Experimental Investigation of Cold-Formed Steel-Timber Board Composite Floor Systems

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***Abstract*—This paper comprises an experimental investigation into the structural performance of cold formed steel (CFS) and timber board composite floor systems. The tests include a series of small-scale pushout tests and full-scale bending tests carried out using a refined loading system to simulate uniformly distributed constant load. The influence of connection details (screw spacing and adhesives) on floor performance was investigated. The results are then compared to predictions from relevant existing models for composite floor systems. The results of this research demonstrate the significant benefits of considering the composite action of the boards in floor design. Depending on connection detail, an increase in flexural stiffness of up to 40% was observed in the floor system, when compared to designing joists individually.

***Keywords*—Cold formed steel joists, composite action, flooring systems, shear connection.

I. Introduction

LIGHTWEIGHT floors built with CFS joists and structural timber-based deck (referred to in this study as timber boards or floor boards) have become increasingly popular in both commercial and residential construction due to their attractive advantages such as high strength-to-weight ratios, speed of build and sustainability [1]. While the benefits of composite construction (e.g. hot rolled steel beam-concrete slab systems or engineered timber joists) are well-established and exploited [2], the interaction between CFS joists and the accompanying flooring is still not well understood, with only a few research studies in the field [3]-[7]. As a result, the advantageous interaction between the timber boards and CFS joists is often ignored, leading to conservative designs.

Recently conducted experiments on cold or hot rolled steel-timber board composite systems show that significant benefits can be achieved by mobilizing the interaction of the floor boards with the steel joists [6]-[8]. It has been shown that the composite efficiency is higher in longer spans [6] and smaller steel gauge [7]. It is also highly influenced by connection type (e.g. screws or bolts [6]), connection spacing and the presence of a structural adhesive [7]. Research by [7] reports that high degrees of shear connection could be achieved by using structural adhesive and a screw spacing of 100 mm leading to 100% and 40% increase in the moment capacity and flexural stiffness of the structural system, respectively, when compared to the performance of a bare steel joist. In another study, specimens with screw spacing of 150 mm and adhesive exhibited more than 40% increase in flexural stiffness, indicating that negligible improvements were attained by decreasing the screw spacing from 150 mm to 100 mm [8].

It is well known that the degree of shear connection as well as the connection load-slip behavior (shear connector stiffness) can have a significant influence on the performance of a composite system [9]. For instance, a lower shear connector stiffness would lead to higher deflections in the system (as a result of slip), making it difficult to achieve the "full shear interaction" of the composite components. To further understand the effect of connection detail on the composite floor interaction, push-out tests have been performed, leading to the development of load-slip predictive equations [7], [10], [11]. Overall, the push-out test results indicate significantly higher strengths and connection stiffness, in joints with glue, compared to specimens with only mechanical connectors [7], [10]. Nevertheless, despite the apparent benefits of adhesives on composite interaction behavior, their effect has not been included in predictive models.

This study aims to examine, experimentally, the interaction between CFS joists and floor boards, typically used in residential flooring, with different connection details. The potential benefits of considering their composite behavior is assessed, in terms of strength and stiffness, by comparing to control bare steel joists. Finally, the results are compared to analytical equations from the literature and concluding remarks are provided. This research contributes to the understanding of the behavior of CFS-timber board composite flooring systems, leading to its future implementation and standardization. The work presented in this article 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), sponsored by Innovate UK.

II. Experimental Program

A. Materials

All joist sections are manufactured from S350 (min yield strength of 390 MPa) zinc coated Z275g/m^2 galvanized steel coils to EN 10326:2004 using roll-formers at the Fusion Building System production facility. Joists are lipped C-sections of depth: 254 mm, flange width: 50 mm; lips:12 mm and a thickness of 1.5 mm.

Floor boards are 22 m thick, 2400 mm x 600 mm P5 grade

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randomly oriented chipboard, which follows the BS EN 312-2010 recommendations for flooring products. The mechanical properties of the floor boards (as per manufacturer) are: Modulus of Elasticity: 2150 MPa; Bending Strength: 14 MPa.

