A Review of Structural Behavior and Composite Action Between the Steel Beams and Concrete Slabs

P. Panjehbashi Aghdam, S. Parent, and N. Roy

Abstract The steel–concrete composite construction is known as one of the fast, economical, and eco-friendly methods due to its advantages in terms of saving in weight of steel and concrete. Composite constructions are extensively used in multi-story buildings and medium-span bridge decks. The longitudinal shear transfer between the steel beam and reinforced concrete slab is achieved through various mechanical devices called shear connectors. The mechanical properties of the shear connector, including the strength and stiffness, play a vital role in the composite action of the steel–concrete beam. The stud-type connectors are widely used in composite construction and are subjected to flexural and axial forces when resisting the interface forces by means of dowel action. In a composite slab, the degree of shear connection, the shear strength, and the stiffness of an individual stud can be determined experimentally by conducting push-out tests. Previous studies have conducted flexural tests to investigate the composite interaction in steel–concrete composite beam elements. This paper reviews different types of push-out and flexural tests proposed in the literature to evaluate the characteristics of composite slabs. The paper also provides different approaches to investigate the interaction of composite elements. This research contributes to the field by providing a comprehensive discussion of the advantages and challenges of the experimental methods to perform the push-out and flexural tests and how these two types of tests can cooperatively promote the understanding of the behavior of composite slabs.

Keywords Composite steel–concrete beams · Composite construction · Composite interaction · Shear connector · Flexural behavior · Push-out test · Shear stud

P. P. Aghdam · S. Parent · N. Roy (✉)
Université de Sherbrooke, Sherbrooke, Longueuil, QC, Canada
e-mail: Nathalie.Roy@USherbrooke.ca

R. Gupta et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2022*, Lecture Notes in Civil Engineering 348,
https://doi.org/10.1007/978-3-031-34159-5_34

1 Introduction

Advancement of material properties and construction technologies, as well as human challenges to the height and span of structures, led to creative innovations in the construction industry, such as composite steel–concrete systems. This is formed by connecting concrete slabs to the supporting steel members in the composite beam/floor system, enhancing its structural performance. Many previous studies have investigated the behavior and design of steel–concrete composite members [1, 2]. Compared with conventional reinforced concrete beams, steel–concrete composite beams have significant bending resistance and stiffness advantages. This is achieved mainly by fully utilizing the steel's material strength, such as high strength, ductility, and ease of erection, and reinforced concrete, such as high rigidity and low cost. The efficiency of a composite beam lies in restraining the slip between the steel beam and concrete slab and enabling shear force transfer between them to ensure the composite action through mechanical action, friction, and adhesion [3]. Mechanical action is provided by different shear connectors that guarantee the transfer of shear forces at the interface between the steel beam and the concrete slab, which are directly related to the bearing capacity of the whole composite beam [4, 5]. If the shear connectors are rigid, the full composite action or the full interaction is achieved [6, 7]. The degree of shear connection and the degree of composite interaction are the two terms used to describe the behavior of shear connectors in a steel–concrete composite beam. The degree of shear connection refers to the equilibrium of forces in a composite beam at the ultimate limit state (ULS). In contrast, the degree of interaction refers to the compatibility of displacements and, more specifically, the shape of the strain profile through the depth of a given section [8]. The degree of shear connection, η, is provided in Eq. (1) and is defined as the ratio of the ultimate shear strength of the interface in a shear span, F_i, to the minimum strength necessary for the section to develop its full flexural capacity at the end of the shear span, F_f.

$$\eta = \frac{F_i}{F_f} \tag{1}$$

This connection can be full, partial, or there can be no connection at all. Figure 1a shows the longitudinal equilibrium of forces at the ULS for a full shear connection ($\eta = 1$), partial shear connection ($0 < \eta < 1$), and no shear connection ($\eta = 0$). In design codes, the shear strength of the interface is calculated using the ultimate strength of all shear connectors in the shear span, neglecting friction and bond. It should be noted that the degree of shear connection is independent of the load at any given time. As a result, a beam or girder can be described as having a constant degree of shear connection [9]. Although the degree of shear connection can be defined straightforwardly, the degree of composite interaction, φ, is difficult to define without using differential calculus and complex compatibility equations. Newmark et al. [10] formulated the linear elastic partial-interaction theory, which was later extended, and a simplified equation (Eq. (2)) was proposed [8] based on the ratio of the neutral axis

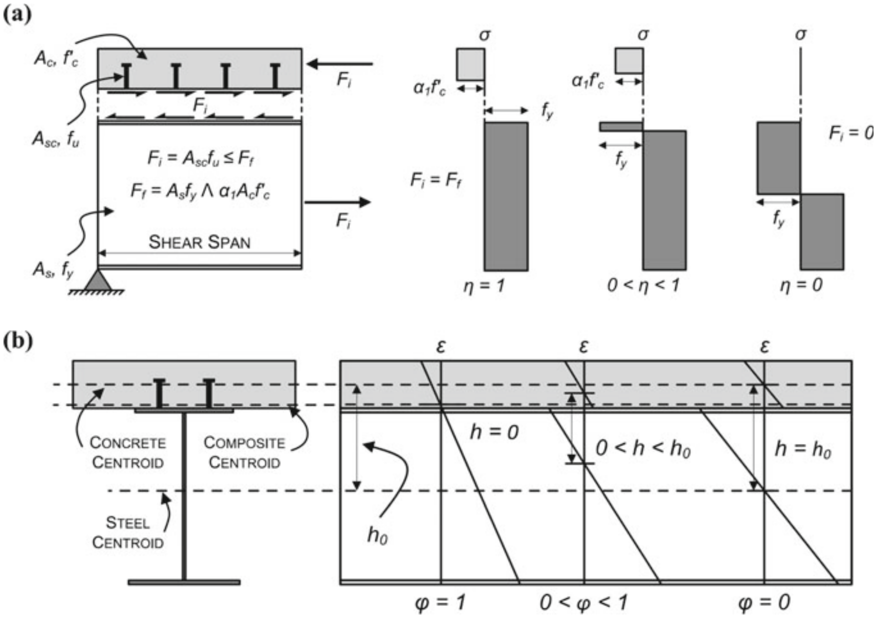

Fig. 1 Degree of **a** Shear connection; **b** Composite action [9]

separation, h, to the maximum neutral axis separation, $h_\circ$.

$$\varphi = 1 - \frac{h}{h_\circ} \tag{2}$$

This maximum neutral axis separation is the distance between the steel and concrete neutral axis in case of non-composite behavior. Figure 1b schematically shows strain profiles in full ($\varphi = 1$), partial ($0 < \varphi < 1$), and no interaction ($\varphi = 0$) cases. Unlike the degree of shear connection, the degree of composite interaction changes with loading history, over the beam's length, and the beam's life.

