Experimental characterisation of connection behaviour for coldformed steel panels sheathed with calcium silicate boards

Citation for published version:
Ringas, N & Huang, Y 2023, Experimental characterisation of connection behaviour for coldformed steel panels sheathed with calcium silicate boards. in *ce/papers: EUROSTEEL 2023.* vol. 6, ce/papers, no. 3-4, vol. 6, Wiley, pp. 1871-1878, The 10th Eurosteel conference, Amsterdam, Netherlands, 12/09/23. https://doi.org/10.1002/cepa.2400

Digital Object Identifier (DOI):
10.1002/cepa.2400

Document Version:
Publisher's PDF, also known as Version of record

Published In:
ce/papers

ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

ORIGINAL ARTICLE

eurosteel AMSTERDAM 2023

Experimental characterisation of connection behaviour for cold-formed steel panels sheathed with calcium silicate boards

Nikolas Ringas[1] | Yuner Huang[1]

Correspondence

Nikolas Ringas
Institute for Infrastructure and Environment
School of Engineering
The University of Edinburgh
John Muir Building
Colin Maclaurin Rd
King's Buildings
EH9 3DW Edinburgh, UK
Email: n.ringas@ed.ac.uk

[1] School of Engineering, The University of Edinburgh, Edinburgh, UK

Abstract

Construction trends aim towards the use of modular cold-formed steel (CFS) wall panels, comprising of CFS studs and sheathing. Their capacity is influenced by different components employed, with the fastener connection between the sheathing board and the frame being the most critical. Furthermore, as repeated loading scenarios are expected to occur within the life cycle of a structure, it is important to address the uncertainty surrounding the connection behaviour under cyclic loading. A series of push-out tests were carried out for cold-formed steel sections sheathed with Calcium Silicate Board, using monotonic and cyclic loading protocols. The cyclic protocol employed focuses on the serviceability limit state with a repeated load-unload step applied for 10 cycles. Two assembly arrangements, namely back-to-back and single stud arrangements were employed. Push-out test results are presented and discussed herein. Recommendations for the test procedure and design of connection in sheathed cold-formed steel shear walls are proposed.

Keywords

Cold-formed steel; connection behaviour; cyclic loading; calcium silicate board;

1 Introduction

Cold-formed steel (CFS) frames have been extensively used as a load-bearing component in low to mid-rise buildings. Their popularity in construction arises from their high strength-to-weight ratio, ease of assembly and high stiffness. Nevertheless, even though such Modern Construction Methods (MCM) come as a substitute to traditional labour-intensive practices due to off-site manufacturing, they still incorporate time-consuming activities such as installation of precisely cut bracing members, in K- or X-arrangements to enhance a frame's capacity against lateral loads.

These frames are covered with sheathing boards, which currently are regarded as non-structural members. However, substantial evidence has been provided as per the influence of the sheathing board in the lateral stiffness and capacity of the panel [1], with direct comparisons made to braced CFS frames [2]. Serrette and Peyton [3] have previously described the endurance of sheathed CFS frames as a function of the capacity of all the components employed within its envelope. Their capacity is further affected by factors such as wall aspect ratio, screw spacing, stud spacing, material thickness and loading conditions [4]–[7]. Nevertheless, past research suggests that the predominant failure mode will normally occur at a fastener location. However, current design standards [8], [9], disregard the influence of the sheathing material in connection design, leading to conservative predictions and material waste.

Furthermore, all past research conducted aiming to determine the shear characteristics of fasteners were carried out using different testing arrangements. Hence, there is a need to present a systematic testing methodology for accurate characterisation of fastener shear behaviour in sheathed CFS components. This article presents an experimental investigation on the connection behaviour in cold-formed steel (CFS) studs sheathed with calcium silicate boards (CSB) through push out testing. Two testing arrangements were utilised, namely single stud and back-to-back stud. Finally, the specimens were tested under a monotonic and a cyclic protocol, emphasising the behaviour of individual connections under repeated loads within the range of their expected service loads.

2 Experimental programme

The CFS studs have a S350GD+ZA steel lipped channel section, with a typical geometry of 100mm web height, 45mm flange width, 10mm lip depth and 1.2mm thickness. The sheathing boards employed were 12mm thick calcium silicate boards (CSB), which were attached to the

