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Stability of wall-diaphragm connections in cold-formed steel framed buildings

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Abstract
In cold-formed steel buildings, ledger framing represents the current state-of-the-practice in which floor joists are effectively hung from the walls via a rim track (ledger) and clip angle connection. Not only do full-scale shake table tests on a cold formed steel building confirm the presence of alternate load paths, but recent efforts at Johns Hopkins University to experimentally test these wall-diaphragm connections demonstrate that these load paths and resultant failure modes are complex. Observations from these experiments indicated that ledger flange buckling and wall stud web crippling are predominant limit states. Notably, these stability modes are not currently considered in design codes, where fastener shear dictates connection design. The work presented herein expands these experimental tests via a computational modeling effort using finite element analysis. Experimental parameters (clip angle location, presence of top/bottom screws, location of ledger relative to flanking studs) are broadened to capture a range of stability behavior. This study is part of a larger effort to discern diaphragm behavior and wall-diaphragm interactions in cold-formed steel systems, with the goal of motivating full system analyses and improved design recommendations.

1. Introduction

There are three common framing systems used in light-frame construction; platform framing, balloon framing, and ledger framing as shown in Fig. 1. In platform framing, floor joists will rest on a sill plate or 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 to the top of the interior wall stud flange, as illustrated in Fig. 2. The sheathed floor is connected with the top track of wall stud, and the next level of wall sits on top of the sheathed floor. An advantage of using ledger framing is that the spacing of floor joist is independent of the spacing of wall studs because the ledger will transfer all the load from the floor joist to the wall stud (Ayhan et al. 2016). 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 system is used, while in ledger system is not an issue. According to the

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Industry Advisory Board (IAB), ledger framing is currently the dominant CFS framing system in construction (Madsen et al. 2012).

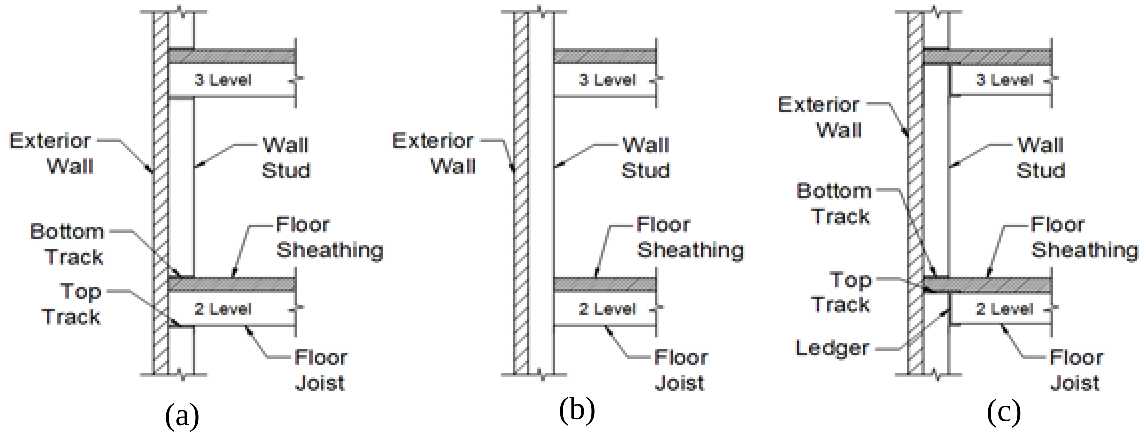


Figure 1: Types of cold-formed steel framing systems; (a) Platform framing; (b) Balloon Framing; (c) Ledger Framing

