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Shear behaviour of fixings in sheathed light steel wall panels

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ABSTRACT

The performance of screwed connections in sheathed cold-formed steel frames was investigated in this study through push-out testing of specimens representative to wall panels sheathed with cement-based boards. An extensive experimental programme was carried out, focusing on parameters including fixing diameter, loading conditions, sheathing material and the effect of wings at the tip of the fixing. Measured characteristics such as peak connection load and stiffness were obtained for each specimen type. Failure modes comprising of bearing, tilting, and pull-through were consistent amongst the tested specimens. Those sheathed with calcium silicate boards showed that the respective connections can achieve higher peak loads and stiffness compared to fibre-cement sheathed specimens. The removal of wings from the tip of the fixing resulted in increased thread engagement on the board material as the hole was not enlarged by the wings. This was identified as a significant factor, leading to increased shear resistance and stiffness, with some of the fibre-cement specimens performing comparably to those using calcium silicate boards and winged fixings.

1. Introduction

Cold-formed steel (CFS) wall panels are the most widely used load bearing systems in modern residential buildings up to eight storeys within the United Kingdom [1]. CFS wall panels offer considerable advantages due to their high strength-to-weight ratio and ease of assembly, that result in overall reduction of construction time. Such systems can provide a viable alternative to traditional construction methods like concrete frames, masonry and hot-rolled steel frames even in areas of high seismic activity [2]. The CFS wall panels that arrive prefabricated to the construction site feature C- profiles spaced at intervals of 300 mm or 600 mm mounted on tracks at the top and bottom. Though design standards mandate the use of X- or K-bracing to satisfy stability requirements [3,4], research has extensively demonstrated significant evidence on the beneficial contribution of sheathing boards on the in-plane strength and stiffness of CFS wall panels. The ability to account for the sheathing contribution in the resistance of cold-formed steel frames could lead to the broad application of modern methods of construction (MMC), reducing the construction industry's carbon footprint and meeting the United Nations' agenda for sustainable development [5].

Dry construction materials, such as gypsum or cement-based sheathing boards, have typically been used in CFS wall panels due to beneficial properties they provide such as compartmentation, to provide acoustic, thermal and fire insulation. Cement-based sheathing boards, such as fibre-cement boards and calcium silicate boards, are typically fixed onto the panel using self-drilling screws at regular intervals. This facilitates diaphragm action that can provide comparable panel stiffness to that achieved with a steel-braced panel [6]. However, the effectiveness of diaphragm action heavily depends on the resistance of the connection between the sheathing board and the CFS frame. Resistance of the CFS wall panels is typically taken as the minimum of the strength of the CFS frame ($H_{c,frame}$), the sheathing element ($H_{c,panel}$), the connection created by the fasteners ($H_{c,connections}$) or the tensile strength of the anchors connecting the wall panel to the foundation ($H_{c,anchors}$), with many researchers identifying the connection between the sheathing and the steel studs as the weakest in the system [7]. Thus, there is a requirement to characterise connection resistance and ductility in sheathed cold-formed steel panelised construction to allow for the identification of the optimised combination of fixings, sheathing board and steel.

Small-scale tests (i.e. push-out, pull-out) have been identified as an accurate and straightforward assessment method of connection shear performance to predict the behaviour of sheathed CFS frame assemblies, while also recording complex failure mechanisms such as tilting, bearing and pull-through of the fixing [8,9]. Extensive research has explored fixing behaviour for CFS panels for a broad range of sheathing materials, including gypsum [10–12], cement-based boards

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(e.g. fibre cement boards, calcium silicate boards) [7,13,14] and timber bi-products (e.g. OSB/3, plywood, engineered bamboo panels) [15,16]. Typically, the dominant failure modes in connections between the sheathing and steel components result from the interactions between the fixings and the sheathing board, particularly around the screw-head area [17,18]. The mechanical properties of various sheathing materials [19] and for board thicknesses ranging between 9–15 mm [14,20], not only affect connection strength but also modify the failure mode. On the other hand, parameters like steel stud thickness have been identified to have a negligible effect on the strength of the connection [7,15]. However, the fixing geometry (i.e. threaded diameter) has long been recognised as a critical factor influencing the connection resistance and stiffness of the panel, varying with the type of sheathing material used [21,22]. Additionally, the ratio of the pitch of the thread to the thickness of the steel stud can increase the pull-out resistance of the connection [23] and, potentially, affect its failure mode. Moreover, the testing arrangement employed is crucial in the determining fixing performance, with setups such as single-lap shear tests [21,24,25] and parallel stud arrangements [8,12,15,26] providing results (i.e. shear strength, ductility) that are affected by the edge distance and sheathing material properties. A more detailed discussion is provided in Section 3.1.

The findings indicated above suggest that connection performance is influenced by a wide range of parameters, including the mechanical properties of the sheathing under tension ($f_{b,t}$) and compression ($f_{b,c}$), the thickness of the sheathing board (t_b), fastener diameter (d_f), thickness of the steel profile (t_s) and fixing edge distance (d_e). However, the extent of their influence has not been thoroughly discussed in literature. More specifically, the fixing geometry and its characteristics are not addressed beyond properties such as nominal threaded diameter and pitch. The presence of wings attached to the tip of the fixing, which normally allow for ease of assembly by enlarging the drilled hole, have not been determined as either beneficial or negative to the performance of the fixing.

This paper presents an extensive experimental study to investigate the shear behaviour of board-to-CFS screwed connections, with the aim of providing a reliable testing methodology for fixings in sheathed CFS framing. The key parameters such as the sheathing material, fixing diameter, the presence of wings, and the influence of varying loading conditions were investigated for a total of 39 test specimens. Mechanical tests were carried out for both sheathing materials and the cold-formed steel studs to obtain the properties of the employed components under tension and compression (the latter for the boards only). The influence of component variations is compared through the recorded experimental results and their effect on strength, stiffness and ductility, offering practical design considerations for screw diameter limits to optimise connection geometry for optimal performance.

2. Materials tests

2.1. Methodology

Material testing was performed on both sheathing and steel materials. For the steel materials, the specimens were extracted from lipped C-sections identical to those used for the push tests. Tensile coupon tests were carried out for both CFS and sheathing materials, with their geometries obtained from ISO 6892-1:2019 [27] and Kyprianou et al. [11] respectively. The steel specimens had their coating removed from the gauge length of the coupons using a hydrochloric acid solution of 37% purity, allowing for the measurement of the virgin cross-sectional area at gauge length [28].

Similarly, compressive tests were conducted on the sheathing materials only, for specimens similar to those proposed in [29], to allow for a comparison of the results obtained through the push-out tests based on the mechanical properties of the components consisting the specimens. All tests were conducted using an electro-mechanical 100 kN Instron 68FM-100 universal testing machine (UTM) under displacement control. Force recordings were extracted directly from the UTM using the Bluehill data acquisition software at a recording frequency of 10 Hz [30]. The geometries of tested specimens are illustrated in Figs. 1 and 2. The mechanical properties for fixings made of AISI C1022 were not included in these materials tests; instead, properties were adopted from the manufacturer's data-sheet.

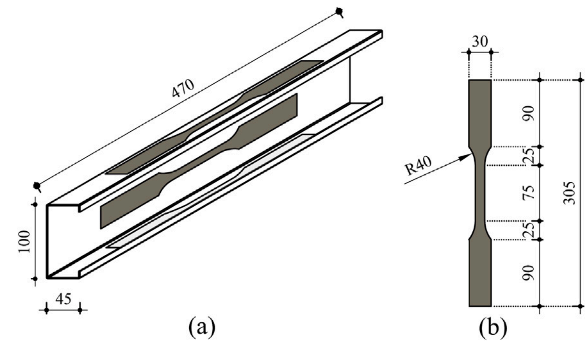

Fig. 1. Cold-formed steel coupon specimens: (a) areas of coupon extraction, (b) coupon dimensions (unit - mm) [27].

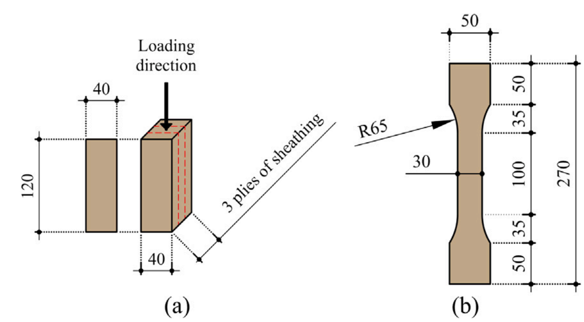

Fig. 2. Sheathing materials testing: (a) compressive coupon [29], (b) tensile coupon [11] (unit - mm).

Table 1
Cold-formed steel properties.

	E (GPa)	$f_{y,o}$ (MPa)	f_u (MPa)	ε_f (%)
Average	192.7	408.2	508.4	20.4
CoV	0.01	0.04	0.01	0.14

The applied loading protocol for a total of 6 CFS coupons was derived from [28], for a displacement controlled test employing three different loading steps, with 3 min load holds applied at each of them. A constant displacement rate of 0.4 mm/min was applied throughout the test. Meanwhile, the load rate for both types of sheathing materials and for both loading directions was kept at a rate of 0.1 mm/min, given the absence of any specific materials testing guidance for either CSB or FCB. Finally, strains were measured using a 50 mm knife-edged extensometer for all types of tensile coupons, with the strains on compressive coupons measured through two 25 mm strain gauges attached to the faces of the specimens.

