Research Repository UCD

Title	An experimental investigation into span length effect in composite CFS and timber-based flooring systems
Authors(s)	Raffoul, Samar, Sun, Yao, McCrum, Daniel
Publication date	2023-09-12
Publication information	Raffoul, Samar, Yao Sun, and Daniel McCrum. “An Experimental Investigation into Span Length Effect in Composite CFS and Timber-Based Flooring Systems.” Wiley, September 12, 2023. https://doi.org/10.1002/cepa.2350.
Publisher	Wiley
Item record/more information	http://hdl.handle.net/10197/26035
Publisher's version (DOI)	10.1002/cepa.2350

Downloaded 2026-05-02 00:23:30

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)

© Some rights reserved. For more information

ce/papers Proceedings in civil engineering

Ernst & Sohn
A Wiley Brand

Check for updates

ORIGINAL ARTICLE

eurosteel
AMSTERDAM 2023

Ernst & Sohn
A Wiley Brand

An experimental investigation into span length effect in composite CFS and timber-based flooring systems

Samar Raffoul[1,2] | Yao Sun[1] | Daniel McCrum[1,2]

Correspondence

Dr. Samar Raffoul
University College Dublin
School of Civil Engineering
Newstead, Belfield
Dublin, Ireland
Email: samar.raffoul@ucd.ie

[1] University College Dublin, Dublin, Ireland
[2] Construct Innovate, University Road, Galway, Ireland.

Abstract

Cold-formed steel (CFS) panelised built-offsite modern methods of construction offer economy of scale, high precision, reduction in construction waste and a more streamlined manufacturing and construction process, compared to traditional construction. Floors made with CFS joists and timber-based flooring systems, often jointed using screws and structural adhesives, have become increasingly popular. Nevertheless, the beneficial effect of the timber flooring on overall floor structural behaviour is often ignored in design due to limited understanding of CFS joist-timber board interaction and the effect of various influencing parameters. This article investigates, experimentally, the structural performance of such composite floors. This paper presents eighteen large scale bending tests of CFS composite floors and five pushout tests to investigate the effect of span length on composite action. The results demonstrate that a high degree of composite action can be achieved when both screws and adhesives are utilised, resulting in around 40% increase in flexural stiffness when compared to joist performance without boards. This can lead to a more efficient and sustainable design of CFS joisted floors. The results also show that further research is needed to extend existing design equations to cover short span lengths.

Keywords

Cold-formed steel, steel-composite floor structures, modern methods of construction, offsite construction, sustainable design, self-drilling screws, timber adhesives.

1 Introduction

Cold-formed steel (CFS) joists with timber-based flooring present an attractive floor solution that offers rapid manufacture and construction, sustainability and a high strength-to-weight ratio compared to other systems [1-4]. These floors often consist of CFS channel (C) sections closely spaced (400mm or 600mm) with floorboards (e.g. chipboard or oriented strand boards) that are screwed and glued to the top flange of the joists to provide a finished surface [1].

Floorboards are often considered in the design of panelised CFS structures, for their contribution to the load transfer and stability of the structure (e.g. through diaphragm action) and for the lateral restraint they provide to the steel joists [1]. However, when it comes to floor flexural performance, the composite behaviour of these boards with the CFS joists is often not considered in design [5]. This is due to limited understanding of CFS joist-to-board interaction and a lack of established design guidelines.

Existing research has demonstrated significant improvements to the floor flexural performance if the composite action between CFS and timber boards is exploited [5-9]. Such composite action relies on the efficacy of connection (e.g. degree of shear connection and shear stiffness), to enable the two components to work together as a composite system, to resist flexural loads [4]. The degree of composite action achieved is a function of various parameters such as fastener spacing and type, the presence of adhesives, joist gauge, floorboard thickness and floorboard stiffness [4-9]. For instance, the use of a wood adhesive alongside screws at 150mm (which is the current industry standard) in composite floors exhibited around 40% increase in flexural stiffness and 100% increase in bending moment capacity, when compared to the performance of bare steel specimens [7]. Without adhesives and a similar screw spacing, the increase in flexural stiffness was limited to 17%, compared to corresponding bare steel specimens [7,9]. Other parameters investigated in the literature include the effect of joist gauge, board type, and board thickness on composite performance [4-8], leading to the development and verification of design equations [5]. Nevertheless, the effect of span length on composite efficiency has not been investigated to date.

