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Review

The evolution of composite flooring systems: applications, testing, modelling and eurocode design approaches

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ABSTRACT

Steel–Concrete Composite (SCC) structural systems are increasingly used in the construction industry and becoming the subject of intensive research by the world's leading universities and companies because of their efficient material usage. This review paper summarises some historic and recent developments as well as the new trends for SCC systems. It presents the design philosophy and specific definitions for basic structural elements, including composite beams and slabs with emphasis on the applications, static tests, modelling techniques, design approaches as well as current design limitations. This paper concludes with a call for more research for the improvement of Eurocode 4, which in turn can help the fast-growing construction industry to take full advantage of the benefits of composite construction techniques implemented with safety.

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1. Scope of study

The scope of this review paper is to give an overview of current developments in steel-concrete composite (SCC) beams and flooring systems, as well as to clarify and support future research directions and trends which the industry will take in the coming years. The driving forces of research in this field are the following: (i) Innovative construction methods and new construction products, (ii) Best usage of new and underdeveloped materials, and (iii) Socioeconomic and environmental considerations towards sustainability and resilience.

The breakdown of this review paper is given below for the ease of the readers:

beams were first tested in Canada at the Dominion Bridge Works in 1922. Welded shear studs were first tested at the University of Illinois in 1954, which led to the publication of a design formula in 1956 and the first use of shear studs in bridges and building projects in the same year. The partial interaction theory was proposed in 1951 by the team from Illinois. Metal decks first appeared in the 1950s, with the first recorded use of through deck stud welding on the Federal Court House in Brooklyn in 1960. It was not until 1978, however, that this arrangement was recognised in the AISC specification.

Within Europe, parallel developments had been taking place, in 1950 a "Provisional Regulations for the Design of Girders in Composite

2. Background history and technological advancements

In the context of buildings and other civil engineering structures, the term "composite construction" is normally implied to the use of steel and concrete formed together into a component in a way that the resulting configuration functions as a single unit comparable to reinforced concrete construction. The aim is to achieve a higher performance level than would have been the case had the two materials functioned separately. Consequently, the design must identify inherent differences in properties and ensure that the structural system properly accommodates them. As a result, some form of connection is clearly necessary. The reduction in self-weight of composite elements has an important effect in reducing the forces in those components supporting them, such as the foundations. In addition, composite systems also offer benefits in terms of speed of construction. The design of flooring systems is considered as one which has the highest impact to the overall weight of steel buildings, in particular, taller structures, and it is getting more significant with the high demand of increased column spacing (i.e., large spans). Thus, reduced floor slabs have been proposed in the last decade to account for lightweight systems. The reductions in floor depth which can be obtained using composite construction can also offer substantial benefits in terms of services costs and building envelope with a serious impact on the real estate market. Since its introduction, the application of composite action has been further recognised as an effective method of enhancing structural performance and reducing cost. Consequently, a high proportion of steel structures are designed compositely.

Within the USA, the first use of concrete encased beams was on a bridge in Iowa and a building in Pittsburgh in 1894. Composite

Construction" has been published. The British researchers Chapman & Johnson mentioned a research project in progress and buildings under construction that had been designed compositely at City University London, Imperial College London, and Cambridge University. The early UK composite bridge applications and background studies for buildings have appeared in the late 1950s.

The conventional jack arch flooring system was first established in the UK at the end of the 1990s and was extensively used in industrial buildings. It consists of shallow brick arches spanning between steel floor beams (joists) with the arches packed tightly between the beams to provide the necessary resistance to thrust forces, as shown in Fig. 1 [1]. The main features of this type of flooring system are speed in construction, technical simplicity, and overall low cost. The disadvantages of the jack arch flooring system make it inconsistent for the seismic loads. The inconsistency of the floor prevents it to act as a semi-rigid diaphragm in which significant damages including the floor collapse were observed during past earthquakes.
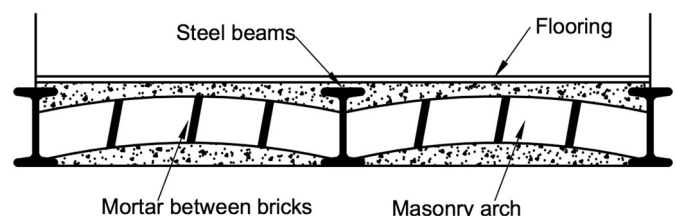

Fig. 1. Typical type of jack arch slab and its details [1].

In contrast, a new type of composite systems which is used in steel frame building construction is the steel-concrete composite (SCC) beam which behaves better than the jack arch slab for the seismic loads. Composite beams are defined as; "elements resisting only flexure and shear that comprise two longitudinal components connected together either continuously or by a series of discrete connectors" [2]. The downstand composite beam is the most common type of composite beam. It consists of a composite slab sitting on the top flange of the beam connecting through the deck by the use of welded shear studs connections. The composite slab comprises from in situ reinforced concrete cast on top of the metal deck with two types trapezoidal or re-entrant, as shown in Fig. 2.

The depth of the trapezoidal metal deck can be over 200 mm deep, in this case, it called as a 'deep' metal deck. In this type of trapezoidal metal deck, additional reinforcement can be located through the metal deck troughs [3]. This type of construction shows a number of advantages as the decking acts as formwork and a working platform during the construction stage with the wet concrete, and as an external reinforcement at the composite stage. It could also provide lateral restraint to the beams during the construction stage. This type of construction significantly reduces the erection/installation lifts when compared with pre-cast units because the decking is lifted in large packages during the construction stage, which is then easily separated through the floor area. Trapezoidal decking of 80 mm deep can span up to 4.5 m while deep decking with 200 mm deep can span 6 m without propping during construction.

To increase the span of the downstand composite beam, another type was established with the use of precast concrete unit slab sits on the top flange of the downstand steel beam. The effective span range of the downstand composite beam with a precast unit is around 6 m to 12 m, which makes it a competitor to the concrete flooring options and the composite downstand beam with metal decking. The Concrete Centre defines as hybrid concrete construction a method of construction which integrates the same precast concrete (hollow-core slabs) and cast in-situ concrete frames to make the best advantage of their different inherent qualities. There are other hybrid construction methods combining the use of various materials such as timber, concrete, and steel. However, this paper focuses only on steel-concrete composite structural systems which are known as systems used for steel frames. The stud shear connection is required a specific detailing when precast units are used so that the body of the precast units can be mobilised (follow the plastic neutral axis of the composite system) as part of the concrete compression flange. Precast units should be as light as possible to ease the transportation, lifting and, positioning processes.

On the other side, the steel sections of the downstand composite beam are often heavier than needed as the flanges thickness increases with the increase of steel section span [4]. The downstand composite beam is not a cost-effective solution for structures that consist of columns and walls placed at short distances across the building (e.g., residential buildings, hotels etc.) [5]. In such buildings, electric and hydraulic services are mainly placed horizontally on the floor sides (within the walls) and are not as many as the services required for offices. For the aforementioned reasons, shallow flooring systems are developed to replace the downstand composite beam including the Slimfor presented by ArcelorMittal [6], and Ultra-Shallow Floor Beams (USFB) presented by Kloeckner Metals UK | Westok [7]. The shallow flooring systems offer many advantages compared to the downstand composite such as reducing the overall height of a building for a given number of floors which maximise the number of floors, achieving flat soffit with complete freedom for the distribution of services below the floor.

ArcelorMittal's slim-floor is characterised by incorporating the main steel beams into the structural floor depth, typically achieving a minimum floor depth of about 300 mm [8]. The steel beam is designed as a special type of girder with the bottom flange be wider than the upper flange. This arrangement allows for the floor slabs to sit on the lower flange of the beam so that the two components thus comprise the floor. Different types of the slim-floor beam are used in practice, however, the floor slabs are divided into two generic types: (a) deep composite slabs, and (b) the precast concrete slabs. The shear connection in this system is represented by the bonding between the concrete slab and the slim-floor steel beam. Different types of slim-floor structures are presented in Fig. 3, with a limited span of about 9 m. This type of construction offers a number of advantages such as reducing total floor thickness (approximately 250 mm to 400 mm) based on general structural arrangements, constructing floors of variable thicknesses, incorporating under-floor services, creating an open working space by reducing the number of intermediate columns, enhancing the fire resistance of floor, and reducing the cost [9]. slim-floor construction is widely used for residential buildings which require a minimum floor-to-floor height as low as 280 mm, and for hospitals when the control of vibration is important.