2.2. Test results

Key material properties for the CFS tensile coupon specimens including Young's modulus (E), yield stress ($f_{y,o}$), tensile strength (f_u) and strain at fracture (ε_f) extracted from the static material response are presented in Table 1. A set of measured and static stress–strain curves, representative to the average values, is indicatively presented in Fig. 3.

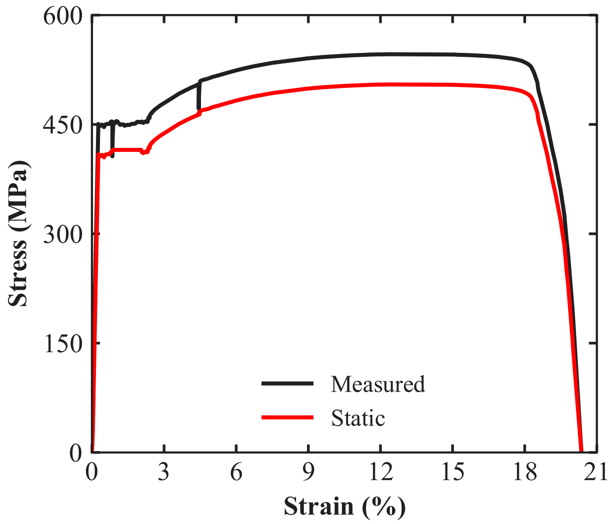

Fig. 3. Cold-formed steel stress–strain curves.

Table 2
Average values of the mechanical properties of sheathing materials.

Compression				
		E (GPa)	$f_{b,c}$ (MPa)	ε_c (%)
CSB	Average	10.0	36.9	0.40
	CoV	0.01	0.05	0.01
FCB	Average	9.0	26.0	0.38
	CoV	0.01	0.02	0.02
Tension				
		E (GPa)	$f_{b,t}$ (MPa)	ε_T (%)
CSB	Average	9.7	7.2	0.08
	CoV	0.02	0.02	0.03
FCB	Average	9.0	7.0	0.08
	CoV	0.03	0.11	0.10

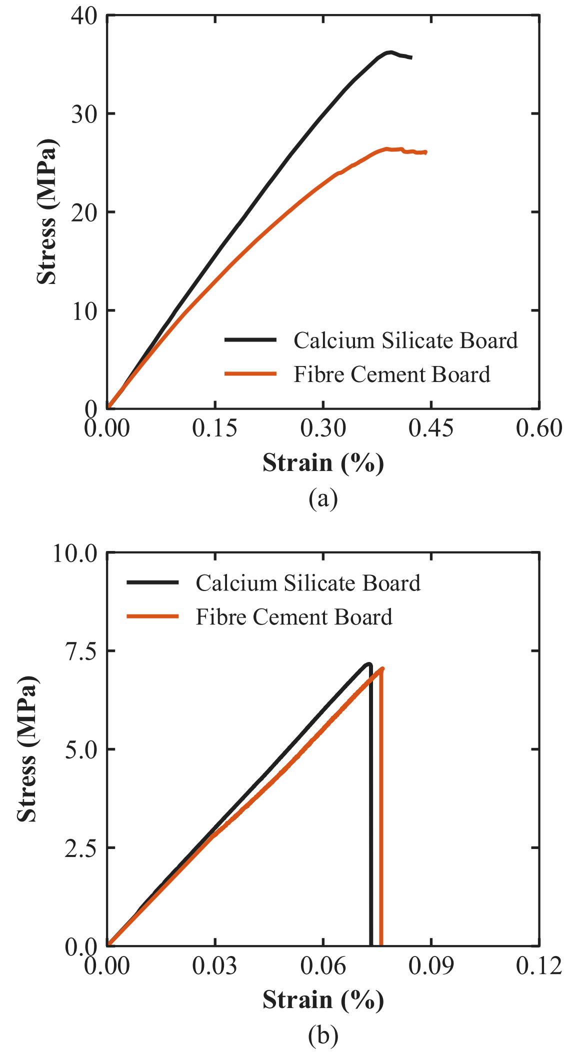

Fig. 4. Representative sheathing materials tests results under (a) Compression, and (b) Tension.

Both CSB and FCB sheathing materials exhibit brittle behaviour with an almost linear response observed until failure, except for FCB-C which is non-linear from an early loading stage. However, post-peak behaviour could not be recorded for specimens tested under compression due to strain gauge detachment from the board post-peak. Similar behaviour is observed for specimens tested under tension, with linear behaviour until ultimate strength, followed by a sudden load drop at cracking. Material properties including Young's modulus (E), peak strength for either tension ($f_{b,t}$) or compression ($f_{b,c}$), followed by their respective strains for tension (ε_t) and compression (ε_c), were extracted from the raw data obtained from the UTM. The average values of both tensile and compressive tests are provided in Table 2 and illustrated on Fig. 4.

3. Push-out tests

3.1. Existing testing methods

Testing standards developed to investigate the shear behaviour of connections for plasterboards fixed on timber [31] or for steel studs embedded in concrete slabs [32] have previously been adopted to research the shear behaviour in CFS framing connections. Fiorino et al. [7] and Macillo et al. [33] used a single-shear test setup in their study to investigate the shear behaviour of connections to the sheathing boards. The test setup they used was similar to the one proposed in [31], where the gypsum boards were fixed to two cold-formed steel studs instead of timber members that are pulled apart. Innella et al. [34] further reduced the specimen size by only using steel plates of identical thickness to the employed steel stud. Similarly, single lap shear tests were performed in [21,24,25] using sheathing boards attached to steel plates of identical thickness to that of a commonly used steel stud using a single screw. The parallel stud arrangement developed by Reynaud et al. [8] and modified by Schafer and Peterman [15], are adopted in [12,26] for a testing arrangement where the sheathing board is fixed on the flanges of two parallel CFS studs that are pulled apart by attaching their webs to the cross-head of the UTM. Furthermore, double stud arrangements were proposed in [6,11,20,35], replicating the method from [32] by creating a built-up I- section, attaching the sheathing boards with four screws on each side and with the load applied on the cross-section.

However, all tested arrangements discussed earlier present several challenges and limitations when accommodating different specimen configurations. Lap shear tests require the creation of adaptors to ensure that the shear plane remains on the board-steel interface, given differing thicknesses of the materials employed in the specimen. Furthermore, the parallel stud arrangement is suitable for specimens focusing on the effects of edge distance of the fixing head from the edge of the board. Thus, it will not record the full resistance of the connection. Finally, the built-up I- section setup requires increased assembly detail as the steel studs need to be fixed onto each other and ensure that their flanges remain aligned.

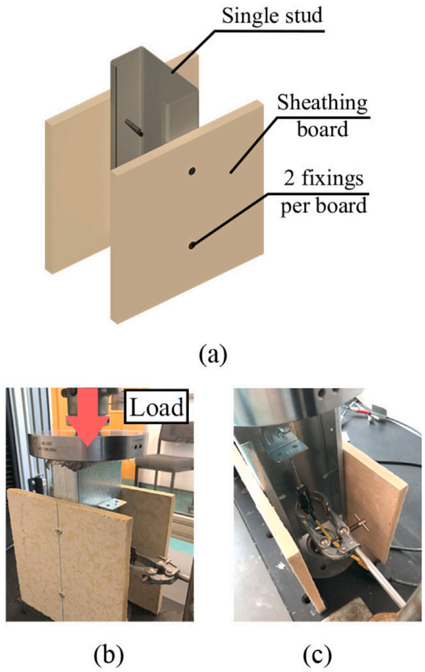

Fig. 5. Push-out test: (a) Specimens with a single stud, (b) Actual test setup, and (c) Position of Linear Variable Displacement Transducer (LVDT).

Table 3
Nominal geometrical properties of the materials employed in the push-out tests.

Material	Parameter	Dimension (mm)
Steel studs	Thickness	1.2
Sheathing	Thickness	12
Fixings	Threaded Diameter	4.2, 4.8, 5.5[a]

[a] Only winged fixings.

A test setup modified to overcome the above challenges and shortcomings was developed in this study (see Figs. 5 and 6). Specimens employing standard single C- profiles at a length of 230 mm were used for the push out tests. Two 200 mm square boards were employed for each specimen, attached to the flanges using two self-drilling screws on each side respectively. Both winged and non-winged fixings were used to record the influence of the hole clearance induced by the wingtip on connection performance. Nominal geometrical properties of the materials employed in the push-out tests are listed in Table 3, with those of the fixings illustrated through Fig. 7. However, it should be noted that neither the built-up I- section or single stud setup proposed herein can be employed against fully cyclic loading protocols [36], unless vertical restraints are provided [37].

A monotonic protocol based on [38,39] was employed for specimens with all fixing types and diameters, and for both sheathing materials. The protocol consisted of a load reversal in the 10% to 40% range of the expected peak load (F_p). Load holds were applied at both 10% and 40% limits for a period of 30 s. The second batch of specimens was tested under cyclic loading conditions. Although various protocols have been developed to investigate the cyclic behaviour of structures in seismic regions [36], no previous study has investigated the effect of repeated loads expected during the service life of a structure (e.g. wind gusts). The protocol proposed herein comprised of 10 cycles in the 10% to 40% range of F_p, assumed to be the serviceability range of the connection. Similarly to the monotonic protocol, load holds were applied at both the 10% and 40% limits based on the assumption that a typical wind gust lasts for 30 s [40] and loads the structure in up to 40% of its peak load. Displacement rates of the same magnitude as for the monotonic

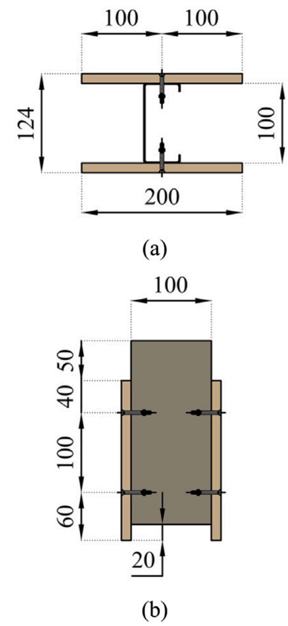

Fig. 6. Push-out test schematic: (a) Cross-section, (b) Side view (unit - mm).

