State-of-the-Art on Composite Cold-formed Steel Flooring Systems

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Abstract

The current study presents a comprehensive review of the state-of-the-art on composite cold-formed steel flooring research over the past couple of years. The most relevant and significant literature references were reviewed to provide some profundity in the trends and development of the composite cold-formed steel floors. Advantages of this type of composite flooring system are also highlighted. A broad description of mainly two types of the composite floors mainly consisting cold-formed steel and concrete, and cold-formed steel and timber-based floorboards have been outlined in this study. The experimental and numerical investigations that have been carried out worldwide is likewise discussed in the paper. The most important aspects covered are shear connection behaviour, flexural and dynamic behaviour of the floors, and a brief description of fire testing.

Keywords: *Cold-formed steel beams, Composite flooring system, Concrete, Timber-based floorboards, Shear connection, Structural behaviour, Dynamic behaviour*

1 Introduction

In recent years, cold-formed steel (CFS) members have a significant growth in the construction industry because of higher strength materials and a broader range of structural applications in comparison to conventional hot-rolled steel members (Hancock, 2003). The main areas of use for cold-formed steel in structural applications traditionally are roof purlins, storage racks, stud walling, and many other framings or similar applications, while nowadays they are being used for primary structures such as portal frames and composite flooring system (Hancock, 2016). The increasing interest of building professionals in using cold-formed steel members over other construction materials such as hot-rolled steel or timber is due to the lightweight, cost-effectiveness, durability, sustainability, and ease of installation (NASH, 2007).

Cold-formed steel members are usually thinner than hot-rolled sections and have modes of failure and deformation which are not commonly found in ordinary steel members; hence design specifications are required in order to guide the design of cold-formed steel structures or thin-walled members. Recent studies (e.g. Far et al. 2017; Saleh et al. 2018) have highlighted the merits of using cold-formed steel in building industry and proved that cold-formed steel beams are often preferred over other structural members design standards such

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as AS/NZS 4600:2018 (Standard Australia, 2018), American Iron and Steel Institute Specification (AISI, 2007), EN 1993-1-3(2006) (Eurocode 3) set out the requirement for cold-formed steel members and their connections.

With an increasing interest in the building construction industry to minimise resources and materials used, composite structures are proved to be an innovative system as they can fulfil the required performance criteria (Loss and Davison, 2017). A composite structure is known to combine two or more materials together in a structural member. The main advantage of composite structures over non-composite structures is that they generally perform better compared to the sum of their individual parts which means an increase in structural capacity and contribution to the minimal utilisation of resources by decreasing the size of the structural members (Rackham et al., 2009).

The objective of this paper is to provide up to date literature review of composite cold-formed steel flooring systems which have been studied so far and will cover various aspects that influence the structural and dynamic behaviour of the flooring systems. A brief overview of the fire performance of the flooring systems is also covered.

2 Advantages of Using Cold-formed Steel Flooring System

Cold-formed steel members are chosen for the construction of flooring systems because of high strength-to-weight ratio, ease of fabrication, ease of transportation, and rapid installation. If an adequate interconnection between cold-formed steel beam and slab (for example, concrete or timber-based floorboards) can be achieved, this type of composite flooring system has many benefits over traditional flooring system (e.g., Kyvelou et al. (2017b), Lakkavalli and Liu (2006)). Cold-formed steel composite flooring systems offer an advantage of high strength to weight ratio, which eventually reduces the self-weight of floors and less imposed load on the foundation. This type of flooring system can be manufactured off-site and assembled on-site easily and quickly in a modular way which will reduce the construction time (Loss and Davison, 2017), Loss et al. (2016). The modular construction of the flooring system also helps to make the project cost-effective and better quality controlled. For small or medium projects, where shorter span hot-rolled steel sections are not available, cold-formed steel sections are readily available in various section sizes and spans because of their manufacturing technology of mass production (e.g., Lakkavalli and Liu (2006), Hanaor (2000)).

3 Design Considerations

Composite floors predominantly carry vertical imposed loads in bending and shear. It is well known that the efficiency of the composite construction is governed by the strength and stiffness of the used shear connection. In an ideal case the system is said to have a full shear connection if the number and strength of the shear connector is such that the ultimate load on the system is governed by the moment resistance of the system, and not by the strength of connection. If this cannot be achieved, the shear connection is known to be partial (Kyvelou et al., 2017a). The moment capacity of cold-formed steel flooring system is based on the attained degree of partial shear connection and its magnitiude lies between the moment resistance of steel beam alone and of the equivalent composite beam with full shear connection(e.g.,Lakkavalli and Liu (2006), Kyvelou et al. (2017a)). The effective flexural stiffness of the composite system is calculated based on the shear bond coefficient and its magnitude lies between the values of the flexural stiffness of the corresponding system with zero and full interaction at the interface (Kyvelou et al., 2017a). Shear bond coefficient is the function of slip modulus and spacing of the employed shear connectors.

In some of the studies covered in this review paper, researchers have generated the design equations to evaluate the moment capacity and deflection of composite floors after verification with their experimental or numerical results. The design specification is mentioned below in the relevant topic.

4 Cold-formed Steel and Concrete

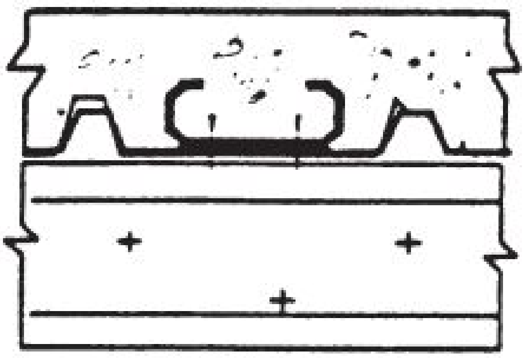
Conventional composite floors which combine hot-rolled steel beams and reinforced concrete slabs are designed so that the both materials are utilised by means of composite action that occurs at the interface by means of shear connectors (Rackham et al., 2009) . The efficiency of this type of composite floors is due to exploitation of the strength of concrete in compression and steel in tension which is achieved by force transfer mechanism between the top flange of the steel beam and concrete (Couchman, 2016). In small to medium-sized buildings, the use of hot-rolled steel section is known to be uneconomical because of material wastage, cost of cutting and more labour. Hence the readily available section sizes and spans of cold-formed steel joists is an economical solution for composite floors to use in small to medium scale projects (Lakkavalli and Liu, 2006).

