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Sheathing Braced Design of CFS Studs using Direct Stiffness-Strength Method Design

Sivaganesh Selvaraj[1], Mahendrakumar Madhavan[2]

Abstract

A new design procedure for considering the bracing effect of sheathing boards to the cold-formed steel (CFS) structural members is proposed. The previous investigations show that the current AISI design specification for sheathing bracing design of CFS wall panels is unconservative (i.e. design standard predict a larger failure load than the experimental test results) due to exaggerated sheathing stiffnesses calculated from ideal loading conditions rather than worst-case loading conditions. Therefore, a new design procedure is suggested based on the performance (strength and stiffness) of the individual sheathing fastener connections. A new and simplified test setup is also introduced to simulate the realistic failure modes of the sheathing fastener connections using a conventional universal testing machine. A total of 67 individual sheathing fastener connection tests were carried out, including parameters such as ten different dimensions of the CFS stud (to account for the slenderness) and seven various sheathing board types (to account for the performance of each sheathing type). Based on the individual sheathing fastener connection test results, new expressions are formulated to predict the stiffness and strength of the individual sheathing fastener connections. An application-oriented merit-based and statistical assessment indicated that the proposed expressions are appropriate for the design.

1. General

The cold-formed steel structural members are being used for construction practices since several decades. Despite the advantages of the CFS such as strength-to-weight ratio, shape and dimensional flexibility, ease of transportation and installation speed, the lack of design guidelines prevents its use as a mass replacement for concrete intensive unsustainable construction. Therefore, there is a need to develop and update the current design standards. This paper presents an efficient design procedure for sheathed CFS wall assemblies by considering the inherent bracing effect offered by the sheathing boards (external covering). The sheathing boards are attached to the CFS wall assemblies by self-drilling fasteners with regular spacing (a or d_f), as shown in Fig. 1.

The authors have recently carried out comprehensive experimental investigations to understand the structural behaviour of sheathed CFS wall panels with various sheathing boards and to validate the appropriateness of AISI design method [1-7]. The outcome of the previous investigations clearly indicates that the current AISI design specification for sheathing braced design is not suitable for out of plane loading. In addition, the authors have also attempted to modify the sheathing stiffnesses combination suggested by AISI (Selvaraj and Madhavan 2018a) [1]. However, the attempt was not successful for all the tested specimens as the sheathing fastener connection stiffness predictor equations were not formulated with the design parameters that influences the failure mode of the CFS stud [6-7]. Therefore, this paper endeavors to carryout comprehensive testing to understand the parameters that influences the structural behaviour of sheathing fastener connection and formulate expressions to determine the strength and stiffness of the individual sheathing fastener connections. The novelties of the present paper are the new test setup to determine the strength and stiffness of the sheathing fastener connections, design expressions for strength determination and the demand (required strength and stiffness) - supply (available strength and stiffness) based design approach. This paper is organized such that the reader could understand the history of the sheathing braced design concepts, recent developments, currently available design methods, test standards and the inadequacy associated with it.

2. Sheathing braced design of cold-formed steel structural members Direct Stiffness Strength Method

The present approach for determining the design strength of the sheathed CFS structural member is based on the concept elucidated by Winter (1960) [8] and Yura (2001) [9]. This method is simple as that the strength and stiffness (supply) of the fully effective fasteners (sheathing-fastener connection) shall be equal to the required bracing's stability

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[1] Postdoctoral fellow, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong. sivaganesh.selvaraj@polyu.edu.hk

[2] Professor, Department of Civil Engineering, Indian Institute of Technology Hyderabad, Telangana, India. mkm@ce.iith.ac.in

(demand), i.e., checking the adequacy of the sheathing-fastener connection. Therefore, this method requires two sets of expressions; (i) expressions to predict the strength and stiffness demand to brace the CFS member from instability failures; and (ii) expressions to predict the actual resistance (stiffness and strength) of the sheathing board and fastener connections. These expressions should be based on the behavior of the sheathing-fastener connections against the worst-case instability failure of the CFS studs. AISI (Section C2.3 of AISI 2016) [10] provides an expression to calculate the required strength ($\overline{P}_{rb}$) and stiffness (β_{rb}) for the adequate bracing effect (demand), but only for axial compressive loading.

Further, the section C2.2 of AISI suggests not to provide additional steel bracing for the CFS studs that are sheathed on both the flanges and subjected to out-of-plane loading ("*when both flanges are so connected, no further bracing is required*"). The section C2.2 of AISI may not be accurate as the sheathing bracing design is based on the slenderness and structural behavior of the member. Conversely, more applicable expressions were proposed by Yura (2001) [9] with the consideration of non-uniform moment region, the number of curvatures, top flange loading or other loading cases, and the number of braces, which follows the recommendations of Winter (1960) [8]. Therefore, the expressions proposed by Yura (2001) [9] is used in the present work to determine the required strength (Eq. 1) and stiffness (Eq. 2) of the sheathing board.

Bracing Strength Requirement (F_{br}) as per Yura (2001) [9]

$$F_{br} = \frac{C_L C_d M_f}{100h} \tag{1}$$

Bracing Stiffness Requirement (β_i) as per Yura (2001) [9]

$$\beta_i = \frac{2[4-(2/n)]C_b P_f C_L C_d}{L_b} \tag{2}$$

Where F_{br} and β_i are the required bracing strength and stiffness to brace the single flexural member with a factored axial compression load of P_f, $P_f = \pi^2 EI_{yc}/L_b^2$, E is Young's modulus of the CFS member, I_{yc} is the out-of-plane moment of inertia of the compression flange which is $I_y/2$ for doubly symmetric cross-sections, L_b is the unbraced length of the CFS member, n is the number of the bracings, M_f is the design moment of the CFS member, h is the web depth of the CFS cross-section, C_b is the bending coefficient to consider the effect of uniform moment, C_L is 1+(1.2/n) for top flange loading and unity other loading cases, C_d is 1 + $(M_S/M_L)^2$ for double curvature and unity for single curvature. Despite the availability of the above expressions [Eqs. (1-2)] to determine the required strength and stiffness (demand) for the bracing, the impediment in developing a robust design method is in determining the actual strength and stiffness (supplied) of the sheathing-fastener connections. Typically, the actual strength and stiffness of the bracing member are calculated from the simple mechanics (Yura 2001) [9]; strength (F) = $F_y A$ and stiffness (F/δ) = AE/L, where F_y is the yield or ultimate stress of the member, A is the cross-sectional area, F is the load (strength), E is the young modulus of the member and L is the length of the bracing member. Nevertheless, the above expressions apply to only the bracing system or member subjected to axial compression and tension and shall not be applicable for the worst-case failure modes (full and partial pull-through, breakage or cracking of sheathing and withdrawal of fasteners) of the sheathing boards attached to the CFS wall assemblies owing to the following conclusions obtained from the previous investigations [4, 11-17].

i. In the case of sheathing as a bracing element, the resistance offered by the sheathing-fastener connection is significantly low compared to the sheathing board due to the concentric loading [Fig. 1(d-g)]. Therefore, it is not appropriate to use the axial loading based expression for determining the actual strength (F) and stiffness (F/δ) of the sheathing fastener connections.
ii. The various types of sheathing boards used in the CFS wall assemblies exhibit a different characteristic of bracing systems as follows:
    (a) Soft sheathings (with high particle composition such as gypsum or cement board) - bearing or pull-through failure or severe cracking - these sheathing boards are adequate only to brace the instability of the CFS structural members with high global and local slenderness [18].
    (b) Stiff sheathings (steel or sheathing boards made of fibers, for example, fiber cement boards, plywood, and corrugated steel sheets) - failure of plies or partial pull-through failure or breakage of screws - these sheathing boards are adequate for most of the CFS studs types; However, the contributory effect of bracing vary significantly depending on the material properties (tensile modulus and material composition).

The above conclusions and deficiencies of AISI design approach (AISI 2013) necessitates the need for a new experimental test up to simulate the realistic and worst-case failure modes of the sheathing-fastener connections. In addition, the previous investigations [1-2] also indicate that the worst-case failure mode of the CFS wall panel assembly is torsional buckling (LTB or FTM – cross-sectional twist). The definition of pull-through failure is pulling of the fastener through the thickness of the sheathing due to the cross-sectional twisting of the CFS structural member. Therefore, a unique test setup has been developed to simulate the torsional buckling of the CFS stud, and this newly proposed test-setup is an improved version of the previous test standards of AISI [19-20].