ce/papers 6 (2023), No. 3-4

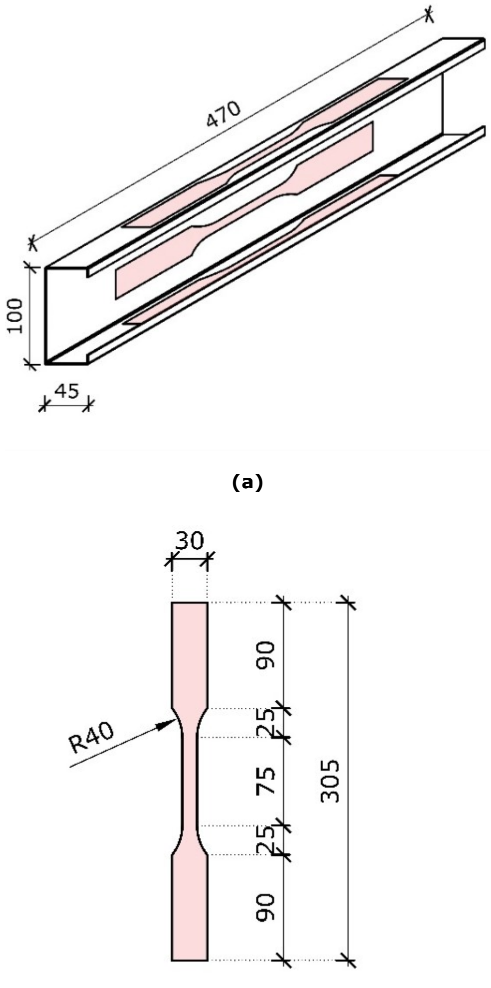
https://doi.org/10.1002/cepa.2400

wileyonlinelibrary.com/journal/cepa

frame using wingtip self-tapping screws of 4.2mm in diameter and 38mm length. Tests to investigate mechanical characteristics of all materials employed were carried out, followed by connection shear tests.

2.1 Cold formed steel material tests

The mechanical properties of S350GD+ZA cold-formed steel were determined through a series of tensile coupon tests, with the coupon dimensions conforming to ISO 6892-1 [10]. A total of four coupons were extracted from the webs and flanges of fabricated studs. The coating consisting of zinc and aluminium was removed prior to the tensile coupon tests by applying a 37% purity hydrochloric acid solution on the surface along the gauge length, allowing the base steel material to be exposed and its cross-section to be accurately measured.



(a)

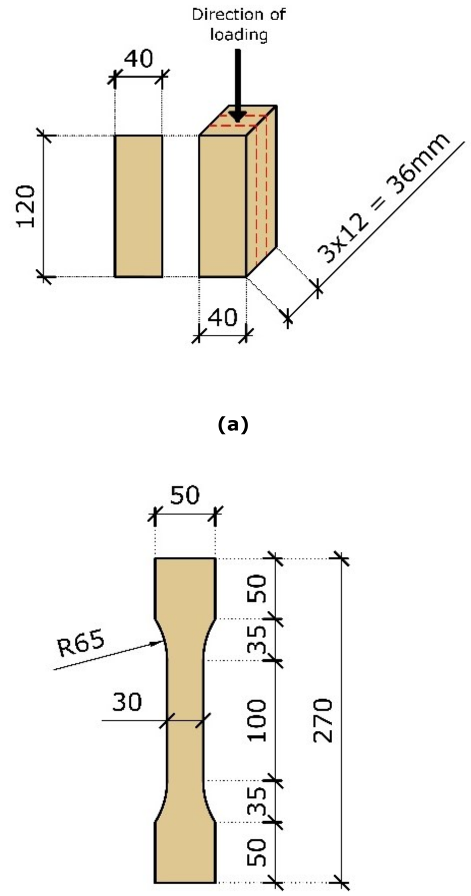
(b)

Figure 1 Cold formed steel: (a) areas of coupon extraction, (b) specimen dimensions according to ISO 6892-1 [10] (unit – millimetres)

Tensile testing was performed using a 100kN Instron 4505 electro-mechanical universal testing machine (UTM), with strains measured through a 50mm knife-edged extensometer. The loading was applied in displacement control with a loading rate of 0.20mm/min up to the yield plateau, followed by a 0.40mm/min rate up to the ultimate load and a 0.80mm/min rate until fracture. Constant straining was held for 3 minutes within the yield plateau and near the ultimate strength, in order to determine the corresponding static stress-strain curves. Raw data extracted from the actuator are presented as engineering stress and strain. Those were subsequently adjusted to static stress, based on the magnitude of stress relaxation recorded through the constant straining steps, and to eliminate the effects of the loading rate [11].

2.2 Calcium silicate board material tests

Since calcium silicate exhibits orthotropic material behaviour, it is crucial to record its properties both in tension and compression. Material tests were conducted using the same UTM mentioned in Section 2.1. The testing methodology was based on BS EN 383 [12] and the framework employed by Kyprianou et al. [13] and Stergiopoulos et al [14]. It should be noted that there is no standard that fully specifies testing of calcium silicate.



(a)

(b)

Figure 2 Calcium Silicate Board: (a) compressive coupon [21], (b) tensile coupon [13] (unit – millimetres)

Three tensile coupons were extracted along the longitudinal direction of CSB. Likewise, a series of compressive coupons were extracted to obtain the properties parallel to the faces of the board. In order to examine the later, three 12mm plies measuring 120mm in the longitudinal direction and 300mm in the transverse direction of the board glued together using a two-component epoxy adhesive. Those were subsequently cut in specimens of 40mm width, to form the compressive coupons, as illustrated in Figure 2. Both tests were executed with a constant loading rate of 0.10mm/min until failure.

