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Computational Modeling of Joist-to-Ledger Connections in Cold-Formed Steel Diaphragms

Hernan Castaneda, M.Eng.[1], Kara D. Peterman, Ph.D.[2]

Abstract

Cold-formed steel framed buildings can involve a range of options for framing systems, including balloon framing, platform framing, and ledger framing. Transfer of lateral forces from the diaphragms to the wall system (and ultimately to the ground) depends on the interactions within the wall-diaphragm connection, which is dependent on choice of framing system. In ledger framing, floor joists are hung from top of wall studs via a rim track (ledger) and clip angle connection. Recent experimental efforts at Johns Hopkins University studied the wall-diaphragm connection with the goal of quantifying its contribution to overall diaphragm response. Results from these experiments showed the contribution to the rotational stiffness based on the location relative of floor joist and wall stud, location of clip angle, presence of top/bottom screws at ledger/joist flanges and presence of oriented strand board (OSB). In addition, it was observed that ledger flange buckling, and wall stud web crippling were the primary limit states. In current design codes there is not check for these limit states. The objective of this paper is to provide a robust computational model for a joist-to-ledger connection in CFS floor diaphragm with the ultimate goal of expanding the experimental test variables via a parametric study the computational model is compared and validated with experimental results. This detailed work at the connection level will motivate and inform future efforts for complete diaphragm system modeling. Furthermore, the work herein will lead to more robust modeling and prediction capabilities for CFS diaphragms.

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1. Introduction

In Cold-formed steel framed buildings there are a range of options for framing systems, including balloon framing, platform framing, and ledger framing as shown in Figure 1. In platform framing, floor joist sits on top track of wall stud, and the next level of wall sits on top of the sheathed floor joists. In balloon framing, floor joists are hung from the inside of the walls allowing continuity of wall stud members from base to top of the structure. Finally, in ledger framing, floor joists are hung through a ledger framed which is connected to the top of the wall stud flange. The sheathed floor is extended to the top track of wall stud, and the next level of wall sits on top of the sheathed floor.

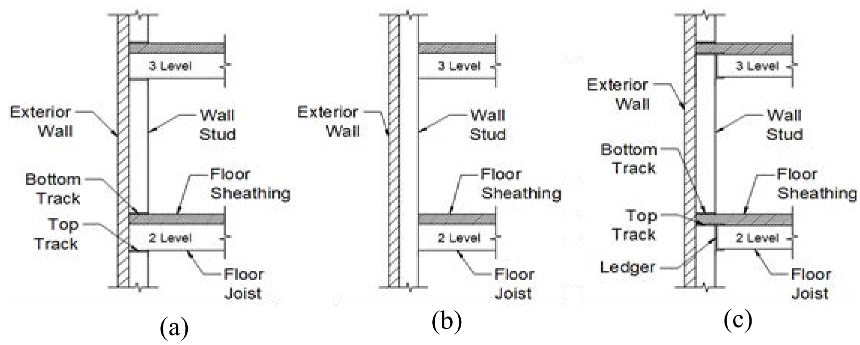


Figure 1: Types of cold-formed steel framing systems; (a) platform framing; (b) balloon framing; (c) ledger framing

According to feedback from industry advisors, ledger framing is currently the most used framing system in CFS construction (Madsen et al. 2012). An advantage of using ledger framing is that the ledger beam collects all the loads from the floor joists and transfers them to the wall stud. In addition, floor joist spacing is independent of wall studs spacing as illustrated in Figure 2. Another advantage of using ledger framing is that in multi-story buildings the axial load in wall studs increases with the number of levels. In the case of platform system, that increment affects the stability in floor joist at floor level intersection, while in ledger system is not an issue as shown in Figure 3 (Ayhan et al. 2015).

