Research Article

Investigation on the Design Method of Shear Strength and Lateral Stiffness of the Cold-Formed Steel Shear Wall

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The assembled cold-formed steel (CFS) stud shear walls are the main lateral force resisting members of cold-formed steel residential buildings due to higher strength/weight ratio and faster construction [1]. The CFS stud shear walls are commonly assembled by C-shaped CFS studs (lipped channel), U-shaped CFS tracks (unlipped channel), sheathing (such as gypsum board and oriented strand board (i.e., OSB), ), which are connected by fasteners, typically self-drilling screws, as shown in Figure 1.

American Iron and Steel Institute provides design rules for CFS framed buildings in AISI S100, S200, and S213 [2–4]. Notably, based on the research conducted by Serrette et al. [5, 6], the AISI S213 [4] provides nominal strength for three different types of sheathing. Tabled values are based on maximum aspect ratio, fastener spacing at the panel edge, and stud and track thickness.

1. Introduction

The assembled cold-formed steel (CFS) stud shear walls are the main lateral force resisting members of cold-formed steel residential buildings due to higher strength/weight ratio and faster construction [1]. The CFS stud shear walls are commonly assembled by C-shaped CFS studs (lipped channel), U-shaped CFS tracks (unlipped channel), sheathing (such as gypsum board and oriented strand board (i.e., OSB), ), which are connected by fasteners, typically self-drilling screws, as shown in Figure 1.

The shear strength of the CFS shear wall is related to the material and dimension of the sheathing, the spacing and dimension of the screws, the height and length ratio of the shear wall, the spacing of the studs, and so on. Due to the need for understanding the behavior of these structures, the lateral resistance behaviors of CFS shear walls have been investigated both experimentally [5–14] and theoretically [15–17].

The shear resistance performances of the CFS shear walls with different sheathing materials (plywood, OSB wallboard, gypsum wallboard, and FiberBond wallboard) was investigated through both full-scale static racking tests and small-scale lateral shear tests by Serrette et al. [5, 6]. The structural behavior of CFS walls under combined lateral and vertical loads was studied by Lange and Naujoks [7]. The experimental studies of the structural strength of CFS shear wall with different sheathing materials (gypsum board, calcium silicate board, and OSB board), different sheathing
thicknesses, and wall aspect ratio under monotonic shear loading were carried out by Pan and Shan [8]. The static lateral load tests were conducted on CFS shear walls with OSB sheathing to investigate the performance of CFS walls utilizing primarily the construction details used in Turkey by Baran [9]. Liu et al. [10] explore and characterize the impact of practical construction details on the cyclic performance of CFS framed shear walls sheathed with OSB board. Javaherifar-Taft [11], Yu [12], Attari [13], and Mohebbi [14] investigated the shear behavior of the CFS shear wall with steel sheet sheathing by test and evaluated the failure modes of the systems. The experimental and theoretical studies on the racking strength and stiffness of CFS wall frames braced with different strap configurations were performed by Tian [15]. The analytical method, which considers the material properties, geometrical dimensions, and construction details, was proposed to determine the ultimate lateral strength and associated displacement of the shear wall panel by Xu [16]. Nithyadharan [17] carried out the experimental study on the behavior and strength of the CFS shear wall with calcium silicate board as sheathing and proposed a simplified design equation was to evaluate the ultimate shear strength of the CFS shear wall based on the strength of the screw connection.

The shear strength and the deformation capacity of the CFS shear wall to resist lateral load are two of the most important issues of the CFS framing buildings. In current practice, the lateral shear strength and the lateral displacement of the shear walls with CFS framing are primarily determined by tests, owing to the lack of applicable analytical methods. As the CFS applications become more popular in the low-rise and mid-rise commercial buildings, the wider range options of the CFS shear walls are desired by engineers.

The main purposes of this study are to observe the failure modes of the CFS shear wall utilizing primarily the construction details, obtain the shear strength of the shear wall, and propose the design method to calculate the shear strength and lateral stiffness of the CFS shear wall.

In this paper, three CFS shear walls with different types of sheathing (the gypsum board and the OSB board) were tested under the monotonic lateral loading. The failure modes, the shear strength, and the load-displacement curves of the CFS shear walls were obtained and analyzed to investigate the relationship between screws and shear walls. The design methods of the shear strength and the lateral stiffness of the CFS shear walls were proposed. And the design methods were evaluated by comparing the calculated results with the test results.

