Composite slim floor beams with innovative shear connections

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An innovative form of slim floor beams is proposed in which the shear connection is formed by combining the concrete passing through the web openings with a steel tie-bar element. A numerical study was conducted to evaluate the flexural behaviour of these composite shallow cellular beams. The force transferring mechanism, load-bearing capacity and failure patterns of the shear connections were also evaluated. Two different configurations of shear connection were designed and a parametric study was carried out to determine the parameters likely to influence their performance. The findings were incorporated with bending and push-out test results to develop design methods for this form of shear connection. A tentative design procedure for the composite shallow cellular beams is proposed.

Notation

A_c	cross-sectional area of infill concrete (area of concrete in tensile splitting)
A_s	cross-sectional area of structural steel beam
A_{st}	cross-sectional area of reinforcing tie-bar
B_b	width of bottom flange
B_{eff}	effective width of concrete slab
B_t	width of top flange
D	diameter of opening
D_c	concrete topping depth above top flange of steel beam
D_s	depth of concrete slab above profiled steel decking
D_{tb}	diameter of tie-bar
d	depth of concrete slab in compression
E_c	elastic modulus of concrete
E_s	elastic modulus of steel element
f_{ct}	concrete tensile strength
f_{cu}	concrete cube compressive strength
f_{sd}	design yield strength of reinforcing tie-bar
f_y	yield strength of steel web post
H_s	depth of steel section
H_t	overall depth of composite beam
h_D	height of web opening
I	second moment of inertia of composite section
I_{comp}	moment of inertia of the composite section
I_s	moment of inertia of structural steel beam section
L	span length
M	moment resistance of composite beam
N_i	number of shear connectors within a shear span
P_o	opening parameter
R_q	actual longitudinal shear resistance provided by shear connectors

R_{sh}	ultimate shear resistance of an individual shear connection
R_{sw}	shear resistance of steel web post
S	web opening spacing
S_b	depth of steel web base
S_y	static moment of beam section
t_b	thickness of bottom flange
t_t	thickness of top flange
t_w	thickness of steel web post
V	longitudinal shear force
w	length of steel web post
Y	distance between neutral axis of the composite section and the steel web post base
y_{ec}	depth of elastic neutral axis of composite section
y_s	depth of elastic neutral axis of steel beam section
α_e	modular ratio of the composite section ($= E_s/E_c$)
γ_s	partial safety factor for steel section ($= 1.25$)
$\sigma_{c,Rd}$	uniaxial compressive strength of concrete
σ_d	maximum design stress within steel beam

1. Introduction

In recent years, there has been increasing demand for buildings that are quick to construct, have large uninterrupted floor areas and are flexible in their intended final use. Modern design and construction techniques enable steel–concrete composite construction to satisfy such demands by producing structures that are competitive in terms of resistance and overall cost. The trend is towards the use of longer spans and lightweight floor systems, which has resulted in the development of various slim floor systems (e.g. Slimflor, Slimdek, asymmetric Slimflor

beams and ultra-shallow floor beams), likely being used in commercial and residential buildings, hospitals, schools and so on.

The composite shallow cellular floor beam (SCFB) is a generic term used to describe a type of composite slim floor construction in which the key feature is that steel beams with regularly spaced openings are contained within the concrete slab depth. This results in a flat appearance and offers important benefits in terms of cost, long spanning capabilities without (or with fewer) secondary beams, shallow floor depths, passages for building services, efficient fire resistance and so on (Hicks, 2003; Lawson *et al.*, 1997, 1999, 2006), as well as other advantages offered by conventional composite beam construction.

They can comprise precast units, hollow-core concrete slabs with or without a concrete topping or deeply profiled steel decking and cast-in-place concrete. The embedded steel beam can be fabricated by welding two highly asymmetric T-sections together along the web and forming regularly spaced openings,

or it can be obtained by welding three different steel plates with regularly spaced openings formed on the web post.

