ENHANCED CONNECTIONS FOR IMPROVED ROBUSTNESS OF STEEL GRAVITY FRAMES

Jonathan M. Weigand
National Institute of Standards and Technology, Gaithersburg, MD 20899 USA
jonathan.weigand@nist.gov

Joseph A. Main
National Institute of Standards and Technology, Gaithersburg, MD 20899 USA
joseph.main@nist.gov

ABSTRACT

Potential vulnerability to collapse under column loss has been identified for steel gravity framing systems with simple shear connections. To address this potential vulnerability, an enhanced connection for steel gravity frames is proposed that incorporates U-shaped top and seat plates with long-slotted holes bolted to the beam flanges. Finite element analyses are used to evaluate the effectiveness of the enhanced connection under column loss scenarios. Addition of the U-shaped slotted plates is shown to increase the vertical resistance of a two-span beam assembly under center column loss to 2.5 times the resistance with conventional connections. Analysis of a composite floor system subject to interior column loss shows that incorporation of the enhanced connections achieves a 90 % increase in the ultimate vertical capacity, relative to the system with conventional connections, under uniform static loading. Under sudden column loss, the ultimate capacity of the floor system with enhanced connections is essentially equivalent to the applicable gravity load combination of 1.2*D* + 0.5*L*, while the system with conventional connections sustains only 56 % of the applicable gravity loading.

INTRODUCTION

Recent full-scale experiments (Lew et al. 2012) and computational analyses (Main and Liu 2013) have demonstrated the effectiveness of seismically designed steel moment frames in redistribution of gravity loads under column removal scenarios. In contrast, computational analyses (e.g., Main 2014) and experimental studies (Johnson et al. 2015) have indicated that steel gravity frames are potentially vulnerable to disproportionate collapse under column loss. Four column removal tests performed on a half-scale steel gravity framing system with composite slab on steel deck, by Johnson et al. (2015), showed that the floor system could only carry between 44 % and 62 % of the applicable gravity load combination of 1.2*D* + 0.5*L* for extraordinary events from American Society of Civil Engineers (ASCE) Standard 7-10 (ASCE 2010), where D = dead load and L = live load. To help address this potential vulnerability, researchers have begun to consider two primary approaches for enhancing the robustness of steel gravity frames: (1) enhancing the floor slab capacity through improved slab detailing, and (2) enhancing the connection capacity through improved connection detailing. While previous analyses have shown that the concrete slab on steel deck adds significant capacity under column removal, that capacity is sensitive to small variations in the slab thickness, slab continuity, detailing between deck sheets, and the attachment method to the perimeter framing (Main et al. 2015). Enhancements to the steel gravity connections are potentially more versatile and can be implemented both for new construction and for retrofit of existing structures.

In this study, high-fidelity numerical models of single-plate shear connections were first validated against experimental data from Weigand and Berman (2014) and then used to investigate steel gravity framing systems with enhanced connection detailing. The enhanced connections used U-shaped slotted steel plates, which were welded to the column flange and bolted to the beam flanges, to increase both the flexural capacity of the connection (at small rotations) and the tensile capacity of the connection (at large rotations). High-fidelity analyses were used to evaluate the component-level behavior of the U-shaped slotted plates under axial loading and to evaluate the behavior of the enhanced connections in a two-span beam assembly under center column loss. Reduced-order models were then used to evaluate the effectiveness of the enhanced connections in a two-bay by two-bay composite floor system under interior column loss.