2. Test Program

2.1. Test Specimens. The dimensions and configurations of the shear wall are illustrated in Figure 2. As can be seen from Figure 2, the studs inside the wall were C-shaped (lipped channel) CFS channel with the spacing of 600 mm; the top and bottom tracks were U-shaped (lipped channel) CFS channel. The types of the sheathing were gypsum and OSB, whose thicknesses were 12 mm and 9 mm, respectively. The gypsum and OSB board were connected to the CFS studs with ST42 × 32 (its diameter is 4.2 mm and length is 32 mm) and ST48 × 19 (its diameter is 4.8 mm and length is 19 mm) self-drilling screws [18] (as shown in Figure 2), respectively. According to the Chinese standard JGJ 227–2011 [19] Section 8.2, the spacings of the screws were 300 mm at the intermediate of the board and 150 mm at the boundary of each board. The studs in the intermediate of the CFS shear wall were single C-shaped CFS channel, and the studs at both sides of the wall were C-shaped channels built-up studs with back-to-back connected by screws. The M16 (its diameter is 16 mm) hold-down anchors were used to connecting the walls to the steel beam at the bottom corner of the wall. The top and bottom tracks of the wall were fixed to the steel beam by M12 (its diameter is 12 mm) antishear anchors. It needed to be mentioned that there was a vertical connecting seam on all walls and a horizontal connecting seam on the OSB sheathed wall because the length of the OSB board was shorter than the height of the CFS shear wall. Therefore, the steel strap with 50 mm × 1.0 mm (width × thickness) was set to strengthen the connecting along the horizontal seam. The numbers and parameters of the specimens are presented in Table 1.

2.2. Test Setup and Loading Protocol. The test setup is depicted in Figures 3 and 4. The arrangement of the displacement meters is shown in Figure 5. The lateral load was applied to the shear wall through the electrohydraulic servo actuator, and the lateral braces were also provided to limit
the out-of-plane movement of the specimen. The test process was controlled by the servo-control mechanism and computer. All the test data were collected by a 7V08 data collector.

The CFS shear walls were loaded under the monotonic loading. According to the Chinese standard (JG 227–2011) [19], the shear wall was subjected to 1 kN of lateral loading at each stage. After the shear wall yielded, the lateral loading was controlled by the displacement with the speed of displacement loading set as 2 mm/min. The specimen was applied 4 mm of lateral displacement at each stage. The shear wall was held for 3 minutes before proceeding to the next stage until the shear wall was destroyed.

2.3. Observation from the Test. The failure modes of the three specimens were similar, and the failure modes of partial specimens are presented in Figure 6. When the specimens were failed under the lateral load, most of the screws at the outer rim of the wall were damaged, but the gypsum board or OSB board did not fall down due to the less failure of the screws inside the shear wall. The local buckling occurred on the studs, which were on the sides of the shear wall (as shown in Figure 6(e)). The shear strength and lateral stiffness of the WALL1 specimen were lower than those of the other two specimens. The relative rotation between the two gypsum boards took place, with the vertical connecting seam offset in the same specimen. The gypsum board tore at the corner of the shear wall (as shown in Figure 6(b)). The shear strength of the WALL2 specimen was higher than that of the WALL1 specimen, but the horizontal connecting seam in the WALL2 specimen influenced its mechanical behavior. With the increase of loading, the steel strap buckled obviously (as indicated in Figure 6(c)) and the slippages of the panels of the OSB board were relatively greater (as presented in Figure 6(c)). The integrity, strength, and stiffness of the WALL3 specimen were better than those of the WALL1 and WALL2 specimens.

| Numbers | CFS member | Sheathing material | Screw spacing |
|---------|------------|--------------------|---------------|
| WALL1   | Studs: C89 × 44.5 × 12 × 1.0 (lipped channel: the web is 89 mm, the flange is 44.5 mm, the lip is 12 mm, and thickness is 1 mm) | With one-side gypsum board, the dimension is 1.2 m × 3 m (width × height) and the thickness is 12 mm | At the boundary of the board: 150 mm; at the intermediate of the board: 300 mm |
| WALL2   | Tracks: U92 × 40 × 1.0 (unlipped channel: the web is 91 mm, the flange is 40 mm, and thickness is 1 mm) | With one-side OSB board, the dimension is 1.2 m × 2.4 m (width × height) and the thickness is 9 mm | |
| WALL3   | Strap: 50 mm × 1.0 mm (width × thickness) | Gypsum board with a thickness of 12 mm on one side and OSB board with a thickness of 9 mm on the other side | |

Figure 2: Configuration of the shear wall (unit: mm). (1) Built-up CFS channel stud with back-to-back; (2) C-shaped CFS channel stud; (3) U-shaped CFS channel track; (4) strap; (5) self-drilling screw; (6) gypsum board; (7) OSB board

Table 1: Numbers and parameters of the specimens.
Figure 3: Configuration of the test setup.

(a) Photograph of (a) the test setup and (b) the bottom beam.

Figure 5: Arrangement of the displacement meters.
2.4. Test Results. The load-displacement curves of specimens are shown in Figure 7. The yield strength of the shear walls was determined by the method prescribed in the Chinese specification [21]. The method is illustrated in Figure 8.

