



Stiffness, stability, and strength of floor-to-wall connections in ledger-framed cold-formed steel construction

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Abstract

The objective of this paper is to present the effect of floor-to-wall connection details on ledger framing performance for light-framed cold-formed steel construction. The possibility of alternative lateral load paths to current seismic design, which assumes load flows to and through only shear walls was observed in recent full-scale shake table tests on a two-story cold-formed steel building where ledger framing was a key feature. The building exceeded predictions based on sub-system level design. One hypothesis is that joist-to-ledger connections contributed to the lateral load resisting system. The tests conducted here aim to quantify the strength and stiffness of the joist-to-ledger connection so that this hypothesis may be explored further. Current design for these connections is based on screw shear. However, test results indicate that newly observed limit states such as ledger flange buckling and stud web crippling drive joist-to-ledger connection moment-rotation response. The experimental program was designed to evaluate the clip angle location (inside or outside of the joist section) and presence of top and bottom screws connecting joist and ledger flanges depending on joist location relative to studs (mid studs, close, and on stud). These tests are a part of a broader experimental study on ledger framing construction to support future 3D seismic building analysis and design for cold-formed steel construction.

1. Introduction

Cold-formed steel (CFS) framing has been around and widely used in construction for decades. In cold-formed steel construction, three framing systems are traditionally used: platform framing, balloon framing and ledger framing Fig. 1.

In platform framing, a floor joist system sits on top of the wall plate, with the next level's walls sitting on top of the floor system, creating a point load on the floor joist. This necessitates a reinforcement with web stiffeners on the end connection and other additional clips, bridging bars, lateral blocking, joist hangers and/or squash blocks.

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Balloon framing is defined as hanging the joist system off inside of the walls. The possibility of the joists being offset from wall studs, allow more flexibility than in-line framing within the system, but necessitates long members.

Ledger framing consists of floor and roof joists which are connected to the interior flange of the load-bearing studs via a combination of a rim-track and clip angles. For ledger framing, the building is constructed one floor at a time, but the floor joists are hung from the top of the studs. The joists and studs are not required to be aligned since a ledger, or carrier track, is attached to the interior face of the studs running along its length to provide a connection point for the joists.

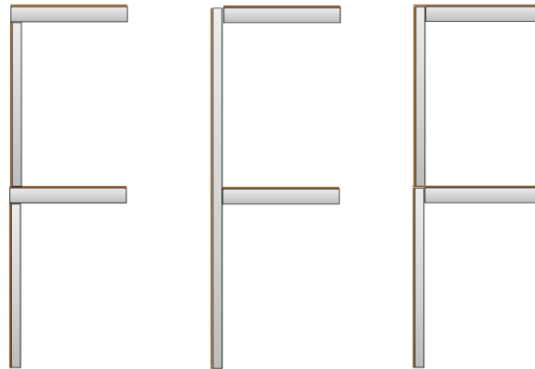


Figure 1: Cold-formed steel framing types (Nakata et.al 2011)

Ledger-framing is commonly used in cold-formed steel construction. The seismic behavior of ledger-framed cold-formed steel buildings was recently investigated in the CFS-NEES project with shake table tests of two identical full-scale two-story archetype cold-formed steel buildings (Madsen 2011). Fig. 2 illustrates a joist-to-ledger framing connection, as used in the CFS-NEES building. The results from the CFS-NEES project indicated that load paths might be different than the traditional concept during the seismic response (Schafer 2014). An alternative lateral force resisting element provided by the joist-to-ledger connection could in part explain these non-traditional load paths.

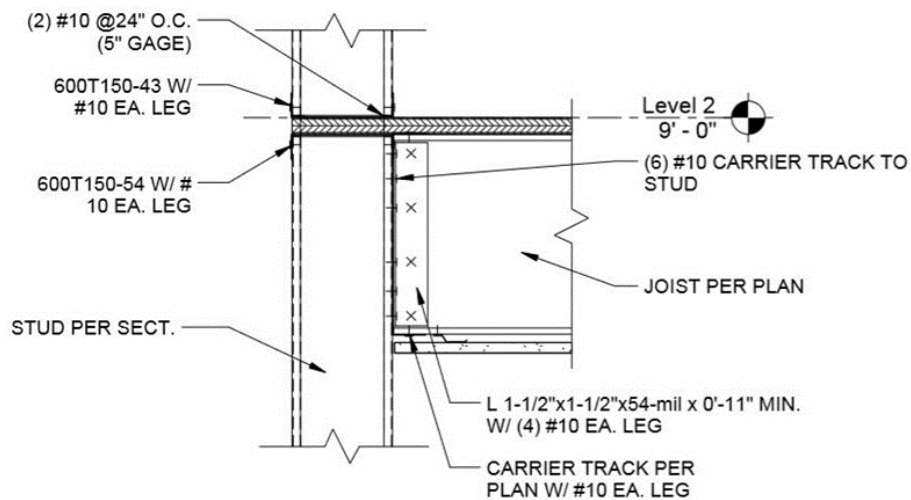


Figure 2: Detail of ledger framing system as drawn in building specimen construction drawings of CFS-NEES building

The framing action between the floor joists and wall studs is related to the stiffness of the joist-to-ledger connections. Discontinuity of the load paths at the connection point and stiffness of the thin-walled members makes rigid or full moment resisting connections difficult to achieve in practical construction. Therefore, quantifying stiffness, and moment and rotational capacities of exiting connections is sought through sub-assembly experiments on floor-to-wall connections.

