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Stiffness based design method for sheathed cold-formed steel members subjected to torsional buckling

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Abstract
The objective of this paper is to study the bracing effect of various sheathing boards in inhibiting the instability failure modes of cold-formed steel (CFS) studs in the wall panel construction. A development of accurate and robust sheathing braced design concepts for CFS wall panels will eliminate the need for additional steel bracing, thereby leading to efficient use of construction materials. The design method of American Iron and Steel Institute lacks in accurately predicting the design strength of the sheathed CFS wall panel. Therefore, the current investigation endeavors to fill the gap. A total of sixty-seven experiments were carried out with seven different sheathing board types and ten different CFS studs. The experiments were carried out using a newly devised test set-up that simulates the worst case failure mode of the sheathing board. The experimental results indicate that the strength, stiffness and failure modes of the sheathing boards vary depending on; (i) material properties and fiber composition of the sheathing boards; (ii) dimensions of the CFS stud. Based on the inferences (trend of sheathing stiffness and failure modes) from the test results, a new expression is formulated to determine the stiffness of the sheathing board on a function of the tensile modulus of the sheathing board and dimensions of the CFS stud. The validation study indicates that the new expression is accurate in terms of both statistical and design application.

1. Introduction

The key objective of a structural engineer is to use the materials efficiently in the design to arrive at the optimum dimension. As the construction industry deals with large varieties of materials and different types of structural components, it is necessary to carry out design optimization in every structural element to achieve the maximum structural economy. An approach that can lead to design optimization in light gage steel construction is to consider the use of sheathing board (external cover) as a structural component in sheathed CFS wall panel design. Previous research on CFS wall panels indicated that the sheathing board could increase the strength of the CFS wall stud tremendously by restraining the global instability (flexural torsional and lateral torsional buckling) of the CFS studs especially for the highly slender ones. However, the sheathing's bracing effect depends on the specification of the sheathing board (material property and thickness) and fastener connection spacing (center to center distance between the fastener

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connections - df) (Fig.1a). It should also be noted that the current CFS structural member design methods are overly conservative for the highly slender CFS structural members especially the Direct Strength Method (DSM) by American Iron and Steel Institute. Therefore, the consideration of sheathing board as a structural component in the design strength calculation would benefit the structural engineering community due to the increase in member strength by decreasing the global slenderness (reduced unbraced length) of the CFS stud resulting in an efficient design.

The structural contribution of the sheathing boards in the CFS wall panels is not widely considered in the design of CFS wall studs due to the non-availability of robust design specifications that considers the sheathing's bracing effect accurately. The sheathing stiffness requirements of EN (2006) and AS/NZS (2005) were not included in the present study as the calculation procedures are based on the steel profiled sheeting, which is typically used in roof purlins. The use of profiled steel sheeting in the present studies will result in excessive restraint than is required to prevent torsional buckling of the CFS stud. Though, there are other design procedures by AISI (2013) (based on sheathing stiffness and DSM approach) and AISI (2016) (all steel design) to consider the sheathing effect in the structural design of sheathed CFS wall studs, the previous investigations (Selvaraj and Madhavan 2018a, 2018b and 2018c) indicates that the design strength calculations by AISI (2013) and AISI (2016) are unconservative due to the incorrectly predicted failure modes. Particularly, the observation from the experimental investigation by (Selvaraj and Madhavan 2018a, 2018b) shows that the gypsum sheathing board can restrain the lateral torsional buckling of the CFS stud only when both the global and local slenderness of the CFS stud is higher than unity ($\lambda_e > 1$ and $\lambda_l > 1$). Whereas the design procedure by AISI (2013) predicted that the gypsum sheathing could arrest the LTB failure mode for all CFS studs irrespective of the slenderness and led to reach the next possible failure mode (LTB to local buckling or yielding). Further, the investigation by Selvaraj and Madhavan (2018b) revealed that the unreliable design prediction by the current provisions of AISI (2013) may be attributed to the fact that the expressions used to predict the actual sheathing stiffnesses (which quantifies the magnitude of sheathing bracing effect in terms of stiffness) were formulated based on the very limited experimental test results [carried out using only one type of CFS stud (C shaped stud with single dimension)] and implicitly recommended for all CFS members (various slenderness and various shapes) and all loading cases (axial compression and out-of-plane bending). Therefore, it is necessary to formulate a correct and robust design procedure for the consideration of the sheathing board's bracing effect in the structural strength of the CFS wall stud for the efficient use of construction materials.

Although the required bracing stiffness to arrest the LTB failure of CFS studs can be obtained from the Winter (1960 and 1970) and Yura (2001) approach, as per authors knowledge, no study was carried out to investigate the actual stiffness offered by sheathing fastener connection with respect to the CFS stud geometry. Therefore, the present investigation endeavors to determine (formulate an expression) the stiffness provided by the various types of sheathing boards against the worst-case failure mode of sheathing fastener connection. The objective is to develop a simple design approach for a sheathed CFS panels thereby an appropriate sheathing board type and thickness can be chosen by the designer to satisfy the bracing stiffness requirements. In addition, if the sheathing is designed to brace the torsional buckling of the highly slender CFS stud the need for additional steel braced can be eliminated thereby achieving the structural economy.