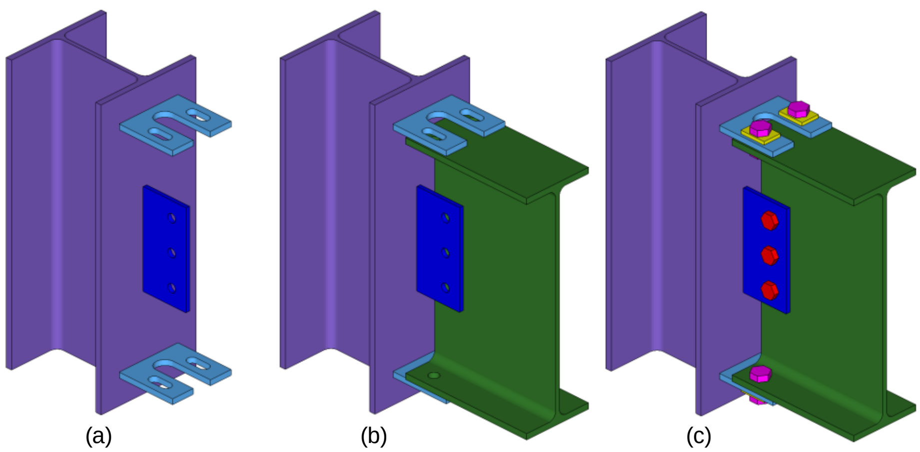

Figure 1: Enhanced single-plate shear connection: (a) U-shaped slotted top and seat plates welded to column; (b) beam in position; (c) bolted with rectangular plate washers.

ENHANCED CONNECTION DETAILS

The enhanced connection configuration includes top and seat plates, which are welded to the column and then bolted to the beam flanges (Figure 1). The top and seat plates have long-slotted holes to permit large slip displacements of the flange bolts prior to the initiation of bearing at the ends of the slots. Each top or seat plate has a U-shaped cutout that serves two purposes: (1) it allows the plate to be placed on either the interior or the exterior face of the beam flange (exterior placement would be used in new construction while interior placement could be preferable for retrofit in some cases), and (2) it reduces the net section of the plate relative to the shear area of the bolts to ensure that tensile yielding develops in the plate sections adjacent to the slots, thus achieving significant plastic elongation of the slotted portion of the plate prior to tensile rupture (similar in concept to how a reduced beam section connection enhances ductility in flexure). Rectangular plate washers (Figure 1(c)) distribute the bearing stresses induced by pre-tension in the flange bolts. Standard holes are used in the beam flanges.

COMPUTATIONAL MODELING

High-fidelity finite-element modeling of the connections followed the approach described by Main and Sadek (2014) except that reduced-integration solid elements were used, rather than fully integrated elements, in order to better capture the localization of shear strain in the bolts. In the connection region, finely meshed hexahedral elements were used to represent the shear plate, top and seat plates, bolts, plate washers, and the beam (Figure 2). Outside of the connection region, the beam was modeled using shell elements, and nodal constraints were used to enforce compatibility of displacements and rotations at the solid/shell interface. Typical solid element sizes were 1.5 mm (0.06 in) for the bolts and 3 mm (0.12 in) for all other components. Contact was defined between all solid components to transfer forces through the bolted connection, and friction was included, with a static coefficient of friction of 0.34 for all interfaces, corresponding to an average value calculated from the extensive data compiled by Grondin et al. (2007).Piecewise-linear plasticity models were used to model the material behavior, with fracture simulated using element erosion, as described by Main and Sadek (2014). The stress-strain curve used to model the A325 bolts was based on tensile test data reported by Kulak et al. (1986). Stress-strain curves used to model the plates and wide-flange sections were obtained from tensile coupon testing of the actual materials used in single-plate shear connection tests by Weigand (2014), and data from one of these connection tests was used for model validation, as described in the following section.

Model Validation

The modeling approach was validated against results from a connection sub-assemblage test conducted by Weigand and Berman (2014), for a 3-bolt single-plate shear connection with a W12×72 column, W21×50 beam, 19.1 mm (¾ in) diameter ASTM A325 bolts, and a 9.5 mm (⅜ in) thick ASTM A36 shear plate (Specimen sps3b|STD|34|38|). Figure 2 illustrates the model used in the analysis, which consisted of two loading phases. In the initial phase, pre-tension was introduced in the bolts through thermal contraction, by artificially reducing the temperature of the bolts to achieve an average pre-tension of 185 kN (42 kip) per bolt. In the second phase, displacement-controlled axial and transverse loads were applied to the beam end, replicating the loading conditions used in the test (Weigand and Berman 2014), which imposed a combination of rotational and axial demands on the connection to represent a column loss scenario.

