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Correlating Fastener Damage to Hysteretic Response and Performance Levels in Steel Sheet Sheathed CFS Wall-lines

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ABSTRACT

Cold-Formed Steel (CFS) framing has gained substantial popularity in the North American market in the recent years, particularly in mid-rise building construction. Buildings framed with closely spaced CFS members repetitively placed in the walls develop resistance to lateral loads through a variety of systems including steel sheet sheathing attached to the CFS members. Damage to walls sheathed with steel sheet largely manifests in the form of local failure of screw fasteners. To this end, in the present paper, the damage observed in fastener connections between steel sheet sheathing and CFS framing members in wall-lines subjected to quasi-static cyclic loading is systematically quantified. Four symmetric and unfinished wall-line configurations, including two each of Type I and Type II shear wall detailing systems, are evaluated at different performance levels. Tilting/bearing and sheet pullover are identified as the two predominant fastener connection failure modes and damage statistics for each failure mode demonstrate the progression of connection damage. Specimens with a larger quantity of fastener connections demonstrated 1.5-3.0 times greater hysteretic energy dissipation at similar cumulative drift. However, the number of fasteners used had no apparent effect on equivalent hysteretic damping due to the reduction in wall lateral strength developed.

Introduction

Cold-Formed Steel (CFS) framed walls develop lateral resistance by using repetitively placed and closely spaced members with AISI S400 [1] defining a variety of seismic force resisting systems including steel sheets as sheathing installed using fasteners on one or both sides of the wall. Particularly in steel sheet sheathed shear walls, these fastener connections govern wall lateral capacity and energy dissipation capability through development of well-defined ductile zones along diagonal struts in the steel sheet. Shear walls provide more hysteretic energy dissipation when fastener damage controls the failure mode [2]. However, the correlation between fastener damage (mode and quantity) with wall hysteretic performance has yet to be well established. To this end, in the present paper, the damage to fastener connections used to attach steel sheet sheathing to shear wall framing members in CFS-framed wall-lines, subjected to a quasi-static cyclic loading protocol, is quantified.

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Experimental Program

The CFS-NHERI wall-line quasi-static cyclic test program consisted of ten wall configurations tested at the UC San Diego Structural Engineering Powell Laboratory [3, 4]. The walls were subjected to a displacement controlled cyclic CUREE protocol [5] by employing two hydraulic 220 kN actuators with ±60 cm stroke, used in parallel (total lateral load capacity of 440 kN), to push (north direction) and pull (south direction) along the wall longitudinal axis. The reference displacement required to define this protocol was taken as Δ=2%. This was determined from measured wall-line behavior during prior shake table experiments [6]. Two hollow steel sections were employed as top and bottom transfer beams which connected the specimens to the strong floor and to the top concrete mass. Two concrete slabs, together with the top HSS transfer beam, were used to apply a total of 12.4 kN/m gravity load. Out-of-plane columns with roller guides provided the required restraint preventing top mass movement in the transverse direction. Figure 1 shows a front and end view of wall specimen SGGS-2 installed in the test setup. It should be noted that the specimen names refer to the characteristics of each 1.22 m quadrant length of the 4.88 m long specimen appended with a number indicating whether it is a Type I or Type II wall system as defined by AISI S400 specifying the locations of tension tie-rods or holdowns (tie-down system options). Thus, for example, the specimen SGGS-2 is a symmetric, unfinished wall with a 2.44 m gravity wall segment in the middle and 1.22 m Type II shear wall segments on each end (**S**hear-**G**ravity-**G**ravity-**S**hear) with a tension tie-rod at both wall ends. Individual walls were 4.88 m in length and 2.74 m in height. Compression chord studs were built-up 600S250-97 members while top and bottom tracks were 600T250-97 members [7]. The tie-down assemblies consisted of either a ϕ29 mm Grade B7 tension tie-rod (877 MPa measured yield point) in the middle of the stud packs or a pair of holdowns (400 kN combined nominal capacity) installed on the built-up chord stud. Type II shear wall segments had tie-down detailing located at the wall ends, while Type I shear wall segments had tie-down detailing at each shear wall segment end. It should be noted that these Type II wall-lines were not detailed with any members to collect and carry the shear to the shear segments at the ends. They shared the most salient characteristic of Type II walls, even though they were not entirely code compliant Type II shear walls as defined in AISI S400. A 0.76 mm thick steel sheet sheathing (230 MPa nominal yield strength) was attached to the shear wall framing exterior face using No. 12 flat pan head screws at 51 mm o.c edge and 305 mm o.c. field spacing. A 1200T250-97 ledger track was attached to the top 1 m of the wall on the interior face. The gravity wall framing utilized 600S250-68 studs placed at 610 mm o.c. All framing members had 345 MPa nominal strength and were assembled using No. 10 flat pan head screws. These wall details were motivated from a designed CFS-framed archetype building which utilized the available experimental data and existing code guidelines [8].