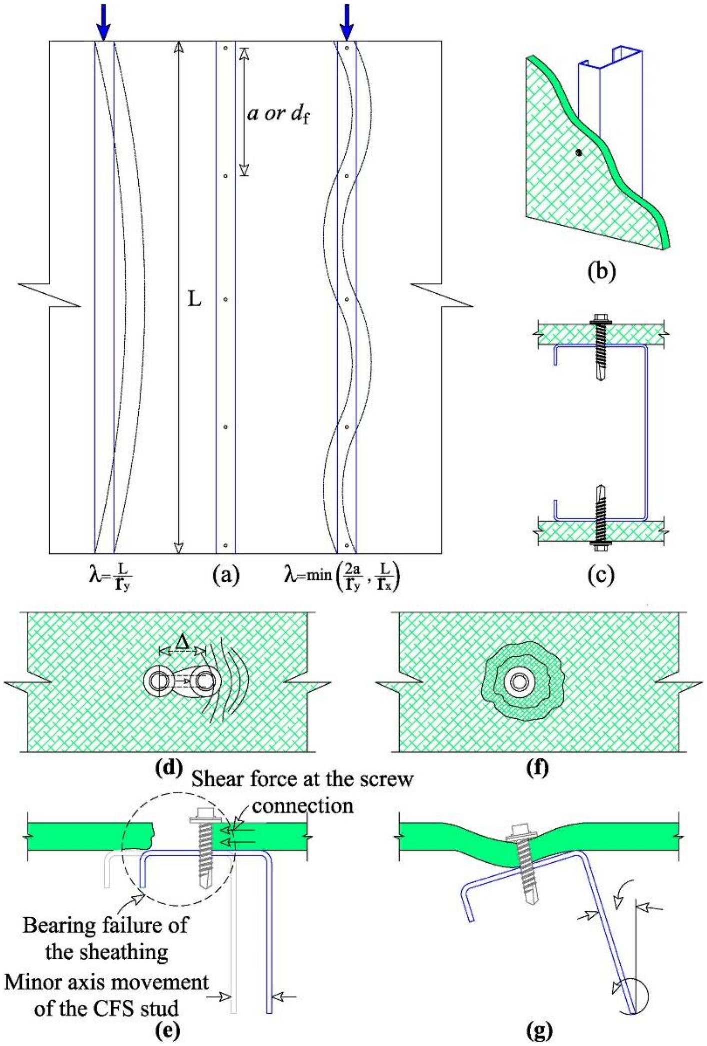

Fig. 1. Sheathed Cold-formed Steel Wall Assemblies: (a) Minor axis buckling of CFS stud versus reduced unbraced length due to sheathing effect; (b) Attachment of Sheathing by self-drilling fastener; (c) Two sided symmetrically sheathed CFS wall stud; (d-e) Bearing failure of sheathing due to shear force developed at the sheathing fastener connection (minor axis buckling); (f-g) Initiation of the pull-through failure due to the diagonal force developed at the sheathing fastener connection (cross-sectional twist).

3. Development of a new test-setup for determining the performance of the sheathing fastener connection as bracing

3.1 Test-setup proposed by AISI

The concept of test-setup proposed by AISI [19-20] is to rotate the CFS stud by connecting the sheathing with actual fastener connection in one flange and pulling from other flange (Fig. 2b). In the authors' perspective, this test-up does not accurately simulate the worst-case/appropriate failure mode between CFS stud and sheathing-fastener connection. The following are the inadequacy in the proposed test-up proposed by AISI.

1. Typically the sheathing-fastener connection failure is a combination of both horizontal and vertical displacement of the CFS stud (cross-sectional twist). However, the present approach by AISI has two separate rotational stiffness calculations as follows: (i) rotational stiffness ignoring the separation between sheathing and fastener, without the horizontal displacement ($\triangle_h$ in Fig. 2) of the CFS stud (ii) rotational stiffness including the separation between sheathing and fastener. Nonetheless, no specific rotational stiffness approach is suggested by AISI for design calculation. Moreover, the test-setup proposed by AISI is such that the vertical and horizontal displacements are almost similar as one influences the other [the separation between sheathing ($\triangle_h$) and fastener happens due to the vertical pulling ($\triangle_v$)].
2. In the authors' opinion, the test-setup by AISI does not simulate the rotation of the CFS stud (cross-sectional twist). Instead, it unilaterally applies the force at one side of the sheathing-fastener connection and creates more stress concentration at the weak end (sheathing board), as shown in Fig. 2c. However, in reality, the failure of the sheathing fastener connection occurs at both flanges simultaneously because of which the total force is distributed evenly to both sheathing-fastener connections (Fig. 2d).
3. The test setup demands to use the movable (horizontal translation) actuator, as shown in Fig. 2a. In the case of stiff sheathing such as plywood, this horizontal translation of the loading actuator will make the connection failure mode more critical by directly pulling the fastener from sheathing resulting in the withdrawal of screws (Fig. 2e) rather than a pull-through failure of sheathing. Such direct pulling of fastener due to the horizontal movement of the actuator may not reflect the actual resistance offered by the sheathing. The failure of the sheathing fastener connection should happen due to the realistic failure mode of the CFS stud rather than direct pulling. In addition, the horizontal movement of the actuator might create a breakage failure in the case of soft sheathing (Fig. 2f).
4. The test setup suggests connecting the sheathing at the rigid beam, as shown in Fig. 2a to create the reaction at the sheathing connections. However, the soft sheathing materials such as gypsum and particle cement board may fail (cracking or breaking) at the rigid beam connection either while drilling a hole for bolting or while loading, as shown in Fig. 2g. This phenomenon will significantly affect the sheathing-fastener connection stiffness determination and will not reveal the actual stiffness exhibited by the soft sheathing board.
5. The test setup requires a bolted connection at one flange for twisting of the CFS stud (Fig. 2a). However, this bolted connection could damage/deform the CFS

stud if the flange plate slenderness is high (Fig. 2h). This vulnerability of the bolted connection further increases if the CFS stud is an unlipped one owing to lower torsional flexibility.

By considering the above shortcomings, it can be deduced that the test setup proposed by AISI is not suitable to determine the actual performance of the sheathing board against the worst-case instability failure of the CFS stud.

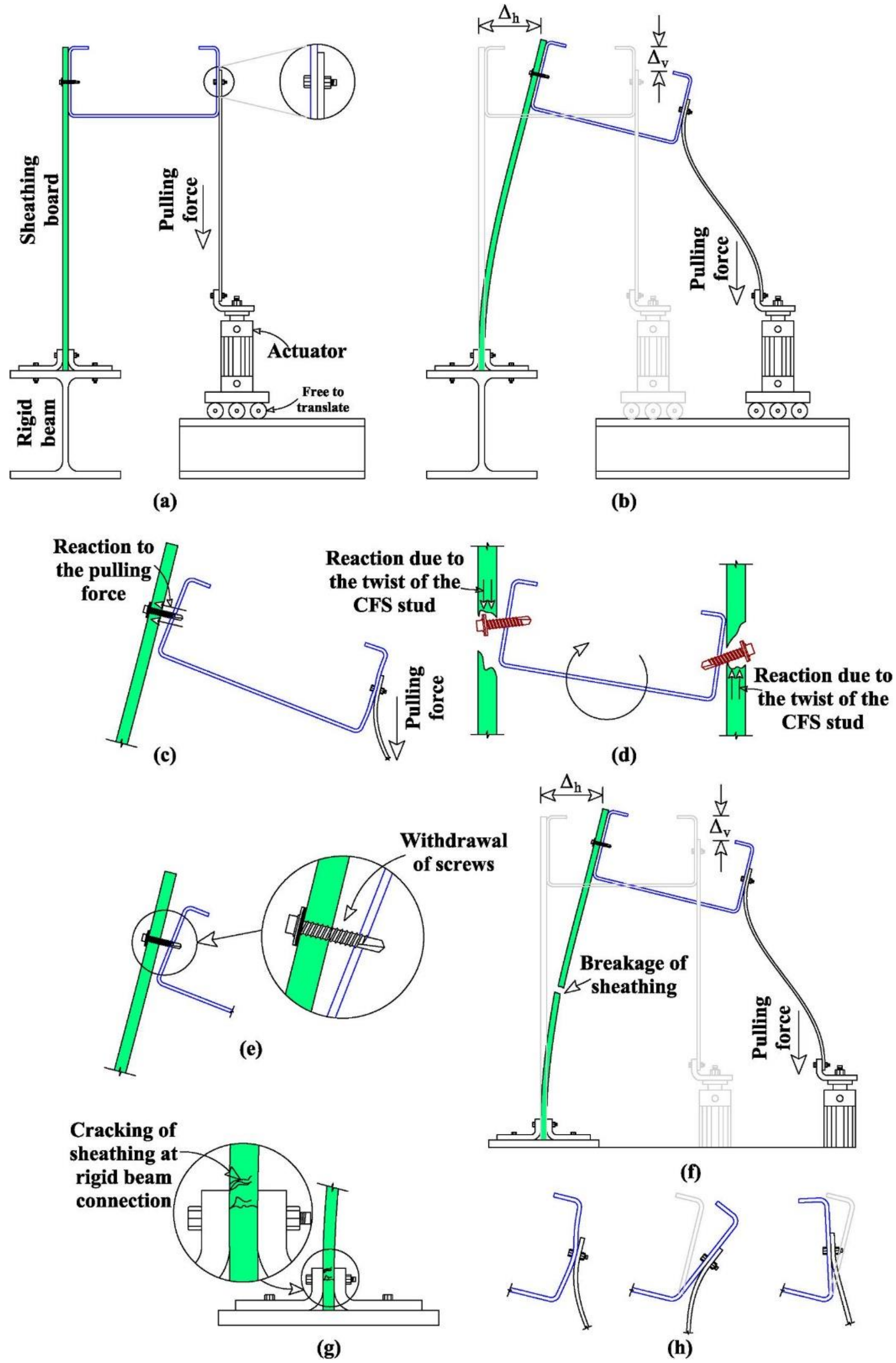

Fig. 2. (a) Test setup prosed by AISI (2017a and 2017b) to determine the rotational stiffness of the sheathing; (b) Loading pattern at the sheathing fastener connection; (c) Concentrated force at the sheathing fastener connection; (d) Actual failure of the sheathing due to cross-sectional twist of the CFS stud; (e) Withdrawal of the fastener due to direct pulling with horizontal movement of the actuator; (f) Breakage of soft sheathing due to horizontal movement of the actuator; (g) Failure of the soft-sheathing at the rigid beam connection; (h) Deformation of the CFS stud flange due to the effect of predrilling for bolted connection.