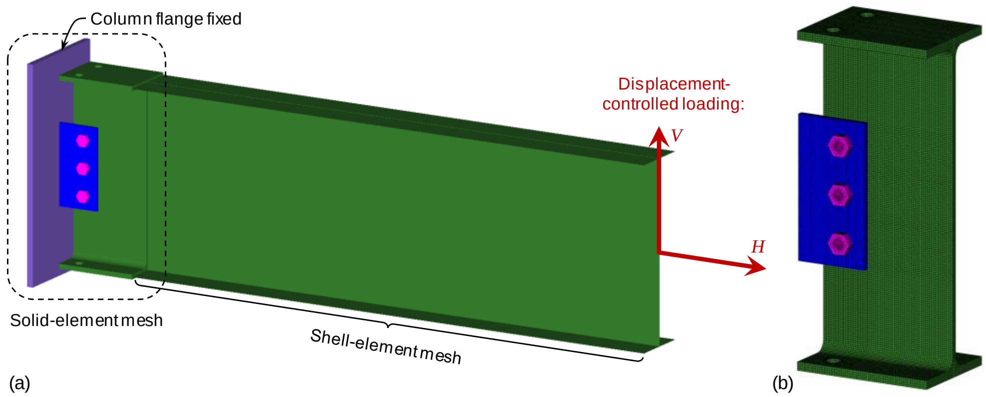

Figure 2: Computational model of specimen sps3b|STD|34|38| from Weigand and Berman (2014): (a) overview of model; (b) solid-element mesh.

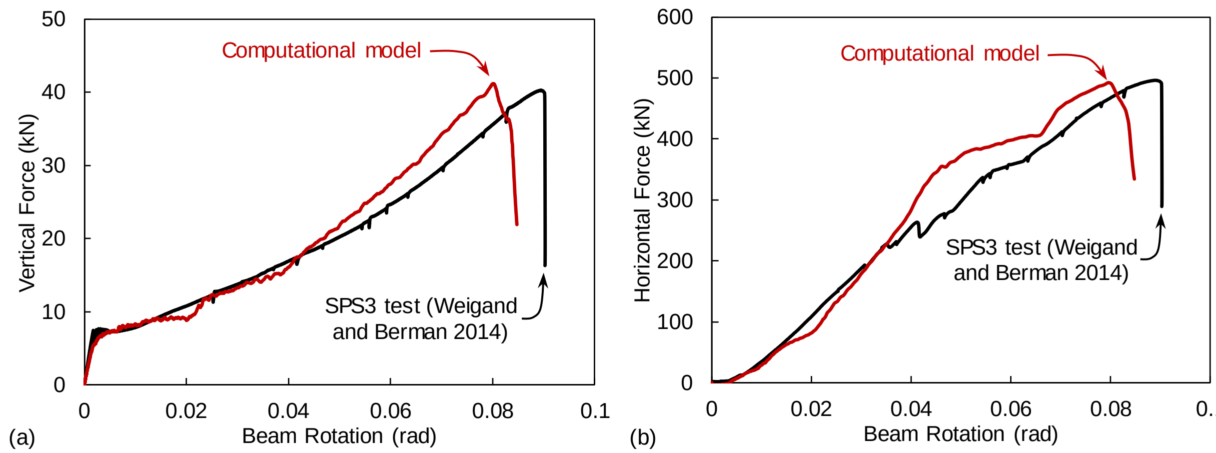

Figure 3: Comparison of computational and experimental results for (a) vertical force and (b) horizontal force vs. beam rotation. (Uncertainties in the experimental measurements are discussed by Weigand and Berman (2016).)

Figure 3 compares the computed vertical and horizontal forces with those obtained experimentally for Specimen sps3b|STD|34|38|. The peak vertical force from the computational model is 2 % greater than the experimental value and the peak horizontal force from the computational model is 1 % less than the experimental value. A somewhat larger discrepancy is observed for the rotation at peak load, for which the computational model underestimated the experimental value by 11 %. These discrepancies give an indication of the degree of uncertainty in the predictions of the computational model.

Component-Level Axial Behavior of U-Shaped Plate with Long-Slotted Holes

Prior to considering the behavior of enhanced connections under column loss, the model shown in Figure 4(a) was used to investigate the component-level behavior of a U-shaped plate with long-slotted holes under axial loading. A rectangular plate with standard holes was also modeled for comparison (Figure 4(b)). Plates made of ASTM A36 steel with a thickness of 12.7 mm (½ in) were considered, which were bolted to the flange of an ASTM

A992 W21×50 beam using two 22.2 mm (⅞ in) diameter ASTM A325 bolts. ASTM A36 plate washers with a thickness of 7.9 mm (5⁄16 in) were used for the U-shaped plate with long-slotted holes. One flange of the beam was modeled, including the flange-to-web-fillet, and nodes along the toe of the fillet were constrained to permit axial displacements only. Displacement-controlled axial loading was applied to one end of the beam flange, and the opposite ends of the A36 plates were fixed (Figure 4). Prior to axial loading, initial pre-tension of 234 kN (53 kip) was introduced in each bolt through thermal contraction.

