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Stability behavior of dual skin diaphragms: cold-formed steel framed floors sheathed with steel deck and cementitious panels

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Abstract

Cold-formed steel (CFS) floor systems generally consist of a frame with a series of equally-spaced CFS joists sheathed with structural panels. While wood and oriented strand board sheathing are common options for cold-formed steel floor systems, steel deck, either filled with concrete or unfilled is increasingly specified. The advent of new fire-resistant cementitious sheathing materials motivates a dual structural skin system: fiber cement boards fastened to steel deck. However, the capacity and behavior of these dual skin systems is unknown. This paper explores this structural system via a computational approach. The authors developed a three-dimensional high-fidelity shell finite element model to explore the shear strength and stiffness of steel deck floor diaphragms and to better understand the shear behavior and flow of forces in steel deck diaphragms, and steel deck diaphragms sheathed with fiber cement board. The computational model consists of a series of equally-spaced floor joist framed to a ledger beam via clip angle connections and sheathed with steel deck. Diaphragms are designed such that shear capacity is governed by either fastener strength or panel buckling, which can be dependent on fastener scheme. Results indicate that the modeling approach accurately captures diaphragm strength and primary failure mode. Furthermore, bespoke fastener schemas tailored to specific desired structural function are able to tune failure modes for ductility and strength. Fiber cement board panels can restrict buckling of the panel and increase strength and stiffness of the floor system.

1. Introduction

A typical cold-formed steel (CFS) floor diaphragm consists of a frame of equally-spaced CFS floor joist and sheathed with structural panels as shown in Fig. 1. Transverse elements can be installed to provide additional lateral resistance on the overall diaphragm response (Xu et al. 2018). Plywood and oriented strand board (OSB) are commonly used as the floor sheathing material. However, with the advance in the understanding on how a CFS system could behave, the use of steel deck on top of CFS frames has been increasingly specified.

Given that in current literature there is limited research on CFS diaphragm behavior under lateral loading, there is an evident need to address this to improve prediction capabilities for CFS

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diaphragms and assist professionals in the construction of safer and more efficient CFS structures. In an effort to analyze the behavior of CFS diaphragms and its contribution to the overall seismic response of the CFS structure, 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 2016a, 2016b). CFS-NEES project has motivated an experimental test program on the seismic in-plane response of CFS floor and roof diaphragms sheathed with OSB at McHill University to expand the understanding of the behavior of CFS diaphragms (Nikolaidou et al. 2016). A total of six CFS diaphragm specimens were tested following the cantilever test method. Effects on the floor joist orientation, fastener spacing, and presence of transverse elements were investigated. In addition, effects of non-structural elements on the lateral response were explored. Results showed the floor joists orientation with respect to the loading direction had a minimal effect on the overall diaphragm response. Fastener spacing at the perimeter of the diaphragm and non-structural components showed a significant impact on the overall diaphragm response.

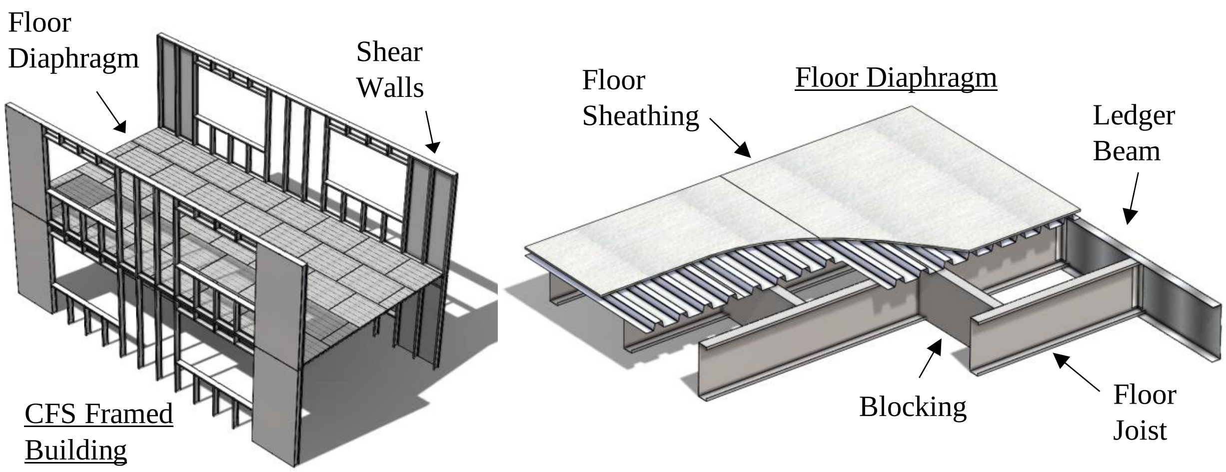


Figure 1: Dual skin CFS floor diaphragm

This paper is aimed on developing a high-fidelity finite element model (FEM) that expands the understanding of the behavior of CFS diaphragms with steel deck sheathing. In addition, the advent of new fire-resistant cementitious sheathing materials motivates a dual structural skin system: fiber cement boards fastened to steel deck, in which the capacity and behavior of these dual skin systems is unknown. This FEM explores this structural system. Modeling and connection parameters are taken from a sub-system level modeling effort on the response of diaphragm-to-wall connection under gravity load (Castaneda and Peterman 2021). A reliable FEM can simulate the behavior of CFS floor diaphragms for different types of floor sheathing, and structural configurations with the ultimate goal of improving prediction capabilities for CFS diaphragms. As future work, experimental tests of full-scale CFS floor diaphragms will be tested at the University of Massachusetts Amherst. These tests will follow the cantilever test method to characterize the lateral response of CFS diaphragms sheathed with steel deck and the dual skin system presented herein. Ultimately this work will provide data and tools for the analysis and design of CFS diaphragms. In addition, this work will lead to an experimental test program of CFS diaphragm in a shake table test, as part of the design of a ten-story full-scale CFS framed building in the CFS-NHERI project.