3.2 *Proposed test-setup*

The newly proposed test-setup for determining the performance of the individual sheathing fastener connection against the cross-sectional twist of the CFS stud is shown in Fig. 3. The cross-sectional twist of the CFS stud (torsional buckling) is simulated by pulling the flanges (displacement causing overall twist of the cross-section) in the opposite direction, as shown in Fig. 3b. The test setup is developed to determine the structural response of the individual sheathing fastener connection so that the result can be directly used with Yura's bracing strength and stiffness design approach (Eqs. 1 and 2). The test setup was also developed such that it allows the sheathing fastener connection to experience failure without any constraints. Besides, the test setup enables the possibility of testing two or more sheathing fastener connections in parallel (Fig. 3d). The test setup was developed such that it can be carried out using a typical universal testing machine by directly applying a pulling force at the sheathing ends. Moreover, the proposed test setup gives the direct measurement of the stiffness and strength of the sheathing fastener connections as follows: (i) the displacement of the CFS stud is directly equal to the applied displacement, hence it is easy to calculate the stiffness of the sheathing-fastener connection; (ii) the resistance of the sheathing-fastener connection can be directly obtained from the machine reaction force, and it should be noted that additional calculations are not required to determine the resistance of each sheathing fastener connection as both the connections in the test specimen are loaded simultaneously with an equal displacement of CFS stud. As shown in Fig.3a and 3b, the wooden blocks are used to precisely align the loading ends in the same axis. The bearing blocks are stiff woods (dense) compared to the test samples to avoid damage during loading. Moreover, the wooden blocks are connected to a loading plate with two parallel bolt connections (a total of 6 bolts), as shown in Fig. 4c, thereby the deformation of the wooden blocks is prevented.

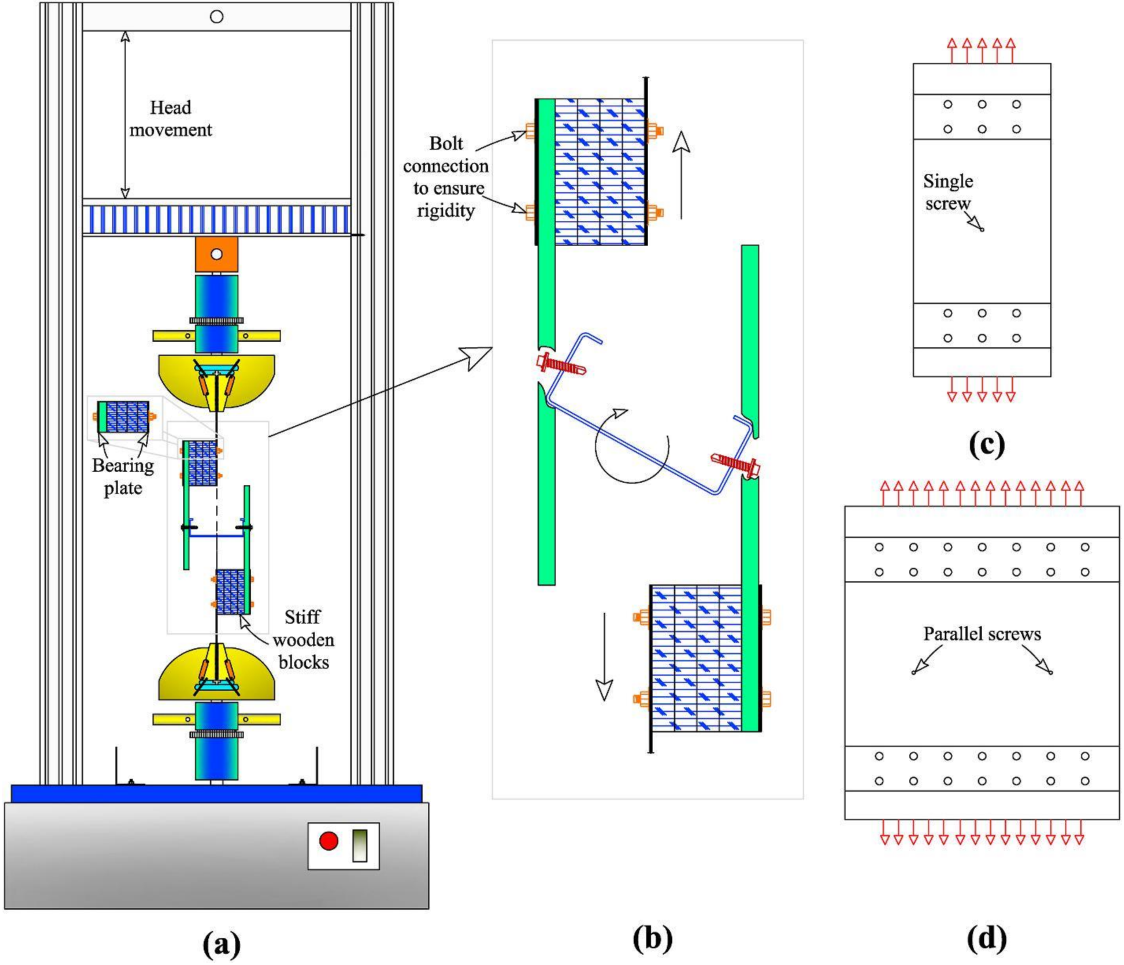

Fig. 3. Newly developed Test set up for determining the performance of the sheathing board against the failure of the CFS stud: (a) View of the test setup (prior to application of load); (b) Occurrence of failure at the sheathing board from the proposed test setup; (c) Single screw specimen; (d) Parallel screw (more than one) specimen

