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Abstract

This research is concentrated on the study of structural strength and behavior of cold-formed steel frame with strap bracing subjected to horizontal loads. The wall specimens with and without calcium silicate board sheathing were tested to compare the differences of shear resistance. Based on the test data, the ultimate strength, stiffness, ductility ratio, and failure behavior were studied for each specimen, and the wall's movements were also discussed in this paper. The cold-formed steel framing wall without bracing from previous study was introduced for the comparison purpose. As expected, the ultimate strength was increased for the cold-formed steel wall sheathed with calcium silicate board after installing strap bracing. However, the initial stiffness and ductility ratio of cladded wall specimens with bracing did not show much difference as compared to cladded wall specimens without bracing. It was found that the ultimate strength of cold-formed steel wall frame installed with both sheathing and strap bracing is not the sum of ultimate strengths of cold-formed steel wall frame with sheathing and cold-formed steel wall frame with strap bracing only. A better performance of energy absorption beyond the portion of ultimate strength was found for the wall specimen with both sheathing and bracing. It was also observed that the failure type and location are different for the cladded wall specimens with and without bracing.

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1. Introduction

Cold-formed steel framing structures are getting popular and accepted type of residential buildings in North America and other areas such as Australia, Japan and Europe, due to the characteristic of high strength-to-weight ratio, design flexibility for architect and builder, easy to fabricate and construct, and no influence on temperature and humidity changes. Basically, steel framing building is constructed by wall system which is used to carry vertical and horizontal loads. The wall system is fabricated by cold-formed steel framing sheathed by cement fiber board, gypsum board, calcium silicate board, and steel panel. Because the steel framing walls with panel sheathing have been studied by many researchers, this study is focused on the structural strength and behavior of cold-formed steel frame with both sheathing and strap bracing subjected to horizontal loads. The LVDTs were adopted to measure the lateral and vertical displacements of specimen, and strain gages were mounted on the surface of sheathing boards and strap bracings to record to strain changes during the test.

Zeynalian and et al (2012) conducted a series of experiments to investigate the lateral performance of K-braced cold-formed steel structures and their response modification coefficients, R factor. As can be seen in Figure 1, total of 12 full-scale 2.4×2.4 m specimens of different configurations were studied under a standard cyclic loading regime. All of the frame elements, such as top and bottom tracks, noggins, studs and K-elements were made by an identical C-section of dimensions 90×36×0.55 in mm. The dimensions of the straps' cross sections are 30×0.8 mm. Based on the test result, the common failure mode for most of the specimens was plastic local buckling in the K-elements to studs connections, which was followed by rivet pull-out. For specimen K11, which consisted of both strap and K-braces, the failure mode was the pull-out of the screws of the strap-to-stud connections while no significant buckling was observed in the elements during the test. This is because the stiffness of the strap-brace system is higher than the K-stud system. They concluded the strength of shear panels having both lateral resistant systems concurrently is not equal to the sum of the strengths of two separate panels having either of the systems only.

An experimental program was designed and tested by Moghimi and Ronagh (2009a & 2009b) to provide information on the failure modes of walls braced with different types of strap braces and to study the effects of various parameters on the vertical and lateral performance of cold-formed steel shear panels subjected to cyclic loads. The test program consisted of 20 full-scale specimens to evaluate the performance of five different strap-braced walls. All of the frame components, i.e. top and bottom tracks, noggings and studs, were identical C channels of 90_36_0:55, connected together by one rivet at each flange. In specimens using gypsum board as cladding, two 10 mm thick sheets of 2400×1200 mm size were placed horizontally and connected to one side of all frame members by self-tapping screws at 150 mm intervals. Each back-to-back double section was constructed by connecting the web of two sections by screws at 150 mm centers. Figure 2 shows two typical strap-braced specimens with/without sheathing.