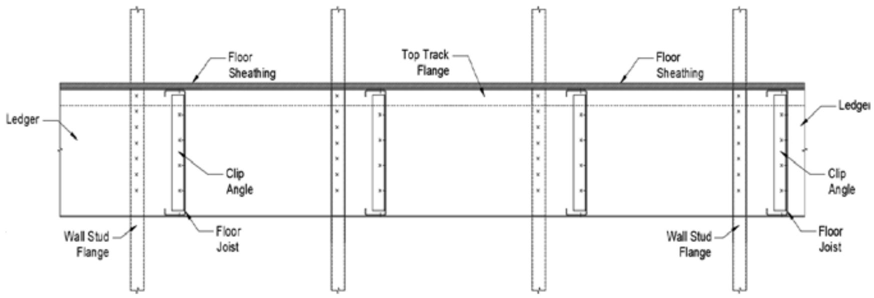
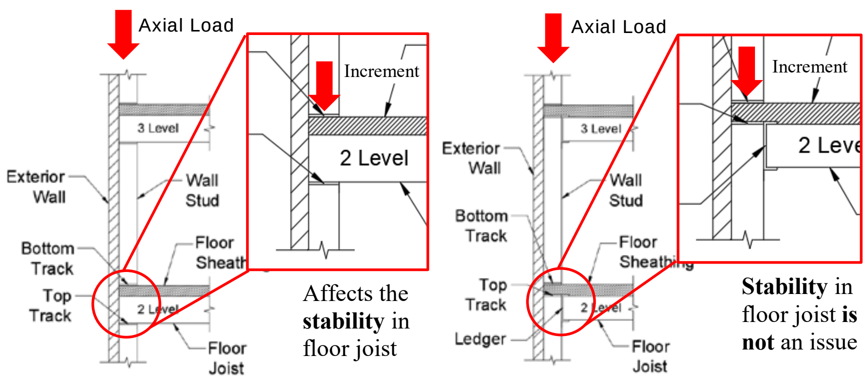


Figure 2: Ledger Framing/ Floor Diaphragm



(a) Platform Framing (b) Ledger Framing

Figure 3: Stability issue in floor joist at floor level intersection

Seismic behavior of ledger framing was recently investigated in the CFS-NEES project (Peterman 2014). two full-scale two-story cold-formed steel framed buildings were tested on a shake table under different ground motion accelerations. The results showed that nonstructural elements of the building may contribute to the lateral load-resisting system of the building along with the main lateral load resisting system such as shear walls. In addition, the CFS-NEES project showed that floor and roof diaphragms behaved as semi-rigid diaphragms (closer to rigid diaphragms) while being designed as flexible diaphragms based on current design codes. It is believed that studying the load paths through the ledger framing will show its contribution to the overall diaphragm response (Ayhan et al. 2016).

CFS-NEES project has motivated an effort to expand understanding of the stiffness of joist-to-ledger connections in ledger framing. It is known that the framing action between floor joists and wall studs is related to the stiffness of the joist-to-ledger connections. Ayhan et al. quantified the stiffness and investigated the behavior of joist-to-ledger connections in ledger framing via several experimental tests at Johns Hopkins University, as shown in Figure 4. Full-scale specimens were designed considering the same ledger framing design in the CFS-NEES project. In these experimental tests, location of floor joist relative to wall studs, and presence and no presence of oriented strand board (OSB), under monotonic loading were explored as shown in Table 1 (Ayhan et al. 2015). Results showed that presence of OSB significantly increased the rotational stiffness, especially when combined with beneficial joist location. Joist location affected the rotational stiffness, when floor joist was located on wall stud, its rotational stiffness generally decreased. While in the case that floor joist was located near to the wall stud, its rotational stiffness increased. In addition, primary limit states observed during the tests were ledger bottom flange buckling, wall stud web crippling, and screw pullout. It should be noted that in current design guidance for connections design is primarily based on a simple shear assumption and this is not enough to understand the actual connection behavior.