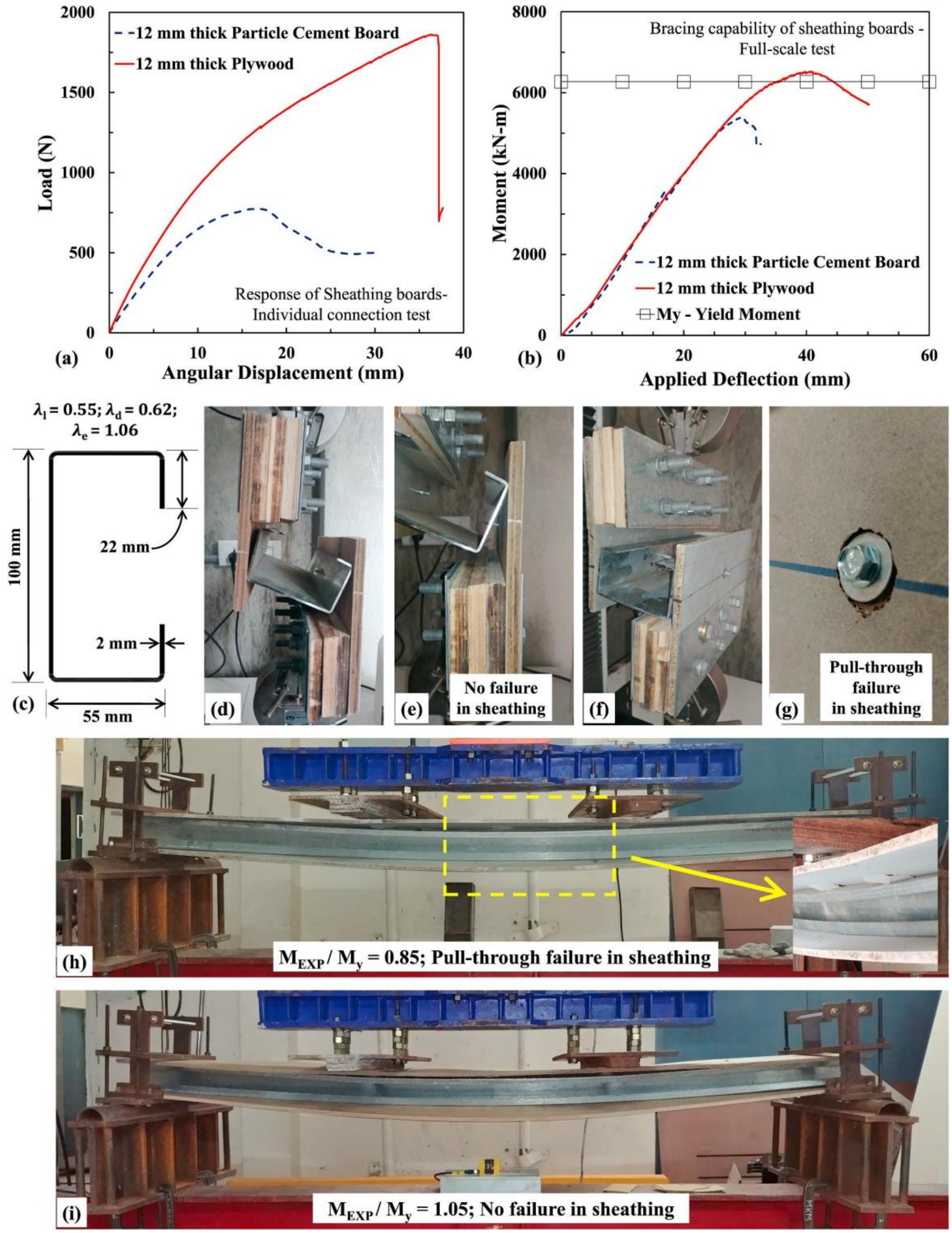

Fig. 4. (a) Merit Assessment of the proposed test setup: (a) Performance of the sheathing boards (PCB and Plywood) against the cross-sectional twist of the CFS stud; (b) Actual bracing effect of PCB and Plywood sheathing boards; (c) Cross-sectional dimension of the CFS stud investigated; (d-e) Plywood - failure mode observed in the individual sheathing fastener connection; (f-g) Particle cement board - failure mode observed in the individual sheathing fastener connection; (h) Actual bracing effect of PCB sheathing for CFS wall studs subjected to out-of-plane loading; (i) Actual bracing effect of Plywood sheathing for CFS wall studs subjected to out-of-plane loading

3.2.1 Merit assessment for the test set up

The performance of the sheathing board observed in the individual sheathing-fastener connection test was compared with the full-scale sheathed CFS wall panel test results to assess the merit of the proposed test setup. The suitability of the test setup was evaluated by two significant parameters; (i) failure mode of the sheathing boards; (ii) strength and stiffness of the sheathing fastener connection. The failure modes of the individual sheathing-fastener connection tests with the proposed test setup matches precisely with the full-scale experimental failure modes for both stiff [plywood – comparison of Figs. 4d,e (individual connection test) and Fig.4i (full-scale test)] and soft [particle cement board (PCB) – comparison of Figs. 4f-g (individual connection test) and Fig. 4h (full-scale test)] sheathing. Further, the structural bracing performance of the sheathing board also matches with the full-scale test results. Among the two full-scale test results with stiff and soft sheathing, the LTB of the CFS stud was inhibited by stiff sheathing without any failure [M_{EXP} / M_y = 1.05 (plywood); No failure in sheathing - Fig. 4b and i] while the soft sheathing failed in pull-through failure [M_{EXP} / M_y = 0.85 (particle cement board); Pull-through failure in sheathing - Fig. 4b and h]. Where M_{EXP} is the experimental moment capacity and M_y - Yield moment capacity of the CFS stud cross-section (section modulus x yield stress). Similar performance sheathing is exhibited against the pull-through failure in individual sheathing fastener connection tests as the stiff sheathing exhibited higher strength and stiffness compared to the soft sheathing, as shown in Fig. 4a. Further, the bracing capability exhibited by the sheathing boards from the proposed test setup is validated quantitatively by comparing the sheathing fastener connection strength required to brace the CFS stud from LTB with the resistance offered by the sheathing board. The required strength of the sheathing fastener connection was calculated using the Eq. (1). The comparison shown in Table 1 indicates that the 12mm thick plywood sheathing has the adequate strength (Available strength is higher than the required strength) to brace the CFS stud from LTB. In comparison, the 12 mm thick particle cement board failed to provide adequate resistance (Available strength is less than the required strength). Based on the above, it can be inferred that the proposed test setup indeed simulates the actual failure mode of the CFS stud by appropriately distributing the loads.

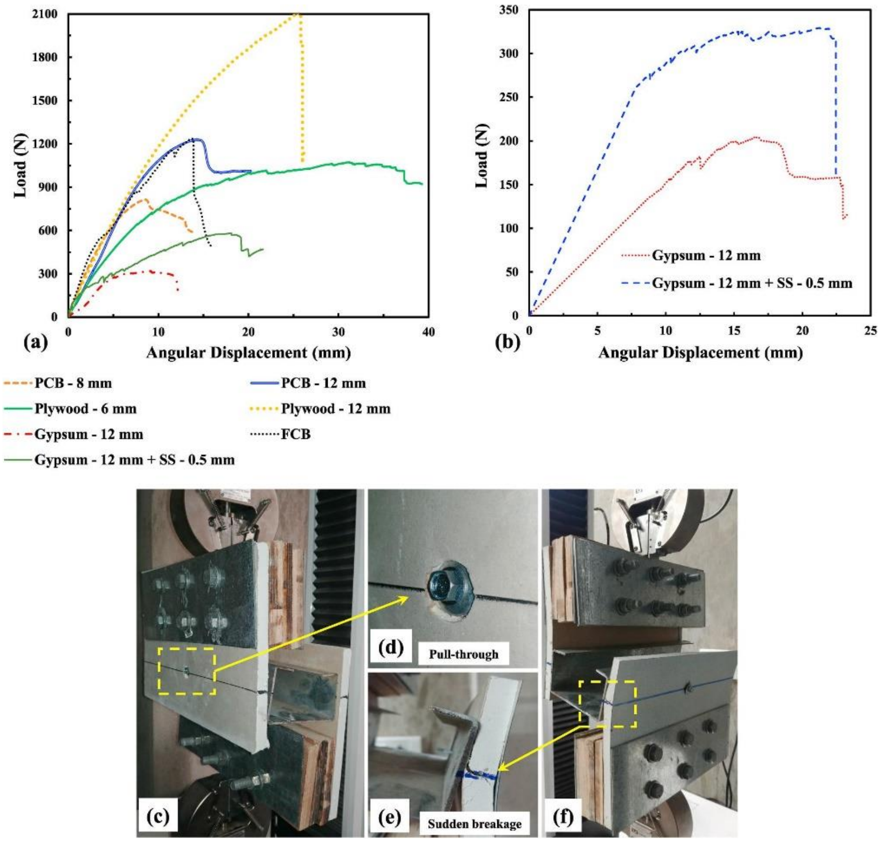

Fig. 5.(a) Performance of the various sheathing boards against the cross-sectional twist of the CFS stud; (b) Influence of steel sheet of thickness 0.5 mm in performance of gypsum sheathing board; (c-d) Failure mode of the gypsum sheathing; (e-f) Failure mode of the gypsum sheathing with 0.5 mm thick steel sheet of the 0.5 mm steel sheet layer attached over the gypsum board.