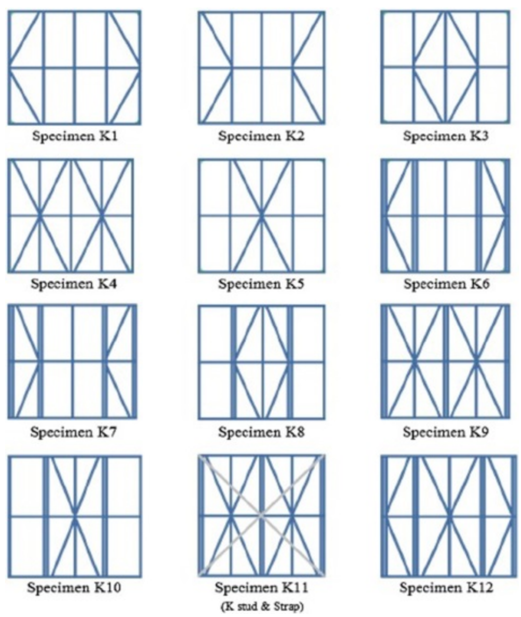

Figure 1 Configuration of specimens K1 to K12

They found out that adding brackets at four corners of the wall panel improves the lateral performance (strength, stiffness and ductility) of the wall panel considerably, even when only a single stud is used as a chord member; gusset plates provide enough room for connecting straps to the panel (eliminating the possibility of strap-to-panel connection failure), and present a good performance with sufficient ductility and stiffness; and strap-braced walls without gypsum board or bracket members present severe pinching in their hysteretic loops due to plastic slack of strap braces and lack of redundancies. The energy absorption capacity therefore is not satisfactory and cyclic loads may present an additional impact due to the straps' slack.

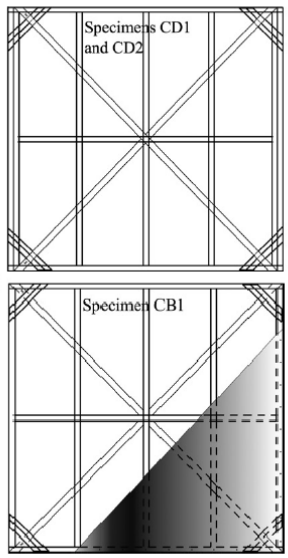

Figure 2 Configuration of specimen CD and CB1

2. Experimental Study

2.1 Specimen

The material designated Chinese National Standard (CNS) No. 6183 and G3122 (1995) is used to fabricate the cold-formed steel wall framing members. The mechanical properties are in accordance with a nominal ultimate strength (F_u) of 400 MPa and up, and a yield strength (F_y) above 245 MPa. Based on the tensile testing, the material properties had a F_u of 414.5 MPa and a F_y of 330.1 MPa, which met the regulations. The 9-mm thick calcium silicate board of categorized in the No. 13777 and A2266 of fibred cement plate in Chinese National Standard (2001) is adopted as sheathing material.

The test wall specimen is assembled by cold-formed steel framing, calcium silicate board, and two steel straps. The steel framing employed C-shaped studs of 92 mm×65 mm×12 mm section which had a thickness of 1.6 mm and length of 240 cm, and channels having a cross-sectional dimension of 95 mm×45 mm, thickness of 2.3 mm, and length of 128.4 cm, which placed on the two ends of studs and connected together by # 10 self-drilling screws. The 39 mm×39 mm openings with center to center distance of 50 cm are utilized in the web of stud. Figure 3 shows the dimensions of wall specimen and the screw arrangement. Four rectangular steel plates placed on the corners of steel framing by self-drilling screws are utilized to connect steel strap to the steel framing. Same as steel framing section, the thickness of both steel strap and gusset plate is 1.6 mm. Figure 4 shows the configuration of wall specimen with calcium silicate board on one side and X strap bracing (diagonal strap bracing) on the other side.

2.2 Test setup

As can be seen in Figure 5, the bottom track of specimens was bolted to the support I-beam. The hold-down devices were used to anchor two chord studs of steel frame to the support beam as well. A 50-ton capacity MTS testing machine was used to apply the monotonic shear load to the top beam of wall specimen. The horizontal load is applied in a constant speed of 5 mm/min to the test specimen until the test failure occurred. The LVDTs were applied to obtain lateral and vertical displacements. Strain gages attached on sheathed board were also used to determine the strain variations during test.

