The Role of Gravity Framing in the Seismic Performance of Steel Buildings

JUDY LIU

INTRODUCTION

Ongoing work on the seismic performance of steel buildings is highlighted. Dr. Michael Engelhardt leads the University of Texas at Austin team of Dr. Patricia Clayton, Dr. Todd Helwig, Dr. Eric Williamson, and Ph.D. student Sean Donahue. Dr. Engelhardt is the Adnan Abou-Ayyash Centennial Professor in Transportation Engineering and director of the Ferguson Structural Engineering Laboratory. Dr. Clayton is an assistant professor who has been awarded both the AISC Milek Fellowship and the AISC Early Career Faculty Award, among other honors. Dr. Helwig is a professor and associate chair for civil engineering, holds the J. Neils Thompson Centennial Teaching Fellowship in civil engineering, and is this year's AISC T.R. Higgins Lecturer. Dr. Williamson is a professor and holds the J. Hugh and Betty Liedtke Centennial Fellowship in Civil Engineering.

The research fills knowledge gaps with respect to the role of the gravity framing in the seismic response of steel buildings. Beam-to-column connections in gravity load-resisting frames are typically designed as "simple shear" or "pin" connections with no flexural strength or stiffness. However, these simple shear connections do have some flexural resistance. With consideration of these connections acting compositely with the floor slab, the flexural strength and stiffness increase. Given the number of gravity frame connections in a typical steel building, their overall contribution to the seismic response of the structure could be significant. However, the available data on cyclic behavior of simple shear connections are limited. The current research is expanding the database with a series of large-scale experiments and developing models and tools to quantify the role of the gravity framing in the seismic performance of steel buildings.

The research described here complements numerical studies conducted by Foutch (2000), Krawinkler (2000), and Foutch and Yun (2002) as part of the post-Northridge SAC-FEMA studies, which included research on the effects of gravity framing on the seismic performance of steel buildings constructed with moment frames. More recently, a study by Flores et al. (2012) also examined the influence of gravity framing on the seismic collapse risk of steel buildings with moment frames, using the FEMA P-695 (2009) methodology. These past studies have shown that gravity framing can contribute significantly to the lateral load resistance of a building. For buildings with lateral force-resisting systems of limited ductility (e.g., similar to older, "pre-Northridge" moment connections), the effects of the gravity framing could mean "the difference between collapse or survival" for a building (Foutch and Yun, 2002). For buildings with ductile moment frames, including the gravity framing in the building model can significantly reduce collapse risk; this reduction can be attributed to the combined effects of the flexural resistance of the gravity connections and the gravity column continuity helping to prevent soft-story mechanisms (Flores et al., 2012). The current research investigates the flexural resistance provided by gravity connections, particularly with consideration of the composite concrete floor slab. To supplement past experimental testing of single plate shear connections with and without concrete slabs tested under cyclic loading by Liu and Astaneh-Asl (2000), the large-scale experimental program in this study focuses on double-angle shear connections with variations in composite floor slab details that are prevalent in existing building construction. Preliminary results from this study are discussed.

RESEARCH OBJECTIVES

Some of the past work on shear connection behavior was motivated by observations after the 1994 Northridge earthquake; damaged steel buildings had significant fractures in the welded moment connections, but none of the buildings collapsed (Anderson et al., 1995). Numerical studies of steel buildings suggested that the gravity frames supplemented the lateral resistance of the moment frames (e.g., Foutch and Yun, 200; Gupta and Krawinkler, 1999). Experimental studies prior to and after Northridge also highlighted the contribution of the floor slab to the flexural strength and stiffness of simple and semi-rigid connections (e.g., Liu and

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Astaneh-Asl, 2000; Leon, 1990; Azizinamini and Radziminski, 1989). "While those studies have shown that simple shear connections can exhibit significant flexural capacity, especially in the presence of a composite floor slab, the strength, stiffness and ductility of those connections can vary significantly depending on connection and floor system details. Given the large number of different configurations seen in gravity connections, questions still remain as to the behavior of such systems" (Donahue et al., 2017).

The overarching goal of the research is to fill knowledge gaps with respect to the data and models needed to quantify the effect of the gravity framing system on seismic performance. Specific research objectives are to:

- Develop a database of previous experiments on typical simple beam-to-column shear connections used in gravity framing.
- Generate new experimental data from a series of large-scale experiments on simple shear connections under combined gravity and cyclic lateral load.
- Develop gravity connection models at various levels of complexity and detail for use in seismic analysis.

