

Review Article

Innovation of Shear Connectors in Slim Floor Beam Construction

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Composite slim floor systems are increasingly applied in the construction industry. Therefore, several experimental and numerical studies have been conducted to investigate the composite flooring systems and examine the various details that may affect the production of composite floors. This review paper summarises some important developments of composite slim floor beams, such as the type of steel beam cross section and shear connectors used, presenting essential results and important notes from various studies. The fundamental structural elements and the contribution of conducted studies towards improving the shear capacity of composite beams in enhancing the general structural behaviour were also described. Finally, the paper concludes with the potential of a deeper investigation of some issues that accompany the application of certain types of shear connectors or steel shapes used to improve the composite slim floor system so that the improvement construction industry may make the most out of using composite construction techniques.

1. Introduction

Composite construction systems are used worldwide and applied across different types of buildings and bridges. Typically, the composite structure consists of concrete and steel combined to form the composite members (flexural and compression members). The best characteristics of steel and concrete are used to make composite steel-concrete constructions highly efficient and economical. The earliest form of composite construction was a composite steel-concrete beam.

Composite construction is deemed desirable because it offers an efficient combination between steel and concrete, allowing for transferring forces between them and resulting in unique behaviours of the composite members. In composite construction, the tensile stresses are resisted by the highly efficient tensile resistor, steel. Simultaneously, concrete, which can perform well to resist compression stresses, will be resistant to pressure stresses. However, a longitudinal slip between these elements was revealed almost

immediately due to an insufficient bonding between the steel and concrete elements. This necessitated the use of alternate means and procedures to increase coherence and connect the two elements to act as one composite member [1–6].

The shear connector transfers internal forces from the slab concrete or the composite slab deck to the steel beam. Shear flow forces must be resisted by the mechanical shear connectors used for tying concrete components to steel components. Many studies have developed a patent for different types of shear connectors of various sizes, an arrangement with (or without) hoops. It is applied to the top flange of a universal steel beam section by many methods such as deconstructable steel bolted or welding for headed shear stud, arc-shaped reinforcement, channel, Tee, and other types of mechanical connectors to the top flange of a universal steel beam section to prevent a longitudinal slip. Figure 1 shows various kinds of shear connectors [7–23].

In addition, there are kinds of shear connectors that are classified as rigid due to the addition of extra hoops [17], wherein the connector resists the shear forces from the front

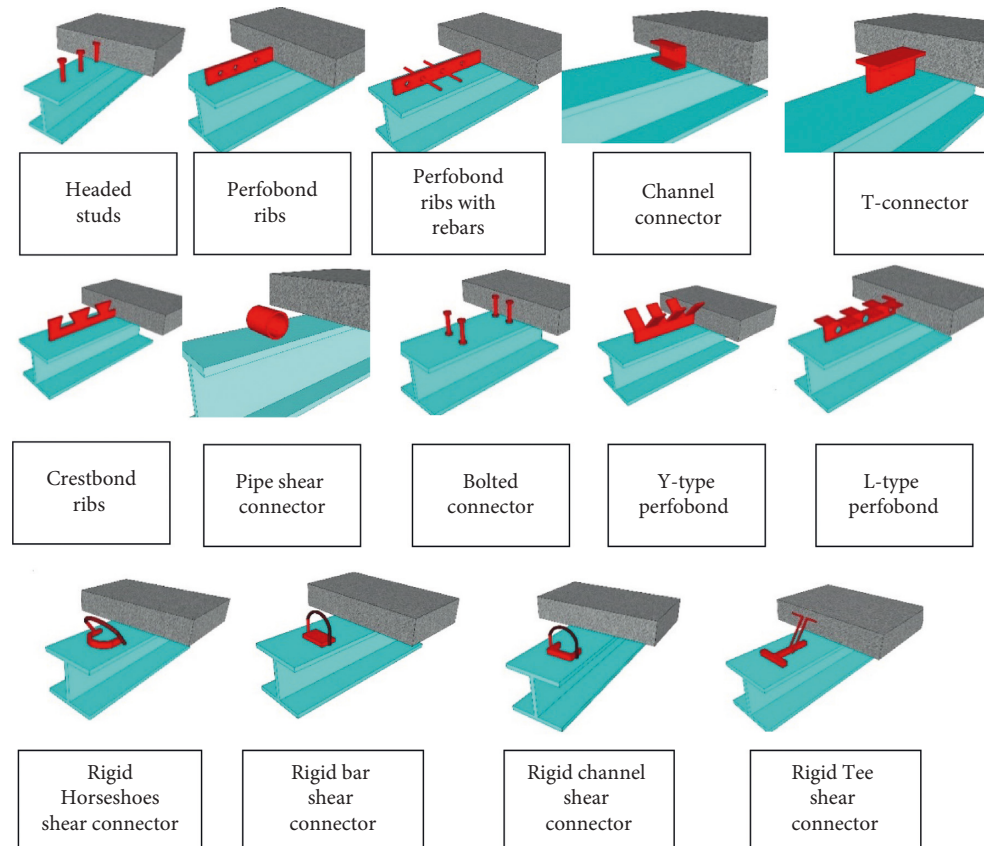


FIGURE 1: Types of shear connectors applied to the top of the steel beam.

side through shearing with minor deformations in the proximity of its ultimate strength. The rigid connectors result generating high stress in concrete around the connector, which leads to concrete or weld failure, such as bar connectors, Tee, channels, and horseshoes, have been depicted in Figure 1. These are welded upon the top flanges of the fabricated steel section.

The composite system has evolved through several stages, often having the steel beam partially or completely incorporated into the concrete slab, instead of being placed underneath. Additionally, due to their specific advantages, different shapes and sizes of connectors are used to produce efficient composite floors to meet the growing demand for shallow floor beams (or cellular slim/shallow floor beam systems). The composite slim/shallow floor construction system is fitted to the range of the flat slab beam, which is applied in the building technology.

Although similarity is observed between the composite shallow floor beam and the slim floor, the web opening feature and the production process of composite slim/shallow floor beams are more advantageous as compared to the conventional downstand composite slab. The increased interest in developing steel-concrete composite slim floor systems resulted in several variants utilising different shapes and sizes of shear connections. In cases of such cellular beams, the first notable advantage is the flat slab structure, which minimises the overall floor depth because the steel beams are embedded in the depth

of the concrete slab. The second feature is the service integration offered by the exclusive characteristic of web openings, which have the ability of passing service pipes through web openings. Another benefit is the improved composite action due to the concrete plug passing through the web opening with tie rebar, where the steel rebar passes through the web opening to the concrete slabs, transferring the longitudinal shear forces. The characteristics of shear connection possess a fundamental significance for the strength and behaviour of these composite systems and the stiffness of the shear connection slip, which satisfy ductility requirements and shear resistance. This is due to the fact that longitudinal shear forces are transferred between the interface of the embedded steel beam within the concrete slab.

This paper presents an overview of composite slim/shallow floor construction systems, including reviews of both experimental and analytical studies. There is a need to describe the significant evolutions particular to this subject, outlining the common advancements in steel-concrete composite slim floor construction methods, and offer solutions proposed to ensure that those shear connections employed are the optimum shear connectors needed. Thus, providing a general overview of modern upgrades in steel-concrete composite slim floor construction methods, describing the ideal composite fabricating methods, and identifying common steel-concrete composite slim floor upgrades were vital.

2. Composite Slim Floor System

Interest in structural solutions to improve the cost efficiency of building flooring systems has steadily grown over several decades. Solutions that propose a decrease in the floor depth are becoming more popular among the many options available. Incorporating the steel beam into the concrete slab makes it possible to reduce the overall size of the building in case the number of floors has been specified or more floors can be laid out within the maximum allowable height of the building.

Fire protection is enhanced by embedding the steel beam in concrete, as the concrete would cover most of beam. Additionally, a higher stiffness through a two-way response will provide better vibration performance (a problem typical of buildings open to the public, such as schools and hospitals). Several features of the composite slim floor attract the attention of various researchers who wish to develop and optimise the most efficient solutions (shapes and connectors) to generally enhance the composite slim floor beam. Figure 2 represents the typical types of components of composite beams based on the shape of the steel beam used and the kind of shear connectors used to tie the steel beams to types of the concrete slab.

2.1. Asymmetric Slim Floor. Slim floor construction has recently become a major interest in the construction field. One of the main reasons for such an interest is the optimum placement of the steel beam within the height of the concrete slab, rather than above it, thus reducing the thickness of the floor construction, providing more interconnections, and enhancing fire protection. Various composite slim floor beams have been introduced in steel frame buildings, including the Asymmetric SlimFlor Beam (ASB), SlimFlor beam, Slimdek beam, and Rectangular Hollow SlimFlor Beam (RHSFB), as presented in Figure 3. The slim floor construction primarily helps eliminate the downstand beams, resulting in a ribbed or flat floor with the lowest thickness and a lower requirement for protection from fire [24]. Most manufacturers are concentrating on the recently proposed SlimFlor to produce novel systems with light components and larger openings, with capabilities to pass services within the web of the steel beam. Consequently, the Slimdek floor system was proposed [25, 26]. In the Slimdek floor system, the steel plate is welded to the bottom flange of the universal column section to create ASB [24]. This is accompanied by an in situ concrete placed upon the profiled steel deck formed to provide composite action without using a traditional shear connector. Various types of slim floor beam systems are presented in Figure 3.

The construction steel markets have introduced a slim floor system named Slimdek. This system is an improved form of the SlimFlor beam, combined with various innovative elements that shall certainly prove beneficial to slim floor construction. Slimdek contains asymmetric steel beam ASB, used in combination with a composite slab of in situ concrete positioned upon a steel profiled deck. The asymmetric beams can be 25% lighter than the traditional

SlimFlor beams. These also allow for the application of larger openings for services on the web. In the manufacturing process, an embossed diamond pattern is flattened on the bottom flange of the beam, and thus, the interaction with the floor slab would not require for the welded shear stud. This is due to the inscriptions on the profile steel sheet that act as shear connections. Moreover, there are other shapes of steel beams that are used in conventional composite beams as square, rectangular, and hexagonal [27], which can be investigated to employ in composite slim floor systems.

These composite floors were based on the need to increase the steel area at the tensile zone compared with the compression zone. Therefore, a difference is created in the flange area while fabricating the steel beam, a reduction is conducted, and the steel is replaced with concrete in the compression zone. Thus, a larger steel area would be placed in the lower part to resist the tensile stresses, and concrete and some parts of steel would remain in the upper part to withstand compression stresses. Figure 3 shows that the red area in the cross section of the steel beam, located under the natural axis, is the area subjected to the tensile stresses, while the blue area on the cross section of the concrete slab and steel beam above the natural axis is subjected to compressive stresses.

In general, the slim floor systems have more features, such as the ability to form several types of shear connectors on the web or flanges of a steel beam. This is a significant advantage as it allows various shapes and types of shear connectors to be built to enhance shear capacity. Furthermore, the interaction faces will increase, which means more interaction between the steel beam and the concrete slab. Also, it will provide fire protection, opportunities to form the fit shear connectors, and depth reduction.

The steel beam with one part (for example, asymmetric I section) is more fully homogeneous than the welded built-up section. That is because extra cutting or welding is not needed to build the steel beam. The welding zone could be a weak point or may need additional work to protect it from corrosion.

In contrast, there may be limitations during designing because the standard section would be a fixed steel area, thus making it inflexible in designing the required moment capacity. Meanwhile, the built-up steel beam sections will be more flexible in designing various resistance capacities as required.