It is possible to perform both flexural beam tests or push-out tests to establish a stud shear connector's load-slip behavior, nominal shear strength, and stiffness. These tests are characterized by several shear connectors embedded in a small section of the concrete slab and attached to a steel section. The schematic view of a typical push-out and flexural test for a composite beam is shown in Fig. 2a, b. The steel section or the concrete slab is loaded during testing while the other element is held in position. In Fig. 3, the strain profile is shown in the steel and concrete section of the composite beam in flexural and push-out tests. In this figure, the deformed shapes are also illustrated.

Instead of expensive full-scale beam tests, push-out tests are preferred, and specifications such as AISC [11] and Eurocode 4 [12] provide empirical equations based on push test results to calculate the stud shear resistance. The shear stud strength in

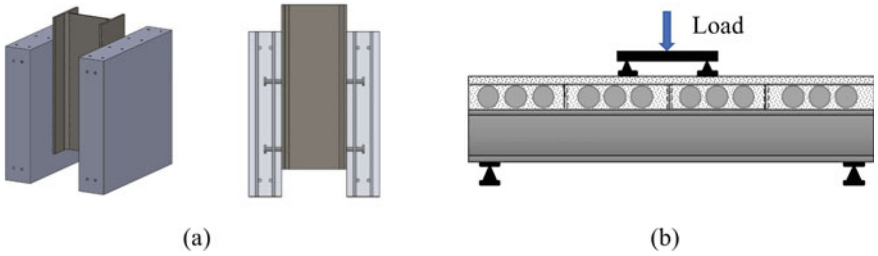

Fig. 2 Typical experimental test of composite beam: **a** Push-out test; **b** Four-node flexural test

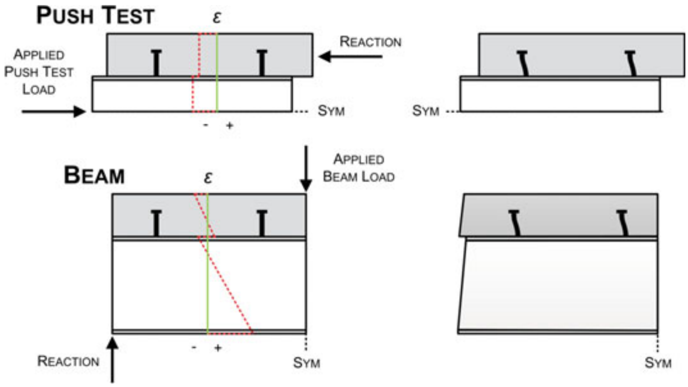

Fig. 3 Strain profiles and deformed shape in: **a** Push-out test; **b** Flexural test [9]

solid reinforced slabs was first determined by [13] and presented in terms of empirical formulas such as Eq. (3) by performing 48 push-out tests.

$$Q_u = 0.5A_s\sqrt{f_c'E_c} \leq A_sF_{\mathrm{ut}} \tag{3}$$

where Q_u is the normal shear stud strength embedded in a solid concrete slab, A_s is the effective cross-sectional area of a stud anchor (mm^2), f_c' is the cylinder compressive strength of concrete (MPa), E_c is the modulus of elasticity of concrete (MPa) and F_{ut} is the ultimate tensile strength of the steel stud (MPa). In a typical push-out test, the cast in situ or precast concrete slabs are attached to the flanges of a steel beam using pre-welded shear studs. The concrete slabs are symmetrically placed at both sides of a steel beam to simulate the actual loading condition and are restrained for any lateral movements during the test procedure. The loading process can be monolithic or cyclic, applied in a displacement or force-controlled mode. In general, failures observed in push-out tests can be categorized into five different modes: (1) stud shearing; (2) concrete pull-out; (3) rib shearing; (4) splitting, and (5) rib punching.

In a composite beam flexural test, the shear studs are welded to the flange of the steel beam, which is set on a bearing plate and roller assembly that restrain the vertical movement and allow rotation at each end. Then, the cast-in-place or precast concrete slabs are placed on the steel beam, and the load is applied through hydraulic pistons to load distribution elements. The loading process can be cyclic or monolithic, with specific increments until a specified midspan displacement or a sudden loss in load-carrying capacity is observed [14]. However, in a composite beam test, the connectors are loaded indirectly from the flexural forces within the beam. The force on a connector is not directly proportional to the load applied to the beam but depends on the stiffness of various components of the composite beam.

Therefore, the main difference between the push-out and beam tests is how the shear forces arise. In the beam test, the externally applied load causes a strain gradient with a discontinuity at the interface (also called "slip strain"). Connectors are subjected to shear force to resist slip accumulation due to the strain discontinuity on the length of the beam. In a push-out test, however, connectors resist shear force because they are part of the load path between the applied load and the balancing reaction at the base of the specimen. The drawback of the load-slip curve obtained from the push-out test is that it does not give a quantitative indication of the composite action that may result from the presence of a connector in a beam. In other words, in a push-out test, the shear forces on individual connectors remain constant relative to one another throughout the test. In contrast, in a beam test, when one shear stud begins to fail and crack, the other neighboring shear studs begin to compensate for the increased shear force, and as a result, the force redistribution is featured. Since the induction of composite action is the primary function of a shear connector, the push-out test fails to evaluate connectors on this basis.

Consequently, to quantify the flexural capacity of the composite steel beam with concrete slab, it is essential to perform both push-out and composite beam tests with complete information on the degree of shear connection and degree of composite interaction. The primary purpose of the current paper is to review different types of push-out and flexural tests proposed in the literature to evaluate the characteristics of composite slabs. The paper also provides different approaches for investigating the interaction of composite elements. This research contributes to the field by providing a comprehensive discussion of the advantages and challenges of the experimental methods to perform the push-out and flexural tests and how these two types of tests can cooperatively promote the understanding of the behavior of composite beams.

2 Literature Review

This section provides an overview of the literature about the previous studies investigating the composite action between the steel beam and concrete slab in composite steel beams. The first subsection of this review investigates the different push-out tests conducted to determine the shear strength of the shear connectors. The second subsection will highlight recent research on the composite action between the steel beam and the concrete slabs.