These objectives will be achieved through a large-scale experimental program conducted together with computational modeling, including a component spring model to simulate the cyclic behavior of the gravity framing connections in OpenSees (McKenna et al., 2000). Development and validation of these component spring models is ongoing. For the experimental program, questions related to the connection parameters and floor slab details are addressed. Some of the results and preliminary conclusions from those experiments are highlighted in this article.

TEST PROGRAM

A prototype steel frame building provides the basis for the design of the test set-up, loading and details of the test specimens. Initial testing in this study found that the flexural resistance at the gravity connections can be significant due to the tensile capacity of the metal decking. Therefore, in addition to double-angle and floor slab parameters to better understand moment-rotation behavior, changes in detailing and their effects on the tensile resistance from the floor slab are a primary focus of the study.

Test Set-Up

The test set-up was designed based on the boundary conditions and gravity loading at a typical girder to column joint in a prototype building. The prototype building has W14×22 filler beams framing into W21×55 girders at 7.25-ft intervals. The girders are supported by 11.5-ft story-height W12×96 columns at 29.5-ft spacing. The cruciform test specimen shown in Figure 1 represents a portion of the gravity framing from mid-span to midspan of girder and from

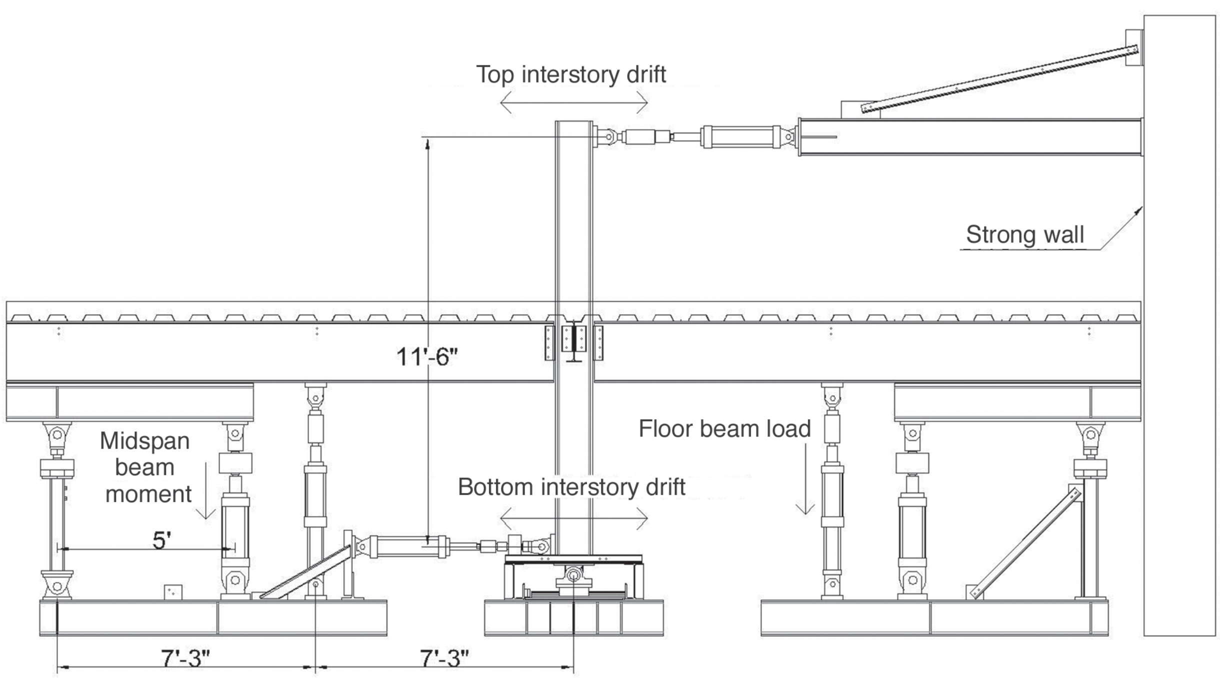


Fig 1. Test set-up.