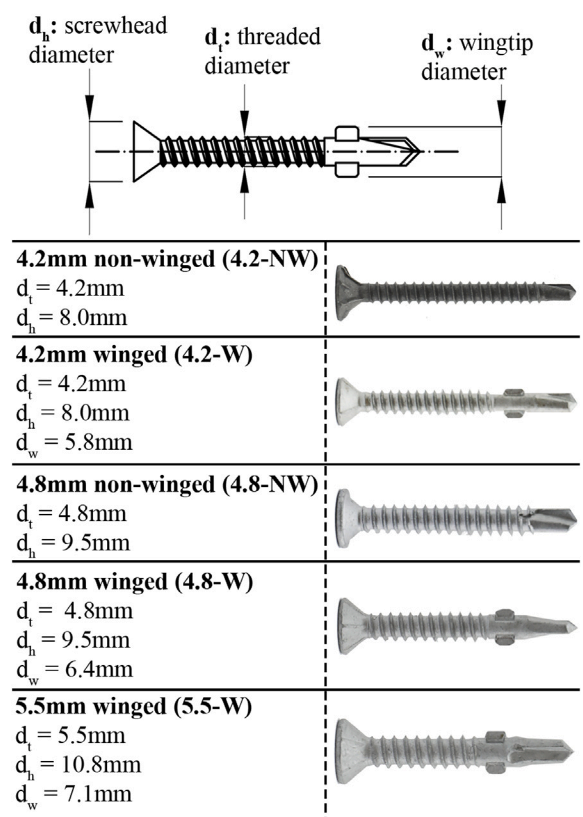

Fig. 7. Investigated fixings.

protocol were applied for each of the steps of the load-unload sequence at 1 mm/min and increase to 2 mm/min following the 10th cycle until failure. The monotonic and cyclic loading protocols are presented in Fig. 9. Two linear variable displacement transducers (LVDT) were employed to progressively record the displacement of the CFS stud, as shown in Fig. 5b. Specimen notation key is provided in Fig. 8.

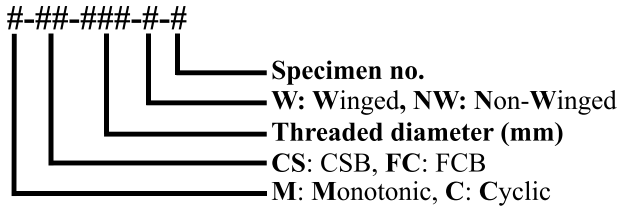

Fig. 8. Push-out specimen notation.

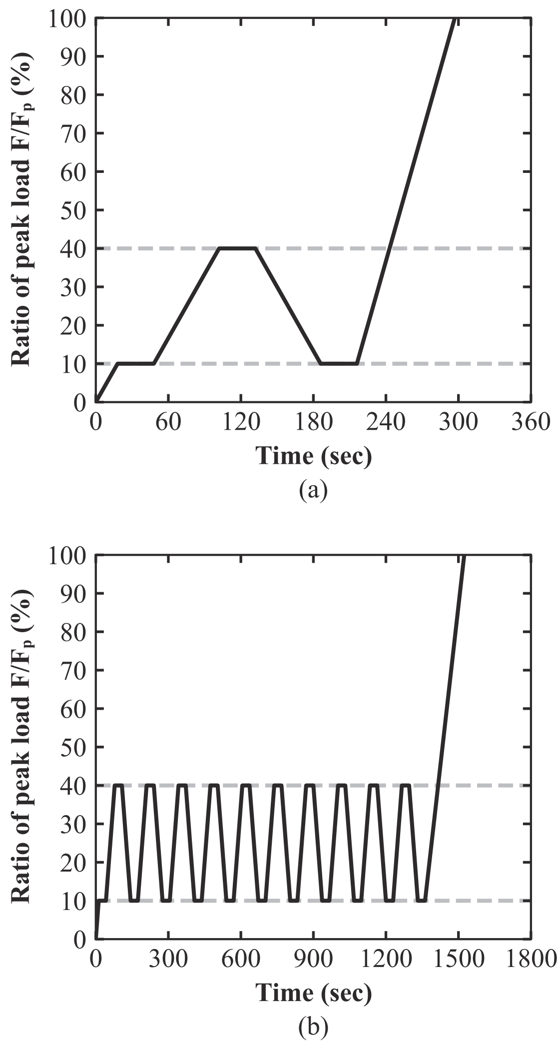

Fig. 9. Loading protocols: (a) Monotonic [38,39], (b) Cyclic.

3.2. Result interpretation

The force-slip response of the specimens was recorded by the UTM at a sampling frequency of 10 Hz for raw results in terms of total force (F_{tot}) and displacement (d). The total load was subsequently converted to load per fixing as $F = F_{tot}/n$, where F_{tot} is divided by the number of screws (n) corresponding to each push-out test, only for the screws connecting the boards to the CFS sections, excluding those connecting the C- profiles to each other to form the built-up I- section. This was done to reflect individual composite connection strength. Properties such as peak fixing resistance (F_p), displacement at peak load (d_p), and ultimate displacement (d_u) corresponding to the displacement at the 20% drop past peak strength (F_p) are reported. Stiffness (K) is provided based on two separate methods as listed below:

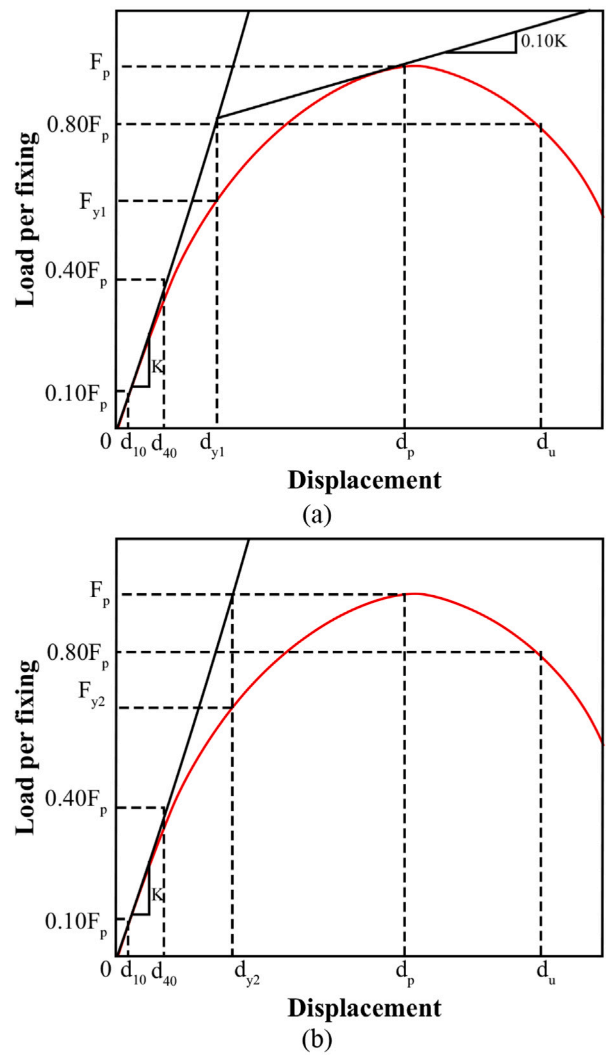

Fig. 10. Force–displacement curve parameters: yield displacement (d_{y1}) definition from [41] and (d_{y2}) from [42,43].

1. K_1: taken as the slope defined at 10% and 40% of peak fixing resistance before the first load reversal [14,38,41] $K_1 = F_{40}-F_{10}/d_{40}-d_{10}$, and
2. K_2: taken as the slope defined by the origin and the load and slip at 40% of peak fixing resistance [42] $K_2 = F_{40}/d_{40}$.

Additionally, the stiffness at the 10th load reversal is reported to discuss the effects of repeated loading conditions in fixing behaviour. The stiffness at the 10th cycle is defined as the ratio of the force and slip values at 40% peak fixing resistance (F_p) at the beginning of the 10th load hold over the same properties at 10% of F_p at the ascending branch of the force-slip response and before any load reversal. The estimation of the stiffness is based on the method from [41], illustrated through Fig. 11 and provided in Eq. (1).

$$K_{10} = \frac{F_{40} - F_{10}}{d_{40,C10} - d_{10}} \tag{1}$$

A range of methods for the estimation of ductility (μ) have been proposed in literature, with different methods used to extract the necessary values from the force-slip curve of the specimen and to calculate its value. Given the uncertainty in result interpretation but also to be able to provide a systematic comparison with results available in literature, the following four methods were assessed:

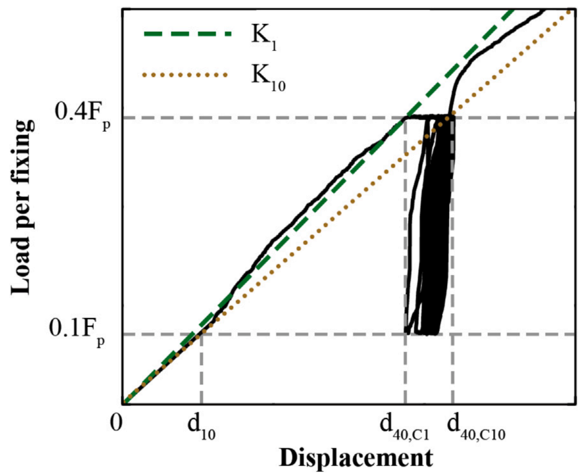

Fig. 11. Comparison between initial fixing stiffness (K_1) and after 10 repeat loading cycles(K_{10}).

