Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Baltimore, Maryland, April 10-13, 2018

Development of a computational model to estimate the rollover resistance of open web steel joist seats

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Abstract

Joist seats play a critical role in the performance of open web steel joist systems because they transfer loads from the floor or roof deck to the end supporting girders or walls. The strength of these seats might be controlled by local sides-way instability or “rollover” when they are subjected to the combination of gravity and lateral loads. The current objective of this research is to develop and utilize a nonlinear finite element model to predict the stiffness and strength of typical steel joist seat configurations subjected to forces that produce local sides-way instability. The configurations studied include lapped and three-plate welded joist seats. Numerical results are validated against experimental data documented in the literature. Findings indicate that three-dimensional nonlinear finite element models are capable of estimating the response of laterally loaded steel joist seats, and also demonstrate that the strength and stiffness of joist seats strongly depend on the seat configuration. In addition, these models show how the load is transmitted to the supports through the seats, and indicate the development of plastic zones as the seats deform. Future work includes preparing a parametric study to investigate the impact of design variables, including dimensions, configuration type and material properties, on the rollover resistance of open web joist seats with welded and bolted connections. Currently, the design of some joist seats can be completed by means of elastic or plastic mechanism approaches. Therefore, this study aims to generate more comprehensive design recommendations and guidelines to determine the rollover capacity of such seats.

1. Introduction

Open web steel joists are primarily used as beams within structural roof and floor systems. When designed efficiently, their high strength-to-weight and stiffness-to-weight ratios make them ideal alternatives to traditional steel I-beams or reinforced concrete beams. There are four basic components to an open web steel joist, including the top chord, bottom chord, web members, and joist seats (Fig. 1). This research focuses on the latter.

Joist seats play a critical role in the performance of open web steel joist systems, because they transfer gravity loads, such as occupancy and snow loads, from the floor or roof deck to the end supporting girders or walls. Fisher et al. (2002), Kempfert (2003), and Doyle (2010) have

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presented significant work on methods for analyzing and designing such components. A controlling strength limit state is the sides-way failure or "rollover" of the joist seat when it is subjected to significant amounts of lateral (out-of-plane leftward or rightward) loads (Fig. 2).

Fisher et al. (2002) originally proposed a joist seat rollover design model based on two different approaches: one based on elastic analysis and another on ultimate strength analysis. In general, results obtained from these two approaches can be substantially different. According to Doyle (2010), both these approaches typically produce conservative values, but in several cases cannot be adapted to predicting the strength of certain seat configurations.

One of the main contributions from Doyle's research is a database obtained from 27 typical joist seat configurations that were experimentally loaded to failure. This comprehensive study produced experimental values for elastic stiffness, elastic limit load, elastic limit displacement, ultimate load, and displacement at the ultimate load. After deriving a simplified two-dimensional frame model, Doyle (2010) concluded that the development of a detailed three-dimensional finite element model was needed to better understand the behavior of joist seats, and eventually be able to produce data of a wide range joist seat configurations, all with the goal of establishing a robust method for designing these components.

The intent of this research project is to develop a computational finite element model that could be used to determine the stiffness and strength of typical steel joist seat configurations subjected to forces that produce a rollover failure mode. Results from Doyle's experimental studies are used to validate the model, and a limited parametric study is performed to illustrate how such a model can be used to identify and study the effect of key design variables on the performance of steel joist seats.