The use of composite slim floor systems requires comprehension of the behaviour of all the structural components, among which the shear forces transferring between the steel beam and the concrete slab are the most important aspect. In ordinary slim floor beams such as Slimflor, Slimdek and asymmetric Slimflor beams, shear transfer is only assumed by the bonding effect at the interface between the concrete and the steel beam. However, this adhesive strength has been found to be very limited and is prone to shear failure under small loads. An enhanced form of slim floor beam, called the composite shallow cellular slim floor beam, designed with an effective and innovative shear connection configuration is proposed. It consists of a row of regularly spaced openings preformed within the web post, which provide passage for the concrete cast-in-place. The infill concrete combines with the additional steel reinforcing bar to form a shear connection that is able to

Figure 1. Proposed shear connection system: (a) typical arrangement of shear connection with circular opening configuration; (b) circular opening shear connection; (c) clothoidal opening shear connection

transfer longitudinal shear forces between the concrete slab and the encased steel beam (Figure 1(a)).

Slim floor systems have been studied previously (Lawson *et al.*, 1997, 1999; Mullett, 1998) and experimental studies on integrated slim beams were conducted at Helsinki University of Technology (Bernuzzi *et al.*, 1995). Mullett (1992) proposed design guidance for Slimflor beams using hollow-core precast units, while Mullett and Lawson (1993) investigated the behaviour of slim floors as well as the shear transfer mechanism between the steel beam and the concrete slab. Wang *et al.* (2009) reported on an experimental investigation of the flexural behaviour of slim floor beams using deep decking. However, the mechanism of this integrated composite beam is not yet well understood and the roles that shear connections and shear transfer play in the overall behaviour of a composite slim floor have been overlooked.

Research into shear connection systems and composite action within slim floor systems is very rarely reported in the literature. Huo and D'Mello (2013) presented 24 full-scale push-out tests to investigate shear connections for shallow cellular beams, under direct longitudinal shear force.

The research reported in this paper combined the results of an experimental programme finite-element analysis (FEA) conducted on four full-scale SCFBs. The scope of the study was to investigate the load-bearing behaviour and the longitudinal shear transferring mechanism, and to provide benchmarks for the evaluation of the flexural performance and longitudinal shear resisting capacity in slim floor beam systems. A further aim was to develop a design method and pre-design tools for shallow cellular slim floor beams.

2. Description of the innovative shear connection

The enhanced form of the SCFB developed is capable of producing efficient shallow floor constructions with greater spanning capability and more significant load-bearing capacity. For this particular form of composite beam, a steel beam with regular openings along the steel web is embedded within the concrete floor. In addition, reinforcing steel bars pass through the middle of the web openings and are anchored within the ribs of the steel decking. The cast-in-place concrete passing through the web openings is able to combine with the reinforcing bars to produce an effective shear connection system, this being referred to as a 'concrete plug with tie-bar shear connection'.

Two different configurations of shear connections were devised and designed, representing different web opening geometries: circular opening and clothoidal opening shear connections. The circular opening configuration is cut from an asymmetric I-section steel beam, while the clothoidal opening is cut from an inverted T-section steel beam (Figures 1(b) and 1(c)).

3. Composite shallow cellular floor beam tests

Flexural load tests were carried out on both partially and fully encased composite SCFBs. The key parameters investigated were the configuration of the steel beam, the configuration of the web openings and the configuration of the concrete slab. Details of the flexural tests and the numerical analysis results have been presented elsewhere (Chen *et al.*, 2015; Limazie and Chen, 2016). The effectiveness of the SCFB with the proposed shear connection system was demonstrated. All specimens experienced significant ductile behaviour, effective load-bearing capacity and significant composite behaviour. The experimental and numerical investigations also revealed the shear transfer and failure mechanisms of the shear connections (Chen *et al.*, 2015; Limazie, 2015; Limazie and Chen, 2016).

4. Analytical procedures for design of the SCFB and the shear connection system

The experiments and numerical parametric studies previously conducted provided important and comprehensive information on the load-bearing behaviour, the shear resisting capacity and the overall behaviour of the shear connection system.