This paper presents an experimental investigation into the

© 2023 The Authors. Published by Ernst & Sohn GmbH.

https://doi.org/10.1002/cepa.2350

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited

structural performance of composite CFS floors with timber boarding and different span lengths. All composite floor tests considered in this study include both screws (nominal spacing of 150mm) and adhesives, based on previous studies that presented a high composite efficiency for such connections [6,7,9]. The results were compared to corresponding floor tests without boarding. Since the design of CFS floors is usually limited by serviceability requirements rather than bending moment capacities [1], this paper mainly focuses on the flexural stiffness of the composite floors, which can be used for determining floor deflections under serviceability loadings.

This research is part of an ongoing study that aims to develop practical design rules for CFS-timber board with different parameters, enabling more efficient CFS floor designs.

2 Experimental programme

2.1 Materials

The floor joists consisted of single-symmetric lipped channel sections of the following cross-sectional dimensions: depth= 254mm, flanges= 50mm, flange stiffener lips= 12mm and nominal thickness= 1.5mm. All joists were manufactured using roll-formers at the Fusion Building Systems production facility using S350 zinc coated Z275g/m^2 galvanised steel. The joist elastic modulus, E_s= 203 GPa. The gross cross-sectional area, A_s, and gross second moment of area about the major axis, I_s, calculated based on EN 1993-1-3 [10] are 530.1 mm^2 and 446.9 cm^4, respectively.

Floorboards were 2400mm x 600mm x 22mm thick P5 grade Egger structural chipboard, finished with a tongue and groove joints for a tighter fit. These joints were orientated perpendicular to the span. All boards were cut to 1200mm lengths to suit test dimensions (see Section 2.2). The mechanical properties of the board are: modulus of elasticity, E_b= 2150 MPa and bending strength, f_b= 14 MPa. Note that the same boarding was used in all composite tests.

The floorboards were screwed into the top flange of the CFS joists using loose countersunk self-tapping, self-drilling screws with reamers of following dimensions and mechanical properties: head diameter= 7.5mm, thread diameter= 4.15mm, length= 40mm, tensile strength= 10kN, shear strength= 4.6kN. The nominal spacing for the screws was 150mm. A PU D4 adhesive was also used, in addition to the screws, to fix the boards to the joists. Such adhesive is typically used in board-to-board and board-to-joist connections as well for sealing board edges to reduce squeaking and movements in the flooring [1].

2.2 Specimens, test setup, load protocol, and instrumentation

The tests consisted of 18 large-scale floor specimens and 5 pushout tests, assembled to simulate typical construction detail. For the floor tests, two CFS joists were spaced at 600mm and orientated such that their flanges point in opposite directions, to minimise torsional effects [1] (see Figure 1(b)). The joists were topped with 1200mm wide floorboards, which were connected to the CFS joists' top flanges using screws (nominal spacing of 150mm) and adhesives along the full joists' span. For comparison purposes, identical specimens without the floorboards were also tested for each specimen. At least three identical floors were tested per parameter.

To simulate uniformly distributed loading, the floors were simply supported and subjected to bending using a refined loading system [2], which applies four line loads across the floor span, using two actuators and spreader beams, as indicated in Figure 1 (a). These loads were applied through rollers to ensure that the load remains vertical. For all specimens, the CFS joists were stiffened locally at the underside of the loading points to avoid premature failures. At midspan, two large angle brackets were used to prevent excessive twisting, particularly in the un-boarded specimens.