Table 1. Test Matrix						
Spec. ID	Number of Bolts	Bolt Diameter	Angle Size	Concrete Slab	Deck Rib Orientation	Additional Comments
BS-WB	4[a]	¾ in.	L4×3½×¼	None	N.A.	
BS-BB	4	¾ in.	L4×4×¼	None	N.A.	
S-SC	4	¾ in.	L4×4×¼	N.W.	Par.	
S-LS	4	¾ in.	L4×4×¼	N.W.	Par.	Longitudinal seam in decking at column line
S-HA	6	¾ in.	L4×4×⅝	N.W.	Par.	
W-SC	4	¾ in.	L4×4×¼	N.W.	Perp.	
W-CC	4	¾ in.	L4×4×¼	N.W.	Perp.	Crack control reinforcement at column line
W-RB	4	¾ in.	L4×4×¼	N.W.	Perp.	Ring beam to simulate frame expansion restraint

[a] Angle leg connected to the column is bolted, and angle leg connected to the beam is welded.
N.A. = not applicable; N.W. = normal weight; Par. = ribs parallel to beam; Perp. = ribs perpendicular to beam

mid-height to mid-height of column. The tributary width of the floor slab corresponds to the girder span divided by 4, or 7.25 ft. The vertical actuators closest to the column simulate the gravity loading from each pair of filler beams at those locations. The adjacent actuator and strut assemblies simulate the midspan loading and moment. The gravity loading is applied first and held constant. Then, the actuators at the top and bottom of the column apply equal and opposite displacements to simulate the interstory drifts from a seismic event, following the SAC loading protocol (Clark et al., 1997).

Test Specimens

All specimens have bolted, double-angle shear connections, with the exception of one test specimen for which the angle leg to the column is bolted and the angle leg connected to the beam is welded. Bolts are ¾-in. diameter. Test parameters include angle size, number of bolts, presence of the floor slab with normal-weight concrete, orientation of the metal deck ribs, and other floor slab details. Additional floor slab parameters are used to investigate continuity of the deck and associated tensile capacity of the floor slab, additional tensile capacity in the floor slab from slab reinforcement, and slab confinement simulated by a ring beam to restrain frame expansion. When present, the floor slab has a 6½-in.-thick concrete slab on 20 gage corrugated metal decking with 2-in. ribs; 6×6×2.9 welded wire reinforcement is used for temperature and shrinkage reinforcement. Approximately 25% composite action between the concrete and steel is provided with ¾-in. steel headed stud anchors.

Table 1 provides a summary of the test program. The specimen ID indicates whether it is a bare steel connection (BS), has metal decking oriented in the "strong direction" (S) with the deck ribs parallel to the girder, or has metal decking oriented in the "weak direction" (W) with the deck ribs perpendicular to the beam. For the bare steel connections, WB indicates a welded-bolted angle, and BB indicates a bolted-bolted angle. The bolted-bolted angle is the "standard connection" (SC) for tests with concrete on metal decks, and the metal deck is continuous across the column line. Figure 2 shows a detail of specimen W-SC, an all-bolted, double-angle connection with L4×4×¼ angles, deck ribs perpendicular to the beam, and a continuous deck.

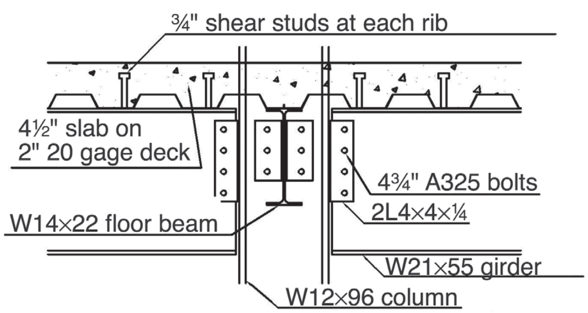
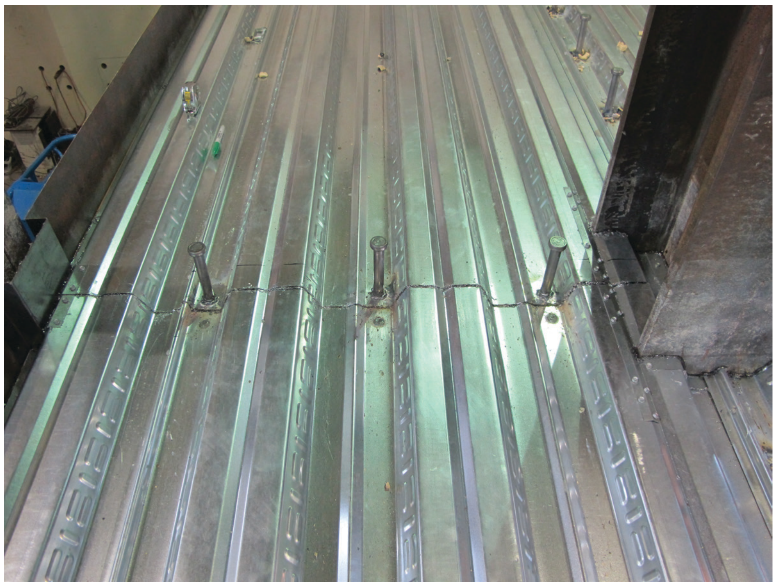