2.3 Push-out tests

The standard testing practice to measure the load-slip response in a system comprising of a CFS stud, a sheathing board and self-tapping fasteners is based on the push-out test described in EN 1994 [15]. However, for comparison purposes, the tests conducted within the present paper used both a back-to-back stud arrangement and a reduced-size single stud specimen taken from [16].

The experiments were executed using a 250kN servo-hydraulic Instron 8800 actuator for both test arrangements, as illustrated in Figure 3. The displacement was recorded through a 30mm linear variable displacement transducer (LVDT) pointing towards a plate attached to the web of the specimen. The single-stud arrangements employed two CSB boards, identical to those for the back-to-back specimen, attached to the flanges of the stud at 100mm spacings and for a total of 4 screws, as illustrated in Figure 4a. For the back-to-back specimens, the test setup comprised of 230mm long CFS studs connected to each other using three 5.5x25 self-tapping screws at 100mm spacings along the web. Two 200mm square CSB boards of 12mm thickness, one on each side of the created I-section, were fastened at 100mm spacings along the height and 45mm across the width, for a total of eight 4.2mm x 38mm self-tapping screws for each specimen, with the cross-section of the specimen presented through Figure 4b. The screw spacing and arrangement of the steel and sheathing components is presented in Figure 4c.

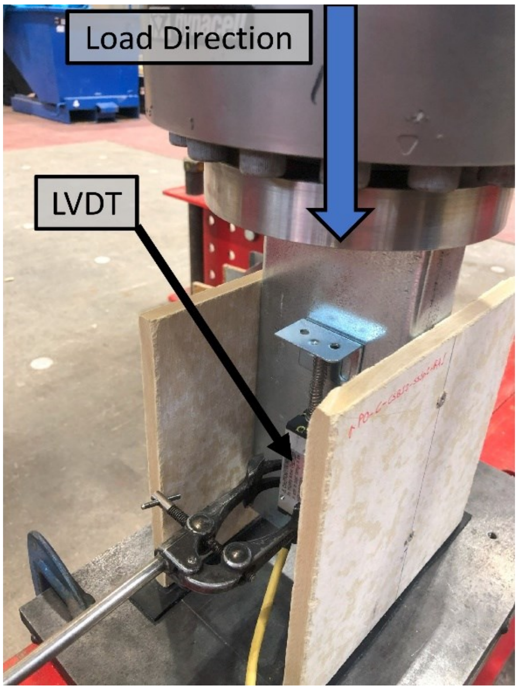
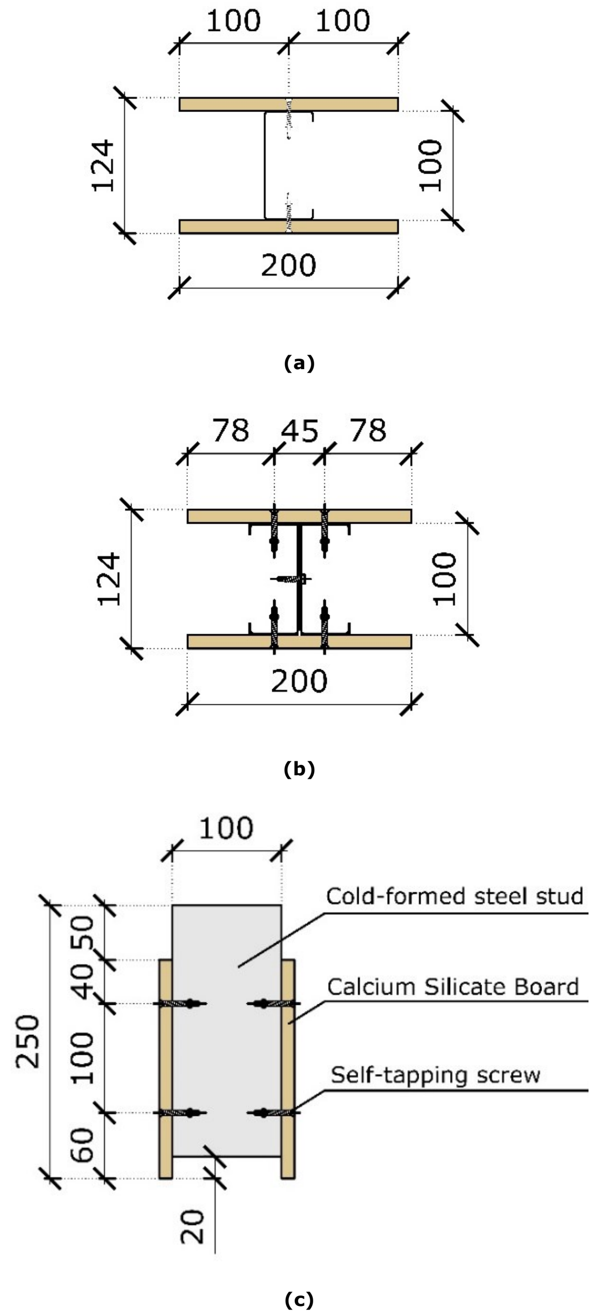


Figure 3 Pushout testing experimental setup

The monotonic protocol for both test arrangements was based on BS EN 383, BS EN 26891, BS EN 12512, BS EN 594 and ASTM E2126 [12], [17]–[20]. The specimens were subjected to an initial loading cycle up to 40% of to the expected ultimate load (F_u) per fastener as recorded in [16], followed by a load reversal to 10% and, finally, loaded until failure. A displacement rate of 0.8mm/min was kept throughout the load-unload cycles which was subsequently doubled to 1.6mm/min until failure.