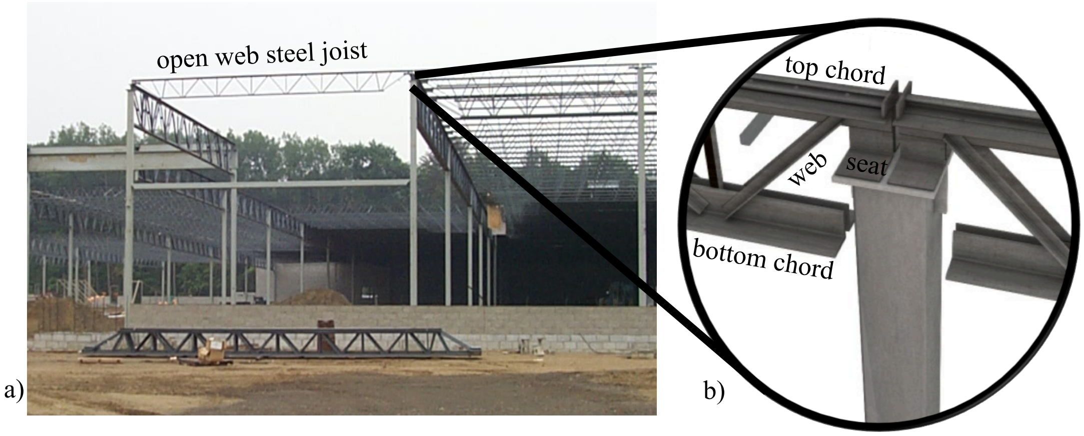

Figure 1: a) Open web steel joist and b) its components

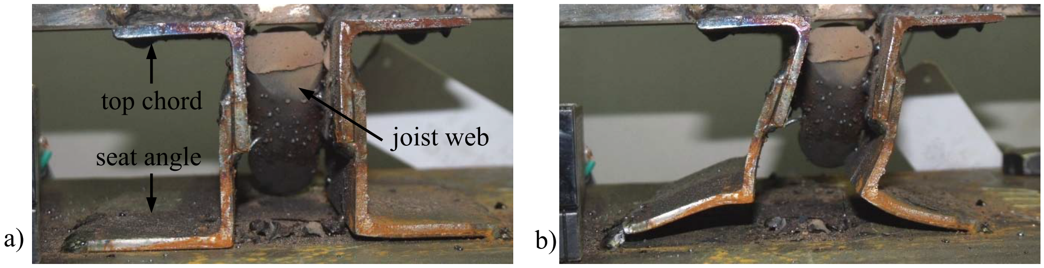

Figure 2: Typical joist seat (a) before and (b) after lateral load test (Doyle, 2010)

2. Methodology

This project embraced three main tasks, including the development and validation of a computational model, and the analysis of typical steel joist seats under lateral loads. A nonlinear finite element model was developed using a computational software package (ABAQUS, 2017) to estimate the strength and stiffness of typical lapped and three-plate joists seats with depth h = 2.5 in. and length L = 4 in. These configurations were chosen following recommendations from the Steel Joist Institute.

Experimental results reported by Doyle (2010) were used to validate numerical results, and assess the capabilities of the finite element model. In Doyle's experiments, specimens consisted of a segment of the top chord, toe angle or plate, and web member, with dimensions as shown in Fig. 3 and provided in Table 1. The legs of a pair of seats (labeled as front and rear) were welded at the toes to a non-yielding support (Fig. 4). A very stiff load transfer plate was connected to the top chord of each joist seat, using eight ¼ in. fillet welds. Therefore, the axial load applied to the load transfer plate produced lateral loads on the steel joist seats until failure occurred. Failure was defined as the development of plastic deformations in the seat angles or fracture of the connections.

An LVDT was placed at the end of the load transfer plate to measure lateral displacements while the load was applied.