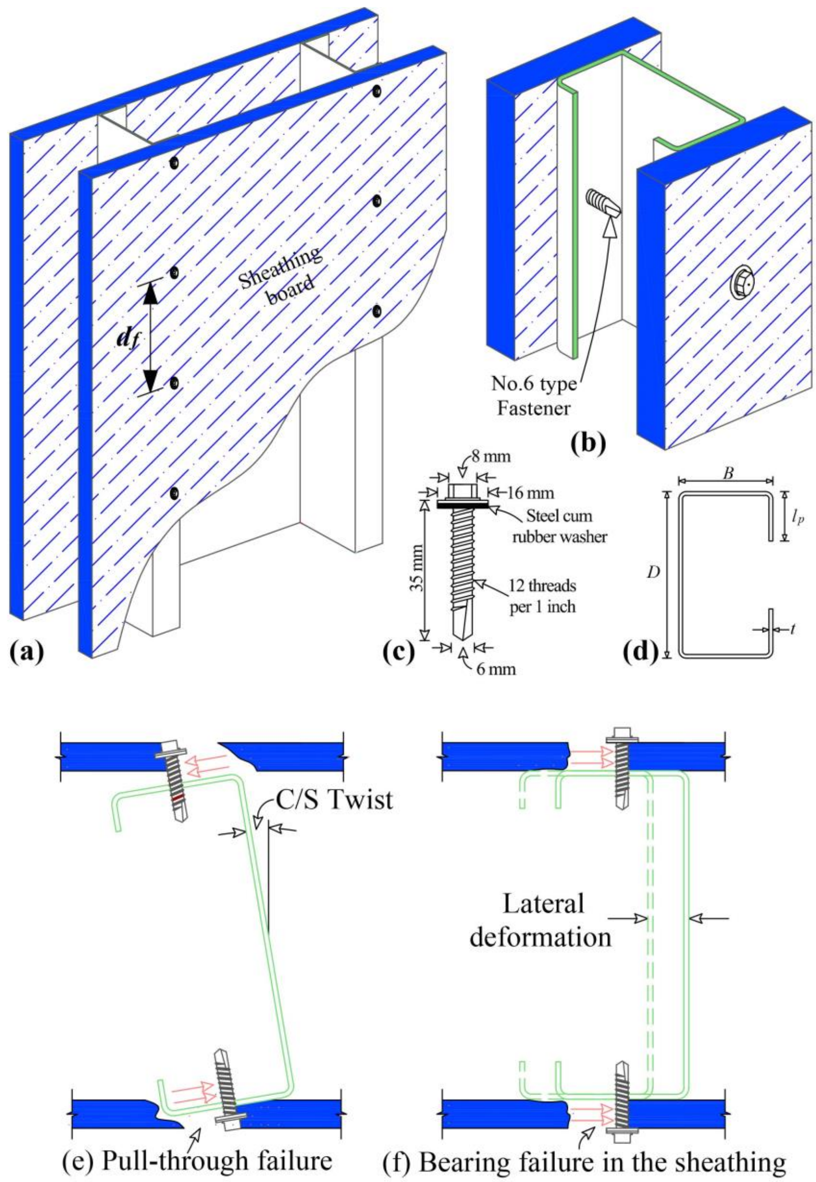

Figure 1. (a) Sheathing board in CFS wall panels; (b) Sheathing fastener connection; (c) Self-drilling fastener (No.6 Type) with steel cum rubber washer; (d) C shaped CFS stud (with notations); (e) Pull-through failure of self-drilling fastener at sheathing-fastener connections; (f) Bearing failure of sheathing at sheathing-fastener connections

2. Examination of the pull-through capacity of various sheathing boards

2.1 Test Parameters

This testing was carried out by a newly devised test setup proposed by Selvaraj and Madhavan (2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h, 2019i, 2020j, 2020k, 2020l and 2020m). A total of sixty-seven experiments were carried out including seven types of sheathing boards (Table 1) and ten different dimensions of CFS studs (Table 2) to determine the trend of sheathing stiffnesses. It should be noted that the various sheathing board types which are commonly used in the cold-formed steel construction are investigated in this work. To be specific, the sheathing boards were chosen based on the tensile modulus and material composition; both the stiff (plywood - fiber) and soft (gypsum board - fiberless) sheathing boards were tested. In addition to this, a combination of soft sheathing (gypsum) with a layer of steel sheeting is also used. The material specifications of the various sheathing boards and dimensions of the CFS studs are summarized in Tables 1 and 2, respectively.

Table 1. Specifications and Material property of the sheathing boards

Sheathing type		Thickness (t_b) (mm)	Tensile modulus* (E_s) (MPa)	Density (kg/m^3)	Material composition
Gypsum		12.5	2100	771.7	Gypsum slurry placed between two paper layers
Gypsum+LGSS	Gypsum	12.5	2100	771.7	The LGSS sheeting is attached as an external cover
	LGSS	0.45	215000	7850	
Particle Cement Board		8	2707	1250	Comprised of wood particle (28%) and cement (62%) mixture, where the cement plays a role of a bonding agent
		12			
Plywood		6	7983.3[a]	910-1100	Manufactured using layered wood veneers
			3701.2[b]		
		12	7983.3[a]		
			3701.2[b]		
Fiber cement board		12	6274.4	1355.8	Cellulose pulp fibers and cement

*obtained from the tensile test; [a] longitudinal direction; [b] transverse direction;
E_s - Tensile modulus of a sheathing board obtained from the tensile test

Table 2. Cross sectional dimensions and Material property CFS studs

Stud ID	d (mm)	b (mm)	t (mm)	Lip (l_p) (mm)	E (GPa)	f_y (MPa)	f_u (MPa)	ε_f
S1-50-60-U-1.5	50	60	1.5	-	202.7	378.3	442.8	18.2
S2-70-30-U-1.5	70	30	1.5	-	217.9	376.4	439.2	18.3
S3-70-37.5-18-1.5	70	37.5	1.5	18	202.7	378.3	442.8	18.2
S4-70-55-U-2	70	55	2	-	211.5	330	425	18
S5-80-30-25-2.5	80	30	2.5	25	214.8	329.6	417.3	18
S6-80-40-10-1.5	80	40	1.5	10	217.9	376.4	439.2	18.3
S7-80-50-25-1.5	80	50	1.5	25	212.2	377.4	440	16.1
S8-90-60-U-1.5	90	60	1.5	-	212.2	377.4	440	16.1
S9-100-55-U-1	100	55	1	-	221.3	330.1	425	18
S10-120-40-U-1	120	40	1	-	210.93	365.2	426.4	17.6

d - out-to-out depth of CFS stud; b - breadth of the CFS stud ; t - thickness of the CFS stud; l_p - depth of the lip in CFS stud;E - Young's modulus of steel; f_y - yield strength of steel; f_u - ultimate tensile strength; ε_f - strain at fracture

2.2 General trend in failure modes, stiffness and strength of sheathing fastener connections

The strength and stiffness response of the various sheathing boards and failure modes against the CFS stud rotation (displacement of two flanges in the opposite direction) are summarized in Table 3 and Figs. 2-7. In general, the experimental results indicate that the stiffness provided by the sheathing against the twist of the CFS stud primarily depends on the depth of the CFS stud (d) and material properties of the sheathing board [tensile modulus (Es), and fiber composition)]. More specifically, the resistance offered by the sheathing board with a fiber composition (plywood and fiber cement board) against the twist of the CFS stud is significantly higher than the sheathing boards made of particles (fiberless - cement board and gypsum board) as shown in Figs. 2a, 3(a-b), 4(a-b) and 6.