4.1 Experimental Investigations

Numerous experimental studies of cold-formed steel and concrete floors have been carried out to investigate the feasibility of this composite system. Push-out tests and composite beam tests were carried out to study the behaviour of the shear connector and load-carrying capacity of the composite system. The significance of each parameter that has an influence on the behaviour of the composite system is discussed below separately.

4.1.1 Shear Connection and Structural Behaviour

Research works have been carried out on the use of cold-formed steel sections with concrete as an alternative solution to replace hot-rolled steel and reinforced concrete in residential buildings (e.g., Hanaor (2000), Lakkavalli and Liu (2006), Hsu et al. (2014)). The design of composite slabs/beams relies mainly on shear transfer between the concrete slab and steel beams by shear connectors. The practice of welding shear stud to the top flange of the steel beams, similar to traditional composite systems, is not applicable in cold-formed steel flooring system as the thickness of steel beam is too less for the welding of studs. So careful attention should be given in design of shear connectors in composite flooring systems comprising cold-formed steel sections to mobilise maximum shear connection (Hanaor, 2000). Hanaor (2000) conducted push-out tests and composite beam tests with double cold-formed channel sections and used different types of shear transfer methods between cold-formed steel beam and concrete slab. They were screwed and welded cold-formed channel sections for cast-in concrete, while powder actuated nails, expansion anchors, through bolts and concrete screws were used for hardened concrete as shown in figure 1. The researcher concluded the response of the composite beam tests to be highly ductile and the capacity of the shear connector can be estimated conservatively by using cold-formed steel codes or the data on anchorage in concrete.



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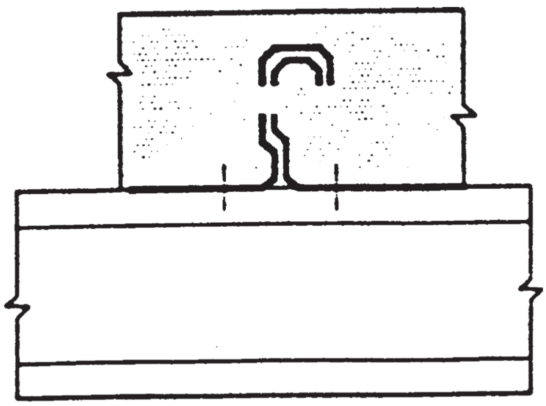

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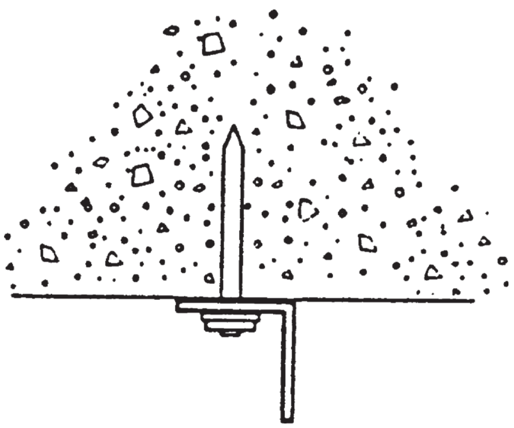

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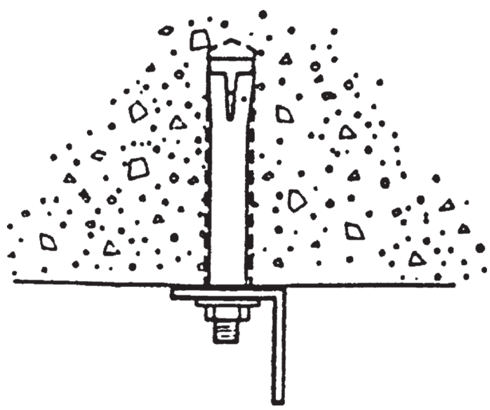

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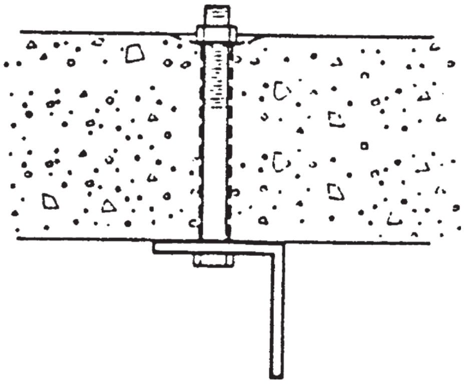

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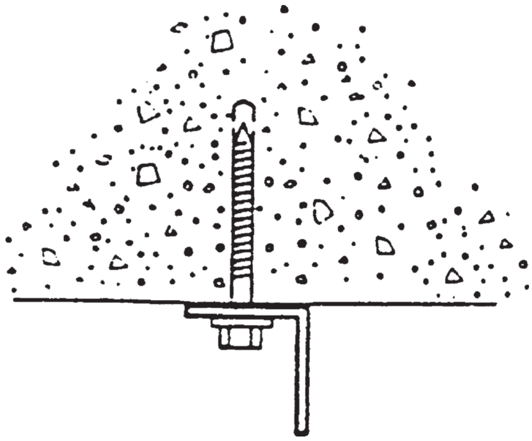
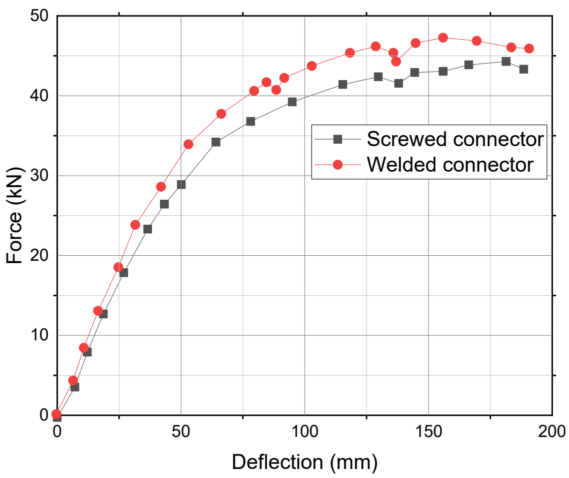