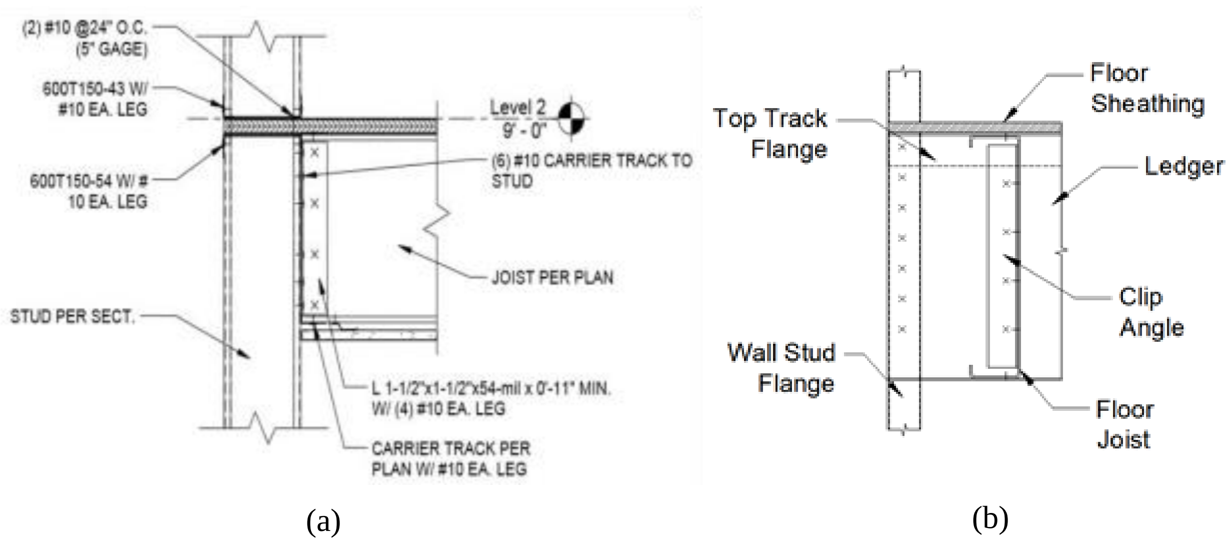


Figure 2: Details of joist-to-ledger connection in CFS-NEES project (Peterman et al. 2016); (a) View normal to web joist; (b) View normal to ledger

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). The ledger framing used in the CFS-NEES project was a key feature for the floor and roof diaphragm, its connection joist-to-ledger and wall stud is shown in Fig. 2. Results from the CFS-NEES project showed that floor and roof diaphragms behaved as rigid diaphragms while being designed as flexible diaphragms. 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).

Ayhan et al. investigated the stiffness and 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. These tests explored clip angle location, presence of top/bottom screws, location of joist relative to wall studs, and presence of oriented strand board (OSB), under monotonic and cyclic loading (Ayhan et al. 2015, 2016). Results showed that the presence of OSB significantly contributed to the rotational stiffness of the joist-to-ledger connection and reduced the effects of joist location relative to the wall studs. In addition, the primary limit states observed during the tests were ledger bottom flange buckling and wall stud web crippling. It is important to mention that current design codes do not check for these limit states. Location of the clip angle outside of the joist web and not presence of top/bottom screws had significant impact on reducing initial rotational stiffness of the joist-to-ledger connection.

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, and different screwed configurations. In addition, it can be extended to model a full-scale floor diaphragm at a lower cost.