As shown in Figure 8, the horizontal line $AB$ was drawn from the point $A$ (the point of the maximum strength $P_{\text{max}}$) firstly; then, line $OD$ was drawn to intersect line $AB$ and curve $OA$ at point $D$ and $C$, respectively; at the same time, the area $ADCA$ was equal to the area $CFOC$; finally, a vertical line $DG$ was drawn from point $D$ to intersect curve $OA$ at point $E$. The value of load and displacement of point $E$ was defined as the yield strength $P_y$ and the yield displacement $\Delta_y$ of the shear wall, respectively. When the load descends to $0.85P_{\text{max}}$, the corresponding load and displacement were defined as the failure strength $P_u$ and the failure displacement $\Delta_u$, respectively. The test results are presented in Table 2.

As shown in Table 2, the yield strength $P_y$, maximum strength $P_{\text{max}}$ and failure strength $P_u$ of WALL2 specimen were approximately 2.87, 2.94, and 2.94 times than those of WALL1 specimen. The sum of yield strength and maximum strength of the WALL1 and the WALL2 specimens was 28.98 kN and 35.96 kN, respectively, which are close to the yield strength 29.12 kN and the maximum load 34.99 kN of the WALL3 specimen, respectively.
3. The Design Method of the Shear Strength of the Shear Wall

According to the failure modes of the CFS shear walls as shown in Figure 6, the shear strengths of the specimens were usually governed by the strength of the screw connections between the board and the CFS stud. The design method was based on the relationship between the shear strength of the CFS shear wall per unit length and the shear strength of the single screw. The screw spacings inside the shear wall, the force direction, and the internal CFS studs were considered; however, some secondary factors were neglected in the design method. The mechanism of the CFS shear wall to resist the lateral shear loading was analyzed.

3.1. Basic Assumptions. The assumptions of the mechanical model of the screws on the CFS shear wall were made as follows, and the mechanical model based on the equilibrium equation of the moment is shown in Figure 9.

(1) The shear force $F_{yi}$ of the screws at the upper and bottom ends of the CFS shear wall could be decomposed into the component force $F_{ex}$ in the $X$ direction and the component force $F_{eyi}$ in the $Y$ direction. The component force $F_{ex}$ in the $X$ direction is evenly distributed, and the component force $F_{eyi}$ in the $Y$ direction is proportional to the distance of the screw to the centerline of the sheathing ($X_{eyi}$).

(2) The screws, which are on both left and right sides of the CFS shear wall, bear the component force $F_{yi}$ in the $Y$ direction only, and the distribution of the component force $F_{yi}$ is uniform along the studs of the CFS shear wall.

(3) The screws, which are at the inside of the CFS shear wall, bear the component force $F_{si}$ in the $Y$ direction only. The value of $F_{si}$ is proportional to the distance of the screw to the centerline of the sheathing ($X_{si}$).

(4) The CFS shear wall varies with the number, size, type, spacing of the screws, the stud spacing, and the sheathing material. The type of screws in the same CFS shear wall is identical. The screws and the studs of the CFS shear wall are symmetrically arranged along the centerline of the CFS shear wall.

(5) When the shear strength of the screw reaches the maximum value, the shear strength of the CFS shear wall is considered to reach the maximum value too.

| Numbers | $P_y$ (kN) | $\Delta_y$ (mm) | $P_{\text{max}}$ (kN) | $\Delta_{\text{max}}$ (mm) | $P_u$ (kN) | $\Delta_u$ (mm) | Shear strength (kN·m$^{-1}$) |
|---------|------------|----------------|-----------------------|--------------------------|------------|----------------|-----------------------------|
| WALL1   | 7.48       | 13.5           | 9.12                  | 48                       | 7.75       | 74.8           | 3.8                         |
| WALL2   | 21.50      | 23.9           | 26.84                 | 51.21                    | 22.81      | 68             | 11.18                       |
| WALL3   | 29.12      | 19.6           | 34.99                 | 59.62                    | 29.72      | 74             | 14.58                       |

Note: $P_y$ is the yield strength; $\Delta_y$ is the yield displacement; $P_{\text{max}}$ is the maximum strength; $\Delta_{\text{max}}$ is the maximum displacement; $P_u$ is the failure strength; $\Delta_u$ is the failure displacement.
3.2. Calculation Formulas. According to the mechanical model, as shown in Figure 9, the moment equilibrium equation is established as shown in equation (1) about the point O, which is the center of the shear wall:

\[
F_x n_L - F_{ex} n_e H + 2 \sum_{i=1}^{n_i} F_{exi} x_{ei} + n_{si} \sum_{i=1}^{m} F_{si} x_{si} = 0, \tag{1}
\]

