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Moment-rotation characterization of cold-formed steel joist-to-ledger connections with variable sheathing

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Abstract

Ledger framing is currently the dominant framing system in cold-formed steel construction. Chief among the advantages of using ledger framing is that the spacing of floor joist is independent of the spacing of wall studs, enabling architectural flexibility, distribution of diaphragm forces independent of axial members, and ease in construction. In this system, the ledger or rim track, typically a deep unlipped channel section, collects loads from the floor joists and transfers them to the walls studs. The ledger is installed directly on the wall such that the floor is hung from the wall (as opposed to platform framing, where the floor is installed between stories). Experimental work has demonstrated that joist-to-ledger connection behavior is complex and involves limit states such as ledger flange buckling, stud web crippling, and fastener pull-out. These limit states change based on the floor joist location with respect to the wall studs. However, current design codes for these connections assume only pure shear of the clip angle fasteners used to connect joist to ledger, and fasteners connecting the ledger to the wall studs, ignoring the experimentally-observed limit states. The work presented herein provides a robust finite element model for a joist-to-ledger connection in CFS floor diaphragm. Experimental parameters (floor joist location, and presence of OSB) are considered to capture a range of stability behavior. In addition, the influence of floor sheathing material and metal deck on the connection stiffness and strength is explored. Fasteners are treated carefully and robustly to capture complex failure modes. Pull-out behavior of the fasteners through multiple steel plies is characterized via experimental testing. Finally, this work will lead to more robust modeling and prediction capabilities for CFS diaphragms.

1. Introduction

In low-to-mid rise light frame constructions there are three common framing systems; ledger framing, platform framing, and balloon framing as shown in Fig. 1. In balloon framing, floor joists are hung from the inside of the walls as illustrated in Fig. 1(a). In platform framing, floor joists are placed on top of the wall frame as illustrated in Fig. 1(b). Finally, in ledger framing, floor joists are hung through a ledger framed which is connected to the top of the wall studs flange as illustrated in Fig. 1(c).

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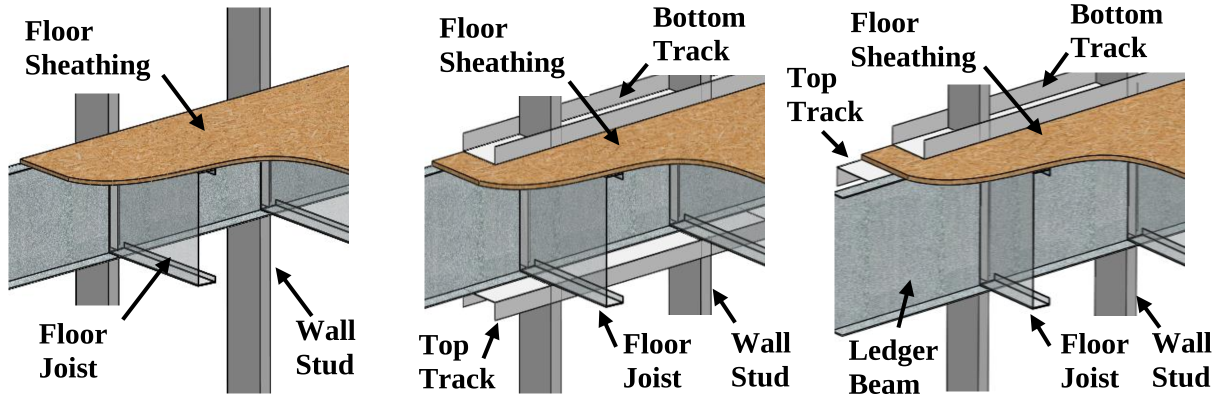


(a) Balloon Framing (b) Platform Framing (c) Ledger Framing

Figure 1: Types of cold-formed steel framing systems

Ledger framing is predominantly used in cold-formed steel construction due to the many benefits associated with it (Nakata et al. 2012). As an example, floor joist spacing is independent of wall studs spacing as is shown in Fig. 2. Another advantage of using ledger framing is that the ledger collects all the loads from the floor joists and transfers them to the wall stud. In addition, in multi-story buildings, the axial load in wall studs increase with the number of levels. That increment affects the stability in floor joist at floor level intersection when platform framing is used, while in ledger framing is not an issue.