2. Simulation of Cold-Formed Steel Floor Diaphragm Sheathed with Steel Deck and Cementitious Panels

A three-dimensional shell Finite Element Model (FEM) was developed using ABAQUS software (Dassault-Systems 2014) to simulate the lateral response of CFS floor diaphragms sheathed with steel deck. In addition, the influence of structural cementitious panels on top of steel deck on the overall diaphragm response. Furthermore, the effects of floor joist spacing and steel deck fastener spacing were explored.

2.1 Geometry, Mesh and Material Properties

The computational model consists of a series of equally-spaced floor joist framed to a ledger beam via clip angle connections and sheathed with steel deck as shown in Fig. 2. Dimensions of the floor joist, ledger beam, clip angle, and steel deck are provided in Table 1. All parts in the computational model are modeled with four-node S4R thin shell elements. Mesh is structured using quadrilateral elements keeping an approximately aspect ratio of 1:1 (see Fig. 2). Mesh sizes are equal to 12 mm for a coarse mesh and 6 mm for a finer mesh. 7 integration points are considered through the thickness of each component (Schafer 2008).

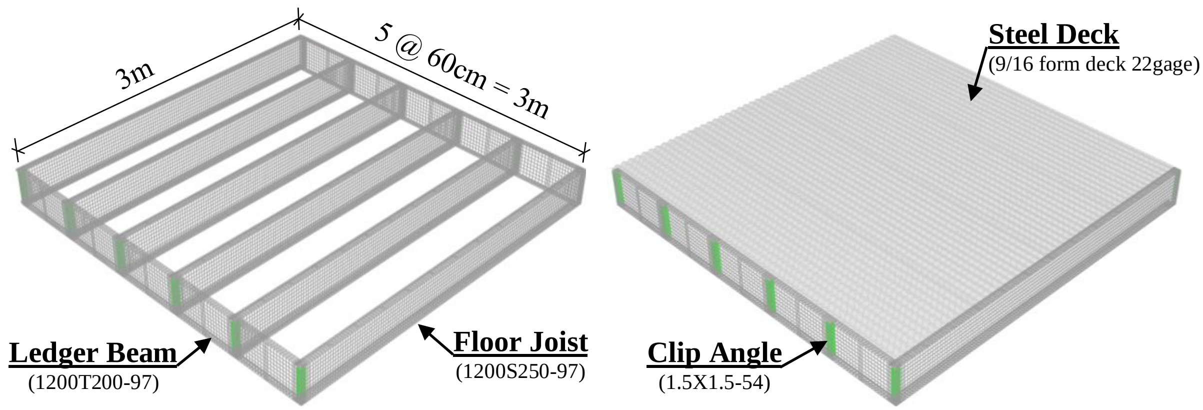


Figure 2: CFS floor diaphragm configuration

Table 1: Computational model dimensions

Component	Length (mm)	Depth (mm)	Width (mm)	Thickness (mm)
Floor Joist	3000	305	64	2.5
Ledger Beam	3000	305	51	2.5
Clip Angle	280	38	38	1.4
Steel Deck	3000	14	762	0.8

Steel is modeled as a homogeneous material with a bi-linear elastic-perfectly plastic constitutive relationship. Elastic modulus of steel is taken as 203,500 MPa with a Poisson's ratio of 0.30. For plasticity, yield strength of steel is taken as 345 MPa and 414 MPa is taken for the steel deck according with the Diaphragm Design Manual (SDI 2015).

2.2 Contact Interactions

Seven contact pairs are identified through all the computational model as illustrated in Fig. 3. Surface-to-surface and node-to-surface contact formulations are used. All the master surfaces are chosen relatively to the most 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).