1. μ_1: defined as the ratio of the ultimate displacement (d_u) over the yield displacement (d_{y1}), calculated as the point of intersection between the initial stiffness slope and a line crossing peak strength at a slope of 10% of the initial stiffness slope [41] (see Fig. 10a),
2. μ_2: defined as the ratio of the ultimate displacement (d_u) over the displacement at 40% of the peak fixing resistance (d_{40}) before the load reversal [14] (Note - d_{40} may also be referred as d_e in literature),
3. μ_3: defined as the ratio of the ultimate displacement (d_u) over yield displacement (d_{y2}), corresponding to that on the initial slope at the peak force (F_p) level [42] (see Fig. 10b), and
4. μ_4: ductility defined as the ratio of the displacement at peak strength (d_p) over the displacement at 40% of peak fixing resistance (d_{40}) before the load reversal.

4. Push-out test results

4.1. General observations

Specimen notation is provided in Fig. 8. Failure modes were consistent amongst the specimens, including tilting (T) of the fixings that bear (B) onto the board and result in board bulging, cracking, and fixing pull-through (PT). Localised board bulging followed by board delamination extending radially around the screw-head was observed for specimens of both sheathing materials (see Fig. 12a).

However, its extent varied with the increase of the screw-head diameter and the degree of thread engagement. Significant fixing pull-through was observed past ultimate displacement (d_u) and primarily for both types of 4.2 mm fixings and non-winged 4.8 mm fixings. Furthermore, the sequence of failure initiation differed between winged and non-winged fixings. Specimens with winged screws experienced tilting before contact with the board, given the increased distance of the threaded part from the board interface as a consequence of the hole enlargement caused by the wingtip. On the contrary, non-winged fixings were always in direct contact with the board, resulting in bearing failure before screw tilting. None of the specimens experienced steel deformation around the screw-hole on the inside of the flange of the channel section or on the fasteners (see Fig. 12b).

The statistical variation in the shear stiffness of the fixings, using either estimation method, is generally greater than the variation in their shear resistance. This is because the stiffness is more affected by any out-of-verticality and movement during the drilling process, causing hole enlargement on the board material. The characteristic shear

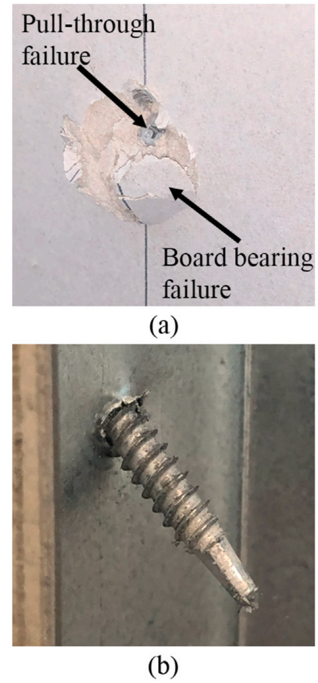

Fig. 12. Push-out test failure modes on the (a) board side, (b) steel side.

resistance of the fixings may be determined from normal statistical methods. However, the stiffness of the fixings is not an ultimate limit state parameter; as such, a wider statistical variation in the stiffness results is acceptable. Furthermore, when interpreting the stiffness of a large panel with multiple fixings, the response of the panel is dependent on the combined stiffness of many fixings. This suggests that the overall response is more dependent on the mean of the stiffnesses obtained from the push tests. A summary of the test results for specimens sheathed with CSB and FCB is provided through Table 4 and Table 5 respectively under monotonic loading conditions, and through Table 6 for cyclic loads. The force-displacement curves are provided in Figs. 13–15.

4.2. Effect of loading conditions

The effect of loading conditions on the force-slip behaviour is examined for a benchmark specimen employing 4.2 mm winged fixings for both types of sheathing materials. The cyclic protocol followed for this batch of specimens is illustrated in Fig. 9b. Ratcheting occurs on specimens with both types of sheathing, particularly in the first 5 cycles of the protocol, with its value stabilising afterwards (see Fig. 15). No effect was recorded on either connection stiffness or peak strength keeping similar values to those obtained for the specimens tested with the monotonic protocol. However, CSB specimens recorded significantly reduced displacement at peak load (d_p), ultimate displacement (d_u), and ductility (μ) with either metric, with their statistical variation being substantially increased. Meanwhile, FCB specimens kept similar values to those obtained through monotonic tests, remaining unaffected by repeated loading conditions in the elastic range of the connection. The results of the cyclic tests are provided in Tables 4 and 5, with Fig. 15 providing the force-slip response for both the CSB and FCB sheathed specimens. A comparison of key properties against their monotonic equivalents are provided through Tables 6 and 7 for specimens of both sheathings.

Table 4
Push out tests: results for CSB-sheathed specimens.

Specimen	F_p (kN)	d_p (mm)	d_u (mm)	K_1 (N/mm)	K_2 (N/mm)	μ_1 (–)	μ_2 (–)	μ_3 (–)	μ_4 (–)
M-CS-4.2-W-1	3.62	8.31	10.05	1312	1436	4.35	9.02	3.65	7.46
M-CS-4.2-W-2	4.24	9.04	10.83	1270	1346	3.71	10.05	3.24	8.39
M-CS-4.2-W-3	3.87	8.69	11.33	1209	1239	4.06	9.70	3.55	7.44
Average	3.91	8.68	10.74	1264	1340	4.04	9.59	3.48	7.76
CoV	0.08	0.04	0.06	0.04	0.07	0.08	0.05	0.06	0.07
M-CS-4.2-NW-1	4.42	8.87	12.98	1268	1295	4.16	10.51	3.72	7.18
M-CS-4.2-NW-2	4.17	7.85	13.44	1333	1453	4.78	15.18	4.30	8.86
M-CS-4.2-NW-3	4.19	9.53	14.11	1381	1442	5.66	13.48	4.65	9.10
Average	4.26	8.75	13.51	1327	1397	4.87	13.06	4.22	8.38
CoV	0.03	0.10	0.04	0.04	0.06	0.15	0.18	0.11	0.12
M-CS-4.8-W-1	3.61	7.78	12.20	1673	1752	7.38	13.46	5.66	8.58
M-CS-4.8-W-2	3.66	8.61	11.84	1543	1629	6.53	12.07	4.99	8.77
M-CS-4.8-W-3	3.74	7.28	11.31	1849	2032	7.29	14.39	5.60	9.27
Average	3.67	7.89	11.78	1688	1804	7.07	13.31	5.41	8.87
CoV	0.02	0.08	0.04	0.09	0.11	0.07	0.09	0.07	0.04
M-CS-4.8-NW-1	4.17	7.11	11.89	1914	1998	4.20	9.38	3.78	6.22
M-CS-4.8-NW-2	4.42	8.95	11.77	1827	1891	4.38	11.45	4.15	5.82
M-CS-4.8-NW-3	4.51	5.60	10.77	2139	2389	4.60	10.87	4.28	5.67
Average	4.37	7.22	11.48	1960	2093	4.39	10.57	4.07	5.90
CoV	0.04	0.23	0.05	0.08	0.13	0.04	0.10	0.06	0.05
M-CS-5.5-W-1	3.98	6.68	10.07	1493	1491	4.20	9.38	3.78	6.22
M-CS-5.5-W-2	4.00	5.91	11.61	1429	1539	4.38	11.45	4.15	11.61
M-CS-5.5-W-3	3.96	5.99	11.50	1476	1513	4.60	10.87	4.28	11.50
Average	3.98	6.19	11.06	1466	1514	4.39	10.57	4.07	11.06
CoV	0.01	0.07	0.08	0.02	0.02	0.04	0.10	0.06	0.08

Table 5
Push out tests: results for FCB-sheathed specimens.