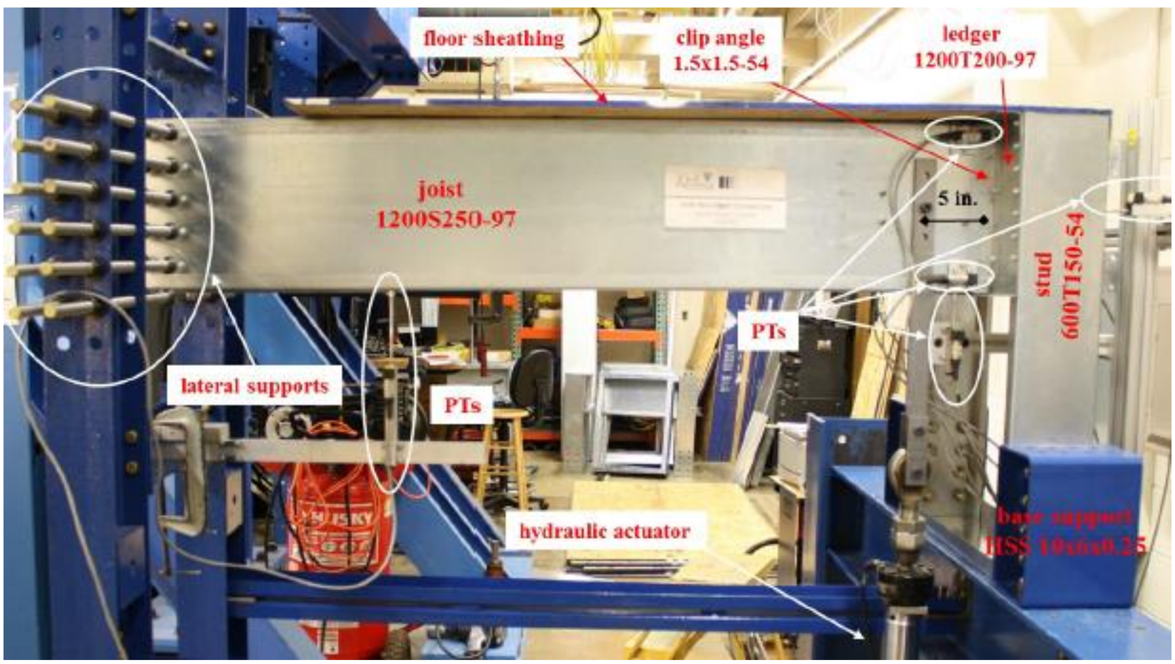


Figure 3: Test setup of wall-diaphragm connection at Johns Hopkins University (Ayhan et al. 2016)

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. For example, increasing the number of integration points through the thickness of the element can decrease sensitivity to the initiation of yielding (Schafer et al. 2010). This paper summarizes the modeling process using the finite element analysis software ABAQUS, starting from geometric and material properties, following by interactions and connections, mesh, and then loading and boundary conditions. Finally, the computational model is compared with experimental results. The work herein will lead to more robust modeling and prediction capabilities for CFS diaphragms.

2. Computational Modeling

A three-dimensional Finite Element Model (FEM) computational simulation of wall-diaphragm connections in CFS framed was developed using ABAQUS/CAE software. The computational model was created based on experimental research of Ayhan et al. at Johns Hopkins University (Ayhan et al. 2015, 2016) to determine the stiffness and behavior of joist-to-ledger connections in ledger framing for improving design recommendations.

2.1 Geometry and Material Properties

The computational model of joist-to-ledger connections consist of a floor joist connected to the web of a ledger beam via a clip angle connected by four hex-washer head, and 5 mm shank diameter (No. 10 screws) per leg. In addition, both top and bottom flanges of the joist and ledger are connected using a single No. 10 screw. The ledger beam is connected to one side of two wall studs via seven No. 10 screws through the ledger web and the stud flange. Dimensions of the floor joist (1200S250-97) are: 1575 mm long, 305 mm depth, 64 mm, and 2.5 mm thick. Dimensions of the ledger beam (1200T200-97) are: 610 mm long, 305 mm depth, 51 mm wide, and 2.5 mm thick. Dimensions of the wall stud (600S162-54) are: 813 mm long, 152.5 mm depth, 41 mm wide, and 1.4 mm thick. Dimensions of the clip angle (1.5x1.5-54) are: 280 mm long, equal leg 38 mm, and 1.4 mm thick. All sections were created in ABAQUS/CAE part module including roundness at the corners of the cross-sections. Once a cross-section was defined, then it was extruded to create a three-dimensional shell model as is shown in Fig. 4.