Table 3. Experimental results of a pull-through capacity of various sheathing boards

Stud ID	Fiber cement board (FCB) – 12 mm		Plywood – 12 mm		Plywood – 6 mm		Particle cement board (PCB) – 12 mm		Particle cement board (PCB) – 8 mm		Gypsum board 12.5 mm + LGSS 0.5 mm		Gypsum board 12.5 mm	
	k_p (N/mm)	F (N)	k_p (N/mm)	F (N)	k_p (N/mm)	F (N)	k_p (N/mm)	F (N)	k_p (N/mm)	F (N)	k_p (N/mm)	F (N)	k_p (N/mm)	F (N)
S1-50-60-U-1.5	239.95	1235.84	174.81	2108.06	117.64	1073.42	132.76	1229.6	118.93	812.95	88.40	580.16	56.42	318.9
S2-70-30-U-1.5	73.53	810.99	39.56	923.02	26.54	595.60	44.66	737.73	35.99	493.21	31.69	317.80	24.08	198.1
S3-70-37.5-18-1.5	65.39	786.96	74.26	1102.21	46.89	853.07	61.63	684.65	54.90	547.27	-	-	33.00	281.8
S4-70-55-U-2	106.03	833.87	104.84	1681.90	51.46	672.74	73.82	826.57	73.14	646.44	52.61	441.03	29.83	319.4
S5-80-30-25-2.5	64.16	600.11	71.69	1243.43	49.55	780.73	47.44	613.63	45.57	467.84	-	-	21.55	243.9
S6-80-40-10-1.5	42.54	495.12	50.53	1084.43	35.58	865.77	38.03	475.37	32.68	471.78	-	-	22.73	233.3
S7-80-50-25-1.5	63.08	868.77	69.94	1175.89	38.60	686.35	59.45	646.15	41.87	512.97	33.48	329.20	15.44	204.5
S8-90-60-U-1.5	49.10	1084.62	34.36	1521.61	30.32	597.65	34.81	643.00	32.31	336.98	14.30	301.29	8.69	236.1
S9-100-55-U-1	10.79	726.60	11.43	542.52	9.27	576.53	11.13	711.82	10.51	461.34	9.76	312.85	8.52	244.7
S10-120-40-U-1	6.80	458.23	8.28	529.64	5.56	299.60	5.28	414.72	4.80	405.67	6.85	187.57	4.51	149.0

In addition, to the resistance offered (strength and stiffness), the failure modes of sheathing fastener connection of fiberless sheathing boards are also unpredictable (sudden) and undesirable. It was observed that for fiber less sheathing boards (gypsum and PCB) with the same thickness and material properties, the failure mode of the sheathing fastener connections vary depending on the dimensions of the CFS stud [Figs. 4(c-j), 5 and 7(a-f)]. For example, in the failure modes of the sheathing fastener connections with sheathing boards made of particles (PCB and gypsum boards - no fiber), the experimental results showed an explicit variation between the CFS studs with lower and higher depth. The smaller depth CFS studs (S1-50-60-U-1.5) exhibited failure due to breakage of sheathing boards [Figs. 4(c-d), 5(a-b) and 7(a-b)] whereas, the deeper CFS studs (S6-80-40-10-1.5, S7-80-50-25-1.5 and S10-120-40-U-1) exhibited pull-through failure [Figs. 4(e j), 5(c-h) and 7(c-f)]. As mentioned previously, the variation in the sheathing fastener connection failure modes should be attributed to the lever arm (d/2) of the CFS stud which influences the magnitude of the rotation causing deformation at the sheathing fastener connection between the CFS stud and sheathing. However, this was not the case for sheathing boards with fiber content (plywood and fiber cement board) where the specimens exhibited a single failure mode [Figs. 2(b-i), 3(c-m)].

It was further observed that the increase in the thickness of the sheathing board by 1.5 or two times does not increase the strength and stiffness by the same amount, but will depend on the failure mode of the sheathing against the twist of the CFS stud. In particular, the thickness of PCB and plywood are varied in the present investigation. Figure 8 shows the variation in initial stiffness and strength for the same type of sheathing with increased thickness. The results indicate that the increase in the PCB sheathing board thickness from 8 mm to 12 mm (1.5 times) did not improve the strength and stiffness of the sheathing fastener connection by 1.5 times as shown in Figs. 8d and 8f. Similar behavior was observed in the sheathing fastener connection of plywood boards in which the thickness was doubled (6 mm to 12 mm) (Figs. 8a and 8c). It should be noted that the improvement in the sheathing stiffness after increasing the thickness is negligible (minimum – 1%, maximum – 42% and mean 13%) for PCB (Fig. 8e) and considerable for plywood sheathing (minimum – 13%, maximum – 104% and mean 51%) (Fig. 8b). However, both these sheathing boards response against the twist of the CFS stud cannot be treated in the same fashion, since there is a distinct change in the failure mode behavior of PCB and plywood sheathing. It should be noted that even after changing the thickness of the PCB sheathing board from 8 mm to 12 mm, the failure mode of the sheathing fastener connection remains same (pull-through) for a constant CFS stud as shown in Figs. 4-5. However, in the case of plywood sheathing, the failure mode of the sheathing fastener connection shifts from breakage of sheathing [Fig. 3(c-g) – 6 mm] to the withdrawal of fastener from the CFS stud [Fig. 3(h-m) – 12 mm]. Therefore, based on the test results the following can be ascertained: (i) Fiber less sheathing board (gypsum and PCB) should not be considered to offer resistance against the torsional buckling of the CFS stud (ii) the resistance offered by the plywood sheathing of 6 mm is sufficient to prevent the torsional buckling of the CFS stud or in other words the required bracing stiffness is attained by employing a plywood sheathing of 6 mm thereby no failure was observed in the plywood sheathing of 12 mm [Fig. 3(h-m)].