Specimen	F_p (kN)	d_p (mm)	d_u (mm)	K_1 (N/mm)	K_2 (N/mm)	μ_1 (–)	μ_2 (–)	μ_3 (–)	μ_4 (–)
M-FC-4.2-W-1	2.88	8.21	11.34	697	703	2.85	6.80	2.74	4.93
M-FC-4.2-W-2	2.86	9.06	12.06	647	644	2.86	6.62	2.73	4.97
M-FC-4.2-W-3	2.78	6.35	11.25	793	808	3.26	7.59	3.20	4.28
Average	2.84	7.87	11.55	712	718	2.99	7.00	2.89	4.73
CoV	0.02	0.18	0.04	0.10	0.12	0.08	0.07	0.09	0.08
M-FC-4.2-NW-1	3.03	7.04	11.23	1253	1258	5.46	12.34	4.64	7.73
M-FC-4.2-NW-2	3.32	7.21	11.09	1205	1205	4.53	11.63	4.02	7.56
M-FC-4.2-NW-3	3.52	7.37	11.49	1244	1253	4.57	12.52	4.06	8.03
Average	3.29	7.21	11.27	1234	1239	4.86	12.16	4.24	7.78
CoV	0.07	0.02	0.02	0.02	0.02	0.11	0.04	0.08	0.03
M-FC-4.8-W-1	3.05	7.22	9.17	1065	1065	3.57	6.51	3.20	5.13
M-FC-4.8-W-2	3.11	6.73	11.08	1011	1037	3.84	7.66	3.60	4.65
M-FC-4.8-W-3	2.91	6.78	11.55	1041	1041	4.54	8.17	4.13	4.79
Average	3.02	6.91	10.60	1039	1048	3.98	7.45	3.64	4.86
CoV	0.03	0.04	0.12	0.03	0.01	0.13	0.11	0.13	0.05
M-FC-4.8-NW-1	3.93	8.81	12.79	1532	1425	6.34	15.19	4.99	10.46
M-FC-4.8-NW-2	3.43	10.89	14.53	1210	1012	6.93	12.25	5.12	9.18
M-FC-4.8-NW-3	3.64	7.55	14.34	1554	1405	7.54	16.79	6.13	8.84
Average	3.67	9.08	13.89	1432	1281	6.93	14.74	5.41	9.49
CoV	0.07	0.19	0.07	0.13	0.18	0.09	0.16	0.11	0.09
M-FC-5.5-W-1	3.15	6.03	11.49	1093	1093	4.20	10.91	3.99	5.73
M-FC-5.5-W-2	3.40	6.40	10.31	946	946	2.91	8.13	2.87	5.05
M-FC-5.5-W-3	3.29	5.91	12.44	904	919	3.40	9.53	3.42	4.53
Average	3.28	6.12	11.41	981	986	3.51	9.52	3.43	5.10
CoV	0.04	0.04	0.09	0.10	0.09	0.19	0.15	0.16	0.12

4.3. Effect of fixing diameter

Specimens comprising of winged fasteners for the full range of diameters available in the market (i.e. 4.2, 4.8, 5.5 mm) were investigated, with three sets of experiments prepared with each sheathing material. Three specimens were prepared for each fixing and each sheathing material, totalling to 18 test. Those were performed under monotonic loads, since connection ratcheting is minimal for both types of sheathing boards, as identified in the previous section.

Stiffness measurements with both K_1 and K_2 methods provide similar trends for connections with both types of sheathing, with K_1 providing slightly more conservative values than K_2. Connection stiffness gradually increases with the increase in fixing diameter. However, no significant effect is observed past 4.8 mm for specimens of both sheathing types, with 5.5 mm fixings having an almost equal stiffness with 4.2 mm and 4.8 mm winged fixings for CSB and FCB specimens respectively.

Average peak strength (F_p) remains similar for all fixing diameters on connections with CSB boards. On the other hand, all FCB specimens maintain a linear upward trend, with F_p increasing by 6% and 16% for 4.8 mm and 5.5 mm fixings respectively, as it can be observed from Fig. 18. However, displacement at peak load (d_p) is inversely proportional

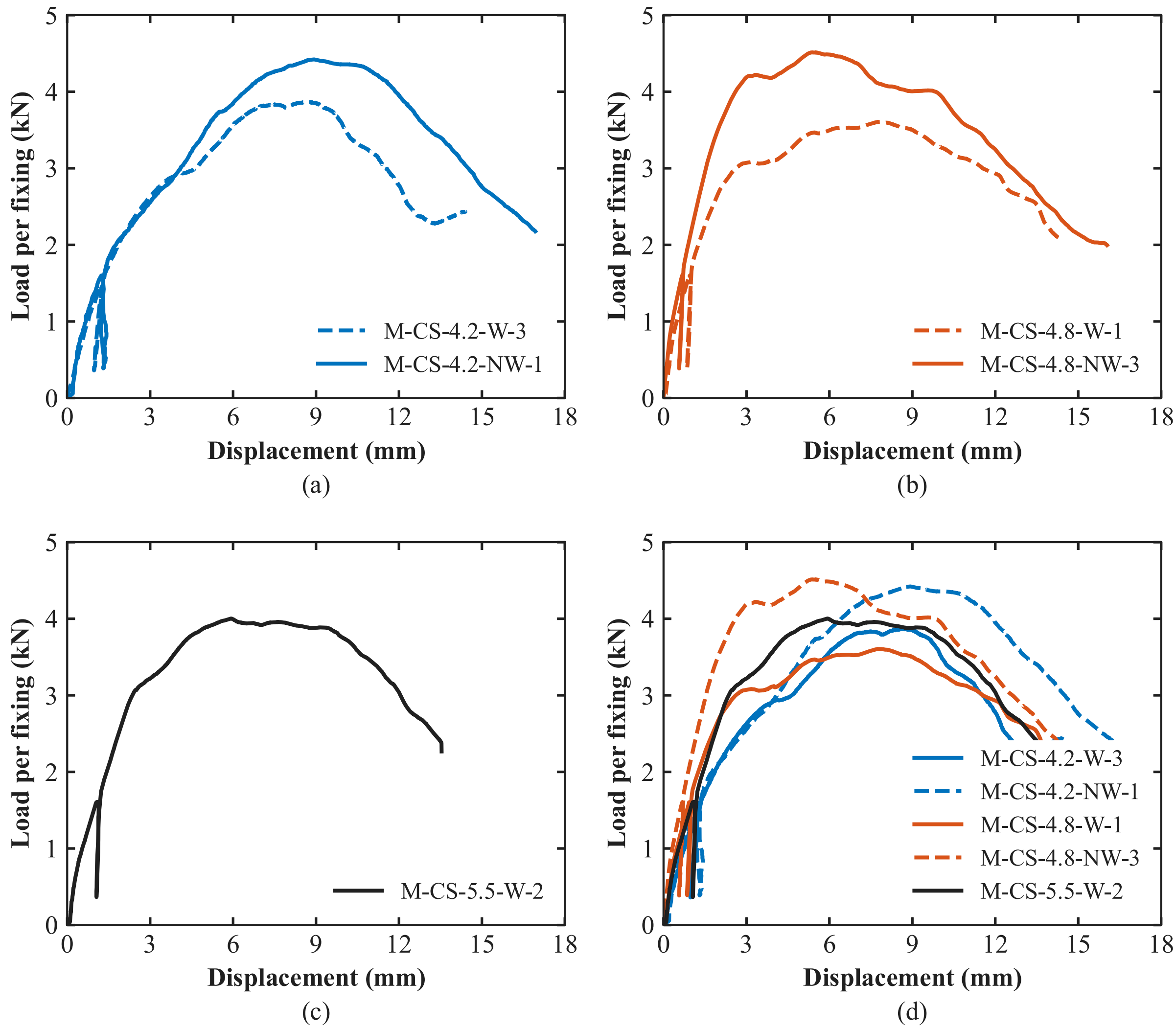

Fig. 13. Representative push-out test results for Calcium Silicate Board (CSB) sheathed specimens under monotonic loads with: (a) 4.2 mm winged (W) and non-winged(NW), (b) 4.8 mm winged (W) and non-winged(NW), (c) 5.5 mm winged (W), (d) comparison of all fixing types.

Table 6
Push out tests: results for specimens subjected to repeated loading conditions.

Specimen	F_p (kN)	d_p (mm)	d_u (mm)	$K_{1,C}$ (N/mm)	$K_{2,C}$ (N/mm)	$K_{10,C}$ (N/mm)	μ_1 (–)	μ_2 (–)	μ_3 (–)	μ_4 (–)
C-CS-4.2-W-1	4.16	6.70	8.67	1621	1547	1320	3.81	9.25	3.38	7.14
C-CS-4.2-W-2	3.97	7.71	11.02	1375	1325	750	4.34	10.14	3.82	7.09
C-CS-4.2-W-3	4.19	6.44	8.07	1349	1243	1112	2.73	6.93	2.60	5.48
Average	4.11	6.93	9.25	1449	1372	1061	3.63	8.77	3.05	6.24
CoV	0.03	0.10	0.17	0.10	0.11	0.27	0.23	0.19	0.19	0.14
C-FC-4.2-W-1	2.96	7.86	11.41	799	775	659	3.97	5.20	3.08	5.20
C-FC-4.2-W-2	2.60	7.77	12.10	662	670	551	3.82	4.45	3.07	4.45
C-FC-4.2-W-3	3.00	9.10	11.49	777	777	675	4.09	6.03	2.98	6.03
Average	2.85	8.26	11.67	746	741	628	3.96	5.23	3.04	5.22
CoV	0.08	0.09	0.03	0.10	0.08	0.11	0.03	0.15	0.02	0.15

Table 7
Effect of repeated loading conditions on 4.2mm winged fixings.