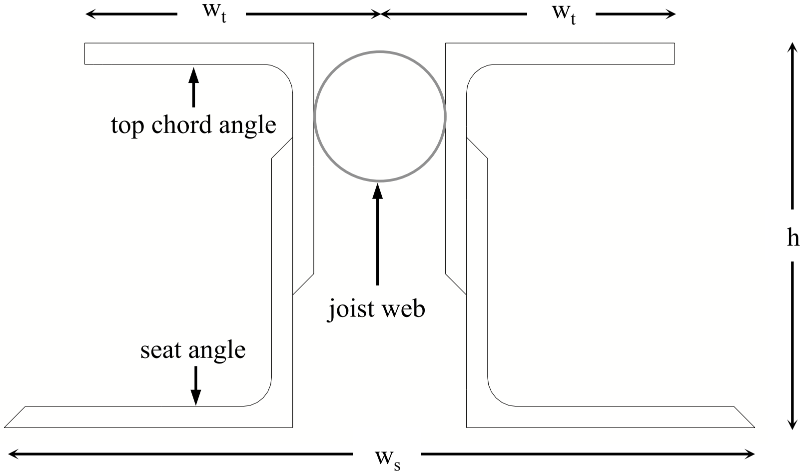

Figure 3: Cross-sectional dimensions of a typical joist seat

Table 1: Seat dimensions

Seat	h (in.)	w_t (in.)	w_s (in.)	Seat Angle or Plate	Top chord
LS1	2.5	2.0	4.78	1.75"×1.75"×0.155"	1.5"×1.5"×0.138"
LS2	2.5	2.5	5.50	2"×2"×0.25"	2"×2"×0.25"
TP1	2.5	2.5	5.00	4"×0.25"	2"×2"×0.25"

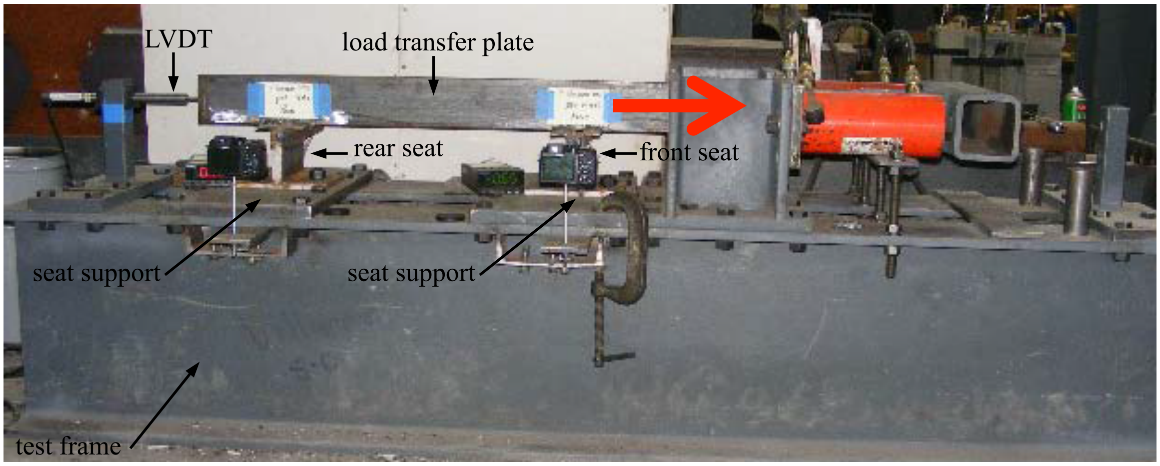

Figure 4: Test setup (Doyle, 2010)

3. Computational Model

Three-dimensional models were developed, using quadratic tetrahedral elements in ABAQUS (Fig. 5-a). The geometries include the top chord, seat angles or plates (for lapped and three-plate seats, respectively), and welds, following the test specimen details reported by Doyle (2010).

Welds connecting the top chord and seat angles were represented by tie constraints. The backs of the top chord angles were connected by using tie constraints to simulate the effect of the joist web end bar, which was oriented at a 30-degree angle from the z-axis (highlighted in red in Fig. 5-b and 5-c). Four ¼ in. wide areas on the legs of the top chord (shown in red in Fig. 5-a) were also tied, simulating the welding connections between the top chord and the stiff load transfer plate. Lateral displacements were prescribed and applied through these four areas, in the x-direction shown.

Displacements on the bottom surface of the horizontal leg of the right seat angle were restrained. The translation of nodes under the weld on the left seat angle toe was also restrained to simulate the welding connection between the left seat angle and the non-yielding support. Finally, frictionless contact between components was assumed.