where, \(F_i\) is the shear force of the screw at the edge of the shear wall; \(F_{exi}\) is the shear force of the \(i\)th screw at the end of the shear wall; \(F_{si}\) is the shear force of the \(i\)th screw inside the shear wall; \(F_{exi}\) is the component force of \(F_{exi}\) in the \(Y\) direction, \(F_{exi}\) is the component force of \(F_{exi}\) in the \(X\) direction; \(n_i\) is the number of screws at one end of the shear wall. \(n_{si}\) is the number of the \(i\)th screws on one internal column inside the shear wall; \(x_{ei}\) is the distance from the \(i\)th screw at the end of the shear wall to the centerline of the sheathing; \(x_{si}\) is the distance from the \(i\)th internal screw inside the shear wall to the centerline of the sheathing; \(L\) is the length of the shear wall; and \(H\) is the height of the shear wall.

According to the equilibrium principle of force, the lateral force \(P\) of the shear wall is resisted by the component force of the screw at the end of the shear wall in the \(X\) direction \((F_{ex})\). It is assumed that each screw is subjected to a uniform horizontal component force \(F_{exi}\) in the \(X\) direction. Therefore, the horizontal component force is given by

\[
F_{ex} = \frac{P}{n_e} = \frac{VL}{n_e}, \tag{2}
\]

where \(P\) is the concentrated load applied to the upper of the shear wall and \(V\) is the shear strength of the shear wall with unit length.

As shown in Figure 9, the component force of \(F_{exi}\) in the \(Y\) direction on the screw at the corner of the shear wall is \(F_{ei}\). Based on the principle of similar triangles, \(F_{exi}\) and \(F_{ei}\) as well as \(F_{si}\) and \(F_{ei}\) have the relationship as shown in the following equations, respectively:

\[
F_{exi} = \frac{2x_{ei} F_{s}}{L}, \tag{3}
\]

\[
F_{si} = \frac{2x_{ei} F_{s}}{L}. \tag{4}
\]

Combining equations (2), (3), and (4) into equation (1), the following equation could be concluded:

\[
F_{ex} n_L - F_{ex} n_e H + \frac{2 F_s}{L} \left( 2 \sum_{i=1}^{n_i} x_{ei}^2 + n_{si} \sum_{i=1}^{m} x_{si}^2 \right) = 0. \tag{5}
\]

Then, the shear force of the screw on the side column of the shear wall is given by

\[
F_s = \frac{VH}{n_x + (4 \sum_{i=1}^{n_i} x_{ei}^2 + 2n_{si} \sum_{i=1}^{m} x_{si}^2)/L^2}. \tag{6}
\]

The shear force \(F_{ei}\) of the screw at the end of the shear wall is composed of \(F_{ei}\) in the \(X\) direction and \(F_{exi}\) in the \(Y\) direction.

Combining equations (6) and (3), the following equation could be concluded:

\[
F_{exi} = \frac{2x_{ei} F_{s}}{L} = \frac{2x_{ei} VH}{Ln_e + (4 \sum_{i=1}^{n_i} x_{ei}^2 + 2n_{si} \sum_{i=1}^{m} x_{si}^2)/L}. \tag{7}
\]

Therefore, the shear force of the screw at the end of the shear wall is given by

\[
F_{ei} = \left( F_{exi}^2 + F_{si}^2 \right)^{1/2} = \sqrt{\left(VL/n_e\right)^2 + \left(\frac{2x_{ei} VH}{Ln_e + (4 \sum_{i=1}^{n_i} x_{ei}^2 + 2n_{si} \sum_{i=1}^{m} x_{si}^2)/L}\right)^2}. \tag{8}
\]

Combining equations (7) and (4), the shear force of the screw on the internal column of the shear wall is given by

\[
F_{si} = \frac{2x_{ei} F_{s}}{L} = \frac{2x_{ei} VH}{Ln_e + (4 \sum_{i=1}^{n_i} x_{ei}^2 + 2n_{si} \sum_{i=1}^{m} x_{si}^2)/L}. \tag{9}
\]

Equations (8), (10), and (11) are given to calculate the shear force of screws in the different parts of the shear wall.

The failure of the screws could occur at the side of the shear wall or at the end of the shear wall, which is controlled and calculated by equations (6) and (8), respectively.

