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Cold-Formed Steel Framed Shear Walls with In-Frame Corrugated Steel Sheathing

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Abstract

The objective of this paper is to find an alternative non-combustible high-performance shear wall system that can be used in mid- and high-rise cold-formed steel (CFS) light-framed buildings. To achieve this goal, an innovative shear wall configuration with corrugated steel sheathing was proposed in this research. The proposed shear wall configuration has the corrugated steel sheathings placed inside the steel framing and hence is known as the in-frame/sheet-in shear wall. The sheet-in shear wall has an equal thickness with its adjacent walls and thus avoids the difficulties in design and installation of finish materials that suffered in common corrugated steel sheathed shear walls. This paper involves the testing of three different shear wall types in which the stud arrangement and sheathing continuity varied. The details of the test specimens and test results are presented. The results indicate that shear walls with lower profiled field stud and continuous sheathing showed satisfactory performance with balanced shear behavior and ease of assembly. Also, the innovative in-frame/sheet-in shear wall demonstrated substantially higher shear capacity than the code certified shear walls.

1. General

Cold-formed steel (CFS) light framed shear wall is the main lateral force-resisting element in CFS building systems. High-performance CFS shear wall with different sheathing materials is a topic researched all over the world. Among those, CFS shear walls with corrugated steel sheathing have showed good prospect due to its high strength, high stiffness and non-combustibility. Nowadays, CFS shear walls with corrugated steel sheathing have been used in storage buildings in U.S., see figure 1.

Figure 1: Application of corrugated steel sheathed shear walls

Shear walls with corrugated steel sheathings have been a subject of interest for multiple researchers in recent years. By experimental tests, Fülöp and Dubina [1] investigated the shear behavior of corrugated steel sheathed shear walls. Failure was attributed to damage in seam fasteners and the subsequent overall failure of the panels. Design values for corrugated steel sheathed shear walls were provided by Stojadinovic and Tipping [2] through cyclic testing of 44 shear wall specimens. Research by Yu et al. [3] mainly focused on establishing a relationship between framing thickness, sheathing thickness, as well as the size and spacing of the fasteners. Opening patterns on the corrugated steel sheathing were also investigated [4]. To explore the influence of gravity loading and to provide an experimental basis for numerical simulation, shear wall as well as bearing wall specimens were tested by Zhang et al. [5,6] under combined lateral and vertical loading. The seismic performance of the corrugated steel sheathed shear wall systems was evaluated through IDA analysis of the whole building system. Shear resistance and design deflection of the corrugated steel sheathed shear walls were also proposed [7].

Results from the above researches shows that shear walls with corrugated steel sheathing can provide greatly enhanced shear strength due to the existence of the corrugation. Traditional shear walls with corrugated steel

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sheathing usually have the corrugated steel sheathings attached on the surface of the framing members (referred as sheet-out shear walls in this research), as is shown in Figure 2. Due to the profile shape of the corrugated sheet, the sheet-out shear wall usually has an unequal wall thickness with its adjacent walls, which would result in difficulties in design and installation of finish materials. Therefore, an innovative in-frame/sheet-in shear wall configuration is conceived in this study. In this configuration the corrugated steel sheathings are placed inside the framing members. The innovative shear wall configuration is non-combustible, and is equal in width with adjacent walls, making it a possible solution in mid- and high-rise residential buildings. The test program included three shear wall types with different stud arrangement and sheathing continuity. The details of the test specimens and test results are presented in the following sections of this paper.

