COMPOSITE BEHAVIOUR OF COLD-FORMED STEEL - TIMBER FLOORS

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Abstract: This article investigates, experimentally, the structural performance of lightweight cold-formed steel (CFS) - timber board composite flooring systems. Fifteen full-scale bending tests and twelve companion pushout connection tests were performed. The effect of connection detail (comprising self-drilling screws with or without a structural adhesive) on structural performance is examined. The results of this research demonstrate that the use of a polyurethane adhesive, in conjunction with screws, leads to a significant increase in connection slip modulus and a higher degree of composite action in the floors, resulting in up to 40% increase in flexural stiffness, when compared to joists designed individually. The experimental results are then compared to predictions from relevant existing analytical models.

1. Introduction

Cold-formed steel (CFS) and timber-based flooring systems have become increasingly popular in the construction industry due to their attractive high strength-to-weight ratio, buildability and sustainability [1, 2]. While, the composite design of such floors provides an attractive solution for increasing the efficiency of lightweight floors and minimising the use of resources, the beneficial effect of the timber board (often referred to as floor boards or decking) on the floor structural performance is often ignored, leading to a more conservative design. This may be due to the limited understanding of the CFS joist-timber board interaction, including the influence of connection detail (often comprising screws and structural adhesives) on shear and load-slip behaviour, instrumental to the prediction of the global behaviour of the floor cassettes.

While a remarkable number of documents and design guides are available on the performance of hot-rolled steel-concrete, timber-concrete or engineered timber composite floors, which have become relatively common technologies [1], only few research articles can be found on the performance of composite CFS joist-timber board flooring systems [1-8]. Overall, the existing research shows that significant improvements in floor flexural performance can be achieved by mobilising the interaction between the timber floor boards and CFS joists. Such improvements are influenced by the spacing of shear connectors [3,4], connection detail (e.g. screws or bolts [5] with or without the presence of structural adhesives [3]), span length [6], joist gauge [3], and the type and depth of floor boards [9].

It is well known that shear connector stiffness and the degree of shear connection can significantly influence the flexural stiffness and bending moment capacity of a composite system [9]. Kyvelou et al. (2017) reported that the use of a structural wood adhesive, alongside screws spacing at 150mm to fix the board to the steel joists, significant increased the degree of shear connection (when compared to specimens with screws only), leading to 40% and 100% increase in floor flexural stiffness and bending moment capacity, respectively, when compared to a bare steel frame specimen of identical steel gauge (1.5mm) [3]. On the other hand, no additional improvements to floor performance were observed when the screw spacing was reduced from 150mm to 100 mm [10]. To fully understand the effect of connection detail on the floor-to-board interaction, complementary pushout tests have often been performed to develop load-slip models [3-5]. While these tests demonstrate superior strength and stiffness in connections with structural adhesives (when compared to joints with mechanical connectors only [3, 5]), the effect of adhesives has not been included in predictive models [1, 6, 9].

This article examines, experimentally, the structural performance of composite CFS joist-timber board flooring systems with various connection details. The benefits of considering such composite action in design is examined in terms of increase in strength and stiffness of the composite floor, when compared to the performance of an identical floor excluding the floor boards (bare steel frame). The results of the experiments are then compared to predictions from relevant existing models in the literature. This research plays an essential role into understanding CFS-timber floor composite performance, leading to its future standardization. The work presented herein is part of a continuing collaborative research project between Fusion Building Systems and Oxford Brookes University, to investigate more efficient structural systems as part of a Knowledge Transfer Partnership (KTP) programme, sponsored by Innovate UK.

2. Experimental programme

2.1 Materials

The joists were manufactured using roll-formers at the Fusion Building System production facility from S350 zinc coated Z275g/m^2 galvanised steel coils as per EN 10326:2004 [11]. The joist profile consists of a single-symmetric lipped C-shaped section of nominal depth= 254mm, flanges= 50mm, lips= 12mm, and thickness= 1.5mm. Floor boards are 2400mm x 600mm P5 grade chipboard of thickness= 22mm. The board mechanical properties, as specified by the manufacturer are: Modulus of elasticity= 2150 MPa and bending strength= 14 MPa. The boards were fastened to the joists using loose countersunk self-drilling screws with reamers (head diameter= 7.5mm, thread diameter= 4.15mm, wire diameter= 3.36mm, length= 40mm) spaced apart at either 150 or 300mm, depending on connection detail. The mechanical properties of the screws, as per manufacturer, were: Tensile strength= 10 KN and shear strength= 4.6 kN. Structural adhesive was a class D4 polyurethane bonding adhesive, typically used in board-to-board and board-to-joist connections in timber construction.