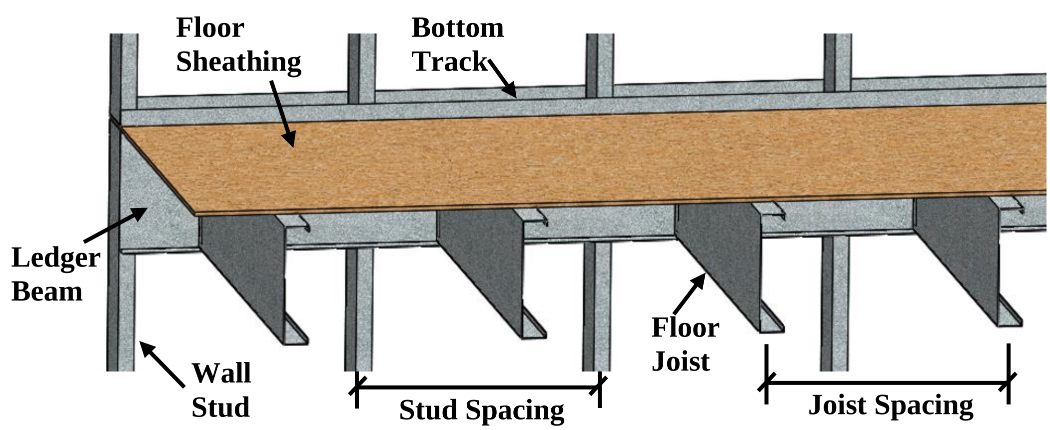


Figure 2: Floor joist spacing and wall studs spacing in ledger framing

In an effort to analyze the behavior of ledger framing, a two story full-scale cold-formed steel framed building was tested as part of system and subsystem seismic testing program in the CFS-NEES project (Peterman 2014, 2016). CFS-NEES project has motivated an effort to expand understanding of the stiffness of joist-to-ledger connections in ledger framing. Ayhan et al. quantified the stiffness and investigated the moment-rotation behavior of joist-to-ledger connections in ledger framing (the same design used in the CFS-NEES project) via several experimental tests at Johns Hopkins University, as shown in Fig. 3. In these experimental tests, location relative of floor joist and wall stud, location of clip angle, and presence of Oriented Strand Board (OSB), under monotonic and cyclic loading were explored (Ayhan et al. 2015, 2016).

Results showed that presence of OSB significantly increased the rotational stiffness, especially when combined with beneficial joist location which was floor joist near to wall stud. In addition, the primary limit states observed during the tests were ledger bottom flange buckling and wall stud web crippling. Current design for this connection assumes a pure shear condition controlled by fastener shear capacity. However, design methods were developed to support strength predictions for these limit states (Ayhan et al. 2019).

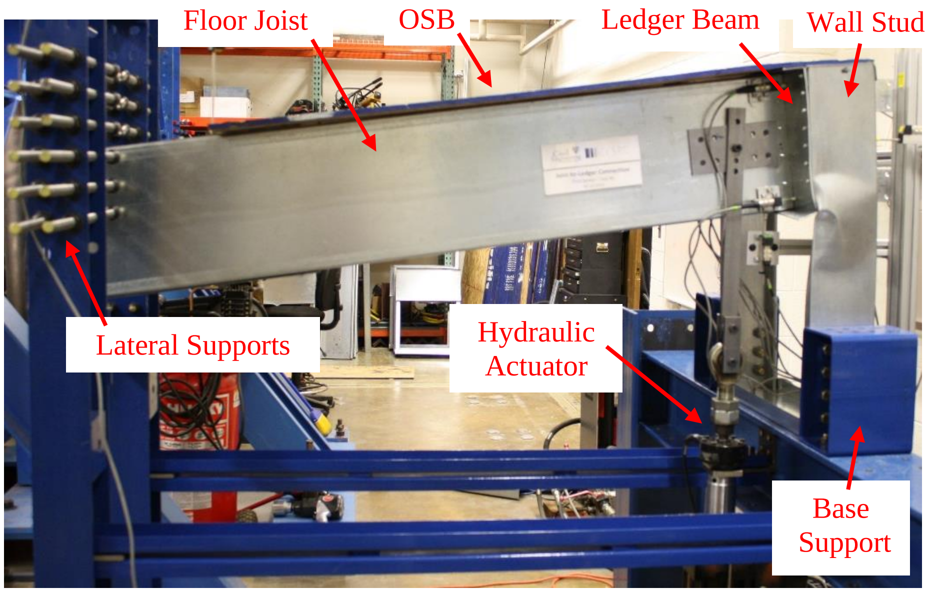


Figure 3: Test setup of wall-diaphragm connection at Johns Hopkins University (Ayhan et al. 2015)

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. Simulation of Cold-Formed Steel Joist-to-Ledger Connection

A three-dimensional Finite Element Model (FEM) was developed using the commercial program ABAQUS (Dassault-Systems 2014) to simulate the behavior of wall-to-diaphragm connections in CFS systems. The computational model was validated based on experimental tests (Ayhan et al. 2015, 2016) and was expanded to simulate the influence of floor sheathing material and metal deck on the connection stiffness and strength.

2.1 Geometry and Material Properties

The computational model consists of a floor joist connected to the web of a ledger beam via a clip angle. The ledger beam is connected to one top side of two wall studs flange. In addition, the two wall studs are framed with a top track as shown in Fig. 4. Dimensions of the floor joist, ledger beam, wall stud, top track, and clip angle are provided in Table 1. All described components herein are connected using 5 mm diameter screws (#10 screws).