Figure 2: Schematic drawing of sheet-out shear walls

2. Test Program

2.1 Test Specimens

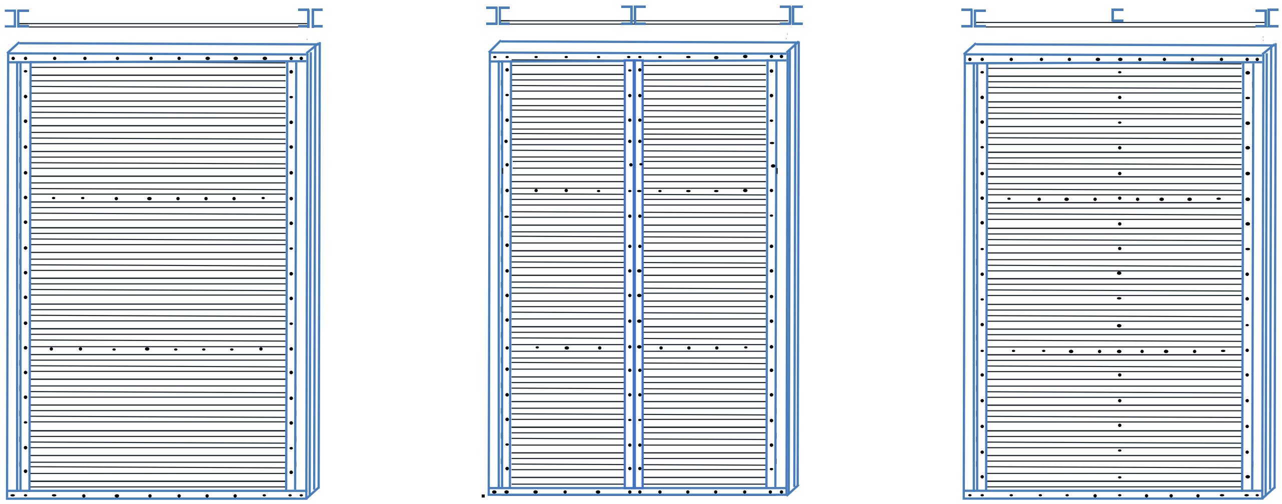
A total of 5 full scale shear wall specimens were tested in this research, including three different shear wall types, as illustrated in Figure 3. For the purpose of installation of corrugated sheathings, the chord studs were replaced with the same gauge back-to-back track columns for all test specimens. Central stud was excluded in type A shear walls and the stud spacing was 1220mm, which exceeded the maximum stud spacing of 610mm stipulated in AISI S240 [8] and AISI S400 [9]. This led to the design of type B shear wall, the interior stud of which used the same back-to-back track column as the boundary studs. The sheathings of wall type B shear wall had to be cut before assembly to fit the interior stud, which is labor-intensive and time-consuming. To avoid unnecessary cutting of the corrugated sheet, a low-profile single track (300T200-68 in this research) was placed at the center in wall type C shear walls. The low-profile C-section has a smaller web depth than the standard members to accommodate the continuous corrugated sheathing.

Table 1 summarizes the general information of grouping, labeling and main components of all test specimens. Test specimens are labeled by following rules: "Wall width (ft.) × Wall height (ft.) × Framing thickness (mil) × Sheathing thickness (mil) – Wall type and test number." The wall specimens were typical shear walls of 1.22m×2.44m (4 ft.×8 ft.) width × height constructed with 1.72mm (68 mil) framing members, 0.69mm (27mil) sheathings and No.12 × 25.4 mm (1 in.) Pan Head (PH) self-drilling screws.

All framing members used Steel Studs Manufacturers Association (SSMA, Chicago, Illinois) structural tracks with nominal strength of 345 MPa. The track columns used two Track sections connected back-to-back by two rows of No.12 × 25.4 mm (1 in.) Hex Washer Head (HWH) self-drilling screws every 152.4 mm (6 in.). The interior stud in group 3&4 shear walls used 300T200-68 and the sheathing was Shallow Verco Decking SV36 corrugated steel sheet with nominal strength of 550 MPa. Detailed profile dimensions of the corrugated deck can be found in Zhang et al. [7]. Restricted by the size of the corrugated sheets, the sheathing involved several separate sheets stitched by No.12 PH self-drilling screws. Screw spacing was 76.2 mm (3 in.) along the wall perimeter and the horizontal seams. Screw spacing along the interior stud in shear wall type C, i.e. group3&4 shear walls, was 152.4 mm (6 in.). The anchorage system comprised two S/HD15S hold-downs from Simpson Strong-Tie® and were installed on bottom portion of each chord track columns using No.14× 25.4 mm (1 in.) HWH self-drilling screws. The hold-down bolts used ASTM 490 [10] bolts with a diameter of 15.9 mm (5/8 in.). For each specimen, two additional ASTM 325 [11] shear bolts with a diameter of 15.9 mm (5/8 in.) were placed to fix the bottom track to the test bed. Layout of the corrugated steel sheets as well as the detailed dimensions of all wall specimens are shown in Figure 4.