2.2. Composite Shallow Floor. One of the recently developed types of beams is the composite shallow cellular floor beam, commercially produced under the name ultra-shallow floor beam [28, 29]. The fabrication of this type of composite floor uses two sizes of T sections of steel beams. Commonly, a universal column (UC) is cut along the web to provide two symmetric parts that are used as the bottom part of the steel beam. The universal beam (UB) engages in the fabrication of the top part of the steel beam by cutting it at the length of the web. Following this, these different sections are welded along the web to develop the asymmetric I section, where the part of the UC is the bottom part, as it is of a larger area, while the

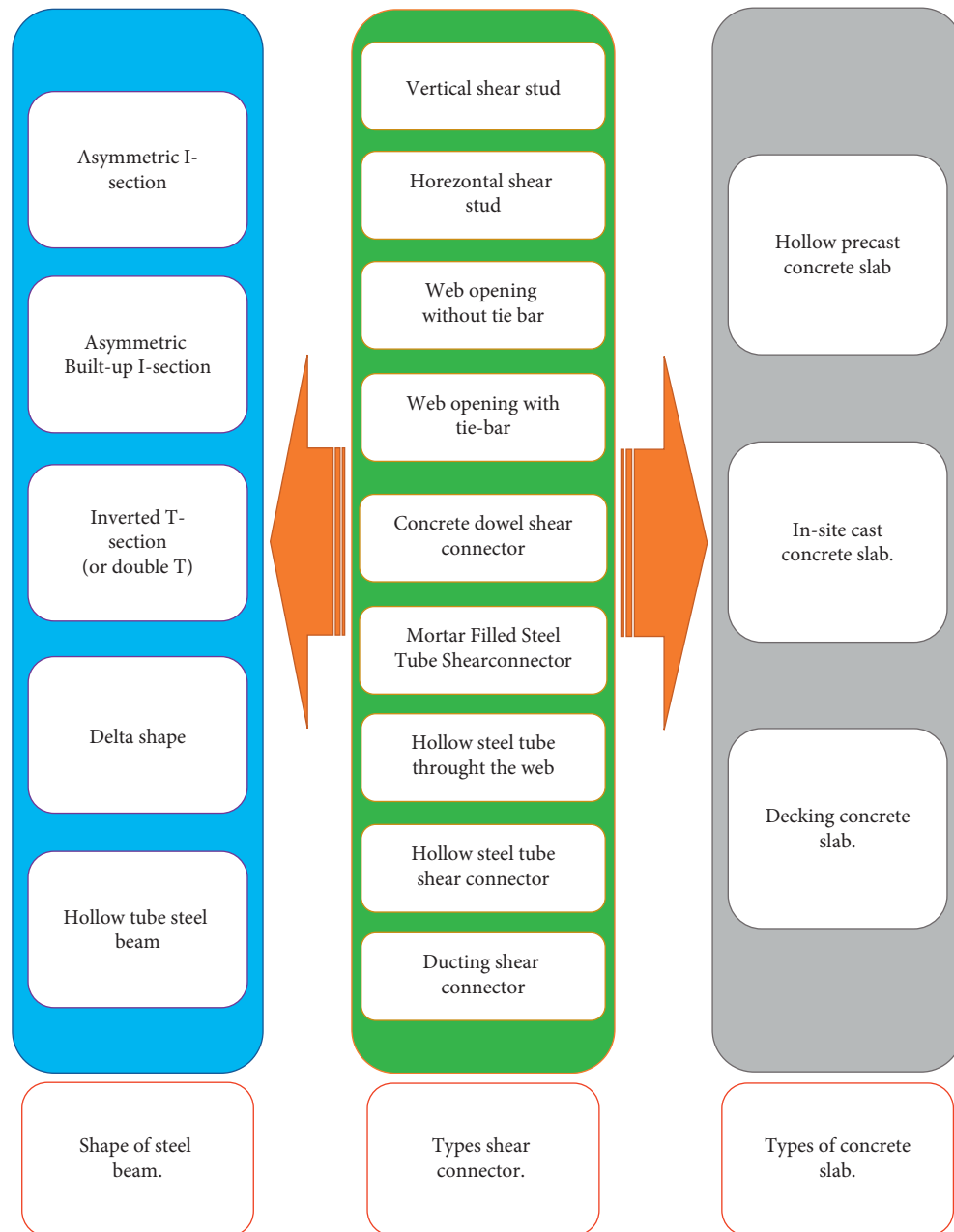


FIGURE 2: Common components of the composite slim beam, steel beam, shear connectors, and concrete slab.

UB is the top part, since it is of a smaller area; see Figure 4. Typically, the top section is of a lighter weight than the bottom steel section. Precast concrete slab or profile steel decking is placed upon bottom flanges, thus creating a shallow flooring system. The construction system of a composite shallow cellular floor beam is suitable in the kinds of a flat slab beam, which is applied to the steel building technology. As mentioned previously, a common characteristic of such beams is that the flat slab system minimises the overall floor thickness [28, 30, 31].

In order to establish flat and shallow flooring systems, the use of an asymmetric section is mandated, allowing for either concrete slab components (precast slabs or steel decks

with the concrete slab) to be set on the bottom flanges of steel sections [32]. The openings are created on the steel web in the composite shallow floor beams, allowing reinforcement tie bars to pass through it [2, 3]. Additionally, some web openings can be utilised to pass construction services as required [29], which reduces the total floor depth [33], removing the undesired additional flooring thickness required for embedding the building services passing beneath the floor. Thus, the system forms a flat floor structure, enabling the building layout design flexibility.

Building up the steel sections is by re-welding the cellular tee along the web to create cellular beams with different cross-sections compared to the parent sections. This kind of

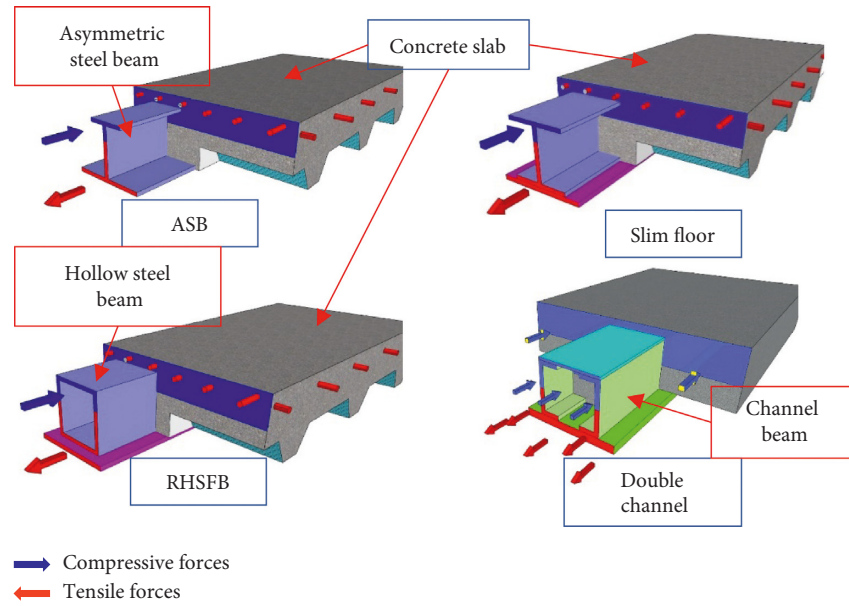


FIGURE 3: Different types of integrated steel beam in composite slim floor.

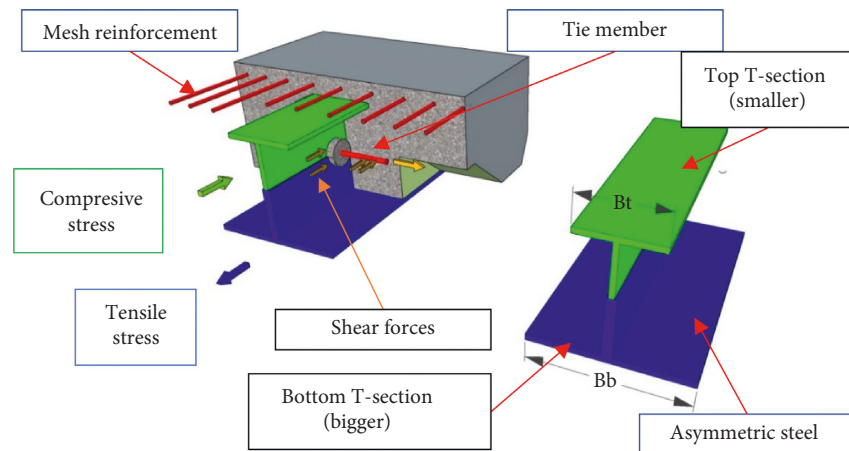


FIGURE 4: Composite shallow cellular floor beam system.

cross section is formed to provide a larger area of steel at the bottom to resist the tensile stresses (blue area under the neutral axis) and reduce the area of steel at the top, replacing parts of the steel area with concrete to withstand the compression stresses (green area above the neutral axis) and contribute to composite action; see Figure 4. The optimum thickness of the steel beam is attained during the designing stage for the asymmetrical section, as the total depth considers a combination of the depths of the bottom and top tees. In general, the manufacturing process offers numerous advantages for the shallow cellular floor beams due to the options available in choosing the area of cross-sectional steel that determines and improves the strength and efficiency of the section and minimisation of the weight and the depth of the beam. A greater capacity of the beam sections can be availed by opting for the stronger parent sections.

The welded zone at the model of the web is vulnerable to higher horizontal shear stresses, as it is known that in a steel

beam with I section, the maximum shear stresses will concentrate in the middle of the section. In addition, the web area will be the position for web opening, which means losing more of the steel area in this zone. Moreover, welding these parts along with the web must consider the quality. All these points should be considered carefully in designing the shallow cellular floor beam.

2.3. Slim Floor with Prestressed Composite Beams. Normal composite systems such as the slim floor or shallow floor are sometimes inadequate to meet certain construction requirements. This limitation motivated various researchers to explore other effective solutions for example, a slim floor structure with pre-tensioned tendons, and this construction system is constructed with a concrete slab (precast or pre-tensioned slabs) and set on a steel beam to be a composite slim floor with prestressed cables, as represented in Figure 5.

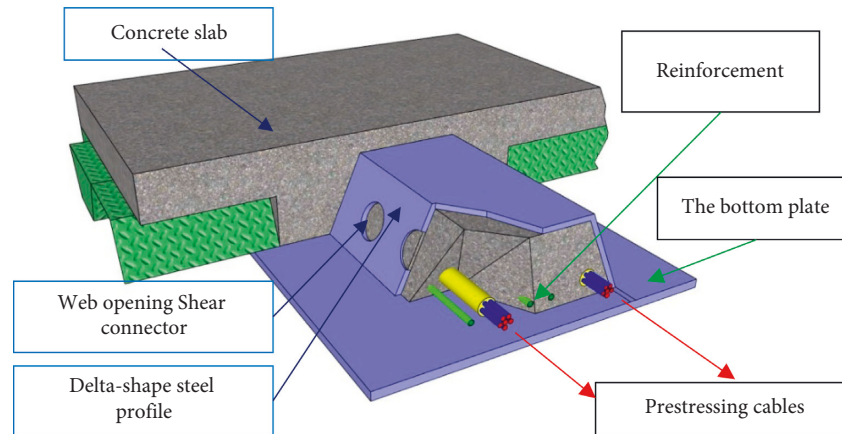


FIGURE 5: Composite slim floor beam with prestressing cable.

This system provides floor slabs with large spans and lower thicknesses, requiring a particular technique for prestressing, significantly increasing the overall system bearing capacity. Prestressing tendons have been placed inside the hollow steel beam to improve the efficiency of the composite structure. Furthermore, it provided a rigid interaction of columns and beams, leading to forming a multispan. In certain cases, design nodes allow for the positioning of continuous cables along the floor system [34].

The results of the analytic calculation showed that the proposed composite construction resulted in an increase of up to 25% of the span length while achieving all necessary designing requirements. Additionally, it can accommodate slabs of spans more than 9 metres, with a thickness of about 40 cm, in constructions where continuous beam applications and posttensioning are required.

The limitation of the deformation is the main concern throughout the composite construction design—the new concept allowed the minimising of deflections using continuous beam and posttensioning wires. Generally, posttensioning was expected to fulfil the requirements for the capacity of the beam due to shear and bending [34]. However, this will redistribute the bending moment along the length of the composite beam, which will result in an extreme value over the intermediate supports, while the area was originally designed to carry a medium amount of bending moment.

Composite slim floor structures with poststressed have been considered as an important development in the evolution of these structures, as they add significant features to the composite slim floor. For instance, it increases the length of the beams without columns, strengthening them to carry extra loads. However, the new concept of the composite floor still requires further investigation to understand the behaviour fully. Some points need to be considered, such as the redistributing bending moment along the spans of the beam frame, which generates the critical moment at the middle support—in the zone where the capacity of the designed elements for bending is the least. At the same time, another question is posed—to what extent is the shear connector able to provide shear resistance, and is it enough to face the

applied shear force by the poststressed system? Additionally, the shear transfer mechanism is not sufficiently explained, especially in the context of applying posttension. The shear connectors used with this type are web opening and shear studs. Therefore, after applying the posttension, stresses will apply on the shear connectors and then later will be subjected to opposed stresses by the loading.

2.4. Composite Steel-Reinforced Concrete Floor. Another new concept to generate an effective and cost-efficient composite steel-reinforced concrete floor slab system has been proposed. These include the flooring systems with an integration of all components of the composite floor. This concept utilises an asymmetric steel beam with a reinforced concrete slab with an appropriately large bottom plate [35]. The feature of this system proposed is using the enforced concrete with the steel beam to resist the tensile stresses, which will fill the gap around the steel beam with the concrete reinforced with steel rebars. The concrete slab could be in situ concrete, precast slabs, or composite concrete slab-steel deck [36]. In controlling the split between the composite beam and concrete slabs, headed shear studs were used and bars were horizontally passed into the web holes of the steel beam. Self-compact concrete is used to fill the gap between the steel beam and precast slab and the openings of the precast slabs (see Figure 6), which redraws the original cross section [35].

The test results exhibited that the failure of the capacity of these types of structures can be regarding the loss of connection between the steel beam and the concrete slab. Certain connector parts were designed to be RC dowels to prevent this failure. Experimental and analytical outcomes displayed sufficient consistency [35].

