} + h_{p2}}{2}\right)\right)\right)\cdot\frac{f_b}{\gamma_{V_L}} \tag{13}$$

where: n_o, h_{p1} and h_{p2} - respectively total number of opening at one web along the beam, big base and small base of trapezoidal opening. γ_{V_L} - partial safety factor for longitudinal shear.

The longitudinal shear strength of concrete dowel without rebars is depended on compressive cylinder strength (f_{ck}) of concrete as well as dimensions, shape and number of openings. In [14], many formulas are summarized and presented to evaluate the predicted longitudinal shear strength of only circular perfobond shear connector. For the inverted trapezoidal concrete dowel, the formula to determine the bearing strength is taken as mention in [8]:

$$V_{Rd,be} = 2\cdot n_0\cdot A_{be}\cdot\frac{(2\cdot 0.85\cdot f_{ck})}{\gamma_{V_L}};A_{be} = t_t\cdot\sqrt{\left(\frac{h_{p1} - h_{p2}}{2}\right)^2 + h_p^2} \tag{14}$$

The degree of shear connection is identified as:

$$\eta = \frac{\min\left[A_a\cdot\left(f_y/\gamma_M\right);0.85\cdot\left(h_s - h_p\right)\cdot b_{eff}\cdot(f_{ck}/\gamma_c)\right]}{2\cdot(V_{Rd,bo} + V_{Rd,be})} \le 1 \tag{15}$$

3.3. Partial shear connection

If $\eta < 1$ then the connection between slab and hollow steel beam is partial shear connection. The reduced moment resistance is:

$$M^{Red}_{Pl,Rd} = M_{a,pl,Rd} + \eta\cdot\left(M_{pl,Rd} - M_{a,pl,Rd}\right) \le M_{pl,Rd} \tag{16}$$

3.4. Bending stiffness

Coordinate center of composite hollow-shallow floor beam with hollow steel cross-section area (A_a) and rectangular ($h_c \cdot b_{eff}$) concrete slab is given by:

$$y_{El} = \frac{\left(h_c \cdot b_{eff} \big/ n\right) \cdot \left(h_c/2 + h_p + t_m/2 - y\right)}{\left(h_c \cdot b_{eff} \big/ n\right) + A_a}; \; n = \frac{E_a}{2 \cdot E_{cm}} \tag{17}$$

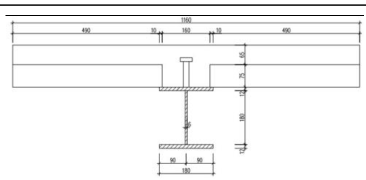
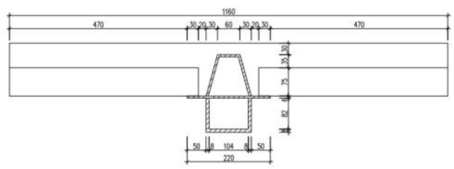
The moment of inertia I_1 of composite hollow-shallow floor beam in elastic is:

$$I_1 = I_a + A_a \cdot y_{El}^2 + \frac{b_{eff} \cdot h_c^3}{12 \cdot n''} + \frac{h_c \cdot b_{eff}}{n''} \cdot \left(\frac{h_c}{2} + h_p + \frac{t_m}{2} - y - y_{El}\right)^2 \tag{18}$$

4. Comparison to conventional composite beam

An example is calculated to evaluate new composite hollow-shallow floor beam with conventional composite beam on their performance. In this case, the criterion is the equivalent of structural steel area. Both types are simply supported composite beam with effective width of concrete slab is 1160 mm; slab thickness is 140 mm, the concrete above the deck ribs is 65 mm. Metal deck is used JFE QL00-75-12, deck height is 75 mm, thickness is 1.2 mm, open trough profiles with trapezoidal shape, big base and small base respectively are 180 mm and 120 mm, center to center distance of ribs is