The code guidance for connection design is primarily based on a simple shear assumption and thus isolated to insuring the screws are adequate in shear. This is not enough to understand the actual connection behavior. Accordingly, full-scaled floor-to-wall connection specimens are designed to explore the connection behavior. The effects of some parameters, such as presence of floor sheathing and applied load location, have already been reported by the authors (Ayhan 2015, 2016). The testing program in the scope of this paper is designed to evaluate the presence of top and bottom screws connecting the joist and ledger flanges, and the clip angle location with different joist locations relative to studs (mid studs, close and on stud). The experimental research aims to examine the stiffness, strength, and ductility of wall-to-floor connections under monotonic loading. This work is a part of a broader comprehensive experimental study on ledger-framing construction to support future 3D seismic building analysis and design for cold-formed steel framing.

2. Experiments on floor-to-wall connections

2.1 Specimen Dimensions

The joist-to-ledger connection sub-assemblages designed according to the CFS-NEES building details are investigated by the current experiments. Correspondingly, members are selected following the building structural system having a floor diaphragm framed with 1200S250-97 joists and 1200T200-97 rim tracks (ledgers) sheathed with 7/16 in. thick OSB sheathing and first story gravity walls framed with two 600S162-54 studs and two 600T150-54 tracks. A clip angle of 1.5x1.5-54 is used to attach joists to ledgers.

2.2 Test Matrix

The parameters to be evaluated in the entire test program are 1. presence of floor sheathing, 2. presence of top and bottom screws connecting joist and ledger flanges, 3. load type (moment/shear ratio), and 4. clip angle location (inside or outside of joist section), depending on floor joist locations relative to studs. Accordingly, tests are grouped in four test series. The tests reported here are under monotonic loading, but the same specimens will be tested under cyclic loading in the next (future) phase of this experimental program.

The effects of the presence of floor sheathing have been examined in the first series and reported previously (Ayhan 2015). T4, T5 and T6 (from the first series) having floor sheathing, top and bottom screws connecting joist and ledger flanges and a clip angle inside face of the joist with low applied moment/shear ratio are being used as reference tests hereinafter. The effect of the applied moment/shear ratio has been studied in the third series and reported by the authors (Ayhan 2016). This paper focuses on the remaining parameters investigated in the second and fourth series: specifically floor joist location relative to studs, under monotonic loading.

The second series includes specimens having the joist connected to the ledger on their webs with only a clip angle on the inside face of the joist. No screws are used to connect the top and bottom flanges of the ledger and the joist. The specimens in the fourth series have the joist-to-ledger connection built with a clip angle to the web, and also top and bottom screws to the flanges. However, the clip angle used to attach the joist to ledger web is placed on the outside of the joist section. In both series the specimens have floor sheathing and loading is applied to the closest possible point to the connection to cause minimum moment/shear ratio (5 in. away from the web of the ledger). The test series included in the scope of this paper are provided in the test matrix shown in Table 1.

Table 1: Test Matrix*

	test no	joist location	top and bottom screws	clip angle location
first series	T4- mid studs	mid studs	✓	inside
	T5- near stud	near stud	✓	inside
	T6- on stud	on stud	✓	inside
second series	T13- mid studs (no screws)	mid studs		inside
	T14- near stud (no screws)	near stud		inside
	T15- on stud (no screws)	on stud		inside
fourth series	T25- mid studs (clip angle)	mid studs	✓	outside
	T26- near stud (clip angle)	near stud	✓	outside
	T27- on stud (clip angle)	on stud	✓	outside

*third series comprises of specimens designed to examine the effects of the applied moment/shear ratio and the results of monotonic tests have been reported in Ayhan 2016.

2.2 Test Setup and Instrumentation

The test setup is depicted in Fig. 4 using a picture from specimen T26. The stud frame is connected to the test rig via the web of the studs, which are bolted to a steel tube (HSS 10x6x0.25) on the test rig frame with eight 3/4 in. diameter Grade 8.8 high-strength bolts, ensuring a fixed boundary condition. The end of the joist is laterally supported (by 3/4 in. threaded rods) to restrain the lateral deformation and restrict twist. A vertical load was applied to the joist by a hydraulic actuator at a distance of 5 in. away from the connected location (practically, the web of the ledger beam).

The schematic diaphragm of the connection is illustrated in Fig. 5 with three different joist locations: in the middle of the studs, at a quarter of the distance between studs, and on the stud. A stud frame, ledger, joist, and floor sheathing compose the joist-to-ledger connection specimen. No. 10 screws are used to form the stud frame with 24 in. long top and bottom tracks attached to 32 in. long studs. The distance between the studs, and accordingly the ledger length are 24 in. A 62 in. 1200S200-97 joist is connected to the web of the ledger via a clip angle connected by four No. 10 screws per leg. The relatively long joist specimen was utilized in test series three where shear-to-moment ratio at the connection was explored.