To increase the span of the slim-floor beams a new shear transfer technology is known as concrete dowels shear connection which connects the slim-floor beam (SFB) with the concrete slabs on either sides as the concrete dowels passing through the openings, as shown in Fig. 4 [10]. These shear connection system allows for the slim-floor to extend the span from 9 m with a depth of 300 mm to 12 m with a depth of 350 mm. This newer development for slim-floors is the so-called composite slim-floor beam (CoSFB). The advantages of the CoSFB are enhancing the structural performance of slim-floor construction, achieving longer spans (up to 12 m), achieving shallower depths than the standard slim-floor beams, reducing the number of intermediate columns, enhancing the fire resistance of floor, and reducing the cost [10].

Another type of shallow floor beams is developed by Westok and used a different type of shear connection, compared with the CoSFB, called 'Plug' composite. This type of shallow floor beams is called as Westok's USFB system which involves a shallow asymmetric cellular beam with reinforcing bars passing through the holes connecting the concrete slab with the steel beam. The composite action of the USFBs is represented by 'Plug' which has been confirmed using laboratory full-scale testing [11], as shown in Fig. 5. The plug composite action can be used with different slab type arrangements; i.e., composite slab
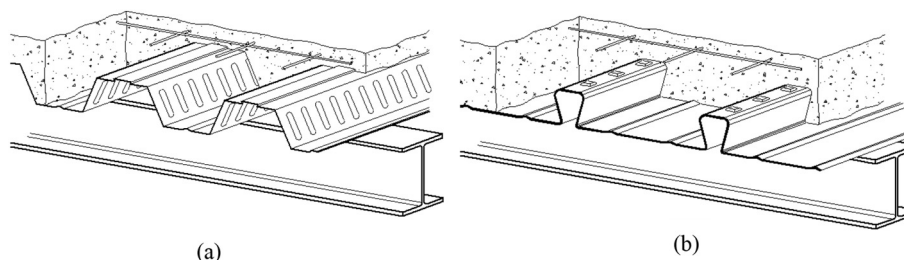

(a)   (b)

Fig. 2. Composite Slabs Types (a): *Re*-entrant decking, (b): Trapezoidal decking [2].

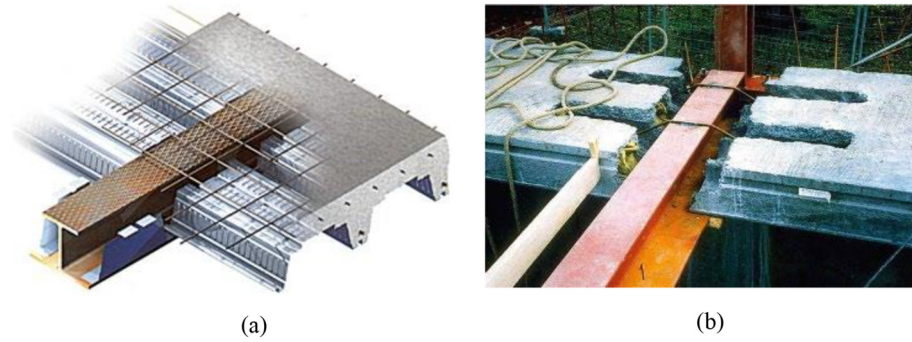(a)   (b)

Fig. 3. (a) Slim-floor construction with deep composite decking, (b) Slim-floor construction with precast concrete slab [8].

with metal deck and concrete casting above or level with the top flange, precast units with a minimum 50 mm topping above or level with the top flange, hollow-core units (see Section 3.1) with every second core broken out and filled with in-situ concrete and re-bars through the hole, and in-situ solid slabs with concrete casting above or level with the top flange as illustrated in Fig. 6. The economic span of the USFBs is up to 10 m with a structural depth of 300 mm (CoSFB reaches a maximum span of 12 m with the structural depth of 350 mm).

3. Steel-concrete composite beams

This section presents different types of flooring systems. Table 1 provides a summary of flooring systems from the literature and identifies the completed numerical and experimental investigation.

3.1. Composite downstand beams

The composite beams further examined here are the ones mainly used nowadays due to the technical and economic benefits they offer. The most common type is the downstand beam which is connected to in-situ reinforced concrete slabs or composite slabs consisted from profile metal deck with shear stud connectors welded on site through the thin galvanized sheets. This type of composite construction has disadvantages related to the high operational cost of the site welding, the delay in curing the wet-in-situ concrete especially in cold weather, achieving short spans corresponding to the depth (for example 150 mm floor depth with a maximum span of 4 m without propping and 210 mm depth with a span of 7 m with propping), the moderate dynamic, thermal, and acoustic performances [12]. To improve some of these limitations a new type of composite beam was later proposed which is incorporating factory-produced precast hollow-core slabs with steel-concrete composite beams as shown in Fig. 7. The term 'hollow-core' refers to cylindrical voids which run internally along the length of the precast slabs, thereby reducing the weight of the slab, typically by about 35%. The main advantage of using hollow core precast units (HCU) is its excellent structural capacity to self-weight ratio,

with span-to-depth ratio equal to 35 for office buildings. The lower weight is enabling for longer spans which is another advantage, especially for office buildings but also for architectural purposes where adding columns can be undesirable or unfeasible. The amount of concrete needed is also reduced, making this system both economical and more environmentally friendly while its carbon footprint is reduced. Transport cost is also a pivotal economic factor. Initially, the steel beam was designed in bending as a separate entity from the concrete precast unit while no account was considered. In addition, there is no much design guidance to cover a wide range of materials and geometric variables found in this form of construction. One of the first studies was carried out at the University of Nottingham where three full-scale bending tests of composite downstand beams with precast hollow-core slabs were conducted in 2000 [13]. The bending tests consisted of $356 \times 171 \times 51$ mm S275 UB and were loaded in four-point bending with a simply supported span of 5.7 m, together with 150 mm deep×1200 mm wide HCUs connected using headed studs shear connections. From the tests, it was apparent that the composite beams are twice as strong and approximately three times as stiff as the equivalent isolated steel beams initially considered – it is worth to note that there is some in-situ concrete fill around the shear studs and transverse reinforcement to provide the longitudinal shear capacity. The shear capacity of the headed studs shear connectors used with precast hollow core slabs was also investigated through finite element (FE) modelling taking into account the linear and non-linear behaviour of all the materials [14]. The accuracy of the model was demonstrated through the validation against test results. More parametric studies investigated the effect of change the transverse gap size, transverse reinforcement diameter, and in-situ concrete strength on the shear connection capacity. Furthermore, the shear capacity of the headed shear studs used with precast hollow core slabs was also examined through 72 full-scale push tests [15]. These tests were validated with seven push-out tests with headed studs in solid RC slabs. Newly proposed design equations for calculating the capacity of shear studs for this form of composite construction were then provided.

Research also expands to the use of composite beams made of cold-formed steel sections that work together with concrete, and they can offer high flexibility in design as well as enabling shallow slab depths,
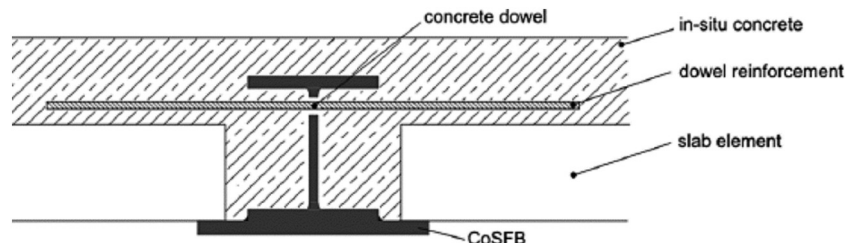

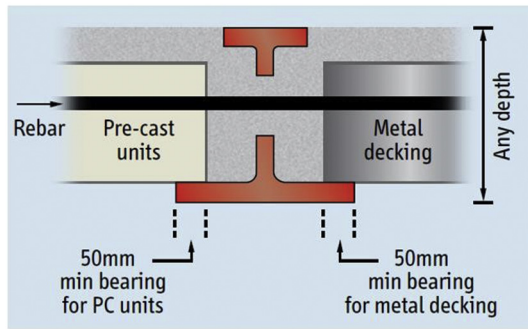**Fig. 4.** Composite Slim-Floor Beam Section (CoSFB) [10].