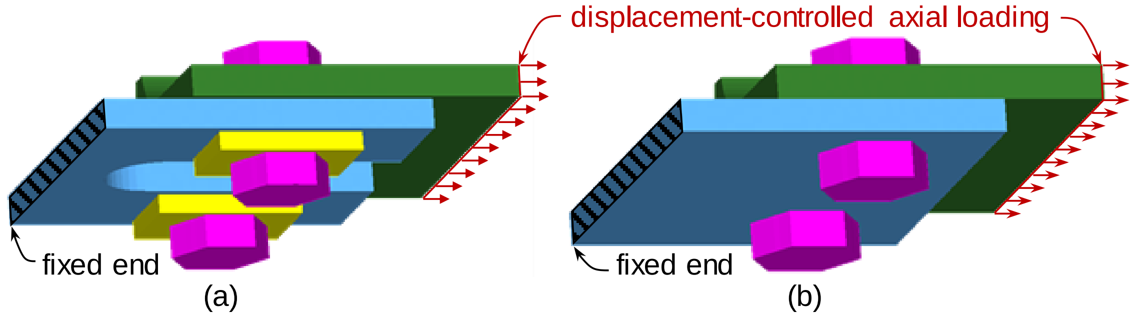

Figure 4: Component-level analysis models: (a) U-shaped plate with long-slotted holes; (b) rectangular plate with standard holes.

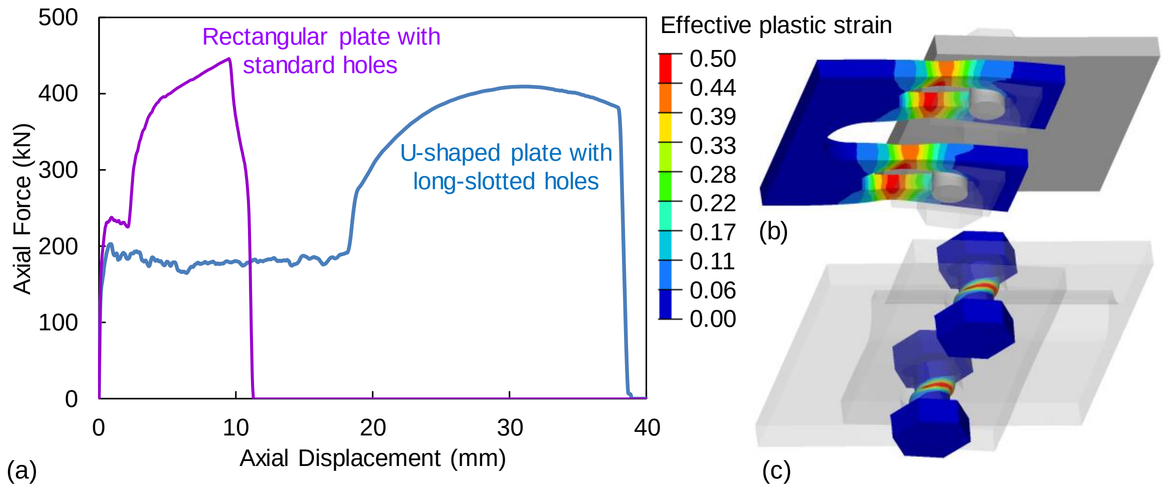

Figure 5: (a) Axial force-displacement results from component-level analyses, along with contours of effective plastic strain just prior to rupture for: (b) U-shaped plate with long-slotted holes; (c) flange bolts for rectangular plate with standard holes.

Figure 5(a) shows axial force-displacement curves obtained from the two models in Figure 4. For the model in Figure 4(a), Figure 5(b) shows contours of plastic strain just prior to tensile rupture of the U-shaped slotted plate, and for the model in Figure 4(b), Figure 5(c) shows contours of plastic strain just prior to shear rupture of the bolts. The peak axial force for the U-shaped slotted plate was slightly less (by 8 %) than that for the rectangular plate with standard holes, because of the intentional reduction in the net section of the U-shaped plate. However, the displacement at tensile rupture for the U-shaped slotted plate (38 mm (1.5 in)) was four times as large as the displacement at bolt shear rupture for the rectangular plate with standard holes. The substantially larger displacements for the U-shaped slotted plate were developed initially through sliding of the bolts through the long slots (for displacements less than 18 mm (0.72 in), and subsequently through a combination of bearing deformations, bolt shear deformations, and elongation of the plate legs on each side of the long slots (see Figure 5(b)).