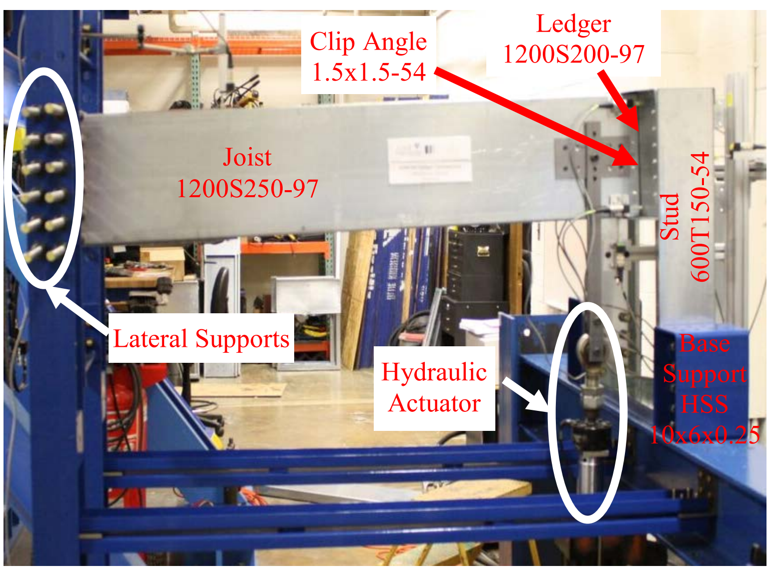


Figure 4: Test setup of wall-diaphragm connection at Johns Hopkins University (Ayhan et al. 2016)

Table 1: Experimental test matrix at Johns Hopkins University (showing varied parameters only)

Specimen name	Joist location	OSB sheathing
T1	Mid studs	
T2	Near stud	
T3	On stud	
T4	Mid studs	✓
T5	Near stud	✓
T6	On stud	✓

This paper is aimed on developing a robust finite element model (FEM) that validates and expands upon the experimental tests at Johns Hopkins University. Where modeling was not included, and it was limited to certain vast arrangements. A reliable FEM can simulate the behavior of joist-to-ledger connection for different types of floor sheathing, different fastener configurations and spacings, and explore a range of structural members. In addition, sub-system level modeling efforts can be extended to model a full-scale floor diaphragm.

2. Computational Modeling

Modeling CFS must consider both nonlinear material properties and geometric discontinuities. As well as, it is necessary to understand the inputs of the model and their sensitivities. This paper summarizes the modeling process using the finite element analysis software ABAQUS, starting from geometric and material properties, following by mesh, interactions, loading and boundary conditions, and connections. Finally, the computational model is compared with experimental results. The work herein will lead to more robust modeling and prediction capabilities for CFS diaphragms to improve design recommendations.

2.1 Geometry and Material Properties

A three-dimensional shell Finite Element Model (FEM) of joist-to-ledger connection was developed. The computational model consists of a floor joist connected to the web of a ledger beam via a clip angle. Floor joist is located at mid span of the ledger beam. The ledger beam is connected to one top side of two wall studs flange as shown in Figure 5. Dimensions of the floor joist (1200S250-97), ledger beam (1200T200-97), wall stud (600S162-54), and clip angle (1.5x1.5-54) are provided in Table 2. To consider geometric imperfections, all members are modeled including their respective corner radius.

Steel is modeled as a homogeneous material with a bi-linear elastic-perfectly plastic constitutive relationship for initial validation purposes. Material properties for steel are provided in Table 3.

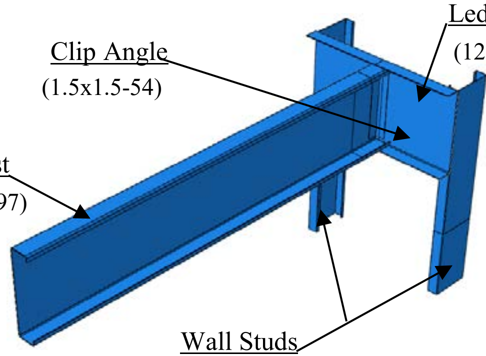


Figure 5: Computational model joist-to-ledger connection

Table 2: Dimensions

Component	Length, in (mm)	Depth, in (mm)	Width, in (mm)	Thickness, in (mm)
Joist	62.00 (1575)	12.00 (300)	2.50 (63)	0.097 (2.5)
Ledger	24.00 (610)	12.00 (300)	2.00 (51)	0.097 (2.5)
Stud	32.00 (813)	6.00 (150)	1.62 (41)	0.054 (1.4)
Clip Angle	11.00 (280)	1.50 (38)	1.50 (38)	0.054 (1.4)