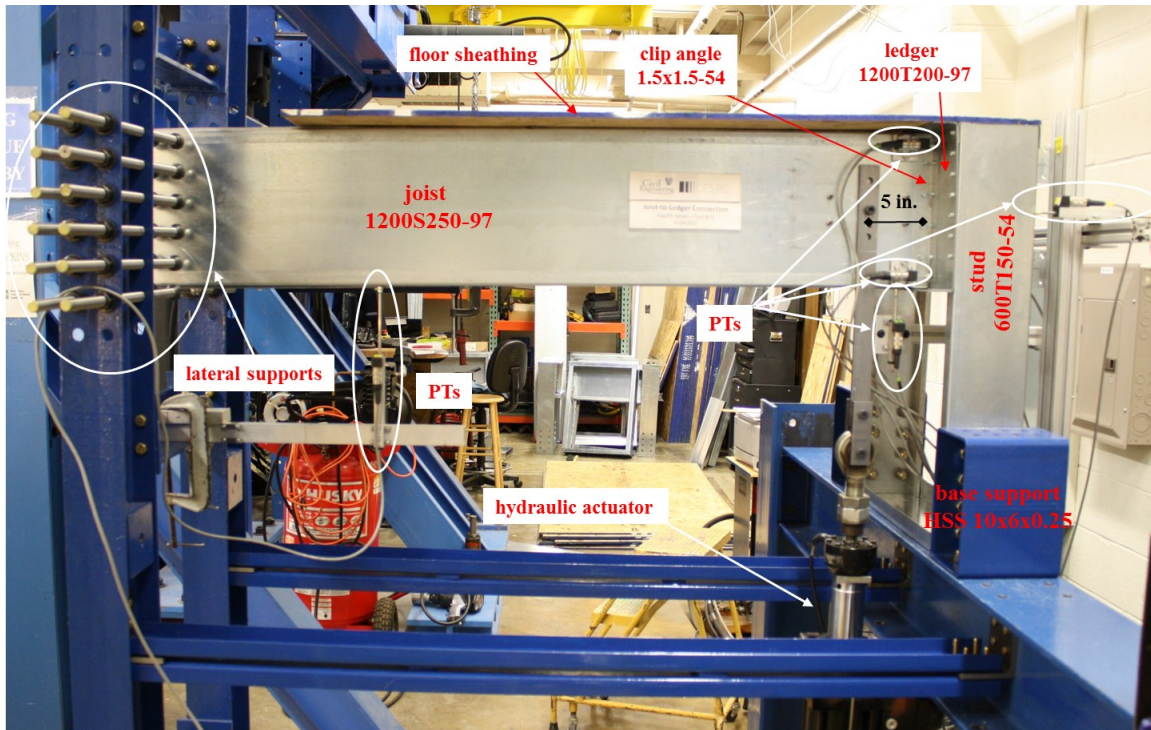


Figure 4: Test setup picture of T26 (specimen having joist attached near stud with a clip angle outside of the joist section and top and bottom screws connecting joist and ledger flanges)

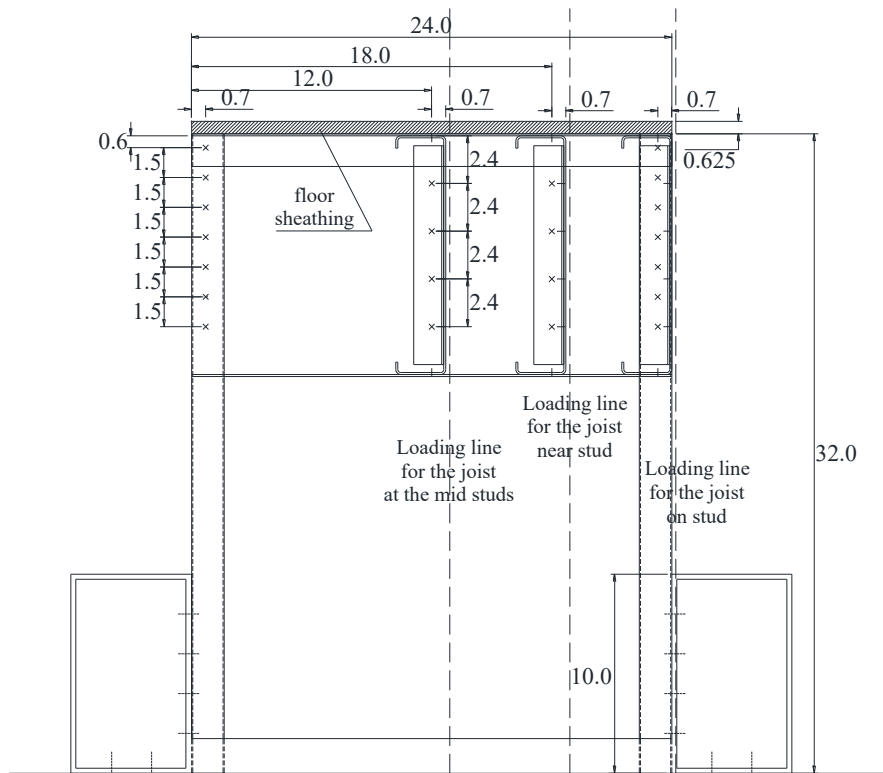


Figure 5: Specimen details including three joist locations on stud frame view (dimensions in inches)

The behavior of each connection was monitored throughout testing by means of measured loads and deformations. In all, 12 position transducers (PTs) were directly connected to the connection specimen measuring the rotations of the studs (θ_{S1} and θ_{S2}), joist (θ_j), and ledger (θ_l); also the joist rotations relative to clip angle (θ_{JA}) and ledger from inside and outside of the joist section (θ_{JLi} and θ_{JLo}).

The measured components of the connection rotation are depicted in Fig. 6. The stud frame rotation (θ_s) is calculated with linear interpolation between stud rotations (θ_{S1} for stud away from joist and θ_{S2} stud close to joist) depending on joist location. The absolute rotation of the ledger (θ_L) and the connection (θ_{con}) are obtained by removing the rigid body rotation contribution of the stud frame (θ_s).

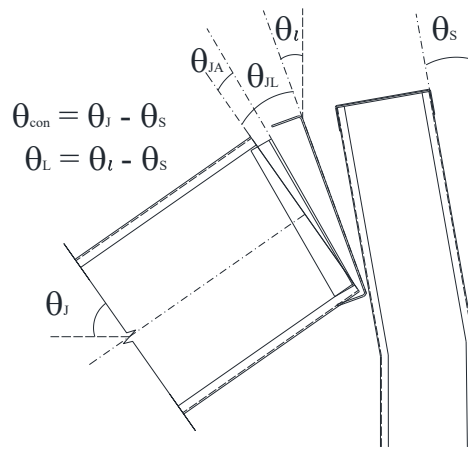
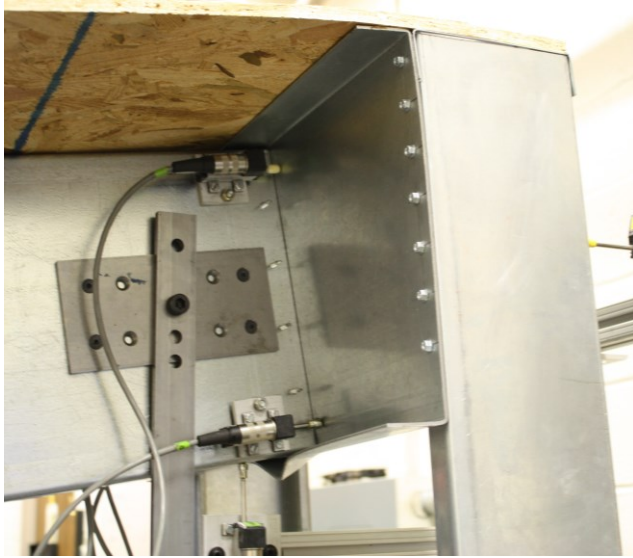