Two-Span Beam Assembly

A two-span beam assembly (Figure 6) was considered to evaluate the effectiveness of enhanced connections in bare steel framing (i.e., no floor slab) under column loss. A computational modeling approach similar to that illustrated in Figure 2 was used to analyze the response of the two-span beam assembly with different types of connections, including the two different types of top and seat plates illustrated in Figure 4. Figure 7(a) compares the results for these connections with those from a conventional single-plate shear connection. Figure 7(a) shows that the additional deformation capacity of the U-shaped plates with long-slotted holes results in a peak vertical capacity that is 46 % greater than that for rectangular top and seat plates with standard holes. Figure 7(a) also shows that the addition of U-shaped slotted top and seat plates results in a peak vertical capacity that is 2.5 times the vertical capacity for a conventional single-plate shear connection. Figure 7(b) shows that pre-tension in the flange bolts provides additional vertical resistance in the initial phase of the response, when the bolts are sliding in the slots, but has an insignificant effect after the onset of bearing deformations at a center column displacement of about 450 mm (18 in).

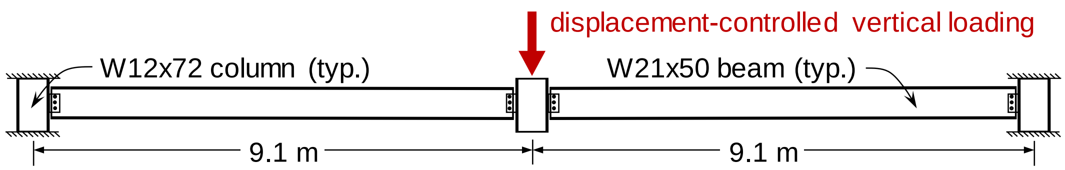

Figure 6: Two-span beam assembly.

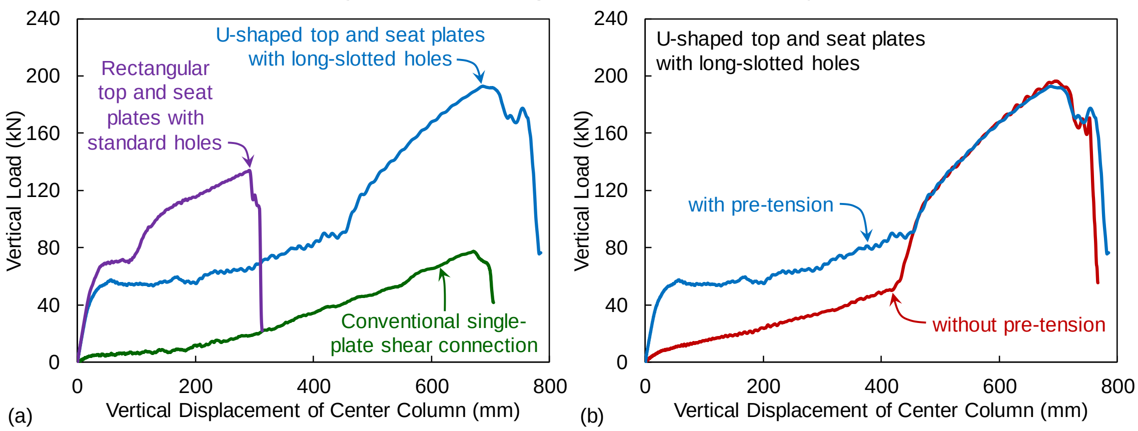

Figure 7: Vertical load-displacement analysis results for two-span beam assemblies: (a) comparison of results for different connection types; (b) influence of pre-tension.