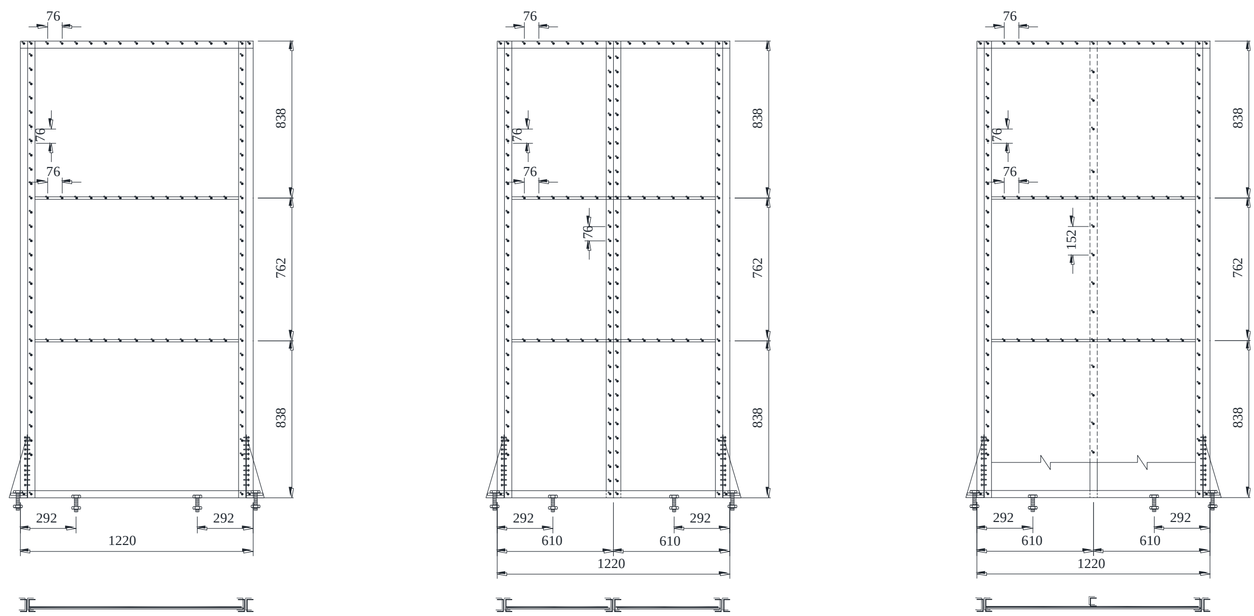
Table 1: Shear wall details

Test label	b(m)	Stud	Track	$t_{sheathing}$ (mm)	Sheathing screw
4×8×68×27-A1	1.22	350T1 50-68	362T1 50-68	0.69	#12
4×8×68×27-A2	1.22	350T1 50-68	362T1 50-68	0.69	#12
4×8×68×27-B	1.22	350T1 50-68	362T1 50-68	0.69	#12
4×8×68×27-C1	1.22	350T1 50-68	362T1 50-68	0.69	#12
4×8×68×27-C2	1.22	350T1 50-68	362T1 50-68	0.69	#12



(a) Type A (b) Type B (c) Type C

Figure 3: Schematic drawing of shear wall configuration investigated



(a) Group 1 (b) Group 2 (c) Group 3

Figure 4: Layout of shear wall specimens investigated

2.2 Test Setup and Loading Procedure

The test was performed on a 4.88 m × 3.66 m (16 ft. × 12 ft.) span × height self-equilibrating steel reaction frame. The shear wall specimen was fixed to the base beam using shear and hold-down anchors. A T-shaped loading beam was connected to the web of top track through No.12 HWH self-drilling screws. The lateral load was applied to the loading beam through a 156 kN (35 kip) hydraulic actuator with ±127 mm (5in.) stroke. Lateral supports were placed at both sides of the loading beam to restrain the out-of-plane movement. The applied lateral force was measured by a 89 kN (20 kip) universal compression/tension load cell placed between the actuator shaft and the load beam. A total of 5 position transducers were placed. The lateral horizontal placement at the top of the wall, the vertical and horizontal displacements at both ends of the wall were recorded. Figure 5 shows the details of the testing frame and the location of the position transducers.