Fasteners used are loose countersunk self-drilling screws with reamers of the following dimensions: Head diameter: 7.5 mm; thread diameter: 4.15 mm; wire diameter: 3.36 mm; length: 40 mm. The tensile and shear strengths of the screws, as per manufacturer are 10 kN and 4.6 kN, respectively.

To improve board-to-board and board-to-joist bonding, a structural adhesive was used in some specimens in conjunction with the screws. The adhesive used was a class D4 polyurethane bonding adhesive, typically used in board-to-board and board-to-joist connections in timber construction. The mechanical properties of the adhesives are not readily available from the manufacturers/literature.

B. Pushout Tests – Specimen Details and Test Setup

Push-out connection tests were performed on small-scale specimens to acquire load-slip characteristics of the joist-to-board connections. To reduce eccentricities, the push-out test specimens were configured symmetrically about both axes. The setup comprised of two C-joists, arranged back-to-back (5mm apart) and sandwiched between two floor boards. The floor boards were mechanically fixed to the joists flanges using i) two screws per flange spaced 300 mm apart (P1.5-300), ii) adhesive only (specimen P1.5-A), or iii) screws and adhesive (P1.5-300-A). Three identical specimens were fabricated and tested per connection type.

The load protocol was based on the recommendations of BS EN 26891 [12] aimed for mechanically fastened joints in timber. Accordingly, the specimens were loaded up 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 achieved. The tests were performed at load-controlled rate of 10 kN/m for P1.5-300 specimens and 20 kN/m for the other specimens.

The relative slip between the board and the steel joists was monitored using four linear variable differential transformers (LVDTs) mounted onto four different corners of the joists' webs. This configuration also captures any twisting/bending in the specimen. The typical specimen dimensions as well as the position of the instrumentation are presented in Fig. 1.

C. Full Scale Tests - Specimen Details and Test Setup

A total of 15 full scale cassette prototypes were tested in bending to evaluate the flexural response of the composite CFS joist – timber board flooring system. The tests comprised both composite cassettes and bare frame specimens (i.e. joists without the board). The main parameters investigated included i) the influence of board-to-joist screw spacing (150 mm or 300 mm) and ii) the influence of the use of adhesives, in addition to the screws, to improve composite performance.

All specimens were simply supported on steel beams arranged to simulate standard pin and roller boundary conditions. The specimens were 5.4 m long, as per [13]. The composite test cassettes consisted of two parallel joists spaced 600-mm apart (to reflect typical construction detail) and fastened to a 22-mm timber-based floorboard (1200 mm wide) using the selected mechanical fixing detail. Fig. 2 presents a schematic diagram of a typical composite system cross-section. The bare frame specimens had similar joist arrangement but excluding the floorboards. To allow for the application of the line loads and to allow for global measurements at midspan, thin strips of timber were placed at the underside of the line loads and at midspan. The joists' webs were stiffened locally using short stud lengths (250 mm) to avoid premature failure at the panel extremities and at the underside of the line loads positions. In the case of the bare frame, angle brackets (lined internally with thin strips of polytetrafluoroethylene) were used to prevent excessive twisting.