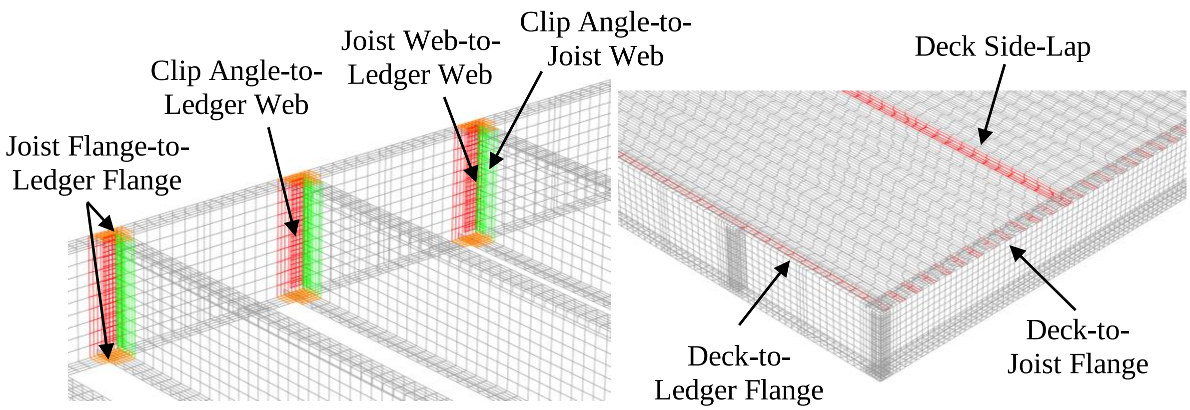


Figure 3: Contact pairs

Two contact interaction properties for all contact pairs are defined: 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 with a non-linear penalty formulation. In addition, separation after contact is allowed.

2.3 Screwed Connections

In this computational model all steel-to-steel connections are fastened via 5 mm diameter screws (#10 screws). The floor joist is fastened to the ledger beam via a clip angle connection as shown in Fig. 4 (a). The connection consists of four screws fastened at each leg of the clip angle and spaced by 61 mm. In addition, the joist and ledger flanges are fastened with a single screw at the midpoint of the top and bottom flanges.

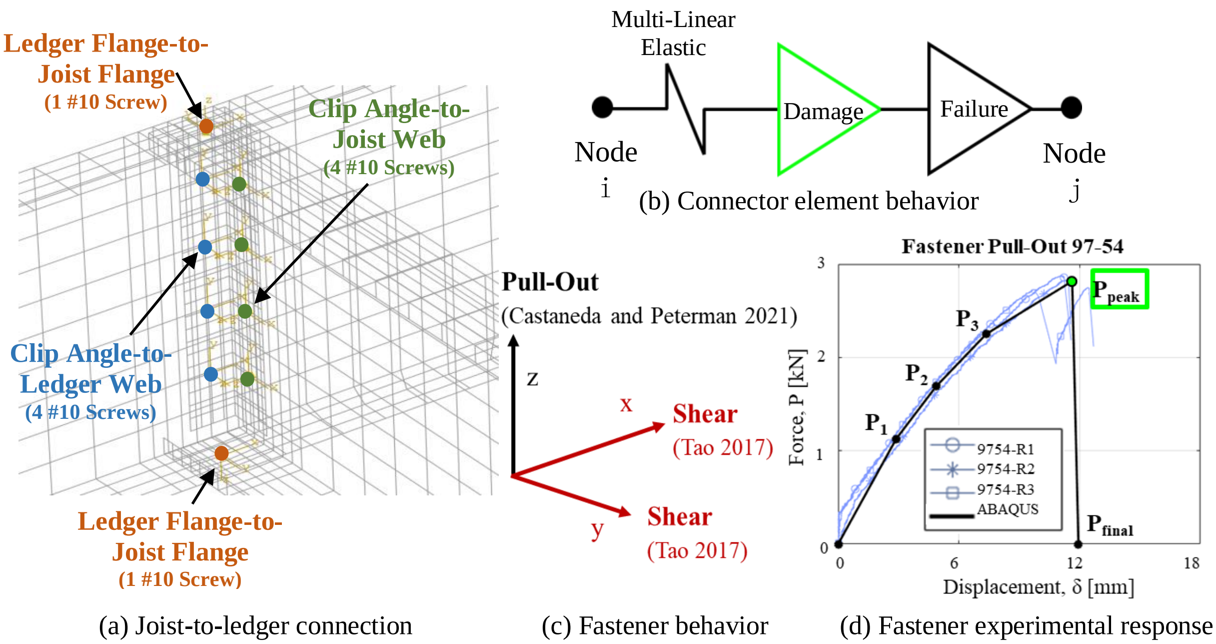


Figure 4: Modeling self-drilling screwed connections

Fastened screw connections are modeled using connector elements (wires) which simplify the geometry in the model reducing time during the analysis. Connector elements are defined by a fastener multi-linear elastic behavior and a failure criterion as illustrated in Fig. 4 (b). The multi-linear elastic behavior is considered to characterize fastener shear and pull-out response based on a local coordinate system at each of the connected nodes, as shown in Fig. 4 (c). All the parameters and details to characterize fastener shear and pull-out behavior are presented in a recent publication by the authors presented herein, on the moment-rotation response of cold-formed steel joist-to-ledger connections (Castaneda and Peterman 2021). Fig. 4 (d) shows an example of a fastener pull-out experimental response and the simplified multi-linear response implemented as fastener behavior in ABAQUS.

2.3.1 Steel deck screwed connections

Fig. 5 shows the steel deck connections, which involve a side-lap connection using #10 screws and spaced 305 mm apart, an edge connection using 5.3 mm diameter screws (#12) and spaced by 203 mm, and a support connection using #12 screws and installed in a 30/4 pattern, as detailed in the DDM04 (SDI 2015). Steel deck connections to the joist require an increased diameter screw, 5.3 mm (#12 screws) and the side lap connection requires a 5 mm screw. Given the lack of available experimental data on thin steel plies, fastener shear behavior is conservatively characterized with an elastic-perfectly plastic relationship and presented in Castaneda and Peterman (2021).