Table 3: Steel Material Properties

Young’s Modulus, ksi (GPa)	29,500 (204)
Poisson’s Ratio	0.3
Yield Strength, ksi (MPa)	50 (345)

The number of integration points through the thickness in each member is considered as 7. For default, ABAQUS considers 5 points of integration, but increasing the number of integration points can decrease sensitivity to the initiation of yielding (Schafer et al. 2010).

2.2 Mesh

Mesh is defined using size control for the seeds. The size of the seeds is dependent on each different part which optimizes the mesh. Element S4R is used for meshing. Element S4R is a four-node element which is suitable for thin or thick components reducing integration time. Mesh is also structured using quad-dominated where quadrilateral elements are primarily used. However, triangles elements are permitted to be used in transition regions. Refine mesh controls are used for contact interactions, where master surfaces are selected based on a surface with coarse mesh, and slave surfaces are selected based on a surface with finer mesh. Sizes for meshing are equal to 0.5 in (12 mm) for a coarse mesh and 0.25 in (6 mm) for a finer mesh. Mesh of the model is shown in Figure 6.

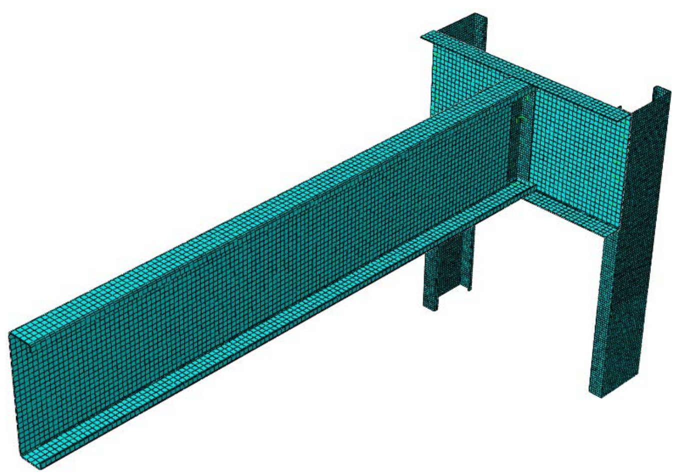


Figure 6: Meshing of joist-to-ledger connection

2.3 Interactions

In experimental specimens, the two wall studs are connected at the top with a top track which forms a stud frame. Top track is modeled through a Multi Point Constraint (MPC) interaction as shown in Figure 7. MPCs allow constraints to be imposed between different degrees of freedom of the model. Two reference points are created at the centroid of the wall studs to constraint relative movement of the wall stud flanges at the top of the wall studs. That constraint is defined based on the contact that should be imposed between the top track flanges with wall stud flanges and their respective screwed connection. From experimental results, the main contribution to the moment-rotation behavior was the ledger rotation rather than the rotation from other components including the top track (Ayhan et al.

2015). Conservatively, beam element is defined for MPC considering its contribution to the moment-rotation behavior from experimental tests.