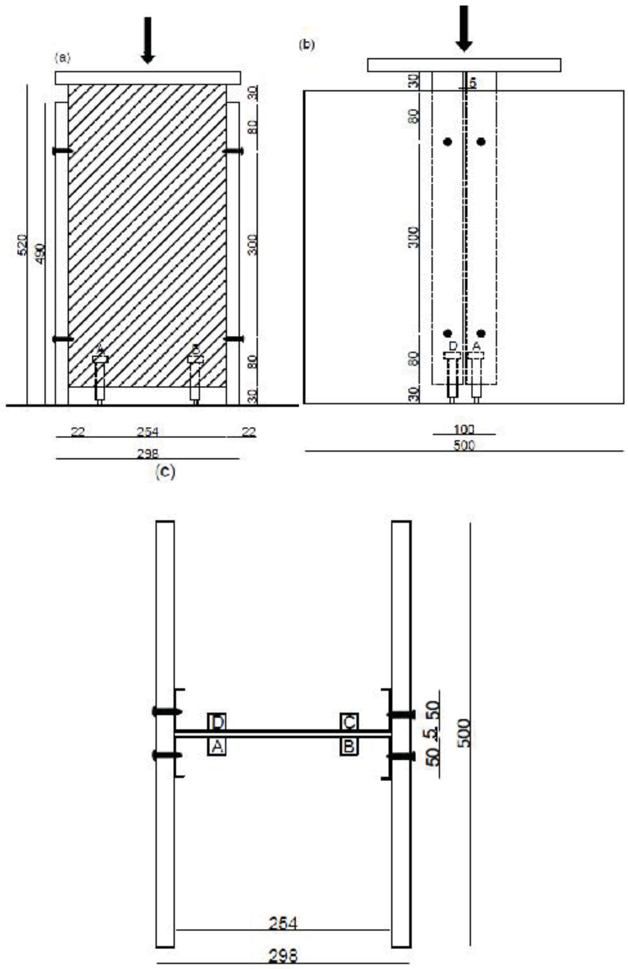

Fig. 1 Connection test setup front elevation (a), side elevation (b), and plan view (c)

The test cassettes were subjected to bending using a refined loading system to simulate a uniformly distributed load, as shown in Fig. 3. The loads were applied through two actuators and distributed through two spreader beams onto two cross beams (each) to generate a total of four line loads across the span of the beam. The cross-beams were positioned apart at quarter span lengths and at a distance of an eighth of the span length from the support. To ensure the vertical application of the load at high deformations, four rollers were placed between the spreader beams and the cross-beams.

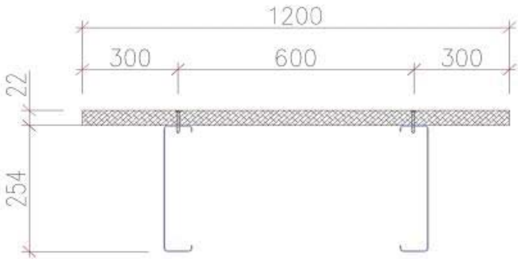

Fig. 2 Cross-section of composite test floor cassette

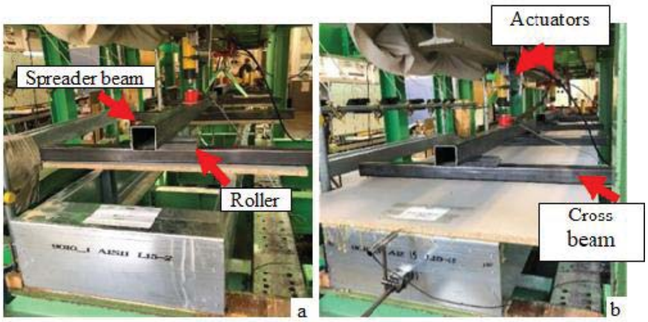

Fig. 3 Typical load configuration for the bare frame (a) and composite cassette (b)

The specimens were subjected to initial load cycling to ensure the appropriate seating of the specimen as well as the proper function of instrumentation. The load protocol was as follows:

1) Load to about 60% of the live-load serviceability loading, then unload at a rate of 0.05 kN/sec
2) Load to full serviceability load, then unload at a rate of 0.05 kN/sec
3) Load to failure at a displacement-controlled rate of 0.1 mm/sec

To measure the vertical displacements of the cassette, two linear variable transducers were placed at the underside of the joists and at the underside of the floor board at specimen midspan. In the case of the bare frame, the latter measurements were taken from a thin timber strip fixed to the specimen at midspan. Two LVDTs were also placed at the underside of the supports to measure any support vertical displacement.