2.1 Determining the Shear Strength of Shear Connectors

Shear stud connectors are the essential components of steel–concrete composite structures that transfer the longitudinal shear force at the interface between the steel and concrete [15]. The push-out tests are the preferred method to establish the load-slip behavior, nominal shear strength, and stiffness of a stud shear connector. In the push-out tests, the strain distribution can be measured more easily because the shear connectors are part of the load path between the applied load and balancing reactions at the base of the specimen. Nevertheless, despite the popularity of push-out tests to establish the static and fatigue capacity of shear connectors, the test method and the layout of the specimen have been discussed for several decades. The common challenges and factors investigated by recent studies conducting push-out tests include: (1) the eccentricity between the load and the supports [16], (2) the support conditions; (3) the absence of normal compressive force at the steel–concrete interface; (4) the width and height of the slab, and (5) the number of shear connector rows. Modified push-out tests have been proposed recently to determine the shear strength and stiffness of stud shear connectors under combined shear and tension forces. Generally, the modified push-out test follows the established standard push-out test recommended in EN 1994–1–1 [17], except the concrete-steel interface is inclined to an angle of about 15° from the vertical [18].

Previous experimental, numerical, and theoretical studies indicate that the shear resistance of a stud shear connection in a composite steel–concrete beam depends on the following factors: (1) compressive and tensile strength of the concrete, as well as the elastic modulus; (2) tensile strength of stud shear connectors as well as their shapes and sizes; (3) welding quality of shear studs and dimensions of welding collars at stud roots; (4) arrangements of the shear stud connectors; and (5) sizes and arrangement of steel reinforcement in the vicinity of the shear stud [19, 20].

Different types of shear connectors have been used in composite structures. However, headed studs' popularity stems because they can be installed easily through the cellular steel deck using a welding gun [21]. The behavior of a headed stud shear connector depends on the stud details and the concrete environment, such as concrete properties and reinforcement detailing. Under cyclic loading, the fatigue failure of headed studs is the primary failure mode and should be considered in structural design [22, 23]. Studies have shown that the stud geometry, shear stress range, concrete material properties, stud welding process, and fatigue test methods affect the fatigue performance of the shear connectors [24–27]. Based on these studies, design codes on composite structures have specified fatigue strength curves of headed stud connectors based on nominal shear stress [28]. Wang et al. [29] conducted a total of 96 push-out tests and investigated the interface shear force-slip curves and the failure modes of shear stud groups (SSGs) (Fig. 4). Their results revealed that the

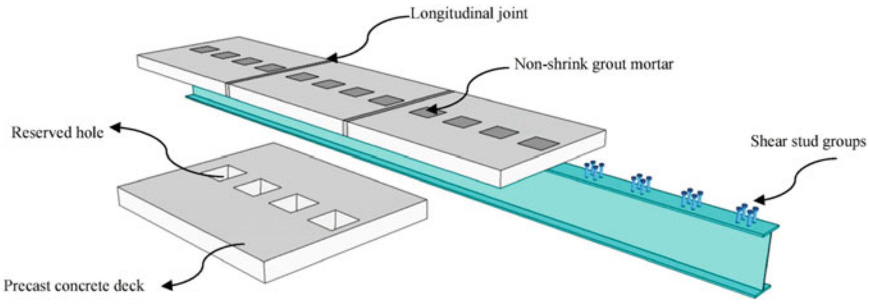

Fig. 4 Shear stud groups on PC composite beam [21]

shear behavior of the SSGs in square reserved holes is more favorable than that in circular reserved holes. They concluded that the shear strength of SSGs in precast (PC) decks is smaller than that in cast-in-place (CIP) decks under monotonic loads, whereas the shear strength of SSGs in PC decks is similar to that in CIP decks under repetitive loads.

Yu-Liang et al. [30] performed nine push-out tests to investigate the mechanical behavior of grouped stud shear connectors embedded in hybrid fiber-reinforced concrete (HFRC), considering the spacing and number of studs. They developed a refined 3D finite element (FE) model of the HFRC incorporating the constitutive model in the ANSYS software. Based on the test and the FE analysis results, an equation was proposed considering the contribution of the steel and polypropylene fiber to estimate the capacity of a single stud. Bonilla et al. [31] developed an accurate nonlinear FE model to study the behavior of headed stud shear connectors welded to the deck in composite beams with profiled steel sheeting. The nonlinear material of the concrete was modeled with damaged plasticity available in ABAQUS software [32]. The FE analyses and the experimental push-out test results were compared with the codified shear resistance of the shear studs calculated using AISC-LRFD [33] and Eurocode 4 [12]. The comparison of the results revealed that the codified shear resistance of stud connectors might not necessarily be conservative.

Sun et al. [34] conducted a series of push-out tests to study the monotonic and cyclic behavior of headed steel stud anchors in composite beams with profiled steel decks by considering profile type, steel deck direction, and load conditions. The results indicated that both monotonic and cyclic responses are affected by the shape of the profile. Tong et al. [35] investigated the shear performance of stud connectors in high-strength steel-UHPC composite beam specimens under static loads considering the diameter and layout of studs. Experimental results indicated that the failure modes of all specimens were stud shank failure, where the diameter of the studs significantly affected their shear performance. Wang et al. [29] investigated the static behavior of large stud shear connectors in steel-UHPC composite structures through 18 push-out specimens. The investigated parameters in their study were the stud diameter, stud aspect ratio, concrete strength, and concrete slab thickness. They resulted that the shear strength, stiffness, and ductility of a stud with a 30 mm diameter were approximately 15, 45, and 60% higher than those of a stud with a 22 mm diameter, respectively. Also, the stud aspect ratio and concrete slab thickness showed no apparent influence on the static behavior of the test specimens.

Finally, they proposed an empirical equation considering stud diameter to predict the load-slip curve of headed studs as:

$$\frac{P}{P_u} = \frac{S\big/d_{\mathrm{stud}}}{0.006 + 1.02\mathrm{S}\big/d_{\mathrm{stud}}} \tag{4}$$

where P is the shear load of stud, S is slip, and, P_u is the maximum shear load.

Souza et al. [36] analyzed the degree of shear connection between hollow core slabs and headed studs connected to the web of the steel beam by performing push-out tests. They found that when the concrete compressive strength is increased, the stress concentration occurs at the base of the stud. Shen and Chung [18] investigated the structural behavior of stud shear connections under combined shear and tension forces. They carried out two series of push-out tests. In the first series, eleven standard push-out tests were performed where the shear connectors only underwent the shear forces. However, in the second series of tests, shear connectors' behavior was studied using modified push-out tests under combined shear and tension forces. The results revealed that when the tension force T_{n} is smaller than or equal to 0.267^*Q_{m}, where Q_{m} is the standard shear resistance, the shear resistance of the shear connection should be reduced with a factor of 0.84 and 0.75.