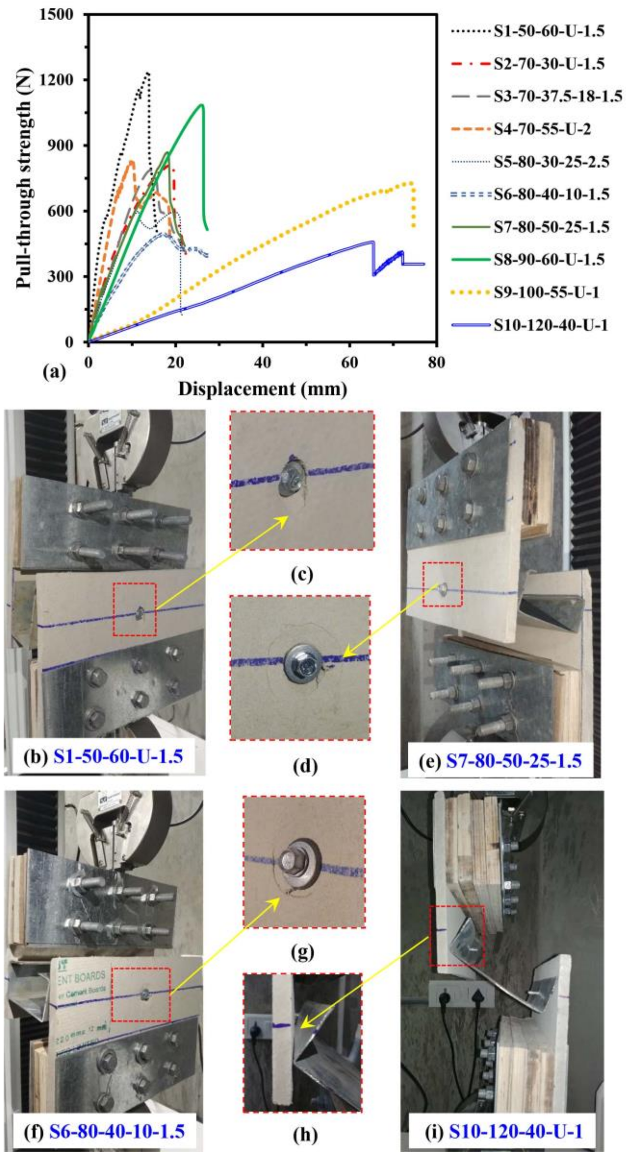

Figure 2. (a) Pull-through strength vs. displacement of response of fiber cement board (FCB) sheathing against the various CFS stud dimensions; Pull-through failure of FCB sheathing board against the various CFS studs (b-c) Stud ID – S1-50-60-U-1.5; (d-e) Stud ID – S7-80-50-25-1.5; (f-g) Stud ID – S6-80-40-10-1.5; (h-i) Stud ID – S10-120-40-U-1;

The above inferences are counterintuitive to the common design perception that the strength and stiffness of the bracing can be increased linearly by increasing the thickness [bearing area in the shearing direction – bearing stiffness (P/δ) depends of the area - (P/δ) = (AE/L)] of the sheathing board. This deviation of results from the common wisdom indicates that the pull through failures in the sheathing boards is catastrophic and requires a different design treatment compared to the shear and bearing design of sheathing boards. In addition, it should also be noted specifically that the presence of the LGSS sheet in the sheathing configuration (gypsum + LGSS sheet) significantly contributed to the initial stiffness magnitudes compared to the gypsum board for few CFS studs (S1-50-60-U-1.5, S4-70-55-U-2 and S7-80-50-25-1.5). However, it was observed during the experiments that the failure in the gypsum begins at the initial loading stage which led to a sudden breakage at the ultimate load. Such behavior of the gypsum + LGSS sheet sheathing configuration indicates that the additional provision of the LGSS may not be successful for resisting the twist of the CFS stud. Therefore, all these above sheathing stiffness trends and failure modes deviation from the conventional wisdom were considered fastidiously in the formation of the generalized sheathing stiffness predictor expression.

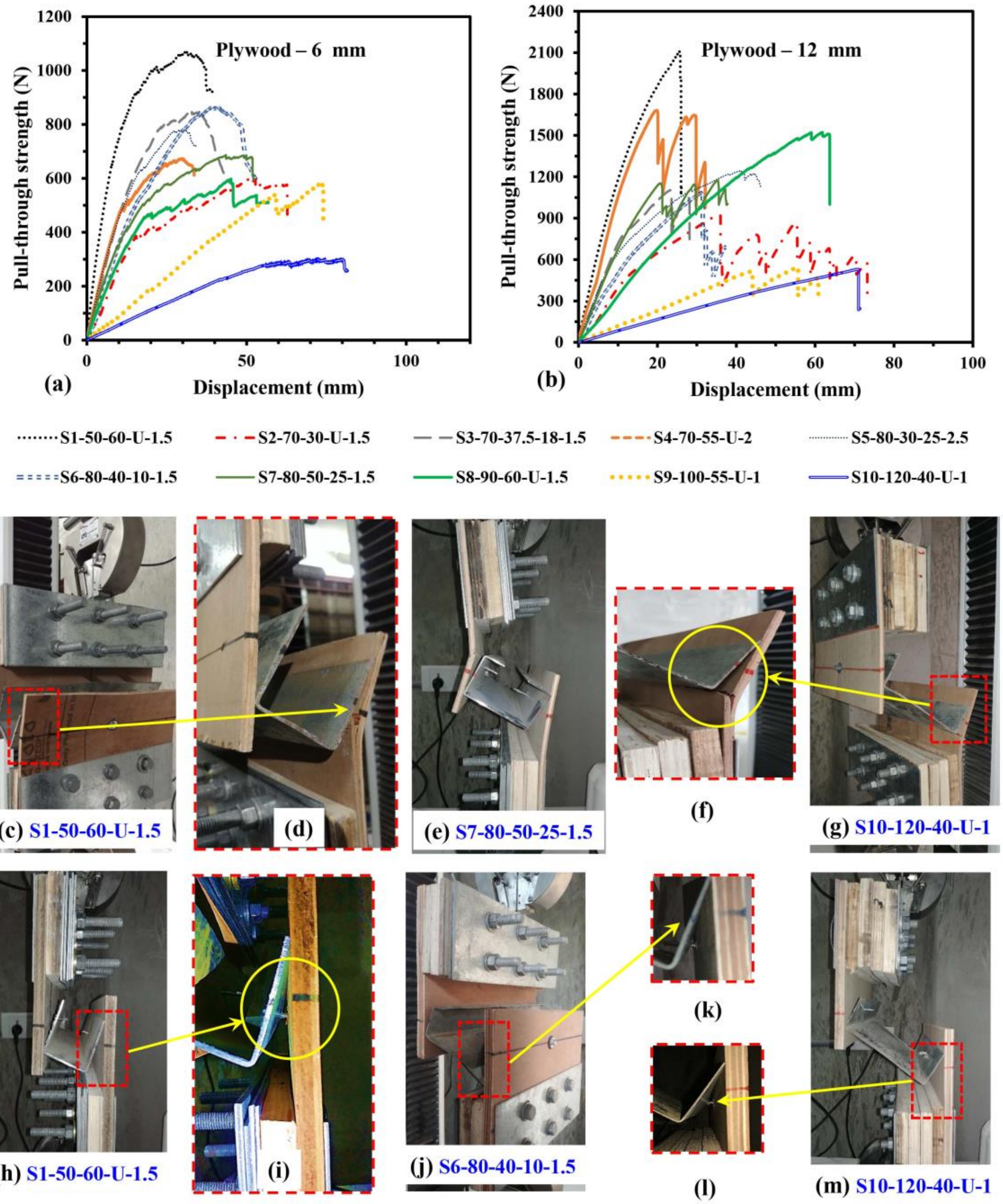

Figure 3. Pull-through strength vs. displacement of response plywood sheathing against the various CFS stud dimensions: (a) Plywood sheathing 6 mm thickness; (b) Plywood sheathing 12 mm thickness; (c-g) Failure modes of plywood (6 mm) sheathing board against the various CFS studs (shown in ascending order of depth of CFS stud) – failure mode is constant – Breakage of sheathing board; (h-m) Failure modes of plywood (12 mm) sheathing board against the various CFS studs (shown in ascending order of depth of CFS stud) – failure mode is common – Withdrawal of self-drilling fastener from CFS stud