2.2 Full scale tests

2.2.1 Specimens and test setup

A total of 15 full-scale floor prototypes were tested in bending to evaluate the flexural response of the composite CFS-timber board floor system. Parameters investigated included the influence of screw spacing (150mm or 300mm) as well the influence of using a structural adhesive, in conjunction with the screws, on the composite behaviour. At least three identical floors were tested per parameter. For comparison purposes, three bare frame specimens (i.e. joists without the board) were also tested.

The tests consisted of a pair of steel joists placed at 600mm centres, to reflect typical construction detail. All floors had a span length of 5.4m, following the recommendations of [12]. Floor boards were 1200mm wide and were fixed mechanically to the joists using the designated connection detail. The floors were simply supported by bearing onto a 100mm wide hot rolled steel beam, set up to simulate standard pin and roller boundary conditions. Fig. 1a presents a schematic diagram of a typical composite floor cross-section. The bare frame specimens had similar joist arrangement excluding the continuous floor boards. Thin (200mm wide) strips of timber were placed at the underside of the line load positions and at the location of global measurements at midspan. To avoid premature failure at the position of the line loads and at the panel extremities, all joists were stiffened locally using short stud length of 250mm, as shown in Fig. 1b. Angle brackets (lined internally with thin strips of polytetrafluoroethylene) were used to prevent excessive twisting in the bare frame specimens.

The test cassettes were subjected to bending using a refined loading system that applies four line loads across the beam span to simulate a uniformly distributed loading. As such, loads were applied through two actuators and were distributed through two spreader beams onto two cross beams (each). The cross-beams were positioned quarter span lengths apart and at a distance of an eighth of the span length from the end support. Rollers were placed between the spreader beams and cross-beams to ensure that the loads are applied vertically at high deformations. The position of the line loads and the appearance of a typical composite specimen during testing are shown in Figs. 1b and 3b, respectively.

2.2.2 Load protocol and instrumentation

To ensure the appropriate seating of the specimen and settlement of components, all specimens were subjected to an initial loading cycle. The following load procedure was implemented:

- Load to 60% of the service live load, then unload at a rate of 0.05 kN/sec

- Load to full service load, then unload at a rate of 0.05 kN/sec
- Load to failure at a rate of 0.1mm/sec

The vertical displacements of the cassettes were measured at midspan using two linear variable transducers (LVDTs A and C) placed at the underside of each joist and one LVDT (B) placed at the underside of the floor board between the two joists. In the case of the bare frame specimens, the latter measurement was taken from a thin timber strip fixed to the specimen at midspan. Vertical displacements of the support were also monitored using two LVDTs (E and D) at each end. Fig. 1b shows the position of instrumentation and line loads along the floor span.