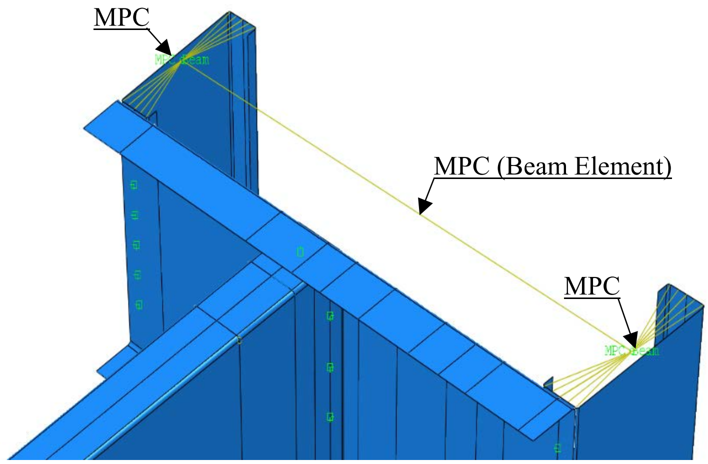


Figure 7: Top track modeling via MPC

Two contact interactions are defined through all the computational model. Surface-to-surface contact and node-to-surface contact. In surface-to-surface contact are identified the following regions: web ledger to flange studs, clip angle to web ledger and web joist, and joist flanges to ledger flanges. Node-to-surface contact is used for the contact between the cross-section of the joist web to ledger web. when using shell elements, its edges cannot be considered as surfaces, instead they are considered as nodes. Two different behaviours are defined in the contact interaction properties: tangential and normal behavior. Tangential behavior is defined using a penalty formulation with a coefficient of friction equal to 0.2, and normal behavior is defined as a “hard” contact. In addition, separation after contact is allowed. In Figure 8 is shown the contact between clip angle to floor joist web and ledger beam web, and floor joist flanges to ledger beam flanges. As it was mention before in the mesh section, finer mesh is used to identified slave surfaces among the master surfaces.

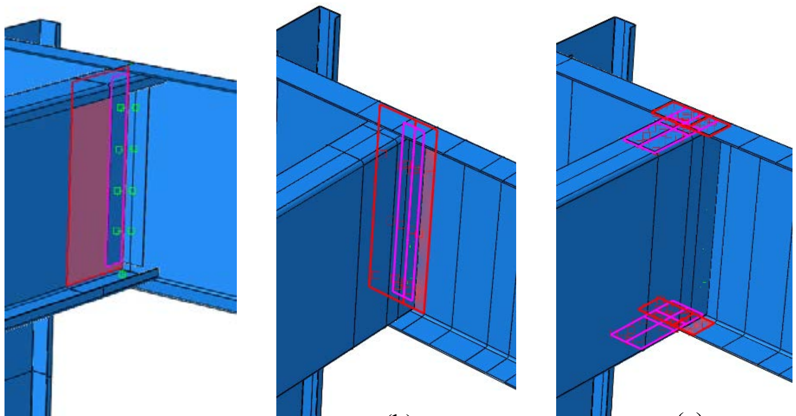

(a) (b) (c)

Figure 8: Contact interactions; (a) Clip angle to joist web; (b) Clip angle to ledger web; (c) Joist flanges to ledger flanges

2.4 Loading and Boundary Conditions

From experimental test, a vertical load was applied to the floor joist where its line of action passed through the shear center of the joist. Shear center of the floor joist is located at 0.3 in (7.7 mm) away from the outside of the joist web. In addition, the applied load was at 5 in (127 mm) away from the web of the ledger beam. A monotonic load is imposed in this model. Quasi-static analysis is used due to the low speed from the applied load during the experimental test. Quasi-static analysis is suitable to solve linear and nonlinear problems. Therefore, it is suitable for geometric nonlinearity models and large deformation analysis (Dassault Systèmes Simulia Corp. 2014). Load is imposed in this model using displacement control. Load is gradually increased as a ramp function within each step increments equal to 0.01. To apply the load in the model, a reference point is created at the same point of application of the load from experimental test as is shown in Figure 9. In addition, the reference point is constrained to the floor joist using an equation constraint which describes a linear constraint between individual degrees of freedom

The free end of the floor joist is lateral restrained only in the direction normal to the joist web to restrict any possible twist of the member. From experimental test, the base of the wall studs is intended to be a fixed condition. Wall studs are connected to the test rig via fastening a steel tube, as is shown in Figure 4. In this model, the region in contact with steel tube and the wall stud web is restrained in all three-translational degrees of freedom.