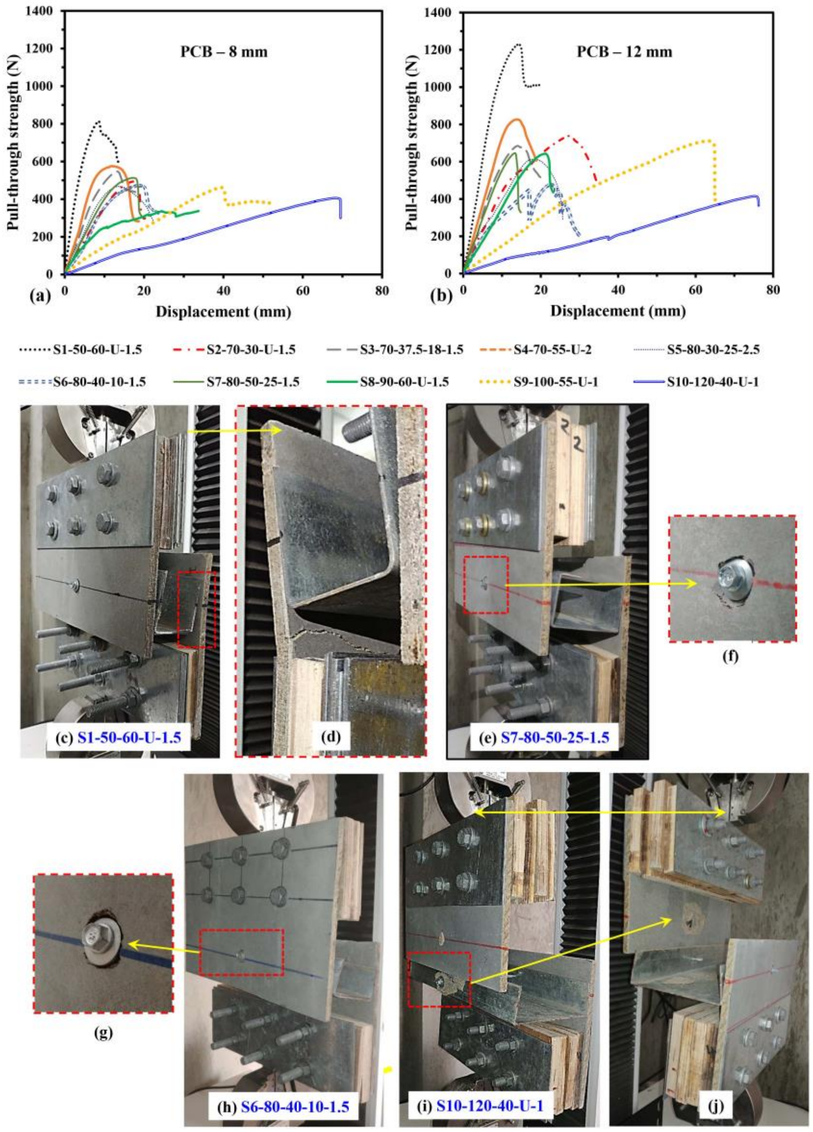

Figure 4. Pull-through strength vs. displacement of response particle cement board (PCB) sheathing against the various CFS stud dimensions: (a) PCB 8 mm; (b) PCB 12 mm; Failure modes of particle cement board (8 mm) sheathing board against the various CFS studs (shown in ascending order of depth of CFS stud) – failure mode is varying: (c-d) Breakage of FCB sheathing; (e-h) Pull-through of fastener; (i-j) Sudden pull-through of fastener

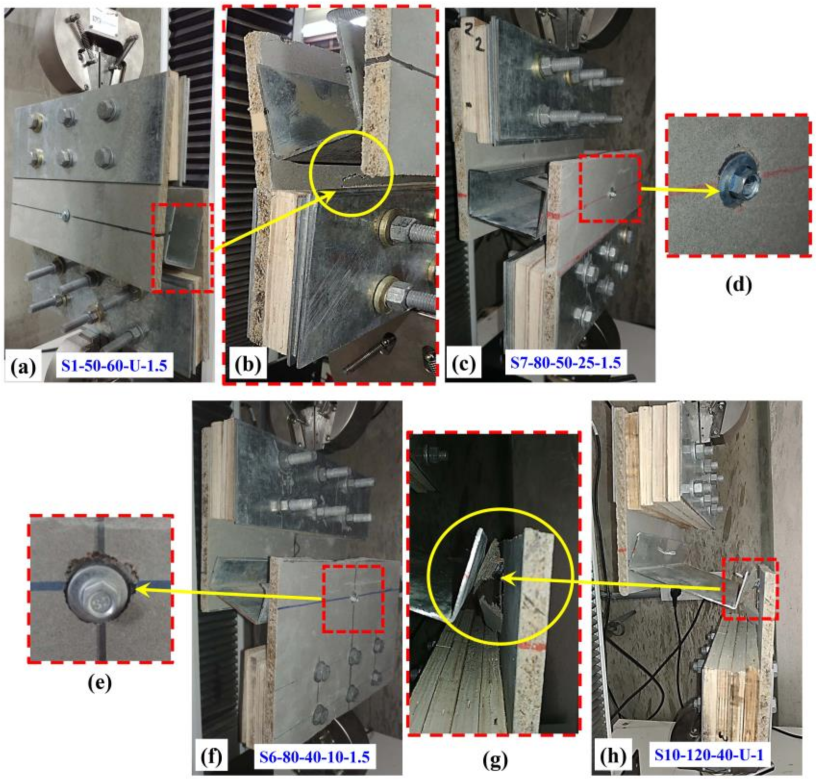

Figure 5. Failure modes of particle cement board (12 mm) sheathing board against the various CFS studs (shown in ascending order of depth of CFS stud) – failure mode is varying: (a-b) Breakage of FCB sheathing; (c-f) Pull-through of fastener; (g-h) Sudden pull-through of fastener