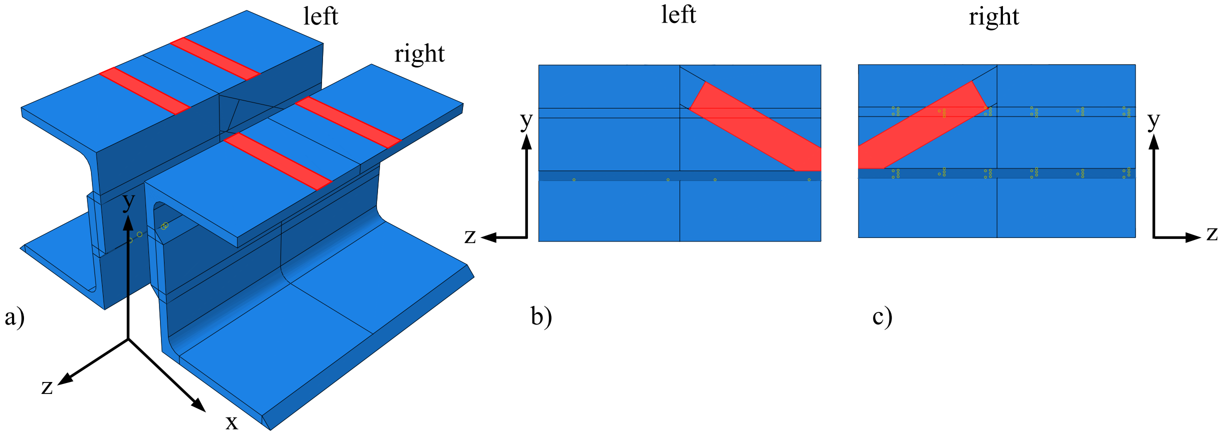

Figure 5: Geometry of the joist seat model, a) 3D view, and 2D view of the back of the b) left and c) right sides

Table 2: Material true stress and plastic strain

σ_{true} (ksi)	$\varepsilon_{plastic}$ (in./in.)
0.0	0.0000
50.0	0.0000
61.0	0.0235
73.0	0.0474
84.0	0.0935
85.0	0.1377
70.0	0.1800
10.0	0.2100

A nonlinear material model was adopted (Table 2), assuming an elastic modulus of 29,000 ksi and Poisson's ratio of 0.3. Additionally, geometric nonlinearity (i.e. large strain and large displacement) was activated in the model, and the Riks solver was used within the analysis.

4. Results

Lateral loads and displacements from the finite element analysis (FEA) are presented and compared with experimental results by Doyle (2010). All cases, the analyses were terminated after the formation of plastic hinges.

4.1 Lapped Seats

It was observed that the joist seats exhibit a nonlinear response as the lateral load is applied to the top chord (Fig. 6). During deformation, the leg of the left angle loses contact with the support, except at the toe, where the weld transfers the load (Fig. 7). Lapped seats LS1 and LS2 have the same height; however, the seat angles of LS2 are 1.6 times thicker. Consequently, seat LS2 exhibits higher strength and stiffness. The maximum rotation of seats LS1 and LS2 in the computational model were 12.60° and 6.04°, respectively.

Left and right seat angles unevenly transfer the lateral load to the non-yielding support. The seat angle on the tension (left) side transfers more load to the support through the welds than the seat angle on the compression (right) side, which transfers the load through the welds and contact between the angle leg and the support. For instance, when the lateral displacement of the top chord is 0.5 in., the left seat carries 65 % of the applied load (Fig. 8).