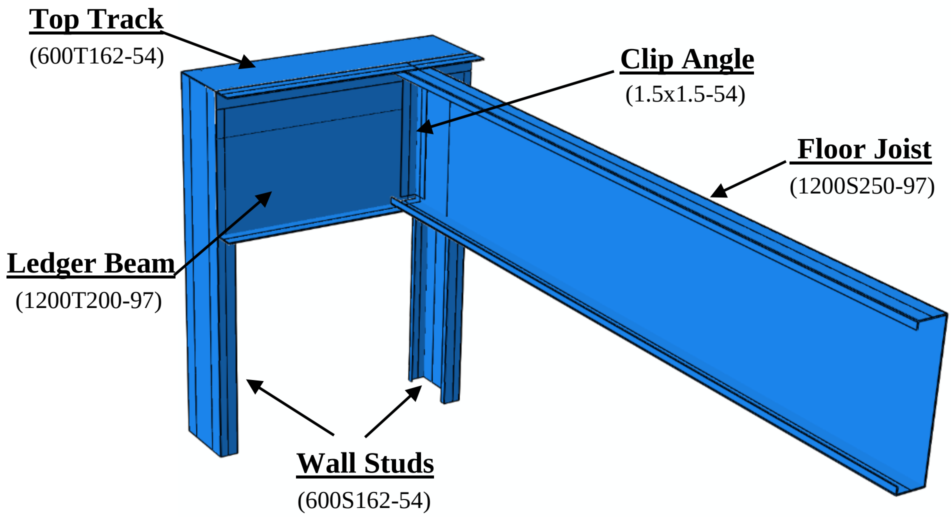


Figure 4: Configuration joist-to-ledger connection

Table 1: Computational model dimensions

Component	Length (mm)	Depth (mm)	Width (mm)	Thickness (mm)
Floor Joist	1575	305	64	2.5
Ledger Beam	610	305	51	2.5
Wall Stud	813	152	41	1.4
Clip Angle	280	38	38	1.4
Top Track	610	152	41	1.4

Steel is modeled as a homogeneous material with a bi-linear elastic-perfectly plastic constitutive relationship. Elastic modulus of steel is assumed as 203,500 MPa with a Poisson's ratio of 0.30. For plasticity, yield strength of steel is assumed as 345 MPa. OSB is modeled as an orthotropic and elastic material. Elastic modulus was determined in two directions, strong axis and weak axis. In direction of the strong axis E_1 was calculated as 7364 MPa, and in direction of the weak axis E_2 was calculated as 1510 MPa. In addition, shear modulus through the thickness G_{12} was calculated as 1379 MPa. Flexural modulus E_3 is assumed to be equal to E_2. Poisson's ratio in all directions are taken as 0.30.

2.2 Contact Interactions

Eight contact pairs are identified through all the computational model; 1) joist flanges to ledger flanges, 2) clip angle to web joist, 3) clip angle to web ledger, 4) web ledger to flange studs, 5) web ledger to flange track, 6) track flanges to stud flanges, 7) web studs to web track, and 8) web joist to web ledger, as it is shown in Fig. 5. Surface-to-surface and node-to-surface contact formulations are used. Master surface is chosen as the thicker surface (more rigid surface) between the surfaces into a contact pair. Finite sliding contact approach is used, which allows for arbitrary relative separation, sliding, and rotation of the contacting surfaces (Dassault-Systems 2014).

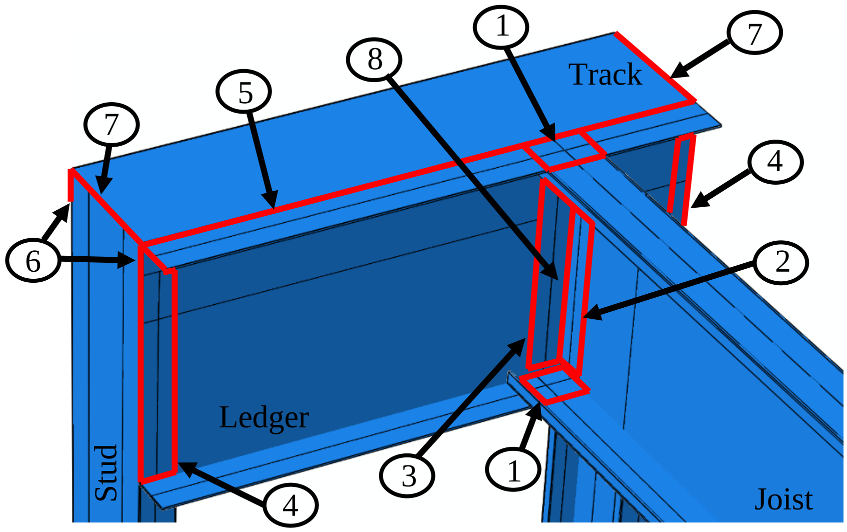


Figure 5: Contact pairs; (1) Joist flanges to ledger flanges; (2) Clip angle to web joist; (3) Clip angle to web ledger; (4) Web ledger to flange studs; (5) Web ledger to flange track; (6) Track flanges to stud flanges; (7) Web studs to web track; (8) Web joist to web ledger

Contact interaction properties for all contact pairs are defined via two types of contact: tangential and normal contact. 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 using a non-linear penalty formulation. In addition, separation after contact is allowed.

2.3 Screwed Connections

In this computational model all self-drilling screws (#10 screws) are modeled using connector elements (wires) which simplify the geometry in the model reducing time during the analysis. Four connections are identified in this model. Track connection, clip angle connection, flange connection, and web connection as shown in Fig. 6.