The results of these investigations showed that the longitudinal shear resisting capacity of the shear connection system is contributed to by a combination of the resistance of both the infill concrete element and the tie-bar element. The force transferring mechanism of the concrete plug with tie-bar shear connection was deduced and is illustrated in Figure 2. The ultimate shear resistance of the shear connection can be calculated from the summation of the concrete compressive capacity and the tensile strength provided by both the infill concrete and the ratio of embedded reinforcement (tie-bar). This is mathematically expressed as

$$1. \quad R_{sh} = 1.2(t_w h_D f_{cu}) + 2.1 A_c f_{ct} \left(1 + 13.5 \frac{E_s A_{st}}{E_c A_c} \right)$$

in which $A_{st} = \pi D_{tb}^2 / 4$.

The first part of Equation 1 represents the local compressive capacity of the shear connection and the second part represents the tensile splitting strength of the shear connection, combining the infill concrete and the tie-bar. A typical concrete plug with tie-bar element is illustrated in Figure 3(a).

To participate in the overall composite action, the shear connection should be designed with an optimum reinforcing ratio, expressed as

$$2. \quad A_{st} \geq \frac{0.2 R_{sh}}{f_{sd}}$$

Figure 2. Illustration of a typical force transfer mechanism in shear connection

Figure 3. Terminology of (a) typical concrete plug with tie-bar element and (b) geometry of steel section

The amount of shear connectors required to ensure full shear interaction within a shear span can be obtained from

$$3. \quad N_i = R_q / R_{sh}$$

where R_q , the actual longitudinal shear resistance provided by shear connectors, is determined as

$$4. \quad R_q = (\sigma_{c,Rd} B_{eff}) d$$

wherein $\sigma_{c,Rd}$ is the uniaxial compressive strength of concrete, B_{eff} is the effective width of the concrete slab and d is the depth of concrete slab in compression.

The available degree of shear connection along the composite beam can therefore be derived as

$$5. \quad \eta = R_q / R_c$$

in which R_c is the compressive resistance of concrete slab in full shear connection determined by the stress block method (Limazie and Chen, 2015).

Test results on 14 push-out specimens with circular openings (Huo and D'Mello, 2013) and 31 numerical simulation results

concerning various opening configurations (Limazie, 2015; Limazie and Chen, 2017) were used to calibrate and verify the method proposed in Equation 1. The comparisons are given in Tables 1 and 2. The average ratios of the calculated shear resistance to the experimental results and the FEA results were 0.99 and 0.76 respectively, indicating that the proposed

Table 1. Comparison of experimental shear resistance ($R_{sh,exp}$) from push-out tests (Huo and D'Mello, 2013) and analytical results ($R_{sh,calc}$) obtained using Equation 1

Specimen	f_{cu} : MPa	f_{ct} : MPa	A_c : mm ²	h_D : mm	t_w : mm	D_{tb} : mm	$R_{sh,calc}$: kN	$R_{sh,exp}$: kN	$R_{sh,calc}/R_{sh,exp}$
T1-B-N	55.6	4.53	31 416	200	9.9	—	429	362	1.18
T1-B-F	58.1	4.85	31 416	200	9.9	—	455	397	1.14
T5-1	35	3.21	17 671	150	8.6	—	173	226	0.76
T5-2	35	3.21	17 671	150	8.6	—	173	194	0.89
T5-3	32	2.9	17 671	150	8.6	—	157	182	0.86
T5-4	30	3.02	17 671	150	8.6	—	158	175	0.90
T2-A-N	54.5	4.54	17 671	150	8.6	2Ø12	426	309	1.37
T2-A-F	51.9	4.07	17 671	150	8.6	2Ø12	384	305	1.25
T2-B-N	54.5	4.54	31 416	200	9.9	2Ø12	584	390	1.45
T2-B-F	51.9	4.07	31 416	200	9.9	2Ø12	526	372	1.41
T6-1	29	2.85	17 671	150	8.6	1Ø16	259	391	0.66
T6-2	32	2.92	17 671	150	8.6	1Ø16	269	386	0.70
T6-3	28	2.49	17 671	150	8.6	1Ø16	230	327	0.70
T6-4	27	2.57	17 671	150	8.6	1Ø16	235	358	0.66
Average									0.99

Table 2. Comparison of shear resistance from FEA ($R_{sh,FEA}$) (Limazie, 2015; Limazie and Chen, 2017) and analytical results ($R_{sh,calc}$) obtained using Equation 1