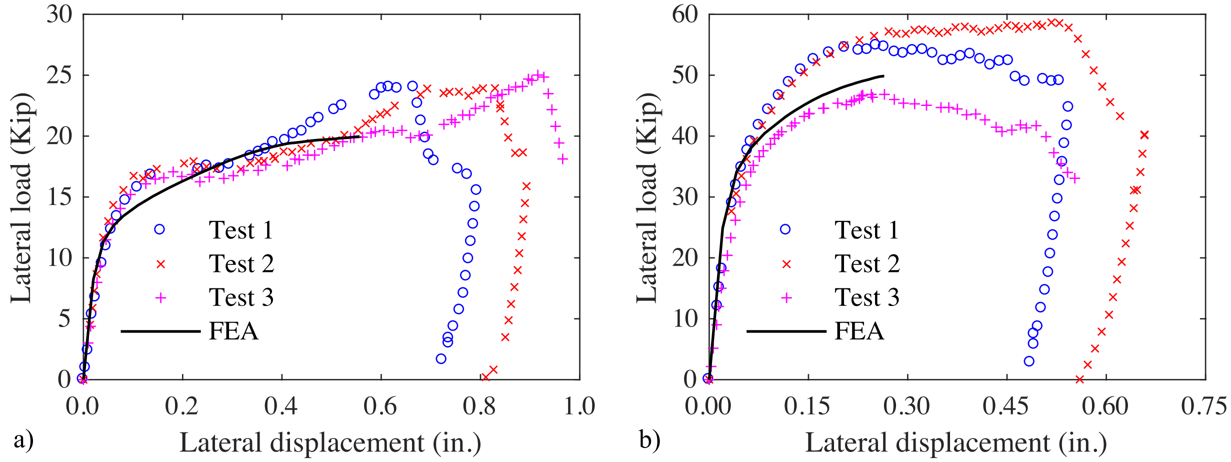

Figure 6: Load-deflection curve for lapped seats a) LS1 and b) LS2 from FEA and Doyle's test results

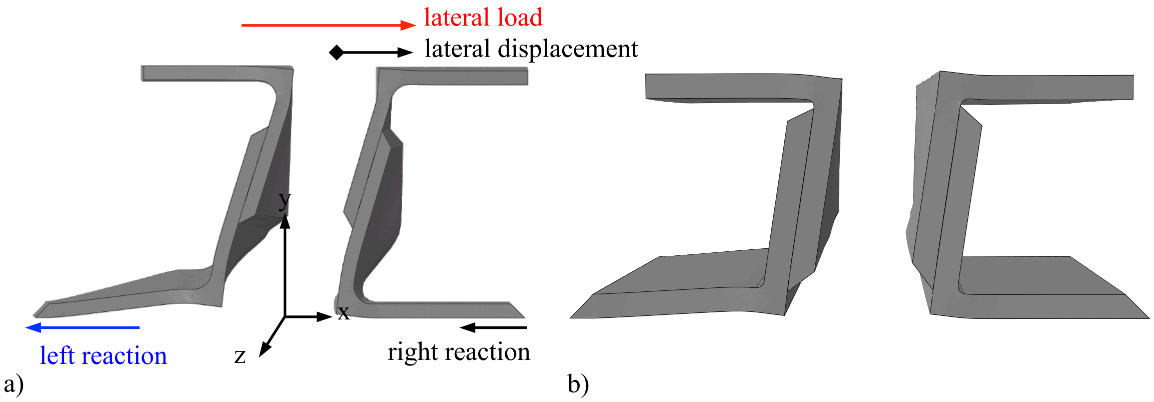

Figure 7: Deformation of lapped seats a) LS1 and b) LS2

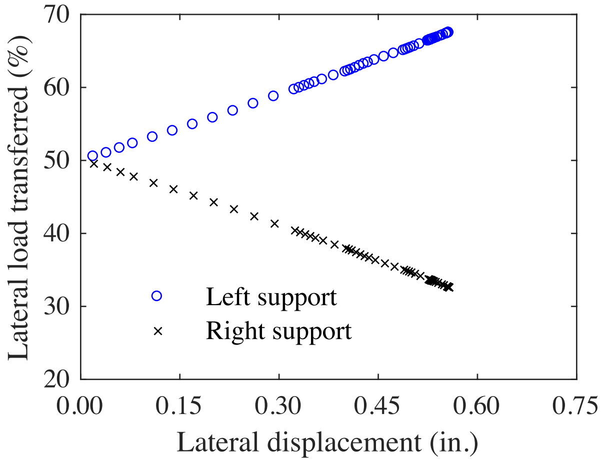

Figure 8: Percentage of lateral load transferred by the supports of lapped seat LS1

4.2 Three-Plate Seats

Under the applied load, three-plate seats deform laterally and, eventually, the vertical leg of the right top chord angle contacts the seat vertical plate (Fig. 9). Seat TP1 developed this contact when the lateral displacement of the top chord was 0.12 in. When this contact occurs, the load-displacement curve displays a distinguishable change in stiffness (Fig. 10).