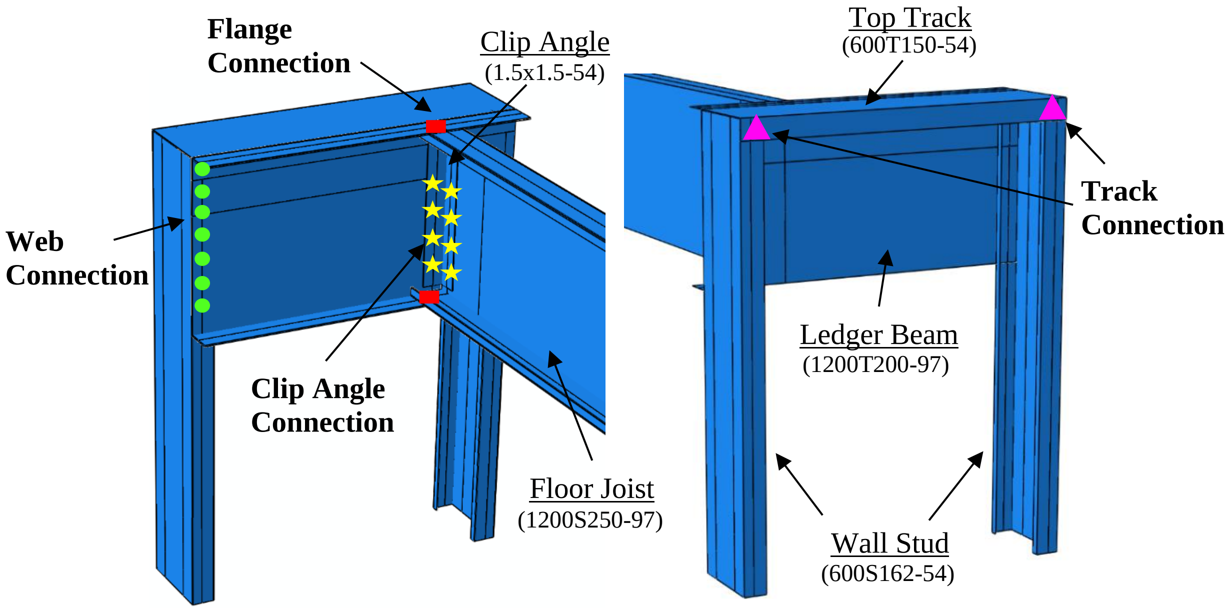
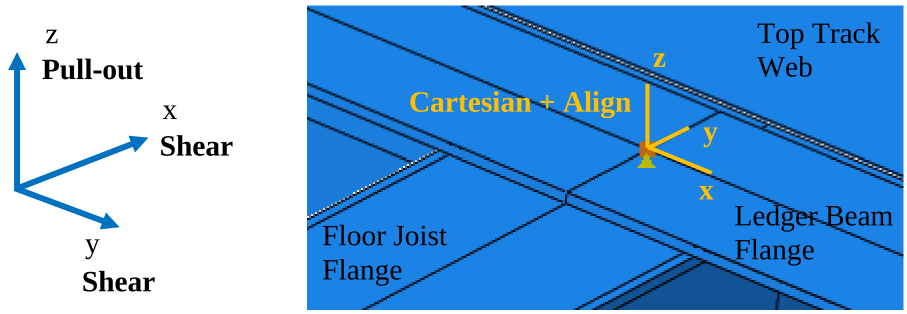


Figure 6: Self-drilling screwed connections

Connector elements are defined by translational components (Cartesian), and rotational components (Align). Cartesian provides a connection between two nodes that allows independent translational behavior in three local cartesian directions. The local directions at connected nodes are defined whit local z axis being normal to the connected parts, and local x and y axis being parallel to the surface of the connected parts. Fig. 7 provides an example for the adopted behaviors at each local direction of the screwed connections. Align is defined to constrain the rotation behavior between the connected nodes. This constraint keeps aligned local directions between connected nodes (Dassault-Systems 2014).



(a) Local behavior (b) Flange connection

Figure 7: Local coordinate system and behavior of connector element

Non-linear elastic behaviors are considered to characterize fastener shear and pull-out response. Parameters to characterize fastener shear behavior are 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 (Tao et al. 2017). Finally, Parameters to characterize pull-out behavior are taken experimentally in the structural lab at University of Massachusetts Amherst. In addition, a failure behavior was defined in the pull-out behavior where pull-out strength was specified as the failure criterion, and all components of relative motion were released upon meeting this failure criterion.

2.4 Mesh and Element Type

All parts in the computational model are modeled with four-node S4R thin shell elements. S4R Elements are suitable for thin or thick components reducing integration time. Mesh in the parts is controlled by uniform seed size. Element aspect ratios are approximately 1:1 as is shown in Fig. 8. Mesh sizes are equal to 12 mm for a coarse mesh and 6 mm for a finer mesh. Mesh is structured using quadrilateral elements. However, triangle elements are permitted to be used in transition regions. Fastener locations and contact interactions dictate local changes in mesh density. The number of integration points through the thickness at each component 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 2008).