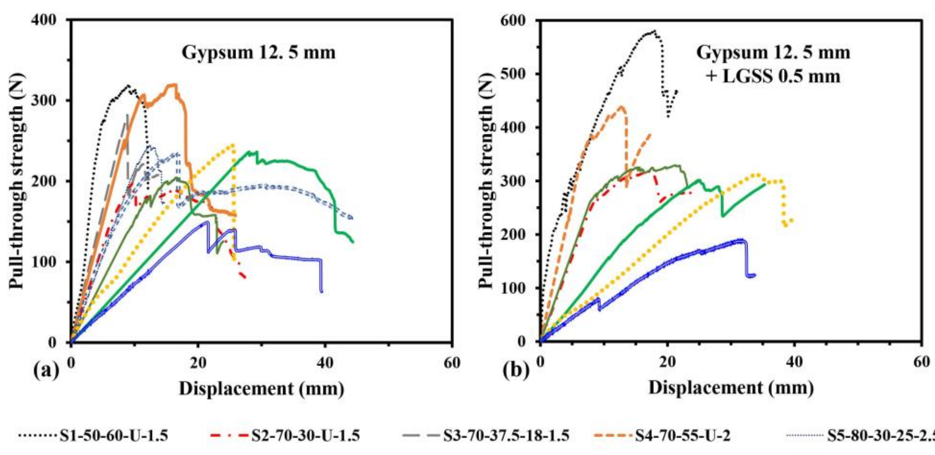

Figure 6. Pull-through strength vs. displacement of response gypsum board sheathing against the various CFS stud dimensions: (a) Gypsum 12.5 mm; (b) Gypsum 12.5 mm + LGSS – 0.5 mm (external addition)

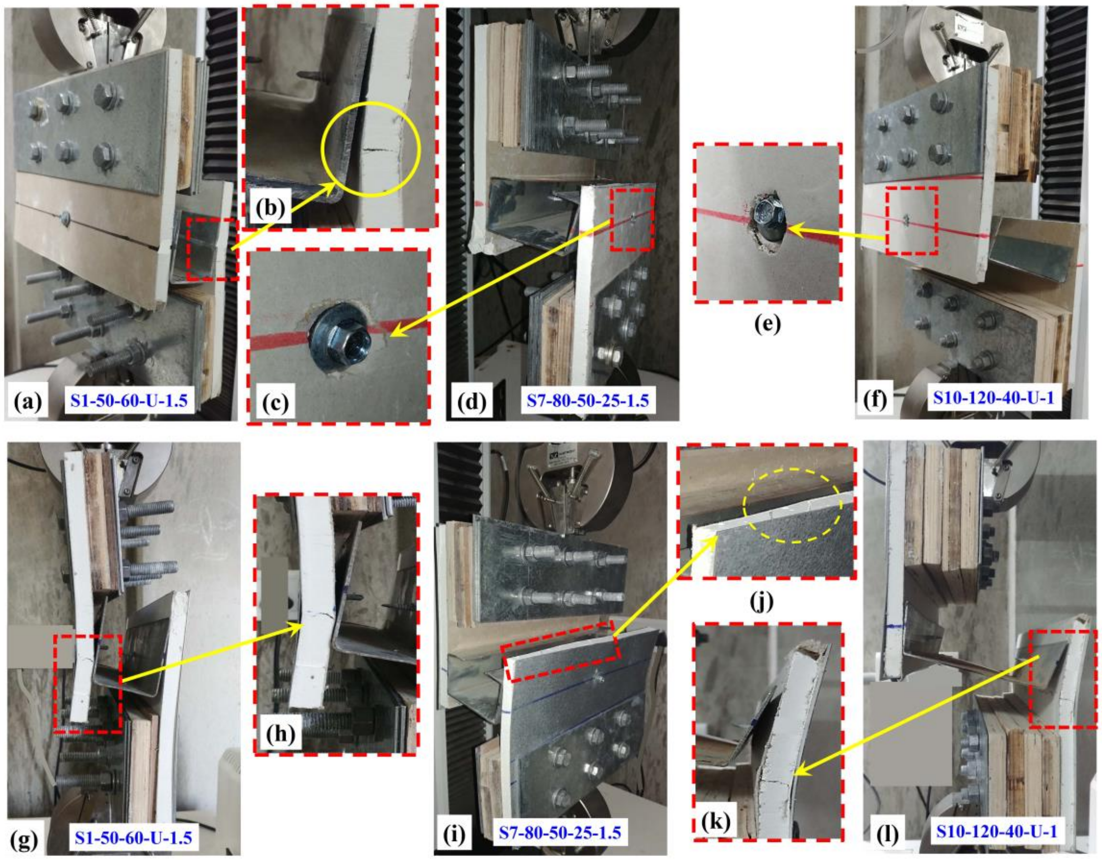

Figure 7. Failure modes of gypsum (12.5 mm) sheathing board against the various CFS studs (shown in ascending order of depth of CFS stud) – failure mode is varying: (a-b) Breakage of FCB sheathing; (c-f) Pull-through of fastener; (g-l) Failure modes of gypsum (12.5 mm) sheathing board + 0.5 mm LGSS external sheet against the various CFS studs (shown in ascending order of depth of CFS stud) – failure mode is constant – Breakage of gypsum board

3. Formulation of expression for sheathing stiffness prediction

The primary objective of this investigation is to formulate an accurate and robust expression for predicting the sheathing stiffness (k_p) for the design of a sheathed CFS wall panel. The robustness and accuracy in the predictor expression mean that it should accommodate all the design parameters of sheathed CFS wall panel (CFS stud dimensions, the material property of the sheathing boards) and it should also avoid undesirable or catastrophic failure modes of the sheathing fastener connections. Having determined the behavior of the sheathing fastener connection against the rotation of the CFS stud, the next step is to calculate the stiffness for each type of sheathing. Although there are other approaches to calculate the stiffness such as considering the slope of the load-displacement plot up to 40% of the load (Winter 1960), an alternate method is used here by considering the limit state of serviceability. As the design criteria for serviceability limits the deflection of the CFS stud under the elastic limit (L/384), the stiffness of the sheathing fastener connection is chosen as the initial stiffness of the load versus displacement curve [response of the sheathing board against the rotation of the CFS stud - Figs. 3(a-b), 4(a-b), and 10]. Similar calculation approach was followed by Vieira (2011) for lateral-translational sheathing stiffness formulation. The determined initial stiffnesses for the various sheathing boards are summarized in Table 3. As mentioned previously, the stiffness magnitudes of the sheathing boards show a trend with the depth of the CFS stud; (i.e.) the magnitude of initial stiffness reduces as the depth of the CFS stud increases. The variation in the magnitude of the sheathing stiffness (k_p) with respect to the depth of the CFS stud for different sheathing boards are shown in Fig. 9.