Fig. 5. Ultra-Shallow Floor Beam Section [11].

flexibility in designing cross-sections and adapting irregular geometries, as well as profit of availability of materials and sections in stock. The system consisted of cold-formed and built-up sections connected with precast concrete planks using self-drilling screwed cold-formed shear connectors as shown in Fig. 8 [16]. This was followed by the development of a new composite beam connecting with a flooring system, which achieves higher strength and ductility and provides an economical design [17]. The new composite beam system consists of three elements, as follows:

• Reinforced concrete slabs on corrugated cold-formed metal decks;
• Back to back cold-formed steel joists;
• Continuous cold-formed furring shear connectors.

It has been indicated that further studies are needed to investigate the use of steel beams with web openings and precast concrete slabs to form long span composite beams, which have a potential impact on the design of multi-storey buildings.

3.2. Slim-floor beams

To replace the composite downstand beam, slim-floor beams are established at the beginning of the 1990s by incorporating the structure within the structural depth of the floor. The reduction in floor-to-floor depths by about 300 mm multiplied by the number of storeys of a building will lead to significant savings on cladding costs (otherwise more floors can be constructed at a restricted building height, thus an important economic benefit). Slim-floor (from the Slimflor system) beam typically consists of a column section up to 305UKC with a thick plate of 15 mm, as shown in Fig. 9. A wide plate is welded under the bottom flange which provides a bearing length of 100 mm for precast units and decking units such as ComFlor 225 metal decking [18]. The same shear connection (stud shear connection) used in the composite downstand beam is used within the Slimflor system. There are two types of Slimflor beams: non-composite or composite with the use of shear stud connections, as shown in Fig. 9. The weight of the Slimflor beam is reduced compared with the composite downstand beam.

Slimflor spans are in the order of 5-10 m. Therefore, the use of downstand beams is somewhat reduced, leading to a flat or ribbed floor of the minimum possible depth and the requirement of fire protection. The design of the Slimflor beam is in agreement with the principle rules of Eurocodes 3 and 4. Intensive experimental work was conducted at City University London investigating the use of slim-floor beams with profiled deep decking with certain proposals made [19,20]. The behaviour of slim-floor beams with hollow core precast slabs was examined through another experimental campaign [21]. Large deformations were observed from the tests due to the plasticity of the supporting beam, which causes earlier failure of the slabs. Design guidance for slim-floor beams with hollow core precast slabs was introduced in BS5950: Part 1:1990. It is worth noting that slim-floor beams can achieve 60 min fire resistance without protection [22]. No studies have been identified to address the SLS criteria which should be verified with particular attention to the vibration performance.

3.3. Asymmetric Slimflor Beams (ASB)

The Asymmetric Slimflor Beam is a rolled beam section with thick flanges to enhance the torsional stiffness. The top flange is patterned to provide the composite action between the steel beam and the concrete slab without the use of shear studs. The additional plate is not required in this type, as shown in Fig. 10, due to the asymmetry of the flanges. This type of slimflor beam has been developed for use with ComFlor225 deep decking to form the Slimdek system (Fig. 8). ASBs are available in two depths, the most common are the 280 mm and the 300 mm ones. The weight of the ASB is reduced compared with the slimflor beam as the underneath plate was eliminated in this type. No shear connectors are used in the ASB. The effective span of ASB is 6–7.5 m with a depth of 310-340 mm compared with the span of slimflor beam 5-10 m with a depth of 280-320 mm. Researchers have done extensive experimental studies of ASB with 280 mm and 300 mm depths and with a span of 7.5 m [24]. Full-scale load tests have been carried out using the ASB section to assess the degree of composite action that can be used at the serviceability and ultimate limit states. The design of ASB with precast hollow core slabs has also been studied and design guidelines have been proposed while they cover two types of structures: with and without the concrete topping [25]. The ASB can achieve 90 min fire resistance, higher than the 60 min fire resistance of the slimflor beam [26]. It is indicated that further studies are needed to investigate the dynamic behaviour of the Asymmetric Slimflor beam including the vibration response of such complex systems.

3.4. iTECH floor beams

Another type of shallow floor beams, a competitive type to slim-floor beams, is developed by Korean researchers in 2002 and called iTECH beam. It consists of an asymmetric steel beam section with web openings, by welding a top plate to a bottom tee-section cuts with a

(a)   (b)

Fig. 6. (a) USFB with Precast Hollow-core Slabs, (b): USFB with deep metal deck [11].

Table 1
Flooring systems types.

	Composite downstand beam	Slim-floor beam	Asymmetric Slimflor beam	ITECH floor beam	Delta floor beam	USFB	CoSFB
Type of shear connection	Shear stud connection	Shear stud connection	Using top flange embossment connections	Bearing concrete passing through the web opening shear connection	Bearing concrete passing through the web opening shear connection	Plug composite action shear connection	Concrete dowel shear connection
Span limitation (m)	4–6 with metal deck 6–12 with HCU	5–10	6–7.5	7.5–15	Up to 13.5	Up to 10	Up to 12
Depth limitation (mm)	steel depth + (120–160) mm slab depth	280–320	310–340	300 and > 300	200–500	300	350
Fire performance (min)	30–240	60	90	40	60	40	60
Vibration performance (Hz)	N.A.	N.A.	N.A.	>3	>3	>3	>3

half hexagon pattern cell. To support the deck, non-structural channels are fixed to the bottom flange of the steel beam. The composite action is provided by the bond strength of the interface between the concrete slab and the steel beam without the need for shear connectors. In addition, the bearing strength of the concrete passing through the web openings is providing a (shear) connection between the steel and the concrete. The advantages of the iTECH floor beam system are: reducing the construction cost by about 5.6% and 6.8% compared with that of steel or RC frame structures, respectively; reducing the construction time compared with that of RC slabs; improving the construction quality and construction management; providing a flexibility in planning; and reducing the depth of the floor due to shallower beam depth. The iTECH floor beam can span from 7.5 m to 15 m with a depth of 300 mm including the services while the span of slim-floor beam reaches 5-10 m with a depth of 280–320 mm. The contribution of each shear component in the iTECH floor beam such as steel web, inner concrete panel, and the outer concrete panel was experimentally investigated and a design methodology for calculating the shear capacity was proposed [27]. Another research has focused on the evaluation of the shear and flexural capacities of iTECH beam [28] and the results have shown that iTECH beam can be efficiently used as a shallow floor beam system for high-rise residential buildings for saving space from the reduced structural depth. The flexural behaviour of iTECH beam was also assessed using a simple beam test [29]. The results were compared with the slim-floor beam and the iTECH bare (non-composite) steel beam to evaluate the horizontal shear resistance under construction loads. A satisfactory horizontal shear resistance and a good composite behaviour were obtained for the iTECH composite system. Since the depth of iTECH system is shallower than the typical SCC beams, the serviceability design was questionable and thus the vibration characteristics of the iTECH system were then tested at each construction stage (i.e., erection stage, concrete casting stage, and finishing stage) [30]. The serviceability responses were also evaluated according to JIS, ISO, and DIN standards. The iTECH system has shown adequate

vibration capacity (>3 Hz). The fire resistance of iTECH system achieves 40 min though, which is less than the one the slim-floor beam can achieve (60 min). It is indicated that further studies are needed to examine the suitability of using other types of slabs, such as hollow core precast slabs and composite slabs together with the iTECH beam technology.

3.5. Delta beams (DELTABEAM)

Another innovative type of shallow floor beams called Deltabeam and comprises from a steel boxed section with web openings was first introduced by Peikko Group. The shear connection is created by the bearing concrete passing through the web openings, which are regularly spaced along the steel beam, and different from the shear connection used in slimflor beam. Several types of slabs can be used with Deltabeam, such as hollow core precast slabs or other types of composite slabs. It is available with a variety of depth ranging from 200 mm to 500 mm (excluding concrete depth) for both single and multi-span beam arrangements, as shown in Fig. 11. According to the manufacturer, it achieves a span of 13.5 m with a depth of 500 mm compared with 10 m of slim-floor beam and 15 m of iTECH beam [31]. The advantages of using Deltabeam are the reduced construction height, the rapid and easy installation, and the cost-efficiency of the system. One of the fundamental components in Deltabeam construction is the concrete dowel connection. The shear-slip properties of the concrete dowel connection were examined extensively through push-out tests using various edge profiles in the circular plate opening [32]. A modification was also applied to Deltabeam to increase its vertical shear resistance by using headed shear studs and take advantage of its tensile resistance when embedded in concrete to make it behave as a "tie" in composite beams [33]. Later on, studies examined the flexural behaviour of long simply supported Deltabeams and the results demonstrated that a beneficial structural response was achieved through such properly reinforced slim floor beams, and can be implemented by the designers not only for typical ultimate states but also for the extreme cases, such as progressive collapse and accidental loadings [34]. The fire resistance and vibration performance of Delta beam was also examined and it achieves 60 min and >3 Hz, respectively [35,36]. It is recognised that further studies are required to examine the fire resistance of Deltabeam due to the complexity its configuration (e.g., the effect of air-gaps). (See Fig. 12.)