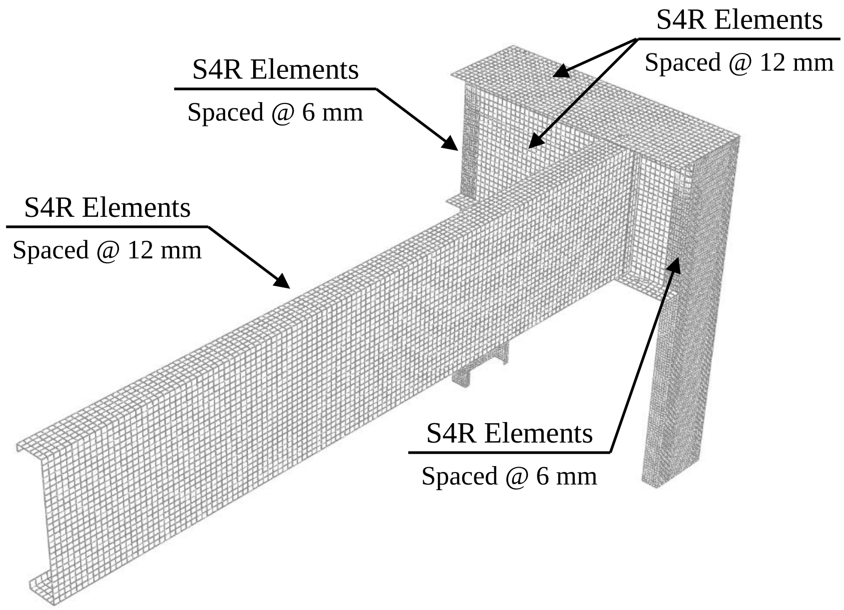


Figure 8: Meshing of joist-to-ledger connection

2.5 Boundary Conditions and Loading

Fig. 9 shows the boundary conditions considered in the model. The free end of the floor joist is lateral restrained only in the direction normal to the joist web to restrict any possible twist, as is illustrated in Fig. 9(a). From experimental test, the base of the wall studs was fixed to the test rig via fastening a steel tube. In this model, eight nodes at the fastening location of the wall studs web were restrained in all three-translational degree of freedom as is shown in Fig. 9(b). In addition, wall studs were framed at the base with a bottom track. This model simplified the modeling of the bottom track via restraining all the cross-section of the wall stud in its normal direction and restraining the wall studs flange in their normal direction as illustrated in Fig. 9(c).

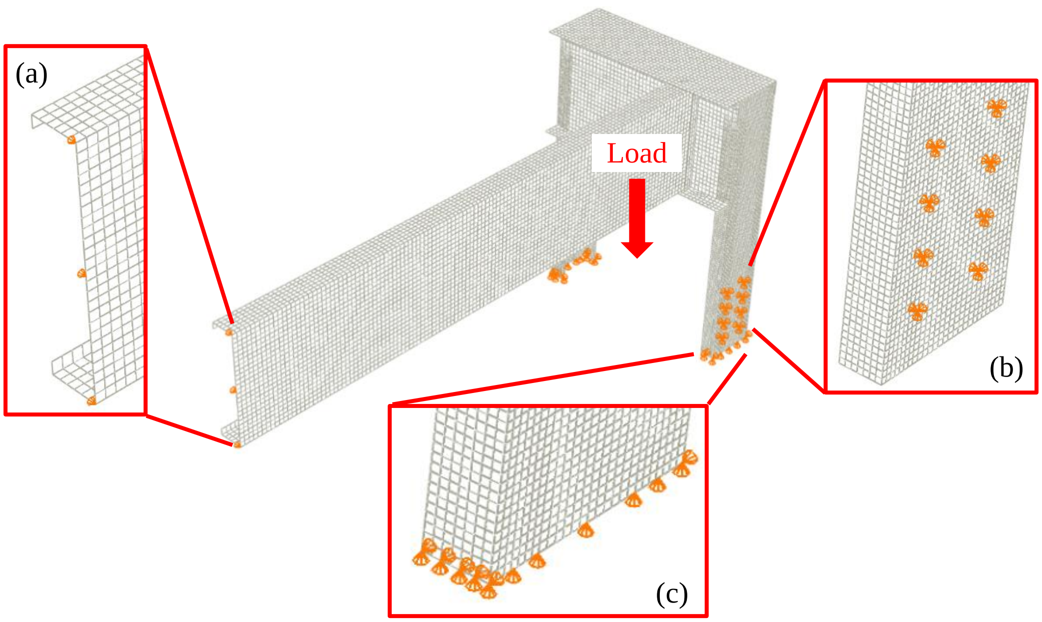


Figure 9: Boundary conditions and loading

From experimental test, a vertical load was applied to the floor joist at 127 mm away from the web of the ledger beam. In addition, line of action of the applied load passed through the shear center of the floor joist. Point of applied load was constrained to the floor joist using a Multi Point Constrain (MPC-PIN) which created a pinned joint between applied load and the floor joist. Load is imposed in this model using displacement control which gradually increased as a ramp function within each step increments equal to 0.01.

3. Simulation Results and Validation

Moment-rotation curve of the joist-to-ledger connection is used to validate the finite element model presented herein with the experimental results, as is illustrated in Fig. 10. A total of six cases were considered for validation purpose in which location of floor joist relative to wall studs, and presence and no presence of Oriented Strand Board (OSB) were considered as shown in Table 2. Comparing experimental and computational results showed that the FEM is capable to capture stiffness and strength of the connection. Stiffnesses are within a 6% difference and peak strengths are within a 7% difference, except of specimen T1 which has a 19% difference. It is believed that boundary conditions and contact formulations play an important role while modeling and significantly can impact computational results. However, these results validate and show accuracy of the finite element model presented herein. Limit states, Local Flange Buckling (LFB), Stud Web Crippling (SWC) and Fastener Pull-Out (FPO) were identified as the primary failure modes in both experimental and computational results.