Figure 8 shows that the behavior of the enhanced connections could be accurately represented using a reduced-order modeling approach in which the components of the connection were modeled as nonlinear springs interconnected by rigid links (Figure 9(a)). Such an approach has previously been successfully applied for moment connections (Sadek et al. 2013) and for single-plate shear connections (Main and Sadek 2014). Figure 8 shows that the reduced-order modeling approach captured the peak load from the high-fidelity model within 1 % and the corresponding displacement of the center column within 4 %. In this study, the force-deformation relationships for the nonlinear connection springs were defined using piecewise-linear approximations of results from high-fidelity finite element analysis of the connection components (Figure 9(b) and (c)). However, analytical models for the connection components could also be used, where available, such as the component-based model developed by Weigand (2016) for single-plate shear connections with pre-tension. The use of such a model facilitates parametric studies and optimization of connection configurations, which will be pursued in future studies.

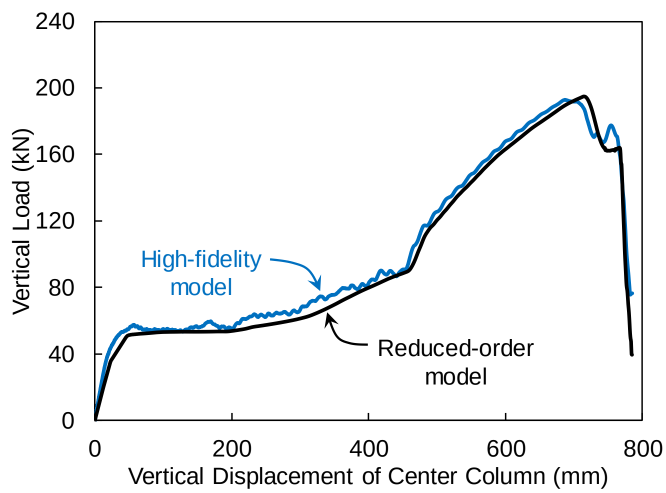

Figure 8: Reduced-order and high-fidelity model results for two-span beam assembly.

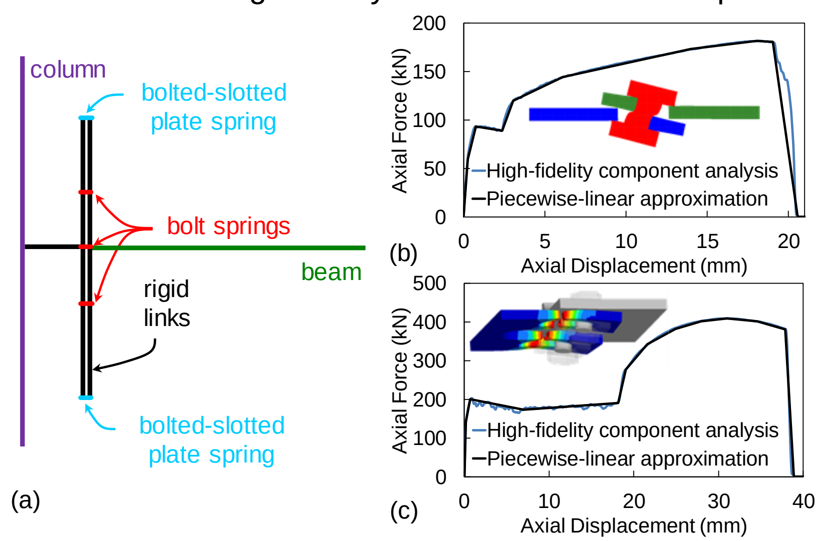

Figure 9: (a) Reduced-order connection model with force-displacement relationships for: (b) single-plate shear connection (one bolt row); (c) U-shaped slotted plate.

Composite Floor System

To evaluate the effectiveness of the enhanced connections in composite steel gravity framing, a prototype two-bay by two-bay composite floor system previously considered by Main (2014) was analyzed under center column loss, both with conventional single-plate shear connections and with enhanced beam-to-column and girder-to-column connections incorporating U-shaped slotted top and seat plates. The modeling approach for the composite floor system, illustrated in Figure 10, followed the approach proposed by Main (2014), in which the girders, beams, and columns were modeled with beam elements, and alternating strips of shell elements were used to represent the ribbed profile of the concrete slab on steel deck, with distinct integration points through the slab thickness for the steel deck, concrete, and welded wire reinforcement. Connections were modeled using a reduced-order approach as illustrated in Figure 9(a). Modeling of the conventional floor system in this study differed from Main (2014) in that a steeper softening modulus was used for the post-ultimate tensile resistance of concrete, as discussed by Main et al. (2015), and improved deformation limits were used for the single-plate shear connections, based on measurements from Weigand and Berman (2014), with a steep drop in resistance when those deformation limits were reached. The enhanced floor system was modeled using the piecewise-linear load-deformation relationship in Figure 9(c) to represent the U-shaped slotted plates.