Reducing the area of steel at the top of the composite beam will force the concrete slab to contribute to a high percentage of resistance to the compression stresses, which is considered a goal of the composite construct. In contrast, the bottom plate, which has a larger area, will resist the tensile stresses. This type of steel beam shape requires the investigation of the uplifting of concrete off the steel beam, as it is

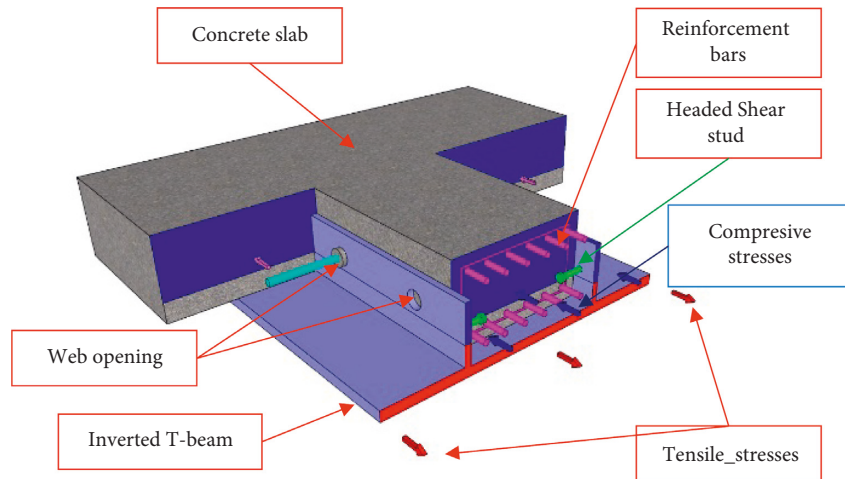


FIGURE 6: Composite slim floor with an inverted TT cross-sectional steel beam.

a significant factor in this type of construction and could use other shapes as the channel section to be a web of the steel beam; in this case, the top flange of the channel will improve the interaction and prevent the concrete uplifting.

In summary, composite slim floor beams consist of a reinforced concrete slab, steel beam, and several kinds of shear connectors. The concrete slab is either site casting or could be a precast slab in case the latter are required to make connectors with steel beam by adding fresh concrete to fill the gap and web opening for forming the shear connectors. The steel beam in the slim floor generally consists of a bottom area of steel more than that of the area on the top part, making it have high tensile resistance to tensile stresses. This is achieved by adding a bottom plate to the section of a steel beam or by welding two different T sections of steel beams together at the web area to fabricate the I-section shape of the steel beam, such that the bottom *T* is bigger than the top *T*. Furthermore, there are other shapes that could consist of the steel beam, such as the inverted *T* section of a steel beam or two inverted *T* sections. Also, any shape such as the delta shape that provides a significantly larger steel area at the steel bottom flange than the top area could be used. Another primary component is the shear connector, responsible for the composite action. The interconnection between the concrete slab and steel beam depends on the properties of the shear connector, such as the type, shape, material, size, and method to build. The shear connector properties will control the degree of the interaction to achieve composite action and provide a ductile behaviour, which significantly affects the composite constructor performance. Composite slim floor systems offer more options for shear connectors, starting with a headed stud, which is welded on web or flanges, to web opening, which is considered more common than other types. Finally, the hollow steel tube may be considered an improvement of web opening, offering solutions to their previous limitations.

3. Shear Connectors for Slim Floor

Shear connectors are required when the bond between the steel beam section and the concrete slab is insufficient to

achieve the required steel-concrete interconnection. Amongst the various types of optimal shear connectors, headed shear studs are the most commonly used to achieve composite action. In contrast, a slim floor system provides more options to form the shear connectors more appropriately. Figure 7 shows the common kinds of shear connectors that are used with composite slim floor beams.

3.1. Headed Stud Shear Connector. The headed shear stud is typically used to build the downstand composite beam. The steel beam is connected to the reinforced concrete slab using headed shear studs to build the composite slab to achieve a composite action [37]. Despite their multifeatures, height is considered one of the most prominent defects with composite slim floor beams. Therefore, many studies have been conducted either experimentally or numerically on the headed studs in increasing the interaction between a steel beam and a concrete slab.

Researchers mainly focused on the experimental investigations on the headed studs used in various arrangements, welded on the web and on the bottom/both flanges of the steel beam proposed for slim/shallow floor construction designs [7, 38–50].

3.1.1. Vertical Shear Stud Welded on Flanges. Typically, the headed shear stud is used as a shear connector by welding it above the upper flanges of the steel beam vertically on the downstand composite floor. The shear stud in this position showed good interaction and the ability to rearrange the studs to reduce the number of studs used to provide the required resistance [51, 52]. However, some researchers suggest using the headed stud with the composite slim floor as well. In such cases, the positions of the shear stud require changing. For instance, one may weld the studs in a vertical position on the bottom flange [53] or in a horizontal position on the steel [54–56]; see Figure 8.

Various benefits may be claimed from placing the concrete between the flanges of the steel beam in the slim/shallow floor system, as it is considered a perfect alternative to the traditional method of positioning it above the steel

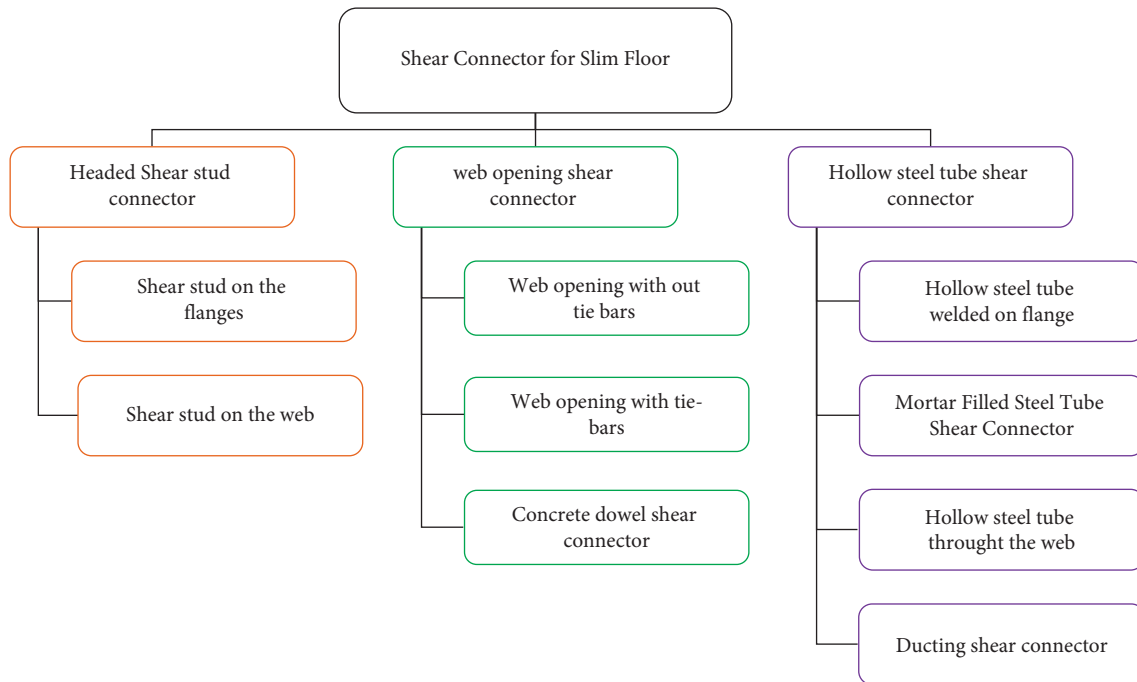


FIGURE 7: Types of shear connectors used in the composite slim floor beam.

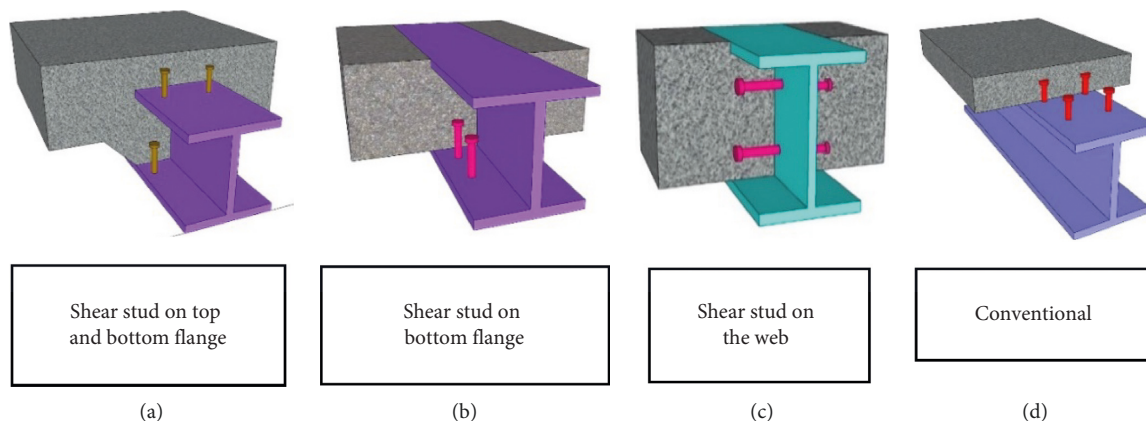


FIGURE 8: Headed stud welded on flanges of the steel beam in the composite system.

section [57]. Several studies were executed to examine the efficiency of the shear stud on the slim floor, with a headed shear stud as a shear connector installed on the bottom and top flanges. Thus, several features were observed in terms of the bending stiffness, the reduction of vertical deflections, and the capability to install shear connectors on the bottom flange or the web of steel beams, as displayed in Figures 9(a)–9(c).

The results of tests that were carried out on the welded headed shear studs in a vertical position on both sides of the bottom flange (Figure 9(b)) proved it as the most efficient of the mechanical connectors tested. In addition, the welded studs on the bottom flange improved the load capacity, as compared to the specimens without studs [55, 56].

A sample was tested with headed studs welded on both the top and bottom flanges of the steel beams; see

Figure 9(a). The results showed that these welded headed studs remained on the hogging moment area of the bottom flange, while in others, they were welded upon the bottom and upper flanges within the sagging moment region, leading to full interaction between the steel beam and the concrete slab [56, 58]. Furthermore, test results were shown that headed studs welding in a vertical position on the bottom flanges in the hogging moment span and on both upper and bottom flanges in the sagging moment span providing interconnections between the steel beam and concrete slab were satisfactory; see Figure 9(b).

3.1.2. Horizontally Lying Shear Stud Welded on Web. When used on the top flange, the headed shear stud will produce a thick concrete slab adverse of the purpose of using

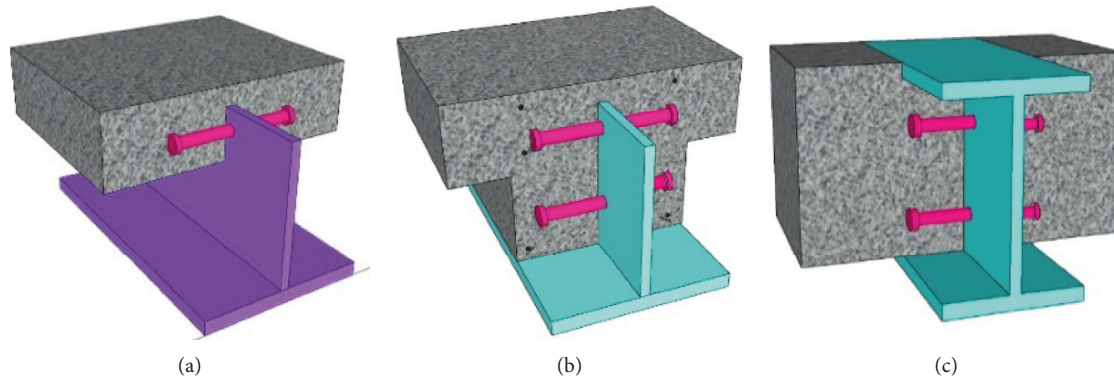


FIGURE 9: Headed stud welded to the web of the steel beam in the composite system.

a slim floor. Considering the same, welding it on the bottom flange was the alternative solution. However, this practice is not recommended for various reasons, such as the difficulty of welding in the presence of the top flange. Furthermore, the part of concrete that needs to be connected with the steel beam is the top half, as it will require to endure compression stresses. This is also due to it being the area that continues to act with the steel beam even after cracks appear. An alternative suggestion was to weld the shear stud on the steel web horizontally.

The composite slim floor system with a reduction of floor depth requires the placement of concrete slabs or precast slabs on the bottom flange of the steel beam. The laying of studs and stirrups on the upper web was used to achieve the composite performance [59, 60] (Figure 9(a)). In other studies, the reinforcement bars and headed shear studs have been applied to achieve the composite action. Besides, the results of the pull-out test of Hegger and Goralski [61] displayed that the loading capacity recorded a higher value for greater sections as a result of contacted surfaces between the flange and the concrete encasement being larger (Figure 9(c)).

Several studies were conducted to investigate the efficiency of using welded headed studs on a horizontal position on the steel web in achieving the composite action between the steel beam section and concrete slab. Breuninger [54] introduced a creative composite beam, where the upper flange of the steel beam is removed and the headed shear stud horizontally to the steel web is welded; see Figure 9(b). In this context, the experimental results of the composite beam with headed studs lying horizontally displayed that loading capacity was dependent on failure modes: the splitting of the concrete and pull-out of the headed stud from the concrete slab. It should be noted that the reinforced bars and stirrups have significant effects in these failure modes [1,54].