Specimen	f_{cu} : N/mm ²	f_{ct} : N/mm ²	A_c : mm ²	h_D : mm	t_w : mm	D_{tb} : mm	$R_{sh,calc}$: kN	$R_{sh,FEA}$: kN	$R_{sh,calc}/R_{sh,FEA}$
CO-1	30	2.10	14 000	134	14	—	130	189	0.69
CO-2	30	2.10	8400	103.5	14	—	105	125	0.84
CO-3	30	2.10	4200	73.2	14	—	56	84	0.67
CL-C-1	30	2.10	14 000	124	14	—	124	180	0.69
CL-C-2	30	2.10	8400	96.5	14	—	99	127	0.78
CL-C-3	30	2.10	4200	68.5	14	—	81	95	0.85
CL-CE	30	2.10	14 000	100	14	—	112	154	0.73
CL-Z	30	2.10	14 000	100	14	—	117	165	0.71
CO-FC25	25	1.80	14 000	134	14	—	109	141	0.77
CO-FC30	30	2.10	14 000	134	14	—	130	189	0.69
CO-FC40	40	2.80	14 000	134	14	—	173	209	0.83
CO-FC50	50	3.50	14 000	134	14	—	215	302	0.72
CL-C-FC25	25	1.80	14 000	124	14	—	105	157	0.67
CL-C-FC30	30	2.10	14 000	124	14	—	125	180	0.69
CL-C-FC40	40	2.80	14 000	124	14	—	157	239	0.66
CL-C-FC50	50	3.50	14 000	124	14	—	207	296	0.70
CO-Tw10	30	2.10	14 000	134	10	—	110	151	0.73
CO-Tw14	30	2.10	14 000	134	14	—	130	189	0.69
CO-Tw20	30	2.10	14 000	134	20	—	159	265	0.60
CL-C-Tw10	30	2.10	14 000	124	10	—	106	127	0.84
CL-C-Tw14	30	2.10	14 000	124	14	—	124	180	0.69
CL-C-Tw20	30	2.10	14 000	124	20	—	151	221	0.69
CO-O-3+Ø8	30	2.10	4200	73.2	14	1Ø8	77	101	0.75
CO-O-3+Ø10	30	2.10	4200	73.2	14	1Ø10	88	113	0.78
CO-O-3+Ø12	30	2.10	4200	73.2	14	1Ø12	103	133	0.77
CO-O-3+Ø14	30	2.10	4200	73.2	14	1Ø14	120	144	0.83
CO-O-3+Ø16	30	2.10	4200	73.2	14	1Ø16	139	153	0.91
CO-O-3+Ø20	30	2.10	4200	73.2	14	1Ø20	186	162	1.14
CL-C-1+Ø8	30	2.10	14 000	124	14	1Ø8	145	199	0.73
CL-C-1+Ø12	30	2.10	14 000	124	14	1Ø12	171	252	0.68
CL-C-1+Ø16	30	2.10	14 000	124	14	1Ø16	208	297	0.70
Average									0.76

analytical method is reliable and accurate in predicting the longitudinal shear resistance of a concrete plug with tie-bar shear connection.

For the local composite action, the steel web post serves to introduce longitudinal shear forces into the infill concrete, leading to significant stresses within the steel part of the shear connection. The longitudinal shear resistance of the steel web post can be obtained from

$$6. \quad R_{sw} = 0.25 S t_w f_y$$

Based on detailed FEA and analytical calculations (Limazie, 2015; Limazie and Chen, 2017), the stress concentration and the maximum design stress within the steel beam part were derived, and can be divided into the stresses caused by the composite action within the opening from the longitudinal shear forces and the stresses caused by the bending moment and axial force, as illustrated in Figure 4. Therefore, the maximum design stress within the steel section part can be estimated using

$$7. \quad \sigma_d = 8.5 \left(\frac{V S_y}{I_w I} \right) + 1.5 \left(\frac{M}{I} Y \right) \leq \frac{f_y}{\gamma_s}$$

On the basis of this work, the following geometrical requirements are proposed for the purposes of economy and overall stability of the composite beam.