Table 2: Experimental test matrix at Johns Hopkins University

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

4. Influence of Floor Sheathing Material and Metal Deck

To evaluate the influence of floor sheathing material, Fiber Cement Board (FCB) and steel metal deck are considered and modeled. In addition, FCB on top of steel metal deck is modeled. Based on the most beneficial floor joist location relative to wall studs (floor joist near to wall stud) in the joist-to-ledger connection moment-rotation behavior, the influence of floor sheathing material and steel metal deck are compared. Four-node shell elements with reduced integration points, S4R, are used to model both FCB and steel metal deck. A 19 mm thick FCB was assumed as a homogeneous material with an elastic modulus of 8,963 MPa and with a Poisson’s ratio of 0.30. For plasticity, yield strength of FCB was assumed as 10 MPa.

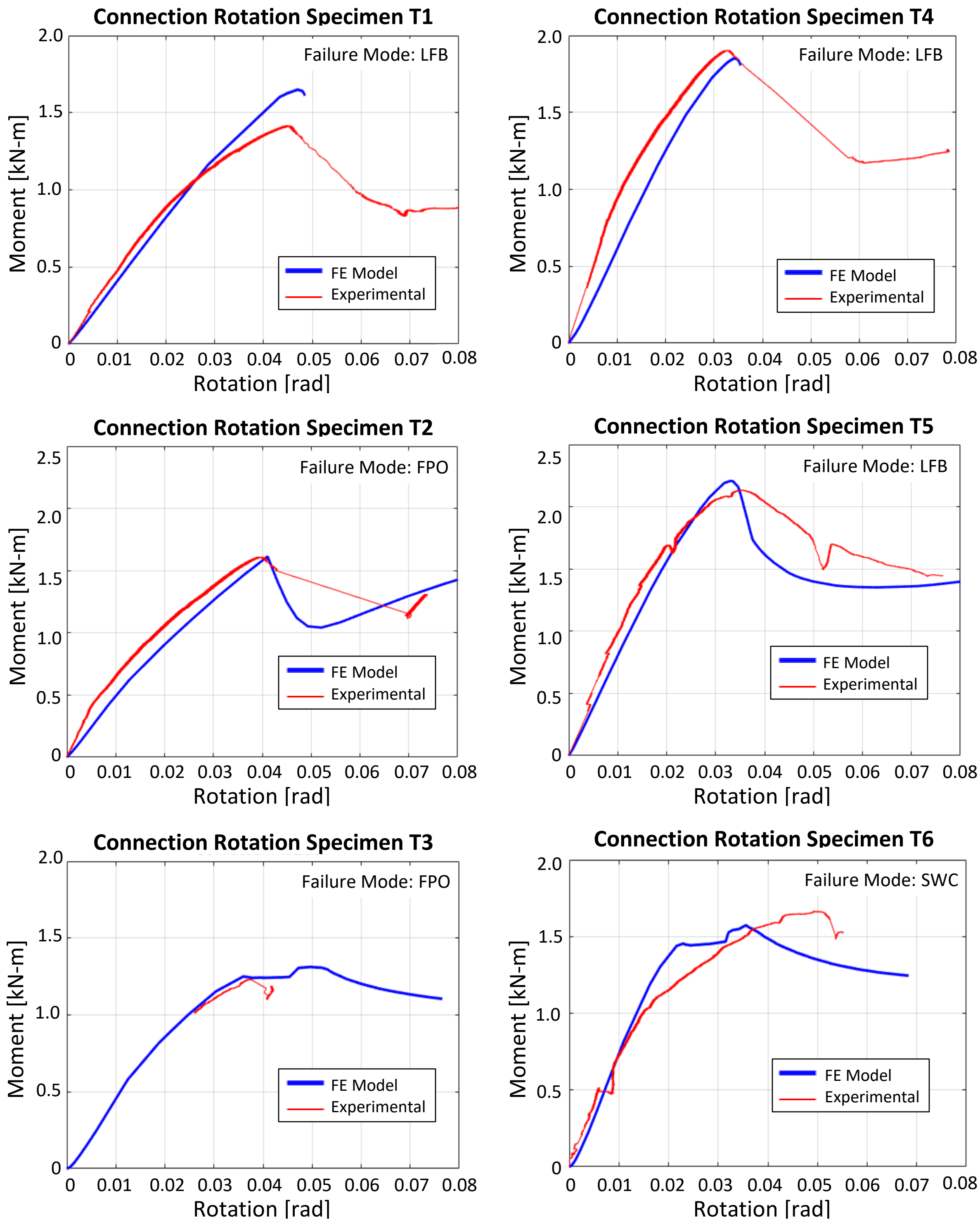


Figure 10: Joist-to-ledger connection moment-rotation behavior

Non-linear elastic behaviors are considered to characterize fastener shear response for connecting FCB and steel. Parameters to characterize fastener shear behavior were taken from an experimental program on shear fastener FCB to cold-formed steel at University of Massachusetts Amherst. Pull-out behavior conservatively was assumed as rigid. A 14 mm form metal deck and 0.45 mm thick was considered as a homogeneous material with an elastic modulus of 203,500 MPa and with a Poisson's ratio of 0.30. For plasticity, yield strength of metal deck was taken as 414 MPa. Shear behavior of fasteners connecting metal deck and steel frame were characterized with an elastic-perfectly plastic relationship. Stiffness and strength were determined according with the SDI Diaphragm Design Manual (SDI 2015). Fig. 11 shows the influence of FCB and metal deck on the joist-to-ledger connection moment-rotation behavior.