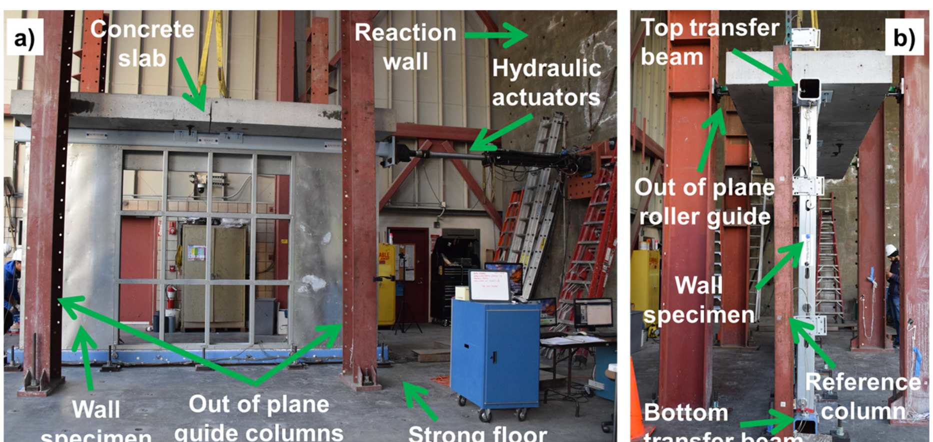

Figure 1. Front and end view of wall specimen SGGS-2 as installed in quasi-static cyclic test setup [4].

Amongst the ten wall-line specimens tested, four symmetric and unfinished configurations are the focus of the present paper. By virtue of being unfinished, the steel sheet fastener damage in these wall-line specimens was readily observable. Additionally, since the specimens were subjected to the same loading protocol, they can be cross compared at different performance levels, namely, at elastic, quasi-elastic, design, and above design levels. These performance levels were defined according to the normalized lateral force and drift response of the individual specimens [9]. Damage assessment of two each of Type I and Type II wall systems as well as their hysteretic response focus on the following: (1) SGGS-2: Type II shear wall detailing, (2) SWWS-2: Type II shear wall detailing and a 2.44 m window opening in the middle, (3) SGGS-1HD: Type I shear wall detailing employing holdowns as the wall tie-down system, and (4) SWWS-1: Type I shear wall detailing and a 2.44 m window opening in the middle. The assessment can be expanded to finished specimens to incorporate gypsum panel fasteners damage modes at different performance levels.

Results and Discussion

Figures 2a and 2b show the force-displacement response comparison between specimen pairs SGGS-1HD and SWWS-1, and SGGS-2 and SWWS-2. Table 1 summarizes key response measurements obtained from the hysteresis curves such as wall strength (V_u), drift ratio at strength (Δ_{Vu}) and elastic stiffness (K), defined as the secant stiffness at $0.4V_u$. The specimens within each pair behaved similar to each other in terms of wall strength, elastic stiffness, and drift ratio at strength. Compared across the two pairs, Type II specimens with ~20% fewer sheet fastener connections, showed ~40% lower wall strength and stiffness on average, as well as a lower drift at strength than Type I specimens. Figure 2c shows the comparison across specimens of the cumulative dissipated energy, calculated as the area enclosed within the hysteresis of the hysteresis curve, with respect to cumulative drift ratio ($\Sigma\Delta$) normalized by the average cumulative drift ratio at strength in the two directions ($\Sigma\Delta_{Vu}$). Type I specimens demonstrated 1.5-3.0 times higher energy dissipation than Type II specimens due to the greater number of fastener connections used to connect the steel sheet sheathing to CFS framing. Figure 2d show equivalent hysteretic damping (ζ) plotted against the normalized cumulative drift ($\Sigma\Delta/\Sigma\Delta_{Vu}$). Equivalent hysteretic damping is computed as $A_{loop} / (2\pi F_{max} D_{max})$, where A_{loop} is the energy dissipated within a cycle in the hysteretic response, and F_{max} and D_{max} are the maximum absolute force and the maximum absolute displacement in the cycle, respectively. Interestingly, the equivalent hysteretic damping characteristics were consistent for all specimens considered, demonstrating ζ = 6% at elastic, ζ = 8% at quasi-elastic, ζ = 12% at design and ζ = 15% at above design performance levels. Figure 2e shows the fastener damage statistics for the failure modes observed at drift levels associated with the different performance levels (Table 1) including a drift level of Δ=4%. The Δ=4% drift level the highest drift amplitude at which screw damage assessment could be performed consistently across specimens. The number of steel sheet fasteners experiencing the bearing/tilting or sheet pullover mechanism as a percentage of total fasteners are shown for the selected specimens. These failure modes are consistent with those observed in other CFS-framed shear wall tests, as noted in [10, 11].