Figure 6: Rotation components of the connection

3. Test Results

The observed failure modes of the tests are grouped as primary and secondary. Primary limit states, which are ledger bottom flange buckling (Fig. 7a) and stud web crippling (Fig. 7b) drove the failure. In addition, secondary limit states are observed due to the excessive deformation. They are partial pull-out of the fasteners connecting the ledger web to the stud flange (Fig. 7c), twist of the ledger flange (Fig. 7d), tilting of the fasteners connecting the top floor sheathing to the top track (Fig. 7e), and excessive bending of the floor sheathing (Fig. 7f).

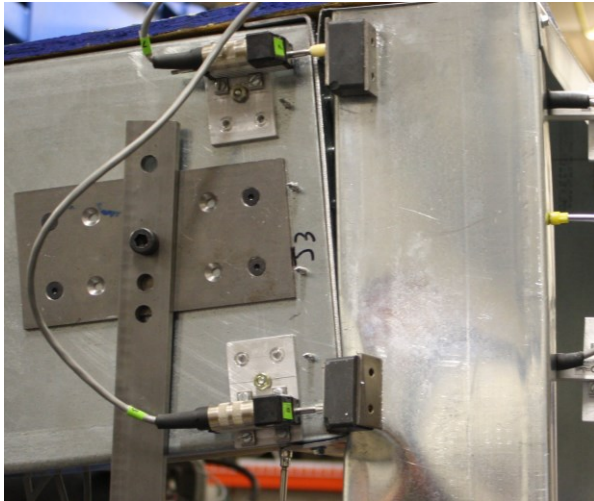
All of the observed limit states are summarized in Table 2. The location of the floor joist relative to the studs dominates the primary limit states. The failure mode of the specimens (T4, T13 and T25) having joist at mid span of the ledger is ledger bottom flange buckling. However, stud web crippling is the failure mode for the rest of the specimens which have the joist close to, or aligned with, the stud.



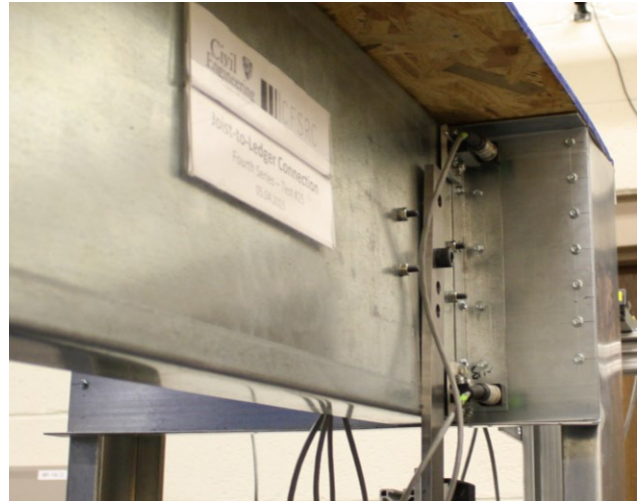
a) Ledger flange buckling sample (T13)



b) Stud web crippling sample (T14)



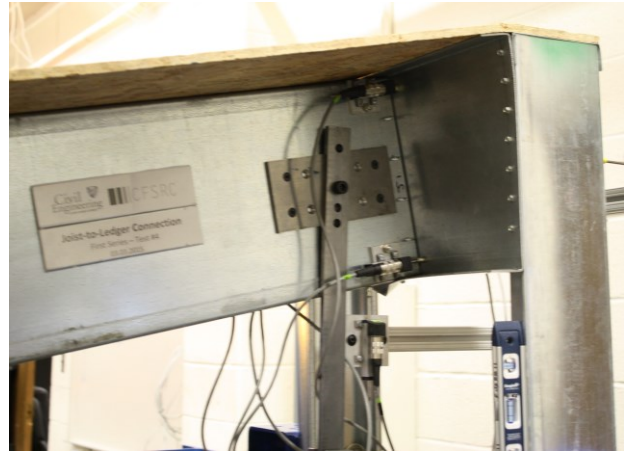
c) Fastener pull-out sample (side view of T6)



d) Twist of the ledger flange sample (T26)



e) Fastener tilting sample (back view of T27)



f) Floor sheathing bending sample (T4)

Figure 7: Examples of primary and secondary limit states from the tests

The observed secondary limit states were controlled by both the presence of top and bottom screws connecting the ledger and joist flanges, and the clip angle location. Bending of the floor sheathing occurred on all of the specimens with joist at the mid span of the ledger (T4, T13 and T25), after the ledger bottom flange buckled. Screws connecting the ledger web to the stud flange partially pulled-out on specimens T6 and T15 which have the joist placed on the stud and the clip angle inside of the joist section. The ledger flange twisted on T5 and T26 with the joist near the stud and top and bottom screws connecting the ledger and joist flanges. Screws connecting floor sheathing to the top track of the stud frame tilted on the specimens with the joist near, or on the stud, and top and bottom screws connecting the ledger and joist flanges (T5, T6, T26 and T27). It is worth nothing that observed primary and secondary limit states correlate.