Cyclic loading was applied in a displacement-controlled mode. The test protocol followed CUREE protocol referring to Method C in ASTM E564 [12] “Standard Practice for Static Load Test for Shear Resistance of Framed Walls for Buildings.” To obtain the post-peak behavior of the walls, 3 additional cycles were added to the standard test method. Therefore, a total of 43 cycles with specific displacement amplitudes were adopted in this research. The ultimate displacement capacity used the same value as the sheet-out shear walls in Zhang et al. [5], i.e. Δ=114.3 mm (4.5 in.). Detailed loading history and the parameters of each cycle can be found in Zhang et al. [5].

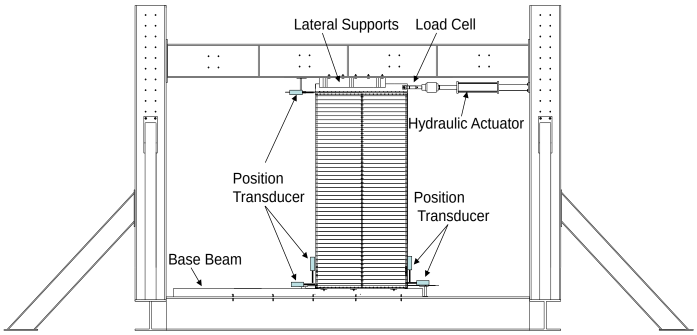


Figure 5: Test setup

3. Experimental Results

3.1 Material Properties

To examine the actual mechanical properties of test materials, coupon tests were conducted as per ASTM A370 [13] "Standard Test Methods and Definitions for Mechanical Testing of Steel Products." The tests were conducted on a universal testing machine in displacement control mode at a constant tension rate of 1.3mm/min (0.05 in./min). Prior the tensile coupon tests, the coating on the steel samples was removed by hydrochloric acid. For each steel profile, three tests were completed and the average results are reported in Table 2.

3.2 Measured Wall Properties

Table 3 summarizes the test results in this research, including the test peak load, lateral displacement at peak load, initial stiffness as well as the ductility factor. The results reported herein are the average of the positive and negative cycle results. Initial stiffness reported herein refers to the secant stiffness at the $0.4P_{max}$. The ductility factor was calculated using Equivalent energy elastic plastic model (EEEP) which is commonly used in evaluating cold-formed steel sheathed shear walls.

3.3 Observed Wall Performance and Discussions

Shear walls 4×8×68×27-A1&A2 in group 1 were shear walls without interior stud. The deformation of both specimens concentrated on the top of the sheathings. The failure initiated with a shear buckling on the corrugated steel sheathing, and progressively evolved to sheet pulling out of screw from behind of the wall on boundary track columns. As loading proceeded, the shear deformation on the top sheathings appeared alternately in both directions. By the end of loading protocol, local buckling on boundary track columns was also observed in multiple positions. Shear wall specimen 4×8×68×27-A1 had assembly defect, which led to edge tearing failure of top sheathings. Thus, the shear strength of 4×8×68×27-A1 was lower than the expected value and was ignored in later analysis. The deformations of shear wall 4×8×68×27-A2 are shown in Figure 6.

Shear wall 4×8×68×27-B used a back-to-back track column as the interior stud. The design caused the specimen to act as two parallel 0.61m×2.44m (2 ft.×8 ft.) shear wall sections. The main failure mode was screw connection failure of sheet pulling out of screws from behind the wall. Also, local buckling around sheathing screws was noticed in multiple positions along the vertical track members, as is shown in Figure 7. Compared with group 1 shear walls, shear wall 4×8×68×27-B showed a very limited improved performance. However, construction of this type of shear wall was extremely labor intensive and time consuming. Usually, 2-3 skilled students had to work almost two hours to build one wall specimen. For the above reasons, it was concluded that the shear wall configuration B was not feasible and this type of shear wall was no longer tested.

Shear walls 4×8×68×27-C1&C2 in group 3 were shear walls with a low-profile single track as the interior stud. The shear walls experienced buckling on the boundary track columns above the hold-down area near the peak point. Immediately followed was screw connection failure along the boundary track columns, characterized by screw pulling-out and elongation of the screw hole. The development of tension field was not obvious in this group walls and the deformation was concentrated on the middle sheet. The deformations of shear wall 4×8×68×27-B are shown in Figure 8.