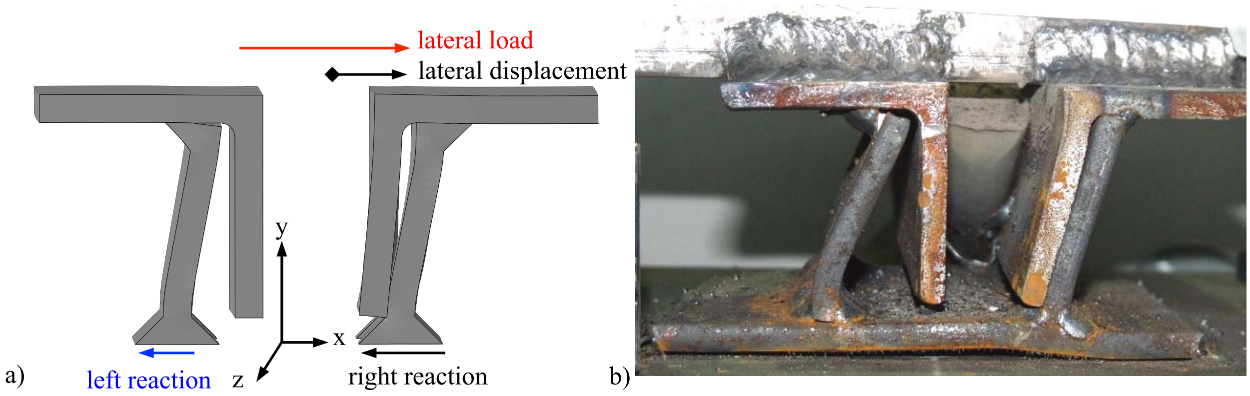

Figure 9: Deformation of three-plate seat TP1, a) FE model and b) Doyle's test

Three-plate seats also unevenly transfer the lateral load from the top chord to the support. As the seat rotates, the left plate seat bends and loses contact with the top chord, except at the location of the weld where large stresses are developed until the material yields and fails (Fig 9). Therefore, the right seat plate carries most of the load. For instance, when the top chord laterally displaces 0.25 in., the right seat plate transfers 76 % of the applied lateral load (Fig. 11).

Numerical results show a stress concentration at the top and bottom of the vertical seat plates, where plastic hinges are formed (Fig. 12). These plastic hinges were also observed and described by Doyle (2010). The maximum rotation of the seat in the computational model was 6.63°.

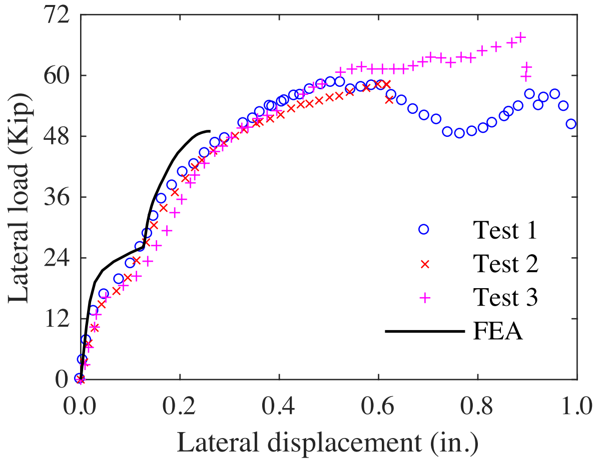

Figure 10: Load-deflection curve for three-plate seat TP1 from FEA and Doyle's test results

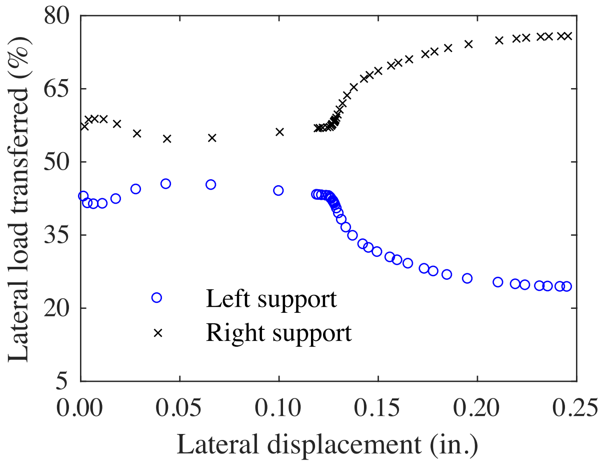

Figure 11: Percentage of lateral load transferred by the supports of three-plate seat TP1