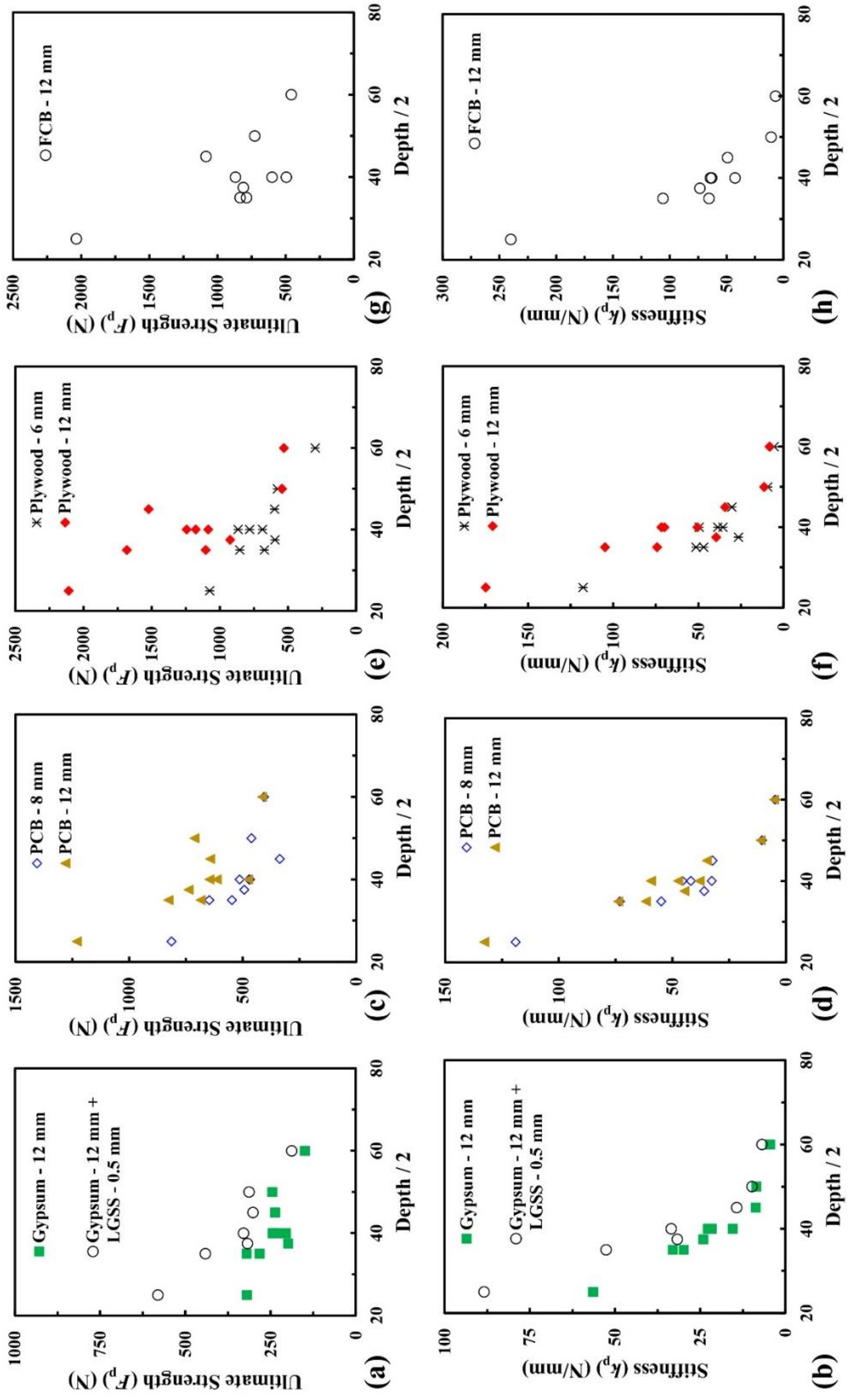

Fig. 6. Performance (strength and stiffness) of sheathing versus cross-sectional dimension of CFS stud: (a-b) Gypsum and gypsum+SS sheathing; (c-d) PCB 8 mm and 12 mm sheathing; (e-f) Plywood 6 and 12 mm sheathing; (g-h) FCB sheathing

Table 1: Quantitative validation for proposed test setup

Sheathing material	Required Connection strength required to brace CFS beam from LTB (Safety factor 2 as used Yura 2001) [Eq. (3)] (N)	Available Connection strength (N) (From Fig. 4a)	Comparison with full scale results	
12 mm thick Particle Cement Board	1216.6	773.4	Available strength is lesser than required strength – indicate that the particle cement board sheathing is not appropriate for bracing the CFS stud	CFS stud failed in LTB : $M_{EXP} / M_y = 0.85$ - Pull-through failure in sheathing - Fig. 4b and h
12 mm thick Plywood	1216.6	1861.5	Available strength is higher than required strength – indicate that the plywood sheathing is appropriate for bracing the CFS stud	CFS stud failed in Yielding : $M_{EXP} / M_y = 1.05$ - No failure in sheathing - Fig. 4b and i

M_{EXP} - Experimental moment capacity; M_y - Yield moment capacity of the CFS stud cross section (section modulus x yield stress)

4 Performance of sheathing boards

As mentioned previously, to develop a simplified procedure for the design of sheathed CFS wall assemblies, it is necessary to develop a robust expression to predict the actual structural performance exhibited by the sheathing board against the instability failure of CFS wall assemblies. Therefore, a total of 67 individual sheathing fastener connection tests were carried out with parameters such as ten different dimensions of the CFS stud (to account the slenderness) and seven various sheathing board types (to account for the performance of each sheathing type). The tests were carried out using the INSTRON Universal testing machine of capacity 35 kN, and a constant displacement of 0.6 mm per minute was applied (ASTM E72 2015 and NIST 2007) [21-22]. The dimensions of the CFS studs are chosen based on the thickness of the wall panel (depth of the CFS stud) used in the industry, from the depth of 50 mm (2 inches) to 120 mm (4.72 inches).

Similarly, the sheathing boards were chosen from the industry with a tensile modulus ranging from 2100 MPa to 6274.4 Mpa. The dimensions and material properties of the CFS stud, material composition, and material properties of the sheathing boards are summarized in Tables 2 and 3, respectively. The test results, including ultimate strength and initial stiffness (up to 40% of the load versus angular displacement plot) of the sheathing fastener connection, are summarized in Table 4.

The results of the individual sheathing fastener connection tests indicate the following

1. The sheathing board with fiber content (fiber cement board and plywood) exhibit higher resistance (stiffness and ultimate strength) against the cross-sectional twist of the CFS stud while the sheathing board made of powdery materials such as gypsum and particle cement boards failed at a significantly lower capacity (Fig. 5a).
2. It was found that the gypsum sheathing has low resistance compared to the other sheathing boards (Fig. 5a) due to its material composition (dry gypsum slurry layer within two paper layers). Therefore, an additional steel sheet layer (external layer of 0.5 mm thickness attached using the existing fastener connections without the use of adhesives) added over a gypsum sheathing for investigation. It was observed that the additional steel sheet layer had influenced the resistance of the sheathing. However, the failure mode remains catastrophic (sudden breakage), as shown in Fig. 5(b-f). Hence, it is suggested not to consider the influence

3. The test results indicate that the stiffness and ultimate strength of the sheathing fastener connection varies based on the dimension of the C channel CFS stud. The comprehensive investigation of the failure mode and resistance of the sheathing fastener connection revealed that the performance of the sheathing fastener connection is influenced by the rate of deformation (at the location of the sheathing fastener connection) due to the twist of the CFS stud. To be precise, the C channel CFS stud with a higher depth (higher lever arm) will have a lesser stiffness against the cross-section twist resulting in more damage at the fastener connection location. Therefore, the strength and stiffness equations are formulated based on the lever arm of the CFS stud, as shown in Figs. 6-7.

4. The failure mode of the sheathing fastener connections also varies depending on the depth of the CFS stud and

material property of the sheathing board, as shown in Fig. 7(c). Based on the observations, the failure modes can be broadly classified into two categories: one is the progressive failure, and the other is a sudden failure. The partial pull-through is a progressive failure as it did not separate the CFS stud and sheathing board. The withdrawal of fastener, sheathing breakage, and pull-through failure is considered as the sudden failure as they separate the sheathing and CFS stud. Although the resistance offered by the sheathing boards with fibers (plywood and FCB) is high, the failure mode is sudden, as shown in Fig. 5a (sudden drop after reaching the ultimate load – curve with legends "Plywood - 12 mm" and "FCB" in Fig. 5a). Hence, it is conservative to underpredict the performance of the sheathing boards that exhibit sudden modes of failure.

5. It is common wisdom that the strength of the axially loaded member (bracing member design - Yura 2001) [9] is linearly proportional to the cross-sectional area of the member. However, the current results are counter-intuitive as the stiffness and ultimate strength of the sheathing fastener connections do not increase proportionally with the increase in thickness for all CFS studs, as shown in Fig. 6. The stiffness and ultimate strength of the sheathing boards are not increased by two-fold even after doubling (from 6 mm to 12 mm) the sheathing thickness, as shown in Fig. 6 d and f for CFS studs S2, S8, S9 and S10 (Table 3). The stiffness of the PCB sheathing boards is almost similar for both 8 mm and 12 mm thicknesses for the CFS studs S4-S10, as shown in Table 4. Moreover, the increase in the sheathing thickness in the case of fibreless sheathing boards (particle cement board) did not improve the failure mode (from sudden failure mode to gradual/progressive failure mode), as shown in Fig. 8. This may be due to the development of diagonal force (due to the cross-sectional twist) that damages the surface of the sheathing board, initiating a loss in stiffness followed by through-thickness failure of the sheathing rather than bearing. Hence, the sheathing board thickness should not be considered as an influential design factor since the increase in stiffness and ultimate strength does not show any specific trend.

The above interpretations pertaining to the performance of the sheathing boards can be summarized as follows: (i) The influence of material property of the sheathing board (tensile modulus) and the geometric dimensions of the CFS stud is prominent; (ii) the sudden and catastrophic failure modes shall not be ignored as they lead to unsafe design; (iii) it is evident that the sheathing thickness did not increase the performance of the sheathing board (strength, stiffness, and failure mode). Therefore, the formulation of the expression for predicting the actual strength and stiffness provided by the sheathing boards against the worst-case failure mode of the CFS wall stud will be based on the above observations from this study.