Table 2: Limit states observed in the tests

test no	Ledger flange buckling	Stud web crippling	Fastener pull-out	Twist of the ledger flange	Fastener tilting	Floor sheathing bending
T4- mid studs	P					S
T5- near stud		P		S	S	
T6- on stud		P	S		S	
T13- mid studs (no screws)	P					S
T14- near stud (no screws)		P				
T15- on stud (no screws)		P	S			
T25- mid studs (clip angle)	P					S
T26- near stud (clip angle)		P		S	S	
T27- on stud (clip angle)		P			S	

P: primary limit state, S: secondary limit state.

In addition to the limit states listed in Table 2, the screw connecting the ledger and joist bottom flanges was ruptured after ledger bottom flange buckling in specimen T25 where the clip angle is placed outside of the joist section (Fig. 8).



Figure 8: Screw failure at bottom ledger of the T25

3.1 Effects of the presence of top and bottom screws

The moment-rotation performance, without the top and bottom screws connecting the ledger and joist flanges, is investigated under monotonic loading in specimens T13, T14 and T15. Fig. 9 depicts the moment-joist rotation of the specimens including the stud frame rotation. The initial

stiffness of T13 is lower than T4 (with screws), the absence of the top and bottom screws caused the ledger bottom flange to buckle early and with a lower moment capacity. The moment capacity of T14 is slightly lower than T5, although they have the same initial stiffness. However, T15 had higher stiffness and moment capacity than T6. The load path is different when the joist is aligned with stud (as in T15 and T6). The highest moment capacity is always observed when the joist is near the stud.

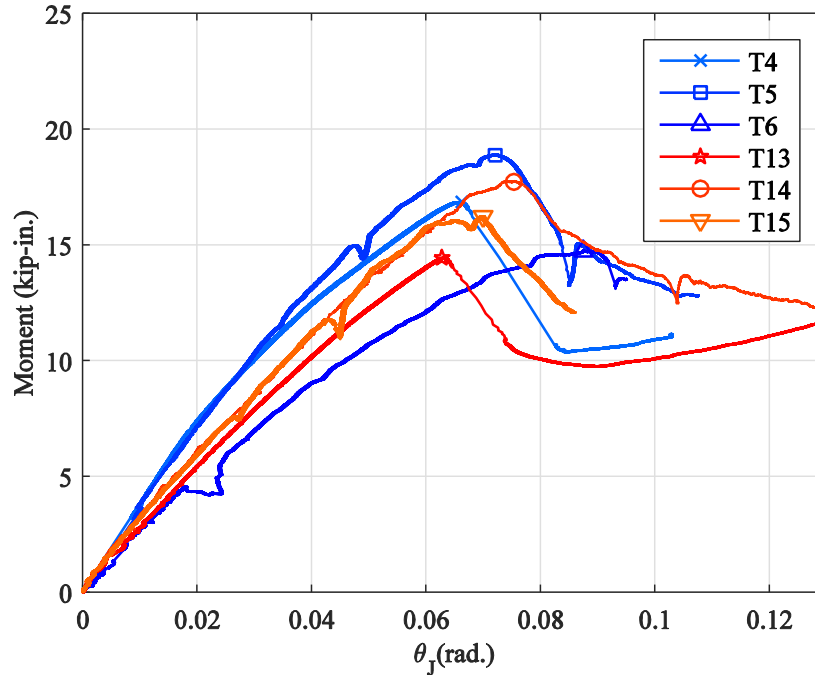


Figure 9: Comparison of joist behaviors for the effect of the presence of the top and bottom screws.

The connection rotation is the difference between the joist rotation and the rigid body rotation of the stud frame subtracted from the joist rotation. The moment-rotation curves of the joist-to-ledge connections are obtained as shown in Fig. 10. The initial stiffness of the moment-connection rotation curves are almost equal to each other for all of the specimens without top and bottom screws, however they are all lower than the reference specimens (with screws).

The moment-ledge rotation of the specimens is obtained by removing the rigid body rotation contribution of the stud frame, and shown in Fig. 11. All specimens provide the same initial stiffness. This phenomenon suggests that the joist location and the presence of top and bottom screws have no significant effect on the initial stiffness of the ledger since the floor sheathing provides the load path between the stud frame and the attached ledger.

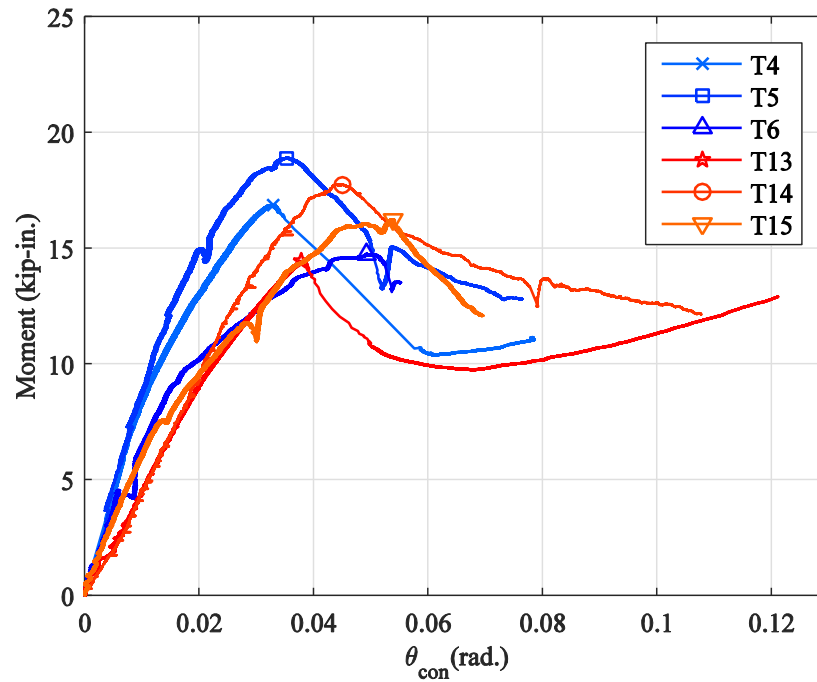


Figure 10: Comparison of the connection behaviors for the effect of the presence of the top and bottom screws.