(f)

Figure 1: Shear connectors utilised by Hanaor (2000); Embedded shear connectors for cast-in concrete a) Screwed, b) Welded; Dry shear connectors for hardened concrete c) Powder actuated nail, d) Expansion anchor, e) Through bolt, f) Concrete screw

Further it was found that the composite beams with welded channel connection was reported to exhibit slightly higher ultimate load than the beam with screw connection as shown in figure 2(a) . Figure 2(b) shows the load-deflection curves of a beam with dry connection to failure.



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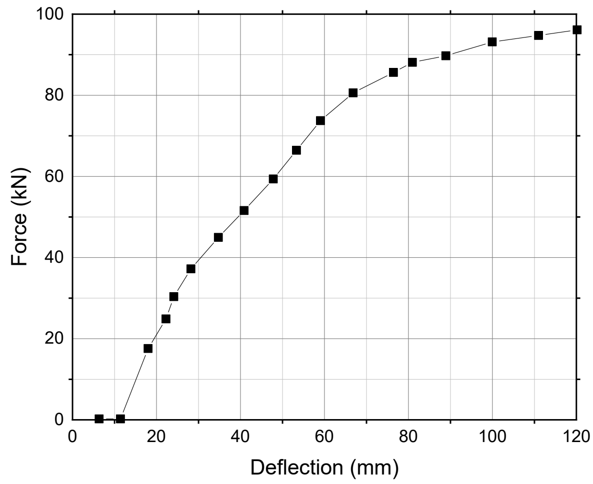


(b)

Figure 2: Load-deflection curve of full scale beams redrawn from Hanaor (2000); (a) for embedded connection (b) for dry connection

Lakkavalli and Liu (2006) studied three different shear transfer methods which were pre-drilled holes, pre-fabricated bent-up tabs and self-drilling screws on the flange of cold-formed steel C-section. Bent-up tabs were reported to be the best method among three. Researchers further concluded that enhancing the composite action between concrete and cold-formed steel beam increased the strength capacity and reduced the deflection compared to those which depend just on the natural surface bond between the concrete and steel. Figure 3 below is a typical cross-section of composite cold-formed steel and concrete flooring system investigated by Lakkavalli and Liu (2006).

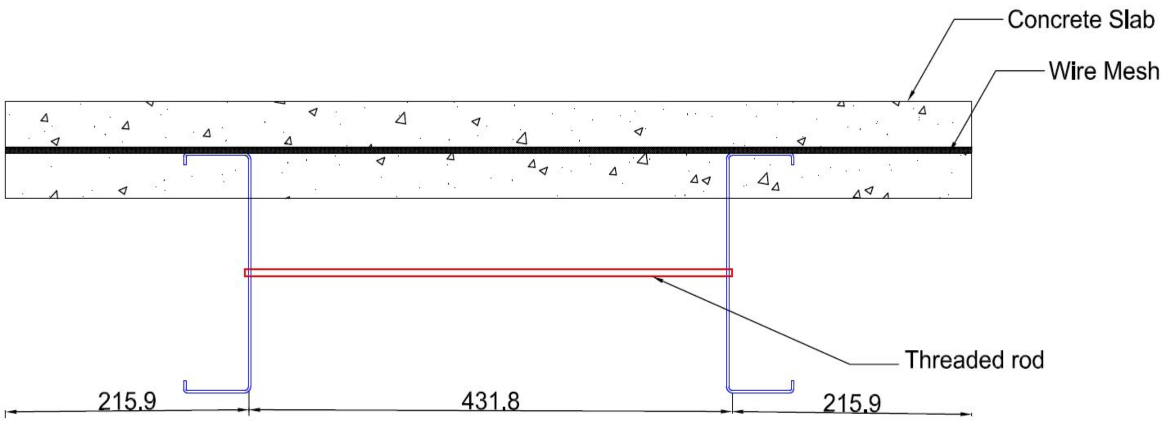


Figure 3: Typical cross-section of composite cold-formed steel and concrete flooring system studied by Lakkavalli and Liu (2006).

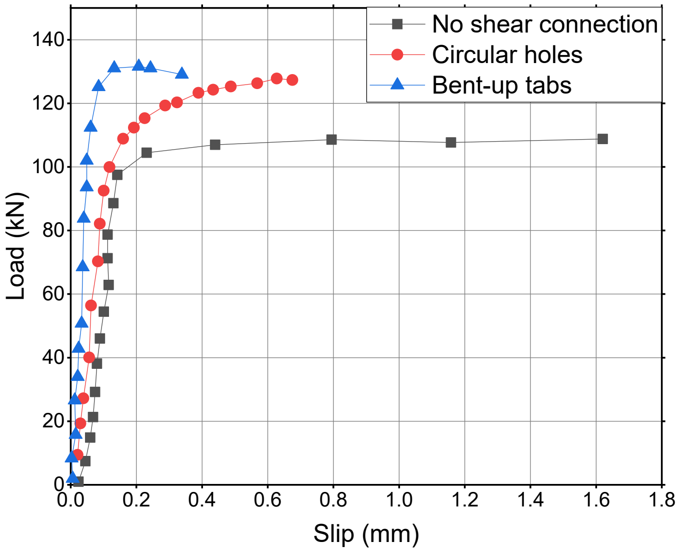
Fox et al. (2008) utilise the top flange chord of cold-formed steel joist which was embedded to the concrete slab to act as shear connector. Push-out tests demonstrated the enough interlocking capacity of shear connection to enable full composite action between the concrete slab and the joist. Irwan et al. (2009), Irwan et al. (2011) investigated a new type of shear enhancement called bent-up triangular tab shear transfer (BTTST) and was found to have more load carrying capacity and ductility than bent-up tabs shear enhancement studied by Lakkavalli and Liu (2006). Wehbe et al. (2011) highlighted the importance of composite action on flexural and shear strength of the composite beam which depends upon the number of shear connectors. Hsu et al. (2014) and Bamaga et al. (2019) demonstrated that the ultimate strength and ductility of the composite section were found to be significantly increased in comparison to non-composite section. More recently, LEAL L.A.A.S and Batista E. M (2020) carried out the full-scale experimental tests on a composite CFS trussed beams and prefabricated concrete slabs, with 7800mm length and 1200mm width, joined together using 0.95mm thin-walled channel as shear connector attached to the top chord of truss with screws.The studies demonstrated that the innovative thin-walled channel connector provide full interaction between the slab and trussed beams, as a result of which load-carrying capacity of the composite beam was significantly enhanced.