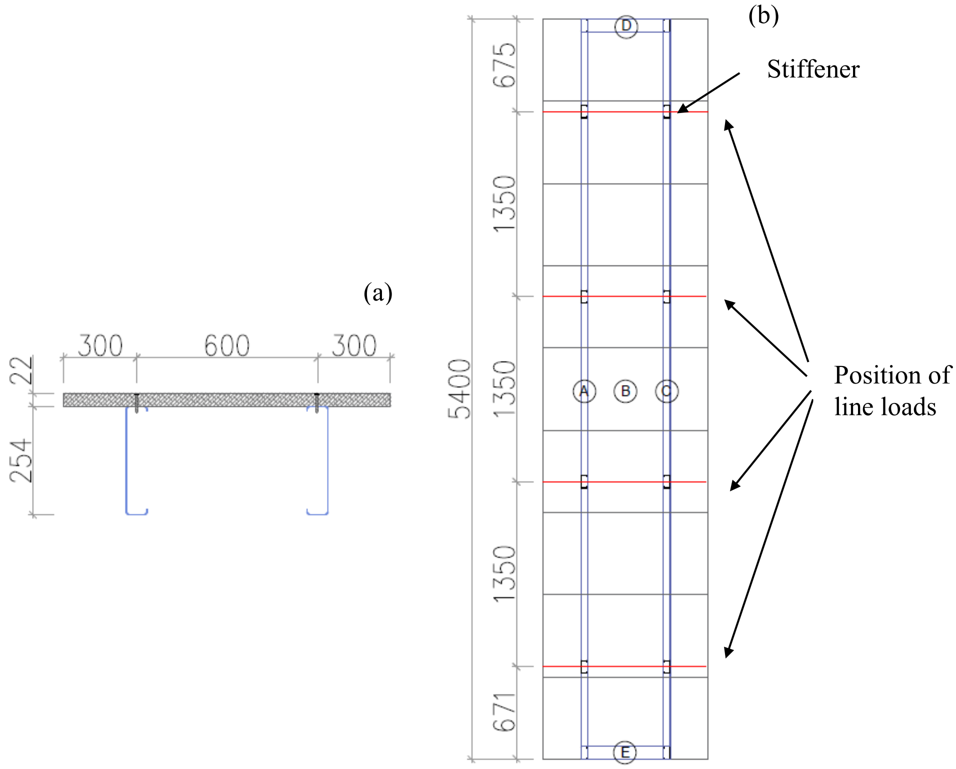

Fig. 1: Typical test floor cassette (a) cross-section and (b) instrumentation and line load position

2.3 Connection tests

2.3.1 Specimens and test setup

A total of 12 small scale push out tests were performed to acquire the load-slip characteristics of the board-to-joist connections. Two joists were arranged back-to-back (5mm apart) and sandwiched between the timber floor boards, as shown in Fig 2c. The boards were fixed to the joists using mechanical fixings that simulate a typical board-to-joist connection detail in a 600mm board in a floor cassette. The connection detail included specimens with screws only at a nominal spacing of 150mm or 300m (P-150 and P-300, respectively) as well as specimens with both screws and adhesives with a nominal screw spacing of 150mm or 300 (P-150-A and P-300-A, respectively). Figs. 2a and 2b present schematic diagrams of specimens with nominal screw spacing of 150mm and 300mm, respectively, while Fig. 2c presents the top view of all tested connections. Three identical specimens were tested for each connection type. All specimens were configured symmetrically about both axes to reduce eccentricities.

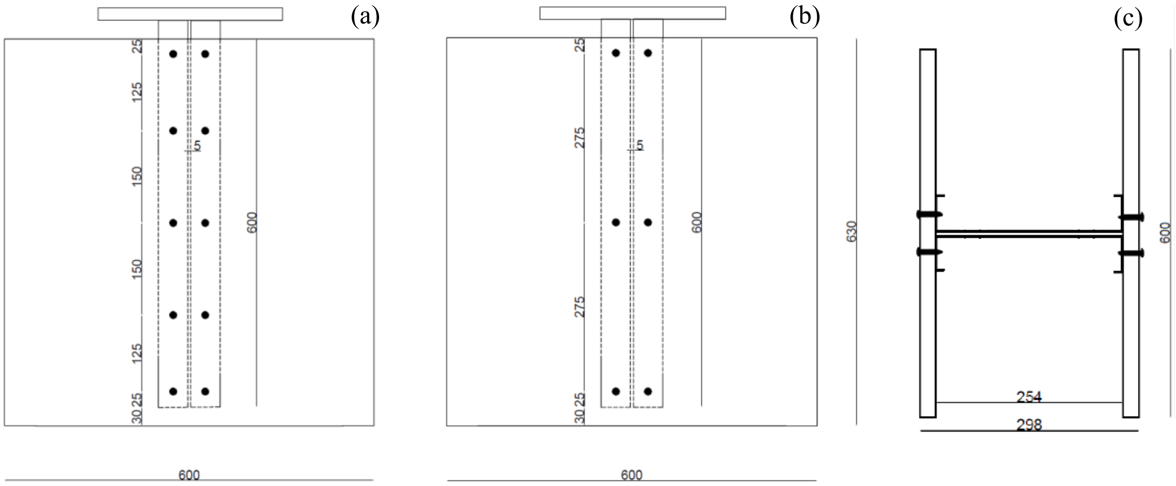

Fig. 2: Elevation view of connection with nominal screw spacing of (a) 150mm or (b) 300mm and (c) plan view view of specimens