Table 2: Cross sectional dimensions and material property of 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	1.5	-	202.7	378.3	442.8	18.2
S2	70	30	1.5	-	217.9	376.4	439.2	18.3
S3	70	37.5	1.5	18	202.7	378.3	442.8	18.2
S4	70	55	2	-	211.5	330	425	18
S5	80	30	2.5	25	214.8	329.6	417.3	18
S6	80	40	1.5	10	217.9	376.4	439.2	18.3
S7	80	50	1.5	25	212.2	377.4	440	16.1
S8	90	60	1.5	-	212.2	377.4	440	16.1
S9	100	55	1	-	221.3	330.1	425	18
S10	120	40	1	-	210.93	365.2	426.4	17.6

d - out-to-out depth of CFS stud (web); b - breadth of CFS stud (flange); t – thickness of CFS stud; l_p – depth of 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

Table 3: Specifications and material property of sheathing boards

Sheathing type		Material composition	Density (kg/m^3)	Thickness (t_b) (mm)	Tensile modulus* (E_s) (MPa)	Ultimate Strength (MPa)
Gypsum		Gypsum slurry placed between two paper layers	771.7	12.5	2100	1.29
Gypsum+SS	Gypsum	The SS sheeting is attached as an external cover to gypsum board	771.7	12.5	2100	1.29
	SS		7850	0.45	215000	440
Particle Cement Board		Comprised of wood particle (28%) and cement (62%) mixture, where the cement plays a role of a bonding agent	1250	8	2707	1.71
				12		1.75
Plywood		Manufactured using layered wood veneers	910-1100	6	7983.3[a]	42.3 (parallel to plies)
					3701.2[b]	24.63 (perpendicular to plies)
				12	7983.3[a]	45.5 (parallel to plies)
					3701.2[b]	20.7 (perpendicular to plies)
Fiber cement board		Cellulose pulp fibers and cement	1355.8	12	6274.4	7.5

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

Table 4: Test results: Individual Sheathing fastener connections

Sheathing Type		Stud ID									
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Gypsum board 12.5	k_p	56.42	24.08	33	29.83	21.55	22.73	15.44	8.69	8.52	4.51
	F_p (N)	318.93	198.19	281.81	319.47	243.98	233.33	204.56	236.17	244.76	149.09
Gypsum board 12.5	k_p	88.4	31.69	-	52.61	-	-	33.48	14.3	9.76	6.85
	F_p (N)	580.16	317.8	-	441.03	-	-	329.2	301.29	312.85	187.57
Particle cement	k_p	118.93	35.99	54.9	73.14	45.57	32.68	41.87	32.31	10.51	4.8
	F_p (N)	812.95	493.21	547.27	646.44	467.84	471.78	512.97	336.98	461.34	405.67
Particle cement	k_p	132.76	44.66	61.63	73.82	47.44	38.03	59.45	34.81	11.13	5.28
	F_p (N)	1229.66	737.73	684.65	826.57	613.63	475.37	646.15	643	711.82	414.72
Plywood – 6 mm	k_p	117.64	26.54	46.89	51.46	49.55	35.58	38.6	30.32	9.27	5.56
	F_p (N)	1073.42	595.6	853.07	672.74	780.73	865.77	686.35	597.65	576.53	299.6
Plywood – 12 mm	k_p	174.81	39.56	74.26	104.84	71.69	50.53	69.94	34.36	11.43	8.28
	F_p (N)	2108.06	923.02	1102.21	1681.9	1243.43	1084.43	1175.89	1521.61	542.52	529.64
Fiber cement	k_p	239.95	73.53	65.39	106.03	64.16	42.54	63.08	49.1	10.79	6.8
	F_p (N)	1235.84	810.99	786.96	833.87	600.11	495.12	868.77	1084.62	726.6	458.23

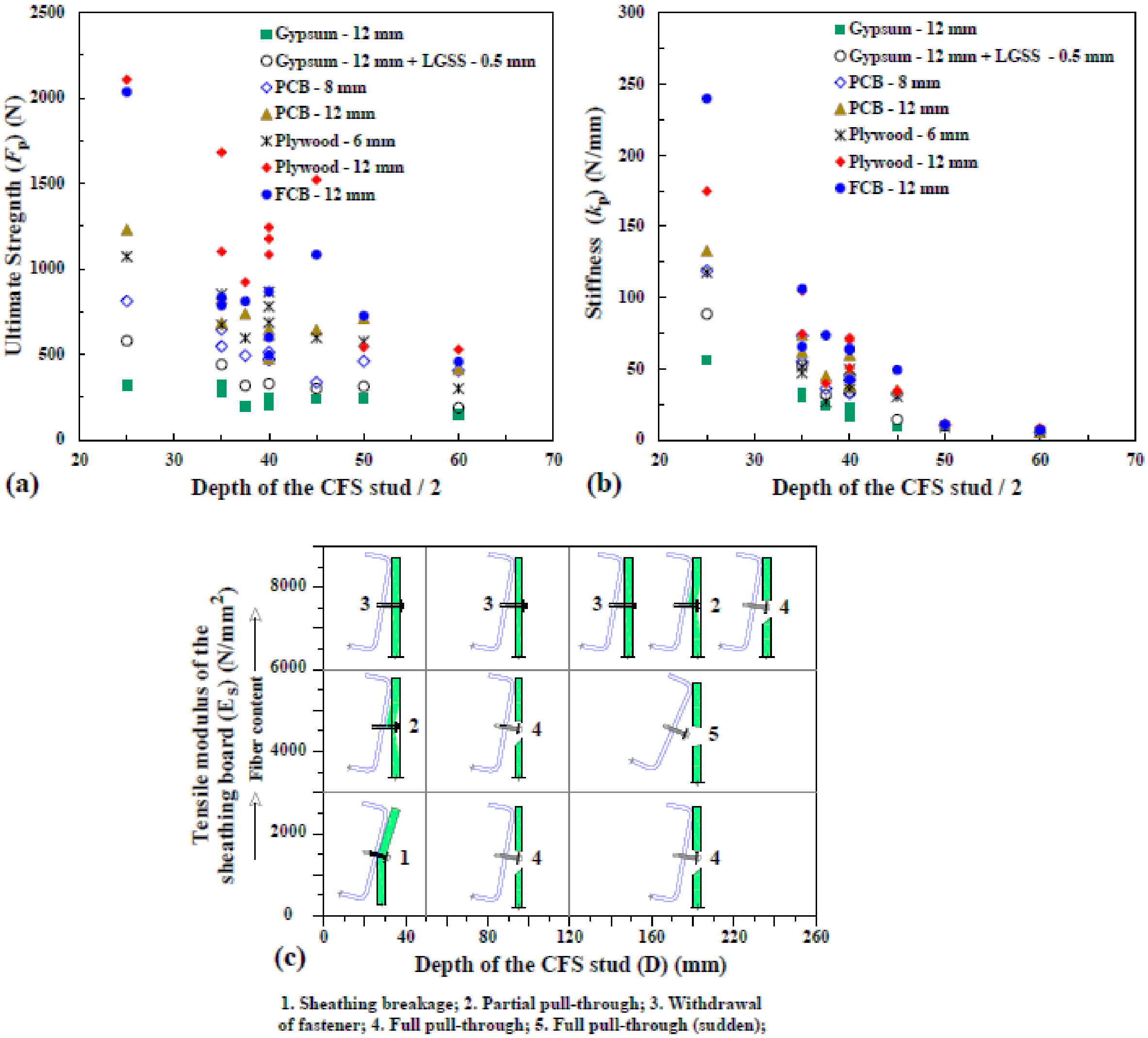

Fig. 7. Trend and formation of expression for sheathing performance against cross-sectional dimension of the CFS stud – (a) Strength of sheathing-fastener connection versus D/2; (b) Stiffness of sheathing-fastener connection versus D/2; (c) Failure modes of sheathing boards versus cross-sectional dimension of CFS stud

5 Formulation of the expression for sheathing resistance

The procedure used for formulating the generalized sheathing strength and stiffness expression with respect to the geometric property of the CFS stud is summarized as follows:

Step 1: Determine the trend for variation of ultimate strength and stiffness of each sheathing board against the lever arm of the CFS stud (*D*/2). There were seven different curves for both strength and stiffness representing each sheathing boards based on Fig. 7(a-b).

Step 2: To formulate a single generalized expression with a tensile modulus of the sheathing (E_S) and lever arm of the CFS stud (*D*/2) as a variable, the trend curve of the sheathing with highest strength and stiffness has been divided by other curves to find the difference in trend (in this case the stiffness and strength curve of FCB is taken). Then the difference in trend has been formulated as coefficients (A, B, and C) that account for the ratio of the highest tensile modulus of sheathing and corresponding sheathing's tensile modulus.

Step 3: The coefficients A, B, and C that account the variation in sheathing modulus are formulated such that the sheathing strength and stiffness are predicted safely by considering the catastrophic failure mode of the sheathing board (Figs. 9-11). Notably, the coefficients A, B, and C for 12 mm PCB sheathing are formulated to underpredict the strength and stiffness, as shown in Fig. 10a, as the failure mode of the PCB sheathing is pull-through which occurs suddenly. Similarly, the plywood sheathing with 6 mm and

12 mm failed predominantly due to withdrawal of fastener and sheathing breakage. Therefore, the coefficients are subdued as can be seen in the actual vs. prediction plots shown in Figs. 9-11.