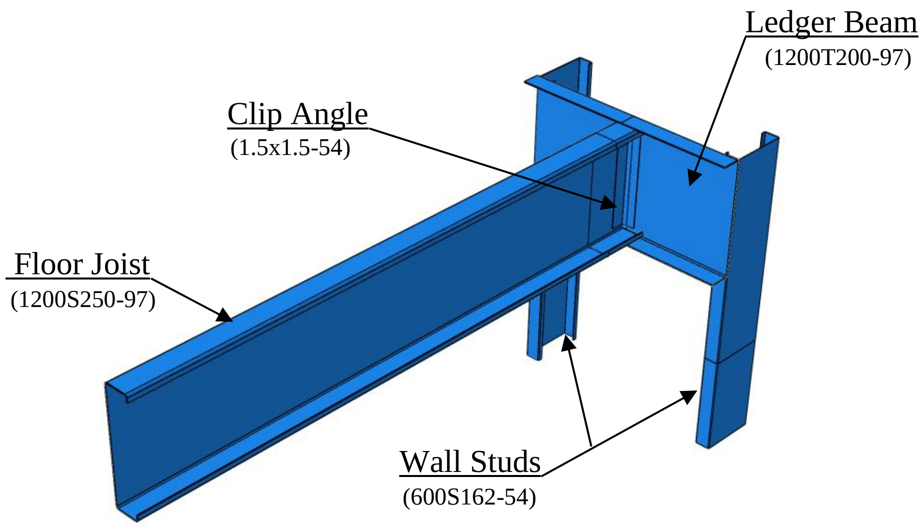


Figure 4: Geometry joist-to-ledger connection

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 1.

Table 1: Steel Material Properties

Density (kg/m^3)	7850
Young's Modulus (GPa)	204
Poisson's Ratio	0.3
Yield Strength (MPa)	345

2.2 Interactions

The experimental specimen consists of a stud frame, where the wall studs are connected to a top and bottom tracks. To simplify the computational model and to reduce the computational time during the analysis, both top and bottom tracks are not considered as a part in part module. Instead, effect of the bottom track is compensated via the boundary condition at the end of the wall stud which is in contact to the experimental test rig. 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). However, the top track in the stud frame contributes to the stiffness and behavior of the wall studs. That contribution from the top track is represented using a Multi Point Constrain (MPC) as is shown in Fig 5.