3.6. Ultra-Shallow Floor Beams (USFB)

An advanced type of shallow floors beams was developed by Westok. known as Ultra-Shallow Floor Beam (USFB), which is a perforated steel beam incorporated the floor slabs within the steel flanges. Two highly asymmetric cellular tee-sections welded together through the web. The two tee-sections are cut from different parent plain
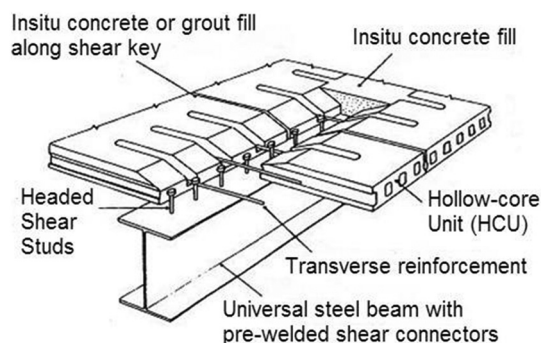

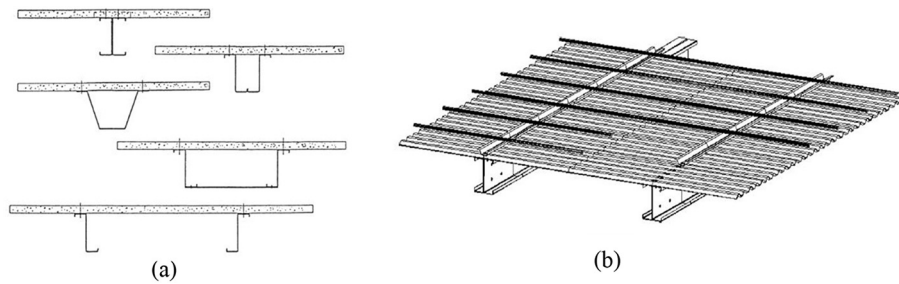**Fig. 7.** Composite beam with hollow-core precast slabs [12].

Fig. 8. (a) Typical composite cold-formed beam sections [14], (b) New composite beam system [15].

sections, as the top tee is a universal beam and the bottom tee-section is a universal column. This configuration has reduced the weight of the beam and increased shear and moment capacity. The shear connection is formed by the concrete which is passing through some or all of the web openings, depending on the configuration of the metal deck (shallow or deep), is similar to the shear connection used in the iTECH beam and Deltabeam and different from the shear connection used in slim-floor beams. The effective span of the USFB is up to 10 m with a depth of 300 mm, therefore it achieves longer spans with shallower depths compared with other shallow floor beams (slim-floor beam, iTECH beam, and Deltabeam). Like other systems, this construction methodology minimises the structural depth and weight of the composite systems. It is recommended that re-bars are provided within the web openings to improve the continuity of the slabs either side of the beam web. This form of concrete dowels enhances the longitudinal and vertical shear resistance as well as the fire resistance [37]. In case of deep metal decks, the composite systems can be designed in such a way to allow for (approximately) every 2 web openings to be positioned where the troughs of the metal deck are, thus leave the opening free to service integration, such as the incorporation of passive air cooling/heating pipes. During a PhD research published in 2012 from City University London, in collaboration with Westok (Kloeckner Metals UK), it was demonstrated that ducting pipes can replace the tie-bars without the loss of structural integrity, providing the ducts were not located near areas of high vertical shear forces [38]. The contribution of concrete which lies between the flanges of the USFB steel section to resist the vertical shear forces was extensively investigated [11,38]. The results revealed a significant increase in shear resistance of the USFBs comparing with the bare perforated steel beams. Another interesting aspect of the USFB system is the overall flexural action which was addressed in a study of partially encased USFBs. The main objective was to establish the bending resistance of the composite USFB beam and the longitudinal shear resistance of the unreinforced and reinforced 'plugs' using either tie-bars and bearing concrete (concrete dowel), ducting, or headed shear studs welded transverse to the web [39]. It was established that the shear transfer mechanism of the USFB beams

is different from the conventional headed shear studs as it was found through push-out tests. The failure mechanism of the shear connection was extensively studied which led to the development of a calculation method for the shear resistance of the shear connection [40]. Furthermore, two types of concrete (normal and fibre-reinforced concrete with synthetic fibres) were also used for the concrete slabs and push–out shear tests of the USFB system to examine the relationship between the concrete strength and the shear connection [41]. The research can be evolved by further improving the tensile strength of the normal concrete as well as the sustainability aspect with the use of steel fibres, plastic fibres, and waste steel wires [42]. Aiming to make the USFB system span longer, be lighter and shallower, the SLS and in particular, the vibration criteria should be met. Experimental and numerical models representing the floor were analysed focusing on the fundamental frequencies in order to understand the probability of resonance of the USFBs [43–45]. The comparison showed that the slabs with fixed supports were more preferred as they yield higher natural frequencies while, as it was anticipated. Moreover, the increase of the slab span reduced the natural frequencies. Interestingly, it was observed that the slab thickness (i.e., type of metal deck – shallow or deep) significantly affected the natural frequencies with a parabolic behaviour (change of the effect at a thickness of 150 mm–measured from the bottom steel flange upwards, for both fixed- and pinned-support slabs) which was consisted in all computational studies independent of the support conditions, spans, and modelling technique [44]. This type of floor beams shows an adequate vibration capacity and fire resistance however, more research is suggested in the area of fire performance of USFBs when steel and plastic fibres are employed.

3.7. Composite Slim-Floor Beams (CoSFB)

A recently developed slimflor is the composite slim slim-floor (CoSFB) which consists of a steel section with web openings and a plate welded to the bottom flange. The shear connection between the steel beam and concrete slab in this type of slim-floor is provided by the concrete dowels and it is different from the shear connection used
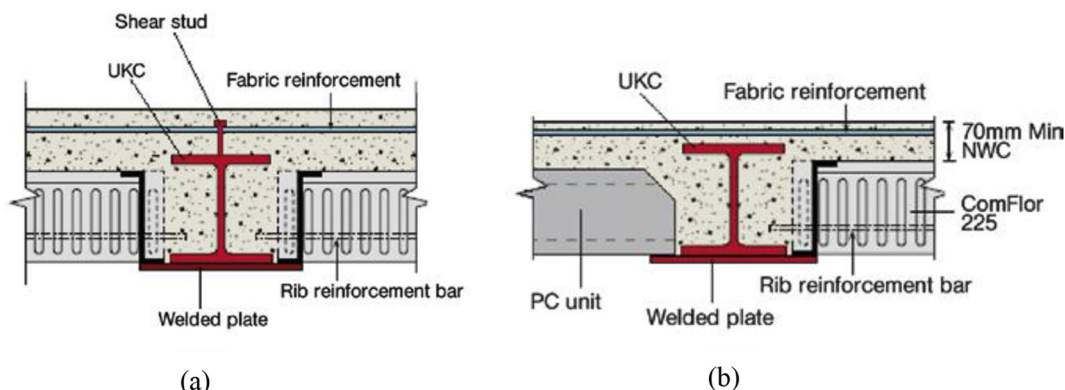

Fig. 9. (a) Composite Slimflor, (b) Slimflor with ComFlor 225 or PC Unit [18].
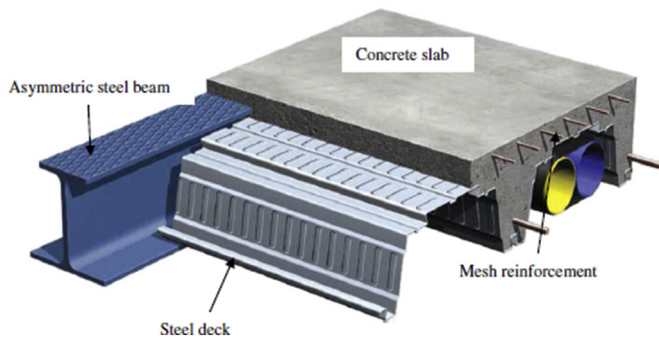
Fig. 10. Asymmetric Slimflor beam incorporated with ComFlor225 deep decking [23].