The generalized expression for predicting the effective strength and stiffness of the sheathing fastener connection is presented as follows

Stiffness of the sheathing-fastener connection

$$k_{\mathrm{p}} = \frac{\left(\frac{E}{58.4}\right)e^{(-0.106(D/2))}}{A.\left(\frac{6274.40}{E_{\mathrm{S}}}\right)e^{(\mathrm{BD}/2)}} \tag{3}$$

$$A = 3112.4\, E_s{}^{-0.909} \tag{4}$$

$$B = \frac{E_S}{142857.1} - 0.0437 \tag{5}$$

Strength of the sheathing-fastener connection

$$F_p = \frac{1783e^{-0.021(D/2)}}{0.6155e^{CE_S}} \tag{6}$$

$$C = 2892E_S^{-1.971} \tag{7}$$

The proposed Eqs. (3-7) for predicting the actual magnitude of stiffness and strength of sheathing-fastener connection is valid in SI units only, where k_{p} and F_{p} are the actual stiffness and strength of the sheathing fastener connection; D is the depth of the CFS stud in millimeters; E and E_{s} are Young's modulus of steel in N/mm^2 and tensile modulus of sheathing board in N/mm^2, respectively. Although the proposed equations [Eq. (3-7)] are purely empirical and formulated with a sheathing tensile modulus ranging from 2100 Mpa to 6274.4 Mpa (Table 3), they can be used for any other sheathing boards with high or less tensile modulus. The variation in sheathing stiffness and strength with respect to the different tensile modulus of sheathing and different range of lever arm of the stud is shown in Fig. 12(a-b).

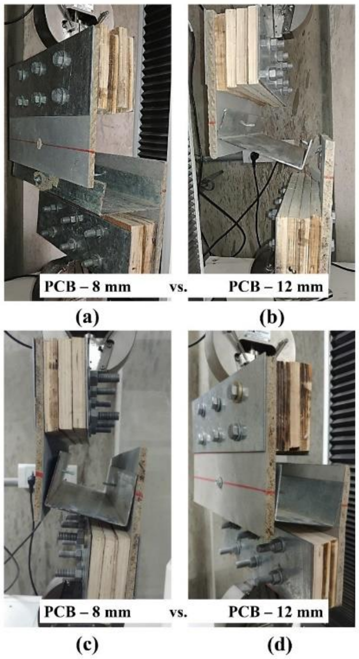

Fig. 8. Failure mode comparison between PCB 8 mm and 12 mm sheathing

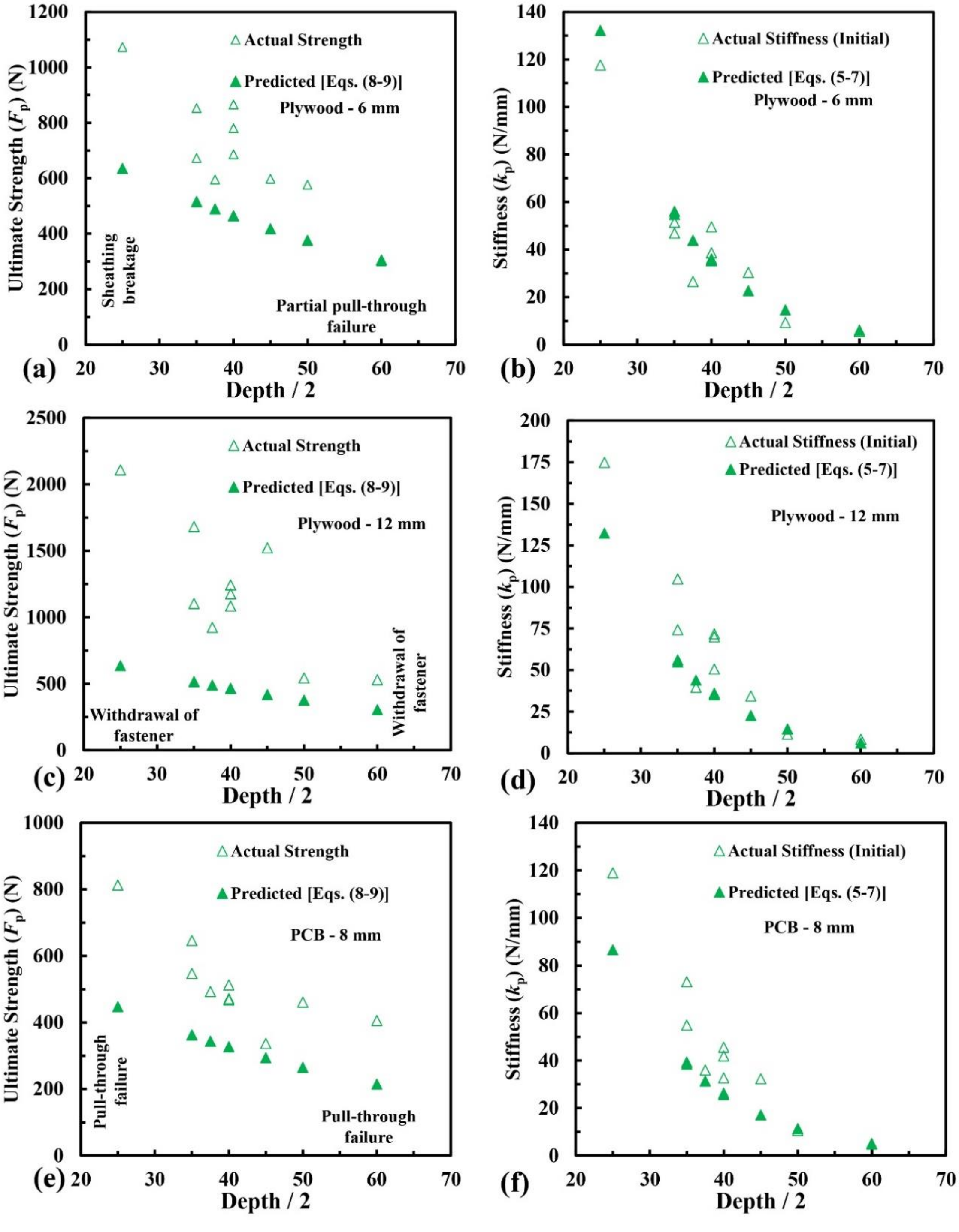

Fig. 9. Actual strength and stiffness of sheathing fastener connection versus cross section dimension of the CFS stud: (a-b) Plywood 6 mm; (c-d) Plywood 12 mm; (e-f) PCB 8 mm