Hence, it is clear from the mentioned studies that the degree of shear connection influences the composite action between the cold-formed steel beam and concrete slab and as a whole enhances the flexural strength of the composite cold-formed steel beam and concrete flooring system.

4.1.2 Load-slip Behaviour

In a composite structure, it is essential to determine the load-slip behaviour of the shear connectors as the ultimate strength of composite beams or floors depends upon strength and ductility of shear connection (e.g.,). Push-out tests were carried out to know the load-slip response of the shear connectors. Hanaor (2000) plotted the load-slip response for embedded connectors, which showed welded channel connectors to be stiffer than screwed channels and screwed deck connectors. For screwed channels and screwed decks, the failure of the push-out specimen was due to bolt shear and screw pull-out, respectively while for the welded channels the failure was due to crushing of concrete and section buckling.

Lakkavalli and Liu (2006) studied the influence of shear transfer mechanism and their load-slip response is shown in Figure 4. Self-drilling screws, pre-drilled circular holes, and bent-up tabs on the flange of CFS embedded in the concrete were investigated as a means of shear transfer mechanism. The specimens with shear enhancement exhibited significant reduction in slip between the concrete and the cold-formed steel sections in comparison to the specimen that was relying on natural bond between steel and concrete.



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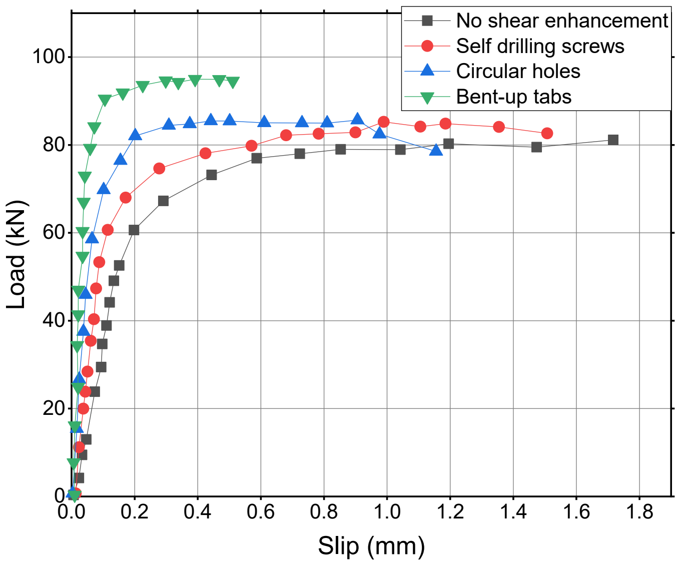


(b)

Figure 4: Comparison of load-slip response redrawn from Lakkavalli and Liu (2006); a) Load-slip response for 1.905mm thick C-section b) Load-slip response for 1.524mm thick C-section

Mujagic et al. (2010) evaluated standoff screws as a shear connector on a full-scale composite truss and concrete beam and highlighted the importance of ductility requirements in shear connector. It was reported that the lack of ability of a shear connection to sustain slip can lead to the premature failure as a consequence of the incapacity of the load to progressively transfer to corresponding shear connectors.

4.1.3 Influence of Cold-Formed Steel Thickness

The influence of the thickness of cold-formed steel memebers on composite cold-formed steel and concrete flooring system has been investigated in number of studies. Lakkavalli and Liu (2006) reported that, on average, there was an approximately 43.5% higher ultimate capacity for C-sections with 1.905mm thickness than the specimen with 1.524mm thickness. The significant increase of the strength is because of failure of the specimens that was initiated by the tension yielding of cold-formed steel C-sections. Similarly, an increase of 17.2% in the moment capacity of 2.4mm thick cold-formed steel sections in comparison to 1.9mm thick was obtained in the flexural test carried out by Irwan et al. (2011). It was further mentioned that the increase of steel beam thickness led to the increase of the shear area of the shear connector (BTTST) which increases the bending capacity of the shear transfer enhancement. However, Irwan et al. (2009) pointed out that if the failure of the specimen is concrete related, the influence of CFS thickness does not have significant influence on the ultimate capacity. More recently, in the experimental investigations conducted by Bamaga et al. (2019), it was demonstrated that the cold-formed steel(CFS) with thickness of 2.3mm exhibited 16.7% greater ultimate moment capacity than 2.0mm thick CFS section with the same shear connectors.

4.1.4 Influence of Concrete Strength

The load-carrying capacity of the specimen enhances as the grade of the concrete increases (Irwan et al., 2009). No further claim on the influence of concrete strength on cold-formed steel and concrete slab has been noted on other relevant literature. But, the findings from the previous researchers (e.g., Ellobody and Young (2006), Hosain and Pashan (2006)) on traditional composite floor system demonstrated that the strength of the shear connectors could be increased by increasing the grade of concrete.

Figure 5 below shows the mean ultimate load versus $\sqrt{Fcu}$ for the push-out test of specimens carried out by Irwan et al. (2009), where the increment of a load to the square root of concrete compressive strength is found to be nearly linear.