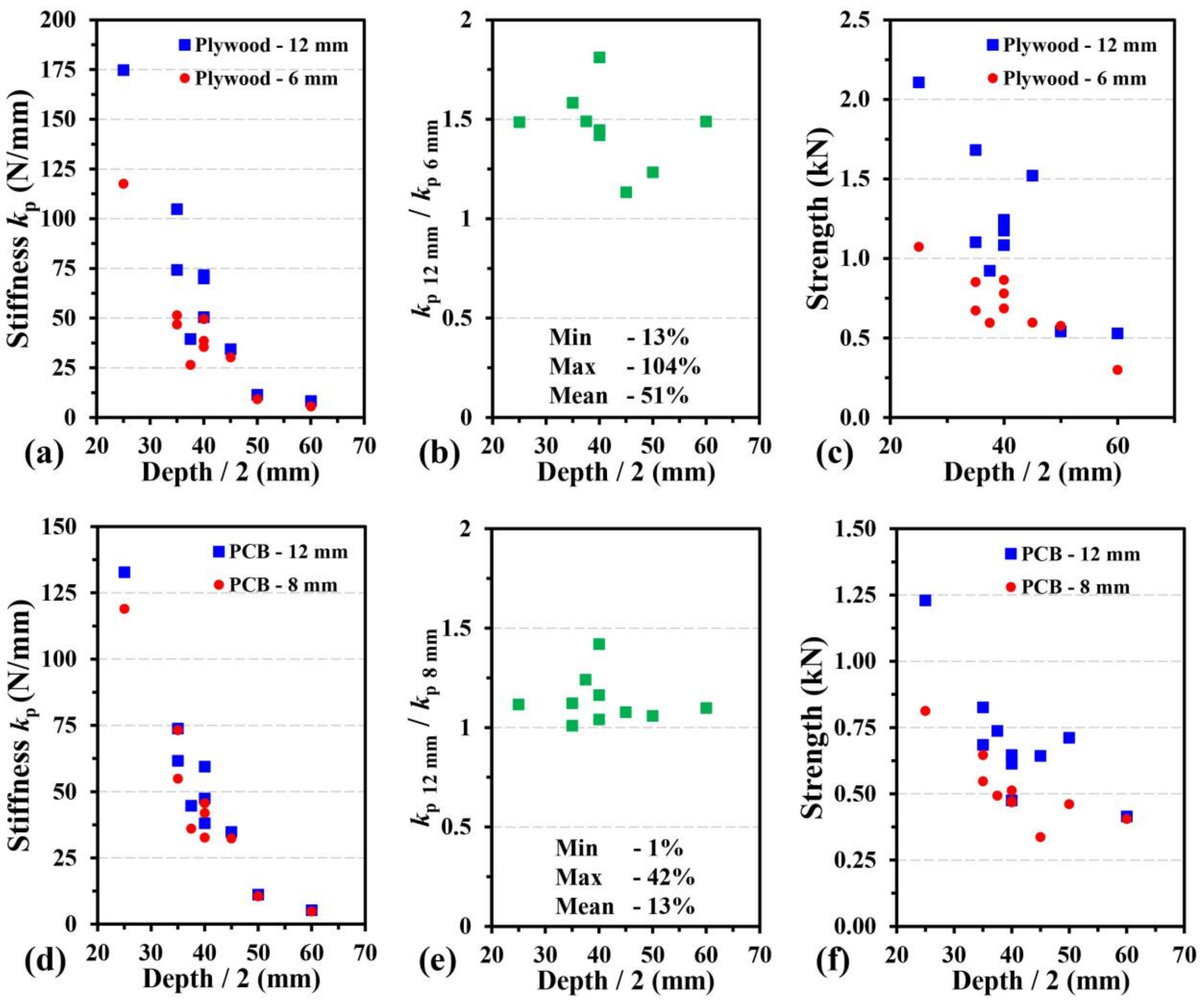

Figure 8. Investigation on effect of sheathing board thickness vs pull-through strength and stiffness

Table 4. Formulation of generalized expression sheathing stiffness prediction

Description	Fiber cement board – 12 mm	Plywood – 12 mm	Particle cement board – 12 mm	Particle cement board – 8 mm	Plywood – 6 mm	Gypsum board 12.5 mm + LGSS 0.5 mm	Gypsum board 12.5 mm
Step 1: Determine the stiffness curve for each sheathing board with respect to the geometric property of the CFS stud from Fig. 9.	$k_p = 3639.5e^{-0.106\left(\frac{D}{2}\right)}$ Eq. (1)	$k_p = 2197.7e^{-0.095\left(\frac{D}{2}\right)}$ Eq. (2)	$k_p = 1909e^{-0.096\left(\frac{D}{2}\right)}$ Eq. (3)	$k_p = 1614.3e^{-0.095\left(\frac{D}{2}\right)}$ Eq. (4)	$k_p = 1133.8e^{-0.088\left(\frac{D}{2}\right)}$ Eq. (5)	$k_p = 688.5e^{-0.08\left(\frac{D}{2}\right)}$ Eq. (6)	$k_p = 423.8e^{-0.078\left(\frac{D}{2}\right)}$ Eq. (7)
Step 2: Determination of trend of difference between sheathing stiffness magnitudes [highest stiffness magnitudes (FCB) to the corresponding stiffness magnitudes (others)] [Eq. (1) / Eq. (x)] x = 2 to 7	-	$\frac{Eq.(1)}{Eq.(2)} = 1.656e^{-0.011\left(\frac{D}{2}\right)}$ Eq. (8)	$\frac{Eq.(1)}{Eq.(3)} = 1.907e^{-0.01\left(\frac{D}{2}\right)}$ Eq. (9)	$\frac{Eq.(1)}{Eq.(4)} = 2.255e^{-0.011\left(\frac{D}{2}\right)}$ Eq. (10)	$\frac{Eq.(1)}{Eq.(5)} = 3.210e^{-0.018\left(\frac{D}{2}\right)}$ Eq. (11)	$\frac{Eq.(1)}{Eq.(6)} = 5.286e^{-0.026\left(\frac{D}{2}\right)}$ Eq. (12)	$\frac{Eq.(1)}{Eq.(7)} = 8.588e^{-0.028\left(\frac{D}{2}\right)}$ Eq. (13)
	Now the equations [Eqs. (8-13)] ascertained from the differences between the sheathing stiffness magnitudes of highest to the corresponding one can be directly used as a divider to the expression [Eq.(1)] which is the exponential trend of the highly stiff fiber cement board sheathing with respect to the d/2 to determine the stiffnesses of the other sheathing boards. For example the sheathing stiffness predictor expression for the plywood sheathing board of thickness 12 mm [Eq.(2)] is equal to [Eq.(1) / Eq.(8)] $k_{p(plywood)} = \frac{3639.5e^{-0.106\,(D/2)}}{1.656\,e^{-0.011(D/2)}}$ Eq. (14)						
Step 3: Process of making the sheathing stiffness predictor expression as a generalized one	To arrive at a generalized expression to evaluate the stiffness provided by sheathing boards, an empirical equation based on a curve fit of experimental data collated from 67 tests are formulated. This was carried out by replacing the numerical coefficient in the expressions [Eqs. (8-13)] using terms A and B that was formulated as a function of the ratio between tensile modulus of the highest sheathing to the other sheathing boards for which the sheathing stiffness is being determined. In addition, the constant in the expression [Eq. (1)] 3639.5 is equated to the ratio of $\left(\frac{E}{58.4}\right)$ to accommodate the material property of the CFS stud. Where *E* is the Young's modulus of a CFS stud material obtained from the tensile test.						
Step 4: Generalized form of the sheathing stiffness predictor expression	$k_p = \frac{(E/58.4)e^{-0.106\,(D/2)}}{A\left(\frac{6274.40}{E_s}\right)e^{(BD/2)}}$ Eq. (15) $A = 3112.4\,E_s^{-0.909}$ Eq. (16) $B = \frac{E_s}{142857.1} - 0.0437$ Eq. (17)						
Definition of the variables	k_p - Stiffness of the sheathing board against the pull-through failure (N/mm); d - out-to-out depth of the CFS stud (mm); *E* - Young's modulus of a CFS stud material obtained from the tensile test (MPa); E_s - Tensile modulus of a sheathing board obtained from the tensile test (MPa); A and B – Coefficients based on the sheathing board type respectively shown in Eq. (16) and Eq. (17).						