Note that the behaviour and resistance may differ based on the loading direction: orthogonal or parallel to the free concrete slab edge. In the longitudinal direction, which parallels to the edge, shear takes place generally due to beam action, while in the other direction, which is orthogonal to the surface of concrete, shear can occur because of direct loading and self-weight [62].

Several studies have been carried out on welded headed shear stud on the steel web of the top Tee of the cellular steel beam in a composite shallow floor system, as redrawn in these sections in Figure 10. Through the use of web-welded stud shear transferring mechanism, the concrete infill elements and headed shear studs concurrently are transferring the longitudinal shear forces [29, 63]. Results of push-out tests investigating a failure mode of the headed shear stud indicated that a disastrous failure of the headed shear stud occurred. There was a great similarity between the slipping behaviour of welded stud shear on the steel web and that of the headed shear studs in standard push-out tests. This indicated that additional studs had a direct effect on the slip behaviour of welded studs on the web steel, enhancing shear connection ductility [63].

Headed shear stud is commonly employed in composite floor structures due to its varying features, such as the ease of application due to the availability of gun machines for welding, workers, and experience of the practice. Additionally, the headed stud shear provides good ductile behaviour. Moreover, the deconstructable steel bolted with nuts was used, which is more simple to install and provides enough interaction and ductility. Thus, it may be used with multiple kinds of shear connectors to enhance the ductility, especially that of brittle connectors. Despite the disadvantages such as the small contact area with concrete, difficulty to weld it on the bottom flange in the presence of a top flange, and failure of the zone welding as a result of the quality of welding, it is still popularly used for its benefits.

3.2. Web Opening Shear Connector. Web opening is one of the primary forms of shear connections in thin floor systems. The shear connection is formed by the web opening and the concrete infill, and in some cases, tie rebar is added through the web opening to resist the tensile force in the shear connector. The shear resistance can be determined by the size of the web opening, concrete strength, characteristics of the tie rebar, and the number of connectors. Furthermore, the form and location of the web openings impact the shear resistance of concrete. All of these characteristics,

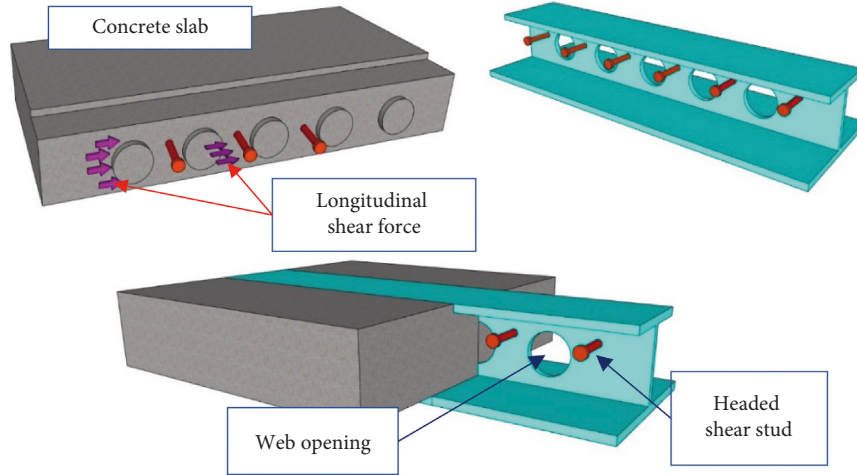


FIGURE 10: Web-welded shear stud connector for the shallow floor system.

compounded by the shape of the steel beam section, will affect the rigidity of the steel beam.

3.2.1. Web Opening Shear Connector without Tie Bars. Several studies were conducted to investigate the web opening shear transfer mechanism. The web opening is created by making an opening in the web of the steel beam section in slim/shallow floor systems. This shear connector will form when casting the concrete to fill the proposed opening of the web. Infill concrete elements interact with the steel web that acts to transfer the longitudinal shear forces. Shear connection configurations are designed to represent various geometries, i.e., circular holes and clothoidal holes that are presented in the redraw concept in Figure 11. The literature consists of numerous push-out tests conducted on circular and clothoidal web opening shear connection configurations. Studies indicated that the web opening shear connection formed by the concrete infill without tie rebars showed a brittle concrete failure [2, 3, 29, 63–65].

Results of the experimental push-out investigations and FE simulations in the shear transferring mechanism of the web opening shear connector configuration indicated that the failure was brittle under direct shear test (push-out test); this is attributed to the shear connector created with infill concrete without adding tie rebar or additional elements. Concrete is a relatively brittle material. The shear connector failure mechanisms in the push-out tests have been confirmed with numerical simulations. In other words, a part of the concrete infill element failed under the local compression and was crushed by the web of steel beam movement in the long direction of applied shear forces, while the remaining infill concrete slipped by the tensile forces. The load capacity of the shear connector is dependent upon the cross-sectional area of the concrete infill part; it ultimately contributes to the tensile splitting resistance and local compression-resistant of the shear connector. However, note that the infill concrete size has a slight effect on the slipping behaviour and slip capacity of the shear connection [2, 63].

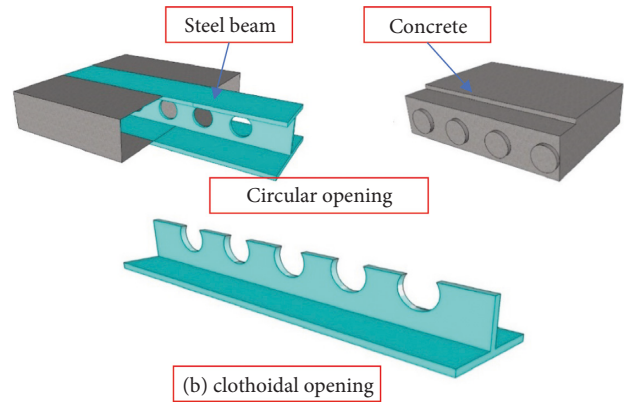


FIGURE 11: Web opening shear connectors for slim/shallow floor steel beam.

In both the circular and the clothoidal shapes, the shear mechanism of web opening shear connectors was projected, and an equation was simulated to solve the results received from the experimental and numerical investigation, wherein the group effects of the web opening shear connectors are taken into consideration by introducing multiple openings on the steel beam. The shear capacity of this type of sheet connector depends on the shear strength of the concrete, which is presented by the area of the web opening. Another term is the compressive strength of concrete, which is given by the thickness of the steel web that will apply the bearing load on the infill concrete. Therefore, Eq. (1) [63] could predict the shear capacity of the circular web opening

$$P_c = 1.68(f_{cu}A_c) + 1.44(f_t A_t), \quad (1)$$

where A_c (mm²) denotes the top compressive area of the concrete infill within the load direction, A_t (mm²) signifies the tensile split area of the infill concrete, f_{cu} stands for the concrete cube compression strength (MPa); f_t represents the tensile strength of the concrete (MPa); and P_c is the shear strength computed in kN.

3.2.2. Web Opening Shear Connector with Tie Bars. The web opening shear connector resistance depends on the compression and tensile strength of concrete. As the tensile strength of concrete is low, the shear connector requires certain modifications to resolve this limitation—adding rebar through the web opening along with the concrete would improve the tensile resistance of the shear connector. The tie bars can provide tie force for concrete slabs on both sides of the steel web. In general, tie bars with various diameters for passing through the web openings are presented in the 3D redrawn section in Figure 12. The combination of the tie bar and infill concrete part leads to an interaction with the web of steel beam, which transfers the longitudinal shear force; see Figure 13, [2].

As shown by the push-out test results obtained from testing the tie-bar shear connection, the shear connections that have concrete infill and reinforcement of tie bar provide substantial ductility behaviour with a considerable slippage capacity and shear resisting capacity. Overall, the optimum shear resistance leads to a good resistance from both combination tie bars and concrete; see Figure 14.

The composition of the perfbond-like connector within the composite slim floor system is carried out by means of passing concrete during web openings with the embedded steel reinforcement tie bar. Figure 14 illustrates a typical shear connection. Thus, the force flows between the interfaces of the concrete element and the steel web element. After the steel beam is embedded, the most significant portion of the shear connector will activate by combining the steel rebar element and the infill concrete. The shear interaction at the contact interfaces between the concrete slab and the steel section also contributes to strengthening the shear transferring mechanism capacity. One interpretation of the principle of force transferring between various elements and mechanisms of composite action within the shallow composite floor system with perfbond-like shear connector is that during flexural loading, the local compression and the friction in steel web opening start activating at the contacting area of the connector. As a consequence, the longitudinal stresses are generated resulting from flexing and shear forces. In addition, the capacity of the shear resistance of the concrete passing from the openings can use. Thus, compared to the shear stud, the presented shear connector can prove itself as an integral element of the composite floor. However, it also leads to an intricate superposition of stress of the shear bonding and inner force within the system [3].

As illustrated by the results obtained from the test, the shear connection that was created by the tie bar and merged with the concrete infill possessed efficient and substantial shear resistance, ductility, and slip capacity. In clothoidal openings, a failure of the shear connection was noticed with three failure modes; firstly, the infill concrete was crushed due to the movement of the steel web; secondly, the prying-out of the concrete infill above the openings took place; and finally, there was a shear collapse of the concrete infill. Shear strength in the length direction of the shear connector can be understood as the collection for the compression strength of the infill concrete and the tensile strength of the steel rebar.

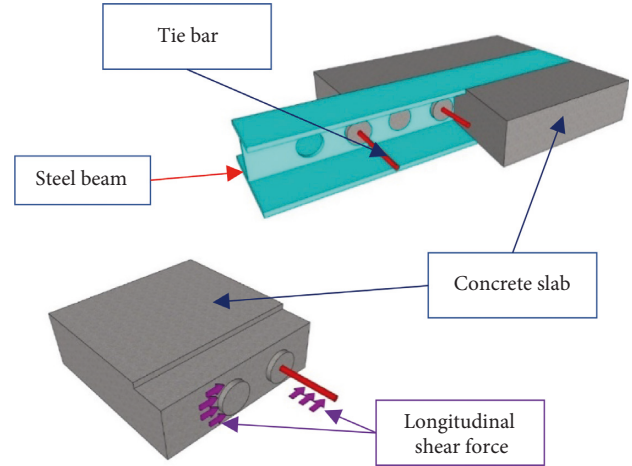


FIGURE 12: Longitudinal shear force transfer mechanism in concrete dowel and tie-bar.

Such a medley has the necessary capability for flexural ductility behaviours of the composite slim beam [3].

The shear capacity in this type of connector depends on the shear resistance of the concrete and compressive strength of the concrete as mentioned before with the web opening, in addition to the tensile resistance provided by rebar. There are many equations (2)–(4) [2, 3, 63] proposed to predict the shear capacity of the clothoidal shape and web opening of the opening shear connectors by considering the tensile strength provided by the reinforcement (tie-bar) embedded presented in the equation, which is not considered in equation (1):

$$R_{sh} = 1.68(f_{cu}A_c) + 1.44(f_{ct}A_t) + R_{add}, \quad (2)$$

$$R_{sh} = 1.2(t_w h_D f_{cu}) + 2.1A_c f_{ct} \left(1 + 13.5 \frac{E_s A_{st}}{E_c A_c} \right), \quad (3)$$

$$R_{sh} = 1.30(f_{cu}A_c) + 1.15(f_{ct}A_t) + \frac{f_y}{1.25} \left(\frac{\pi D_{tb}^2}{4} \right), \quad (4)$$

where R_{sh} signifies the shear strength of one shear connector, A_c is the infill concrete area, f_{ct} is the concrete tensile splitting strength, A_t is the area of the concrete infill in tensile, R_{add} is the shear resistance of the additional elements, t_w is the thickness of the steel web, h_D represents the web opening height, f_{cu} signifies the concrete cube compressive strength, E_c denotes the concrete elastic modulus, E_s stands for the steel element elastic modulus. f_y is the yielding strength of the steel tie member, and D_{tb} is the diameter of the steel tie member.

3.2.3. Concrete Dowel Shear Connector. In the established literature, concrete dowels are described as holes drilled through the steel web. Standard reinforcement bars pass from these holes in a position vertical to the beam span direction, and the holes are filled with concrete. The dowel of the concrete will be resisting the longitudinal shear force (as a concrete stud), while the tie rebar will support in resistance

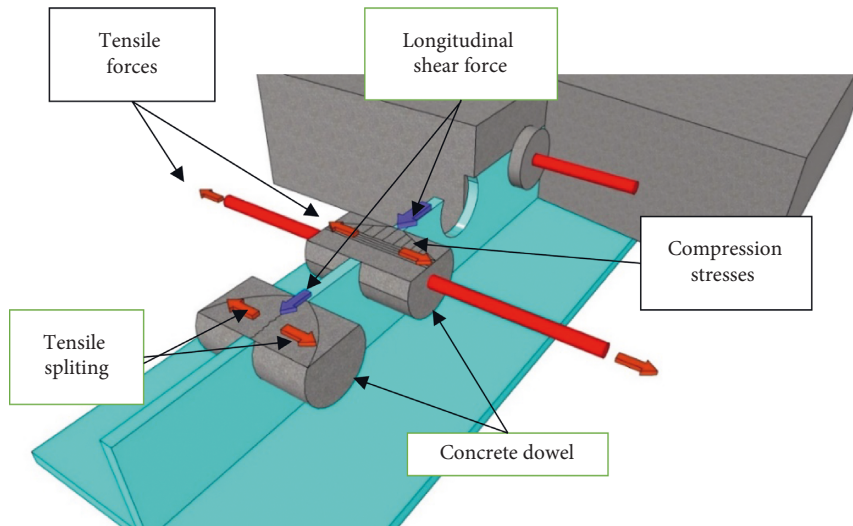


FIGURE 13: Forces distribution in concrete dowel.