Cyclic vs Monotonic	$\frac{F_{p,C}}{F_{p,M}}$	$\frac{d_{p,C}}{d_{p,M}}$	$\frac{d_{u,C}}{d_{u,M}}$	$\frac{K_{1,C}}{K_{1,M}}$	$\frac{K_{2,C}}{K_{2,M}}$	$\frac{K_{10,C}}{K_{1,C}}$	$\frac{\mu_{1,C}}{\mu_{1,M}}$	$\frac{\mu_{2,C}}{\mu_{2,M}}$	$\frac{\mu_{3,C}}{\mu_{3,M}}$	$\frac{\mu_{4,C}}{\mu_{4,M}}$
CSB	1.05	0.81	0.87	1.06	0.96	0.73	0.82	0.87	0.88	0.30
FCB	1.00	1.05	1.01	1.05	1.03	0.84	1.33	0.75	1.05	1.11

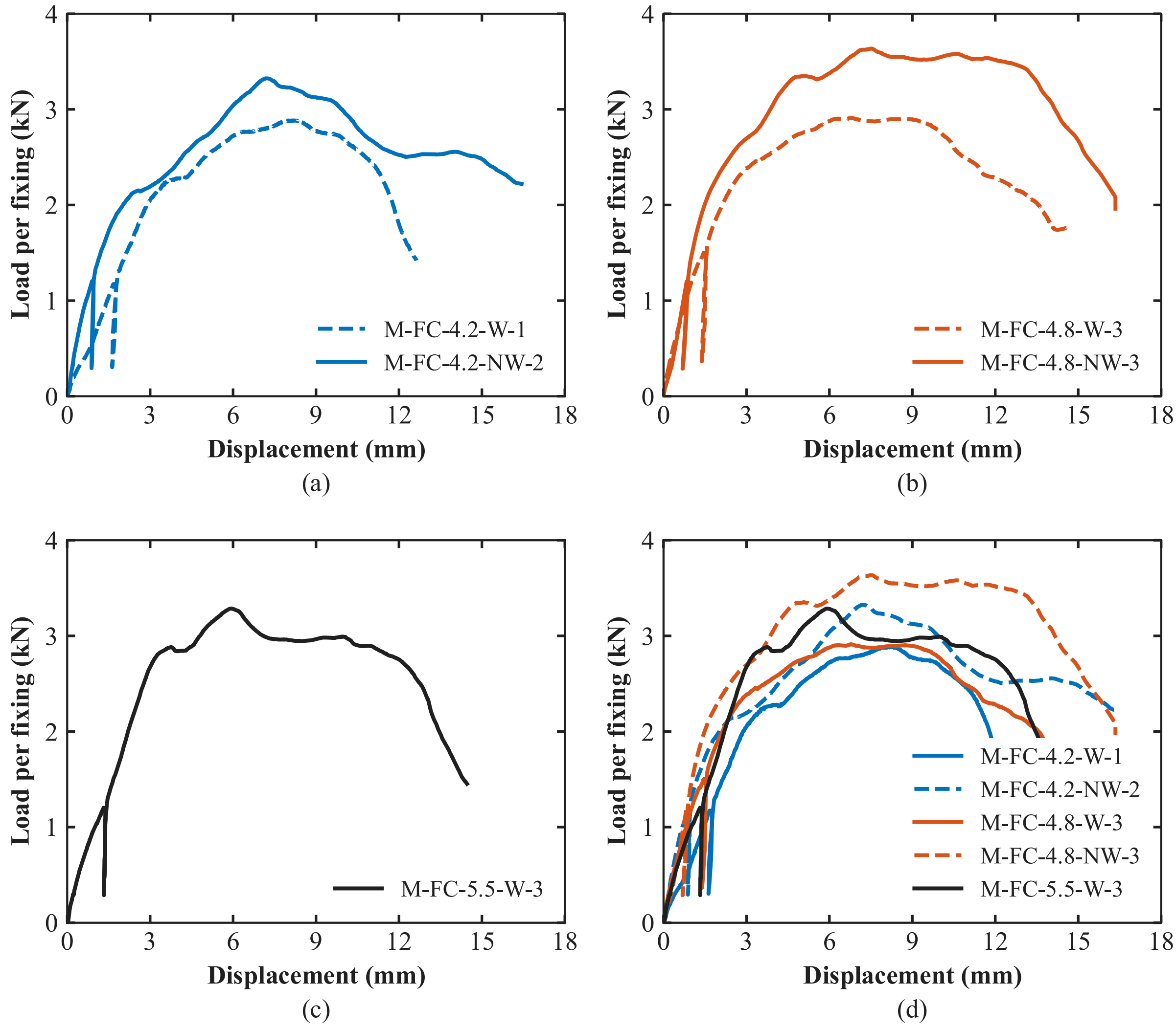

Fig. 14. Representative push-out test results for Fibre Cement Board (FCB) sheathed specimens under monotonic loads with: (a) 4.2 mm winged (W) and non-winged(NW), (b) 4.8 mm winged (W) and non-winged(NW), (c) 5.5 mm winged (W), (d) comparison of all fixing types.

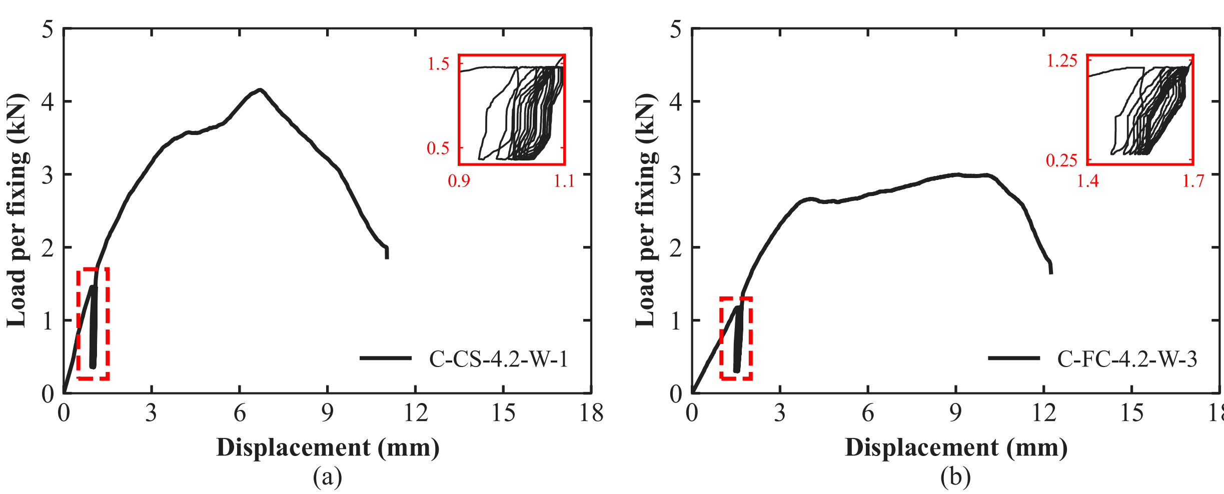

Fig. 15. Representative push-out tests results for specimens with 4.2 mm winged (W) fixings, subjected to cyclic loads: (a) CSB, (b) FCB.

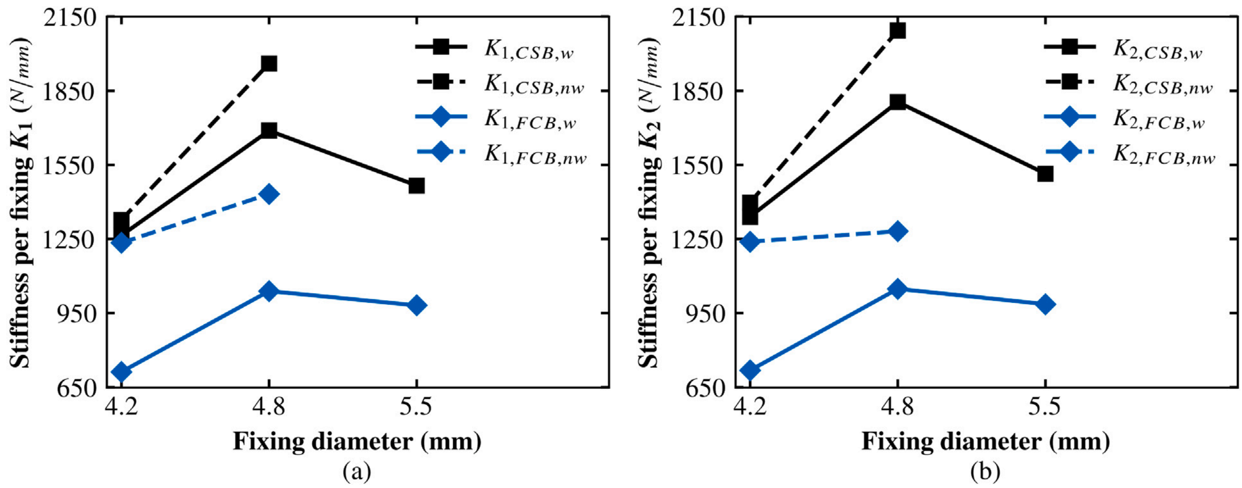

Fig. 16. Stiffness (K) comparison using: (a) K_1 method [14,41], (b) K_2 method [42].