Various cyclic protocols have been employed to characterise the cyclic behaviour of structures through load reversals, with the CUREE protocol being the most notable [20]. However, as any given structure is expected to experience repeated load-unload cycles well below its expected capacity, on a daily basis in the form of wind gusts, it is crucial to determine if those would cause irreversible deformations and ultimate capacity reduction in the connection. Hence, a protocol comprising of ten cycles in the 10%-40% range of the ultimate load (F_u) and then loading until failure is utilised therein. Load-holds were kept at both 10% and 40% limits for a period of 30 seconds, based on the assumption that a typical wind gust lasts for as long [22]. Identically to the monotonic protocol, a constant displacement rate of 0.8mm/min was kept during the load-unload sequence, with that doubled to 1.6mm/min for loading until failure.

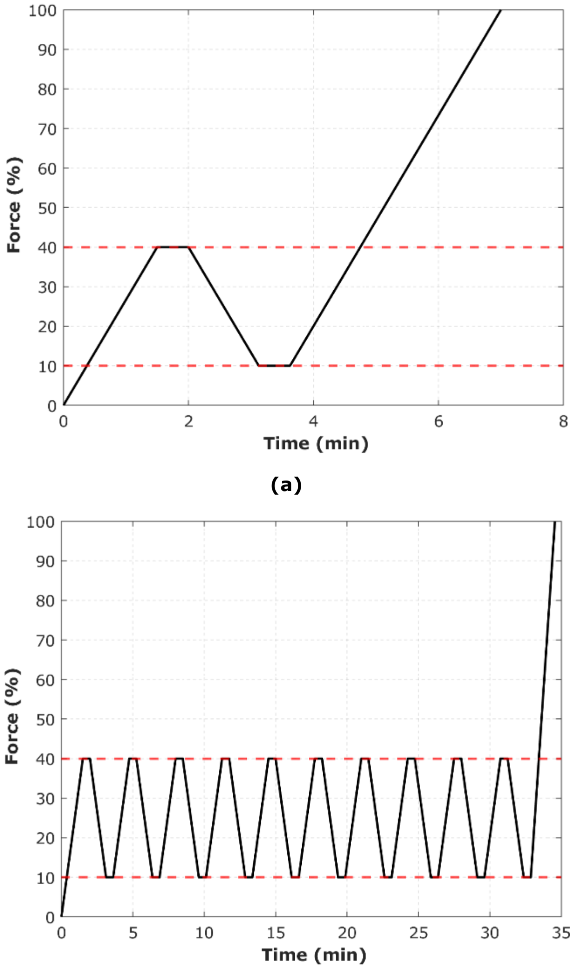


(a)

(b)

(c)

Figure 4 Push-out test specimens: (a) single stud specimen top view, (b) back-to-back specimen top view, (c) specimen elevation view (unit – millimetres)



(a)

(b)

Figure 5 Testing protocols: (a) Monotonic Protocol, (b) Cyclic Protocol

3 Results and discussion

3.1 Materials testing results

Key mechanical properties of steel, such as yield strength (f_y at 0.2% offset), ultimate strength (f_u), strain at fracture (ε_f), and Young's modulus (E) were determined and summarised in Table 1. The labelling of the specimens starts with the acronym for the material (CFS), followed by a letter indicating the location of coupon extraction (i.e. W for web and F for flange). The results for all the specimens tested for the present study are presented in Table 1.

Table 1 Cold-formed steel: mechanical properties

	E (GPa)	*f_y (MPa)*	*f_u (MPa)*	*ε_u (%)*	*ε_f (%)*
CFS-W1	192.1	394.7	496.5	13.4	18.4
CFS-W2	194.3	404.4	501.0	13.6	20.8
CFS-F1	191.2	393.9	504.0	14.7	22.0
CFS-F2	194.9	387.2	495.2	14.9	24.6
Avg.	193.2	395.1	499.2	14.2	19.3