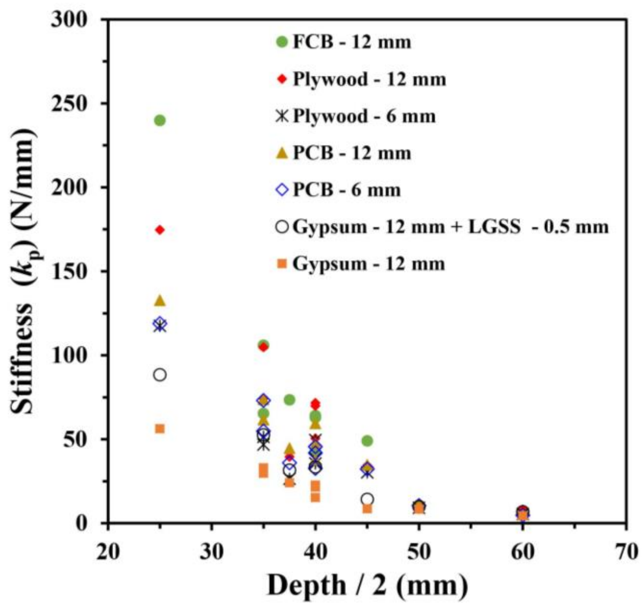

Figure 9. Sheathing stiffness magnitudes versus dimensions of CFS stud

Although, the sheathing stiffness (k_p) shows an exponentially decreasing trend with respect to the depth of the CFS stud for each sheathing type [Eqs. (1-7) in Table 4], it should be noted that in general the following design parameters influence the bracing stiffness of the sheathed CFS wall panel; (i) geometry of the CFS stud, (ii) material property of the CFS stud; and (iii) material property of the sheathing board. Therefore, an attempt has been made to include all the above-mentioned design parameters in the formulation of the sheathing stiffness predictor equations by introducing two different variable coefficients A and B with respect to the type of the sheathing boards. In addition, it should be noted that the generalized form of the sheathing stiffness expression as well as the variable coefficients are made such that it can accommodate many other sheathing board types used in the construction practices. The step-by-step procedure used to formulate the generalized sheathing stiffness expression [Eq. (15)] and the variable coefficients [Eqs. (16-17)] is described in Table 4.
The empirical-generalized sheathing stiffness predictor expression is shown below

$$k_{\mathrm{p}} = \frac{\left(\frac{E}{58.4}\right)e^{(-0.106(D/2))}}{A.\left(\frac{6274.40}{E_S}\right)e^{(\mathrm{BD}/2)}} \tag{15}$$

$$A = 3112.4\ E_s{}^{-0.909} \tag{16}$$

$$B = \frac{E_s}{142857.1} - 0.0437 \tag{17}$$

The proposed Eqs. (15-17) for predicting the magnitude sheathing stiffness is valid only in SI units, where E and Es are Young's modulus of steel in N/mm^2 (Table 2) and tensile modulus of sheathing board in N/mm^2 (Table 1), respectively; d is the depth of the CFS stud (Fig. 1d) in millimeters. A validation [both statistically (according to Amini et al 2016 and Selvaraj and Madhavan 2018c) and application oriented] of the proposed design method is described in Selvaraj and Madhavan (2019h).

4. Conclusions

The new method to determine the sheathing stiffness against the torsional buckling of the CFS stud is presented. The actual stiffness of the sheathing boards against the worst-case failure mode was determined using a newly devised test setup developed by Selvaraj and Madhavan (2019h). A total of sixty-seven experiments including seven different sheathing types and ten different CFS studs were carried out. Based on the test results the following conclusions can be drawn:

1. The strength and stiffness of the sheathing boards against the pull-through failure primarily depend on the tensile modulus of sheathing board and depth of the CFS stud.

2. The resistance offered by the sheathing board with a fiber composition (plywood and fiber cement board) against the twist of the CFS stud is significantly higher than the sheathing boards made of particles (fiberless – particle cement board and gypsum board).

3. The failure modes of fiberless sheathing boards (particle cement board and gypsum board) are undesirable (sudden pull-through and breakage) and vary for different dimensions of CFS studs. Therefore, fiberless sheathing should not be considered as a bracing element in the design of CFS wall panels.

4. More importantly, the experimental evidence indicates that the thickness of the sheathing boards does not influence the stiffness against pull-through failure. However, the failure modes of sheathing less than 8 mm is undesirable and hence it can be conservatively recommended not to use the sheathing boards less than 12 mm thickness when the bracing effect of sheathing is considered in the design.

Based on the inferences obtained from the experimental results, a generalized expression [Eqs. (15-17)] to predict the stiffness of the various sheathing boards is formulated fastidiously. The generalized expression is formulated such that it can accommodate the design parameters of sheathed CFS wall panel (CFS stud dimensions, the material property of the sheathing boards) and inhibit the undesirable or catastrophic failure modes of the sheathing fastener connections.

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