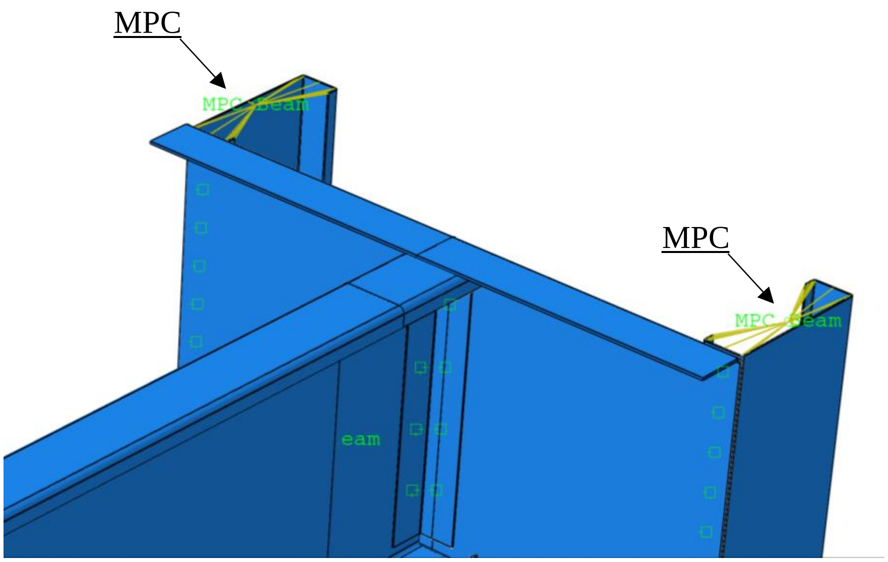


Figure 5: Top track interaction

Contact interaction properties between two surfaces 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 0.3. To restrict elements from the model from having any interference among them, the normal contact is defined as a hard contact. In addition, separation after contact is allowed. Four regions are defined to be in contact surface to surface: web ledger to flange stud, clip angle to web ledger, clip angle to web joist, and joist flanges to ledger flanges. Finally, the contact joist web to ledger web is defined as node to surface contact.

2.3 Connections

In ABAQUS there are different ways for modeling connections. The most common ways are solid elements, wire elements, and connector elements (Korolija 2012). 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. 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). In addition, the pull-out force of the screws is considered in the model. The pull-out force is calculated by Eq. 1:

$$P_{not} = 0.85 t_c d F_{u2} \tag{1}$$

where t_c is the minimum ply thickness, d is the screw diameter, and F_{u2} is the tensile strength of member not in contact with the screw head. Pull-out force is 2.6 kN.

2.4 Analysis and Mesh

In this model is defined to use a quasi-static analysis due to the low speed from the applied load during the experimental test. Quasi-static analysis is used for general purpose analysis and is also able to solve linear and nonlinear problems. Therefore, it is suitable for geometric nonlinearity models and large deformation analysis (Dassault Systèmes Simulia Corp. 2014). Maximum number of increments is defined to save computational time during the analysis when it is presented large deformations. 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. Sizes for meshing are equal to 12 mm and 6 mm as is shown in Fig. 6.

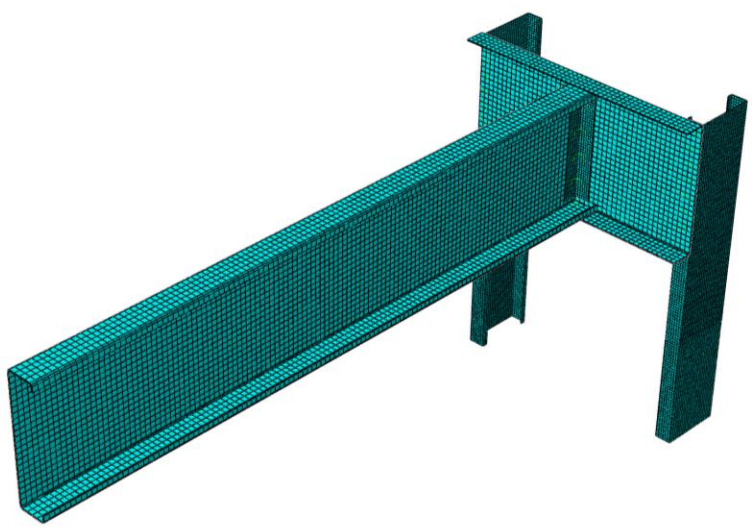
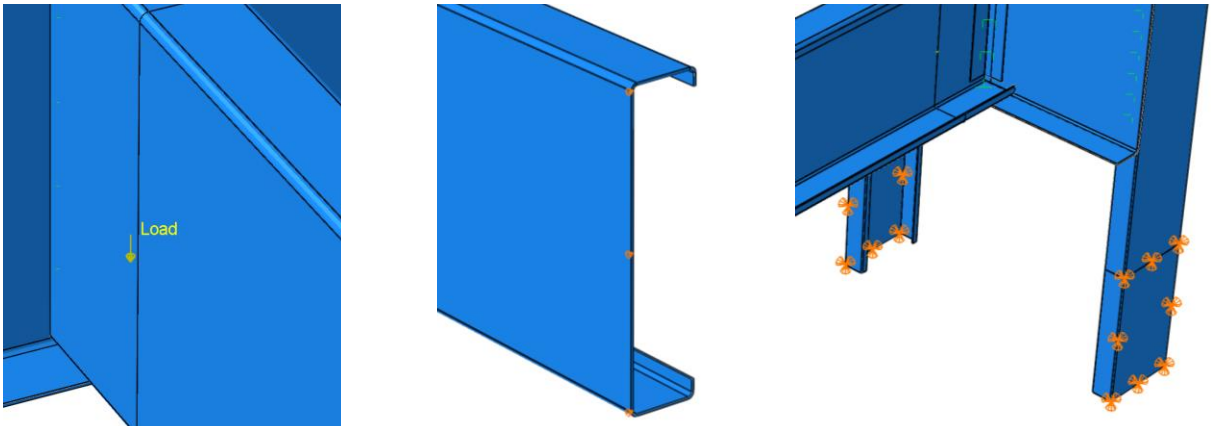