Lowe et al. [37] performed 15 push-out tests to determine the longitudinal splitting characteristics of a concrete slab in a steel–concrete composite beam with headed shear stud connectors under cyclic and monotonic loads. It was concluded that the transverse compression forces across the base of the studs would increase the capacity of the beam against longitudinal splitting. Zhang et al. [38] conducted an experimental study including six push-out and eight flexural composite beam tests to investigate the transverse reinforcement ratio on the degree of shear connection. They proposed an equation for calculating the longitudinal shear resistance of steel–concrete composite beams with longitudinal double-row studs. Etim et al. [39] performed experimental push-out tests on composite slabs comprising normal and pultruded fiber-reinforced polymer (PFRP) concrete. In the first phase of the test, the effects of the headed shear stud configuration on the load-carrying capacity of the composite slabs were studied. The second phase focused on characterizing the behavior of the composite slab by varying the shear stud diameter. The test results revealed that the dominant failure modes were the FRP plates' bearing, net tension, and shear-out failures. These results differed from those prevalent in the conventional steel–concrete composite, either stud shank failure or concrete pull out.

Ahmed and Tsavdaridis [40] performed a series of push-out tests to study the shear resistance and behavior of the connection systems designed for a prefabricated ultra-shallow flooring system consisting of a T-ribbed lightweight concrete floor and C-channel steel edge beam. The studied connection system was either web-welded shear studs only or combined with horizontally lying steel dowels. Prakash

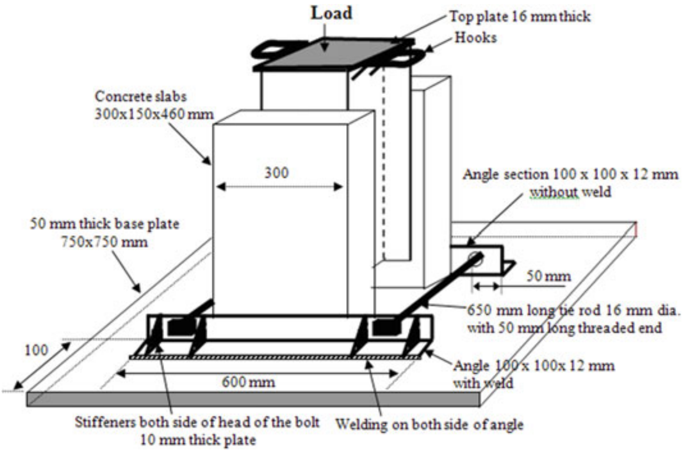

Fig. 5 Schematic illustration of the setup for the modified push-out test [41]

et al. [41] conducted modified push-out tests to determine high-strength steel studs' shear strength and stiffness. The configuration of their test setup is schematically illustrated in Fig. 5. Their experimental study indicated that concrete confinement in the vicinity of the high-strength shear stud connector could significantly enhance concrete's compressive strength and splitting resistance.

Yanez et al. [42] presented a modified push-out test on a joist-type profile to capture the stiffness coefficient when the stud anchor is placed on the weak or strong side relative to the steel deck stiffener. Four different stiffness coefficients were calculated in their experimental study to characterize the overall beam deflection when full-interaction, slip, and shear deformation is considered. They concluded that studs placed on the solid side of the stiffener give better performance when compared with the weak stud position, enhancing deflection values by 5% on average. Table 1 summarizes the previous experimental and numerical studies investigating the load-slip behavior, nominal shear strength, and stiffness of a stud shear connector in steel–concrete composite construction using push-out tests.

2.2 Investigating the Flexural Response of Composite Systems by Bending Tests

The flexural performance and composite action of composite steel beams with concrete slabs have been investigated in previous studies [44–48]. The preferred method for quantifying the composite action between the composite steel beam and the concrete slab is through the bending test, in which shear connectors resist the accumulation of the slip and the externally applied load results in a strain slip with a

Table 1 Summary of the previous push-out tests

Ref	Description of the specimens	Number of tests	Purpose of study	Results
[38]	Composite steel beams connected to the precast (PC) and cast-in-place (CIP) concrete decks with shear stud groups (SSGs)	96	Experimentally investigate the interface shear force-slip curves and the failure modes of the SSGs	The shear behavior of the SSGs in square reserved holes is more favorable than in circular reserved holes. The shear strength of SSGs in PC decks is smaller than that in CIP decks under monotonic loads
[30]	Composite steel beams with SSGs embedded in hybrid fiber reinforced concrete (HFRC)	9	Experimentally and numerically investigate the mechanical behavior of grouped stud shear connectors embedded in HFRC	An equation considering the contribution of steel fiber (SF) and polypropylene fiber (PF) to estimate the capacity of a single stud for grouped stud-HFRC shear connectors was proposed
[35]	Composite steel beams with ultra-high-strength precast concrete (UHPC) slabs	6	Experimentally investigate the shear performance of stud connectors in steel-UHPC composite beam	Failure modes of all the high-strength steel-UHPC push-out specimens were stud shank failure, the diameter of the studs significantly affected their shear performance
[38]	Composite steel beams connected to ultra-high-performance concrete (UHPC) slabs with 22 and 30 mm shear studs	18	Experimentally investigate the static behavior of large stud shear connectors in steel-UHPC composite structures	The shear strength, stiffness, and ductility of a stud with a 30 mm diameter are approximately 15, 45, and 60% higher than a 22 mm diameter

(continued)

Table 1 (continued)

Ref	Description of the specimens	Number of tests	Purpose of study	Results
[36]	Composite steel beams connected to the PCHC slabs by headed shear studs on the web of steel beam	3	Experimentally and numerically analyze the composite action between PCHC slabs and headed studs connected to the web of the steel beam	The concrete compressive strength influences the ultimate capacity and stud forces, as the concrete compressive strength increases, the stress concentration occurs at the base of the stud
[18]	Composite steel beams with solid concrete and composite slabs	11	Experimentally investigate the structural behavior of stud shear connections under combined shear and tension forces with both composite and solid slabs	Provided that the tension force T_n is smaller than or equal to 0.267 of the shear resistance of the shear stud, the shear resistance of the shear stud should be reduced with a factor of 0.84 and 0.75 for the cases of a solid concrete slab and a composite slab, respectively
[43]	Composite steel beams with concrete slabs	6	Investigate the parameters as transverse reinforcement ratio and shear connection degree	Proposed a formula to calculate the longitudinal shear resistance of steel–concrete composite beams with longitudinal double-row studs
[39]	Composite steel beams with slabs comprising of normal density concrete, and pultruded fiber reinforced polymer (PFRP)	6	Experimentally investigate the effects of headed shear stud configuration on the load capacity of the composite slabs, and characterize the behavior of the composite slab by varying the headed stud diameter	Dominant failure modes in the mentioned specimens were the FRP plates’ bearing, net tension, and shear-out failures