- The relationship between the depth of the opening (h_D) and the spacing between adjacent opening (S) should satisfy

$$8. \quad h_D = 0.6S$$

- The steel web post length (w) between two adjacent openings should satisfy

$$9. \quad w \geq 0.5h_D$$

Figure 4. Different action forces inducing stress concentration within a steel element with clothoidal opening shear connection

The depth of the steel web base (S_b , shown in Figure 3(a)) should not be less than 20 mm or less than two times the steel web thickness ($S_b \geq 2t_w$).

5. Design approach for determining flexural stiffness

The strain/stress distribution within the elastic state observed in tests (Chen *et al.*, 2015) revealed the following.

- (a) The stresses at the top fibre of the concrete slab within pure bending and along the slab width region were uniformly distributed.
- (b) The stresses recorded by strain gauges attached to the concrete slab along the slab depth were linear.
- (c) The stresses recorded on the structural steel beam and on the concrete slab, almost at the same position, behaved similarly and were almost identical, indicating that there were no slips between the two elements.
- (d) The stresses measured along the slab depth revealed that the stress of the concrete within the steel decking was very small and almost negligible.

All of these events were also observed during the FEA, confirming the load-bearing behaviour of the SCFB and the stress distribution during the loading process.

Based on the above observations, elastic theory with the plane section assumption and the mechanics of materials were used to implement a calculation method for the flexural stiffness of SCFB. It is recognised that the flexural stiffness of the composite beam would vary along the beam length, as the cross-section also varies from one section to another. However, the difference between considering the stiffness at the mid-span cross-section and the average stiffness along the beam length is relatively small. For simplicity, the method supposes the mid-span section stiffness as the stiffness of the entire composite beam section. The following assumptions were made in calculating the flexural stiffness of the composite floor beam.

- (a) The concrete slab section within the profiled steel decking does not participate in the load-bearing behaviour of the composite beam and is therefore ignored.
- (b) The reinforcing bars within the concrete slab and the steel decking are ignored.
- (c) In the elastic state, the steel beam and the compressive concrete remain plane and perfectly linear-elastic, and behave compositely without slips at their contact interface.

Using these principles and transformations, the flexural stiffness of the composite SCFB (G) can be expressed as

$$10. \quad G = E_s I_{comp}$$

where E_s is the elastic modulus of the steel beam and I_{comp} is the moment of inertia of the composite section, which can be obtained from

$$11. \quad I_{\text{comp}} = I_s + A_s(y_s - y_{\text{ec}})^2 + \frac{A_c D_s^2}{\alpha_e 12} + \frac{A_c}{\alpha_e} \left(\frac{D_s}{2} - D_c - y_{\text{ec}} \right)^2$$

in which A_c is the cross-sectional area of concrete slab.

The position of the neutral axis of the composite SCFB section can be calculated from

$$12. \quad y_{\text{ec}} = \left[A_s y_s + \frac{A_c}{\alpha_e} \left(\frac{D_s}{2} - D_c \right) \right] / \left(A_s + \frac{A_c}{\alpha_e} \right)$$

where α_e is the modular ratio of the composite section ($= E_s/E_c$), with E_s and E_c being the elastic modulus of steel and concrete, respectively.

The cross-sectional properties of the tested specimens are summarised in Table 3. The flexural stiffness calculated using Equation 10 is compared with the test values in Table 4, for different load levels in the elastic state. The difference between the calculated and test values was relatively small and thus the proposed calculation method can accurately predict the flexural characteristics of the shallow cellular composite beam.

6. Pre-design tools for shallow cellular composite slim floor beams

Differences in structural configurations will mean that significant changes need to be considered in the design and

construction of shallow cellular composite slim floors. The appropriateness of design guidance and checks for different stages (construction and normal-use stages) would thus be very important, but cumbersome.