III. Results and Analysis

A. Pushout Tests

The maximum load (F_{max}), displacement at maximum load (δ_{max}) and slip modulus (k_{s1}), which were estimated as per BS EN 2689, are summarized in Table I.

Specimens with screws only (P-300) underwent significant tilting and bending in the screws, until the screws sheared in two. As shown in Table I, these experienced the highest displacement, but failed at much lower loads than the other tested connections. Specimens prepared with adhesive only (P-A) failed predominantly by shearing in the adhesive. The failure was brittle, with very little steel to timber relative displacement. The detached steel and timber board had significant adhesive residue on the surface, indicating strong glue-to-timber and glue-to-steel adhesion (see Fig. 4).

TABLE I
Push out Test Results

Specimen	F_{max} (kN)	δ_{max} (mm)	k_{s1} (kN/m)
P-300-1	29.5	9.67	8.9
P-300-2	30.9	9.67	10.6
P-300-3	27.8	9.78	8.2
P-A-1	56.2	0.29	260.7
P-A-2	78.5	0.45	189.1
P-A-3	46.7	0.57	242.9
P-300-A-1	101.2	1.21	109.7
P-300-A-2	155.8	1.13	177.1
P-300-A-3	88.7	1.75	-*

Fig. 4 Timber board and steel joist interface upon failure in specimens with adhesive only (P1.5-A)

Specimens with screws and glue (P-300-A) exhibited an intermediate failure mode, including tilting in the screws (see Fig. 5), but failure at a much lower overall displacements compared to specimens with screws only.

Fig. 5 Failure in specimens with screws and adhesive (P-300-A)

No visible crushing was observed in the timber, nevertheless, in some specimens, crushing was visible in the top part of the steel joists (at the underside of the loading plate), which may have led to some specimen bending and variability in the test results. This could be due to unintentional eccentricity in some of the tested specimens.

B. Full-Scale Tests

The test cassettes failed predominantly in plane. In the case of the bare frame (BF) specimens, the failure consisted of a combination of local buckling at the top flanges at midspan and a global bending failure (see Fig. 6). Such local buckling mode may have been influenced by the timber strip at midspan used for placing displacement instrumentation.

Fig. 6 Interaction bending/local buckling failures in BF-2

In the case of the composite cassettes, the failure mode was influenced by the shear connection detail. Specimens with screws only tend to experience local buckling at the underside of the line loads position (see Fig. 7 (a)), whereas specimens with screws and adhesive failure occur predominantly by shear (see Fig. 7 (b)). As the specimens approached high displacements, minor twisting was observed in the steel joists; nevertheless, this was effectively controlled in the case of bare frame specimens using the angle brackets.

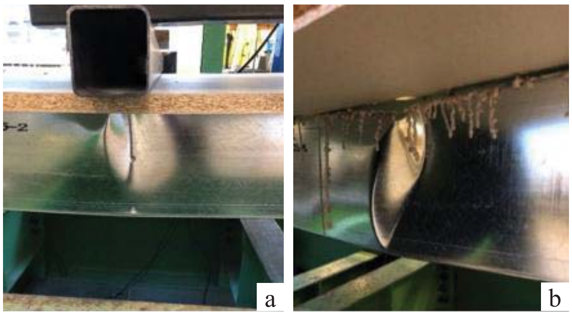

Fig. 7 Typical failure in specimens with a) screws only (C-150-2) and b) screws and adhesive (C-300-A-1)

Fig. 8 presents the load displacement measurements (taken at midspan) for a typical specimen from each tested parameter, while Table II presents average global and local measurements at serviceability live load (LL) + dead load (DL), as well as the experimental flexural stiffness ($EI_{eff,exp}$) and the failure load. The % increase in flexural stiffness relative the bare frame experimental stiffness was also presented in Table II. The experimental flexural stiffness $EI_{eff,exp}$ was derived based on global mid-span deflections between 30% and 60% serviceability DL+LL loading, where the load-deflection curves presented a linear-elastic behavior.