Fig. 2. Detail of specimen W-SC.

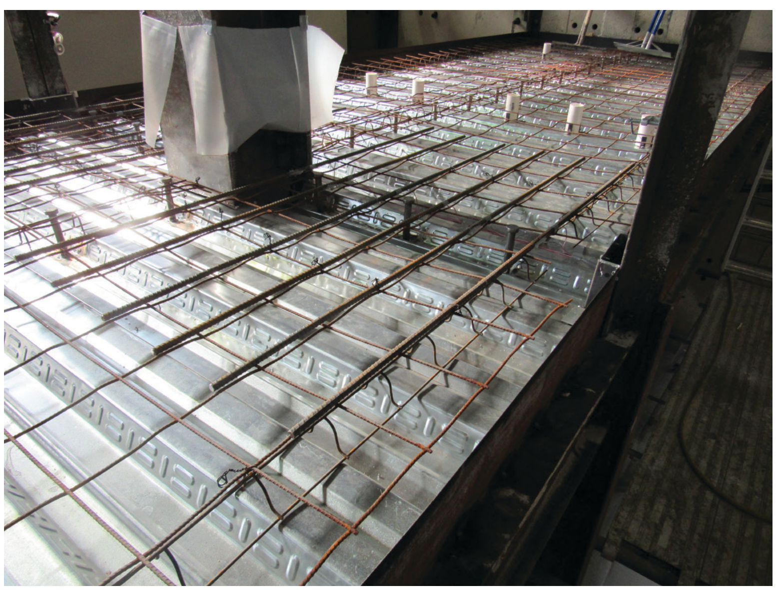
Other test specimens include one with a thicker and deeper double-angle connection; specimen S-HA uses a six-bolt connection with L4×4×⅝ angles. S-LS is a test specimen with four-bolt L4×4×¼ angles, deck ribs are parallel, and there is a longitudinal seam in the metal decking at the column line, as shown in Figure 3(a). Specimen W-CC is nominally the same as W-SC but with crack control reinforcement at the column line, a typical detail in steel frame buildings as shown in Figure 3(b). Specimen W-RB has a ring beam around the concrete and metal deck floor to simulate restraint to frame expansion (i.e., beam growth) that might inherently be present in a real building with many bays; the ring beam simulates the confinement to the concrete and is expected to increase the flexural strength of the composite connection.

EXPERIMENTAL RESULTS

Some of the results related to the contribution of the floor slab are highlighted here. The parameters investigated include the deck orientation, the continuity of the deck, reinforcement in the floor slab, and the effects of slab confinement.



(a)



(b)

Fig. 3. Photographs of (a) longitudinal deck seam and (b) crack control reinforcement.

Contribution of the Floor Slab

As observed in previous research (e.g., Liu and Astaneh-Asl, 2000), the floor slab increased the moment capacity of the connection. The composite, standard, strong deck direction connection (S-SC) resisted positive moment through compression in the concrete slab and tension in the angles. The positive moment capacity increased from less than 10% of the girder plastic moment capacity when no floor slab was present (BS-BB) to approximately 25% of the plastic moment capacity of the girder with the concrete slab and metal deck oriented in the strong direction. Concrete crushing governed over the tearing in angles observed for the bare steel specimens and resulted in degradation of the positive moment capacity after 3% drift (Figure 4). The composite, standard, strong deck direction connection (S-SC) initially resisted negative moment through compression in the angle and tension in the metal deck, reaching approximately 20% of the plastic moment capacity of the girder. At about 2.5% drift, binding (or bearing) of the beam bottom flange on the column and tension in the metal deck resulted in moments over 50% of the girder's plastic moment capacity by 4% drift. The connection was able to sustain a similarly large negative moment capacity up to 9% drift, when tearing in the double angles reached almost the entire length of the connection. Comparitively, the bare steel connection (BS-BB) was only able to reach approximately 10% of the girder moment capacity in the negative bending direction, around 5% drift when bottom flange binding occurred. A photo of the BS-BB specimen angle tearing at 9% drift is shown in Figure 5.