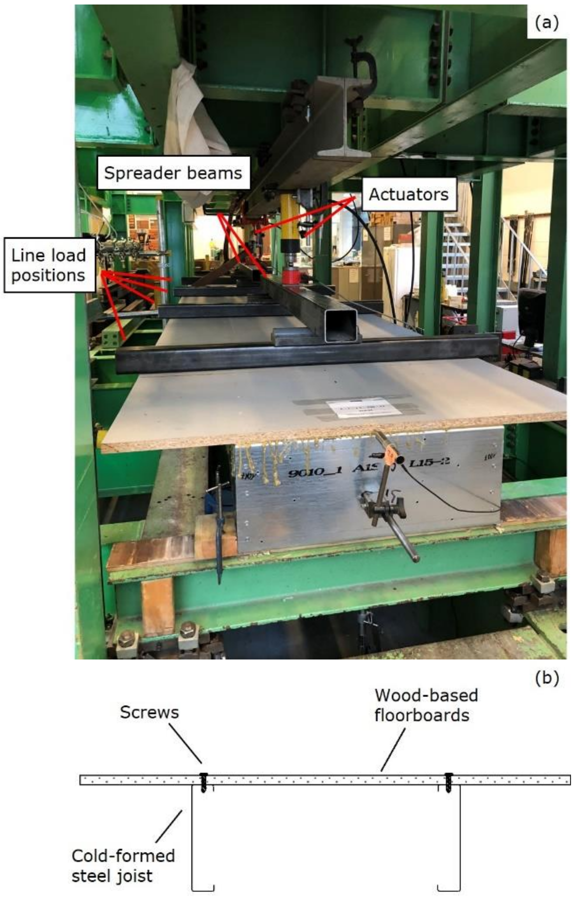

Figure 1 (a) Typical test setup, (b) cross-section of floors with boards

All specimens were subjected to two initial loading cycles, which included loading and unloading to 60% then 100% of the estimated live serviceability loading (F_{est}) at a loading rate of 0.05 kN/sec, followed by loading to failure at a rate of 0.1mm/sec. The load protocol is presented in Figure 2. The vertical displacements of the floors were measured at midspan using three linear variable differential transducers (LVDTs) (two under the joists and one under the floorboards at midspan). For the un-boarded specimens, the latter measurements were taken from small strips of timber positioned at midspan. The vertical displacements at the support were also measured and later subtracted from the displacements taken at midspan as per [10]. Note that measurements used in the analysis in this paper are those taken from the final loading cycle.

25097075, 2023, 3-4, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/cepa.2350 by University College Dublin Libr, Wiley Online Library on [12/09/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

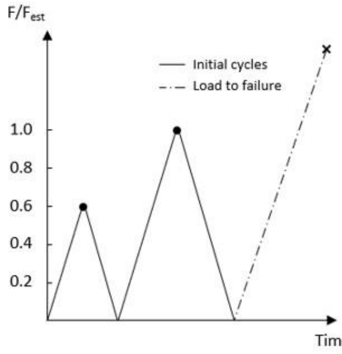

Figure 2 Load protocol

To evaluate the load-slip characteristics of the CFS-timber connection, five pushout tests were performed. The tests comprised two CFS sections of gauge 1.5mm, positioned back-to-back 5mm apart. The joists were sandwiched between the two floorboards and fixed mechanically through the flanges using both screws (nominal screw spacing of 150mm) and adhesive as per the typical floor construction considered in this study (Figure 3(a)). The pushout tests were loaded as per BS EN 26891 [12] and displacements were measured using four LVDTs positioned on different corners of the joist's webs to measure slip.

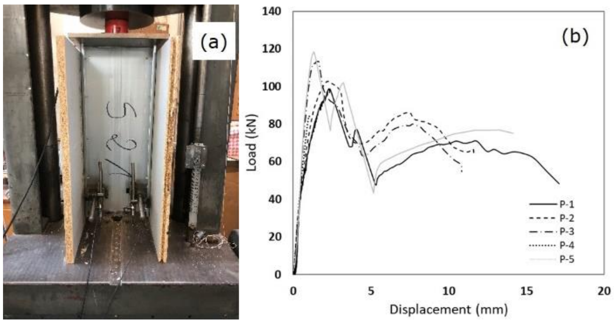

Figure 3 Pushout test (a) setup and (b) data

Based on the pushout test data (Figure 3(b)) and following BS EN 26891 recommendations [12], the key performance parameters for load-slip behaviour of the tested connection detail were maximum load F_{max}= 107.0 kN (standard deviation (SD)= 9.8, coefficient of variation (CoV)= 9.2%), average slip modulus $K_{s,avg}$= 123.4 kN/mm (SD= 10.9 , CoV= 8.8%), and characteristic slip modulus per fastener K_o= 4.9 kN/mm, determined using EN 1993-1-3 coefficients for design assisted by testing [10].