The specimens are identified according to the type of specimen (BF: bare frame or C: composite), following by the screw spacing in mm (300 or 150), followed by specimen number. In specimens where an adhesive was used, the specimen number was preceded by the letter "A".

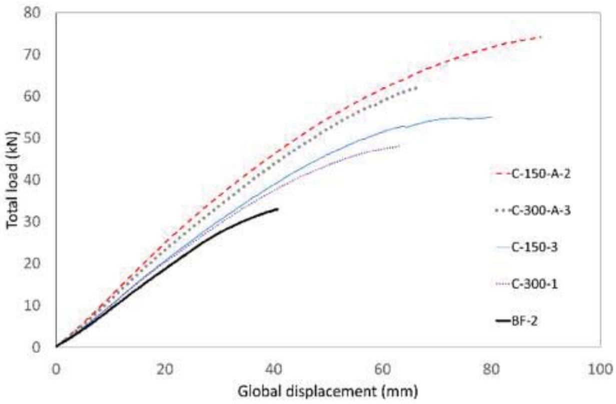

Fig. 8 Load displacement curves for a representative specimen from each tested parameter

TABLE II
AVERAGE LARGE-SCALE TEST RESULTS

Specimen	δGlobal[#] mm (CoV[*])	δLocal[#] mm (CoV[*])	$EI_{eff,exp}$ kN.m^2	Increase relative to BF (%)	Failure load kN (CoV[*])
BF	18.9 (5.6)	19.4 (6.0)	1963.5	-	33.4 (9.4)
C-300	16.3 (2.3)	16.2 (3.7)	2302.4	17.3	51.9 (1.5)
C-150	16.0 (2.2)	16.3 (2.0)	2356.4	20.0	58.9 (3.1)
C-300-A	14.2 (1.7)	14.4 (2.0)	2572.4	31.0	64.9 (0.2)
C-150-A	13.6 (1.8)	13.8 (2.5)	2733.8	39.2	73.3 (7.5)

[#]Deflections measured at DL+LL serviceability loads
[*]CoV: coefficient of variation in %

The results in Fig. 8 and Table II indicate a significant increase in stiffness when the timber board-to-joist interaction was mobilized. For instance, compared to the bare frame response, the composite cassette stiffness increased by a maximum of 39%, respectively, for specimens with screws at 150 mm and adhesive. Additionally, the average failure load of the composite C-150-A increased by up to 120%.

As expected, the lowest increase in flexural stiffness was observed for C-300 specimens with screws only (at 300 mm), which were about 17% stiffer than the bare frame specimens. The use of a smaller screw spacing of 150 mm did not significantly increase this flexural stiffness, which reached 20% increase, compared to the bare frame specimens. The increase in flexural stiffness almost doubled, when adhesives were incorporated at the timber-to-steel joint interface, rather than using screws only. This could be attributed to the much higher slip modulus of specimens with screws and glue, as opposed to specimens with screws only, as presented in Table I. Compared to the bare frame, the increase in stiffness was 31% to 39% for composites with adhesive and screw spacings of 300 mm and 150mm, respectively. The use of a tighter screw spacing led to a more significant increase in composite flexural stiffness in specimens with adhesives, than in specimens excluding adhesives. The above increase in flexural stiffness is reflected by a decrease in the deflection of the specimens at a particular loading, indicating that the composite section can fulfill more serviceability load deflection requirements, when the board action is mobilized.

Overall, the data in Table II are very consistent with an average coefficient of variation <3.7% for deflection in the composite test cassettes and <6% in the bare frame specimens. A slightly higher variability was observed in the ultimate failure loads achieved, i.e. a maximum of 7.5% for the composite specimens and 9.4% for the bare frame specimens. The higher variability in the bare frame specimens and failure load can be due to the higher effect of localized buckling. It must be noted that the failure load does not influence flexural stiffness and serviceability considerations, which are the purpose of this study.