(continued)

Table 1 (continued)

Ref	Description of the specimens	Number of tests	Purpose of study	Results
[40]	Prefabricated ultra-shallow flooring system (PUSS) consisting of a T-ribbed lightweight concrete floor and C-channel steel edge beam	8	Experimentally study the shear resistance and behavior of the connection system comprised of the web-welded shear studs only or combined with horizontally lying steel dowels	The compressive strength of the concrete significantly influences the ultimate shear strength capacity loads and the failure mode of the connection
[41]	Composite steel beam connected to reinforced concrete slabs with shear studs	4	Experimentally determine the shear strength and stiffness of high-strength steel (HSS) studs	The confinement of the concrete in the vicinity of the HSS stud connector significantly enhances the compressive strength and splitting resistance of concrete, which must be considered while designing concrete slabs for push-out specimens
[42]	Composite steel joists (CSJ)	24	Experimentally predict the linear behavior of the shear connector embedded in a concrete slab with a steel sheet profile considering the stud diameter variation	Deflection is better predicted in partial connection studs on the stiffener’s strong side perform better than the weak stud position while enhancing deflection values by 5% on average

discontinuity at the interface. Consequently, bending tests provide a quantitative indication of the composite action that results from the presence of connectors in a beam. Recently, [49] conducted a four-point bending test to investigate the flexural performance of large-scale composite beams composed of a precast UHPC (ultra-high performance concrete) slab connected to the steel girder by large-headed stud clusters embedded with shear pockets. Based on the test results, they proposed a formulation according to a simplified plasticity theory considering the tensile strength of UHPC for predicting the ultimate flexural capacity of the steel-UHPC composite beams. Dar et al. [50] conducted an experimental study on full-scale supported cold-formed steel (CFS) concrete composite beams under four-point monotonic loading to investigate the flexural strength and the degree of shear interaction. They also assessed the performance of various shear connectors in strength, stiffness, and ductility. Baran [51] performed flexural tests and numerical simulations on concrete hollow core panels (PCHC) to understand the effect of concrete topping over the surface of precast concrete hollow core on the flexural response (Fig. 6). Their results demonstrated that significant composite action is developed between the hollow core unit and the topping slab under load levels corresponding to the uncracked state of the cross section. Also, the existence of topping concrete resulted in improvements in the cracking moment and initial stiffness of hollow-core units. Ibrahim et al. [52] investigated the shear-flexural capacity of composite slabs using PCHC units and concrete topping. Their test intended to obtain vertical shear failure considering the effects of surface conditions. Their specimens were subjected to a static three-point bending test on a simple span with roller supports at both ends. The vertical deflection, interface (horizontal) slip and vertical slip (or interface dilation) were measured using potentiometers. Their results revealed that the surface roughness and moisture condition of the PCHC units affect the performance and behavior of composite slabs and the ultimate shear capacity between the PCHC units and the concrete topping.

Zhang et al. [38] performed a three-point bending test on steel-UHPC composite beams with stud and bolt connectors, as shown in Fig. 7. Their results showed that steel-UHPC composite beams exhibited excellent cracking and flexural performance under the hogging moment. Compared with the steel-normal strength concrete

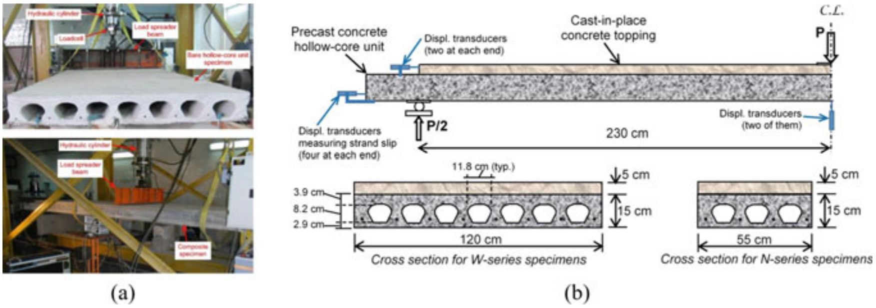

Fig. 6 Specimen cross section, instrumentation, and loading setup details adopted by [51]: **a** On-site photos; **b** Schematic sketch

composite beam, the cracking load and ultimate flexural capacity of steel-UHPC composite beams were increased by around 340 and 26%, respectively. Also, verified by test results, theoretical formulas were proposed in their study to calculate the slip moment, the moment at a crack width of 0.05 mm, and the ultimate moment of the steel-UHPC composite beams under the hogging moment.

As shown in Fig. 8, they calculated the position of the plastic axis of the composite section according to the axial force equilibrium. They predicted the ultimate slip moment (M_{su}) as follows:

$$N_{\mathrm{cr}} + N_{\mathrm{rt}} + N_{\mathrm{st}} + N_{\mathrm{wt}} = N_{\mathrm{wc}} + N_{\mathrm{sb}} \tag{5}$$

$$x = \frac{f_{\mathrm{cr}} b_e h_u + f_{\mathrm{ry}} A_{\mathrm{rt}} + f_{\mathrm{sy}}(A_{\mathrm{st}} + h_w t_w A_{\mathrm{sb}})}{2 f_{\mathrm{sy}} t_w} + t_2 \tag{6}$$

$$M_{\mathrm{su}} = f_{\mathrm{ry}} A_{\mathrm{rt}} y_1 + f_{\mathrm{cr}} b_e h_u y_2 + f_{\mathrm{sy}}(A_{\mathrm{st}} y_3 + A_{\mathrm{wt}} y_4 + A_{\mathrm{wc}} y_5 + A_{\mathrm{sb}} y_6) \tag{7}$$

where the resultant forces of concrete stress block are N_{cr}, forces of steel reinforcement is N_{rt} , forces of the top flange plate is N_{st}, forces of web in tension is N_{wt}, forces of the web in compression is N_{wc}, and forces of the bottom flange plate of the