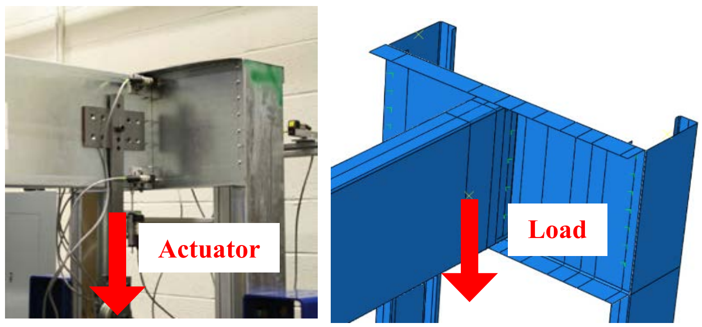


Figure 9: Applied load

2.5 Connections

Three connections are identified in this model. Clip angle connection, flange connection, and web connection as shown in Figure 10. Clip angle connection consists in four screws No. 10 at each leg connecting the floor joist and ledger. Flange connection consists in two screws No. 10 at both top and bottom flange of the joist and ledger. Finally, web connection that consists in seven screws No. 10 connecting ledger web and wall stud flange. Stiffness for the connection is taken from an extensive experimental program on single shear cold-formed steel-to-steel through-fastened screw connections at Virginia Polytechnic Institute and State University (Pham et al. 2015). Ply thicknesses from 0.033 in (0.88 mm) to 0.097 in (2.58 mm) and screw diameters of 0.16 in (4.17 mm) to 0.21 in (5.49 mm) were tested under monotonic loading condition. Fastener load-deformation response showed a multi-linear behavior, which is considered for modeling connector elements. In this model all self-drilling screws are modeled using connector elements which simplify the geometry in the model reducing the time during the analysis. The connector elements are modeled using point-based fasteners. The connections are defined as cartesian and cardan. Cartesian represents three translational degrees of freedom, and cardan represents three rotational degrees of freedom. The mechanical behavior is defined as linear elastic.