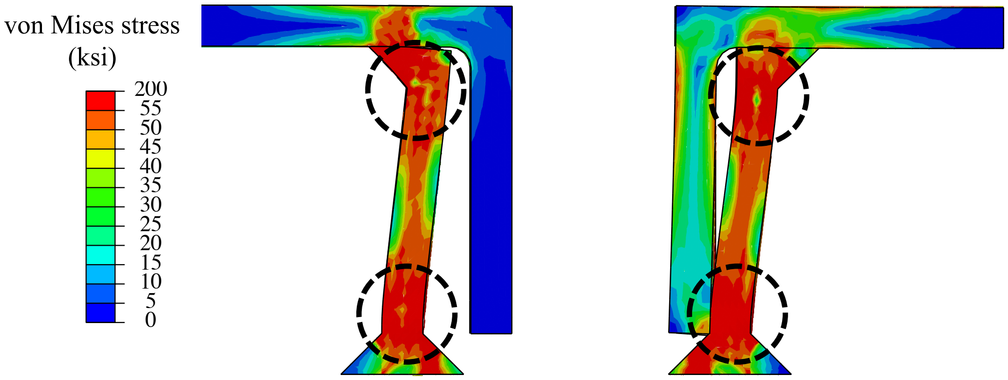

Figure 12: Stress distribution and plastic hinges (in dashed circles) on seat TP1

5. Discussion

The elastic stiffness of the steel joist seats was determined from load-deflection curves by fitting the linear segment, using data from 0 to 0.04 in. of lateral displacement for lapped seats, and from 0 to 0.02 in. for the three-plate seat. Elastic limit loads were recorded at the experimental elastic limit displacements reported by Doyle (2010).

Table 3 provides a summary of the mechanical properties obtained from FEA results, and average experimental results reported by Doyle (2010). The finite element model is capable of estimating the stiffness and elastic limit load for lapped and three-plate seats. However, predicted mechanical properties for the three-plate seat were significantly less accurate. For instance, the model predicts a stiffness of 1.7 times greater than the experimental value. It is noted that the computational model assumes a rigid support with no displacement; however, in Doyle's experiment, the supporting plate deformed significantly near the vertical seat plates (Fig. 9-b). The flexibility of the supporting plate affects the amount of lateral displacement experienced by the seat, and therefore impacts the load-displacement curve and estimated mechanical properties.

Table 3: Comparison of FEM and Doyle's test results

Seat	Stiffness (10^3 Kip/in)		Elastic limit load (Kip)	
	Test	FEM	Test	FEM
LS1	290	281	9.40	9.96
LS2	891	822	22.77	27.24
TP1	497	845	10.57	19.91

6. Conclusions and Future Work

A nonlinear finite element model was developed for the analysis of open web lapped and three-plate steel joist seats subjected to lateral loads. The model appears capable of estimating the strength, stiffness, lateral displacements, load path and stress distribution in laterally loaded seats.

Predicted strength and stiffness significantly vary depending on the seat configuration and the thickness of the seat components. For instance, and as would be expected, thicker seats provide more rollover strength and stiffness when subjected to lateral loads. Additionally, it was observed that the three-plate seat studied was stiffer than a lapped seat with similar cross-sectional area.

The finite element model provides information about the load path, and shows there is an uneven distribution of lateral loads though the seat components. The angle on the tension side of the lapped seats seems to carry more load than the angle on the compression side. In contrast, the plate on the compression side of three-plate seats transfers most of the load to the support. Additionally, the model is capable of predicting the development of plastic zones as the seats deform.

Future work includes the development of a comprehensive parametric study to investigate the effect of variables including, but not limited to, joist bearing seat angle thickness, joist top chord angle size, material properties, and seat configuration (such as T-plate, pre-assembled lapped in, and pegged joist seats) – all with an objective of optimizing pertinent design variables to improve the performance of joist seats. The overarching purpose of this research is to provide a direction forward in the assessment and development of design guidelines for determining the rollover capacity of steel joist seats.

Acknowledgments

The authors thank the Steel Joist Institute for fully funding this research project and providing technical information used to develop the computational model.

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