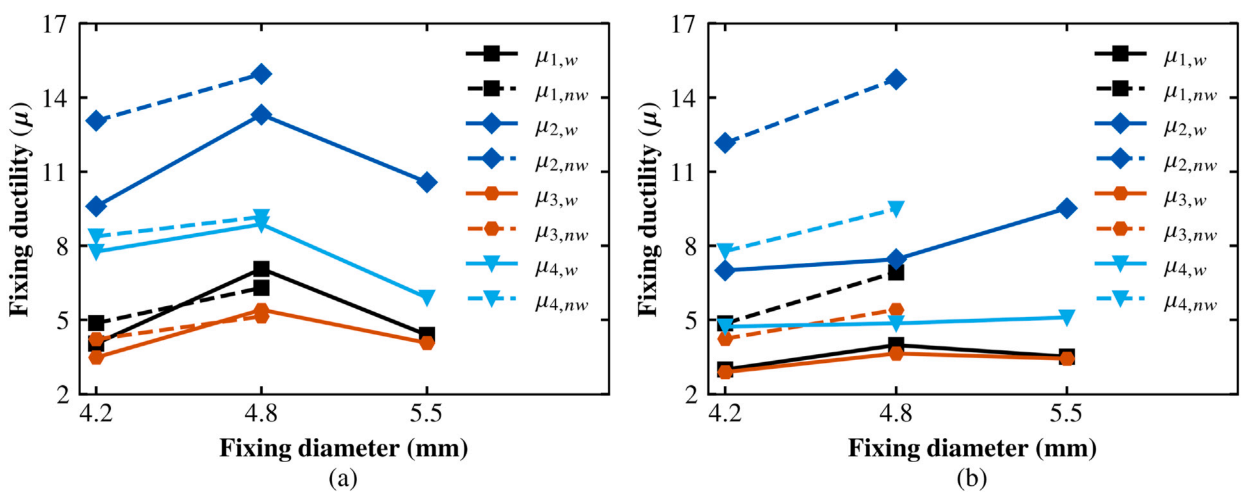

Fig. 17. Ductility (μ) comparison amongst (a) CSB specimens, and (b) FCB specimens.

to the increase in fixing diameter, with its value incrementally decreasing by almost 1 mm for both CSB and FCB sheathed specimens (see Fig. 19a). However, ultimate displacement (d_u) remains almost unchanged across all three diameters and for both types of sheathing, with some variations observed on connections with 4.8 mm fixings.

As discussed in the previous sections, four different ways to measure ductility are employed for evaluation of the methods but also to provide the ability to compare with experimental results found in literature. All four ductility metrics provide the same trend for CSB sheathed specimens, comprising of an increase from 4.2 mm to 4.8 mm fixings, followed by a sharp drop for 5.5 mm fixings to almost the same level as for the 4.2 mm ones. On the other hand, ductility on FCB specimens remains seemingly unaffected for either diameter according to μ_1, μ_3 and μ_4, with only μ_2 showing an upward trend from 4.2 mm to 5.5 mm fixings (see Table 8).

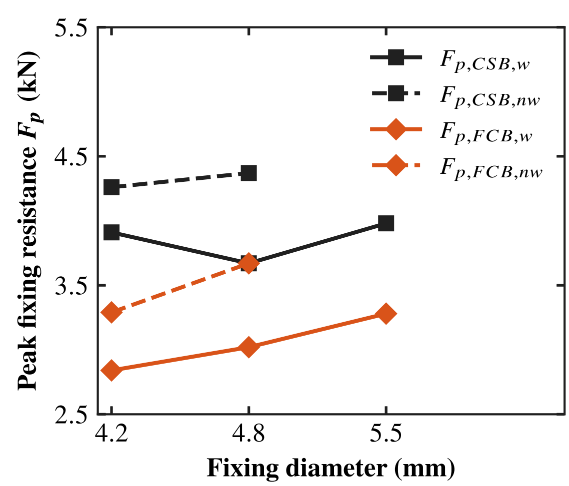

Fig. 18. Effect of fixing type and diameter on peak fixing resistance (F_p).

4.4. Effect of fixing type

The absence of wings at the tip of the fixings significant influences all key connection properties through enhanced screw engagement with the board material. The results reveal that peak connection load F_p increases substantially for both 4.2 mm and 4.8 mm fixings, with increments of 9% and 11% respectively over their winged equivalents for CSB sheathed specimens. Additionally, K_1 and K_2 show improvements of at least 5%. Meanwhile, displacement at peak load (d_p) appears consistent between 4.2 mm winged and non-winged fixings. Conversely, the same property is decreased by more than 9% for 4.8 mm non-winged fixings on CSB boards. Although d_u is noticeably higher for 4.2 mm non-winged fixings when compared to their winged

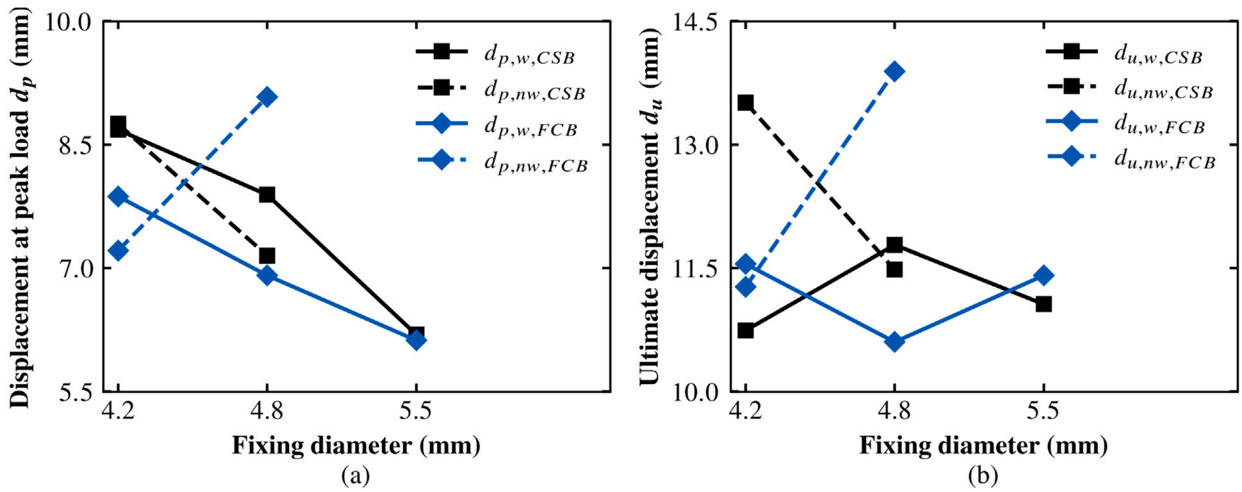

Fig. 19. Effect of fixing type and diameter on: (a) displacement at peak strength (d_p), (b) ultimate displacement (d_u).

Table 8
Comparison of test results on fixing behaviour.

Specimen	$\frac{F_p}{F_{p,4.2W}}$	$\frac{d_p}{d_{p,4.2W}}$	$\frac{d_u}{d_{u,4.2W}}$	$\frac{K_1}{K_{1,4.2W}}$	$\frac{K_2}{K_{2,4.2W}}$	$\frac{\mu_1}{\mu_{1,4.2W}}$	$\frac{\mu_2}{\mu_{2,4.2W}}$	$\frac{\mu_3}{\mu_{3,4.2W}}$	$\frac{\mu_4}{\mu_{4,4.2W}}$
M-CS-4.2-W	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M-CS-4.2-NW	1.09	1.01	1.26	1.05	1.04	1.21	1.36	1.21	1.08
M-CS-4.8-W	0.94	0.91	1.10	1.34	1.35	1.75	1.39	1.56	1.14
M-CS-4.8-NW	1.12	0.82	1.07	1.55	1.56	1.56	1.56	1.48	1.18
M-CS-5.5-W	1.02	0.71	1.03	1.16	1.13	1.09	1.10	1.17	0.76
M-FC-4.2-W	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M-FC-4.2-NW	1.16	0.91	0.98	1.73	1.72	1.62	1.74	1.47	1.65
M-FC-4.8-W	1.06	0.88	0.92	1.46	1.46	1.33	1.06	1.26	1.03
M-FC-4.8-NW	1.29	1.15	0.80	2.01	1.78	2.32	2.11	1.87	2.01
M-FC-5.5-W	1.15	0.78	0.99	1.38	1.37	1.17	1.36	1.19	1.08

Table 9
Effect of wings in fixing behaviour.

Material	Fixing diameter	$\frac{F_{p,NW}}{F_{p,W}}$	$\frac{d_{p,NW}}{d_{p,W}}$	$\frac{d_{u,NW}}{d_{u,W}}$	$\frac{K_{1,NW}}{K_{1,W}}$	$\frac{K_{2,NW}}{K_{2,W}}$	$\frac{\mu_{1,NW}}{\mu_{1,W}}$	$\frac{\mu_{2,NW}}{\mu_{2,W}}$	$\frac{\mu_{3,NW}}{\mu_{3,W}}$	$\frac{\mu_{4,NW}}{\mu_{4,W}}$
CSB	4.2 mm	1.09	1.01	1.26	1.05	1.04	1.21	1.36	1.21	1.08
	4.8 mm	1.19	0.91	1.03	1.16	1.16	0.89	1.12	0.95	1.03
FCB	4.2 mm	1.16	0.91	0.98	1.73	1.72	1.62	1.74	1.47	1.65
	4.8 mm	1.21	1.32	1.31	1.38	1.22	1.74	1.98	1.49	1.96

counterparts, both types of 4.8 mm fixings demonstrate similar. This similarity extends to their ductility, with matching values for winged and non-winged fixings, as methods μ_1 to μ_3 utilise d_u in the estimation of ductility (see Table 9).