The shear force \(F_i\) of the screw on the side column of the shear wall and the shear force \(F_{ei}\) of the screw at the end of the shear wall have the relationship with the shear force \(V\) of the shear wall with unit length as shown in the following equations, respectively:

\[
\alpha_s = \frac{F_i}{V} = \frac{H}{n_x + (4 \sum_{i=1}^{n_i} x_{ei}^2 + 2n_{si} \sum_{i=1}^{m} x_{si}^2)/L^2}. \tag{10}
\]

\[
\alpha_{ei} = \frac{F_{ei}}{V} = \left(\frac{(L/n_e)}{2x_{ei} H/Ln_e + (4 \sum_{i=1}^{n_i} x_{ei}^2 + 2n_{si} \sum_{i=1}^{m} x_{si}^2)/L^2}\right)^2. \tag{11}
\]

The design shear strength of the CFS shear wall is given by

\[
P_c = \frac{VL}{\alpha_{max}}. \tag{12}
\]

The modified design shear strength of the CFS shear wall is given by

\[
P_m = \gamma P_c = \frac{\gamma f_d L}{\alpha_{max}}. \tag{13}
\]

where \(P_c\) is the design shear strength of the CFS shear wall; \(P_m\) is the modified design shear strength of the CFS shear wall; \(f_d\) is the design shear strength of single screw (we have obtained the values of \(f_d\) by the laboratory tests [22]: for gypsum board, \(f_d = 274\) N; for OSB board, \(f_d = 907\) N; and for double-side sheathings, \(f_d = 274 + 907 = 1181\) N); \(\gamma\) is the modified coefficient, which is determined by the test and is related to material of sheathing: for one-side gypsum board \(\gamma = 1.36\), for one-side OSB board \(\gamma = 1.20\), and for
double-sided boards $\gamma = 1.20$; $\alpha_{\text{max}} = \max \{ \alpha_s, \alpha_{ei} \}$, $\alpha_{\text{max}}$ is the maximum value of $\alpha_s$ and $\alpha_{ei}$.

3.3. Comparison and Analysis between the Calculated Results and the Test Results. The resistance factor of the shear strength of the CFS shear wall and the screw was proposed by Nie in the literature [22]. The design shear strength of the CFS shear wall obtained from the test could be calculated by the following equation:

$$P_d = \frac{P_y}{c R}$$ \hspace{1cm} (14)

where $P_d$ is the design shear strength of the CFS shear wall obtained from the test and $\gamma_R$ is the resistance factor, which is equal to 1.25.

The calculated results and test results were compared and analyzed to evaluate the calculated method. According to equations (12) and (13), the results are listed in Table 3 and shown in Figure 10.

According to the assumptions above, the design shear strength of the shear wall is based on the design criteria that the shear strength of the maximum stressed screws, which were usually on the corner of the shear wall, reached the design shear strength. However, it can be found from the experimental phenomena that most of the screws inside the shear wall were still in good condition when the screws on the corner of the shear wall were damaged so that the shear wall still could bear much more lateral load.

As shown in Table 3 and Figure 10, the calculated results of the shear strengths were lower than the test results. The design shear strength of the shear wall ($P_d$) is lower than the test results ($P_d$) from 30% to 19%, and the modified design strength of the shear wall ($P_m$) is lower than the test results ($P_d$) from 3% to 7%.

Therefore, the modified design method of shear strength (equation (13)), which is conservative and feasible to predict the shear strength of the shear wall, is proposed in this paper.

4. The Design Method of the Lateral Stiffness of the Shear Wall

The relationship between the lateral load and lateral displacement is investigated. The lateral stiffness, which named the equivalent brace method, is deduced, and the feasibility of this method was evaluated to design the lateral displacement of the shear wall.

4.1. Deformation Analysis of the Shear Wall. The total lateral deformation of the shear wall, which mainly includes shear deformation of the sheathing, deformation caused by the slippage of screws, and bending and overturning deformation of the shear wall, is given by equation (15), as shown in Figure 11:

$$\Delta = \Delta_M + \Delta_s + \Delta_B + \Delta_O,$$ \hspace{1cm} (15)

where $\Delta$ is the total lateral displacement; $\Delta_M$ is the lateral displacement caused by the shear deformation of sheathing; $\Delta_s$ is the lateral displacement caused by the slippage of self-drilling screws; $\Delta_B$ is the displacement caused by the tensile and compressive deformations of the column, i.e., bending deformation; and $\Delta_O$ is the lateral displacement caused by the extension of the hold-down connectors, i.e., overturning deformation.

4.2. Calculation Formulas

4.2.1. Basic Assumptions. The basic theoretical model of the equivalent brace method is shown in Figure 12. The sheathing of the shear wall was simplified as a diagonal brace; meanwhile, the shear wall with sheathing model was simplified as a frame model.

The basic assumptions in the equivalent brace method are listed as follows:

1. The sheathings of the shear wall are regarded as the diagonal brace
2. The connections of each pole are regarded as hinges in the frame model
3. The sheathings in the sheath wall model or the poles in the frame model are regarded as in the elastic stage under the lateral load
4. The stiffnesses of members are assumed much larger than that of the diagonal brace, which is needed to be calculated by the formulas

| Specimen | $f_d$ (N) | $P_c$ (kN) | $P_m$ (kN) | $P_y$ (kN) | $P_d$ (kN) | $P_c / P_d$ | $P_m / P_d$ |
|----------|----------|----------|----------|----------|----------|------------|------------|
| WALL1    | 274      | 4.19     | 5.69     | 7.48     | 5.98     | 0.7        | 0.95       |
| WALL2    | 907      | 13.86    | 16.63    | 21.50    | 17.20    | 0.81       | 0.97       |
| WALL3    | 1181     | 18.04    | 21.65    | 29.12    | 23.30    | 0.77       | 0.93       |

Figure 10: The comparison between the calculated results and the test results.