2.3.2 Load protocol and instrumentation

The push-out test specimens were loaded to approximately 40% of the estimated ultimate load capacity, unloaded, then reloaded until either failure or an average slip of more than 15 mm was reached, as per BS EN 26891 [13]. Specimens with screws only were loaded at a rate of 10 kN/m, whereas the remaining specimens were loaded at a rate of 20 kN/m. Four LVDTs were mounted onto the corners of the joist's webs to monitor the relative slip between the board and the steel joists and to capture any bending in the specimen during the tests.

3. Results and analysis

3.1 Full scale tests

Fig. 3a presents average midspan load-displacement measurements from the three tested floors per parameter, whereas Fig. 3b presents the appearance of a typical composite test specimen (C-300-A) during testing. The specimens are identified according to the type of specimen (C for composite or BF for bare frame) followed by the nominal screw spacing in mm (150 or 300), followed by the letter "A" in the case of specimens where an adhesive was used.

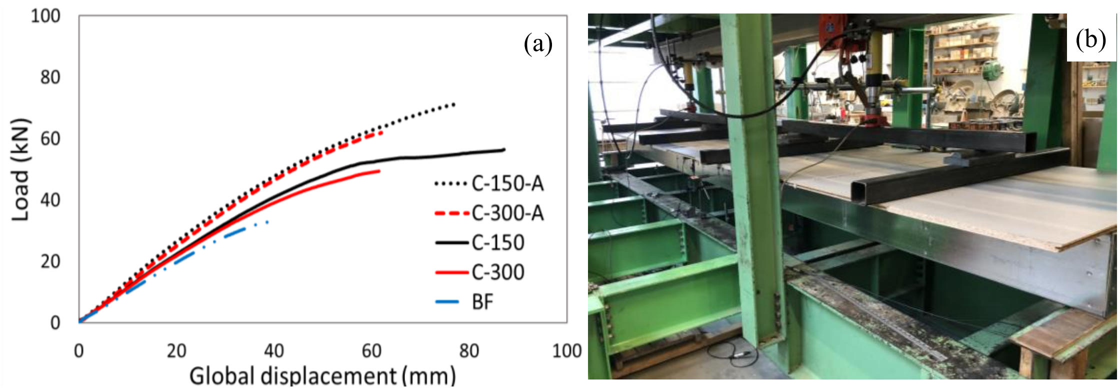

Fig. 3: Average load-displacement curves of tested composite and bare frame floors behaviour (a) and typical composite specimen (C-300-A) during testing (b)

The average experimental flexural stiffness (EI_{exp}), load at failure and increase in flexural stiffness relative to the bare frame specimens, are presented in Table 1.

Table 1: Full-scale test results (average)

Test	EI_{exp} kN.m^2 (CoV*)	Increase relative to BF (%)	Load at failure kN (CoV*)
C-150-A	2823 (4.2)	40.0	73.2 (7.5)
C-300-A	2720 (4.2)#	34.9	64.8 (0.2)#
C-150	2413 (2.0)	19.6	58.7 (3.1)
C-300	2378 (2.6)	17.9	60.8 (11.3)
BF	2016 (8.5)	-	33.2 (9.4)

*CoV: Coefficient of variation (in %)
#only two specimens included in average due to instrumentation error

The results in Fig. 3 and Table 1 indicate that, compared to the bare frame specimens (BF), all composite floors exhibited an increase in flexural stiffness (18-40%) and an increase in load-carrying capacity (77%-120%), regardless of connection detail. As expected, the lowest increase in flexural stiffness was observed for C-300 specimens (screws only, 300mm apart), which had a flexural stiffness about 18% higher than that of the BF specimens. The use of a smaller screw spacing (150mm in specimens C-150) did not noticeably increase such flexural stiffness, which was merely 1.5% higher than C-300 specimens.