Fig. 12. Typical Deltabeam [32].

in slimflor beams but similar to the shear connection used in iTECH beam, Deltabeam, and USFB. This new slim-floor beam is developed by ArcelorMittal through combining concrete dowel technology with SFB. The advantages of the CoSFBs are increasing the span of the slim-floor beam from 10 m with a depth of 320 mm to 12 m with a depth of 350 mm, improving the performance of slim-floor construction due to the composite action, reducing the steel consumption and cost, simplifying the fabrication and erection, reducing the CO_2 impacts from the construction process, enhancing the fire resistance up to 60 min and anticipated vibration performance [7]. One of the first studies on composite slim-floor beams investigates the global behaviour of these flooring beams through experimental analyses with full and partial innovative shear connections (i.e., concrete passing through all holes or some of them, respectively) [10]. Sufficient load bearing capacity and ductile behaviour of this innovative shear connection system was estimated for such beams. Another experimental program was performed with the intention of investigating the load bearing behaviour of deep embedded concrete dowels in CoSFBs through experimental tests [46]. Specific focus was given to the effect of the concrete dowel resistance to the concrete compression class. The results proved that the use of concrete dowels considerably increase the load-bearing capacity of the floor beam. To simulate the load bearing behaviour of concrete dowels in CoSFBs, a finite element analysis study was developed [47]. It was proved by the validated model that the concrete dowels demonstrate high stiffness under service loads and ductile behaviour in reaching the load bearing resistance. The serviceability limit state for this type of slim-floor beam was also examined and it showed an adequate performance in terms of vibrations.

Table 2 summarises information about selected building projects with the aforementioned flooring systems.

4. Steel-concrete composite slabs

Composite slabs proposed as a solution to speed the construction process eliminating or reducing falsework and formwork, and making construction sites cleaner and safer. The American and European industries offer a large variety of products to be used as metal decks. There is a number of profiled metal sheets available, from shallow to deep profiles
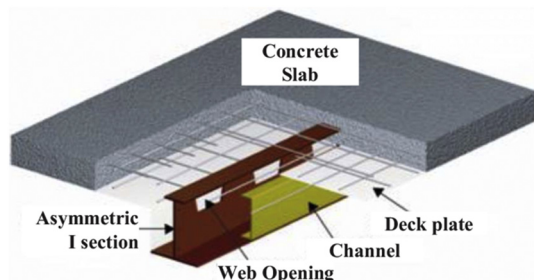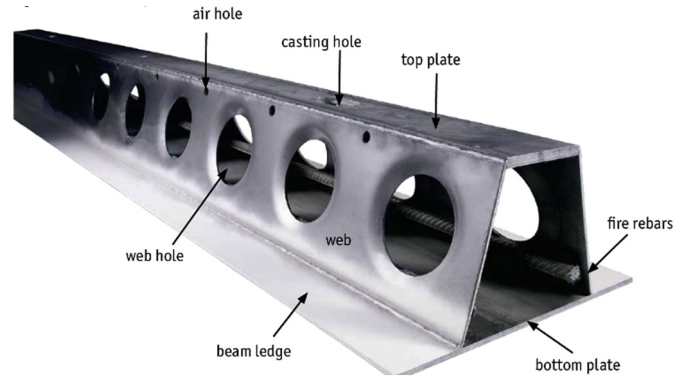

Fig. 11. Schematic of iTECH beam [28].

ideal to be used for slim-floor construction systems. One of the first studies on full-scale composite slabs investigated the behaviour of metal decks through experimental testing, established well-documented data on the overall performance and the maximum load-carrying capacity of slabs [48]. A new calculation procedure was then proposed and provided an alternative to full-scale testing for composite slabs with metal deck used in buildings. The design process involves the combination of shear-bond test results with numerical analyses to predict the behaviour and strength of composite slabs. Reasonable and conservative predictions of the ultimate load-carrying capacity for one-way spanning composite slabs were established when compared with the experimental findings. The effect of using end-anchorages provided by the shear studs on the shear-bond action in simply supported and continuous composite slabs with metal decks was also examined [49]. Experimental analyses demonstrated that slabs with end-anchorage provided by the steel shear connectors offer higher shear-bond strength than the ones without it [50]. Further experimental analyses provided a better understanding of the shear behaviour of composite deck slabs to establish the shear strength under flexural loads. One failure mode which was observed for all tested specimens was the rupture of the shear bond. To improve the shear bond characteristics, the cold-formed profile sheeting is provided with embossments. The shear bond behaviour of the embossed composite deck slab was also investigated under imposed loads and evaluated using the m-k method (an empirical method to predict the longitudinal shear resistance of composite slabs).

4.1. Cofradal slab

The use of the steel-concrete composite prefabricated slabs is significantly increased, as it leads to further reduction of the overall floor weight, primary energy and resources consumption in addition to the overall building cost comparing with traditional composite slabs. Cofradal slab is one of the steel-concrete composite prefabricated slabs which is used with the CoSFB [51]. It is a fully prefabricated composite slab, which consists of a cold-rolled metal deck, and a thermal insulation layer. The depth of the unit is fixed at a total thickness of 260 mm and weight 2.8 kN/m^2. Two widths can be provided 600 and 1200 mm with a span of 7.8 m. Table 3 shows different depths of Cofradal slab with different spans.

4.2. Prefabricated Ultra-Shallow System (PUSS)

Another type of fully prefabricated steel-concrete composite slab, which can be a comparable slab to the Cofradal slab, is developed in 2017. This is a fully prefabricated system and is using lightweight concrete (LWC) [52,53]. As a result, the self-weight of the floor is dramatically reduced which then results in the reduced size of beams, columns, and foundations. Due to the use of lightweight materials, the Prefabricated Ultra-Shallow System (PUSS) offers savings in site

Table 2
Building projects with selected flooring systems.

Floor beam type	Slab type	Project	Location	Use	Completed
Integrated floor beam	Hollow core	ArcelorMittal Office Building	Luxembourg, German	offices	1993
Slimflor beam	Hollow core	Santa Maria della Misericordia Hospital	Udine, Italy	Hospital	2013
Slimflor beam	Cofradal slab200	Petrusse Building	Luxembourg, German	offices	2016
Slimflor beam	Cofraplus 220	Galerie Kons building	Luxembourg, German	offices, retail shops, residential flats, underground parkings	2016
CoSFB	Cofradal slab 260	University residence	Nimes, France	residential	2016
USFB	Hollow core precast slab	Phoenix Medical Centre	Newbury, UK	Hotels and retails	2010

transportation and handling of the prefabricated units as well as reduces the need for formwork and propping during construction. Its thermal properties were also optimised in the design of this new system using insulation materials. It also shares a common feature with the flat ribbed slabs, as shown in Fig. 13, which further minimises the overall floor depth and weight in addition to the use of lightweight concrete and shallow thin-walled C-channels. The manufacturing process and the particular composite mechanism developed offer three key advantages [54]: (i) the reduced number of erection (installation) lifts by using lighter elements and the wider possible units to fit road tracks for transportation; (ii) the reduced site work by the full offsite fabrication - examining the material cost against the fabrication and site erection costs are proportionally in the order of 35% and 65%, respectively; and (iii) the reduced energy consumptions and CO_2 emissions by using prefabricated lightweight materials. The unique shear transfer mechanism of the proposed flooring system is formed by the combination of dowels and web-welded studs with two different types of concrete which have been investigated through push-out tests [55], while the research is still ongoing. Consistent behaviour is demonstrated by this type of shear connection system with plastic distortions occurring before and after the ultimate load. In general, the shear capacity of the connectors increases with the increase of the concrete strength. It is suggested that further studies are required to investigate the bending behaviour of large span PUSS slabs as well as their fire performance; especially due to the prefabricated nature of it with PUSS units placed next to each other and back-to-back steel. Table 4 shows different examined spans and depths of the ultra shallow flooring system with lightweight concrete of a density of 1700 kg/m^3. (See Figs. 14 and 15.)