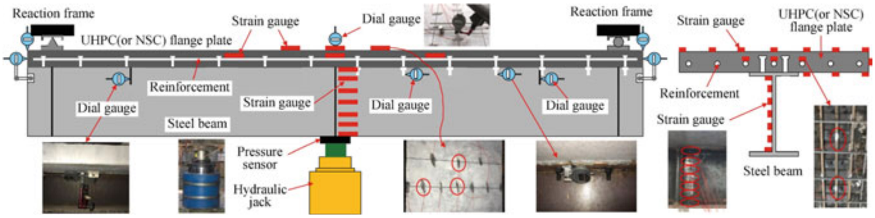

Fig. 7 Flexural test setup and measurements [38]

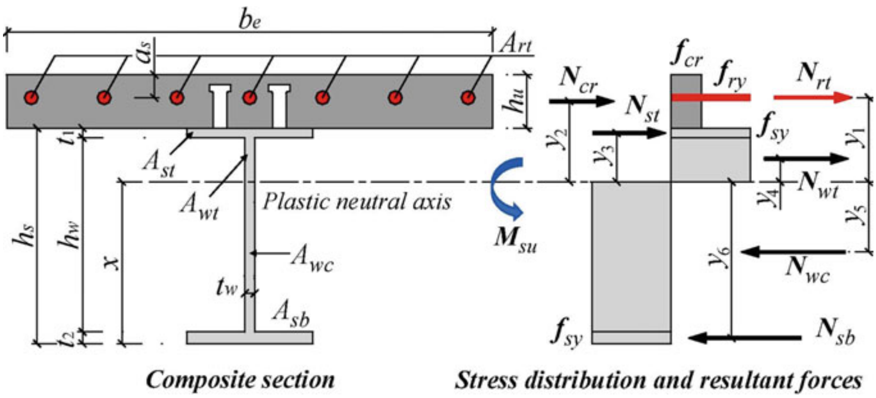

Fig. 8 Analytical model of SU-S under hogging moment at the ultimate state [38]

steel beam is N_{sb}. Also, f_{cr} is the cracking strength of UHPC, and f_{ry} and f_{sy} are the yield strengths of steel reinforcement and steel beam, respectively. As denoted in Fig. 8, A_{rt} is the reinforcement area in tension, A_{st} is the flange area of the steel beam in tension, A_{wt} is the web area of the steel beam in tension, A_{wc} is the web area of the steel beam in compression, and A_{sb} is the flange area of the steel beam in compression.

Qi et al. [53] studied the flexural behavior of steel-ultra high-performance fiber-reinforced concrete (UHPFRC) composite beams by conducting bending tests and an analytical program. They performed four-point bending tests on two large-scale beams, one made of normal-strength concrete (NC) slab and another consisting of a UHPFRC slab. The results showed that using the UHPFRC slab increased the stiffness and improved the crack control capacity of the composite beam. Bandelt et al. [14] conducted an experimental study on the full-scale and component specimens to investigate the flexural response of a girder-slab © composite system. The system combines steel beams, precast hollow core slabs, steel reinforcement, and composite floor assembly for residential and commercial construction applications (Fig. 10). Furthermore, they compared the experimental results with the predicted flexural strength of the system based on two analytical methods: (1) a strain compatibility analysis using principles of displacement-curvature behavior and (2) a simplified plastic composite section analysis. Their results showed that both methods could accurately predict the full-scale specimen's experimental strength but over-predicted the component specimen strength due to the boundary conditions.

Table 2 summarizes previous experimental and numerical studies investigating the composite action between the composite steel beam and concrete slabs using bending tests.

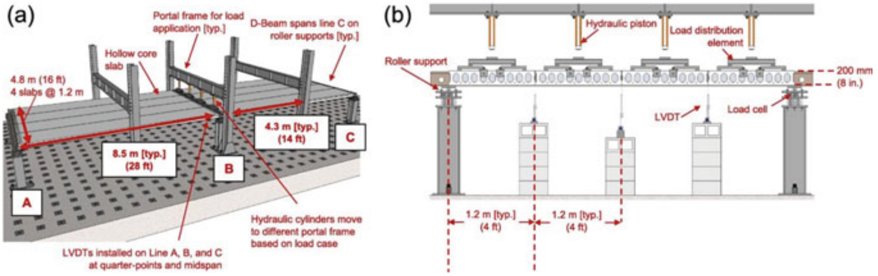

Fig. 9 **a** Overview of the full-scale composite experimental setup, **b** Elevation of the composite component specimen [14]

Table 2 Summary of the previous bending tests

Ref	Description of the specimens	Number of tests	Purpose of study	Results
[49]	Composite steel beams connected to the ultra-high-performance concrete (UHPC) slabs by large-headed stud clusters	2	Investigate the flexural performance of composite steel beams with UHPC slabs performing four-point bending tests	A formulation according to a simplified plasticity theory considering the tensile strength of UHPC to predict the ultimate flexural capacity of the steel-UHPC composite beams
[50]	Simply supported cold-formed steel (CFS) concrete composite slab	7	Investigate the flexural strength and the degree of shear interaction of CFS concrete composite slabs performing four-point bending tests	CFS concrete composite slabs structurally perform better than conventional reinforced concrete (RC) slabs
[51]	Precast hollow core concrete (PCHC) slabs	5	Demonstrate the effect of concrete topping placed over the as-cast surface of PCHC units in improving the flexural response	Significant composite action is valid between the PCHC unit and the topping slab under load levels corresponding to the uncracked state of the cross section. Topping concrete improves the cracking moment and initial stiffness of PCHC
[52]	Precast hollow core concrete (PCHC) slabs	2	Investigate the shear-flexure capacity of composite slabs using PCHC units and concrete topping, performing a three-point bending test	The surface roughness and moisture condition of the PCHC units affect the performance and behavior of composite slabs and the ultimate shear capacity between the PCHC units and the concrete topping
[38]	Steel-UHPC composite beams with stud connectors (SU-S) and bolt connectors (SU-B)	5	Investigate the crack resistance, ultimate flexural capacity, failure modes, and of SU-S and SU-B under negative bending moment at the supports	Compared with the steel-normal strength concrete composite beam, the cracking load and ultimate flexural capacity of steel-UHPC composite beams increase by around 340 and 26%, respectively

(continued)

Table 2 (continued)

Ref	Description of the specimens	Number of tests	Purpose of study	Results
[53]	Composite steel beams with ultra-high-performance fiber-reinforced concrete (UHPFRC) slabs	2	Study the flexural behavior of steel-UHPFRC composite beams by performing four-point bending tests	UHPFRC slabs increase the stiffness and improve the crack control capacity of the steel-UHPFRC composite beam
[14]	Composite steel beams with reinforced precast hollow core slabs	1	Investigate the flexural response of a girder-slab © composite system that combines steel beams, precast hollow core slabs, steel reinforcement, and composite floor assembly	Two analytical methods: (1) a strain compatibility analysis using principles of movement-curvature behavior and (2) a simplified plastic composite section analysis, accurately predicting the flexural strength compared with the experimental results