The increase in flexural stiffness almost doubled when both screws and adhesives were used. For instance, compared to the BF specimens, C-300-A and C-150-A exhibited a respective 35% and 40% increase in flexural stiffness (14% and 17% increase, respectively, when compared to identical specimens with screws only).

Overall, the data in Table 1 are very consistent. The coefficient of variation (CoV) in flexural stiffness data is < 4.2% for the composite floors and < 8.5% in the bare frame floor specimens. A slightly higher variability was observed in failure loads (maximum CoV of 11.3%). It must be noted, however, that the failure load does not influence serviceability considerations (flexural stiffness) which are the focus of this study. The higher variability observed in flexural stiffness of bare frame specimens may be attributed to possible twisting (less restraint in the bare frames) and the effect of localised buckling.

3.2 Connection tests

Figs. 4a and 4b present the average load-slip behavior of connections with 150 or 300mm nominal screw spacing, with or without a structural adhesive, while Table 2 presents the average data including slip modulus (K), ratio of slip modulus to nominal screw spacing (k), 75th percentile of the k value based on three tested specimens per parameter ($k_{0.75}$), maximum load at failure (F_{max}) and displacement at maximum load (δ_{max}). The slip modulus (K) was determined from the slope of the load-slip curves between 10% and 40% of the failure load (serviceability stiffness), as proposed in previous research [5,14].

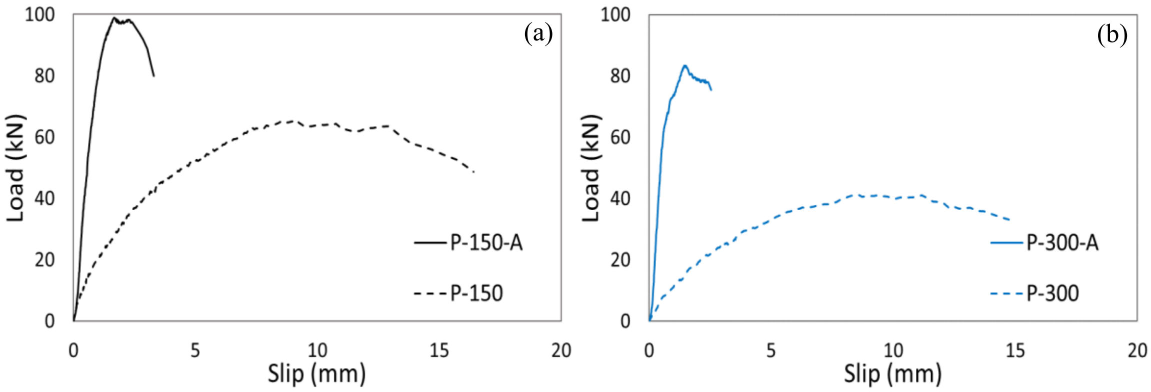

Fig. 4: Load-slip behaviour of connection tests with nominal screw spacing of 150mm (a) or 300mm (b) with or without the presence of a structural adhesive

Table 2: Push-out test results (average)

Specimen	K (kN/mm)	k (N/mm^2)	$k_{0.75}$ (N/mm^2)	CoV* (%)	F_{max} (kN)	δ_{max} (mm)
P-150	45.5	18.9	17.4	9.2	68.1	9.4
P-150-A	130	54.1	44.0	25.0	105.0	2.1
P-300	36.2	15.0	14.8	2.9	44.6	10.5
P-300-A	147.7	61.5	56.0	11.9	91.7	1.8

*Coefficient of variation for slip modulus data based on three tested specimens per connection type

The results in Fig. 4 and Table 2 indicate that specimens with screws only (P-150 and P-300) exhibited a ductile behaviour with significant displacements (δ_{max}= 9.4 - 10.5mm) observed at failure load. On the other hand, specimens with screws and adhesives (P-150-A and P-300-A) exhibited a less ductile behaviour (δ_{max}= 1.8 – 2.1mm) but a significantly higher slip modulus (increase of 188% and 311%, respectively) and failure load (increase of 54% and 105%, respectively) when compared to identical specimens without the adhesives.
The higher slip modulus for connections P-150-A and P-300-A, correlates with the full-scale test results, where a markedly higher flexural stiffness was observed for specimens with screws and adhesives, compared to specimens with screws only.