$P_c$, $P_m$, $P_d$, $\alpha_{\text{max}}$
Based on the above assumptions, the bending deformation ($\Delta_B$) could be ignored. The hold-down connectors are fixed on the floor tightly so that the influence of the overturning deformation ($\Delta_O$), which could also be ignored, is very small compared to the total lateral deformation. Therefore, the total lateral displacement is simplified as follows:

$$\Delta = \Delta_M + \Delta_S.$$  \hfill (16)

### 4.2.2. Theory of the Equivalent Brace Method

As shown in Figure 13, under the same lateral force $P$, the upper lateral displacement ($\Delta$) in the shear wall model is regarded as equal to the lateral displacement of point $D$ ($\Delta_1$) in the frame model, i.e., $\Delta = \Delta_1$. After that, the equivalent stiffness and section area of the diagonal brace $AD$ could be calculated in the simplified method.

Firstly, the lateral displacement of point $D$ ($\Delta_1$) should be calculated under lateral load $P$ in the frame model. As shown in Figure 13, a line $D_1D_2$, which is perpendicular to the
extension line of $AD$ and intersects at the point $D_2$ with the extension line of $AD$, is drawn through the point $D_1$. The extension of brace $AD$ is regarded as equal to $DD_2$, approximately.

The force of brace $AD$ is calculated as follows:

$$N_{AD} = \frac{P}{\cos \theta} = \frac{PL_{AD}}{L} = \frac{P \cdot \sqrt{L^2 + H^2}}{L}.$$  \hfill (17)

The extension of brace $AD$ could be calculated by the following equation:

$$\Delta_{AD} = DD_2 = \frac{N_{AD} L_{AD}}{E A_B} = \frac{P \cdot (L^2 + H^2)}{E A_B L}.$$  \hfill (18)

Therefore, the total lateral displacement is calculated by the following equation:

$$\Delta_1 = DD_1 = \frac{DD_2}{\cos \theta} = \frac{(L^2 + H^2)^{3/2}}{L^2} \cdot \frac{P}{E A_B}.$$  \hfill (19)

And

$$\Delta = \frac{P}{K} = \Delta_1.$$  \hfill (20)

Therefore, the lateral stiffness of the shear wall could be calculated as follows:

$$K = \frac{E A_B L^2}{(L^2 + H^2)^{3/2}}.$$  \hfill (21)

where $K$ is the shear stiffness of the shear wall; $E$ is the elastic modulus of the diagonal brace; $A_B$ is the equivalent section area of the diagonal brace; $\Delta_1$ is the lateral displacement in the frame model; $L_{AD}$ is the length of the diagonal brace $AD$; $N_{AD}$ is the force of the diagonal brace $AD$; $N_B$ is the force of the column; and $\theta$ is the angle between member $AD$ and $AB$.

4.2.3. Lateral Displacement of the Shear Wall. Based on the basic theory of the equivalent stiffness, the new formula of the equivalent stiffness of the diagonal brace considering the influencing parameters is deduced. These influencing parameters are material characteristics of the sheathing, slippage of the self-drilling screws, screw spacing, and the thickness of sheathing.

(1) Shear deformation of sheathing $\Delta_M$: as Figure 14 shows,

$$\frac{P}{L t} = G \frac{\Delta_M}{H},$$  \hfill (22)

$$\therefore \Delta_M = \frac{PH}{L t G}.$$  \hfill (23)

where $t$ is the thickness of sheathing and $G$ is the shear module of sheathing, $G$ is 392 N/mm$^2$ [22].

(2) Shear deformation caused by slippage of screws $\Delta_S$: in the shear wall, the lateral displacement caused by the slippage of self-drilling screws ($\Delta_S$) is calculated according to the cumulating slippage of the screws, as shown in Figure 15. The screw spacing along the height $H$ is the same as that along the length $L$. If the ratio of $H/L$ is the same with the ratio of $n_{sh}/n$, where $n_{sh}$ is the screw number along the height direction of $H$ and $n$ is the screw number along the length direction of $L$), each screw bears the same strength approximately.