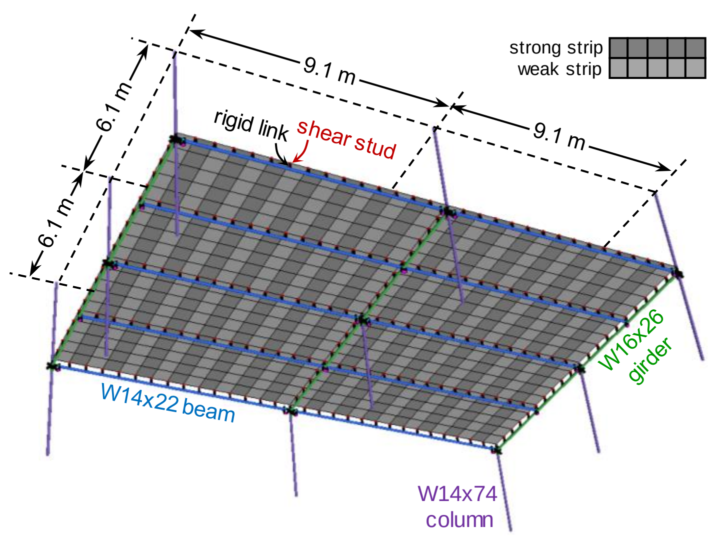

Figure 10: Reduced-order model of a 2-bay by 2-bay composite floor system.

Figure 11(a) shows computed curves of load intensity vs. center column displacement for floor systems with conventional and enhanced connections under uniform static loading with an unsupported center column. Figure 11(b) shows corresponding curves for sudden column loss, which were obtained from the curves in Figure 11(a) using the energy-based approach described by Main (2014). The floor system with conventional connections was unable to sustain the applicable gravity loading of 1.2*D* + 0.5*L*, even under static loading. However, the enhanced connections increased the capacity of the floor system under static loading by 90 %, resulting in a capacity that significantly exceeded the applicable gravity loading. As proposed by Bao (2014), a robustness index was calculated by normalizing the ultimate capacity under sudden column loss by the applicable gravity loading, whereby robustness indices of 0.56 and 0.99 were obtained for the systems with conventional and enhanced connections, respectively. The enhanced connections thus increased the robustness of the floor system by 76 %, resulting in an ultimate capacity under sudden column loss that was essentially equivalent to the applicable floor loading.

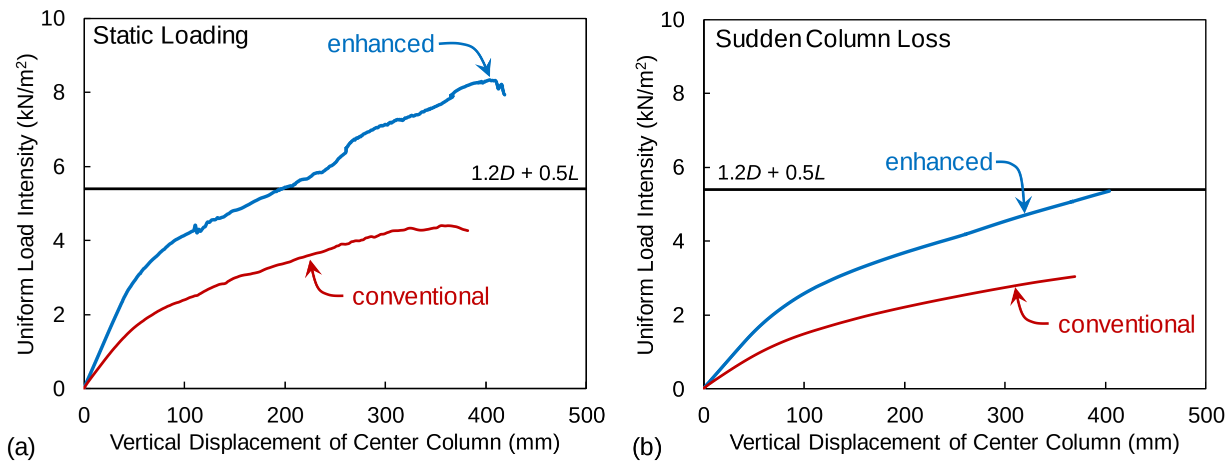

Figure 11: Uniform load intensity vs. center column displacement for floor systems with conventional and enhanced connections: (a) static loading; (b) sudden column loss.