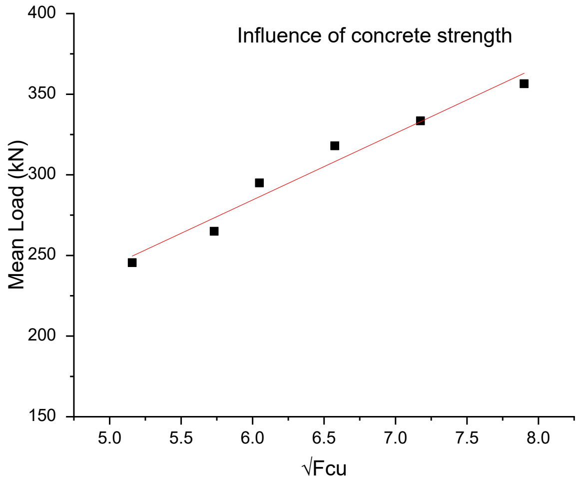


Figure 5: Load versus square root of compressive strength redrawn from Irwan et al. (2009).

4.2 Design Specifications

Although there are very detailed information and developed design methods for traditional composite beams consisting hot-rolled steel beams and reinforced concrete slabs, no design guidelines have been developed for the composite cold-formed steel and concrete slabs that considers the beneficial effect of composite action on the flexural capacity (Lakkavalli and Liu, 2006). Fox et al. (2008) carried out theoretical analysis based on elastic shear flow approach and ultimate strength approach and found out the applicability of both the methods to determine the flexural strength after comparison with test results. Detail about the analytical method and comparison of theoretical and experimental results can be found in the relevant literature.

Hsu et al. (2014) proposed the design methods of the composite beams comprising cold-formed steel joist and concrete slab with little modification for the composite section as described in AISC specifications and found out the design methods to be able to predict ultimate strength and deflection check after comparing with experimental results. Bamaga et al. (2019) are found to use interpolation method and stress block method for their theoretical analysis of composite beam. The calculations for stress block method was based on British standard BS5950 (BSI, 2010). It was reported that the ultimate moment capacities calculated from interpolation method were conservative than those from stress block method because interpolation method assumes a linear relationship between the composite action and degree of shear connection.

4.3 Numerical Modelling

There have been many studies involving finite element models to study the behaviour of hot-rolled steel and concrete composite structures(e.g., Queiroz et al. (2007); Sebastian and McConnel (2000), Baskar et al. (2002)). But, a very few technical literature which is related to finite element analysis of cold-formed steel and concrete floor system is found in comparison to the experimental studies. More recently, Majdi et al. (2014) carried out finite element investigation using ANSYS to investigate the structural behaviour of composite flooring system comprising cold-formed steel and concrete slab, and they found out their numerical studies to be in good agreement with the experimental studies performed by Punurai (2007). The use of furring channel to transfer the shear force is expected to have some slip, so bond-slip behaviour of the shear connector has also been numerically evaluated. The application of bond-slip behaviour between steel and concrete in finite element model was found to reduce the ultimate strength and flexural stiffness of the system while compared to the perfect bond condition.

5 Cold-Formed Steel and Timber Based Floorboards

Most recently, there is an increasing interest in the building construction industry to minimise energy consumption throughout the building's lifecycle. Some growing interests are arising among building professionals to limit the energy demand during the whole building life cycle as a prime demand for green and eco-friendly buildings (Akadiri et al., 2012). Lightweight flooring systems which are made up of cold-formed steel joist and timber-based floor panels can be an economical and durable solution (Kyvelou et al., 2017b). Considering the impact of building on energy consumption and greenhouse gas emissions, the use of steel and timber, both of which are recyclable, make this flooring system a novel and sustainable solution that has a minimal impact to the environment in comparison to other flooring systems that uses concrete or other non-recyclable materials.

5.1 Structural Behaviour

The utilisation of cold-formed steel joists with timber-based flooring panels for the construction of lightweight flooring system is common. But no design guidelines have been published yet for the flooring system to consider the beneficial effect of composite action on the flexural capacity (e.g., Kyvelou et al. (2017a), Zhou et al. (2019)). It is only recently researchers have started to investigate on the structural behaviour of this type of lightweight flooring system. Li et al. (2012) conducted full-scale experimental testing of six different floors consisting cold-formed steel joist and bamboo. An analytical equation was also developed to calculate deflection and flexural capacities. It was found that the predicted value from the simplified analysis was in good agreement with experimental results and demonstrated the potential of cold-formed steel and bamboo composite floors to replace concrete or wooden slabs in residential buildings. Loss and Davison (2017) carried out full-scale prototype testing for two different floor solutions fixing cross-laminated timber to cold-formed steel beam with screws and adhesives respectively. Numerical investigation was also performed using SAP2000 to simulate experimental tests. It was reported that both the floor solutions exhibited adequate structural performance and the composite floor system demonstrated the potential in terms of load bearing capacity, stiffness and method of construction. Kyvelou et al. (2017a, 2017b, 2018) conducted comprehensive experimental and nemerical investigations for the composite floors comprising cold-formed steel joist and particle-board. Four-point bending tests were performed on composite beam that used 38mm thick particleboard screwed to 3mm thick CFS beam, which were spaced at 600mm. The beam was supported across a span of 5800mm. Figure 6 below demonstrates the load-deflection behaviour plotted form the experimental testing of the composite flooring system with 3mm thick beam sections. It can be seen that flooring system with minimum screw spacing and the use of structural adhesive exhibits higher stiffness and load bearing capacity. Finite element model was developed on ABAQUS and parametric studies were carried out to study the influence of key parameters after the developed model was validated against physical tests. Furthermore, design equations for the flooring system is developed and their theoretical background is also presented. The accuracy of the design method is verified with the results from experimental tests and numerical simulations. Overall, it was reported that there is a potential for significant improvements in the structural behaviour of the flooring system mobilising composite action.