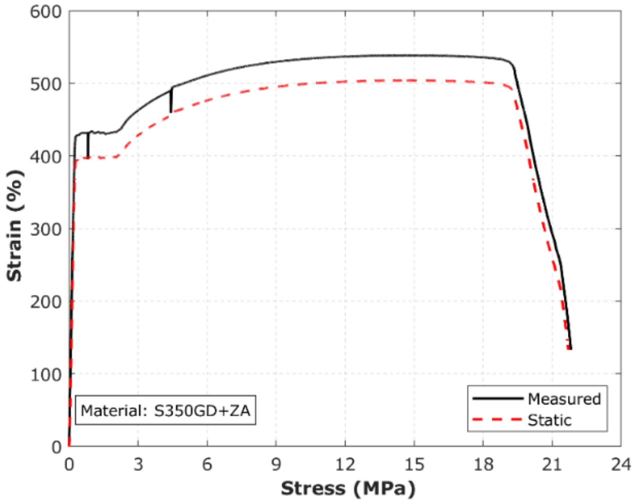


Figure 6 Cold formed steel: indicative stress-strain curve (CFS-F1)

Table 2 Calcium silicate coupons: tensile properties parallel to the surface

	E (GPa)	*f_u (MPa)*	*ε_u (%)*
CSB-T1	10.1	7.3	0.08
CSB-T2	10.5	7.2	0.07
CSB-T3	10.2	7.3	0.08
Avg.	10.3	7.3	0.08

Table 3 Calcium silicate coupons: compressive properties parallel to the surface

	E (GPa)	*f_u (MPa)*	*ε_u (%)*
CSB-C1	10.4	38.9	0.4
CSB-C2	10.4	36.2	0.4
CSB-C3	10.2	35.7	0.4
Avg.	10.3	36.9	0.4

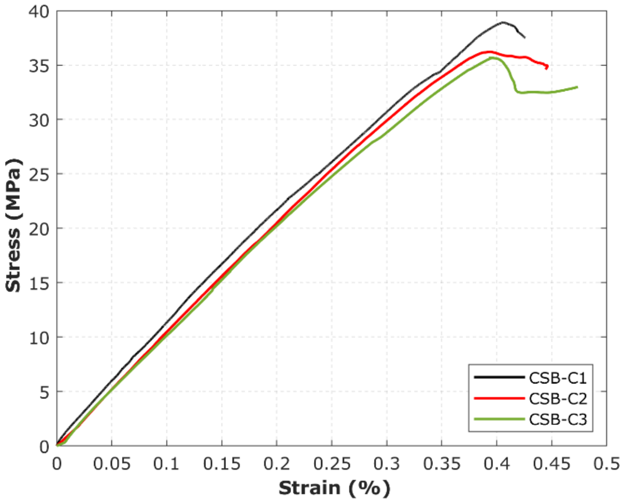


Figure 7 Calcium silicate coupons: compressive properties parallel to the surface

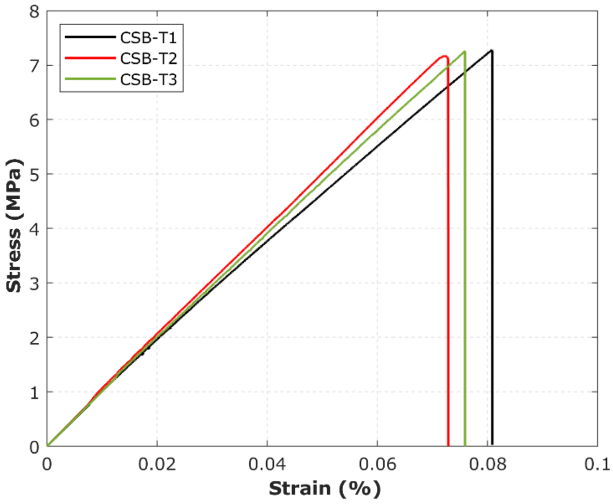


Figure 8 Calcium silicate coupons: tensile properties parallel to the surface

3.2 Push out tests

Connection stiffness is defined as the tangent to the force-slip curve in the 10%-40% range, estimated based on [12] and through the following equation:

$$K = \frac{F_{40}-F_{10}}{d_{40}-d_{10}} \qquad (1)$$

where F and d correspond to the force and slip at the 10% and 40% load reversals. Furthermore, the connection ductility is calculated based on [23] as provided below:

$$D = \frac{d_u}{d_{40}} \qquad (2)$$

with d_u and d_{40} corresponding to the displacements at ultimate load and at 40% of the ultimate capacity. The measured force-slip responses for the single stud and back-to-back arrangements are illustrated in Figure 10 and Figure 12 respectively. The single stud experiments all recorded a localised bearing failure to the sheathing board, followed by screw tilting and pull through at higher displacements as presented in Figure 9. However, the back-to-back specimens all recorded shear failure of at least one screw on either side, with the capacity of the specimen dropping significantly after that and by presenting an unsymmetrical failure mode that is illustrated in Figure 11. A summary of the results for the single stud and back-to-back tests, including connection stiffness (K), ductility (D), ultimate load per fastener (F_u) and displacement at ultimate load (d_u), is presented in Table 4 and Table **5** for the single stud and the back-to-back stud specimens respectively.