3 Results and analysis

Figure 4 presents average load-displacement curves from the floor bending tests up to peak load, while Table 1 presents average experimental data, including bending stiffness (EI_{exp}) and ultimate bending moment at failure ($M_{u,exp}$). The increase in bending stiffness and bending moment at failure in the composite floors relative to the bending stiffness and bending moments in the bare/un-boarded floors (EI_{exp}/EI_B and $M_{u,exp}/M_{u,B}$), respectively, is also presented. EI_{exp} was calculated based on the test load configuration [2] and by considering the change in loads corresponding to midspan deflections between 30% and 60% of the beam serviceability deflection limits as per [1], within which the load-displacement behaviour is linear elastic. Support displacements were measured and subtracted from the midspan displacements.

In Table 1, the specimens are identified using a test ID, which specifies the type of specimen (C=Composite, B=Bare/un-boarded joists), followed by span length. Note that every test type in Table 1 corresponds to average results from three identical tests. Apart from one test type highlighted in Table 1, all data exhibited a low coefficient of variation (CoV < 10%), which meant that the characteristic flexural stiffness may be taken directly from the average flexural stiffness, presented in Table 1, as per the recommendations of EN 1993-1-3, cl. A 6.3.3 (3) [10].

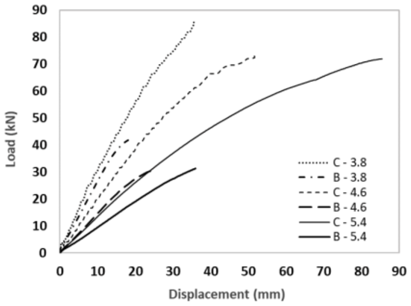

Figure 4 Average load-displacement curves from floor bending tests

Table 1 Key results from the floor bending tests

Test ID	EI_{exp} (kN.m^2)	EI_{exp}/EI_B (%)	$M_{u,exp}$ (kN.m)	$M_{u,exp}/M_{u,B}$ (%)
B-5.4	1814	-	21.6	-
C-5.4	2638	45.4	46.6	115.7
B-4.6	1721	-	18.4	-
C-4.6	2374	37.9	43.1	134.2
B-3.8	1694	-	20.7	-
C-3.8	2024	19.5	39.6*	91.3

*Coefficient of variation of 11-13%.

The increase in bending stiffness for the composite specimens, relative to the un-boarded specimens is also shown in Figure 5, where the standard deviation of the test data obtained from three identical tests for each specimen type is provided in the form of upper and lower bound values.

As expected, the effect of composite action on floor flexural stiffness was much more substantial for the longer spans [13]. For the 5.4m floors, the average increase in flexural stiffness was around 45% relative to the un-boarded specimen, whereas this increase was only 20% for the 3.8m spans. It is expected that for some short span lengths, the benefits of utilising composite action in the design may not be substantial. Therefore, practical guidelines with cut-off lengths for utilising composite action in the design of such floors may be useful.

25097075, 2023, 3-4, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/cepa.2350 by University College Dublin Libr, Wiley Online Library on [12/09/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

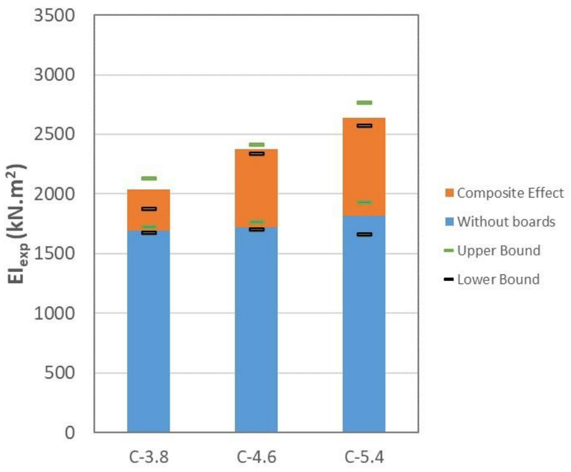

Figure 5 Average experimental flexural stiffness (EI_{exp}) for the unboarded specimens and additional stiffness due to composite effect