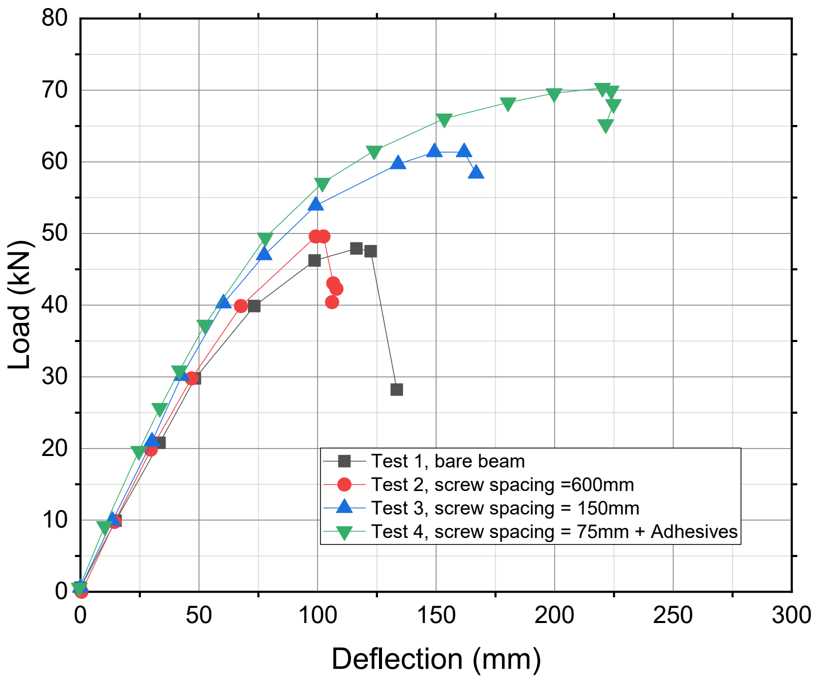


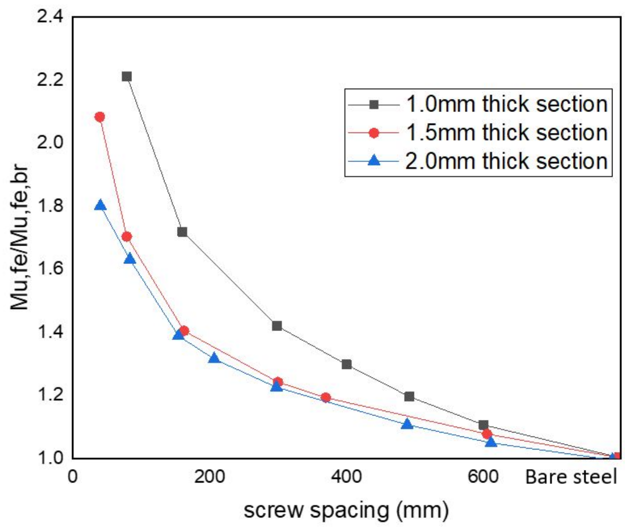
Figure 6: Load-deflection curves of flooring system with 3mm thick steel section beams (Kyvelou et al., 2017b)

Zhou et al. (2019) carried out two full-scale experimental tests, and finite element analysis using ANSYS and parametric studies to investigate the flexural capacity of cold-formed steel C-section and oriented strand board (OSB) floors. The OSB sheathing were fixed to CFS joist using self-drilling screws. It was found that the numerical results was in good agreement with the test results and concluded that the ultimate flexural capacity of the composite flooring system was found to be higher than those evaluated based on cold-formed steel joist alone due to composite action between the cold-formed steel joist and OSB sub-floor. Raffoul et al. (2019) demonstrated that composite flooring system with screws at 150mm and structural adhesives in contrast to bare steel frame exhibited 40% increase in flexural stiffness and 120% increase in failure load. In contrast, the specimen with 150mm screw spacing and without adhesives demonstrated 20% increase in flexural stiffness and 75% increase in failure load in comparison to bare steel frame. Similarly, 31% increase in stiffness and 94% increase in failure load for the specimen with 300m screw spacing and adhesives, and 17% increase in stiffness and 55% increase in failure load for the specimen with 300mm screw spacing without adhesive in comparison to bare steel frame is reported.

Hence, the above studies confirms that the composite flooring system comprising cold-formed steel joists and timber-based floor panels have the required load bearing capacity and stiffness if the shear connection is adequately provided to take the advantage of composite action. Further, this type of flooring system has an immense potential to be used as a lightweight flooring system in small to medium scale buildings leading to sustainable buildings.

5.1.1 Influence of Shear Connection

The benefits of composite action are well known for hot-rolled steel beams and concrete slabs, but the shear interaction between timber panels and cold-formed steel joists is not available in any technical literature or ignored by the construction industry (Kyvelou et al., 2017b). Li et al. (2012), Loss and Davison (2017), and Far (2020) confirmed that the shear connector has an influential effect on the strength of composite system as bending stiffness is provided by the composite action between the floor elements. Kyvelou et al. (2017b) and Raffoul et al. (2019) reported that the composite performance of the flooring system was found to be improved with the use of adhesives along with screws. Figure 7 below shows the influence of screw spacing for 220mm deep cold-formed steel section of three different thickness of the composite flooring system relative to the corresponding bare steel system. As can be seen from the figure, Kyvelou et al. (2018) reported the enhancement of composite action between the beam-board interface while decreasing the spacing of screws and further it was seen that thinner steel section exhibited greater ultimate moment capacity and flexural stiffness from composite action due to the higher ratio of board to steel area. Zhou et al. (2019) introduced a coefficient of composite action η, which considered the influence of composite action between the OSB and cold-formed steel joist and reported the composite action coefficient η to be 16% higher for the screw spaced at 150mm in relative to the 300mm screw spacing.