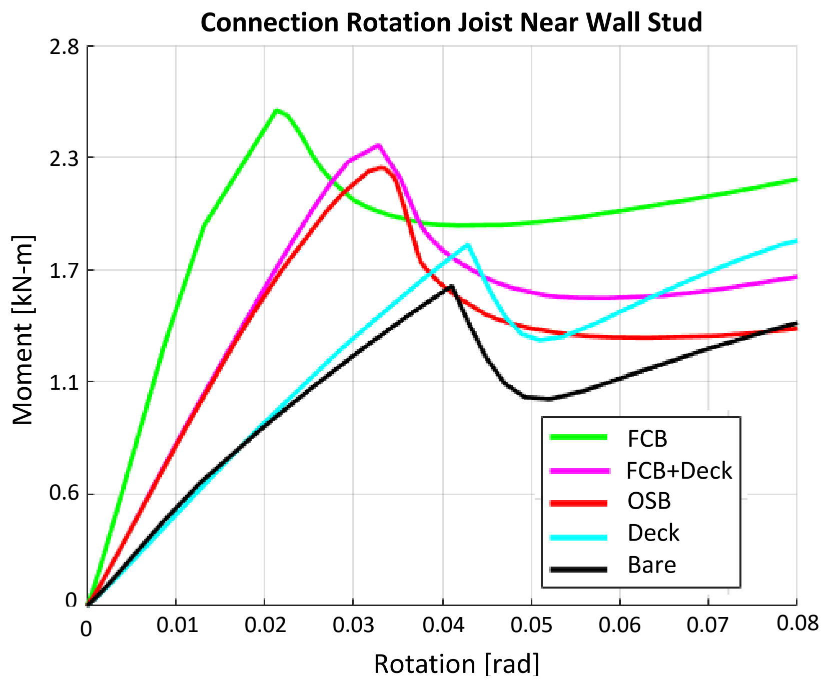


Figure 11: Influence floor sheathing material and metal deck on joist-to-ledger connection

Results showed that FCB significantly increased stiffness and strength on the moment-rotation behavior in comparison with the joist-to-ledger connection with not sheathing (Bare). FCB had shown an increase of the peak strength of 55%. Primary failure mode for FCB was ledger local flange buckling as is shown in Fig. 12. FCB on top of metal deck (FCB+Deck) increased peak strength on 44%. In this case, it is believed that the steel deck worked as a weak shear plane between the steel frame and the FCB as is shown in Fig. 13. In addition, ledger local flange buckling was identified. Finally, in the case for steel deck, peak strength showed an increase on the peak strength of 13% and small difference on stiffness in comparison with the bare case. Primary failure mode for metal deck was fastener pull-out followed by ledger local flange buckling as illustrated in Fig. 14.