Table 1. The brief calculation results

Info.	Conventional composite beam	New composite hollow-shallow floor beam
Cross-section		
Shear connector	20 Studs, d = 19 mm, h = 115 mm, f_u = 450 MPa	19 inverted trapzoidal openings
Total height	344 (mm)	236 (mm)
Area	Net: 5400 (mm^2)	Gross: 5248; Opening: 933; Net: 4315 (mm^2)
Self-weight	0.424 (kN/m)	0.378 (kN/m)
I_a	42,780,960 (mm^4)	17,536,360 (mm^4)
I_1	183,537,323 (mm^4)	53,463,011 (mm^4)
$M_{a,el,Rd}$	109.8 (kN.m)	56.9 (kN.m)
$M_{a,pl,Rd}$	121.3 (kN.m)	68.6 (kN.m)
$M_{pl,Rd}$	281.4 (kN.m)	154.4 (kN.m)
η	0.45	0.51
$M_{pl,Rd}^{Red}$	192.9 (kN.m)	112.6 (kN.m)
q_{Rd}^{ULS}	42.9 (kN/m)	25.0 (kN/m)

I: moment of inertia; $M_{a,el,Rd}$ and $M_{a,pl,Rd}$: elastic and plastic moment resistance of hollow-steel section.

300 mm. Structures are used concrete C25/30 and structural steel grade S275. The brief calculation results of both conventional and new hollow-shallow floor composite beam are shown in Table 1 and reality construction photo is illustrated in Fig. 8.

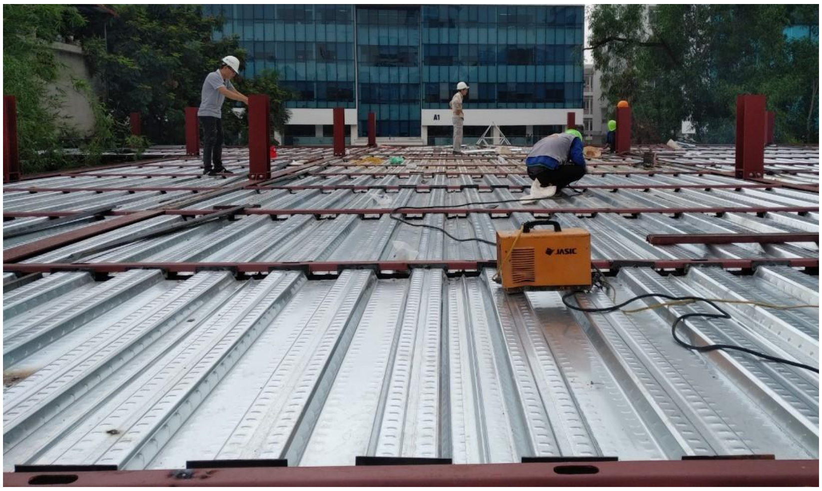


Figure 8. Illustration of construction in A2 building - NUCE campus

The degree of shear connection of both type of composite is decided by the arrangement of headed studs and perforated webs of beam. The moment resistance of proposed hollow-shallow composite beam could be bigger if the shear connection level is improved. In [8], evidently the longitudinal shear strength is just taken the bearing strength component. Actually, based on the pushout test results for the equivalent shape of concrete dowel [15], the longitudinal shear resistance has not only bearing but also splitting component of dowel. With the 50×90×70 mm trapezoidal opening, the test results indicate the longitudinal shear for each dowel is 42.2 kN compared to the value 16.5 kN of Eq. (14). If longitudinal shear strength is based on the test, then the composite action will be full shear connection, so there will be no reduction for plastic moment resistance.