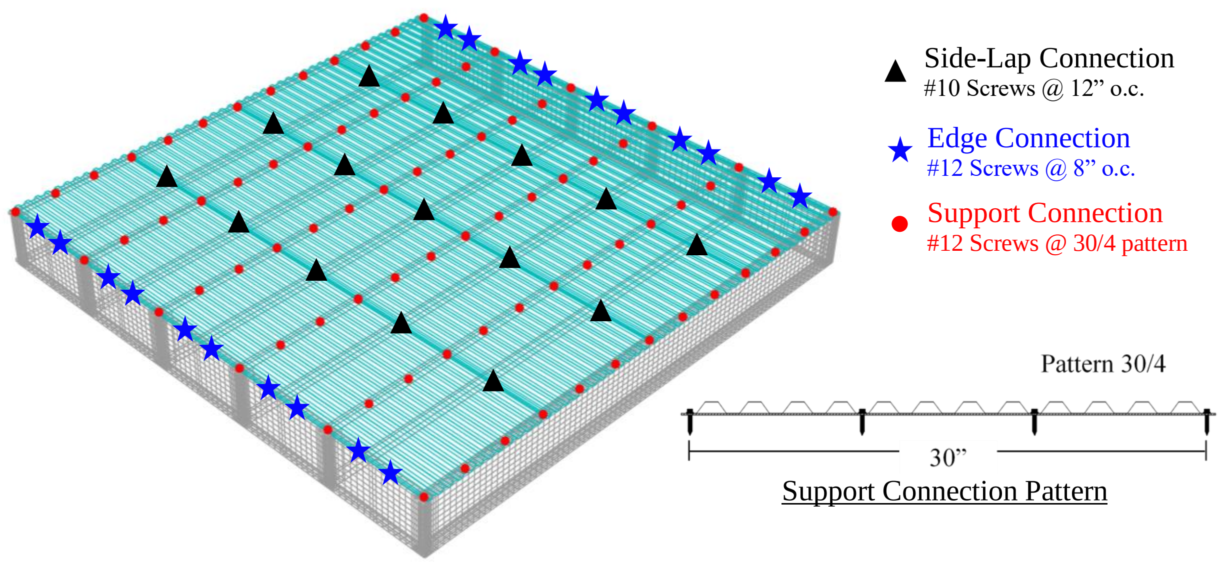


Figure 5: Steel deck connections

2.4 Boundary Conditions and Loading

The boundary conditions considered in the model are shown in Fig. 6. Strip areas are defined on the web of the ledger beams. The width of the strips corresponds to the flange width of a wall stud, and they are typical spaced by 610 mm. Conservatively, the motion of the nodes contained in the strips (red strips Fig. 6) is restricted in all three orthogonal directions (Ux=Uy=Uz=0). At the opposite strips (green strips Fig. 6), load is imposed by using displacement control in the x direction (Uy=Uz=0; Ux=varies) that gradually increases as a ramp function. In addition, at both ends of the ledger beam that is pinned, the web is lateral restrained only in its normal direction (Uz=0) to restrict any possible bending of the ledger beam at the ends.