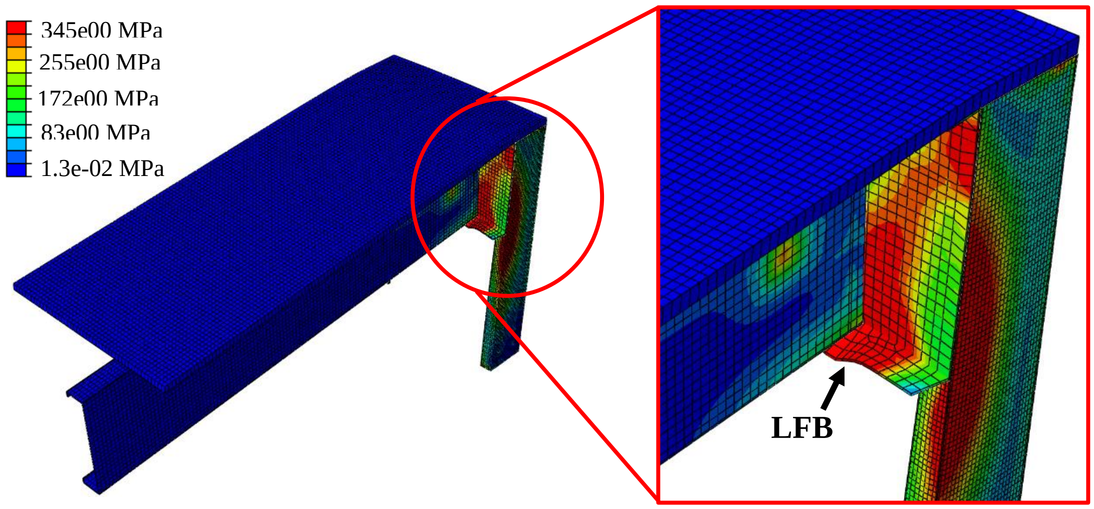


Figure 12: Primary failure mode FCB

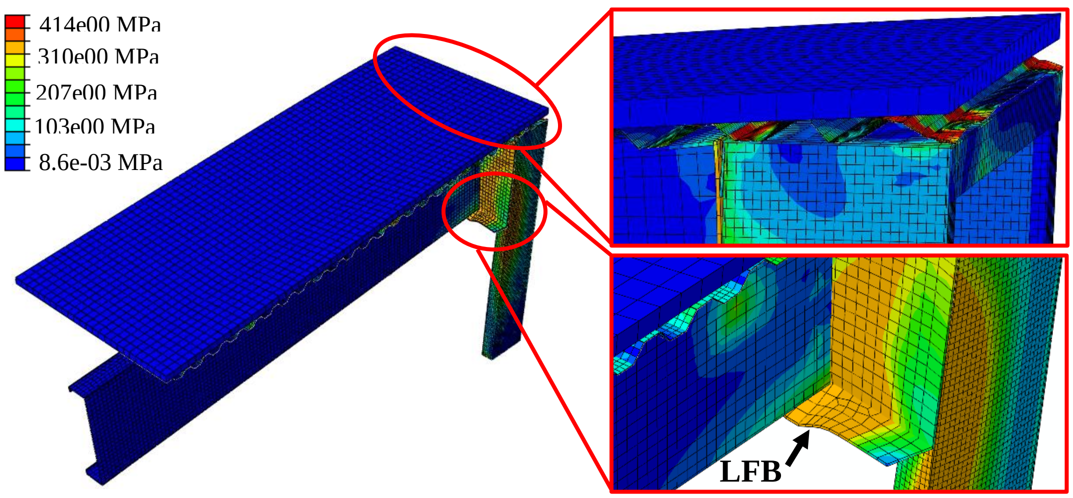


Figure 13: Primary failure mode FCB on top steel metal deck

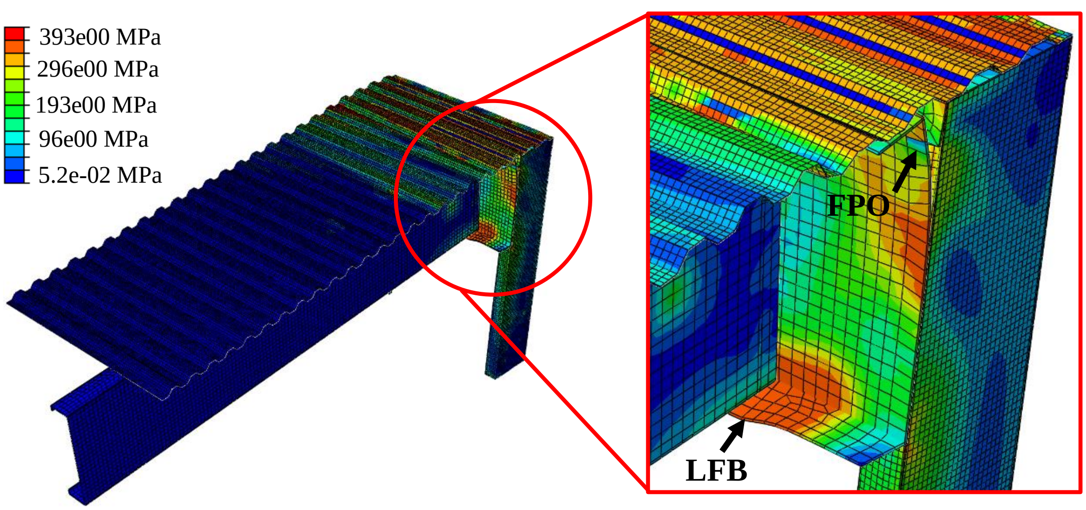


Figure 14: Primary failure mode steel metal deck

5. Conclusions

A three-dimensional shell Finite Element Model of a joist-to-ledger connection in cold-formed steel framing was developed using ABAQUS/CAE software. The computational model consists of a floor joist connected to the web of a ledger beam via a clip angle, and the ledger beam is connected to one top side of two wall studs flange. In addition, the two wall studs are framed with a top track. Three floor joist locations were modeled with the presence and no presence of Oriented Strand Board. Joist at mid of two wall studs, joist near to a wall stud, and joist on wall stud were considered. A monotonic load displacement was imposed in the model at 127 mm away from the web of the ledger. The line of action of the load passed through the shear center of the floor joist. Screwed connections were modeled with non-linear elastic behaviors to characterize fastener shear and pull-out response. Parameters to characterize fastener shear and pull-out behavior were adopted from experimental programs. A total of six computational models were compared and verified with experimental results. Results showed that the computational model presented herein was capable to capture stiffness and strength of the joist-to-ledger connection. Stiffnesses were within a 6% difference and peak strengths were within a 7% difference, except of one model (floor joist at mid of two wall studs with no sheathing) which had a 19% difference. These results validated and showed accuracy of the finite element model. In addition, primary failure modes, ledger local bottom flange buckling, fastener pull-out, and stud web crippling were captured in the computational model. Influence of floor sheathing material and metal deck on the joist-to-ledger connection stiffness and strength were explored. Fiber Cement Board significantly increased stiffness and strength on the moment-rotation behavior. Strength showed a 55% difference in comparison with the steel frame (no sheathing). In addition, ledger local flange buckling was observed as the primary failure mode. Metal deck had minor influence on the stiffness and strength of the connection. Strength showed a 13% difference and fastener pull-out was the primary failure mode. 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.

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