SUMMARY AND CONCLUSIONS

This paper presented an enhanced steel gravity connection that used steel plates, bolted to the upper and lower flanges of the beam and welded to the column flange, to increase the flexural and tensile capacity of the connection. Analysis of the enhanced connection in a two-span beam assembly showed that it had a peak vertical resistance under column loss that was 2.5 times as large as that for a conventional single-plate shear connection. When implemented in system-level analyses of a two-bay by two-bay composite floor system, the enhanced steel gravity connections increased the vertical load-carrying capacity of the system under center column loss by 90 % under static loading. Robustness indices of 0.56 and 0.99 were calculated for the floor systems with conventional and enhanced connections, respectively, indicating that the enhanced connections increased the robustness of the floor system by 76 % and that the ultimate capacity of the enhanced floor system under sudden column loss is essentially equivalent to the applicable gravity loading. Future work will involve experimental evaluation of the performance of the enhanced connections under column loss scenarios and development of design procedures for the enhanced connections.

REFERENCES

ASCE (2010). *Minimum Design Loads for Buildings and Other Structures, SEI/ASCE 7-10,* American Society of Civil Engineers, Reston, VA.

Bao, Y, Main, J.A., Lew, H.S., and Sadek, F. (2014). "Robustness Assessment of RC Frame Buildings under Column Loss Scenarios." *Proc., Structures Congress*, Boston, MA, May, 2014.

Grondin, G., Jin, M. and Josi, G. (2007). "Slip-critical bolted connections – a reliability analysis for design at the ultimate limit state." *Structural Engineering Report No. 274,* University of Alberta.

Kulak, G.L., Fisher, J.W., and Struik, J.H.A., (1986). *Guide to Design Criteria for Bolts and Riveted Joints*, 2nd Edition, John Wiley & Sons, New York.

Lew, H.S., Main, J.A. Robert, S.D., Sadek, F., and Chiarito, V.P. (2012). "Performance of steel moment connections under a column removal scenario. I: Experiments," *Journal of Structural Engineering*, 139(1), 98-107.

Johnson, E.S. Meissner, and Fahnestock, L.A. (2015). "Experimental Behavior of a Half-Scale Steel Concrete Composite Floor System Subjected to Column Removal Scenarios." *Journal of Structural Engineering,* 04015133.

Main, J.A. (2014). "Composite Floor Systems Under Column Loss: Collapse Resistance and Tie Force Requirements." *Journal of Structural Engineering*, 140(8), A4014003.

Main, J.A. and Liu, J. (2013). "Robustness of Prototype Steel Frame Buildings against Column Loss: Assessment and Comparisons." *Proceedings of the ASCE/SEI Structures Congress*, Pittsburgh, PA, May, 2013.

Main, J.A. and Sadek, F. (2014). "Modeling and Analysis of Single-Plate Shear Connections under Column Loss." *J. Struct. Eng.*, 140(3), 04013070.

Main, J.A., Weigand, J.M., Johnson, E.S., Francisco, T.W., Liu, J., Berman, J.W., and Fahnestock, L.A. (2015). "Analysis of a Half-Scale Composite Floor System Test under Column Loss Scenarios." *Proceedings of the ASCE/SEI Structures Congress*, Portland, Oregon, April, 2015.

Sadek, F., Main, J.A., Lew, H.S., and El-Tawil, S. (2013). "Performance of Steel Moment Connections under a Column Removal Scenario. II: Analysis." 139(1), 108-119.

Weigand, J.M. (2016). "A Component-Based Model for Single-Plate Shear Connections with Pre-tension and Pinched Hysteresis." *J. Struct. Eng.* Under review.

Weigand, J. M. and Berman, J. W. (2014) "Integrity of Steel Single Plate Shear Connections Subjected to Column Removal Loading." *Journal of Structural Engineering.* 140(5), 04013114.

Weigand, J. M. and Berman, J. W. (2016) "Steel Gravity Connections Subjected to Large Rotations and Axial Loads." *Proc., Eighth International Workshop on Connections in Steel Structures (Connections VIII)*, Boston, Massachusetts, May, 2016.