4. Analytical predictions

4.1 Full-composite action

The analytical flexural stiffness of a fully composite system (EI_{comp}) can be determined using Eq. (1), where E_s and E_b denote the modulus of elasticity of the steel and timber board, respectively; I_s and I_b denote the second moment of area of the steel joist and the board about their major axes, respectively; A_s and A_b denote the gross area of the steel and board sections, respectively; z_s and z_b denote the distance from the centroid of the steel section or the board section, respectively, to the centroid of the composite.

$$EI_{comp} = E_s.I_s + E_s.A_s.z_s^2 + E_b.I_b + E_b.A_b.z_b^2 \quad (1)$$

Accordingly, the analytical flexural stiffness of the section (see Fig. 1a), assuming full composite action, can be determined as: EI= 2846.8 kN.m^2. The analytical flexural stiffness of the bare steel frame (i.e. excluding the effect of the board) is: E_sI_s= 1971.6 kN.m^2.
It must be noted that the analytical flexural stiffness of the BF almost concurs with the experimentally determined BF flexural stiffness, as it falls within the variability of the experimental

data (EI_{exp} = 2016 kN.m^2 ± 8.5%). It can also be observed that the experimental flexural stiffness for specimens C-150-A (EI_{exp} = 2823 kN.m^2 ± 4.2%) almost coincides with the analytical flexural stiffness obtained assuming full composite action, indicating that the specimen is nearly fully composite and that a high shear transfer occurs using such connection detail.

4.2 Predictive equations

Table 3 presents predictions of the flexural stiffness of the tested floors derived using existing models in [1], [6] and [9] as well as their deviation from experimental data. For each connection type, the analytical flexural stiffness was determined using results from the average pushout tests (in particular, $k_{0.75}$).

Table 3: Analytical predictions of flexural stiffness

Specimen	$EI_{[1]}$ (kN.m^2)	Error* (%)	$EI_{[6]}$ (kN.m^2)	Error* (%)	$EI_{[9]}$ (kN.m^2)	Error* (%)
C-150-A	1360.2	- 3.6	1358.0	- 3.8	1356.8	- 3.9
C-150	1298.0	+ 7.6	1288.8	+6.8	1287.7	+ 6.7
C-300-A	1371.8	+ 0.9	1370.3	+ 0.7	1369.1	+ 0.7
C-300	1284.6	+ 8.1	1273.3	+ 7.1	1272.1	+ 7.0

*+ve error indicates that the predicted flexural stiffness is higher than EI_{exp}; -ve error means that the predicted flexural stiffness is lower than EI_{exp}.

The results in Table 3 indicate that all models gave slighly unconservative predictions for specimens with screws only (C-150 and C-300) with an error of around 7%. The models appear to predict well the behaviour of specimens with screws and adheisve when the experimental slip modulus from connection tests was input. Future research including more small-scale connection tests may be useful to evaluate the effect of other screws and adheisve detailing and to account for the variability observed in slip modulus, to enable the calibration of existing models to suit the various connection types.

5. Conclusions

A total of 15 full scale bending tests and 12 pushout tests were performed to investigate the effect of screw spacing (150 or 300mm) with or without the presence of a structural adhesive on the flexural performance of a timber board-CFS joist composite flooring system.

The application of a structural adhesive at the beam-to-board interface, in conjunction with screws, led to 40% increase in floor flexural stiffness, when compared to a bare steel floor cassette. The benefits of such board-to-steel composite action, if included in design, can significantly minimise the use of resources, leading to lighter, more efficient and sustainable floors. On the other hand, reducing the connection screw spacing from 300mm to 150mm for specimens with or without a structural adhesive did not significantly affect the floor flexural performance. The results from the full-scale bending test results are corroborated by pushout test results, which show that the effect of using a structural adhesive led to much higher connection slip modulus, when compared to specimens with screws only.

Ongoing research involves additional experimental and analytical work to establish the effect of other key parameters and to incorporate the effect of both screws and adhesives in predictive models, leading to the development of comprehensive design equations.

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