IV. Analytical Calculations

A. Fully-Composite Section

The effective flexural stiffness of a fully composite system is calculated using (1)

$$E_{cc} = E_s I_s + E_s I_s (d_s)^2 + E_b I_b + E_b I_b (d_b)^2 \qquad (1)$$

where I_s is the moment of inertia of the steel about its major axis, A_s is the gross area of the steel section, d_s is the distance from the centroid of steel section to the centroid of the composite, I_b is the moment of inertia of the transformed board section about its major axis, A_b is the area of the transformed board section, and d_b is the distance from the centroid of the board section to the centroid of the composite

The analytical flexural stiffness of the bare frame specimens comprising two 5.4 m steel joists is calculated as follows: E_s:210 GPa; I_s: 469.4 cm^4; E_sI_s: 1971.5 $kN.m^2$. Based on (1), the flexural stiffness of the section is shown in Fig. 2, assuming that a fully composite system is 2838 kN/m^2.

It can be observed that the analytical flexural stiffness of the bare frame specimens almost concurs with the flexural stiffness obtained experimentally (see Table II). It can also be observed that the experimental flexural stiffness ($EI_{eff,exp}$) for specimens with the highest stiffness (C-150-A) reaches almost 96% of the flexural composite section, indicating that the specimen is nearly fully composite and that high shear load transfer occurs at such connection detail.

B. Flexural Stiffness Predictions

Few models are proposed in the literature to predict the effective flexural stiffness of timber board-steel joist composite systems [5], [14]. These models account for the slip modulus of the shear connector, mainly consisting of mechanical fasteners. Table III presents the predictions from equations in [5], [14], compared to the stiffness obtained from the experimental data for specimens with screw spacing of 300 mm, with or without the presence of an adhesive. The slip moduli used in these equations are based on the average of the data presented in Table I. To determine the modulus/mm for specimens with adhesive, the full length of the flange was used, rather than screw spacing, as in [14].

TABLE III
Predictions of Flexural Stiffness

Specimen	EI predicted ($kN.m^2$) [5]	Error (%) Relative to experiment	EI predicted ($kN.m^2$) [14]	Error (%) Relative to experiment
C-300	1983	-16%	2056	-12%
C-300-A	2057	-25%	2065	-24%

The above comparisons indicate that existing models do not capture very well the advantageous performance of composite cassettes, particularly those with structural adhesives. Further tests including connection tests using other screws and adhesive detailing may be useful to calibrate these models to suit various connection properties.

V. Conclusion

An experimental program comprising of a total of 15 large-scale tests and nine push-out tests were implemented to investigate the effect of connection detail on the flexural performance of a timber board-CFS joist composite flooring system. Two screw spacings, namely 150 mm and 300 mm were investigated as well as the influence of a structural adhesive, when applied at the joist to board interface.

Among the parameters investigated, the application of a structural adhesive (in accompaniment to the screws) presented the highest benefits to the overall performance of the floor (in terms of flexural stiffness and failure strength) while reducing the screw spacing from 300 mm to 150 mm, did not seem to have a significant influence. This could be due to the much higher slip modulus achieved in specimens with glue and screws, as opposed to specimens with screws only.

The results indicate a significant improvement in the structural performance of the composite flooring system when the board-to-steel interaction was mobilized. Compared to the bare steel frame, specimens with screws (at 150 mm) and adhesives experienced about 40% increase in flexural stiffness (reaching 96% of the fully composite section stiffness) and 120% increase in failure load. Such improvements in floor performance, if implemented in design, can either lead to reducing the steel requirements for a specific span length or increasing the span lengths capabilities of a specific steel section, leading to invaluable material and embodied carbon savings.

Predictive equations available in the literature do not appear to capture well the performance of composite floors including adhesives. The results of this study, including the composite cassette test data and load-slip relationships from push-out tests are fundamental for the development of analytical equations that can reflect the effect of both screws and structural adhesives on the performance of such flooring systems. On-going research involves additional experiments and numerical modeling to establish the influence of other key parameters, leading to the development of more comprehensive design equations.

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