5. Advanced numerical modelling

The aim of this section is to present an overview of the approaches which are widely used for modelling steel-concrete composite systems and identify the differences between them in terms of accuracy and time-cost. There is a variety of SCC structural systems such as framed structures using SCC members, components (e.g., composite beam-to-column joints), and sub-assemblages (e.g., steel and reinforced concrete (RC) components) which are designed in a way to optimise the resistance and deformation capacity [56]. SCC structures have been widely used because of the effectiveness in combining these two structural materials which are identified for their excellent seismic performance due to their high ductility, high strength, and high energy absorption [57]. These structural systems have better structural damping properties due to the friction between steel and concrete interfaces which make them a good alternative for seismic resistance. The integaration of these two materials (steel and concrete) can further enhance the lateral stiffness and the strength of SCC frames,

with improving their vibration response. However, a complex behaviour is shown by SCC beams when subjected to lateral loading due to the number of factors involved (i.e., the interface slip between the steel beam and the concrete slab, the variation of longitudinal stress through the slab width, and the overall configuration of different types of models). Consequently, it is critical to account for the local connections (for example, the interface behaviour between steel and concrete) throughout the analysis of SCC structures in addition to the local behaviour of the structural system (e.g., beam-to-column connections and base plates). A plethora of experimental works and FE analyses were performed to improve the understanding of SCC structures while a number of numerical modelling procedures were established and validated to simplify the analysis of these hybrid structures. In addition, commercial FE packages (such as ANSYS, ABAQUS, ADINA, DIANA, LS-DYNA, and MIDAS) use validated constitutive models which confirm on the description of post-peak material characteristics; for example, the strain hardening and softening, the tension stiffening, the shear retention ability, etc. [58].

5.1. Modelling of SCC systems

Researchers have developed various models to accurately and reliably represent the behaviour of SCC systems based on either concentrated or distributed plasticity. Nonlinear analysis models of SCC elements and frames found in the literature can be generally categorised into micro-models using continuum finite elements, and macro-models using macro-elements such as line elements and spring connections.

5.1.1. Micro-modelling approach

The micro-modelling approach can be used to simulate the behaviour of composite members with better resolution than the macro-modelling approach which is adequate but provides reduced accuracy due to the reduced modelling resolution, while simplified models are least accurate. However, micro-models consume more time especially for the nonlinear analysis of a structural system or a complete structure. They use extremely fine meshing techniques which involve three-dimensional solid finite elements with dense distributions. Some examples of these modelling techniques required for the analysis of SCC structures are introduced by Nethercot and Ahmed [59], Baskar et al. [60], El-Lobody and Lam [61], and Nie et al. [62]. The available commercial FE software packages (e.g., ABAQUS, ANSYS, and similar) which are used for such simulations apply concrete constitutive formulations which have been established from small-scale unreinforced or uncracked concrete elements. The increased calculation time and modelling effort make this simulation approach unpractical for common engineering practice. It is suitable for studies of local structural areas

Table 3
Load span of Cofradal slab with depths <300 mm [51].

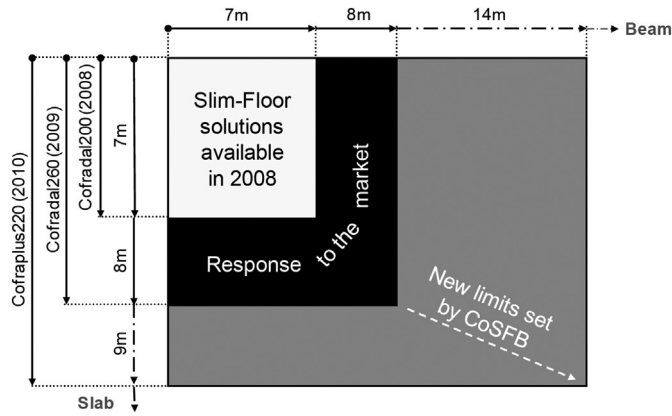| Floor Type	Maximum Span (m)	Unit Depth (mm)	Overall Floor Depth (mm)	Total Floor Weight (kN/m^2)	Live Load (kN/m^2)	Unit Width (mm)
Cofradal 200	7.0	200	200	2.4	4.3	1200
Cofradal 230	7.5	230	230	3.1	3.5	1200
Cofradal 260	7.8	260	260	2.8	2.5	1200

Fig. 13. Economic floor solutions [10].

as well as sensitivity studies with detailed knowledge of geometry and composing elements and materials.

5.1.2. Macro-modelling approach

Macro-models provide a new approach for estimating the nonlinear responses of frames. Many studies have focused on developing the discrete line elements for simulating the composite members through integrating concentrated and distributed plasticity (Ayoub and Filippou [63] El-Tawil and Deierlein [64], Sebastian and McConnel [65], Ranzi et al. [66], Salari and Spacone [67]). An ideal application of concentrated plasticity is a beam with hinge elements as formulated, for example, by Hajjar and Gourley [68], Hilmy and Abel [69], and Kim and Engelhardt [70]. The models of distributed plasticity are based on discrete fibre elements which can be found in the research works of El-Tawil and Deierlein [71], Hajjar et al. [72], and Lee and Pan [73]. However, most of the formulations for these two approaches are complex and not adjustable to routine and generic application in structural engineering analysis and design.

Macro-modelling approach is applicable when the structure is comprised from solid elements with sufficiently large dimensions that the stresses across or along a macro-length will be essentially uniform. Noticeably, macro-modelling is more practical compared to micro-modelling, due to time reduction and need for lower computing power requirements which usually provides a user-friendly mesh generation. In the case of conventional reinforced concrete (more computationally intensive than steel) FE modelling; it is not uncommon for macro-modelling techniques to be shown to provide superior results to many micro-modelling techniques presented in the literature and done via commercial packages.

5.1.3. Simplified modelling approach

Due to the aforementioned reasons, a new simplified modelling approach was introduced based on the research works of Thevendran et al. [74], Spacone et al. [75], Bursi et al. [76] and Zhao et al. [77] focusing on the nonlinear analysis of the SCC beams and frames using deformable shear connectors. In this approach, the beam and column members are simulated using line elements, and the interface between the steel

and concrete using nonlinear spring elements. The proposed method can be used in existing software for the nonlinear structural analysis. The modelling resolution of the proposed macro-model is validated against experimental results of full-scale composite beams tests under both positive and negative bending. The macro-model responses are also compared with results generated from highly-reliable FE simulations. The proposed macro-model is established from the distributed plasticity approach. The computational time is significantly reduced by using simplified elements.

6. EUROCODE 4 provisions and research updates

The focus of this section will be on presenting the design methodologies of new shallow steel-concrete composite flooring systems which involve different types of shear connections developed for these particular shallow systems. This section is limited due to the availability of information of these types of shallow composite flooring systems while the research is still ongoing. As a guideline for the research findings in the area of shallow flooring systems, this section will also present the design of downstand composite beam using headed studs shear connectors according to Eurocode 4.

6.1. Shear connection

6.1.1. Stud shear connectors

According to BS EN 1994-1-1, §6.6.3 [78], the design resistance of headed shear connectors (studs) embedded in solid concrete should be determined from the smaller of:

$$P_{Rd} = \frac{0.8 f_u \pi d^2 / 4}{\gamma_v} \tag{1}$$

$$P_{Rd} = \frac{0.29 \alpha d^2 \sqrt{f_{ck} E_m}}{\gamma_v} \tag{2}$$

$$\alpha = 0.2 \left(\frac{h_{sc}}{d} + 1 \right) \quad \text{for } 3 \le \frac{h_{sc}}{d} \le 4 \tag{3}$$

$$\alpha = 1 \qquad \text{for } \frac{h_{sc}}{d} > 4$$

Where d is the diameter of the shank of the stud (16 mm ≤ d ≤ 25 mm), h_{sc} is the nominal height of the stud, f_u is the specified ultimate tensile strength of the stud material, f_{ck} is the characteristic cylinder strength of the concrete (of density not <1750 kg/m³), and E_{cm} is the secant modulus of elasticity of the concrete.

6.2. Design of downstand composite beam

6.2.1. Partial shear connection

The design of composite beams is regularly controlled by the degree of shear connection that is provided. Therefore, it is not possible to develop the full plastic moment resistance of the composite section in cases where a fewer number of shear connectors than the number required for full shear connection are provided. This is known as a partial shear connection. The degree of shear connection is defined as at the

Table 4
Span limits for the proposed flooring system.