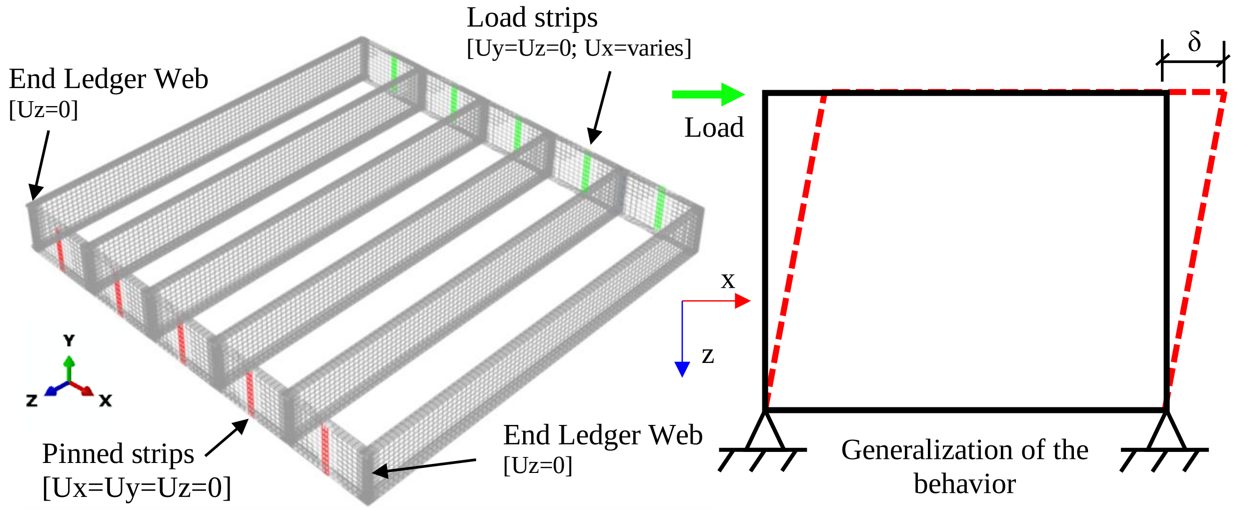
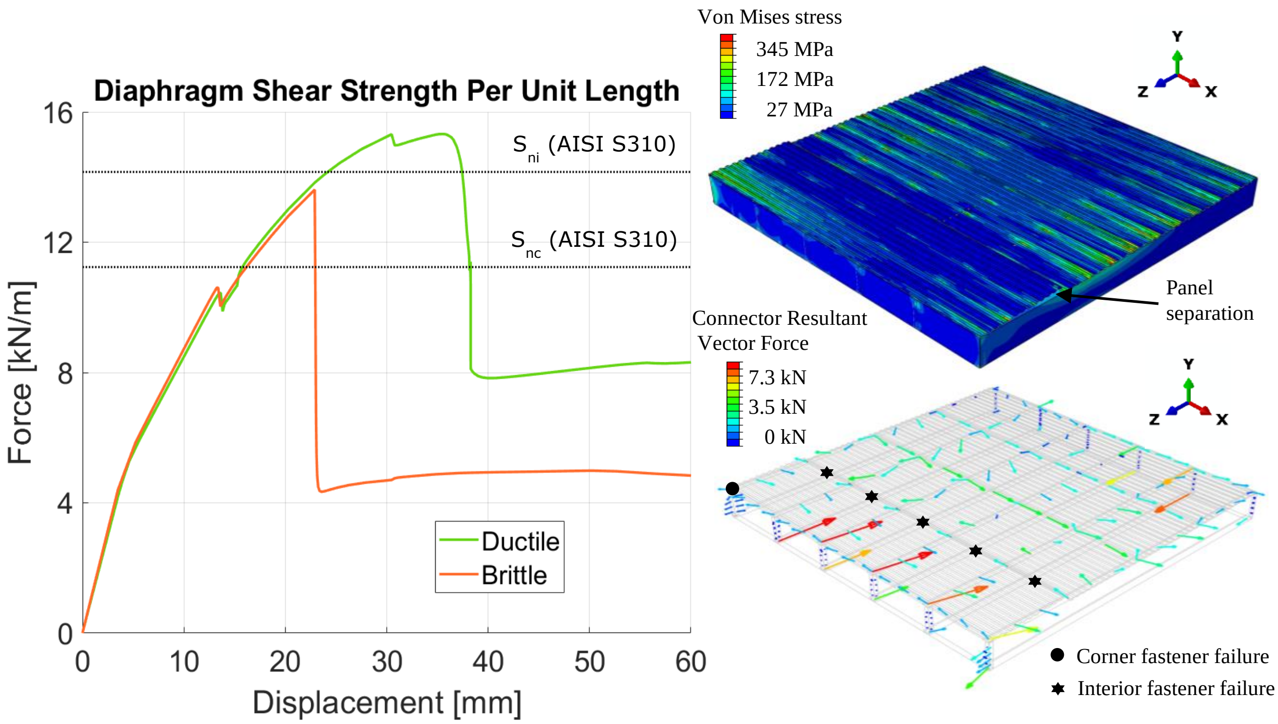


Figure 6: Boundary conditions and loading

3. Simulation Results Floor Diaphragm Sheathed with Steel Deck

Fig. 7 shows the lateral response of CFS floor diaphragm sheathed with steel deck. In addition, effect of fastener shear behavior modeling is compared. From the simulation results was observed that the diaphragm response is affected by the fastener behavior modeling. When the fastener shear behavior is modeled assuming a brittle failure criteria (Brittle), the overall response of the diaphragm suddenly failed upon reaching the maximum strength as shown in Fig. 7 (a). However, in the case of a ductile fastener shear behavior modeling (Ductile), the diaphragm response showed a higher strength. Simulations results are compared with predicted strength values according with the North American Standard for the design of profiled steel diaphragm panels AISI S310-16 (AISI 2016) and the Diaphragm Design Manual 04 (SDI 2015). In this case, the diaphragm shear capacity is governed by the fastener strength of the connections at the corners of the panels, S_{nc}. In addition, shear strength controlled by connections at the interior of the panels, S_{ni} was compared. Primary failure modes observed in the simulation results were shear failure of the fastener connection at the corner of the end panel, see Fig. 7 (b). which corresponds to the first drop in the diaphragm response, see Fig. 7 (a). Followed by the shear failure of the fastener in the side-lap connection of the end panel and interior panel, see Fig. 7 (b).



(a) (b)

Figure 7: Diaphragm simulation results

4. Simulation of Dual Skin Floor Diaphragm

To evaluate the influence of dual skin sheathing on the lateral response of the floor diaphragm, fiber cement board (FCB) is conservatively assumed as a rigid body. That assumption simplifies contact interaction between the sheathing panels on top of the steel deck. A similar approach was used for modelling CFS shear walls sheathed with OSB (Tun 2014) in which the OSB sheathing panels were modeled as rigid diaphragm. Given that the dual skin is a new system in the literature to be evaluate, the fastener spacing of connecting the sheathing panels and the steel deck is assumed based on the geometry of the steel deck as is show in Fig. 8.