Detailed design procedures for shallow cellular composite floors based on the stress block method have been established and have led to pre-design tables and figures that could be used for practical purposes. The pre-design tools mainly consist of tables and graphs giving the allowable loading capacity for a wide range of composite beam sections for spans of 3–10 m. The load-bearing capacities of both steel beams and composite sections were determined using the plastic analysis procedure (Limazie and Chen, 2015). Eight cases of shallow cellular composite slim floor beams were studied, and two different steel beam configurations were designed (the asymmetric I-section steel beam and the inverted T-section steel beam) with different opening sizes, different steel decking depth and different span length.

6.1 Pre-design tools for the structural steel beam

For both I- and T-sections, the size and spacing of the openings are governed by the longitudinal shear resistance of the composite section, as detailed in previous sections. However, some specific limitations are proposed here and should be considered in the selection and checking of the steel section. To propose realistic and economic solutions, steel sections should be selected ensuring that they approximately fulfil the condition

$$13. \quad L/25 \leq H_s \leq L/30$$

Table 3. Geometrical characteristics and calculated moment of inertia of the beam specimens

Specimen	B_{eff}	H_t	D_c	B_b	B_t	t_b	t_t	t_w	H_s	α_e	y_{ec}	I_{comp} : mm ⁴ ^a
SCFB 1	1000	200	38	250	150	14	10	10	162	5.81	37.47	7.97×10^7
SCFB 2	1000	162	—	250	150	14	10	10	162	5.89	58.46	4.97×10^7
SCFB 3	1000	200	38	250	150	14	10	10	152	5.87	38.97	7.04×10^7
SCFB 4	1000	152	—	250	150	14	10	10	152	5.67	60.59	3.96×10^7

^aCalculated moment of inertia

Table 4. Comparison of flexural stiffness between analytical and experimental results

Specimen	Calculated value		Experimental value		
	y_{ec} (mm)	$G (= E_s I_{\text{comp}})$	$G (= E_s I_{\text{comp}})$ ^a		
			Span/500	Span/360	Span/200
SCFB 1	37.47	1.5×10^{13}	1.37×10^{13}	1.42×10^{13}	1.28×10^{13}
SCFB 2	58.46	9.3×10^{12}	9.45×10^{12}	9.37×10^{12}	9.14×10^{12}
SCFB 3	38.97	1.3×10^{13}	1.37×10^{13}	1.32×10^{13}	1.07×10^{13}
SCFB 4	60.59	7.4×10^{12}	6.90×10^{12}	6.61×10^{12}	5.99×10^{12}

^aFlexural stiffness derived for mid-span deflection of span/500, span/360 and span/200

where L is the span length and H_s is the depth of the steel section. Here, the span length was varied from 3 m to 10 m in increments of 1 m.

6.1.1 Geometrical conditions

The opening diameter (D) and the height of the steel beam section (H_s) are chosen as follows.

- The opening parameter (P_o) should be limited to a maximum value of 6.0, as

$$14. \quad P_o = 1 + \frac{6D}{H_s}$$

- The clear spacing of openings should fulfil the condition

$$15. \quad S \geq 1.2D$$

- The web post length (w) should satisfy the condition

$$16. \quad w \geq 2t_w$$

where t_w is the web post thickness.

In the pre-design example (tables and graphs, Limazie (2015)), the overall depth of the selected steel beams was varied from a minimum of 150 mm to a maximum of 280 mm. The opening diameter was varied from a minimum of 80 mm to a maximum of 180 mm.

6.1.2 Profiles and steel grades

The steel beam sections were assumed to be obtained by welding different steel plates to form the desired sections (built-up section). For convenience, the steel beams were labelled as ICB (ICB150–ICB280) and TCB (TCB150–TCB280) for asymmetric I-sections and inverted T-sections respectively. ICB150 and TCB150 refer to a composite section with a 150 mm height asymmetric I-section and inverted T-section respectively. Only steel grade Q345 was adopted in this pre-design, with a nominal design strength of 345 N/mm² for an element of thickness $t_w \leq 16$ mm or 335 N/mm² for an element of thickness $t_w > 16$ mm; the elastic modulus was considered equal to 206 000 N/mm². The layout of the pre-design calculations (loading capacity and deflection capacity) follows the format of plastic analysis principles (Limazie and Chen, 2015).