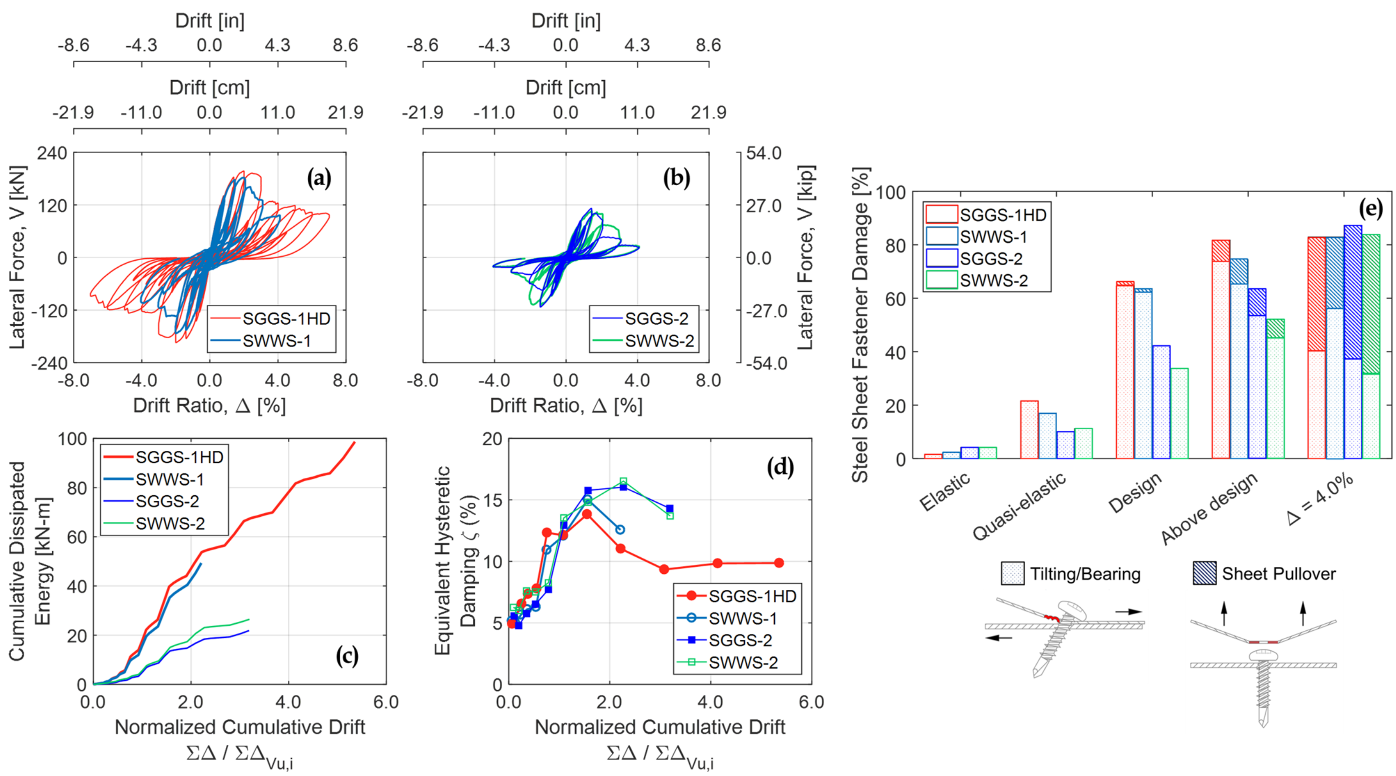

Figure 2. Force-displacement behavior of (a) Type I specimens and (b) Type II specimens, (c) cumulative dissipated energy, (d) equivalent hysteretic damping and (e) fastener damage statistics for each failure mode. Different color for each specimen and different shading for each failure mode.