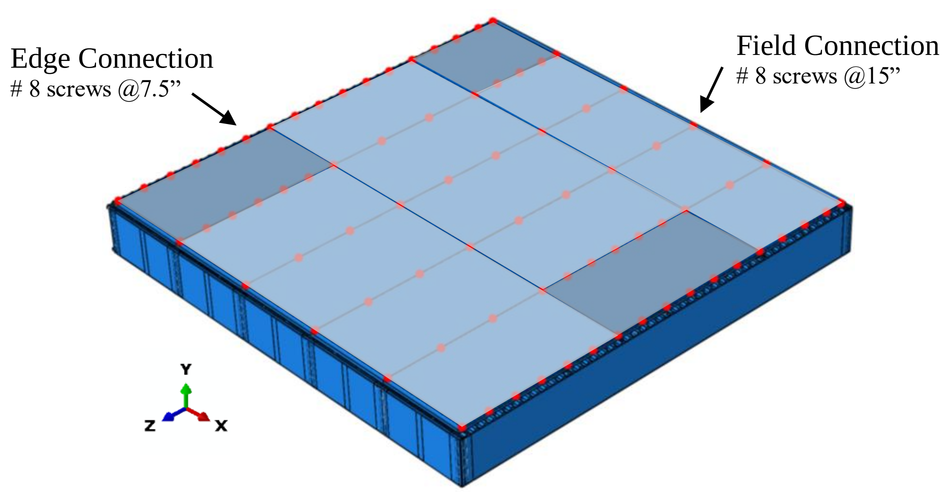


Figure 8: Dual skin diaphragm configuration

Four-node shell elements with reduced integration points, S4R, are used to model the FCB. 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 taken as 10 MPa. Multi-linear elastic behaviors are considered to characterize fastener shear response for connecting FCB and steel deck (Castaneda and Peterman 2021). Fig. 9 shows the influence of the dual skin floor sheathing on the lateral response of CFS diaphragms.

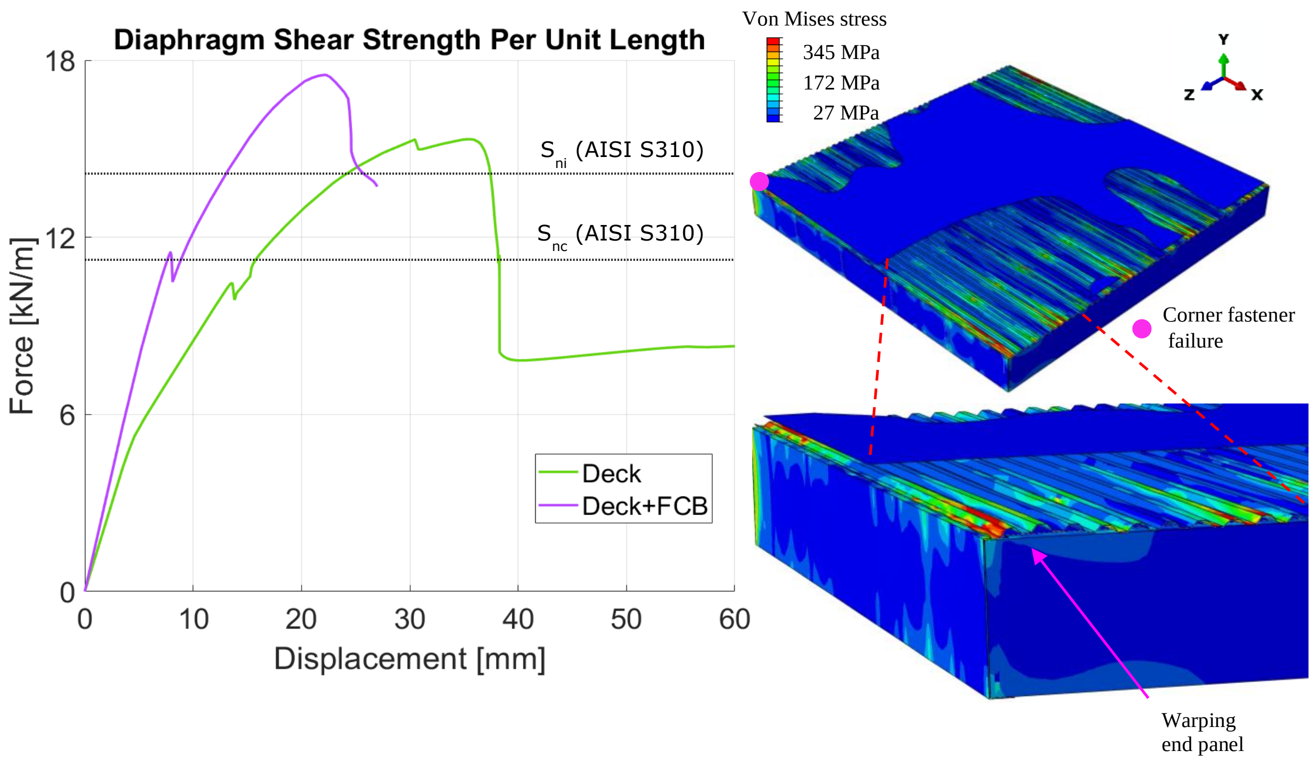


Figure 9: Dual skin diaphragm lateral response

Results showed that dual skin sheathing (Deck+FCB) increased stiffness and strength on the lateral response of the floor diaphragm in comparison with the floor diaphragm sheathed with steel deck (Deck). Dual skin had shown an increase of the peak strength of 13%. Primary failure mode was fastener shear failure at the corner connection of the end panel. It is believed that the strength and stiffness increased due to a composite action between the FCB and steel deck. In addition, failure at the side-lap connections of the steel deck panels was not observed. However, warping at the end of the steel deck was observed after the failure at the corner fastener. It is believed that the FCB increased the rigidity of the floor sheathing causing this deformation at the end of the steel deck panel.