5. Conclusions

A new concept of hollow-shallow steel and concrete composite floor beam and its design method is presented in this paper. Considerable advantages of proposed concept are reducing the total depth of floor beam structure, saving the steel material and making use of concrete parts go through the perforated webs performed as connectors. A comparison of theoretical design to conventional composite beam has been implemented. The results showed that with 31.4% decrease in height, 25.1% saving in weight, shear studs free, the plastic moment resistance is reduced by 41.6%, however distributed load bearing of the beam still reaches 25 kN/m as loads in normal floor beam systems. The degree of shear connection of new composite beam concept is 13.3% greater; with further series of pushout test, the authors could evaluate exactly the longitudinal shear behavior of trapezoidal concrete connectors and provide formula to identify the shear strength more accurate than Eq. (14) [8].

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References

[1] Duc, H. N., Tuan, V. A., Dat, N. T. (2018). Behaviour and push-out test of concrete dowel connectors for longitudinal shear in shallow-hollow composite beams. *Journal of Science and Technology in Civil Engineering (STCE) - HUCE*, 12(5):1–9.

[2] Ahmed, I. M., Tsavdaridis, K. D. (2019). The evolution of composite flooring systems: applications, testing, modelling and eurocode design approaches. *Journal of Constructional Steel Research*, 155:286–300.

[3] Hicks, S. (2002). Trends in modern floor construction. *Structural Engineer*, 80(21):22–24.

[4] Rackham, J. W., Couchman, G. H., Hicks, S. J. (2009). Composite slabs and beams using steel decking: best practice for design and construction. *The Metal Cladding & Roofing Manufacturers Association*.

[5] Hechler, O., Braun, M., Hauf, G., Kuhlmann, U. (2011). COSFB - The composite slim-floor beam. In *Eurosteel 2011: 6th European Conference on Steel and Composite Structures: Research, Design, Construction*, Budapest, Hungary.

[6] Peikko Group (2014). *DELTABEAM Composite Beam - Technical Manual*. Peikko, Lahti, Finland.

[7] Ju, Y.-K., Chun, S.-C., Kim, D.-Y., Kim, D.-H., Kim, S.-D., Chung, K.-R. (2003). *Structural Performance of I-tech Composite Beam Steel with Web Openings*.

[8] Ju, Y. K., Chun, S.-C., Kim, S.-D. (2009). Flexural test of a composite beam using asymmetric steel section with web openings. *Journal of Structural Engineering*, 135(4):448–458.

[9] Juen, L., Fink, J. (2011). Innovative composite deck slab for railway bridges - Technology, fabrication, laboratory tests and plastic load resistance estimation. In *Eurosteel 2011: 6th European Conference on Steel and Composite Structures: Research, Design, Construction*, Budapest, Hungary, 1989–1994.

[10] Derysz, J., Lewinski, P. M., Wiech, P. P. (2017). New concept of composite steel-reinforced concrete floor slab in the light of computational model and experimental research. *Procedia Engineering*, 193:168–175.

[11] Choi, Y.-C., Choi, D.-S., Park, K.-S., Lee, K.-S. (2020). Flexural Performance Evaluation of Novel Wide Long-Span Composite Beams Used to Construct Lower Parking Structures. *Sustainability*, 12(1):98.

[12] Hoa, N. D., Tuan, V. A. (2016). Design of steel and concrete composite beam using rectangular hollow section steel beam. In *SDCE-Sustainable Development in Civil Engineering*, 170–176.

[13] EN 1994-1-1 (2005). *Eurocode 4. Design of composite steel and concrete structures. General rules and rules for buildings. Part 1-1: General rules and rules for buildings*. British Standards Institution.

[14] Kang, J.-Y., Jung, W.-T. (2015). Evaluation of Shear Strength of Perfobond Rib in Ultra High Performance Concrete. *Journal of the Korea Academia-industrial Cooperation Society*, 16(7):5015–5020.

[15] Han, N.-D., Vu, A.-T., Nguyen, D.-H., Nguyen, T.-K., Nguyen, V.-C. (2021). Experimental Study on Shear Strength and Failure Mechanisms of Concrete Dowel in Shallow-Hollow Composite Beam. In *CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure*, Springer.