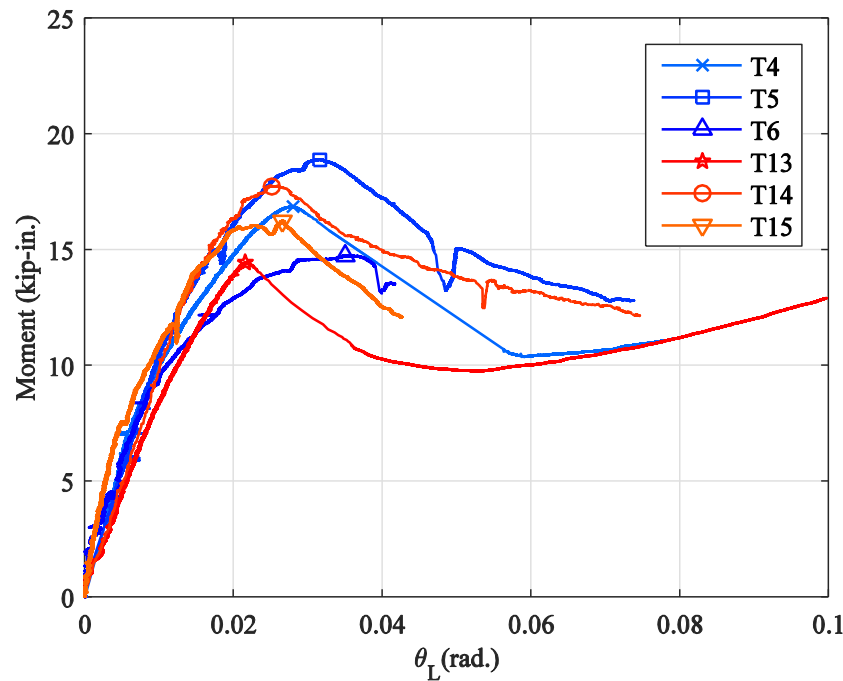


Figure 11: Comparison of the ledger behaviors for the effect of the presence of the top and bottom screws.

3.2 Effects of clip angle location

Specimens T25, T26 and T27 examine the effect of the clip angle location on the connection performance under monotonic loading. Moment-joist rotation of the specimens is depicted in Fig. 12. The move of the clip angle from inside to outside of the joist section causes a decrease in

the initial stiffness for the specimens with the joist in the middle of the studs (T25) and near the stud (T26). However, when the joist is aligned with the stud, the initial stiffness of T27 remained the same as T6, while the connection capacity slightly increased.

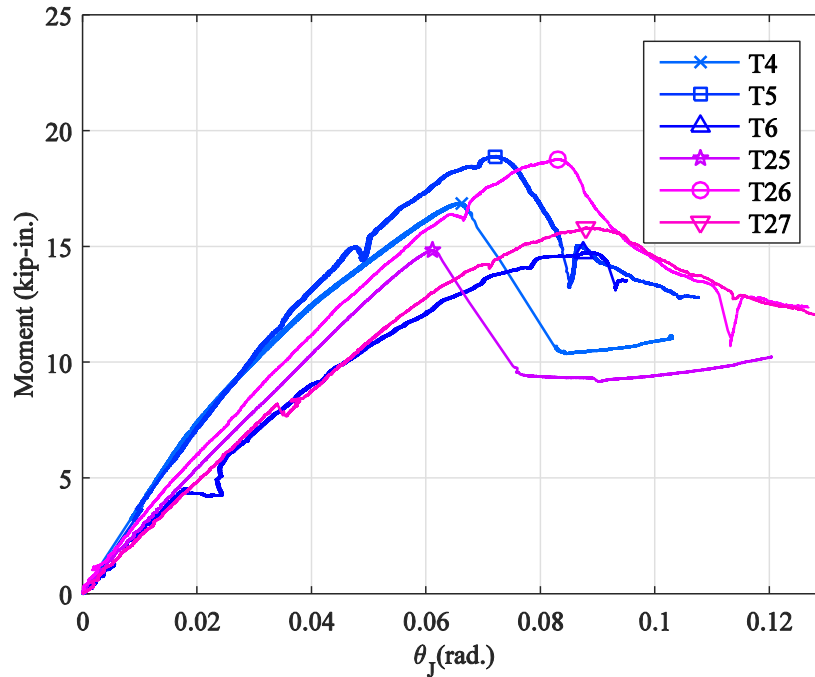


Figure 12: Comparison of the joist behaviors for the effect of the clip angle location.

When the clip angle is attached outside of the joist, ledger bottom flange buckling is observed at lower moments than when attached inside. However the clip angle location has little effect on the stud web crippling capacity when the joist is aligned with the stud. Fig. 13 provides the moment-rotation curves of the joist-to-ledger connections. The initial stiffness is smaller or unchanged when the clip angle is moved to the outside of the joist section, regardless of joist location. It should be noted that for specimens with the clip angle attached outside of the joist, the rigid body stiffness of the stud frame is higher than the others.

The moment-ledger rotation of the specimens is shown in Fig. 14. Ledger stiffness is nearly the same for all selected specimens. This can be explained by the consistency between the stud frame and the attached ledger frame as provided by the floor sheathing, regardless of clip angle location, such that local effects of the joist location and construction details are minimized.