5. Influence of Floor Joist Spacing on Dual Skin Floor Diaphragm

A 2.4 X 3 m floor diaphragm sheathed with steel deck is modeled to evaluate the influence of floor joist spacing on the lateral response of the CFS diaphragms. A total of three floor joist spacing are considered, 61, 122, and 244 cm center-to-center distance between floor joists. Note that 61 cm is the typical joist spacing in CFS construction. 122 cm is a potential joist spacing that can be used while using steel deck on top of the CFS framing system. The last joist spacing is conducted for comparison purposes. FCB to steel deck connections followed the same fastener configuration presented herein before. While increasing the joist spacing, the steel deck support connections are reduced. Fig. 10 shows the effects of floor joist spacing on the stiffness and strength response of diaphragm sheathed with steel deck in comparison with the dual skin system.

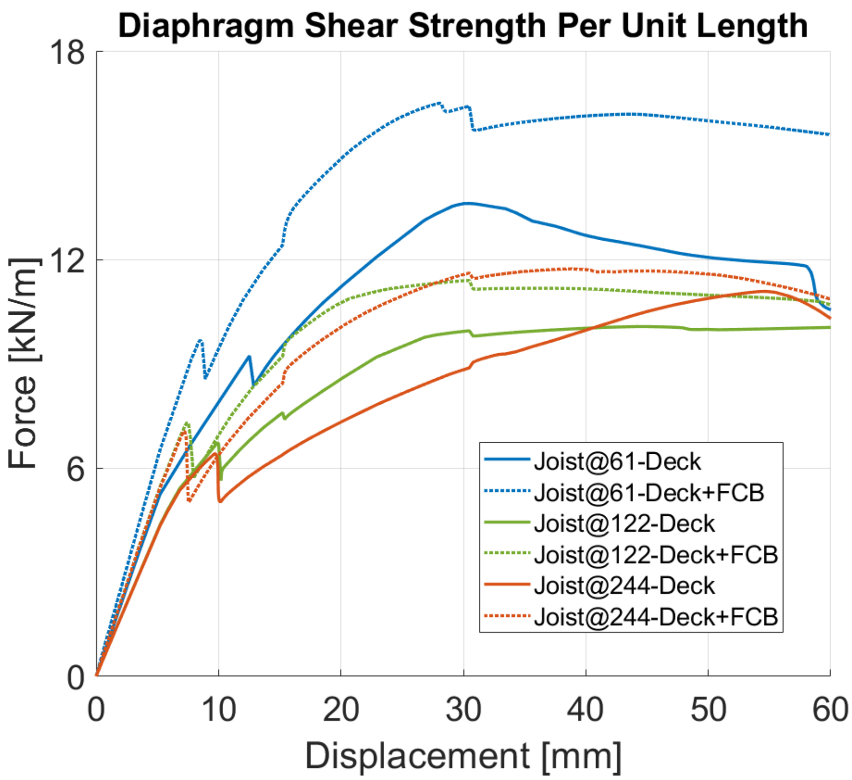
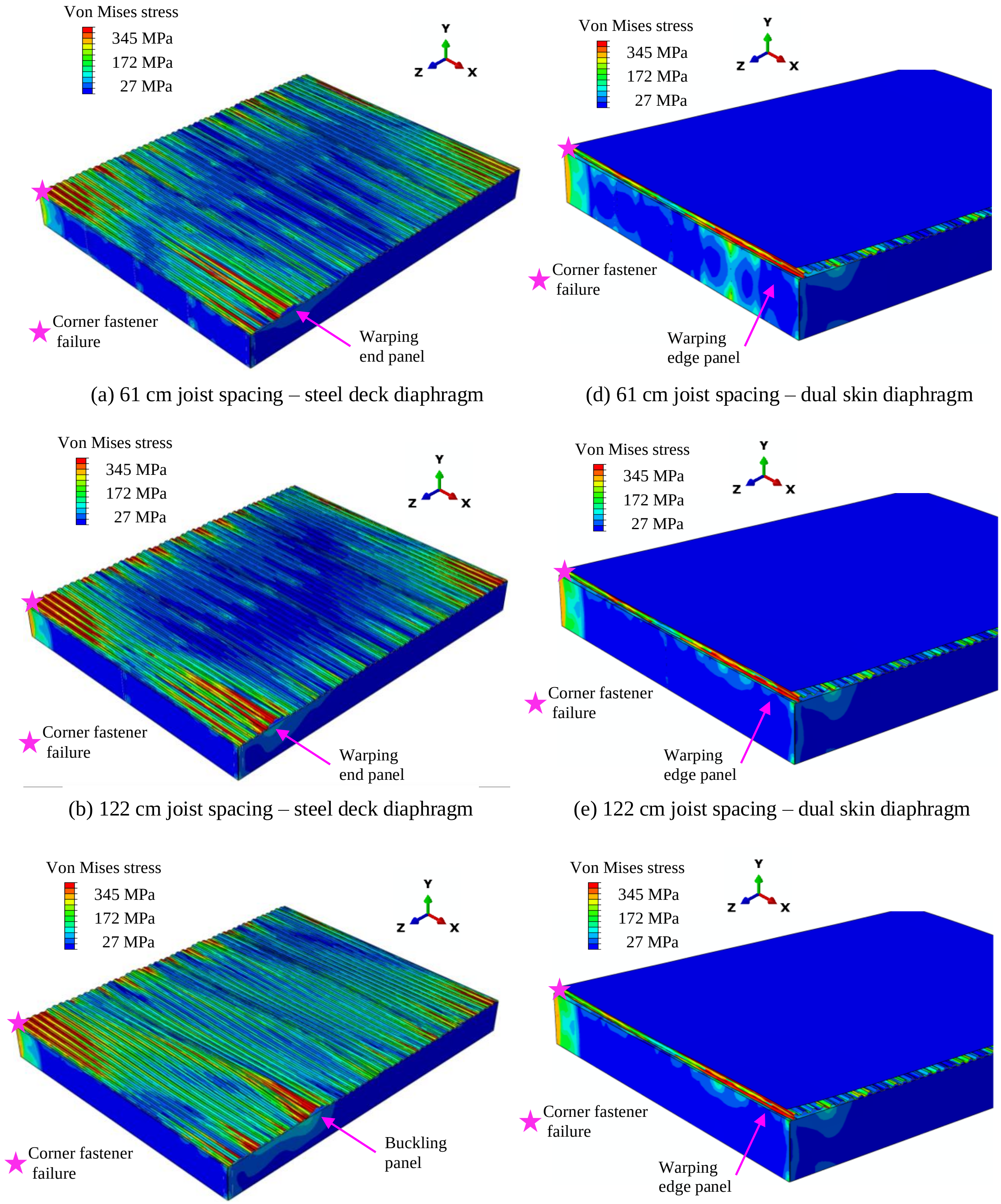