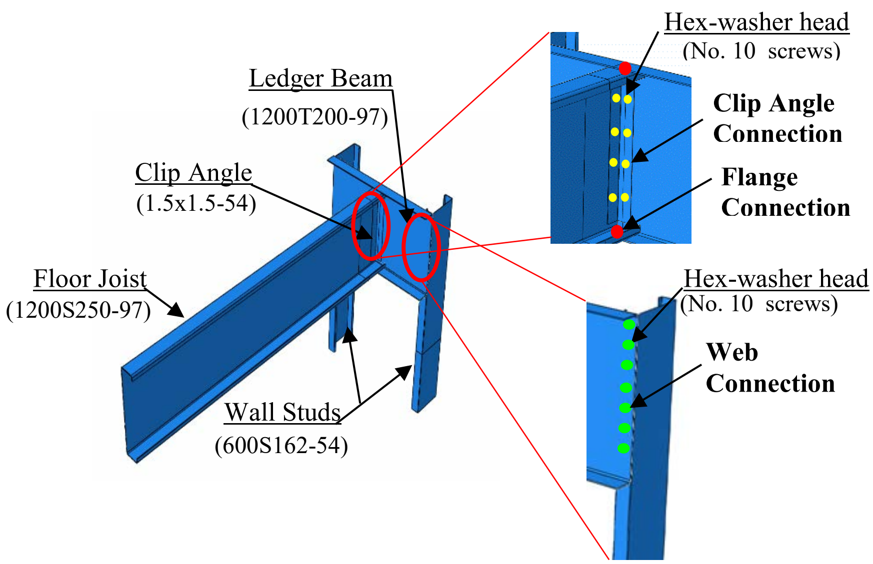


Figure 10: Screwed connections

3. Results

Moment-rotation curves of the joist-to-ledger connection are used to validate the finite element model presented herein with the experimental results, as is illustrated in Figure 11. Comparing experimental and computational results showed that the developed FEM is capable of capturing the initial stiffness. However, at a rotation of 0.02 rad the computational model considerably increased in stiffness. Moment-rotation curves of joist, ledger, and studs alone (as opposed to the moment-rotation characteristics of the entire connection) were compared with experimental results, as is shown through Figure 12 to Figure 14 respectively. Comparing their individual rotational behavior showed that the rotational behavior in wall studs is considerably stiffer in comparison with experimental results while rotational behavior in joist and ledger showed similar behavior in the joist-to-ledger connection, as illustrated in Figure 11. Ledger bottom flange local buckling was identified as the primary failure mode in both experimental and computational results. Comparison of the primary failure mode is shown in the deformed shapes in Figure 15.