Figure 6: Meshing of joist-to-ledger connection

2.5 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. In addition, the applied load was at 127 mm away from the web of the ledger beam. A monotonic load is imposed in this model. Load is gradually increased as a ramp function within each step increments equal to 0.01. A reference point is created at the position of applied load and then is connected to the nodes at the cross section of the joist using a MPC as is shown in Fig. 7 (a). 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 7 (b). From experimental test, the base of the wall studs is fixed to the test rig via fastening a steel tube, as is shown in Fig 3. In this model and for simplification purpose, only the region in contact with steel tube and the stud wall web is restrained in all three-translational degree of freedom as is shown in Fig. 7 (c).



(a) (b) (c)

Figure 7: Loading and boundary conditions; (a) Applied load; (b) Lateral constrain free end joist; (c) Constrain base wall studs

3. Results

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 8. The values of k1 and k2 represents the experimental bi-linear behavior in moment-rotation of the joist-to-ledger connection up to the failure point. Comparison of initial stiffness, maximum applied moment, and joist-to-ledger rotation are presented in Table 2. Ledger bottom flange local buckling was identified as the primary failure mode. Comparison of the primary failure mode with experimental results is shown in Fig 9.

Table 2: Compared maximum applied moment, (M_{max}); Joist-to-ledger rotation (θ), and initial moment-rotation stiffness (K)

Sample	M_{max} [kN-m]	θ [rad]	K [kN-m]
Experimental	1.416	0.045	45.082
Finite Element	1.878	0.048	44.971

These results validate and show accuracy of the finite element model presented herein. However, other parameters and details of the connection still need to be investigated and validated with experimental results. For example, non-linear behavior of the screw connection, location of the floor joist near to the wall stud, floor sheathing, and cyclic loading.