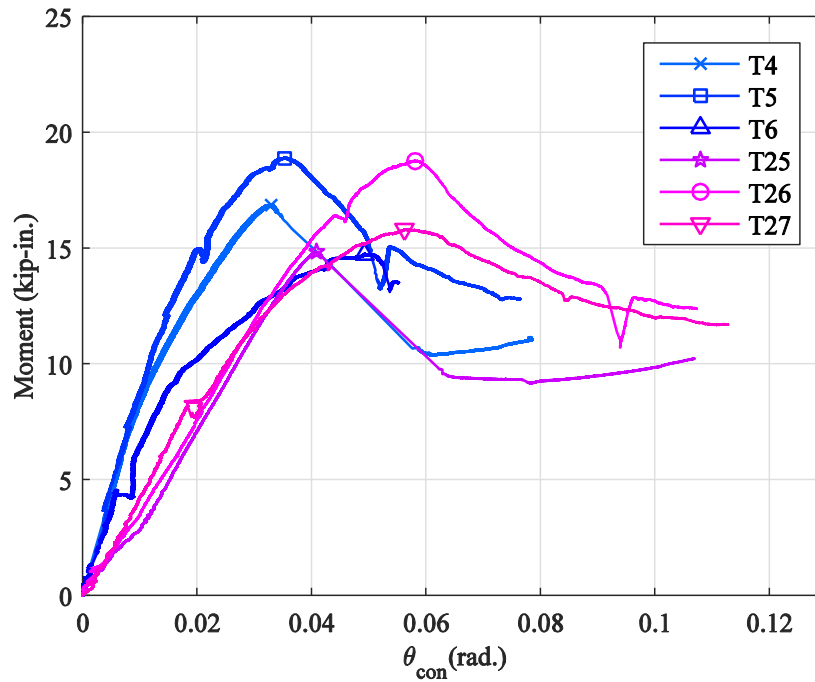


Figure 13: Comparison of the connection behaviors for the effect of the clip angle location.

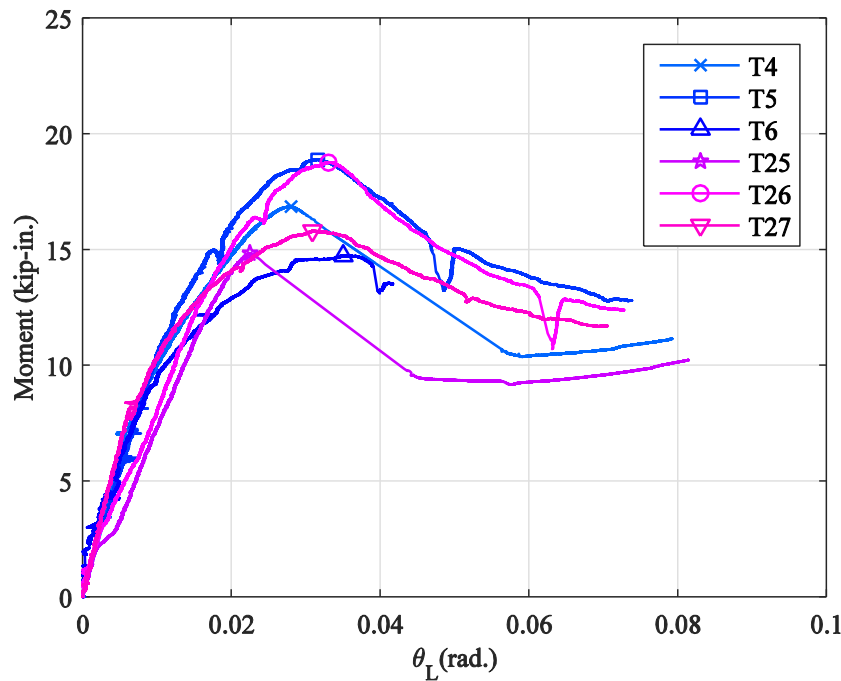


Figure 14: Comparison of the ledger behaviors for the effect of the clip angle location.

3.3 Quantitative comparison of test results

The maximum applied moment (M_{act}), and the connection rotation (θ_{con}) corresponding to M_{act} are summarized for all tests in Table 3. The characterization of the moment-rotation behavior of the connection up to the failure point with a bilinear curve having an inflection at 60% of M_{act} is

depicted in Fig. 15 and the connection stiffness observed up to M_{act} is represented by k_1 and k_2 in Table 3. Table 3 also provides the ledger rotation (θ_L), rotations between joist and ledger (θ_{JL}), between joist and angle (θ_{JA}), and stud rotations (θ_{S1} and θ_{S2}) corresponding to M_{act} .

Table 3. Measured quantities for joist-to-ledger specimens

test no	M_{act} kip-in	θ_{con} rad	k_1 kip-in	k_2 kip-in	θ_L rad	θ_{JL} rad	θ_{JA} rad	θ_{S1} rad	θ_{S2} rad
T4- mid studs	16.84	0.033	762.13	340.72	0.028	0.001	0.001	0.031	0.036
T5- near stud	18.89	0.035	823.08	349.17	0.032	0.002	0.000	0.034	0.038
T6- on stud	14.74	0.049	602.27	170.02	0.035	0.007	0.007	0.016	0.038
T13- mid studs (no screws)	14.43	0.038	448.91	309.76	0.022	0.003	0.000	0.025	0.025
T14- near stud (no screws)	17.74	0.045	477.92	312.28	0.025	0.002	0.000	0.030	0.030
T15- on stud (no screws)	16.22	0.054	475.04	194.52	0.027	0.006	0.006	0.016	0.022
T25- mid studs (clip angle)	14.82	0.041	365.09	358.52	0.022	0.003	0.002	0.020	0.020
T26- near stud (clip angle)	18.76	0.058	393.08	255.22	0.033	0.002	0.001	0.024	0.025
T27- on stud (clip angle)	15.80	0.056	396.22	195.06	0.031	0.003	0.001	0.025	0.032