Given the large deviations provided through the monotonic results for the back-to-back specimens, only the single stud arrangement was employed for the protocol presented in Figure 5b. The failures modes observed under cyclic loading were identical to those for the monotonic, i.e. bearing of the screw onto the board, followed by tilting and pull-through. It was also recorded that the interface between the CSB and the screw experienced irreversible deformations (d_{pl}) attributed to localised damage on the board, with its magnitude not increasing significantly after the 6th cycle. Those are calculated as the difference between the slip at 10% force for the ultimate cycle ($d_{10}(10)$) minus the slip at 10% force for the first cycle ($d_{10}(1)$).

$$d_{pl} = d_{10}(10) - d_{10}(1) \qquad (3)$$

Figure 9 Bearing failure onto the board for a single stud specimen

A zoomed-in version presenting the tips of the load-unload sequence of the force-slip curve for specimen PO-C-SS-CSB-1 is presented in Figure 14, to demonstrate the irreversible deformations recorded under the repeat cycles. However, this did not affect the ultimate capacity of the specimen, as presented through the results provided in Table 6 and illustrated in Figure 13.

Table 4 Single stud (SS) monotonic push-out tests: Experimental results per fastener

	K (N/mm)	D (-)	F_u (kN)	d_u (mm)
PO-M-SS-CSB-1	1635	9.8	3.9	8.3
PO-M-SS-CSB-2	1156	6.6	3.9	7.7
PO-M-SS-CSB-3	1306	7.1	4.2	9.2
PO-M-SS-CSB-4	1649	8.1	4.1	6.9
Avg.	1437	7.9	4.0	8.0

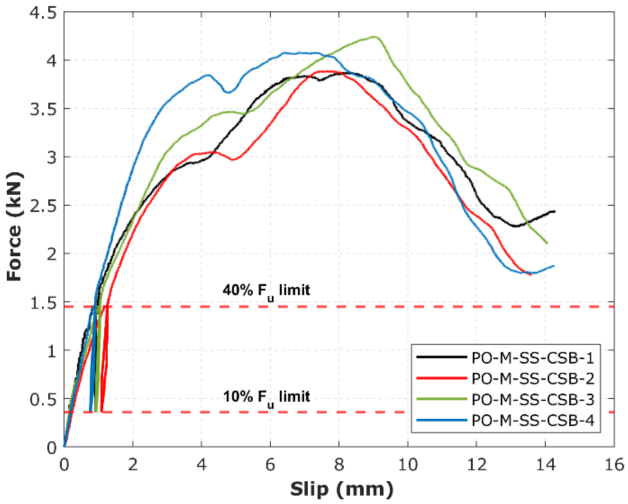


Figure 10 Monotonic push-out tests: Single stud

Table 5 Back-to-back (B2B) monotonic push-out tests: Experimental results per fastener

	K (N/mm)	*D (-)*	*F_u (kN)*	*d_u (mm)*
PO-M-B2B-CSB-1	1104	3.9	3.3	4.6
PO-M-B2B-CSB-2	1018	3.5	3.1	5.1
PO-M-B2B-CSB-3	1185	2.8	2.6	3.4
PO-M-B2B-CSB-4	1045	6.0	3.0	7.9
Avg.	1088	4.1	3.0	5.3

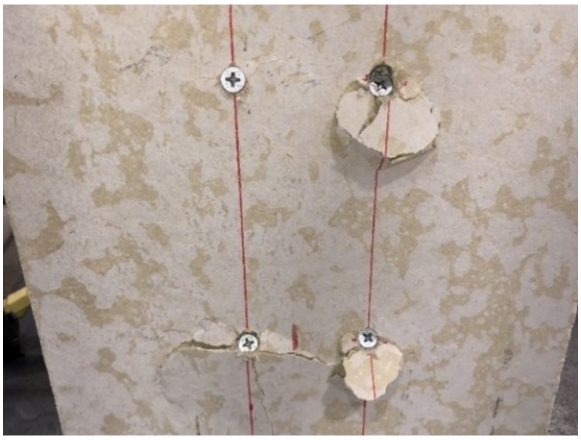


Figure 11 Unsymmetrical failure for a back-to-back specimen

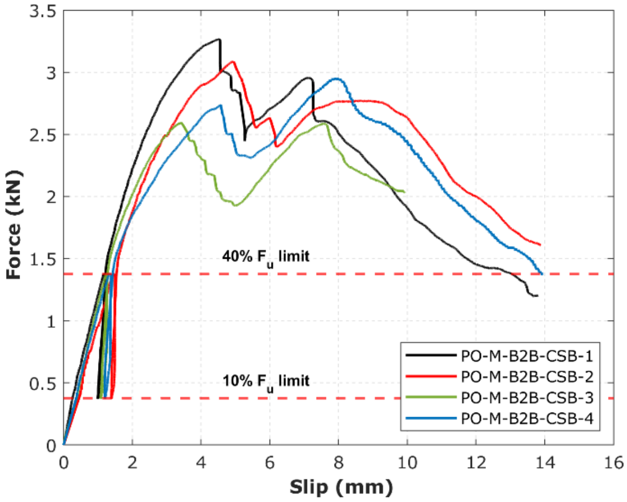


Figure 12 Monotonic push-out tests: back-to-back studs

4 Conclusions

An experimental investigation was carried out to characterise the connection shear behaviour in cold-formed steel frame systems, sheathed with calcium-silicate boards. The material properties were recorded through an extensive materials testing framework. Those were followed by push-out tests, using both single and back-to-back stud arrangements, under a monotonic and a repeated loading protocol to determine the capacity of the connection.