3 Summary and Discussion

The findings of this paper can be summarized below:

- The main difference between the push-out and beam tests is how the shear forces arise. In a push-out test, connectors resist shear force as a part of the load path between the applied load and the balancing reaction at the base of the specimen. The shear forces on individual connectors remain constant relative to one another throughout the test. The drawback of the load-slip curve obtained from the push-out test is that it does not give a quantitative indication of the composite action that may result from the presence of a connector in a beam. In the beam tests, however, connectors are subjected to shear force to resist the slip accumulation due to the strain discontinuity on the length of the beam. When one shear stud begins to fail and crack, the other neighboring studs start to compensate for the increased shear force, and as a result, the force redistribution is featured. In other words, in the push-out test, the degree of shear connection is measured, referring to the equilibrium of forces in a composite beam at the ultimate limit state. It is independent of the loading condition, while the degree of composite interaction refers to the compatibility of displacements and changes with the loading conditions. Typically, performing the flexural tests is costly and requires a relatively complex setup in which controlling the boundary conditions is difficult. On the contrary, push-out tests are easy to perform, requiring the least instrumentation to capture and interpret the results. Consequently, many code provisions interchangeably use the degree of shear connection and composite action for defining design procedures.
- To better understand the behavior of the composite beams, performing both the push-out and flexural beam tests is recommended. The push-out tests establish the load-slip behavior, nominal shear strength, and stiffness of stud shear connectors in composite beams. The beam tests quantify the flexural capacity of the composite beams.
- At the University of Sherbrooke, 11 standard push-out tests and two full-scale flexural tests have been conducted on composite steel beams with precast concrete hollow core (PCHC) slabs. Verified numerical finite element models will follow the research to modify the design equations of clause 17-composite beams, trusses, and joists of the S16-19 [54] design of steel structures for PCHC applications. As a result, the appropriate configuration of the shear studs and the degree of composite action between the PCHC slab and the steel beam connected via cast in situ cover concrete would be quantified. Finally, a new design methodology will be proposed which considers the composite action between the composite steel beams and PCHC slabs.

References

1. Behnam A, Denavit MD (2020) Plastic stress distribution method for predicting interaction strength of steel-concrete composite cross sections. J Constr Steel Res 170:106092. https://doi.org/10.1016/j.jcsr.2020.106092
2. Lai B, Liew JYR (2020) Axial-moment interaction of high strength concrete encased steel composite columns: design recommendation. J Constr Steel Res 170:106136. https://doi.org/10.1016/j.jcsr.2020.106136
3. Hou H et al (2016) Experimental evaluation of flexural behavior of composite beams with cast-in-place concrete slabs on precast prestressed concrete decks. Eng Struct 126:405–416. https://doi.org/10.1016/j.engstruct.2016.07.065
4. Deng W et al (2019) Static and fatigue behavior of shear connectors for a steel-concrete composite girder. J Constr Steel Res 159:134–146. https://doi.org/10.1016/j.jcsr.2019.04.031
5. Zhang Q et al (2018) Internal force transfer effect-based fatigue damage evaluation for PBL shear connector groups. J Constr Steel Res 148:469–478. https://doi.org/10.1016/j.jcsr.2018.06.016
6. Kalibhat MG, Upadhyay A (2020) Numerical study on the deformation behavior of steel concrete composite girders considering partial shear interaction. Structures 23:437–446. https://doi.org/10.1016/j.istruc.2019.10.007
7. Suwaed ASH, Karavasilis TL (2020) Demountable steel-concrete composite beam with full-interaction and low degree of shear connection. J Constr Steel Res 171:106152. https://doi.org/10.1016/j.jcsr.2020.106152
8. Oehlers DJ, Seracino R (2002) A tiered approach to the fatigue assessment of composite steel and concrete bridge beams. Proc Inst Civ Eng Struct Build 1523:249–257
9. Sjaarda M (2018) The fatigue behavior of welded and bolted shear connectors in composite highway bridges
10. Newmark NM, Siess CP, Viest IM (1951) Tests and analysis of composite beams with incomplete interaction. Proc Soc Exp Stress Anal 9(1):75–92
11. American Institute of Steel Construction (2016) Specification for structural steel buildings, ANSI/AISC 360–16. American Institute of Steel Construction, p 676
12. CEN E (2004) Eurocode 4: Design of composite steel and concrete structures. Part 1–1: general rules for buildings. Brussels, Belgium
13. Ollgaard JG, Slutter RG, Fisher JW (1971) Shear strength of stud connectors in lightweight and normal weight concrete. Eng J Amer Inst Steel Constr 8(2):55–64
14. Bandelt MJ et al (2019) Flexural behavior of a composite steel and precast concrete open web dissymmetric framing system. Eng Struct 198(June):109456. https://doi.org/10.1016/j.engstruct.2019.109456
15. Xu X, Zhou X, Liu Y (2020) Behavior of rubber-sleeved stud shear connectors under fatigue loading. Const Build Mater 244:118386. https://doi.org/10.1016/j.conbuildmat.2020.118386
16. Hällmark R, Collin P, Hicks SJ (2019) Post-installed shear connectors: push-out tests of coiled spring pins vs. headed studs. J Constr Steel Res 161:1–16. https://doi.org/10.1016/j.jcsr.2019.06.009
17. BS EN 1994–1–1 (2004) Eurocode 4: design of composite steel and concrete structures. Part 1.1: general rules for buildings
18. Shen MH, Chung KF (2017) Experimental investigation into stud shear connections under combined shear and tension forces. J Constr Steel Res 133:434–447. https://doi.org/10.1016/j.jcsr.2017.02.021
19. Katwal U et al (2020) Load sharing mechanism between shear studs and profiled steel sheeting in push tests. J Constr Steel Res 174:106279. https://doi.org/10.1016/j.jcsr.2020.106279
20. Shen M-h et al (2020) Structural behaviour of stud shear connections in composite floors with various connector arrangements and profiled deck configurations. Eng Struct 210(February):110370. https://doi.org/10.1016/j.engstruct.2020.110370
21. Wang YH et al (2019) Shear behavior of shear stud groups in precast concrete decks. Eng Struct 187(February):73–84. https://doi.org/10.1016/j.engstruct.2019.02.002