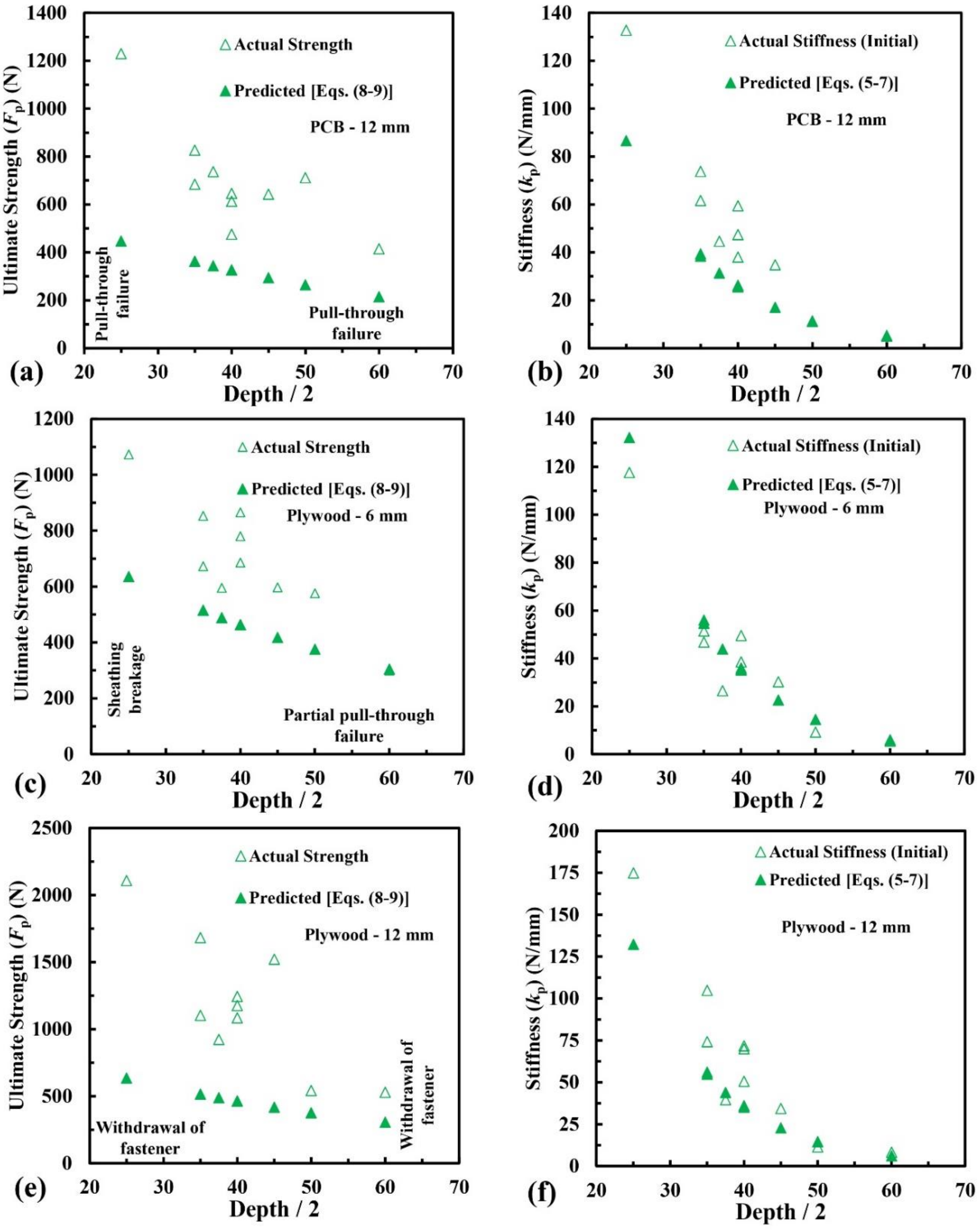

Fig. 10. Actual strength and stiffness of sheathing fastener connection versus cross section dimension of the CFS stud: (a-b) PCB 12 mm sheathing; (c-d) Gypsum - 12 mm sheathing; (e-f) Gypsum - 12 mm + LGSS - 0.5 mm sheathing

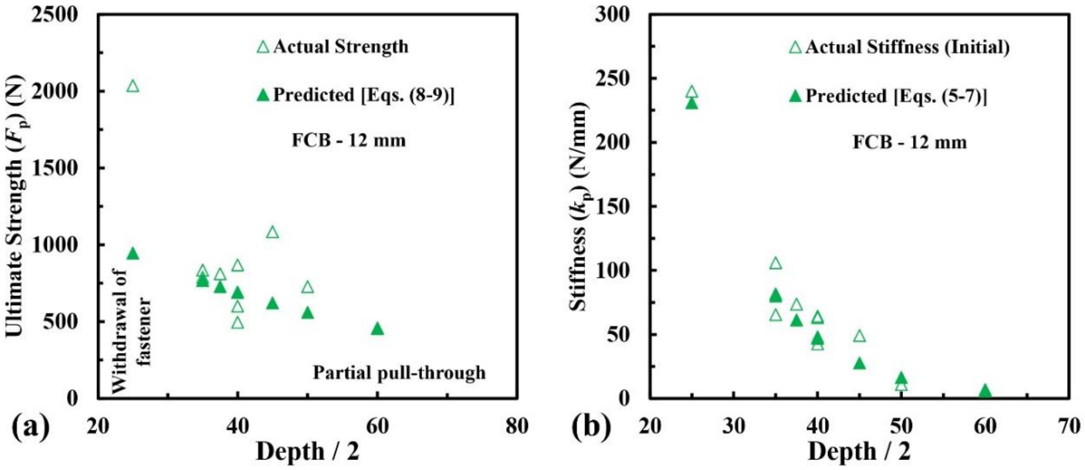

Fig. 11. Actual strength and stiffness of sheathing fastener connection versus cross section dimension of the CFS stud: (a-b) FCB 12 mm sheathing

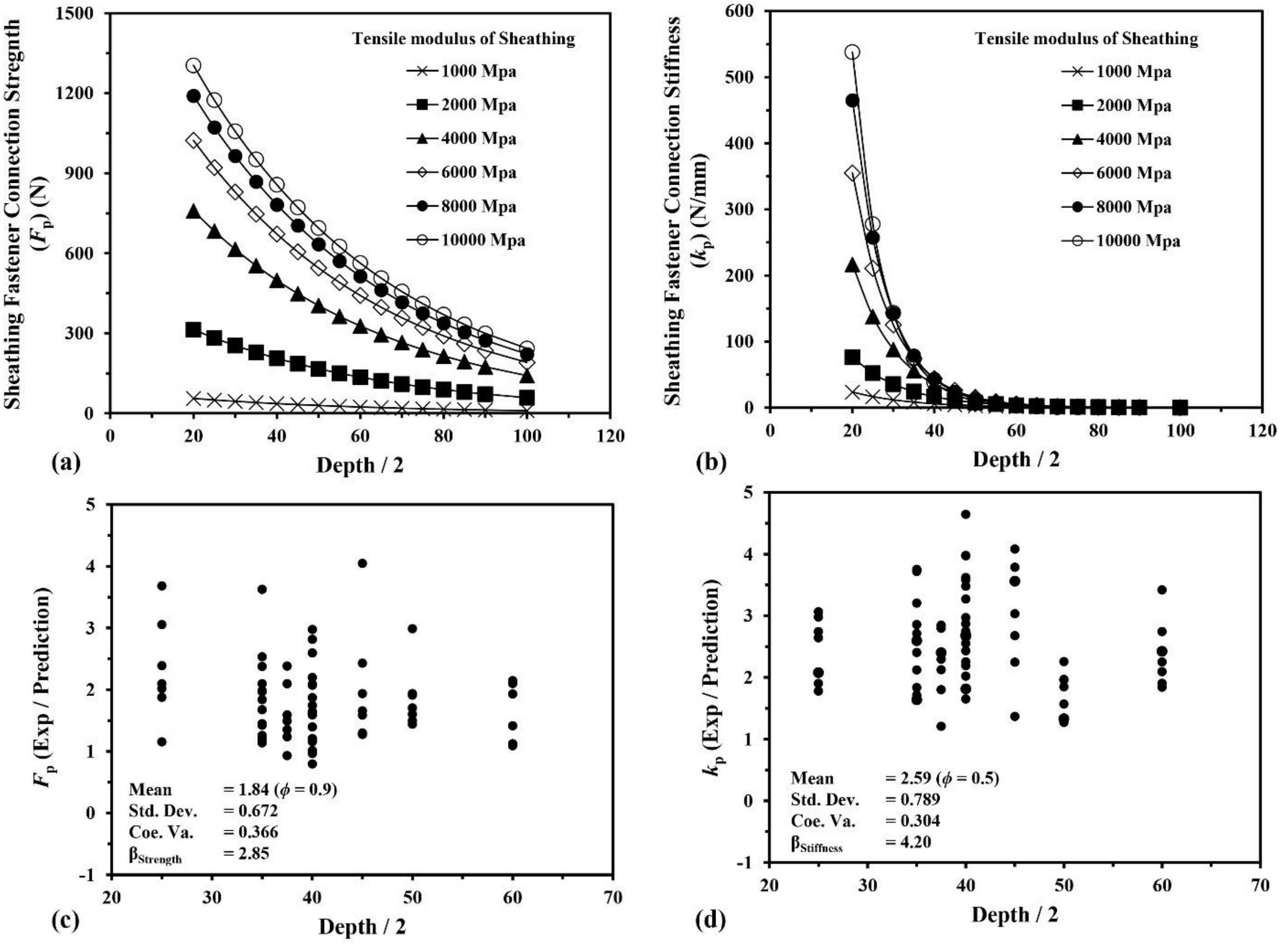

Fig. 12. (a-b) Generalized sheathing-fastener connection performance curve for sheathing boards with various tensile modulus; Merit statistical assessment of proposed equations: (c) Sheathing fastener connection strength: Actual versus Predicted; (d) Sheathing fastener connection stiffness: Actual versus Predicted;

6 Conclusions

This paper presents a new design method for sheathing braced cold-formed steel structural members, namely, “Direct Stiffness-Strength Method.” The concept of this proposed design method is simply to consider the inherent sheathing as a structural bracing to restrain forces developed at the fastener connections, thereby to prevent instability failure modes of CFS wall stud. Although the origin of the concept is inspired by Green et al. (1947) [25], Winter (1960) [8], and AISI (2013) [26], the new design method is developed by addressing the technical flaws in the previous investigations. This paper also summarized the detailed history, development, and shortcomings of the current design methods. The current design method by AISI (2013) [26] is inappropriate and unconservative for the sheathing braced design of CFS wall panels subjected to out-of-plane loading as indicated in the previous investigations of the present authors (Selvaraj and Madhavan 2018a) [1]. Indeed, the objective of this investigation was developed after AISI (2016) [10] said that the “New guidelines and procedures are expected in near future” for the sheathing braced design of CFS structural members.

A new test setup is developed to explore the performance of various sheathing fastener connections against the instability failure of the CFS wall studs. The appropriateness of the proposed experimental test setup is examined and reported. A total of 67 number of sheathing-fastener connections tests were carried out, and the detailed performance of the sheathing boards is presented. Based on the resistance of the sheathing boards and failure modes observed, an empirical expression to predict the actual strength and stiffness of the sheathing fastener connection is formulated. The expressions are formulated such that it applies to a large range of CFS stud dimensions and sheathing types. The validation for the expressions is assessed by statistical and direct design applications to demonstrate the effectiveness of the proposed expression. The applicability of this DSSM method and validation is provided in the latest paper by the authors [27].

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