Figure 10: Floor joist spacing effects on the lateral response of dual skin diaphragm and steel deck diaphragm

Results showed that with increasing joist spacing, the shear strength of steel deck diaphragm is reduced by 26%. While for having the dual skin system with 61 cm joist spacing, the stiffness and strength significantly increased in comparison with all the configurations. Strength showed an increase of 18%. For 122 and 244 cm joist spacing, the dual skin system showed minimal effect on the response. It is believed that the steel deck support connection contributes to this behavior, increasing the support connections will increase the diaphragm strength. The first peak observed in the results of all the configurations corresponds to the fastener shear failure at the corner connection of the end panel as indicated in Fig. 11. After the fastener shear failure, for 61 and 122 cm joist spacing steel deck diaphragm, warping at the end of the panel was observed, see Fig. 11 (a) and (b). For 244 cm joist spacing, buckling of the panel was observed as shown in Fig. 11 (c). For all three dual skin diaphragms, warping at the edge of the end panel was observed, see Fig. 11 (d), (e), and (f). It is believed that the dual skin sheathing developed a composite action that makes the system more rigid. In addition, buckling of the panel was prevented.



(a) 61 cm joist spacing – steel deck diaphragm
(d) 61 cm joist spacing – dual skin diaphragm
(b) 122 cm joist spacing – steel deck diaphragm
(e) 122 cm joist spacing – dual skin diaphragm
(c) 244 cm joist spacing – steel deck diaphragm
(f) 244 cm joist spacing – dual skin diaphragm

Figure 11: Primary failure modes steel deck diaphragm and dual skin diaphragm due to joist spacing

6. Conclusions

A three-dimensional shell Finite Element Model of a cold-formed steel floor diaphragm sheathed with steel deck was developed using ABAQUS software. In addition, a dual structural skin system: fiber cement board fastened to steel deck was modeled. The model followed a cantilever test method, in which one side of the diaphragm was pinned and at the free end, a monotonic load displacement was imposed. Screwed connections were modeled with multi-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. Behavior of the fastener modeling, brittle and ductile behavior, were found to be sensitive on the overall lateral response of the diaphragm. Dual skin diaphragm in average increased the diaphragm strength by 15% in comparison with the steel deck diaphragm. Fastener shear failure at the corner of the end steel deck panel was observed, which is correlated by the predicted strength and behavior of steel deck diaphragm dictated in design codes. Effects of floor joist spacing on the diaphragm strength was investigated on both systems. It is believed that the dual skin system developed a composite action of the fiber cement board and the steel deck. Failure at the side-lap connection was prevented by the dual skin system. Furthermore, buckling of the steel deck panel was restricted. Forthcoming experimental full-scale tests of CFS diaphragms sheathed with steel deck and dual skin system will validate the work presented herein. In addition, influence of floor joist spacing, and fastener spacing will expand the characterization of the lateral response of CFS diaphragms.

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