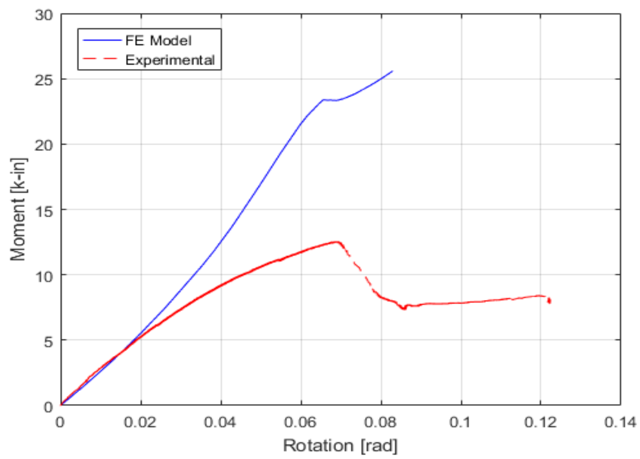


Figure 11: Joist-to-ledger connection moment-rotation behavior

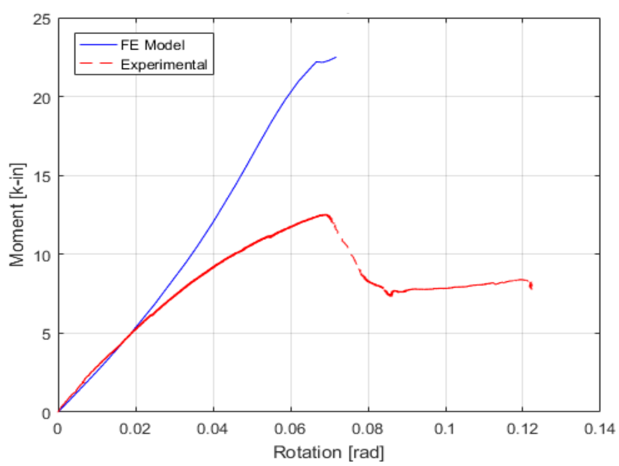


Figure 12: Joist moment-rotation behavior

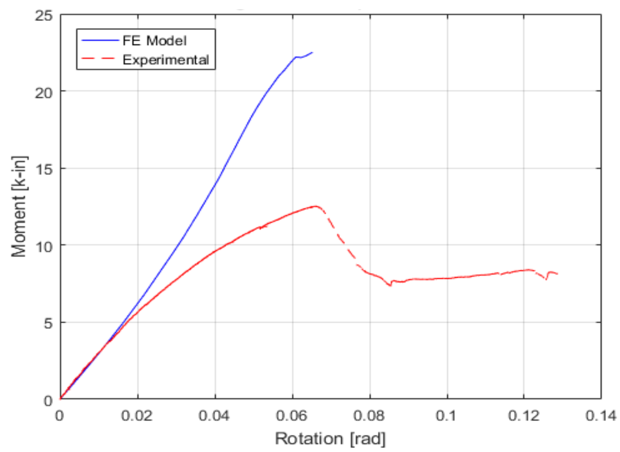


Figure 13: Moment-rotation behavior in ledger alone

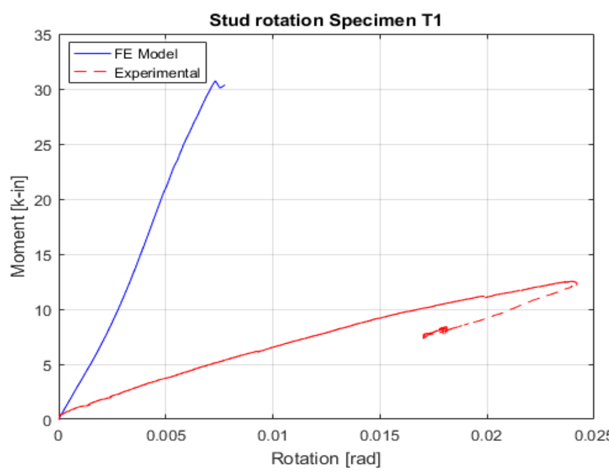


Figure 14: Moment-rotation behavior in studs alone

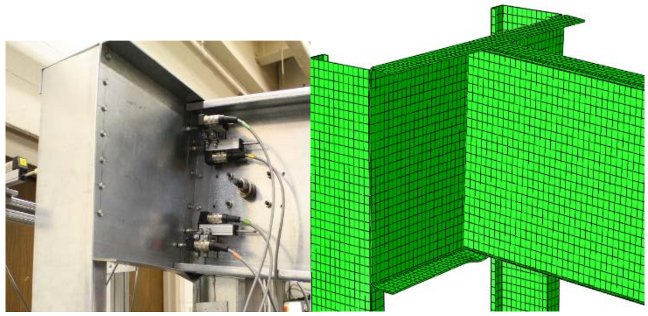


Figure 15: Photo from experimental testing and deformed shape from ABAQUS demonstrating primary failure mode of ledger flange local buckling

These results are part of a preliminary calibration process. However, other parameters and details of the wall stud boundary condition still need to be investigated and validated with experimental results. It is believed that the boundary condition at the end of the wall stud, which is modeled as a fixed end, is conservative, and it should be modeled as a semi-rigid end condition. To model a semi-rigid end condition at the base of the wall studs, spring elements will be used.

4. Conclusions

A three-dimensional shell Finite Element Model (FEM) of joist-to-ledger connection was developed. The computational model consists of a floor joist connected to the web of a ledger beam via a clip angle. Floor joist is located at mid span of the ledger beam. The ledger beam is connected to one top side of two wall studs flange. A monotonic displacement control was imposed in the model at 5 in (127 mm) away from the web of the ledger and passing through the shear center of the floor joist, which was intended to cause maximum shear force to the connection. Initial rotational stiffness and primary failure mode, ledger bottom flange local buckling, are captured in the FEM. However, other parameters and details of the wall stud boundary condition still need to be investigated and validated with experimental results. Which are contributing to the increment of the stiffness behavior in the FEM. Finally, key parameters for modeling were the contact between the cross-section of the floor joist and ledger web, the screwed connections, the mesh size, and the end boundary condition at the wall stud. The work herein has a strong role to play in the future of cold-formed steel framing that leads to more robust modeling to understand diaphragm behavior and wall-diaphragm interactions, with the goal of motivating full system analyses and improved design recommendations.

Future Work

The models shown herein only capture a small portion of the behavior observed in the experimental testing, including primary failure mode and initial stiffness. But additional work is necessary to calibrate these models to the experimental work: stud end conditions are currently stiffer than the observed experimental behavior and must be adjusted to match. The model does not capture ultimate strength or secondary load paths well, and must be improved. Once the model is fully calibrated, we intend to expand upon the experimental program to simulate the behavior of: different types of floor sheathing, different fastener configurations and spacings, and different range of structural members in CFS ledger framing; investigate and validate with experimental results other parameters (floor joist location, floor sheathing, and cyclic loading).

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