The hysteresis curves of the above three groups of shear walls are shown in Figure 9 and Figure 10 shows the comparison of the backbone curves, along with the result of sheet-out shear walls in Zhang et al. [5]. The numerical results are presented in Table 4. As we can see, type C shear walls demonstrated the most balanced behavior among the three: highest strength, highest stiffness and comparable ductility factor of 2.26. Compared with sheet-out shear walls, the type C sheet-in shear wall yielded even higher strength, i.e. 58.1 kN/m vs. 51.8 kN/m. Due to the usage of the low-profile track, construction of such wall configuration was easier and less labor required. It's therefore determined that the shear wall configuration C is the most feasible wall configuration developed in this research. As indicated, the shear strength of shear wall with 0.69 mm in-frame corrugated steel sheathing is much higher than the wood-based panels approved in AISI S400 [9] [25.9 kN/m for 11.9 mm 4-ply Structural 1 plywood, and 33.7 kN/m for 11.1 mm OSB].

Table 2: Material properties

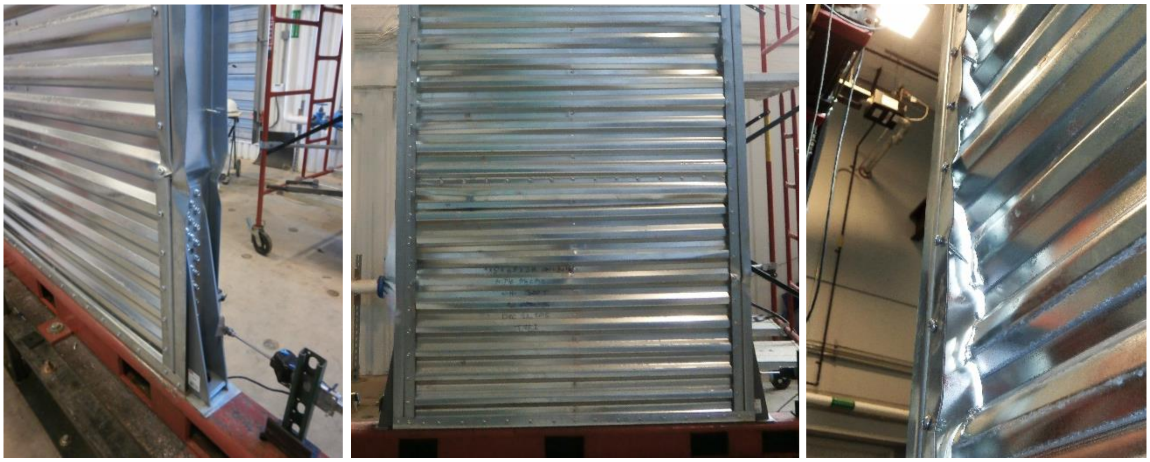
Component	Uncoated Thickness (mm)	Yield Stress Fy (MPa)	Tensile Strength Fu (MPa)	Fu/Fy	Elongation for 51mm Gage Length (%)
0.69 mm corrugated sheet	0.737	601.9	634.9	1.05	3.0
0.46 mm corrugated sheet	0.482	634.3	663.9	1.05	5.2
350T150-68	1.778	388.7	489.3	1.26	13.9
362T150-68	1.831	366.5	483.1	1.32	20.1
350T125-54	1.397	365.4	472.1	1.29	33.1
300T200-68	1.803	379.2	490.0	1.29	29.8

Table 3: Summary of shear wall test results

Group No.	Test label	P_{max} (kN)	Δ_{max} (mm)	Initial stiffness (kN/m)	Ductility factor	Shear strength (kN/m)
1	4×8×68×27-A1	36.51	37.8	1169	2.45	29.93
	4×8×68×27-A2	49.26	54.9	1706	3.24	40.38
2	4×8×68×27-B	57.93	53.9	1424	2.22	47.48
3	4×8×68×27-C1	70.62	52.1	1985	2.34	57.89
	4×8×68×27-C2	71.13	59.2	1613	2.17	58.30

(a) Sheet deformation (b) local buckling on boundary track columns (c) screw pulling out
Figure 6: Failure modes of shear wall 4×8×68×27-A2

(a) Sheet deformation (b) local buckling on boundary track columns (c) screw connection failure
Figure 7: Failure modes of shear wall 4×8×68×27-B