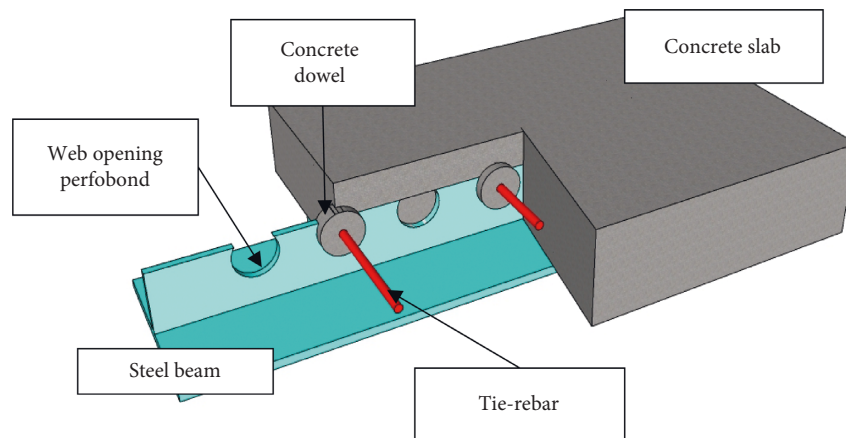


FIGURE 14: Configuration of the steel beam and perfobond-like shear connection.

to the longitudinal shear force and tension forces to prevent the separation [30, 66, 67]. The concept of this composite floor system with dowel shear concrete is redrawn in Figure 15. The activation of the composite action leads to a substantial increase in load-bearing resistance and beam stiffness. Thus, the beam span can be improved. However, the steel section can also be decreased. Alternatively, one could even claim that they are the same formations of web openings and that the only difference is that it may be smaller in size where it seemed as if the concrete stud had been installed through the web of the steel section. In this condition, the effect on the stiffness of the steel beam will be lesser, and the tie rebar can enhance the shear resistance.

Researchers engaged in several studies regarding the significant steps to developing composite dowels to generate basic design concepts of the concrete dowel shear acting mechanism due to the importance of slim/shallow floor construction, a widely applied construction method as compared to the standard floor beams. The concrete dowels employed in composite slim floor beams guarantee the occurrence of a shear connector among the steel sections and that the in-site concrete [30, 66, 68, 69].

Several recent tests have been conducted to transfer the concrete dowel technology, popularly used across filling beam bridges and slim/shallow structures [70]. Due to the condition of the shear connector in the web of hot-rolled steel sections, the beam stiffness considerably increases without any increase in the floor thickness or beam depth. This method is cautiously prepared to assure the composite action, resulting in the efficient utilisation of material without any increase in the complexity and/or cost of production and erection. Consequently, CoSFB is considered a flexible and sustainable construction form [71], which can be combined with various kinds of prefabricated concrete elements: slab, composite, non-composite steel decks, and so on.

Similarly, many experiments were executed on the bearing capacity and deformation of the concrete dowels, having led to significant findings [67]. The push-out test was applied to derive a typically applicable and stochastically proven dimensioning process for shear force transmission between concrete members of the composite girders and steel components. The results led to the development of easy-to-use model methods to compute the dowel properties

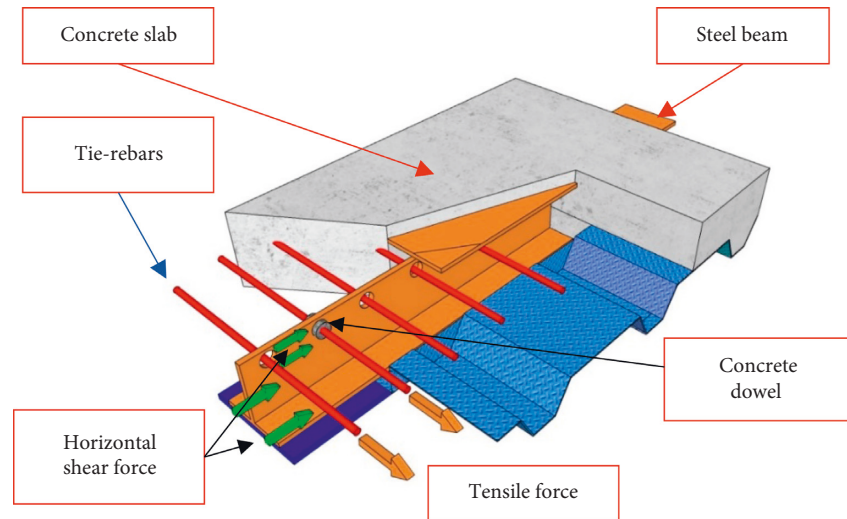


FIGURE 15: Composite slim floor beams with dowel shear concrete.

of concrete dowels with pry-out failure. The concrete dowel is exposed to three direction forces, as shown in Figure 16, longitudinal shear force resulting from slippage, tensile forces due to separation, and up-lift forces due to the various displacements. The concrete dowel with tie rebar will resist the shear and tensile forces, while the shape of the web opening will confine the concrete dowel to prevent the up-lift forces. The existent design techniques assuring ductility deformation conduct have been critically reviewed and modified.

As a conservative result, the cover of concrete should be at least 35 mm. Moreover, a number of studies have been carried out on the fatigue properties of concrete dowel technology with a wide analysis and test program to generate an application for building construction with considerable moving loads that are extremely close to usual structures [25, 69, 72, 73]. In Figure 16, further opportunities are presented to show how concrete dowel technology can be applied to slim floor constructions, with the combination of standard steel profiles and eliminated upper flanges together with concrete slabs.

The composite concrete dowels are a kind of shear connection used with the composite beams, consisting of openings in the steel beams that were filled in by concrete. The key feature of the concrete shear dowels is that it can form the opening with many different shapes, such as a swallow tail connector, a gear connector, a modified gear connector, and also the ability to use the tie bars (instead of the circular opening), thus increasing the interaction and preventing the up-lift of concrete and employment of the concrete from resisting compression stresses. Moreover, the concrete dowel and reinforcement rebar passing throughout the opening as tie bars will resist the tensile and shear forces, which will enhance the ductility. In addition, another benefit, as opposed to the shear studs, is its higher bearing capacity and sufficient deformation capacity even in the heightened strength concrete to be categorised as ductility shear connection, according to EN 1994-1-1 [27, 69, 72–74]. In addition, the composite dowels are principally economic

and ideal for the composite section made up of steel sections with no upper flange, as the steel parts upper in the neutral axis are decreased; see Figure 17. Furthermore, it can be used to arrange the composite dowels appropriately in the concrete T-beams as the external reinforcement.

The potential failure modes of the composite dowels that are under a constant loading are shearing failed in concrete and concrete pry-out, and failed in steel, as depicted, respectively, in Figure 18, [67, 69]. In the case of a thick plate and small openings, the shear failure in concrete is the expected mode. As a result, the bearing capacity depends on the concrete shear resistance and the concrete area subjected to shear stresses (see Figure 18(a)); also, the tie bar is affecting on the capacity of bearing. More studies were conducted to modify the dimensions and shapes of connectors to enhance their shear resistance and reduce disadvantages, and it showed developments in the resistance [75].

If the concrete cover above the concrete dowel is small, a failure mode may occur, comparable to the concrete pry-out of anchors in a state that is under a shear force. At the load introduction zone, the hydrostatic pressure condition produces transversal tension forces, resulting in a cone-shaped concrete pry-out because of the inadequate cover of concrete; see Figure 18(b). Pry-out may occur in the case of the bottom or top concrete cover based on the situation of the concrete dowel. Such a failure mode is considered ductile.

The steel failure may be attributed to the slim thickness of the web plate and the low strength of steel. Such failure mode occurs because of a concurrent shear-bending mechanism, resulting in horizontally static cracks within the web, as can be seen in Figure 18(c). As a result of the structural steel ductile behaviour, this failure mode accompanies great plastic deformation; thus, it is ductile (see Figure 18(d), [69, 72, 73]).

Resistance of the shear connector of the concrete dowel shear connectors can be obtained by the resistance of the concrete, which is concrete shearing, prying-out of concrete, or, in some cases, by the steel failure. Analytically, it can

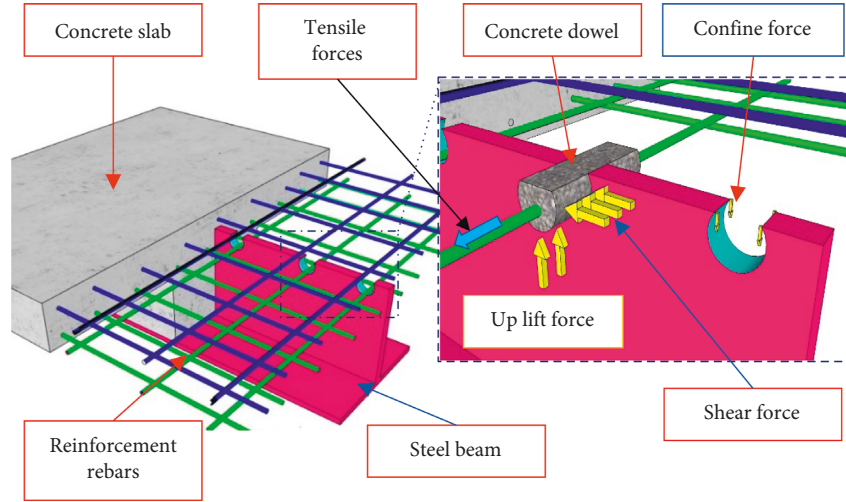


FIGURE 16: Application of concrete dowels for slim floor constructions.

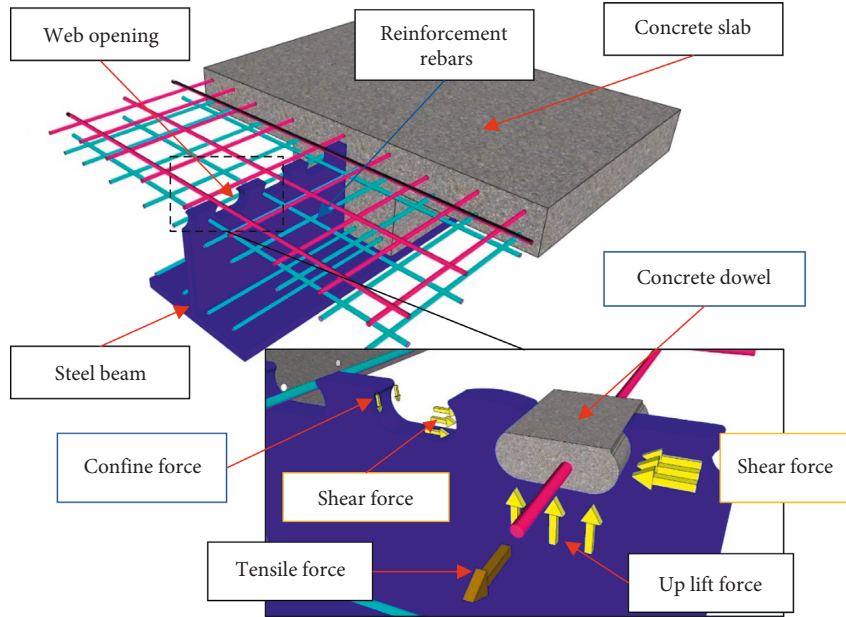


FIGURE 17: Composite dowels in steel beam system without the upper flange.

predict the longitudinal static shear resistance P_{sh} by equation (5), which is found that the failure will occur in concrete [76]

$$P_{sh} = 16.542 \cdot A_D \cdot \sqrt{f_{ck}} \cdot (1 + \rho_D) \cdot \left(1.2 - \frac{h_D}{180}\right), \quad (5)$$

where 16.542 is the factor results in a mean value correction, A_D is the shear area of concrete, ρ_D is the reinforcement ratio, f_{ck} is the concrete compression strength, and h_D represents the steel dowel height.

Concrete dowel shear connector is considered a type of web opening with a lesser size. To resist the longitudinal shear depends on the shearing concrete dowel and tie rebar, and tensile stresses are resisted by the tie rebar, while the shape of the opening will prevent the concrete uplifting. The

small size of the opening will let the web of the steel beam keep its strength against the horizontal shear forces.