If the concentrated lateral load is $P$, the shear strength of the single screw is given by

$$q_N = \frac{P}{n_s},$$  \hfill (24)

If the concentrated lateral load is 1, the shear strength of the single screw is given by

$$\bar{q}_N = \frac{1}{n_s}.$$  \hfill (25)
Table 4: The parameters, calculated lateral stiffness, and comparisons of the lateral displacement between the test results and the calculated results.

| Specimen | $t$ (mm) | $G$ (N-mm$^{-2}$) | $S_0$ (mm) | $n_s$ | $f_d$ (N) | $E_{AB}$ ($\times 10^5$) | $K$ (N-mm$^{-1}$) | $P_{d}$ (kN) | $\Delta_{d}$ (mm) | $\Delta_{yd}$ (mm) | $\frac{\Delta_{d}}{\Delta_{yd}}$ | $P_{y}$ (kN) | $\Delta_{y}$ (mm) | $\Delta_{vy}$ (mm) | $\frac{\Delta_{y}}{\Delta_{vy}}$ |
|----------|---------|-----------------|----------|-------|----------|-------------------------|----------------|--------------|---------------|----------------|-------------------|------------|--------------|----------------|----------------|
| WALL1    | 12      | 392             | 0.55     | 17    | 274      | 12.35                   | 1255          | 5.98         | 4.6           | 4.8            | 1.04              | 7.48        | 13.5         | 5.96           | 0.44            |
| WALL2    | 9       | 392             | 0.9      | 17    | 907      | 15.96                   | 1621          | 17.2         | 11.3          | 10.6           | 0.94              | 21.5        | 23.9         | 13.3           | 0.56            |
| WALL3    | 12+9    | —               | —        | 17    | 28.31    | 2876                    | 23.3          | 8.0          | 8.1           | 8.2            | 1.01              | 29.12       | 19.6         | 10.1           | 0.52            |

$\Delta_{d}$ and $\Delta_{yd}$ are the calculated lateral displacement under the design strength and the yield strength, respectively.

![Figure 16](https://example.com/figure16.png)

Figure 16: Comparison of load-lateral displacement curves between the test results and the calculated results. (a) WALL1. (b) WALL2. (c) WALL3.

According to the principle of virtual work, the shear deformation caused by the slippage of screws is given by

$$1 \times \Delta_t = \sum S_N q_N = 2n_s S_N q_N + 2n_s \frac{H}{L} S_N q_N$$

$$= 2S_N \left( 1 + \frac{H}{L} \right).$$

$$\therefore \Delta_t = 2S_N \left( 1 + \frac{H}{L} \right). \quad (26)$$

The slippage of the single screw is set as $S_0$ (or $S_0$) when the shear strength of single screw reaches (or does not reach) the design shear strength of $f_d$.

Then, there is a relationship as shown in the following equation:

$$R_N = \frac{S_N}{S_0} = \frac{q_N}{f_d}. \quad (27)$$

Therefore, the lateral displacement caused by the slippage of self-drilling screws ($\Delta_s$) could be calculated as follows:

$$\Delta_s = 2S_N R_N \left( 1 + \frac{H}{L} \right) = \frac{2S_N P}{n_s f_d} \left( 1 + \frac{H}{L} \right), \quad (28)$$

where $q_N$ is the shear force of one screw; $R_N$ is the ratio of the shear strength of single screw to the design shear strength of single screw; and $S_0$ is the design slippage of single screw when the shear strength of single screw reaches the design shear strength.

The shear module of sheathing and the slippage of the single screw were investigated by our group [22], according to the test results that for gypsum board, $S_0$ is 0.55 mm, and for OSB board, $S_0$ is 0.9 mm.

(3) Total lateral displacement of shear wall: combining equations (23) and (28) into equation (16), the total lateral displacement of the shear wall is given by the following equation:

$$\Delta = \Delta_M + \Delta_s = \frac{PH}{LtG} + \frac{2S_N P}{n_s f_d} \left( 1 + \frac{H}{L} \right). \quad (29)$$

4.2.4. Equivalent Lateral Stiffness of the Shear Wall.

Under the lateral load $P$, the top lateral displacement ($\Delta$) in the shear wall model is equal to the lateral displacement ($\Delta_t$) in the frame model, i.e., $\Delta = \Delta_t$. Combining equations (19) and (29), the equivalent stiffness of the diagonal brace is given by the following equation:

$$E_{AB} = \frac{(H^2 + L^2)^{3/2}}{(H \cdot L/G \cdot t) + (H \cdot L + L^2)(2 \cdot S_0/n_s \cdot f_d)}. \quad (30)$$

Combining equations (21) and (30), the lateral stiffness of the shear wall $K$ is given by
\[ K = \frac{L^2}{(H \cdot L/G \cdot t) + (H \cdot L + L^2)(2 \cdot S_0/n_s \cdot f_d)} \quad (31) \]

4.3. Comparison between the Test Results and the Calculated Results. The parameters of each specimen, the calculated lateral stiffness, and the comparison of the lateral displacement between the test results and the calculated results are presented in Table 4, and the comparison of load-lateral displacement curves between the test results and the calculated results is shown in Figure 16.