4 Analytical calculations

4.1 Existing models

Current design methods of CFS-timber composites do not provide explicit formulae for predicting the flexural stiffness of such floors. Nevertheless, several models, based on shear bond coefficients can be found in the literature for composites with partial shear connections [2,5,13], most of which are based on formulae given in Annex B of EN 1995-1-1 [14]. The general formula for effective bending stiffness used to calculate the flexural stiffness of tested floors in this study, and derived in [5], is provided as follows:

$$EI_{eff} = E_b I_b + E_s I_s + \frac{[E_b A_b \gamma \alpha^2]}{\left[1 + \gamma \frac{E_b A_b}{E_s A_s}\right]} \qquad (1)$$

where, EI_{eff} is the effective flexural stiffness of the composite floor (eq. 1), E_b and E_s are the modulus of elasticity of the board and steel, respectively, A_b and A_s are the gross area of the board and steel cross-sections, respectively, I_b and I_s are the gross second moment of area of the board and steel cross-sections, respectively, γ is the shear bond coefficient (eq. 2), k is the slip modulus of the shear connection (eq. 3), K_o is the slip modulus, s_f is the fastener spacing, t_b is the board thickness, and h is the height of the joist web.

$$\gamma = 1 / \left[1 + \frac{\pi^2 E_b A_b}{L^2 k}\right] \qquad (2)$$

$$k = K_o / s_f \qquad (3)$$

$$\alpha = (t_b + h)/2 \qquad (4)$$

4.2 Test predictions

Table 2 presents a comparison between the experimental flexural stiffness (EI_{exp}) and analytical predictions for the composite floors (EI_{eff}), determined based on the analytical equation provided in Section 4.1 and as per existing literature [5]. In Table 2, a positive result, indicates that the predicted flexural stiffness is higher than the experimental value (unconservative), whereas a negative result indicates a lower predicted flexural stiffness (conservative).

Previous studies [e.g. 5] indicate that the board was fully effective for a joist spacing of 600mm, with no effects of shear lag observed. Nevertheless, the tested spans were 5.8m in length [5]. As such, an effective width of 600mm was used for C-5.4 (i.e. span length of 5.4m). For the shorter spans in this study (4.6m and 3.8m) an effective width of $b_{eff} = L_e/8$ was assumed, where L_e is the distance between points of zero moments, as per EN 1994-1-1 [15]. I_b and A_b were calculated accordingly.

Table 2 Analytical predictions for flexural stiffness of composite floors

Test ID	EI_{exp} (kN.m^2)	EI_{eff} (kN.m^2)	Error (%)
C-5.4	2638	2505	-5.0
C-4.6	2374	2432	+2.5
C-3.8	2024	2310	+14.1

The results in Table 2 indicate that while reasonable predictions were achieved for specimens with lengths of 4.6m and 5.4m, the results were unconservative for a span length of 3.8m, where predictions presented a flexural stiffness (EI_{eff}) that is 14% higher than observed test results. Therefore, further guidance or amendments to existing equations are needed to cover shorter span lengths. Similar results were observed by [11] where it was observed that span-to-depth ratio in steel-concrete composite beams with partial shear connection can influence the accuracy of existing equations calculating composite bending stiffness.

Further investigation is needed to understand the influence of span length on the shear load transfer at the CFS-board interface, effective board width, and shear deformations, to assess and extend the applicability of existing equations that determine the effective flexural stiffness of CFS composite floors of different lengths. The appropriate effective properties of the steel section to be used in the equation, to account for local buckling, also require further investigation.