The installation of non-winged fixings onto FCB sheathed specimens is more significant on connection performance across both fixing diameters. More specifically, non-winged fixings with a 4.2 mm diameter exhibit increases of almost 75% and 16% for K and F_p respectively, compared to their winged counterparts. Furthermore, all evaluated ductility indices (μ) indicate that connections involving non-winged fixings on FCB sheathed specimens are considerably more ductile. Meanwhile, parameters like d_p and d_u remain close to those recorded on 4.2 mm winged connections. Similarly, 4.8 mm non-winged screws demonstrate elevated stiffness, peak fixing resistance and ductility relative to their winged equivalent. Notably, Fig. 19 highlights this increase, where d_p and d_u are higher by at least 3 mm. Meanwhile, Fig. 17 proves that their ductility almost doubles against that of 4.8 mm winged fixings.

4.5. Effect of sheathing properties

Calcium silicate boards demonstrate enhanced stiffness and superior compressive strength than fibre cement, as detailed in Section 2. That is further evidenced in Table 10, and Figs. 16 and 18, which show that specimens sheathed with CSB consistently exhibit increased stiffness (K) and higher peak loads (F_p) across all types of fixings and diameters when compared to their FCB counterparts. Additionally, CSB specimens display significantly higher ductility (μ) with either metric. However, non-winged 4.8 mm connections with FCB boards can attain comparable peak load values to those obtained for 4.8 mm winged connections on CSB boards. Moreover, displacement at peak load (d_p) follows a decreasing trend in both FCB and CSB sheathed specimens with winged fixings. Meanwhile, non-winged fixings cause opposite effects d_p and d_u as both values progressively increase for FCB specimens with both fixing diameters. On the contrary, CSB specimens experience a substantial increase on d_u only for non-winged 4.2 mm diameters with the values of both d_u and d_p dropping below those of winged fixings for 4.8 mm diameter.

4.6. Effect of fixing type in construction practice

Based on the results presented earlier, non-winged fixings affect fixing behaviour to a higher degree when combined with softer sheathing materials (i.e. FCB) compared to harder sheathing boards (i.e. CSB). Moreover, the effect of non-winged fixings on the strength and ductility

Table 10
Effect of sheathing material on fixing behaviour.

Fixing type	$\frac{F_{p,CSB}}{F_{p,FCB}}$	$\frac{d_{p,CSB}}{d_{p,FCB}}$	$\frac{d_{u,CSB}}{d_{u,FCB}}$	$\frac{K_{1,CSB}}{K_{1,FCB}}$	$\frac{K_{2,CSB}}{K_{2,FCB}}$	$\frac{\mu_{1,CSB}}{\mu_{1,FCB}}$	$\frac{\mu_{2,CSB}}{\mu_{2,FCB}}$	$\frac{\mu_{3,CSB}}{\mu_{3,FCB}}$	$\frac{\mu_{4,CSB}}{\mu_{4,FCB}}$
4.2-W	1.38	1.10	0.93	1.77	1.87	1.35	1.37	1.20	1.64
4.2-NW	1.29	1.21	1.20	1.08	1.13	1.00	1.07	1.00	1.08
4.8-W	1.21	1.14	1.11	1.63	1.72	1.77	1.78	1.49	1.83
4.8-NW	1.19	0.79	0.83	1.37	1.63	0.91	1.01	0.95	0.97
5.5-W	1.21	1.01	0.97	1.49	1.54	1.25	1.11	1.19	1.16
4.2-W (Cyclic)	1.44	0.85	0.80	1.79	1.74	0.84	1.59	1.00	0.44

Table 11
Comparison of test results on fixing behaviour.

Source	Test Setup	Fixing diameter (mm)	Fixing type	Board thickness (mm)	F_p (kN)	K (N/mm)
Plasterboard						
Kyprianou et al [11]	Double C-	5.5	non-winged	12.5	0.59	810
Ye et al [13]	Parallel studs	4.8	non-winged	12.5	0.81	293
Ye et al [21]	Single lap shear	4.8	non-winged	12.5	0.69	660
Calcium silicate						
Present study	Single C-	4.8	non-winged	12.0	4.37	1960
Ye et al [21]	Single lap shear	4.8	non-winged	12.0	1.91	1315
Fibre cement						
Present study	Single C-	4.2	non-winged	12.0	3.29	1234
Fiorino et al [7]	EN 520 [31]	4.2	non-winged	12.5	0.46	1570
Oriented Strand Boards						
Peterman et al [15]	Parallel studs	4.2	non-winged	11.1	2.17	1525
Henriques et al [25]	Single lap shear	4.8	non-winged	12.0	2.55	824

of CSB sheathed specimens almost diminishes at 4.8 mm threaded diameter. Meanwhile, FCB sheathed specimens record increases ranging from 50% to 100% in stiffness and ductility for both 4.2 mm and 4.8 mm threaded diameters. Hence, it is suggested that softer sheathing materials should be combined with non-winged fixings to harness the full potential of fixing performance while harder materials should primarily be used with winged fixings to avoid premature cracking.

4.7. Comparison against available experimental results

A series of experimental data available from literature are compiled in Table 11 for comparison purposes. Given the availability of results from differing test setups, only specimens with edge distances above 20 mm and under monotonic loading conditions were considered. The sheathing materials included in this comparison consisted of plasterboard (PL) and oriented strand boards (OSB) to cover the full range of readily available sheathing materials. Some results from literature for calcium silicate boards (CSB) and fibre cement boards (FCB) are listed to illustrate the effect of varying test setups. Properties such as peak resistance (F_p) and fixing stiffness (K) were compared for specimens with similar fixing types, nominal threaded diameter and board thickness as within the present study.

The majority of the available studies have used 4.8 mm non-winged fixings, with not much data available for either 4.2 mm and 5.5 mm fixings. Evidently, plasterboard is the weakest amongst the available sheathing materials, with fixing resistance below 1 kN and with varying recorded results for its stiffness. Oriented strand boards (OSB) demonstrate slightly higher resistance and stiffness, close to the results obtained for fibre-cement sheathed specimens in the present study. However, the reported values from [15,25] are still below those obtained for CSB sheathed specimens, either from the present study or literature [13,21].

Although the stiffness recorded in [7] for FCB sheathed specimens is almost 22% larger than that obtained within the present study, the resistance recorded is more than 85% lower. The same trend is observed for CSB sheathed specimens from [21] against the findings reported in this section. This comparison highlights the inability of parallel stud arrangements to fully capture the fixing behaviour as the specimen becomes prone to premature failure for edge distances below 25 mm.

5. Conclusions

Connection strength will always be the weakest point of a wall panel, given the complexity on the interaction of the sheathing, stud and fixing. This paper presents an extensive experimental programme to record the screw fixing behaviour for sheathed cold-formed steel panels, sheathed with either fibre-cement or calcium silicate boards. Parameters such as test setup, loading conditions, sheathing material, fixing type and diameter were addressed. The proposed test setup provides a highly controllable experimental methodology that is not sensitive to edge distance effects, capturing the full response of the fixings. The results obtained herein highlight the ability to obtain reliable results for key parameters such as stiffness (K), peak resistance (F_p) and ductility (μ), with coefficients of variation below 0.20. The experimental framework presented herein leads to the following conclusions:

- Both methods of estimating elastic connection stiffness yield almost identical results, with K_1 being more conservative than K_2. However, given the ease of extracting the values for a single point at 40% force and the fact the values of both methods are almost identical, it is suggested to prefer K_2 as it is based only on a single point from the force–displacement curve.
- Ductility trends are almost identical with all four methods, except for μ_2 in FCB sheathed specimens which observes an opposite trend on winged fixings. Methods μ_1 and μ_3 record identical trends across both types of fixings. However, they require a graphical estimation of the yield displacement. Meanwhile, method μ_4 follows the same trend on both materials and for both types of fixings, relying only on recorded data.
- Cyclic loading in the elastic range of the fixing has an insignificant effect on strength and stiffness for both CSB and FCB sheathed specimens. However, they result in a reduction of both d_p and d_u over 19% and 13% respectively on CSB sheathed specimens, while the FCB ones remain unaffected. Furthermore, ductility (μ_4) is decreased by 70% on CSB specimens while FCB specimens experience only 10% reduction.

- The absence of wings is not always beneficial in fixing behaviour. All 4.2 mm non-winged connections with either sheathing material experienced enhanced strength, stiffness and ductility compared with their winged equivalents. Meanwhile, only FCB specimens with 4.8 mm non-winged specimens experience an increase in their connection properties, with CSB specimens providing comparable values to those obtained for winged fixings.
- Increase in fixing diameter increases both strength and stiffness, with their ductility also increasing until 4.8 mm for winged screws. While, d_p is inversely proportional to the increase in diameter, d_u remains almost unaffected to that increase. Similarly, ductility illustrates a sharp drop past 4.8 mm for CSB connections, while it remains unaffected for FCB specimens.
- The absence of any significant effect past 4.8 mm threaded diameter can be observed in the results for winged and non-winged fixings. More specifically, CSB sheathed specimens record almost identical properties between winged and non-winged fixings at 4.8 mm, with the exception on the value for F_p. Meanwhile, FCB sheathed specimens observe a steady increase in all their properties for non-winged fixings of both diameters. Following the above and through the comparison between the two sheathing materials, it is highlighted that non-winged fixings will have a positive effect on softer sheathing materials (i.e. fibre-cement, plasterboard) and almost no effect on stiffer materials (i.e. calcium silicate).

CRediT authorship contribution statement

Nikolas Ringas: Writing – original draft, Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **R. Mark Lawson:** Writing – review & editing, Methodology, Conceptualization. **Dilum Fernando:** Writing – review & editing, Supervision, Resources. **Yuner Huang:** Writing – review & editing, Supervision, Resources, Project administration, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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