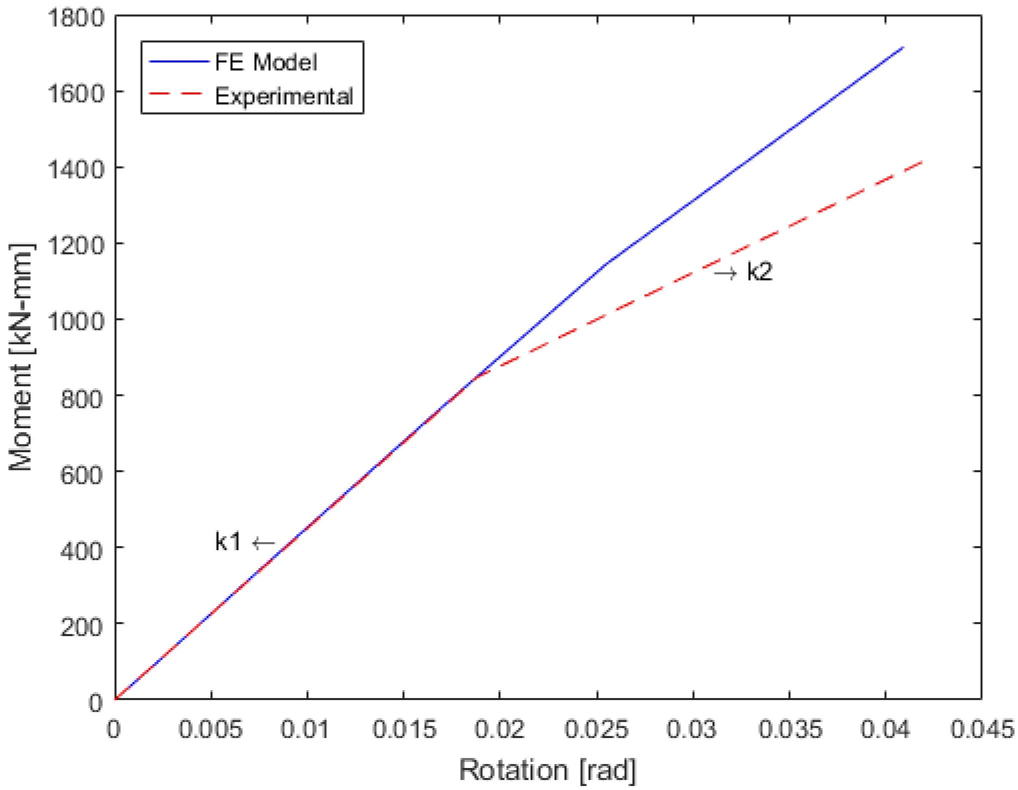


Figure 8: Moment-rotation behavior

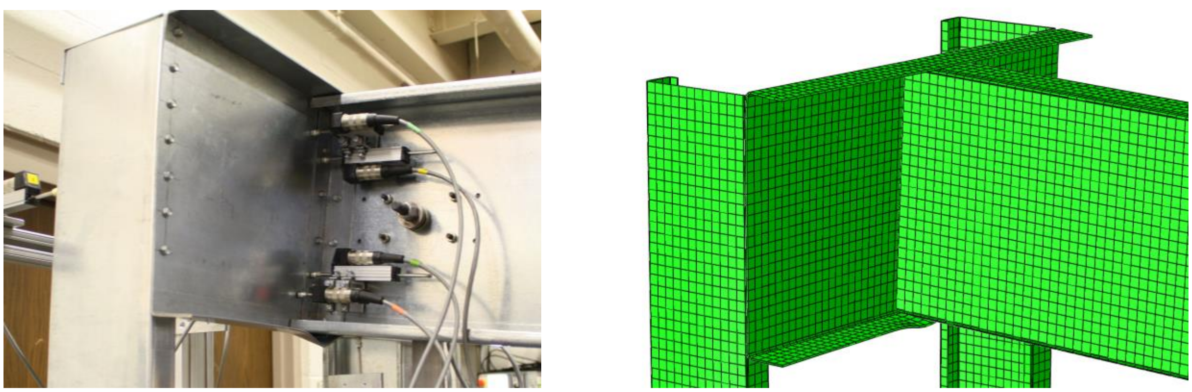


Figure 9: Primary failure mode

4. Conclusions

A computational finite element model (FEM) of a joist-to-ledger connection in CFS framing was developed using ABAQUS/CAE software. Three floor joist locations were modeled. Joist at mid of two wall studs (T1), joist near to a wall stud (T2), and joist on wall stud (T3). Experimental results were used to compare and verify the performance of the three FEMs. A monotonic load was imposed in the model at 127 mm away from the web of the ledger, which was intended to cause maximum shear force to the connection. A bi-linear elastic-perfectly plastic constitutive relationship was used for modeling material properties. In T1 was observed ledger bottom flange local buckling, and in T2 and T3 was observed wall stud web crippling. Moment-rotation curves of T1, T2, and T3 showed similitudes on the initial stiffness of the connection. Finally, key parameters for modeling were the contact between the ledger web and stud flange, the screwed connection, and the mesh size. 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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