3.2.4. Effect of the Opening Shape. Web opening is considered an essential type of shear connector in slim floor systems. The shape, size, position, and the number of web opening shear connectors are crucial to determining the efficiency of web opening as a shear connector. As the web opening and the infill concrete will form the shear connector, the shear resistance is primarily influenced by the size and the number of the web opening connectors. Additionally, the forming and position of the web opening affect the resistance of concrete to the shear force. All the aforementioned parameters will affect the steel beam stiffness as it cuts off part of its web. Therefore, these parameters

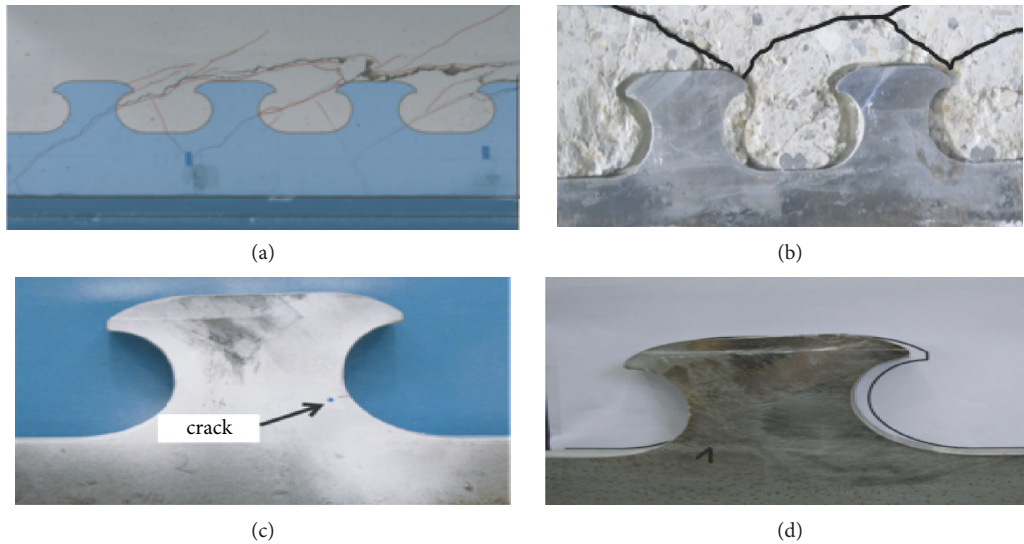


FIGURE 18: Failure mode of concrete dowel shear connector [69]. (a) Shear failure, (b) concrete pry-out failure, (c) steel failure, and (d) plastic deformation.

must be carefully examined to achieve higher shear resistance and ideal beam stiffness.

The effect of the shape in the web opening (WO) as a shear connector has been thoroughly investigated. Push-out tests were conducted on the web opening shear connection by applying direct shear. The universal column (UC) was selected as a steel beam in the composite slim floor. The UCs were cut web opening by three different shapes with an equivalent cut area to be as a shear connector, as redrawn in Figure 19 [77]. The study was an attempt to investigate the optimal shape of the web opening shear connection [77]. Results of these tests showed that the square opening increased the shear strength of the connector. A higher strength of compression and tension for the infill concrete leads to overall higher shear resistance.

Furthermore, a higher thickness of the steel beam web produced greater shear resistance of square opening, as compared to that of circle opening for different degrees of concrete strengths. The behaviour of multiopening was tested by making three openings during the web of the steel beams. The outcomes of FE were verified with the examination outcomes of one connector. The comparison demonstrated that the effective distance for three circular openings was about 250 mm, while it was noted to be nearly 300 mm for squared and rectangular openings [77, 78].

As part of FE studies on the effects of the shape of connectors, [2] conducted analyses on how the shape of the shear connection affects the properties of load-bearing behaviour, failure mechanisms, and slip capacity. The shear connections, termed CL-C, CL-CE, and CL-Z, are shown in Figure 20. The design of clothoidal cutting connectors maintains the same area of the opening (area of infill concrete). Various cutting shapes are compared in terms of load capacity and maximum slip for the investigation of the impacts of the opening shape upon the shear connector behaviour. The thickness influence of the web upon the

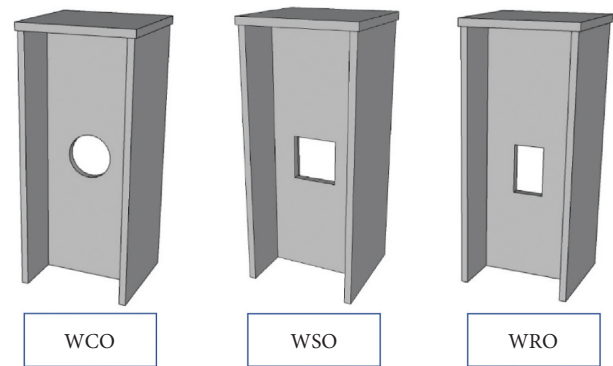


FIGURE 19: The steel beam and opening configuration.

clothoidal openings of the steel beam was studied using finite element (FE) analysis through the ANSYS software. The result shows that the connector with a comparable area of concrete has similar slip behaviour, although there was notable variance in strength shear capacity efficiency. Samples CO-O and CL-C have greater loading capacity than that of samples CO-CE and CL-Z. However, all the connector forms behaved with almost a similar failure style to mention above with circle, square, and rectangular connectors [2].

3.3. Hollow Steel Tube Shear Connector. Hollow steel sections are applied as steel beams into the composite construction. The composite beam with simple support allows for the utilisation of different types of steel beams, which include rectangular- or square-shaped hollow sections as well as hollow sections made up of steel plates [79]. The institute of steel construction recommends the use of a rectangular hollow steel section-based edge beam [80, 81]. In some other studies, the hollow steel sections have been investigated

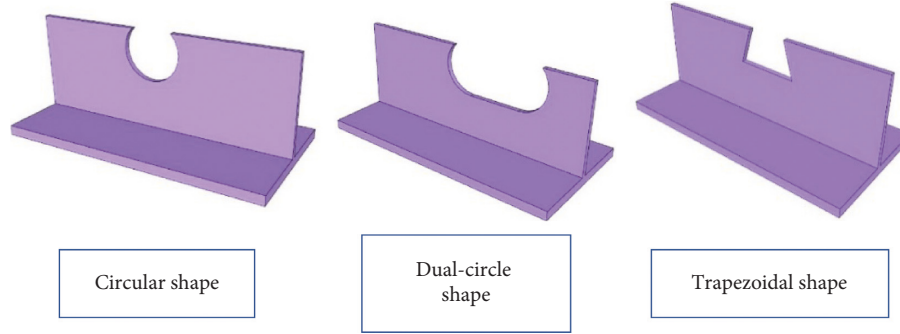


FIGURE 20: Different shapes of web clothoidal opening shear connectors for slim/shallow floor steel beam.

creatively, as shear connectors welded to steel I-beam profile, for the estimation of the improvement of the shearing resisting capacity of the composite construction systems [82–85]. The following section reviews using of hollow steel tubes as the shear connection in composite construction systems.

3.3.1. Hollow Steel Tube Shear Connector Installed on the Flange. In the construction process, the mechanical performance of the composite deck is considerably dependent upon the design of the shear connectors, which transfers the internal forces between the steel and concrete elements. Therefore, several studies were conducted to investigate the efficiency and performance of various kinds of shear connections and locate their essential role in the process. For example, using the hollow steel tube or half tube as the shear connectors, this design takes advantage of the shape of a steel tube to act as a shear connector.

Researchers have investigated the composite deck, by adding hollow steel tube (HST) as shear connectors. In some cases, the connector could be channel shear connector (CSC), and a half-pipe shear connector (HPSC) with the conventionally used headed stud connectors, i.e., channel shear connector (CSC) and half-pipe shear connector (HPSC). Furthermore, the headed shear stud and the proposed shear connectors work together for horizontal shear force, which acts in the longitudinal direction. In addition, the HST was welded to enhance the level of rigidity. This was also carried out to explore the mechanical characteristics, deformability, and shear bond of the proposed connectors, properties that have been greatly impacted by the thickness of the tube to this diameter ratio. Moreover, the HST's shear strength has been compared through various experiments [83–85].

The tests focused on the dimensions changed were examined to explore the shear strength that could be provided by these connectors (Figure 21). Results recorded that cracks have occurred in the concrete, and the failure was a compression concrete failure across both HPSC and CSC. The deformation of specimens with headed stud connectors showed a flexible behaviour. Additionally, it was found that with the increase of t/D , the deformability also increased. Shear capacity Q_{uest} of the HPSC can be predicted by the geometry of the HPSC and concrete strength and d/t ratio as in the following equation [84]:

$$Q_{\text{uest}} = \frac{f_c}{4} r B \left(78.2 \frac{t}{D} \right), \quad (6)$$

where Q_{uest} is the ultimate shear force, t/D is the thickness-to-diameter ratio, r is the radius of the HPSC, and B is the length of HPSC.

As an alternate steel tube shape form of shear connection, rectangular steel pipes (RSPs) were developed to be examined as shear connectors with the steel-concrete composite slab. The samples consisted of two RSP shear connections, two lightweight aggregate concrete LWAC slabs, and a steel column H-shaped, as illustrated in Figure 22 [86]. Push-out tests were performed on three samples under a constant load, and the other five with fatigue loading, to explore the shear characteristics of RSP, recommended as a novel type of shear connection in LWAC.

Findings of the static testing revealed that fractures at the weld zone might be employed to evaluate the shear capacity of the RSPs. Under fatigue stress, two failure types were detected in the individual specimens: RSP fractures and weld separation. The static shear capacity was compared to estimated values using various channel shapes and L-shaped variables, and a headed stud number equivalent to one RSP was recommended. The shear stiffness of one RSP in the static push-out test was 510.9–667.8 kN/mm, and this finding was based on several specification calculation techniques [86]. The influence of RSP dimensions, concrete characteristics, and welding circumstances on the shear performance of RSP shear connectors was not examined in this study. This may warrant further study in the future. Steel-concrete composite deck with HPSC was tested under fatigue loading for more investigation. Findings of the static testing may be employed to evaluate the shear capacity of the RSPs. While, under fatigue stress, two failure types were detected in the individual specimens: RSP fractures and weld separation.

The static shear capacity was compared to estimated values using various channel shapes and L-shaped variables and a headed stud. To calculate the shear capacity of the RSP, the calculations of equations from different shear capacity channel specifications were compared with the experimental RSP shear capacity. Thus, the following equation can be used to predict the shear capacity of the RSP [86]:

$$Q_u = 0.3(t_f + 0.5t_w)l_a \sqrt{f_c E_c}, \quad (7)$$

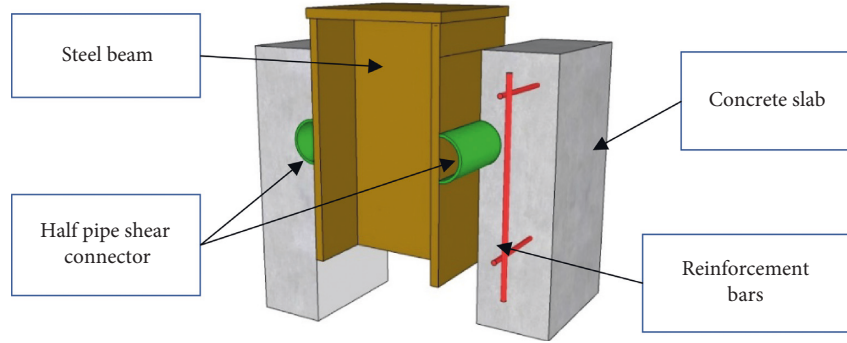


FIGURE 21: Steel-concrete composite deck with HPSC.

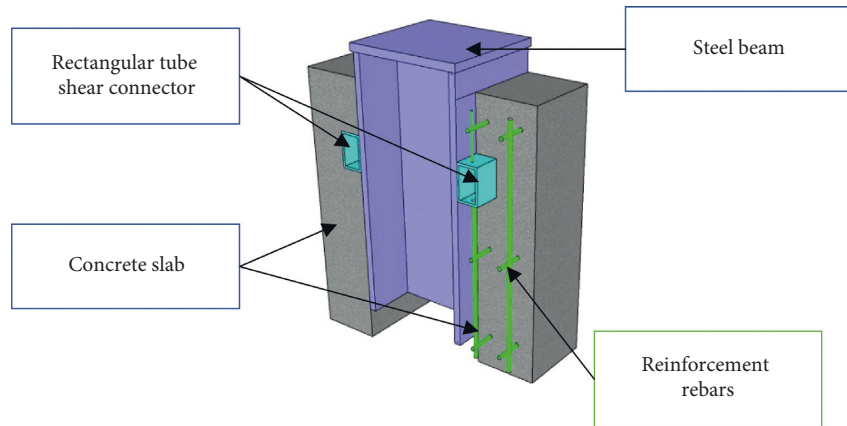


FIGURE 22: Steel-concrete composite slab with RSP.

where t_f is the flange thickness (mm); t_w is the web thickness (mm); l_a is the RSP length (mm); f'_c is the concrete compressive; and E_c is Young's modulus of the concrete.