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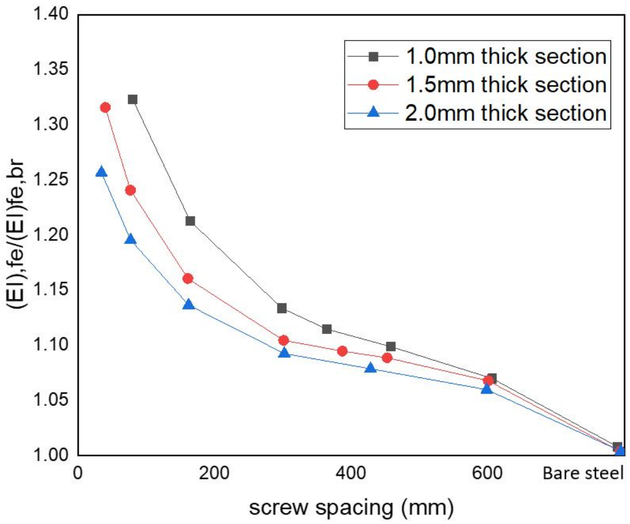

(b)

Figure 7: Influence of screw spacing in (a)moment capacity and (b)flexural stiffness of the composite system corresponding to the bare steel system (Redrawn from Kyvelou et al. (2018))

5.1.2 Influence of Section Geometry

Kyvelou et al. (2018) conducted parametric studies for the cold-formed steel sections with three different depths (220mm, 250mm, and 300mm) and six different thickness. Figure 8 is a typical cross-section of the composite cold-formed steel joist and timber flooring system utilised by Kyvelou et al. (2018) for numerical investigations.

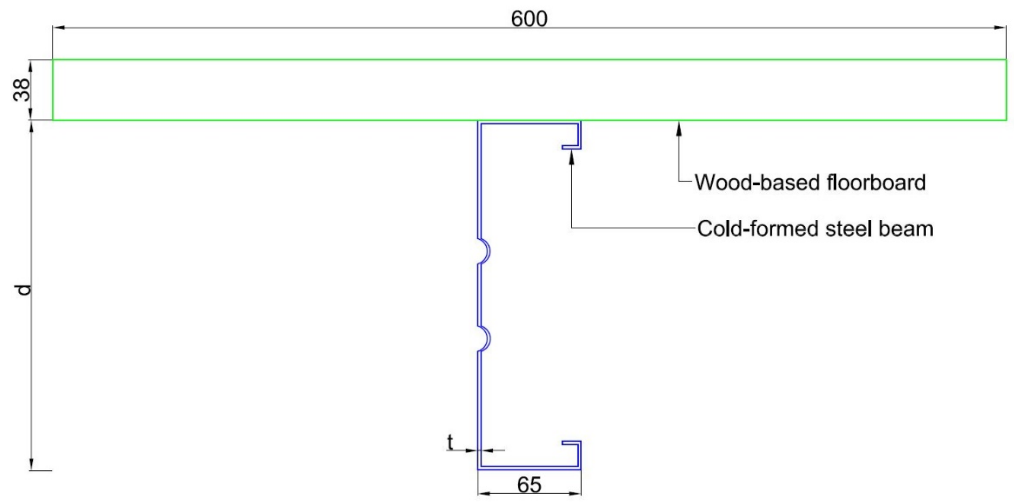

Figure 8: Typical cross-section of the cold-formed steel flooring system (Redrawn from Kyvelou et al. (2018).

The experimental test results and finite element analysis results based on the study of Kyvelou et al. (2017b), Kyvelou et al. (2018) showed that for the cross-section with any given depth, thinner steel section exhibited greater ultimate moment capacity and flexural stiffness which was reported to benefit from the composite section due to a higher ratio of the board to steel area. But the studies from Zhou et al. (2019) reported that the thickness of the cold-formed steel beam has very less influence on the composite action. They further concluded that decreasing the spacing of cold-formed steel beam increased the composite action coefficient which consequently enhances the flexural capacity of composite floor. The influence of oriented strand board (OSB) thickness on composite action was found to be directly proportional, which means that the flexural capacity of the floor increased with the increase in thickness of OSB. It was reported that the increase in yield strength and section depth of cold-formed steel joist has a little influence on the coefficient of composite action.

5.1.3 Influence of Sub-floor Types

More recently, Far (2020) carried out his numerical investigations to analyse the performance of various engineered timber products like particleboard (PB), oriented strand board (OSB), laminated strand lumber (LSL), laminated veneer lumber (LVL) and laminated bamboo after validating his 3D model with the previous studies conducted by Kyvelou et al. (2017,2018). It was found that the ultimate moment capacity of the composite floor increased by 7.5%, 5.9%, 4.5% and 1.5% respectively for laminated bamboo, LVL, LSL and OSB when PB was replaced. He reported that the variation in shear and Young's modulus of elasticity of timber-based floorboards could have effect on ultimate moment capacity of composite flooring systems.

6 Dynamic Behaviour of Floors With Cold-Formed Steel Joists

Cold-formed steel flooring system being lightweight is vulnerable to certain vibration problems as there are less mass and lower structural damping (Kraus and Murray, 1997). The vibration of floor due to human activities like walking can be problematic. Therefore, the evaluation of vibration performance of floors with cold-formed steel joists due to human-induced dynamic loads must be considered in the design. Xu et al. (2000) mentioned that floor vibration associated with human walking had not been adequately addressed in design and construction practice of lightweight cold-formed steel floors as the current practice limit the span deflection to L/480 under specified uniform distributed load, which was actually based on practice on residential floors with timber joists. So, it is crucial to assess the dynamic performance of the floors against the acceptable tolerance criteria's and identify the construction details to control the annoying vibrations.

6.1 Experimental Investigations

Kraus and Murray (1997) carried out vibration tests on 25 residential floor system supported by C- shaped cold-formed steel joists. Alikhail et al. (1999) conducted a full-scale floor structure investigation and the dynamic performance was investigated at three different stages; standalone floor, floor with wall frames and ceiling, and floor with wall frames, ceiling & roof loading. Static tests were performed to measure maximum deflection, dynamic tests were performed to evaluate natural frequency, damping ratio and vibration modes, and subjective tests to acquire human response to vibration.