(a) Buckling of boundary track columns (b) Sheet deformation (c) screw connection failure
Figure 8: Failure modes of shear wall 4×8×68×27-C2

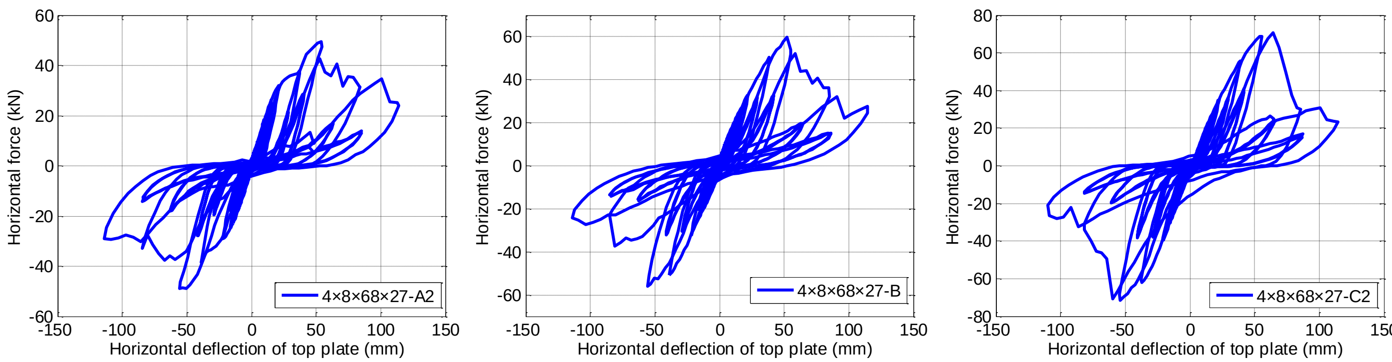


Figure 9: Hysteresis response of shear wall (a) 4×8×68×27-C2 (b) 4×8×68×27-C2 (c) 4×8×68×27-C2

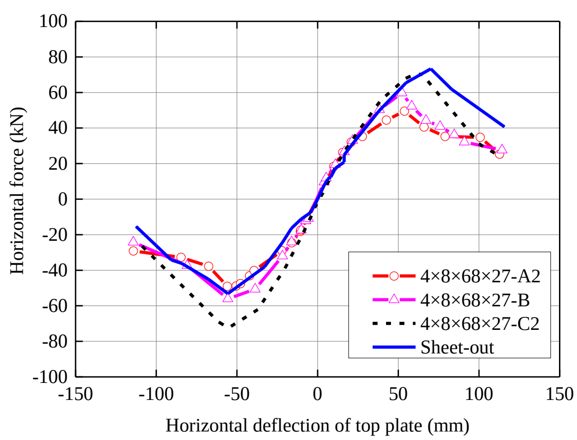


Figure 10: Comparison of the backbone curves with different configurations

Table 4: Summary of shear wall test results

	Sheet-Out [5]	Sheet-In-A	Sheet-In-B	Sheet-In-C
Average Peak Load (kN/m)	51.84	40.38	47.48	58.09
Average drift @ Peak (%)	2.59%	2.25%	2.21%	2.28%
Average initial stiffness (kN/m)	1267	1706	1424	1798
Average ductility factor	1.79	3.24	2.22	2.26
All walls are of 1.22m×2.44m, 1.72mm framing, 0.69mm sheathing, No. 12 screws 76/152mm spaced.				

4. Conclusions

An innovative in-frame/sheet-in shear wall configuration with corrugated steel sheathing was developed in the pursuit of using CFS light framed constructions in mid- and high-rise buildings. The innovative shear wall configuration has a standard wall thickness and a smooth surface with the adjacent walls, which make construction and finishing of the CFS buildings simpler and more efficient. A total of three shear wall types were tested and the results were compared. It's showed that sheet-in shear walls with a low-profile single track placed at the center exhibited the best behavior under cyclic loading. The preferred shear wall configuration avoids the unnecessary cutting of the corrugated steel sheathing and requires less labor of construction. Besides, the shear wall configuration showed significantly higher shear capacity compared with the code certified shear walls, and therefore can be used in mid- and high-rise CFS light framed buildings in high-earthquake areas.

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