3.3.2. Mortar-Filled Steel Tube Shear Connector. For the development of the web opening, high strength mortar was proposed instead of the infill concrete as a shear connector. A design was proposed by Shinozaki, using a perforated steel plate where mortar cylinders (MCY) or mortar-filled steel tubes (MFSTs) are inserted to serve as the shear connector [82]. This idea is characterised by workability and the elimination of the requirement for rebar insertion into the perforated plates; see Figure 23 [82]. Moreover, the mortar is stronger than the concrete, providing a shear connector with a higher shear resistance. In the present study, a direct shear test was executed to evaluate the shear strength and slip characteristics. Then, the static loading test was carried out using a model specimen with roughly half the size of the actual joint structure, and the proposed technique produced the shear connector [82].

The static loading test was carried out using a model specimen with roughly half the size of the actual joint structure, and the proposed technique produced the shear connector. The results obtained from the tests revealed sufficient bearing force of the joints. Following these discoveries, a 3-D non-linear finite element analysis was carried out. The results proved that the behaviour of the joints could

be reproduced in detail [82]. Finally, the validity of the proposed design technique was investigated by distributing the shear force produced in the shear connector. The outcomes obtained from the direct shear test showed, in both MFST and MCY, the tendency of the shear strength to increase in proportion to the compressive strength. Compared to MCY, MFST demonstrated higher shear strength, which further increased, corresponding to the thickness of the steel tubes [82]. In general, this shear connector was considered a good shear connector that can provide shear resistance with acceptable ductility.

3.3.3. Hollow Steel Tube Shear Connector Installed on the Web of the Steel Beam. As previously mentioned, a hollow steel tube was used as a shear connector with a downstand steel-concrete composite beam. However, upon using them as shear connectors with the composite slim floor, passing it through the web of steel beam would result in more advantages. Hence, this would benefit both web opening and steel tube shear connector.

Based on this understanding, a hollow steel tube (HST) as a shear connector was suggested to be one of the compounds of the composite slim floor, in which the steel beam is embedded in the thickness of the slab. The HST was welded through the web of steel beam and married in the concrete slab to form HST shear connectors to be part of the depth of the composite concrete slab; see Figure 24. The

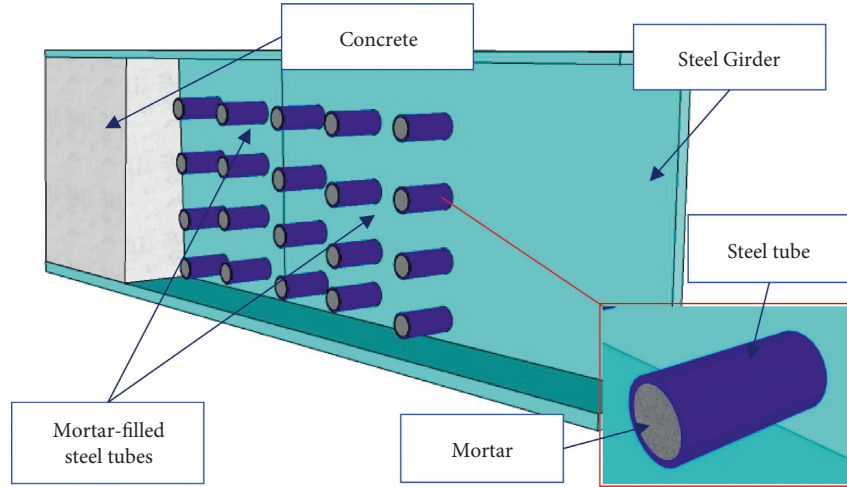


FIGURE 23: Steel tube shear connector filled by mortar in a perforated steel plate.

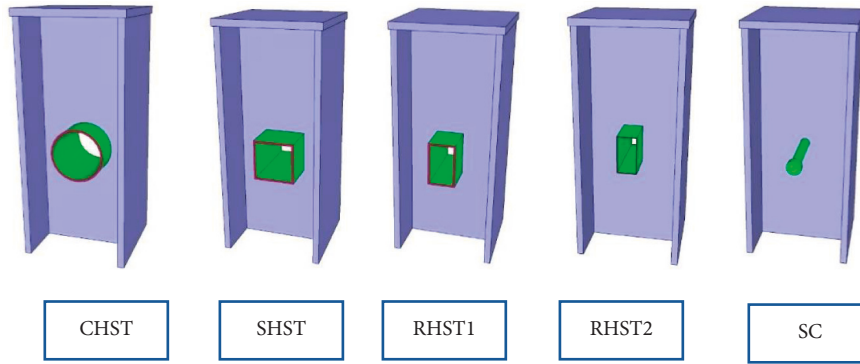


FIGURE 24: The steel beam and hollow tube shear connectors.

hollow tubes allow the concrete to be connected from both sides of the slab, thus forming a continuous slab with the aim of developing a unit of the composite slim floor system [87].

The section of tubes was considered to have the equivalent sectional area to propose the perfect shape regarding the shear resistance of the novel connectors once filled and embedded in the concrete slab. These hollow steel connections were installed to the steel web of the beam by welding. As a control sample testing, the shear stud was welded symmetrical to the web of the UC steel section on both sides, as shown in Figure 24 [87].

Given that the steel beam has been embedded in the reinforced concrete slab, the slab was placed alongside the web, encased between a pair of flanges. The shear strength of the shear connection was studied by applying the direct shear force. This helped us to observe the effect of concrete splitting on the headed stud shear connectors and the HST shear connection shear strength. The outcomes displayed that the shear strength of the HST shear connection in both compressive strengths of the concrete (25 and 40 MPa) was recorded to be higher than the stud connectors (SCs). In contrast, the ductile behaviour of the SC connectors resulted in a higher slip behaviour value than that of HST shear connectors. It was also found that the failure mechanism of the HST shear connection was different from that of SC. The

mechanical failure of the shear stud occurred on the shank of the shear stud and welding zone. Concrete split failure around the embedded head of the shear stud was also recorded, whereas no failure occurred in HST. Compression crush of concrete was noted in the concrete under the connector due to the steel tube. In addition, the split failure of the infilled concrete was noted on the surrounded steel tubes [87]. The mechanism of the failure of the connector was founded on the concrete shearing failure and crushing concrete surrounding the HST.

The results of the experiment were employed to calculate the shear resistance capacity Q_{u-An} of the HST and to propose a method to predict the ultimate shear capacity; the following equation can be used:

$$Q_{u-An} = 0.68Q_{u-be} + 0.5Q_{u-sh}, \quad (8)$$

where Q_{u-be} is the strength of the concrete underneath the HST and Q_{u-sh} is the shear strength of the concrete contact surface.

4. Overall Discussion

4.1. Steel Beam Shape. The steel-concrete composite floor consists of three main elements: concrete slab, steel beam,

and shear connector. This structure had been developed over the years to improve its efficiency. The critical element that plays a major role is the shear connector because composite floor is based on the composite performance. Initially, researchers were interested in the conventional composite floor (downstand floor), and several studies were conducted to investigate different types of shear connectors. Later, the slim floor was suggested to be the ideal option. Based on its numerous advantages, it could be said that important features enhance the interaction and fire protection, as discussed earlier. The composite slim floor can be fabricated by several steel beam shapes, such as symmetric or asymmetric I-section, inverted T-section, delta shape, and square or rectangular steel tube. The steel section is the main element to resist the tensile stresses and will control the moment capacity and stiffness behaviour in the composite beam based on its properties and shapes.

However, the I-section is considered the most typically used, as it quite provides many features to the overall structure. For example, a large bottom flange to resist the tensile stresses (could be larger than the top as in an asymmetric section or may be built up by welding an extra bottom plate). Furthermore, the top flange will resist the compression stresses and significantly increase the interaction by confining the concrete between both flanges. It also contributes to the prevention of the uplifting of concrete and increasing the contact areas. Furthermore, concrete infilled between the top and bottom flanges is partially clamped and could increase the concrete strength due to the confinement effect. While some of these advantages may be found in other shapes, and accompany by some drawbacks, of which the most important ones are listed in Table 1, where Table 1 presents comparisons between the common shapes of the steel beam employed in the composite slim floors. Moreover, in the built-up I-section, the different I-sections are cut, welding them along the web to form the asymmetric I-section, and create web openings as shear connectors. Due to this condition, the middle zone of the web becomes critical, as it combines the welding zone and web opening. In addition, it will also be subject to higher horizontal shear stresses, which demand further care in designing the web opening in general. Therefore, the dowel concrete shear connector, which needs a smaller web opening, and adding tie rebar will provide good shear resistance and keep the steel beam web with a smaller cut.

4.2. Shear Connectors. Although the shear connector is the smallest part of the composite slim floor, it can control the overall efficiency of the composite floor. The optimum performance of the shear connectors could increase the load-bearing, enhance the ductility and deflection behaviour, and prevent sudden failure by increasing the interaction. The composite slim floor can make use of different kinds of shear connections, such as shear stud, web opening with or without tie rebars, mortar cylinders, and hollow steel tubes. Embedding the steel beam in the concrete slab provides multiple opportunities for creating several kinds of shear connections on the web of steel, which is most

commonly observed, or also upon the flanges. The shear capacity of the shear connector can be determined by the properties of the components of the shear connectors. For example, in the shear stud, the size of the stud and yield strength will determine the shear resistance of the shear stud. That is because failure usually occurs in the shear stud. While in the web opening shear connector, failure is expected in the concrete. Thus, the size of the web opening and shear concrete strength will control the shear capacity of the shear connector. In the case of HST, failure is expected in the concrete. Thus, the size of the HST, its length, and the concrete strength will control the shear capacity of the HST shear connector. The concrete area, compressive and tensile strengths of the concrete, the area and yielding stress of steel part, and the number of connectors will contribute (with different ratios) to the shear resistance. Moreover, the number of connectors and the distances between them will determine the total shear resistance in the composite element.

4.3. Shear Stud Shear Connectors. The shear stud is considered the most commonly used shear connector with a conventional composite beam (downstand) welded on the top flange. Its popularity may be attributed to features such as its ease in application, availability of gun machines for welding, and workers' acquaintance and their construction experience. The shear stud (in some cases, bolts and nuts are used instead) performs sufficiently in establishing a connection between the steel beam and concrete slab, as well as acting as a ductile shear connector. However, the composite slim floor systems have garnered more attention from researchers than other types, such as web opening and hollow steel tubes. The other types of shear connectors may provide a higher shear resistance and have more advantages, as mentioned earlier. Hence, the headed shear stud can be compatible with various kinds of shear connections to enhance ductility and provide an excellent ductile behaviour. Installing the shear stud with other types of shear connectors will improve the ductility of composite elements and increase the ultimate shear capacity, a discovery that still has the attention of researchers. Bolts and nuts have a reinstall feature and provide high tensile strength, which can be used in the original construction or qualification the composite structures to keep the continuance of the composite structures and reduce the cost.

4.4. Web Opening Shear Connectors. The web opening shear connectors are commonly employed in composite slim floor systems, as they provide acceptable shear resistance with allowance for passing tie rebars, thus increasing the resistance and ductility. It also allows the passing of some service pipes through the opening. Additionally, the concrete connects both sides through the openings in order to increase interaction. In addition, cutting an opening through the steel web will lead to a lighter steel beam by cutting off parts of the web, which means a lighter composite floor. Reinforcement rebar passing through the web opening provides high tensile strength, preventing brittle failure for

TABLE 1: Comparison of steel beam shapes used in the composite slim floor construction.

Steel beam shape	Tensile strength	Compressive strength	Slab restrain condition	Contact area	Concrete confinement	Workability
Asymmetric I-section	The bottom flange can resist the tensile stresses, but the section availability limits the required resistance.	The top flange provides compressive resistance.	Prevent up-lift force	Have a sizeable top contact area effective in the compression zone.	Partially provide concrete clamping	Provide the workability to cast in and install shear connectors as well as a continuing concrete slab.
Built-up I-section	All have a bottom plate, can resist the tensile stresses, and are flexible to the required resistance design.	The top flange provides compressive resistance.	Prevent up-lift force	Have a sizeable top contact area effective in the compression zone.	Partially provide concrete clamping	Provide the workability to cast in and install shear connectors as well as a continuing concrete slab.
Inverted T-section (or double T)	All have a bottom plate, can resist the tensile stresses, and are flexible to the required resistance design.	Only the top of the web can contribute to compressive resistance (small area in comparison).	Not prevent up-lift force	Not provided.	No concrete clamping	Provide the workability to cast in and install shear connectors as well as a continuing concrete slab.
Delta shape	All have a bottom plate, can resist the tensile stresses, and are flexible to the required resistance design.	The top edge provides compressive resistance in some cases.	Prevent up-lift force	Have a sizeable top contact area effective in the compression zone.	Provide clamping for infilled concrete	Need extra work to avoid the blanks or gaps and in installing shear connectors.
Hollow steel tube beam	All have a bottom plate, can resist the tensile stresses, and are flexible to the required resistance design.	The top edge provides compressive resistance in some cases.	Prevent the up-lift force	Have a sizeable top contact area effective in the compression zone.	No concrete clamping	Need extra work to avoid the blanks or gaps and in installing shear connectors.

the shear connector. Furthermore, the web openings do not require additional work only cutting the steel web. A disadvantage of the web opening shear connector is that the shear capacity significantly depends on the concrete strength, which is generally weaker than that of steel. Adding to this concern, the area of the concrete being subjected to compressive stresses is very limited, leading to further web openings to reach the required shear resistance. This would expose the web of the steel beam to buckling or high shear stresses, which require due consideration. In contrast, it can improve the shear resistance of the web opening shear connector by employing high shear resistant concrete by adding some reinforcement fibres. The size will be affecting on the shear capacity, as shear resistance depends on the concrete area, as the larger size will result in higher resistance. While cutting off a large area of the web of steel beam will reduce the stiffness, and the appropriate size of the web opening then should balance to obtain a higher shear resistance with the required stiffness.