Research studies on the vibration performance of composite cold-formed steel floors were conducted at the University of Waterloo at different phases. Xu et al. (2000), Xu and Tangorra (2007), Parnell et al. (2010) evaluated the vibration performance of cold-formed steel light weight floors and investigated the key parameters that contribute to minimize floor vibrations. Static tests were conducted to examine the stiffness of the joists and dynamic tests to examine the frequencies of the floor system with different span lengths. Laboratory tests (Static and dynamic tests) carried out on floors with different spans and configurations. On-site tests also carried out to compare the results obtained in laboratory tests and assess the actual vibration performance of cold-formed steel residential floor systems. Rack and Lange (2010) and Guan et al. (2019) conducted different experimental tests on composite cold-formed steel flooring system to investigate the vibration performance. Natural frequency, static deflection and damping ratio of floor specimens were assessed by both researchers.

6.1.1 Influence of Construction Details on the Vibration Performance

Xu and Tangorra (2007), Xu et al. (2000) found that when the floor span increases, frequency decreases. When the rotation at the support was restrained, the flexural stiffness of the floor was found to be increased which enhanced the fundamental frequency (e.g., Parnell et al. (2010), Xu and Tangorra (2007)). Guan et al. (2019) performed FEA to study the effect of support conditions and observed similar results as previous researchers. Xu et al. (2000) reported the reduction in deflection and damping ratio of the floor while increasing the blocking depth and blocking pattern. Similar behaviour was also observed by Xu and Tangorra (2007). Minor influence on the deflection, frequency and damping ratio was observed due to the effect of bridging (Xu and Tangorra, 2007). Xu and Tangorra (2007) reported that closer screw spacing enhanced the floor stiffness and when the screw spacing was doubled the floor system was found to have poorer vibration performance resulting in decreased natural frequencies and larger deflections. But, Guan et al. (2019) observed that shear connectors have a negligible influence on the vibration performance. When the subfloor was glued to the joist in addition to the screw fixing, the natural frequency of the floor was found to be decreased and deflection and damping ratio to be decreased (e.g., Xu and Tangorra (2007), Parnell et al. (2010)). Xu and Tangorra (2007) also reported that fastening a gypsum ceiling to the bottom flange of joists decreased the deflection, damping ratio and natural frequencies of the floors.

6.1.2 Comparison Between Laboratory and In-situ Test Results

Xu and Tangorra (2007) made the comparison between the laboratory floors with 5.33m span and on-site floors whose span was closest to the laboratory floors. It was reported that the in-situ unfinished floors normally showed higher first natural frequencies and smaller deflections than the equivalent laboratory floors. When the joist ends were partially restrained on the laboratory tests, it provides close result and behaviour of in-situ floors. It was demonstrated that the first natural frequency of finished in-situ floors was lower than that of laboratory floors, which may be due to the increased self-weight due to the presence of finishing materials. The damping ratios of in-situ floors (both finished and unfinished) were significantly higher than equivalent laboratory floors which may be due to building components like wall that dissipated the impact energy. Overall, it was suggested that the laboratory floors are conservative when compared to on-site floors. Similar observations were reported by Parnell et al. (2010).

6.2 Evaluation of Vibration Performance Based on Existing Tolerance Criteria

Kraus and Murray (1997) , Alikhail et al. (1999), Parnell et al. (2010), Guan et al. (2019) are found to compare their test results against the established tolerance criteria such as static deflection due to 1kN load, fundamental frequency, and acceleration response from walking to evaluate the vibration performance of the examined floors. Kraus and Murray (1997), Zhang (2017), Guan et al. (2019) have further proposed design procedures to check the acceptability of the floors for vibration serviceability. In Australia, AS 3623:1993 Domestic metal framing (Standards Australia, 2018), provide the serviceability criteria for floors in domestic buildings, which is pretty much based on the evaluation criteria by Ohlsson (1988).

7 Fire Studies

Cold-formed steel flooring systems are used in residential construction because of their non-combustibility and dimensional stability. To use in fire situations, it is important to design with adequate fire-resistance rating (FRR). Numerical and experimental studies have been conducted to investigate the structural fire performance of cold-formed steel floors with lipped channel section (e.g., Sakumoto et al. (2003), Baleshan and Mahendran (2010)). It was seen that lipped channel joists are commonly used in flooring system with fire-resistive plasterboards lined on the ceiling side and timber-based floorboards on the unexposed side to provide structural resistance. Because lipped channel joists were found to exhibit local buckling in fire tests, Jatheeshan and Mahendran (2015) developed a new floor system made of welded hollow flange channel (HFC) joists as the section has greater distortional and local buckling capacities. Jatheeshan and Mahendran (2015, 2016) numerically and experimentally investigated the fire performance of floor system with HFC joist. They reported a close agreement between FEA and fire test results and found out the higher fire ratings in comparison to lipped channel joist.

8 Conclusions

In this paper, research and development of cold-formed steel flooring system with concrete and timber has been presented. The advantages, structural behaviour, dynamic behaviour and brief about fire investiagations of the cold-formed steel flooring system have been discussed in the paper. Only relevant literature references which were directly related to the topic of the paper were selected and quoted here. Because of numerous advantages cold-formed steel can offer, composite cold-formed steel flooring system has an enormous potential to be used as a sustainable and cost-effective floor solution. Composite flooring system comprising cold-formed steel and concrete is briefly discussed in this paper. There is still limited information on the long-term behaviour of the flooring system which needs further studies. Creep in concrete slab has a substantial influence on the performance of composite structures and hence needs to be taken into consideration (Kim, 2014). More recently, researchers have also reported that composite flooring system comprising cold-formed steel and timber-based floorboards can be an economical, durable and sustainable solution for the residential and commercial construction. However more detail investigations need to be done on joists with web holes, influence of different types and thickness of timber-based floorboards and further improvements can be done through geometry optimisation as well as using efficient means of shear connections. The influence of creep that may arise in timber-based floorboards is another factor to take into account for further investigation. As discussed in this paper, previous studies suggests that cold-formed steel joists can either be used with concrete or various timber-based floorboards to make composite slabs depending upon the project-specific requirements and loading conditions. However, researchers are more interested and enthusiast in cold-formed steel with timber-based floor boards rather than concrete due to being more light-weight, eco-friendly and cost-effective.

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