Table 6 Single stud (SS) cyclic push-out tests: Experimental results per fastener

	K (N/mm)	**D (-)**	**F_u (kN)**	**d_u (mm)**
PO-C-SS-CSB-1	1622	7.0	4.2	6.7
PO-C-SS-CSB-2	1394	7.1	4.0	7.7
PO-C-SS-CSB-3	1354	6.9	4.2	6.1
PO-C-SS-CSB-4	1352	5.7	4.1	9.2
Avg.	1431	6.4	4.1	7.5

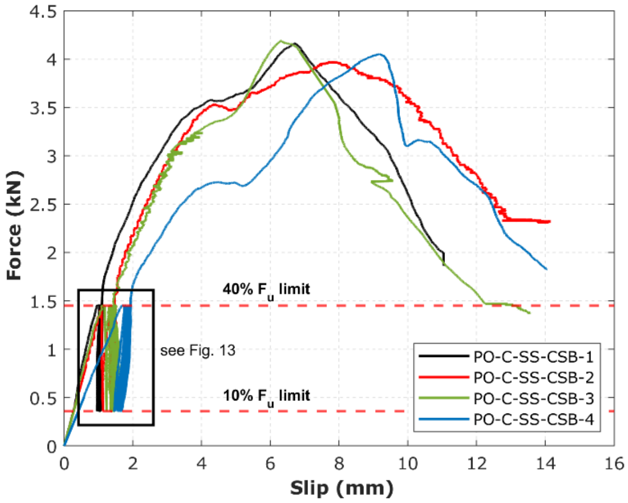


Figure 13 Cyclic push-out tests: Single stud

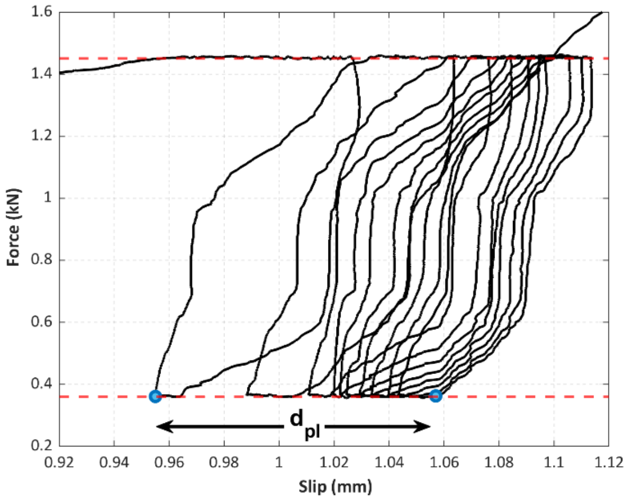


Figure 14 Residual slip for specimen PO-C-SS-CSB-1

The first phase of the push-out testing was carried out using the monotonic loading protocol, as illustrated in Figure 5a. Both the single stud and the back-to-back stud arrangements were employed, for a total of 4 specimens for each arrangement. Through those tests, it was determined that the difference in the stiffness and ultimate strength of the connection differed significantly. The experiments executed using the built-up section recorded a shear failure for at least one screw, with the stiffness for each connection being lower by at least 24% than that recorded for the single stud arrangement. This highlighted the potential of using a small specimen to record the connection behaviour, which is characterised by ease of assembly and specimen geometry control but also significantly reduces material waste.

Expanding from the results recorded on the previous section, only the single stud arrangement was used for the repeated loading protocol. Identical to the monotonic loading protocol, the failure mode observed originated from the bearing failure of the screwhead onto the board and the subsequent tilting of the screws. Stiffness and ultimate strength did not deteriorate, highlighting the ability of such connections to sustain repeated loading excitations without experiencing any reduction.

Future work will expand from the current tests using other sheathing materials, such as fibre-cement boards (FCB) and oriented strand boards (OSB/3). The results obtained will serve as input for advanced numerical modelling for the simulation of connector elements, with the aim of providing a parametric study that quantifies the influence of composite action for full wall panel assemblies. Finally, those will be utilised into providing a concise design methodology to predict the lateral behaviour of wall panels, with potential benefits to both construction practices and material efficiency.

5 Acknowledgements

The authors would like to acknowledge the contribution of Mr Richard Webb and Newton Steel framing for providing the necessary material to complete the presented experimental framework. Also, the authors would like to thank Professor R. Mark Lawson for his contribution in conceptualising the cyclic loading protocol. Finally, the authors would like to thank Mr Mark Partington, Mr Jamie White and Mr Jim Hutcheson at the University of Edinburgh – School of Engineering for their assistance in specimen preparation and testing.