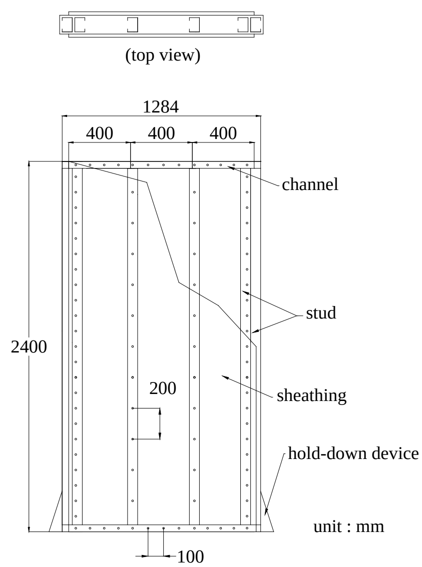

Figure 3 Dimensions of wall specimen

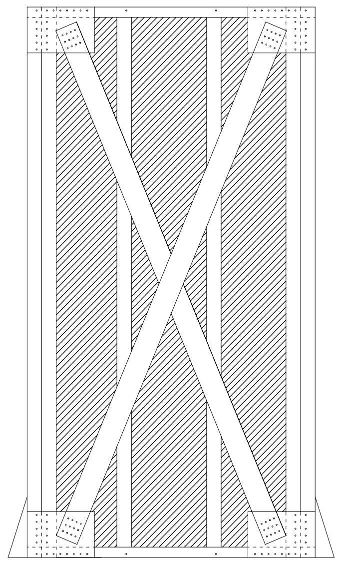

Figure 4 Configuration of specimen

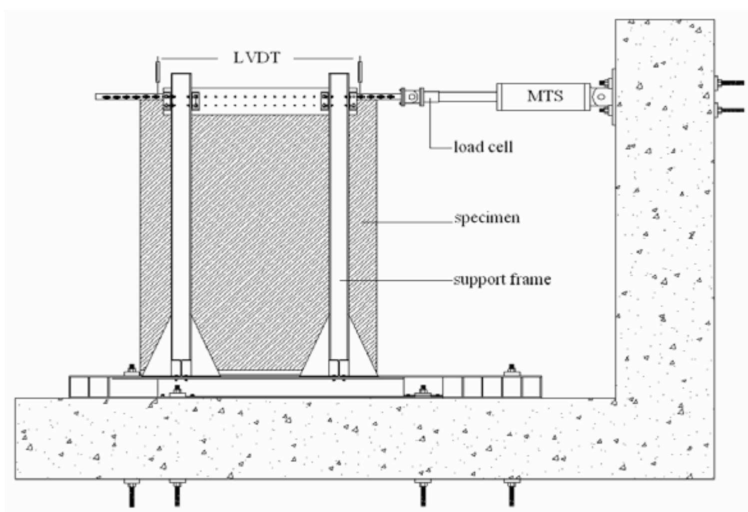

Figure 5 Setup of wall test specimen

3. Test Results and Evaluations

3.1 Failure mode and ultimate strength

A total of 6 wall specimens were conducted in test program. There are three groups of test specimens: (1) steel frame with both steel straps and sheathing; (2) steel frame with steel straps only; and (3) steel frame without strap and sheathing. The specimen numbered as B10 is the steel frame with 10-cm width of strap bracing. The specimen sheathed with 9-mm thick board is numbered as C09. Figure 6 represents the tested load-displacement diagrams for all specimens. The specimen HM-C09-HO1, sheathed with 9-mm thick calcium silicate board, shown in Figure 6 was tested by Chen (2010) for the comparison purpose. Table 1 lists the ultimate strength and its corresponding displacement for each wall specimen including previous test specimen (HM-C09-HO1) under horizontal load.

The rigid body motion of rotation was found for the specimen HMB10-C09-HO1, because the anchor bolt used in the hold-down device was pulled upward from the bottom beam. To prevent local failure of bottom beam, the connected flange of bottom beam was welded a thicker steel plate, and the larger diameter and high strength bolt was utilized as anchored bolt. As a consequence, the failure type of specimen HMB10-C09-HO2 was different from the specimen HMB10-C09-HO1 due to the improvement of anchor condition. From observing the specimen HMB10-C09-HO2 during test, the calcium silicate board started to crack from the bottom area as the load reached 29.79 kN. The crack extended to middle high of sheathing as the load reached 42.32 kN as can be seen in Figure 7. It is noticed that the local buckling of chord studs was found close to the area of top gusset plate as the load reached 39.23 kN. Figure 8 shows the photo of stud's buckling. The load of specimen HMB10-C09-HO2 reached to the maximum (46.12 kN) when the sheathing started to fracture at top area of wall specimen.

Table 1 Tested ultimate strength of each specimen

Specimen	P_u (kN)	ΔP_u (mm)
HMB10-C09-HO1	47.40	63.77
HMB10-C09-HO2	46.12	56.07
HMB10-C09-HO3	50.13	55.07
HM-C09-HO1	33.12	43.35
HMB10-1	22.94	118.01
HMB10-2	22.78	59.32
HM-1	3.49	244.11