4.5. Hollow Steel Tube Shear Connectors. The hollow steel tube is considered a web opening shear connector development, allowing concrete to pass through between the sides of the steel beam. Generally, the shear capacity depends on

the strength of the concrete. It is suggested that the hollow steel tube shear connector faces issues in web opening. For example, the side face of the hollow tube will apply the compressive stresses on the concrete, which will increase the concrete area under the compressive stresses. Instead of the small concrete area, the stresses were applied only by the thickness of the steel web. Furthermore, this increase in the bearing area corresponds with the perfect use of concrete, which takes advantage of its resistance to compressive stresses, an ideal feature of concrete. In addition, the steel tube length would function similar to the tie rebar in resistance to the tensile stresses at the connector. Moreover, the hollow steel tube will prevent the concrete from uplifting, especially in cases without top flanges.

Furthermore, the steel tube will support the steel beam to face the buckling, and also strengthen the steel web to meet the horizontal shear stresses. In contrast, hollow steel tubes need to weld through the web opening, which is additional work compared with the web opening. The hollow steel tube generally improves the interaction between the steel beam and concrete slab and increases shear capacity. Additionally, the hollow steel tube shear connector showed acceptable ductile slip behaviour. While these features are based on the studies conducted using the direct shear tests, the actual behaviour still requires

TABLE 2: Summary of studies on shear connectors in slim floor construction conducted using push-out test.

No.	Author and year	Type of shear connectors	Methods	Parameters considered	Conclusion
1	[54]	Lying shear stud	Experimental and numerical	Shear stud lying in the middle Shear stud lying in the edge	Loading capacity was dependent on failure concrete modes: the concrete splitting and pull-out of the headed stud from the concrete slab.
2	[29]	Web opening Tie bars Headed shear stud Ducts	Experimental and analytical	Spacing Tie (number of tie bars) Ducts	Using a shear stud or tie bar improves the shear resistance. It enhances the slip behaviour and ductility, and shear capacity increases with larger web opening diameter and higher concrete strengths.
3	[64]	Web opening Tie bars Headed shear stud Ducts	Experimental and analytical	Web opening Web opening with tie bar	Tie bar and shear stud showed a unique composite behaviour that increased the ductility, slip capacity, and shear strength in both flexure and push-out tests. Plastic moment capacity increased 1.5 times Failure mode was ductile when the tie bar was used.
4	[63]	Web opening Tie bars Headed shear stud Ducts	Analytical	Spacing. Tie (number of tie bars). Ducts.	The behaviour of the shear connectors in push-out tests is different from the flexural bending. The shear capacity could be influenced by the position of the plastic neutral axis.
5	[32]	Headed shear stud	Experimental and numerical	Headed studs. Concrete strengths.	The shear stud welded to the web with the concrete confinement increases the load capacity of steel-concrete connections. The high strength of concrete reduces the influence of the shear stud strength.
6	[2]	Web opening Web opening and tie rebar	Numerical	Concrete strength and yield stress of steel. Geometrical features (shaping, size, steel dowel shape, the thickness of steel web, the diameter of tie bar).	The loading capacity of the shear connectors depends on the size of the concrete infill. Adding the tie bar led to a significant ductility behaviour with sufficient slipping capacity.
7	[87]	Hollow steel tube	Experimental and analytical	The shape of the hollow tube Strength of concrete Size of the hollow tube	The shear strength of the HST shear connection was recorded higher than the stud connectors. The square HST and circle carried a shear load approximately three times higher than SC. The ductile behaviour of the shear stud is higher than that of HST shear connectors.
8	[77]	Web opening	Experimental and analytical	The shape of the opening Steel beam thickness. The opening size. Spacing and numbers of openings.	The square opening increased the shear strength of the connector. A higher compression and tension strength for the infill concrete leads to overall higher shear resistance. The square shape's shear resistance improved by utilising the whole width of the steel. In the case of the circle opening, approximately 75% of its diameter was effective.

investigation, using further cases of flexural tests. One of the advantages of using the hollow steel tube is to pass some service pipelines. Thus, examining the hollow steel tube without infill concrete will provide information about its composite performance and suitability for use.

4.6. Analytical Discussion. Determining the shear capacity of the shear connection depends on the properties of the shear connection and the failure type. For example, in the shear stud, failure could occur in the stud or the concrete surrounding the stud [88]. Based on that, Eq. (9) can determine

TABLE 3: Summary of studies on shear connectors in slim floor construction conducted using flexural test.

No.	Author and year	Type of shear connectors	Methods	Parameters considered	Conclusion
1	[59]	Headed shear stud	Experimental	Spacing of shear stud	The composite beam showed adequate structural behaviour under flexural shear. Results indicated that the shear stud on the top of web is necessary for the composite action.
2	[28]	Web opening	Experimental	Strengths of concrete.	Concrete infill increased the ultimate load-capacity composite beam up to double. The postfailure load is higher than that of the only steel beam.
3	[55]	Headed shear stud	Experimental	Stud position	Shear studs in a vertical position on both sides of the bottom flange proved it as the most efficient. The studs on the bottom flange improved the load capacity compared to the specimens without studs.
4	[56]	Headed shear stud	Experimental	Positions of shear studs	The shear stud that welds on the bottom flange showed improved loading capacity. The specimens with shear studs are considered more ductility than those without.
5	[64]	Web opening Tie bars Headed shear Stud Ducts	Experimental and analytical	Web opening Web opening with tie bar	Using a shear stud or tie bar improves the shear resistance. It enhances the slip behaviour and ductility, and shear capacity increases with larger web opening diameter and higher concrete strengths.
6	[1]	Headed shear stud Concrete dowels	Analytical	Headed shear studs. Horizontal studs. Dowel reinforcement.	Proposing design equations based on the plastic analysis method to predict the ultimate loading under flexural. The design procedures were in accordance with the principles in eurocode 4.
7	[34]	Web opening	Design proposal	Locations of sections that were analysed during the beam span	Despite the increasing span up to 25%. Achieving optimum advantages of the structural system with keeping the features of a slim floor. Adding to limiting the deformation.
8	[35]	Headed shear stud Web opening	Experimental and analytical	Shear connection Loading With or without concrete dowel	Certain connector parts were designed to be RC dowels to prevent failure to connect between the steel beam and the concrete slab. Experimental and analytical outcomes displayed sufficient consistency.
9	[90]	Headed shear stud Web opening	Experimental	Depth of slim floor beams. Type and size of steel shape beam.	The slim floor beam showed adequate flexural behaviour and well interaction between the steel and concrete. Concrete and steel are considered to work together regarding the flexural capacity, the shape of steel beam, and deformations.
10	[30]	Transverse steel bar	Experimental	Shear interaction: 25/40/100%. Clamping. Concrete cover. Shear studs. Diameter of concrete dowel.	Transverse bars proved to be sufficient shear connections and increased the ductility in a composite beam. Bigger dowels of concrete improved the performance of the slim floor beam.
11	[25]	Web opening dowel shear connector	Experimental and numerical	Diameter of the concrete dowel cylinder. Embedded the tie rebar in the dowel. Strength of concrete.	The concrete dowel in the steel web has a necessary function in the load capacity. A larger hole led to reduced load-moment of the steel beam. The diameter of the tie bar increased the load capacity. Recommended hole to be from 80 to 120 mm.

the shear resistance based on the design code to determine their shear resistance (PRd) in Eurocode 4 (EN1994-1-1, 2004) [89]. Calculating the resistance of shear stud and concrete and whichever is lower is considered to be the controller in design

$$P_{Rd} = \min \left(\frac{0.8 f_u \pi d^2 / 4}{\gamma_v} \text{ or } \frac{0.29 \alpha d^2 \sqrt{f_{ck} E_C}}{\gamma_v} \right), \quad (9)$$

where γ_v is the partial factor; d is the diameter of the shank of the stud, 16 mm \sim $d \sim$ 25 mm; f_u is the specified ultimate tensile strength of the material of the stud; f_{ck} is the characteristic cylinder compressive strength of the concrete; and E_C denotes the concrete elastic modulus.

Furthermore, the researchers suggested other equations to calculate the shear capacity of web opening. Equations were based on the failure that will occur in the concrete, which led to considering the web opening area as a concrete shearing area. The concrete facing the steel web thickness was considered the concrete area under the bearing load. While in some cases, with tie rebar, the term to calculate the tensile resistance of the tie rebar was added, as mentioned earlier in Eqs (1)–(5). The shear capacity of the hollow steel tube was built based on the failure that occurs in steel tubes or concrete, where a concrete failure and steel tube failure were considered as in equations (6) and (7). While in case only the concrete failed, the concrete shearing area and concrete under bearing load were deemed to be considered as in Eq. (8).

4.7. Test Methods. The push-out test is a typical test method that has been used in many studies to obtain the pure shear capacity of the connector system in composite beams, as summarised in Table 2. These studies are based on subjecting the shear connectors to direct longitudinal forces. Studies conducted helped us to estimate the shear capacity and failure mode and were capable of predicting the ductility behaviour of shear connectors. The push-out test is a standard test to determine the behaviour of the shear connector installed on the flanges or throughout the steel beam web.

However, the condition and test loading direction do not reflect the actual conditions of the shear connector in the composite beam. Thus, another type of test was considered in some studies to emphasise realistic investigations. The flexural test was the second test used to study the shear capacity and behaviour of shear connectors. Following the acceptability of the direct test result, the next step is a flexural test to determine the actual conduct of shear connectors. Table 3 summarises the studies conducted using flexural test. It was found that while the push-out test focused on estimating the direct shear capacity and design prediction equations, and the flexural test was used to find the moment capacity resulting from the shear connectors and shear interaction level. A four-point test flexural test is usually conducted to provide a symmetric loading case similar to the distributed load case. In addition, this test provides the constant moment (pure moment) between the two loading points. In some cases, a

three-point test can be conducted to apply a high shear force or concentrate the shear force on one side. Not enough studies were made to correlate the shear capacity obtained in the push-out and flexural tests for different shear connectors. Thus, more studies are needed to determine the relationship between the results of these tests or how to convert the result of these two types of tests.

5. Conclusion

The composite slim floor beam has been developed over many studies to offer the best solutions in fabrication and architectural aspects without compromising the structural capacity. This paper has reviewed important developments in composite slim floor construction, focusing on the various types of innovative shear connectors. Headed shear studs and bolts with nuts are able to be used as shear connections in slim floor systems by welding them on the steel web or bottom flange, and it showed good resistance and high ductility. In addition, headed shear studs are used with web opening shear connectors to enhance the ductility of the slim floor beam. Web opening is one of the most common shear connectors used in composite slim floor systems, and adding a tie bar would increase its ductility behaviour. Furthermore, the hollow steel tube shear connector is considered a development of the web opening, which faces some issues in web opening. For example, increasing the concrete area under the compressive stresses will increase the bearing capacity, and the steel tube length would be resistant to the tensile stresses at the connector. However, it will support the steel beam to face the buckling and resist the horizontal shear stresses. Furthermore, some issues need to be clarified and further studied as given as follows:

- (1) Creating web openings as shear connectors in the middle zone of the web is critical because it combines the web opening and welding zone in the build-up case (a weak zone). Furthermore, it will also be subject to higher horizontal shear stresses, which demand further consideration in designing the web opening in general.
- (2) The hollow steel tube could be one of the alternatives to the web opening as it increases the shear capacity of the shear connector and enhances ductility. However, the performance in flexure is still uninvestigated despite the direct shear results indicating adequate capacity and ductile behaviour, which is the primary feature of using it as a shear connector.
- (3) Most of the studies investigate the shear capacity of shear connectors by conducting the direct shear test, whereas moment capacity and shear interaction ratio were examined using a flexural test. However, the relation between the direct shear capacity obtained in the push-out test and flexure is undefined clearly.
- (4) More studies on fibrous concrete as an infilled material for hollow steel tubes and web opening

connectors in slim floor construction need to be explored to enhance the concrete ductility.

- (5) One of the advantages of using the hollow steel tube is to pass some service pipelines. For that, examining the hollow steel tube without infill concrete will provide information about its composite performance and suitability for this use.

Data Availability

These prior studies are cited at relevant places within the text as references to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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