References

[1] V. Macillo, L. Fiorino, and R. Landolfo, 'Seismic response of CFS shear walls sheathed with nailed gypsum panels: Experimental tests', *Thin-Walled Structures*, vol. 120, no. August, pp. 161–171, 2017, doi: 10.1016/j.tws.2017.08.022.

[2] E. Baran and C. Alica, 'Behavior of cold-formed steel wall panels under monotonic horizontal loading', *J Constr Steel Res*, vol. 79, pp. 1–8, Dec. 2012, doi: 10.1016/j.jcsr.2012.07.020.

[3] R. Serrette and D. Peyton, 'Strength of Screw Connections in Cold-Formed Steel Construction', *Journal of Structural Engineering*, vol. 135, no. 8, pp. 951–958, Aug. 2009, doi: 10.1061/(ASCE)0733-9445(2009)135:8(951).

[4] C. Y. Chen, F. A. Boudreault, A. E. Branston, and C. A. Rogers, 'Behaviour of light-gauge steel-frame - Wood structural panel shear walls', *Canadian Journal of Civil Engineering*, vol. 33, no. 5, pp. 573–587, May 2006, doi: 10.1139/L06-015.

[5] J. Ye, X. Wang, and M. Zhao, 'Experimental study on shear behavior of screw connections in CFS sheathing', *J Constr Steel Res*, vol. 121, pp. 1–12, 2016, doi: 10.1016/j.jcsr.2015.12.027.

[6] J. Ye, X. Wang, H. Jia, and M. Zhao, 'Cyclic performance of cold-formed steel shear walls sheathed with double-layer wallboards on both sides', *Thin-Walled Structures*, vol. 92, pp. 146–159, 2015, doi: 10.1016/j.tws.2015.03.005.

[7] L. Fiorino, T. Pali, B. Bucciero, V. Macillo, M. Teresa Terracciano, and R. Landolfo, 'Experimental study on screwed connections for sheathed CFS structures with gypsum or cement based panels', *Thin-Walled Structures*, vol. 116, pp. 234–249, Jul. 2017, doi: 10.1016/j.tws.2017.03.031.

[8] British Standards Institution, 'BS EN 1993-1-3:2006'.

[9] AISI, 'S100-16. North American Specification for the Design of Cold-Formed Steel Structural Members - 2016 Edition with Supplement 1', *American Iron and Steel Institute*, 2016.

[10] British Standards Institution BSI, *BS EN ISO 6892-1:2019 - Metallic materials - Tensile testing*. British Standards Institution BSI, 2019.

[11] Y. Huang and B. Young, 'The art of coupon tests', *J Constr Steel Res*, vol. 96, pp. 159–175, 2014, doi: 10.1016/j.jcsr.2014.01.010.

[12] British Standards Institution, 'BS EN 383:2007 - Timber Structures-Test methods, Determination of embedment strength and foundation values for dowel type fasteners', BSI, 2007.

[13] C. Kyprianou, P. Kyvelou, L. Gardner, and D. A. Nethercot, 'Characterisation of material and connection behaviour in sheathed cold-formed steel wall systems – Part 1: Experimentation and data compilation', *Structures*, vol. 30, pp. 1161–1183, Apr. 2021, doi: 10.1016/j.istruc.2020.12.056.

[14] M. Stergiopoulos, R. M. Lawson, and P. Lopez, 'Composite action of fixings to gypsum boards acting in shear based on material properties', *Proceedings of Institution of Civil Engineers: Construction Materials*, 2021, doi: 10.1680/jcoma.19.00009.

[15] British Standards Institution, 'Eurocode 4 : design of composite steel and concrete structures. Part 1-1: General rules and rules for buildings.', BSI, 2009.

[16] N. Ringas, Y. Huang, and J. Becque, 'Fastener behaviour in sheathed light-gauge steel stud walls under cyclic and monotonic actions', 2021, doi: 10.1002/cepa.

[17] British Standards Institution., *Timber structures : joints made with mechanical fasteners : general principles for the determination of strength and deformation characteristics*. British Standards Institution, 1991.

[18] British Standards Institution, *Timber structures - Test methods - Cyclic testing of joints made with mechanical fasteners.* 2001.

[19] British Standards Institution., *Timber structures, test methods, racking strength and stiffness of timber frame wall panels*. British Standards Institution (BSI), 2011.

[20] American Society for Testing and Materials, 'ASTM E2126-19: Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings', 2019.

[21] British Standards Institution, 'BS EN 789:2004 - Timber structures-Test methods-Determination of mechanical properties of wood based panels', BSI, 2005.

[22] I. Suomi, S. -E. Gryning, R. Floors, T. Vihma, and C. Fortelius, 'On the vertical structure of wind gusts', *Quarterly Journal of the Royal Meteorological Society*, vol. 141, no. 690, pp. 1658–1670, Jul. 2015, doi: 10.1002/qj.2468.

[23] British Standards Institution, 'BS EN 12512:2001 - Timber structures - test methods - cyclic testing of joints made with mechanical fasteners [including amendment A1:2005]', 2005.