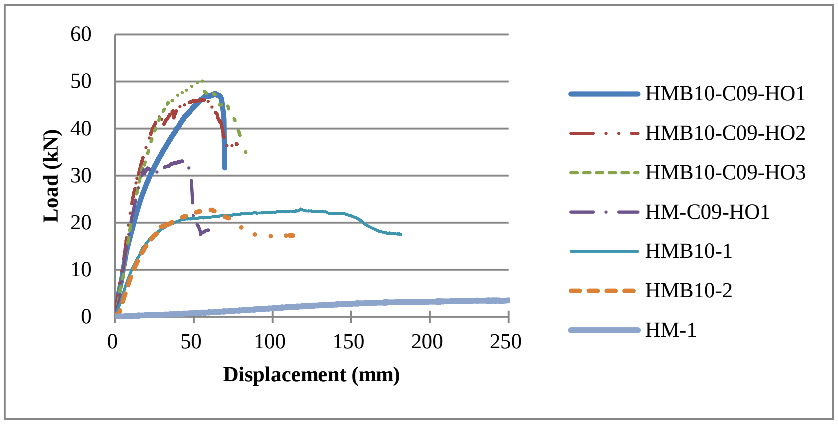

Figure 6 Load and displacement curves of test specimens

For the specimens with steel strap bracing only (HMB10-1 and HMB10-2), the failure mode of local buckling was observed at bottom portion of inside chord stud which was located at loading side (front end) in middle stage of loading. The specimens reached to the maximum when the torsional-flexural buckling was occurred in top portion of chord studs of back end, and the wall twisted outward to the plane with no bracing, due to both shear and bending actions. Similar phenomenon was found in the specimen without sheathing and bracing (HM-1), the local buckling was occurred at lower portion of chord studs located at loading side in middle stage of loading, the ultimate strength (3.49 kN) was reached as the lower portion of chord studs at opposite end buckled locally.

As expected, the steel frame with both sheathing and steel strap has a highest ultimate strength as compared with other groups of wall specimen. However, the strength of steel frame having both lateral resistant devices (calcium silicate board and X strap bracing) is not equal to the sum of the strengths of two separate steel frame with either of the devices only. Similar finding was concluded in the research of Zeynalian and et al (2012).

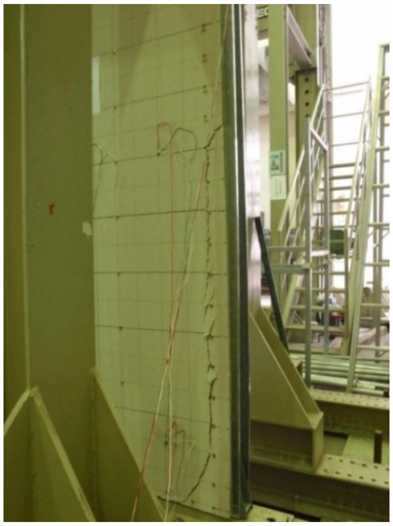

Figure 7 Fracture of Sheathed board

Figure 8 Local buckling of chord studs

3.2 Stiffness and ductility ratio

According to the regulation of ASTM E2126 (2005), the stiffness of structure (K_e) can be defined as the slope of tested load-displacement curve between zero and $0.4P_{max}$ (maximum load). Table 2 lists the stiffness for all tests. The specimen HM-C09-HO1 sheathed with calcium silicate board tested previously was also listed in Table 2. As compared HMB10 specimen to HM-C09-HO specimen, the stiffness of wall specimen with sheathing is about two times than the stiffness of wall specimen with strap bracing only. It is also observed from Table 2 that the stiffness of specimen with both sheathing and strap bracing is quite close to the stiffness of specimen with sheathing only. It is because the sheathing provides most of shear resistance in the early and middle stages of loading for the specimen with both sheathing and bracing.

In order to obtain the stress in horizontal and vertical directions and to calculate the principal stresses at different location in the specimen HMB10-C09-HO2, nine three-axis strain gages were mounted on the calcium silicate board and one three-axis strain gage was attached in the center of diagonal steel strap. Figure 9 shows the readings of strain gage located at steel strap. The angles between longitudinal axis of diagonal strap and 0^o strain gage, 45^o strain gage, and 90^o strain gage are 67^o, 22^o, and 23^o, respectively. This is why the strain changes for 45^o strain gage and 90^o strain gage are very similar, during the test, as can be seen in Figure 9. It is observed from Figure 3 that the steel strap bracing provided a consistent stiffness and shear resistance for wall specimen HMB10-C09-HO2 until the fracture appeared at top area of sheathing of wall. Therefore, the steel strap bracing plays an important role in increasing the strength and energy absorption of wall specimen in the middle and late stages of loading, as well as extends the ductility to prevent the wall from collapse instantly after specimen reaching the maximum load.