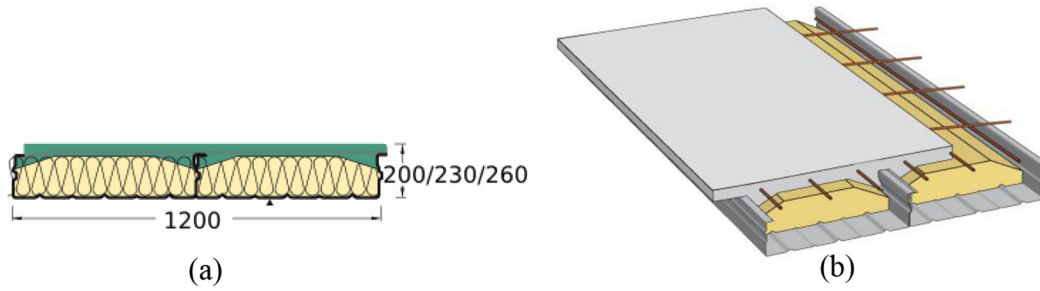| Floor Type	Concrete Type	Concrete density kg/m³	Maximum Span (m)	Overall Floor Depth (mm)	Total Floor Weight (kN/m²)	Live Load (kN/m²)	Unit Width (mm)
Ultra-shallow flooring system	Lightweight concrete	1700	8.0	230	2.67	2.5	2000
			8.0	260	2.71	3.5	2000
			9.5	300	2.81	5.0	2000
			10.0	300	2.81	3.5	2000

Fig. 14. (a) Cross section of Cofradal slab, (b) Cofradal slab [51].

point of the maximum moment, but partial shear connection occurs at all points in the span, depending on the build-up of longitudinal shear.

The degree of shear connection is defined in BS EN 1994-1-1, §6.6.1.2 as:

$$\eta = \frac{n}{n_f} \tag{4}$$

Where n_f is the number of shear connectors required for full shear connection, n is the number of shear connectors provided between the points of zero and maximum moment.

In the case where the tensile resistance of the steel beam exceeds the compressive resistance of the concrete slab over its effective slab width (either limited by concrete compresive resistance of by shear connection provided) ($N_{a,Rd} > N_{c,Rd}$), the above formula can be re-expressed as:

$$\eta = \frac{N_{c,\ max}}{N_{c,s,Rd}} \tag{5}$$

Where $N_{c,max}$ is the total shear force transferred by the shear connectors between the points of zero and maximum moment which is equal to (=nP_{Rd}), $N_{a,Rd}$ is the tensile resistance of the steel section, $N_{c,s,Rd}$ is the concrete compressive resistance over the effective width of the slab ($N_{c,s,Rd} = 0.85\ f_{cd}\ b_{eff}\ h_c$), where f_{cd} is as defined in BS EN 1994-1-1, b_{eff} is the effective width at the position of maximum moment, and h_c is the depth of concrete above the profile, P_{Rd} is the design resistance of the shear connectors used with profiled sheeting (i.e., P_{Rd} as multiplied by k_t or k_l).

For the case when the tensile resistance of the steel beam is less than the compressive resistance of the concrete slab ($N_{a,Rd} < N_{c,s,Rd}$), the maximum force that could be developed in the slab = $N_{a,Rd}$ and the degree

of shear connection can be re-espressed as:

$$\eta = \frac{N_{c,\ max}}{N_{a,Rd}} \tag{6}$$

6.2.2. Linear interaction method

There are two methods of determining the bending resistance of a composite section with a partial shear connection. The simplified method which is the called 'linear-interaction' approach given in BS EN 1994-1-1, §6.2.1.3. The reduced bending resistance is given by BS EN 1994-1-1, §6.2.1.3(5) may be expressed as:

$$M_{Rd} = M_{pl,a,Rd} + \eta \left(M_{pl,Rd} - M_{pl,a,Rd} \right) \tag{7}$$

Where η is as defined in Eq. 5 or Eq. 6, $M_{pl,Rd}$ is the bending resistance of the composite section with the full shear connection, $M_{pl,a,Rd}$ is the bending resistance of the steel section.

For adequate design, $M_{Ed} \leq M_{Rd}$, where M_{Ed} is the design bending moment applied to the beam. The verification may be repeated at opening positions by redefining the shear force transferred as $N_c = n_{sc}\ P_{Rd}$, where n_{sc} is the number of shear connectors from the support to the opening position in the span.

The linear interaction method is conservative with respect to rigid plastic theory (sometimes referred to as the 'stress block' method).

6.3. Design of Delta beams (DELTABEAM)

Peltonen and Leskelä [33] developed a design method for calculating the shear resistance of concrete dowel based on the finding of push-out tests presented as illustrated in Eq. 8. However, the researchers have not
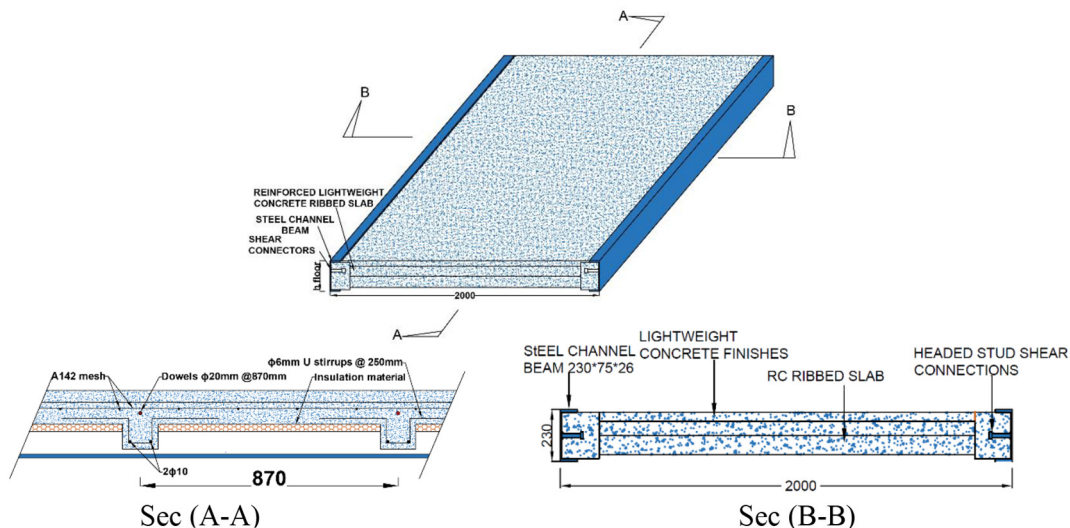

Fig. 15. Recently developed prefabricated flooring system (PUSS) [52–55].

provided any information about the design method for calculating moment capacity of these composite beams.

$$P_{max} = K_R(f_{ctm}) f_{ctm} A_{\varnothing W} \tag{8}$$

f_{ctm}: concrete mean tensile strength;

$K_R(f_{ctm})$: resistance factor which depends on the configuration of the opening (depth and diameter);

$A_{\varnothing w}$: web opening area.

6.4. Design of composite slim-floor beams

Lam et al. [79] proposed a design methodology of slim-floor beam with headed stud shear connectors. The stress block method has been implemented for the design of the slim-floor beams at the ultimate load condition. The design procedures are described in accordance with the principles of Eurocode 4 [78] with two different types of shear connectors (headed stud shear connectors and horizontal headed stud shear connectors).

• slim-floor beam with headed stud shear connectors:

The design formulas given in Eurocode 4 [78] can be used to evaluate the shear capacity of the headed studs shear connectors in slim-floor beams. The concrete failure represented by Eq. (9) while the failure of the headed studs represented by Eq. (10). The smaller value form these two equations is used in the design.

$$P_{Rd} = \frac{0.8 f_u \pi d^2 / 4}{\gamma_v} \tag{9}$$

$$P_{Rd} = \frac{0.29 \alpha d^2 \sqrt{f_{ck} E_m}}{\gamma_v} \tag{10}$$

Where:

f_{ck}: cylinder compressive strength of concrete.

E_{cm}: modulus of elasticity of concrete [N/mm²].

f_u: ultimate tensile strength of headed stud (450 N/mm²).

γ_v: partial safety factor, taken as 1.25 in UK NA and 1.50 in German NA.

α: factor for the height of stud, given by $0.2(h/d + 1) \leq 1$, for $3 \leq h/d \leq 4$.

d: headed stud's diameter.

The effective breadth of the slabs b_{eff} is different for the ultimate and serviceability limit states. For internal beams it can be taken as span/4 however, the value of effective breadth should not exceed the distance between the beam centres. The moment capacity of the composite slim-floor beams depends on the concrete resistance $N_{c,f}$ and steel resistance (steel section N_a, steel plate N_p), which are calculated from the following equations.

$$N_{c,f} = 0.85 \frac{f_{ck}}{\gamma_c} b_{eff} h_s \tag{11}$$

$$N_a = A f_y \tag{12}$$

$$N_p = A_P f_y \tag{13}$$

Where:

$N_{c,f}$: concrete resistance;

f_{ck}: cylinder compressive strength of concrete;

γ_c: partial factor on concrete strength (taken as 1.5 in design and 1.0 for correlation with the beam test);

b_{eff}: effective breadth of slab;

h_s: depth of concrete above the steel flange;

N_a: resistance of steel section;

N_p: resistance of steel plate.