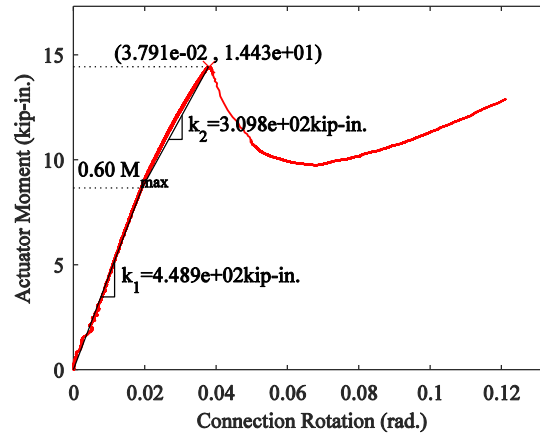


Figure 15: Stiffness degradation observed on T13.

For the connection details examined herein, the specimens with joists near the stud (T5, T14 and T26) always resulted in the maximum moment capacity. Removal of the top and bottom screws connecting the joist to ledger flanges (T13, T14, T15), and moving location of the clip angle from the inside of the joist web to the outside (T25, T26, T27) had only a very modest impact on observed strength. Although different connection designs had only modest effects on moment capacity, the rotation of the connection is observed to be 9~63% larger with the modified connection designs. The initial stiffness of the connection has a dramatic decrease when the top and bottom screws connecting the joist to the ledger are removed. The absence of top and bottom screws and the change in clip angle location to the outside of the joist location had almost no effect on the ledger rotation.

The rotation measured between the joist and ledger webs, which is small compared to the connection total rotation, also comprises the rotation between the joist web and clip angle. Fig. 16 shows the isolated rotations resulting from different elements of the joist-to-ledger connection. As shown, the connection rotation is dominated by the ledger rotation in T4, T5 and

T6 when the joist is attached to the ledger with top and bottom screws connecting webs and with a clip angle placed inside of the joist section. However, the contribution from the ledger rotation is different in the modified connection designs. For these specimens the sum of the ledger rotation and the rotation between the ledger and joist is not as close to the connection rotation, due to additional deformations that are not directly measured in the experiments.

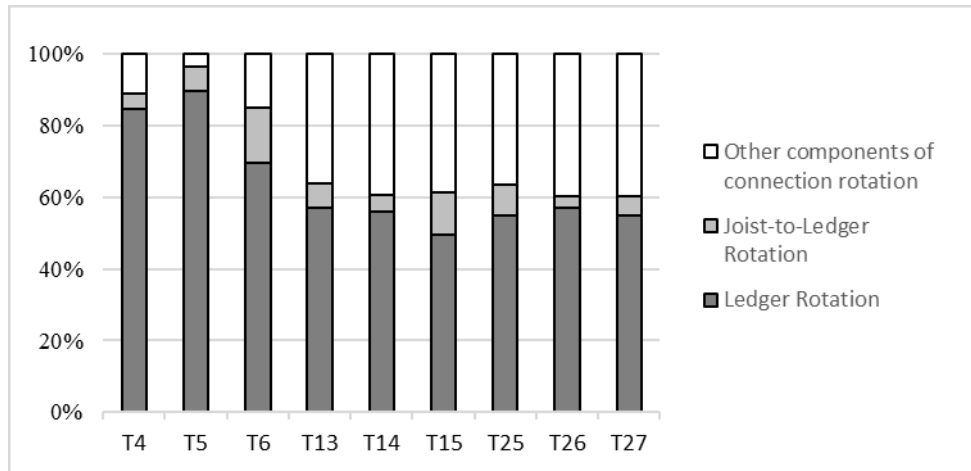


Figure 16: The components of the connection rotation

4. Discussion

The stiffness, stability, and strength of floor-to-wall connections in ledger-framed cold-formed steel construction has been investigated herein depending on connection design details. The results of this study show that the behavior of the joist-to-ledger connection is derived by all elements existing in the connection. Consequently, the presence of top and bottom screws connecting the joist and ledger flanges and the clip angle location (inside or outside of the joist section) has been studied under monotonic loading. However, further experimental work under cyclic loading to investigate these and previously studied parameters such as presence of floor sheathing (Ayhan 2015) and applied load location (Ayhan 2016) is needed. With future tests, not only the static but also the seismic behavior of the floor-to-wall connection in ledger-framed cold-formed steel construction can be characterized. Also, an efficient finite element model of a cold-formed steel joist-to-ledger connection that includes nonlinear hysteretic behavior is needed to support 3D seismic building analysis and design for this form of construction.

5. Conclusions

The effect of connection design details on floor-to-wall connection behavior in ledger-framed cold-formed steel construction has been experimentally investigated under monotonic loading. All connections have floor sheathing and were subjected to shear load applied at a distance of 5 in. from the joist-to-ledger clip angle connection. These tests are a part of a broader experimental study on ledger-framed cold-formed steel construction. Primary limit states observed in the tests are ledger flange buckling and stud web crippling. However, there is a lack of guidance for these limit states in current design codes. In all tests, the limit state is correlated with the floor joist location and its alignment or lack of same with the wall studs. Construction details such as top and bottom screws connecting the joist flanges to the ledger flanges and the location of the joist to ledger clip angle on the inside or outside of the web have minimal impact on the connection capacity, but significant impact on the connection stiffness. The initial stiffness dramatically

decreased, regardless of floor joist location, when the top and bottom screws were omitted or when the clip angle was moved to the outside of the joist web. If the stud frame rigid body stiffness and ledger stiffness are isolated from the connection stiffness, it is shown that these components of the stiffness are not sensitive to the construction details. This indicates that the presence of floor sheathing, connecting the joist and ledger together, is most important for these components.

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