6.2 Pre-design tools for shallow cellular composite slim floor beams

Calculations for the composite SCFBs are similar to those performed for cellular steel beams except that the composite action significantly increases the loading capacity and deflection capacity of the composite beams. The layout of the pre-design calculations for the composite section also follows

the format of the plastic analysis principle presented by Limazie and Chen (2015).

The pre-design tools for composite SCFBs with the asymmetric I-section profiles and the inverted T-section profiles are presented in tables and graphs. They provide the loading and deflection capacities of the composite beams for various span lengths. ICB3–ICB10 refer to composite beams having respectively 150–280 mm high steel I-sections, while TCB3–TCB10 refer to composite beams using T-sections of the same height. The load capacity is taken as the uniform load distributed over the beam span. Therefore, it should be noted that the load and deflection capacities are mainly influenced by the span length.

7. Conclusions

The composite shallow cellular floor beam (SCFB) is a new form of composite floor system that offers many advantages and can be effectively used in modern building construction. An enhanced design for SCFBs with an innovative shear connection formed by combining tie-bar elements with infill concrete passing through the steel web openings has been presented. Analytical design procedures for ‘concrete plug with tie-bar’ type shear connections and the overall shallow cellular composite slim floor beam have been presented and the results were validated against experimental tests and numerical analyses. Design guidance for the composite SCFBs, which offers simple and reliable tools for the pre-design of composite SCFBs, has also been proposed.

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REFERENCES

- Bernuzzi C, Gadotti F and Zandonini R (1995) Semi-continuity in slim floor steel-concrete composite systems. In *Proceedings of the 1995 1st European Conference on Steel Structures, EUROSTEEL'95, Athens, Greece*. Balkema, Rotterdam, the Netherlands, pp. 287–294.
- Chen SM, Limazie T and Tan JY (2015) Flexural behavior of shallow cellular composite floor beams with innovative shear connections. *Journal of Constructional Steel Research* **106**(1): 329–346.
- Hicks S (2003) Current trends in modern floor construction. *Magazine of the British Constructional Steelwork Association* **11**(1): 32–33.
- Huo BY and D'Mello CA (2013) Shear transfer mechanisms in composite shallow cellular floor beams. *Journal of Constructional Steel Research* **88**(1): 191–205.

- Lawson RM, Mullett DL and Rackham JW (1997) *Design of Asymmetric Slimflor Beams Using Deep Composite Decking*. The Steel Construction Institute, Ascot, UK, Publication P175.
- Lawson RM, Bode H, Brekelmans JWPM, Wright PJ and Mullett DL (1999) 'Slimflor' and 'Slimdek' construction: European developments. *Journal of Structural Engineering* **77**(8): 22–30.
- Lawson RM, Lim J, Hicks SJ and Simms WI (2006) Design of composite asymmetric cellular beams and beams with large web openings. *Journal of Constructional Steel Research* **62**(6): 614–629.
- Limazie T (2015) *Shear Transferring Mechanism and Structural Behavior of Shallow Cellular Composite Slim Floor Beams with Innovative Shear Connections*. PhD thesis, Tongji University, Shanghai, China.
- Limazie T and Chen SM (2015) Numerical procedure for nonlinear behavior analysis of composite slim floor beams. *Journal of Constructional Steel Research* **106**(1): 209–2019.
- Limazie T and Chen SM (2016) FE modeling and numerical investigation of shallow cellular composite floor beams. *Journal of Constructional Steel Research* **119**(1): 190–201.
- Limazie T and Chen SM (2017) Effective shear connection for shallow cellular composite floor beams. *Journal of Constructional Steel Research* **128**(1): 772–788.
- Mullett DL (1992) *Slim Floor Design and Construction*. The Steel Construction Institute, Ascot, UK, Publication P110.
- Mullett DL (1998) *Composite Floor Systems*. Blackwell Science Ltd, Oxford, UK.
- Mullett DL and Lawson RM (1993) *Slim Floor Construction Using Deep Decking*. The Steel Construction Institute, Ascot, UK, Publication P127.
- Wang Y, Yang L, Shi Y and Zhang R (2009) Loading capacity of composite slim frame beams. *Journal of Constructional Steel Research* **65**(3): 650–661.

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