Table 1. Key hysteretic response measurements of selected specimens.

Wall specimen	Wall strength V_u (kN)	Drift ratio (Δ) at performance levels[1] (%)				Residual strength at Δ=4% (kN)	Elastic stiffness K (kN/cm)
		Elastic (pre-peak)	Quasi-elastic (pre-peak)	Design Δ_{Vu} (peak)	Above design (post-peak)		
SGGS-1HD	195.8	0.40	0.80	2.00	3.00	123.0	86.2
SWWS-1	177.9	0.42	0.82	1.98	3.06	99.0	74.8
SGGS-2	112.6	0.21	0.62	1.42	2.04	22.2	45.3
SWWS-2	107.2	0.21	0.62	1.43	2.04	23.2	53.4

Note: 1. Drift levels (Δ) associated with performance levels: Elastic ≈ $0.2\Delta_{Vu}$, Quasi-elastic ≈ $0.4\Delta_{Vu}$, Design = Δ_{Vu}, and Above design ≈ $1.5\Delta_{Vu}$

Figure 3 shows the damage in the fasteners at the selected performance levels for specimen SGGS-1HD. Damage in fasteners begins as bearing/tilting of screw heads, which leads to enlargement of the hole around the screw head as the angle of tilting increases. As drift amplitude increases, this hole becomes large enough for the sheet to pull-over the screw head during the drift cycles. In this manner, the damage mode for a significant fraction of screws demonstrating bearing/tilting initially changes to sheet pull-over later. Fastener damage progresses in a similar manner in Type II specimens; however, damage photographs are not shown herein for brevity. The total percentage of screws damaged reaches 80-85% for all specimens at drift ratio Δ=4% (Figure 2e). Interestingly, the presence of a window opening next to shear wall segment (SWWS-1) had no apparent effect on the quantity of steel sheet fasteners damaged.

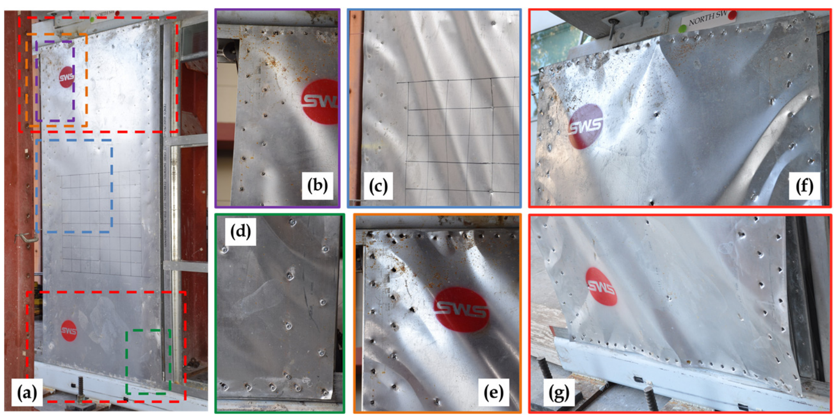

Figure 3. Fastener connection damage in specimen SGGS-1HD (Type I): (a) undamaged steel sheet, (b) elastic, (c) quasi-elastic, (d) design and (e) above design performance levels, (f) and (g) at drift ratio Δ=4.0%.

Conclusions

The objective of this study was to assess the damage in fastener connections between steel sheet sheathing and CFS framing in wall-lines subjected to quasi-static cyclic loading at different performance levels. To this end, the quantity of fasteners that failed under the two identified modes are summarized. Damage in fasteners begins as tilting/bearing of the head for a few screws, which then spreads to other screws, followed by sheet pull-over the heads for 40-50% of the fasteners at very large amplitude drift cycles (Δ=4%). Even properly detailed wall systems can expect 30-60% of fasteners to have tilting/bearing damage but no sheet pull-over failures at design performance level. Specimens which used more steel sheet sheathing fastener connections demonstrated 1.5-3.0 times more hysteretic energy dissipation. However, the number of fasteners used had no apparent effect on equivalent hysteretic damping, because this calculation is normalized by wall resistance which is proportionally reduced with number of fasteners used.

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