As shown in Figure 16, the load-lateral displacement curve of the design model is linear, and in the elastic stage of the shear wall, the calculated curves were approximate to the tangent line of the test curves. As listed in Table 4, the calculated lateral displacement under the design strength (\( \Delta_{cd} \)) is close to that of the test results (\( \Delta_d \)) in the range of −6% to +4%, it could be concluded that the design method is feasible to calculate the lateral displacement of the shear wall in the elastic stage. However, the calculated lateral displacement under the yield strength (\( \Delta_{cy} \)) is lower than the test results (\( \Delta_y \)) in the range of −56% to -44%. Because the shear wall will be in the elastic-plastic stage after the point of design strength, there will be a large plastic deformation of the shear wall, which is not fit for the assumptions above. It could be concluded that the design method is not useful to calculate the lateral displacement of the shear wall in the nonelastic stage.

5. Conclusion

The mechanical behavior of the CFS shear wall under monotonic lateral loading was investigated via experimental study. The design methods of the shear strength and the lateral stiffness of the CFS shear walls were proposed and evaluated. According to the results, the following conclusions are drawn:

1. The material types of sheathings influence the shear strength of the CFS shear wall greatly. The yield and maximum shear strength of the CFS shear wall with one-side OSB board (WALL2) are 2.87 and 2.94 times those of the CFS shear wall with one-side gypsum board (WALL1), respectively. The sum of shear strengths of CFS shear walls with one-side gypsum board (WALL1) and CFS shear walls with one-side OSB board (WALL2) is close to that of the CFS shear wall with both gypsum board and OSB board (WALL3).
2. The shear strength of the screws between the board and the CFS stud played a decisive role in the shear strength of the shear wall, which was usually governed by the shear strength of the screw connections.
3. The modified design strength of the CFS shear wall is lower than the test results from 3% to 7%. The modified design method of shear strength, which is conservative and feasible to predict the shear strength of the shear wall, is proposed to be used in engineering practice.
4. The design method of the lateral stiffness of the CFS shear wall is proposed. The design method is available to calculate the lateral displacement of the CFS shear wall in the elastic stage, but it cannot be used in the nonelastic stage. It can provide a reference for the design of similar engineering.

List of Symbols

| Symbol | Description |
|--------|-------------|
| A_B | The equivalent section area of the diagonal brace |
| E_s | The elastic modulus of the diagonal brace |
| F_ex | The component force of F_{ei} in the X direction |
| F_{ei} | The shear force of the i^{th} screw at the end of the shear wall |
| F_{eyi} | The component force of F_{ei} in the Y direction |
| F_{si} | The shear force of the i^{th} screw inside the shear wall |
| f_d | The design shear strength of single screw |
| G_s | The shear module of sheathing |
| H_s | The height of the shear wall |
| K_s | The shear stiffness of the shear wall |
| L_s | The length of the shear wall |
| L_{AD} | The length of the diagonal brace AD |
| m_s | The number of internal columns of shear wall |
| N_{AD} | The force of the diagonal brace AD |
| n_s | The number of the screws at one end of the shear wall |
| n_{si} | The number of the i^{th} screws on one internal column inside the shear wall |
| n_{siH} | The screw number along the height direction of H |
| n_{siL} | The screw number along the length direction of L |
| V_s | The shear strength of the shear wall with unit length. |
| P_s | The concentrated lateral load applied to the upper of the shear wall |
| P_{cs} | The design shear strength of the CFS shear wall |
| P_{d} | The design shear strength of the CFS shear wall obtained from the test |
| P_{m} | The modified design shear strength of the CFS shear wall |
| p | The maximum strength |
| max | The maximum strength |
| P_{y} | The yield strength |
| P_{e} | The failure strength |
| q_s | The shear force of one screw |
| R_N | The ratio of the shear strength of single screw to the design shear strength of single screw |
| S_0 | The design slippage of single screw |
| t_s | The thickness of sheathing |
| x_{ei} | The distance from the i^{th} screw at the end of the shear wall to the centerline of the sheathing |
| x_{si} | The distance from the i^{th} internal screw inside the shear wall to the centerline of the sheathing |
| y | The modified coefficient |
| y_R | The resistance factor |
| \theta | The angle between member AD and AB |
| \Delta_y | The yield displacement |
Δ: The maximum displacement

Δ max: The failure displacement

Δ cd: The calculated lateral displacement under the design strength

Δ cy: The calculated lateral displacement under the yield strength

Δ: The total lateral displacement

Δ M: The lateral displacement caused by the shear deformation of sheathing

Δ α: The lateral displacement caused by the slippage of self-drilling screws

Δ β: The displacement caused by the tensile and compressive deformations of the column

Δ ω: The lateral displacement caused by the extension of the hold-down connectors

Δ d: The lateral displacement in the frame model

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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