Therefore, the moment capacity for slim-floor beam for full shear connection M_c is given by Eq. 14.

$$M_c = M_s + N_{c,f}\left(h_a + \frac{h_s}{2}\right) + N_p\left(\frac{h_s}{2} + \frac{t_p}{2}\right) - \left(\frac{N_{c,f} - N_p}{4 t_w f_y}\right)^2 \tag{14}$$

Where:

M_c: moment capacity of slim-floor beam for full shear connection;

M_s: moment capacity of slim-floor beam for full shear connection;

$N_{c,f}$: concrete resistance;

h_a: depth of concrete lies between the steel beam flanges;

h_s: depth of concrete above the top steel flange;

N_p: resistance of steel plate;

t_p: depth of bottom steel plate;

t_w: depth of steel web;

f_y: yield tensile strength of steel.

In the case of partial shear connection, the shear force which provided by the number of shear connectors N_q will be less than the shear capacity required to transfer the interface shear force needed. The composite slimflor beam can be designed with a partial shear connection. The moment capacity for the slim-floor beam for partial shear connection $M_{c,partial}$ is given by Eq. 15.

$$M_{c,partial} = M_s + N_q\left(h_s + \frac{h_a}{2} - \frac{y}{2}\right) + N_p\left(\frac{h_a}{2} + \frac{t_p}{2}\right) - \left(\frac{N_q - N_p}{4 t_w f_y}\right)^2 \tag{15}$$

Where:

$$y = \frac{N_q}{0.85 b_{eff} f_{ck}/\gamma_c} \tag{16}$$

N_q: is the longitudinal shear resistance of the shear connectors.

• slim-floor beam with horizontal headed stud shear connectors:

The design shear force of headed studs close to a concrete edge is controlled by a failure which is caused by splitting forces in the slab thickness direction. The rules for calculating the shear resistance of headed stud for the ultimate limit state were based on extensive work of two doctoral theses [80,81], which have been integrated into EN 1994-2, Annex C. The design shear resistance for the longitudinal shear case is determined using Eq. (17) and for transverse shear using Eq. (18). These equations can be used to estimate the ultimate shear capacity of the horizontal headed studs shear connectors in slim-floor beams:

$$P_{Rd,L} = \frac{1.4 k_v (f_{ck} d a_r)^{0.4}(a/s)^{0.3}}{\gamma_v} \tag{17}$$

Where:

a'_r: effective edge distance ($= a_r - c_v - \varphi_s /2 \geq 50$ mm);

$k_v = 1$ for shear connector lies in an edge position;

$= 1.14$ for shear connector lies in a middle position;

γ_v: Partial safety factor according to the National Annex, usually taken as 1.25;

f_{ck}: characteristic cylinder compressive strength of concrete (N/mm²);

d: diameter of stud's shank ($19 \leq d \leq 25$ mm);

h: headed stud's overall height for $h/d \geq 4$;

a: stud's horizontal spacing ($110 \leq a \leq 440$ mm);

s: stirrups' spacing for both ($a/2 \leq s \leq a$ and $s/a'_r \leq 3$);

φ_s: stirrups' diameter for $\varphi_s \geq 8$ mm;

φ_l: longitudinal reinforcement's diameter for $\varphi_l \geq 10$ mm;

c_v: vertical concrete cover (mm).

$$P_{Rd,V} = \frac{0.012 \ (f_{ck}\varphi_l)^{0.5}(d \ a/s)^{0.4}(\varphi_s)^{0.3}\left(a'_{r,o}\right)^{0.7}k_v}{\gamma_v} \qquad (18)$$

Where:

$a'_{r,o}$: effective upper edge distance ($= a_{r,o}\text{-}c_v\text{-}\varphi_s/2 \geq 50$ mm). In addition to the design requirements given, the following conditions should be satisfied: $h \geq 100$ mm; $110 \leq a \leq 250$ mm; $\varphi_s \leq 12$ mm; $\varphi_l \leq 16$ mm.

The splitting force in the slab thickness direction must be resisted by stirrups. Therefore, these stirrups should be designed for the tensile force according to the following equation with $P_{Rd,L}$ and $P_{Rd,V}$ depending on Eqs. (17) and (18):

$$T_d = 0.3P_{Rd,L} + P_{Rd,V} \qquad (19)$$

T_d: splitting force

6.5. Design of Ultra-Shallow Floor Beams (USFB)

The design method for calculating moment capacity of the USFB beams was proposed based on findings of the push-out tests and flexural tests presented by Huo [37]. The proposed design method considered both partial and full composite action provided by the combination of the concrete-infill-only and tie-bar shear connectors.

A new design method for calculating the shear resistance of the shear connectors used in shallow cellular floor beams was also developed. Therefore, the shear resistance of the concrete-infill-only and tie-bar shear connectors is determined from the following equation.

$$P_{uc} = \frac{1.6758(f_{cu} A_c) + 1.4355(f_{ct} A_t) + R_{add}}{\gamma} \qquad (20)$$

P_{uc}: design shear resistance of the shear connectors;
f_{cu}: cube compressive strength of concrete in N/mm^2;
f_{ct}: concrete tensile splitting strength in N/mm^2;
A_c: concrete area in the compression zone;
A_t: concrete area in the tensile splitting;
t: thickness of the web;
D: web opening diameter;
R_{add}: shear resistance of the additional shear connectors such as tie bar or shear studs;
γ: partial safety factor.

The longitudinal shear force of the combined shear connectors in the composite sections, R_q, is calculated using Eq. 21, by using the shear performance of 50%.

$$R_q = \alpha \ P_{uc} \qquad (21)$$

R_q: longitudinal shear force of the shear connectors;
α: shear performance of the combined shear connectors;
P_{uc}: design shear force of the shear connectors.

The concrete slab compressive resistance in full shear connection, R_c, is determined in accordance with BS5950 & EC4.

$$R_c = \sigma_{c,Rd} \ B_e \ D \qquad (22)$$

R_c: concrete slabs full compressive resistance for full composite action;

$\sigma_{c,Rd}$: concrete compressive stress; which obtained from Eq. 23 according to the BS5950, and from Eq. 24 according to EC4.

$$\sigma_{c,Rd} = 0.45fcu \qquad (23)$$

$$\sigma_{c,Rd} = 0.85fcd \qquad (24)$$

f_{cu}: concrete cube compressive strength in N/mm^2;
f_{cd}: concrete design compressive cylinder strength N/mm^2;
B_e: concrete slab effective width;
D: depth of the P.N.A.
The degree of shear connection is determined using Eq. 25.

$$\eta = \frac{R_q}{R_c} \qquad (25)$$

The design moment capacity of the USFB beams in full shear connection, $M_{pl,Rd}$, is calculated using stress block method according to BS5950 or EC4. For the partial shear connection, the design moment capacity M_{Rd} of the USFB beams is determined using linear interaction method in according to BS5950 or EC4.

7. Conclusions

Steel-concrete composite (SCC) structural systems are becoming more popular due to their flexibility, adaptability, and capacity for dismantling and reuse, as well as their environmental and economic impact, in combination with the controlled manufacturing techniques applied in the shop, alike in mechanical, automotive, aerospace and ship-building engineering disciplines. Today, more researchers than ever work towards the development of new sustainable and resilient construction products, supported by the Building Information Modelling (BIM) platform while focusing on the holistic design approach (from handling, operation, maintenance and reuse stages, up to the end-of-life). This paper is a review of some historic and recent developments of SCC systems, with emphasis on the evolution of lightweight and prefabricated systems as they have attracted significant attention the last years.

In particular, the literature has emphasised on the need for more in-depth understanding for the shear-transfer mechanisms in order to further optimise the structural elements and produce more economic and efficient systems. With regards to the structural performance of a frame or a structure, the connections are inevitably the most critical parts of the system and good understanding of their behaviour in different loading conditions is required. Therefore, the flooring systems' contribution to the rigidity of the connections is also a critical design aspect, demonstrating that slabs can have great influence on the behaviour of composite systems. Consequently, their effect must be included in simulation/analyses models. It is also identified that fire assessment and performance of many novel systems is yet to be investigated. Future research will be concentrated in developing eco-friendlier and multi-functional slim and lightweight composite structural systems with particular research efforts focus on the development of robust design approaches and design manuals which allow for flexibility in design and consider installation, dismantling, reuse stages.

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