22. El-Zohairy A, Salim H, Saucier A (2019) Fatigue tests on steel-concrete composite beams subjected to sagging moments. J Struct Eng, United States 145(5):1–11. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002326
23. Sjaarda M et al (2017) Fatigue behavior of welded shear studs in precast composite beams. J Bridg Eng 22(11):1–11. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001134
24. Higashiyama H et al (2014) Fatigue of headed studs welded with improved ferrules under rotating shear force. J Constr Steel Res 92:211–218. https://doi.org/10.1016/j.jcsr.2013.09.012
25. Qi Y et al (2017) Shear force demand on headed stud for the design of composite steel plate shear wall. Eng Struct 148:780–792. https://doi.org/10.1016/j.engstruct.2017.07.023
26. Xu C, Sugiura K, Su Q (2018) Fatigue behavior of the group stud shear connectors in steel-concrete composite bridges. J Bridg Eng 23(8):1–13. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001261
27. Liu Y et al (2019) Static and fatigue push-out tests of short headed shear studs embedded in Engineered Cementitious Composites (ECC). Eng Struct 182:29–38. https://doi.org/10.1016/j.engstruct.2018.12.068
28. American Association of State Highway and Transportation Officials (2017) LRFD bridge design specifications, 7th edn. AASHTO, Washington, DC
29. Wang J et al (2019) Static behavior of large stud shear connectors in steel-UHPC composite structures. Eng Struct 178:534–542. https://doi.org/10.1016/j.engstruct.2018.07.058
30. Yu-liang H et al (2020) Experimental and numerical analysis of grouped stud shear connectors embedded in HFRC. Constr Build Mater 242:118197. https://doi.org/10.1016/j.conbuildmat.2020.118197
31. Bonilla J, Bezerra LM, Mirambell E (2019) Resistance of stud shear connectors in composite beams using profiled steel sheeting. Eng Struct 187(February):478–489. https://doi.org/10.1016/j.engstruct.2019.03.004
32. Manual AU (2012) Abaqus version 6.12–1 documentation. Dassault Systemes SIMULIA Corporation, Providence, RI, USA
33. Construction AIS (2000) Load and resistance factor design specification for structural steel buildings. American Institute of Steel Construction, Incorporated
34. Sun Q et al (2019) Monotonic and cyclic behavior of headed steel stud anchors welded through profiled steel deck. J Constr Steel Res 157:121–131. https://doi.org/10.1016/j.jcsr.2019.01.022
35. Tong L et al (2020) Static behavior of stud shear connectors in high-strength-steel–UHPC composite beams. Eng Struct 218(May):110827. https://doi.org/10.1016/j.engstruct.2020.110827
36. Souza PT, Kataoka MN, El Debs ALHC (2017) Experimental and numerical analysis of the push-out test on shear studs in hollow-core slabs. Eng Struct 147:398–409. https://doi.org/10.1016/j.engstruct.2017.05.068
37. Lowe D et al (2020) Full scale experiments on splitting behaviour of concrete slabs in steel concrete composite beams with shear stud connection. Structures 23:126–138. https://doi.org/10.1016/j.istruc.2019.10.008
38. Zhang Y et al (2020) Flexural responses of steel-UHPC composite beams under hogging moment. Eng Struct 206:110134. https://doi.org/10.1016/j.engstruct.2019.110134
39. Etim O et al (2020) Shear characterisation of pultruded superstructural FRP-concrete push-outs. Structures 23:254–266. https://doi.org/10.1016/j.istruc.2019.10.004
40. Ahmed IM, Tsavdaridis KD (2020) Shear connection of prefabricated slabs with LWC—part 1: experimental and analytical studies. J Constr Steel Res 169:106016. https://doi.org/10.1016/j.jcsr.2020.106016
41. Prakash A et al (2012) Modified push-out tests for determining shear strength and stiffness of HSS stud connector-experimental study. Int J Compos Mater 2(3):22–31. https://doi.org/10.5923/j.cmaterials.20120203.02
42. Yanez SJ, Dinehart DW, Santhanam S (2017) Composite steel joist analysis using experimental stiffness factor from push-out tests. J Constr Steel Res 137(April):1–7. https://doi.org/10.1016/j.jcsr.2017.04.001

43. Zhang J et al (2020) Experimental and theoretical study on longitudinal shear behavior of steel-concrete composite beams. J Constr Steel Res 171:106144. https://doi.org/10.1016/j.jcsr.2020.106144
44. Chen Y et al (2020) Flexural behavior of composite box girders with corrugated steel webs and trusses. Eng Struct 209:110275. https://doi.org/10.1016/j.engstruct.2020.110275
45. Kabir MI et al (2020) Flexural behaviour of ECC-LWC encased slender high strength steel composite beams. J Constr Steel Res 173:106253. https://doi.org/10.1016/j.jcsr.2020.106253
46. Zhang S, Liu J (2007) Seismic behavior and strength of square tube confined reinforced-concrete (STRC) columns. J Constr Steel Res 63(9):1194–1207. https://doi.org/10.1016/j.jcsr.2006.11.017
47. Zhu J et al (2020) Numerical and theoretical research on flexural behavior of steel-UHPC composite beam with waffle-slab system. J Constr Steel Res 171:106141. https://doi.org/10.1016/j.jcsr.2020.106141
48. Qiao W et al (2020) Flexural properties of new cold-formed thin-walled steel and concrete composite slabs. J Build Eng 31(January):101441. https://doi.org/10.1016/j.jobe.2020.101441
49. Hu Y et al (2020) Flexural performance of steel-UHPC composite beams with shear pockets. Structures 27(February):570–582. https://doi.org/10.1016/j.istruc.2020.05.039
50. Dar MA et al (2020) Comparison of various shear connectors for improved structural performance in CFS concrete composite slabs. Eng Struct 220(June):111008. https://doi.org/10.1016/j.engstruct.2020.111008
51. Baran E (2015) Effects of cast-in-place concrete topping on flexural response of precast concrete hollow-core slabs. Eng Struct. https://doi.org/10.1016/j.engstruct.2015.04.017
52. Ibrahim IS et al (2016) Experimental study on the shear behaviour of precast concrete hollow core slabs with concrete topping. Eng Struct 125:80–90. https://doi.org/10.1016/j.engstruct.2016.06.005
53. Qi J et al (2020) Flexural behavior of steel-UHPFRC composite beams under negative moment. Structures 24(January):640–649. https://doi.org/10.1016/j.istruc.2020.01.022
54. CSA Group, CAN/CSA S16–19 (2019) Design of steel structures. CSA Group, Toronto, Ontario, Canada