5 Conclusions

An experimental programme comprising a total of 18 full scale floor bending tests and 5 pushout tests was implemented to evaluate the flexural performance of CFS floors of different lengths, with or without composite action with the timber boarding.

The results show that composite design of such floors provides an attractive solution for increasing the efficiency of lightweight floors and minimising the use of resources. For the longer spans, the increase of flexural stiffness due to composite action is too beneficial to ignore. Existing models were shown to reasonably predict the performance of longer floors (e.g. 5.4m); however, further research is needed to extend the applicability of these models to shorter spans (e.g. 3.8m), commonly used in the industry.

25097075, 2023, 3-4, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/cepa.2350 by University College Dublin Libr, Wiley Online Library on [12/09/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

The results of this research may be used to calibrate analytical and numerical models, enabling the development of appropriate design rules for the design of CFS-timber based floors of different parameters.

Acknowledgments

The work presented herein has received financial support from the UK Research and Innovation, Innovate UK Knowledge Transfer Partnerships (KTP) programme (grant number 10764) and the European Union’s Horizon 2020 programme under the Marie Sklodowska-Curie grant agreement n° 101029972. The authors are thankful to Fusion Building Systems and Oxford Brookes University for their valuable contributions to this research.

References

[1] Yandizio, E.; Lawson, R.M.; Way, A.G.J. (2015) *SCI P402: Light steel framing in residential construction. The Steel Construction Institute, Ascot, UK.*

[2] Loss, C.; Davison, B. (2017) *Innovative composite steel-timber floors with prefabricated modular components. Engineering Structures.* 132, 695-713.

[3] Ye, J.; Mojtabaei, S.M.; Hajirasouliha, I.; Shepherd, P.; Pilakoutas, K. (2018) *Strength and deflection behaviour of cold-formed steel back-to-back channels. Engineering Structures.* 177, 641-654.

[4] Vella, N.; Gardner, L.; Buhagiar, S. (2021) *Analytical modelling of cold-formed steel-to-timber connections with inclined screws. Engineering Structures.* 249, 113187.

[5] Kyvelou, P.; Gardner, L.; Nethercot, D.A. (2017) *Design of composite cold-formed steel flooring systems. Structures.*12, 242:252.

[6] Hassanieh, A.; Valipour, H.R.; Bradford, M.A. (2016) *Experimental and numerical study of steel-timber composite (STC) beams. Journal of Constructional Steel Research.* 122, 367-378.

[7] Kyvelou, P.; Gardner, L.; Nethercot, D.A. (2017) *Testing and analysis of composite cold-formed steel and wood-based flooring systems. Journal of Structural Engineering.* 143, 04017146.

[8] Karki, D.; Far, H.; Saleh, A. (2021) *Numerical studies into factors affecting structural behaviour of composite cold-formed steel and timber flooring systems. Journal of Building Engineering.* 44, 102692.

[9] Raffoul, S.; Moutaftsis, D.; Heywood, M.; Rowell, M. (2020) *Composite behaviour of cold-formed steel - timber floors. Special Issue: XIII Conference on Steel and Composite Construction.* 3 (5-6), 372-380.

[10] EN 1993-1-3 (2006) *Eurocode 3: Design of steel structures – Part 1-3: General rules – Supplementary rules for cold-formed members and sheeting*.

[11] EOTA TR2 (2000) *European organisation for technical approvals – Test methods for light composite wood-based beams and columns*.

[12] BS EN 26891 (1991) *Timber structures. Joints made with mechanical fasteners. General principles for the determination of strength and deformation characteristics.*

[13] Lawson, R.M.; Lam, D.; Aggelopoulos, E.S.; Nellinger, S. (2017) *Serviceability performance of steel-concrete composite beams. Proceedings of the Institution of Civil Engineers.* 170 (2), 98-114.

[14] EN 1995-1-1 (2005) *Eurocode 5: Design of timber structures - Part 1-1: General – Common rules and rules for buildings.*

[15] EN 1994-1-1 (2004) *Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings.*

2509075, 2023, 3-4, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/cepa.2350 by University College Dublin Libr, Wiley Online Library on [12/09/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License