Table 2 Stiffness of each specimen

Specimen	$0.4P_u$ (kN)	$\Delta 0.4P_u$ (mm)	K_e (kN/mm)
HMB10-C09-HO1	18.96	11.18	1.70
HMB10-C09-HO2	18.45	7.89	2.34
HMB10-C09-HO3	20.05	10.26	1.95
HM-C09-HO1	13.25	6.51	2.04
HMB10-1	9.18	9.50	0.97
HMB10-2	10.68	9.11	0.85
HM-1	1.46	83.36	0.01

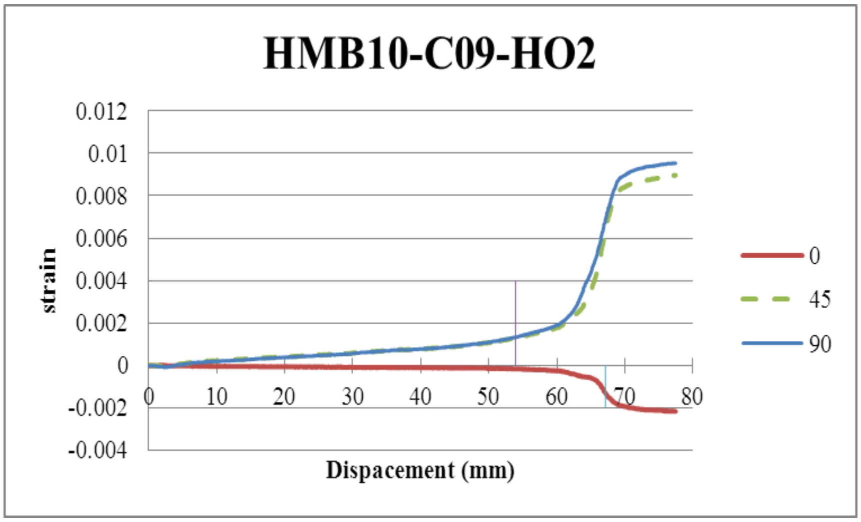

Figure 8 Strain and displacement relationships of strap bracing

The definition of ductility ratio, μ, is the ratio of the ultimate displacement to the yield displacement, D_u/D_y. In the calculation of ductility ratio, the failure limit state (D_u) can be defined as the 80% post ultimate load (AISI, 2007), and the yield state (D_y) can be obtained by adopting the equivalent energy elastic-plastic analysis model which is based on the notion that the energy dissipated by the wall specimen during a monotonic or reserved cyclic test is equivalent to the energy represented by a bilinear curve (AISI, 2007). Table 3 lists the ductility ratio for all tests. It can be observed from Table 3 that the steel fame with steel strap bracing only has highest ductility ratios, and the steel frame having one-side sheathing has lowest value. It seems that sheathed steel frame can increase not only shear resistant capacity but also ductility ratio after installing diagonal strap bracing.

Table 3 Ductility of each specimen

Specimen	D_y (mm)	D_u (mm)	μ
HMB10-C09-HO1	24.15	69.37	2.87
HMB10-C09-HO2	18.09	70.58	3.90
HMB10-C09-HO3	23.05	77.87	3.38
HM-C09-HO1	15.28	48.87	3.20
HMB10- 1	21.80	166.40	7.63
HMB10- 2	18.09	83.87	4.64

4. Conclusions

A total of 6 wall specimens were conducted in this study including steel frame with both steel straps and sheathing; steel frame with steel straps only; and steel frame without strap and sheathing. The cold-formed steel framing wall sheathed with calcium silicate board from previous study was introduced for the comparison purpose. The following conclusions can be drawn from the research's findings:

1. The strength of steel frame having both lateral resistant devices (calcium silicate board and X strap bracing) is not equal to the sum of the strengths of two separate steel frame with either of the devices only. However, the wall specimen with sheathing increases 45% of strength after installing with diagonal steel strap bracing.
2. The energy absorption between origin and yield state for the steel fame with both sheathing and steel strap bracing is equal to the sum of the energy absorptions of wall frame with sheathing and wall frame with strap bracing only.
3. The stiffness of steel frame with steel strap bracing is about 44% less than the stiffness of steel frame with sheathing. The stiffness of steel frame with both sheathing and strap bracing is quite close to the stiffness of specimen with sheathing only. It is found that the sheathing provides most of shear resistance in the early and middle stages of loading for the specimen with both sheathing and bracing.
4. The ductility ratio can be improved for the sheathed steel frame after installing diagonal strap bracing.

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