Effects of Deck Orientation

Comparisons between the composite, standard, strong deck direction connection (S-SC) and the composite, standard, weak deck direction connection (W-SC) highlighted the importance of the metal deck orientation. Figure 6 shows the normalized moment versus story drift for composite connections with the deck ribs perpendicular and deck ribs parallel. For a positive moment producing compression in the floor slab, the specimen with deck ribs perpendicular (W-SC) was able to develop a capacity of approximately

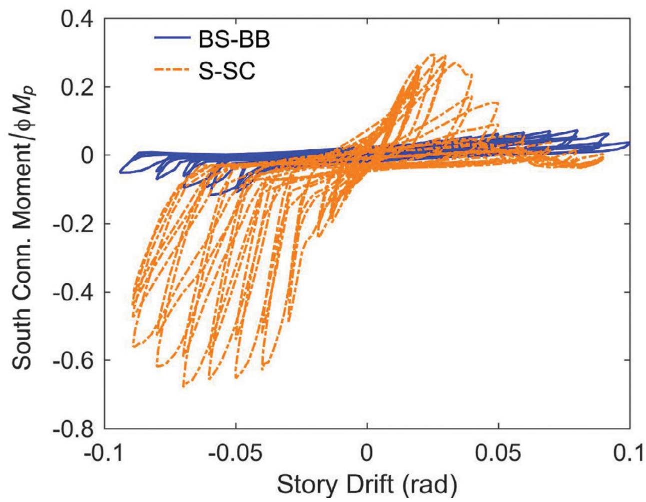


Fig. 4. Comparison of bare steel (BS-BB) and composite test specimen with deck ribs parallel (S-SC); normalized moment vs. story drift.

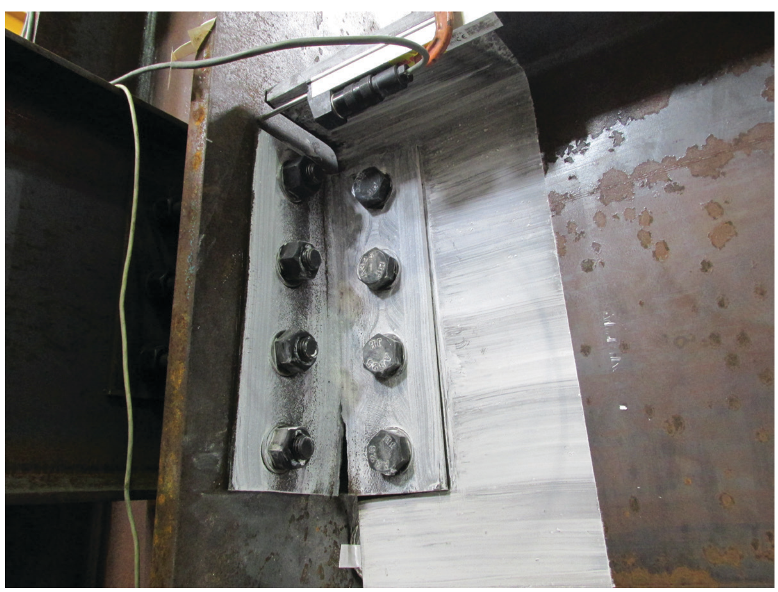


Fig. 5. Tearing in double-angle connection in specimen BS-BB at 9% story drift.

20% of the plastic moment capacity of the girder, compared to 25% for the specimen with deck ribs parallel (S-SC). However, for negative moment, specimen W-SC did not have significant tensile resistance. The concrete cracked, the welded wire reinforcement in the slab fractured, the deck ribs unfolded, and the negative moment capacity was similar to that observed for the bare steel specimen (BS-BB).

Effects of Detailing

Continuity of the metal deck and reinforcement of the floor slab were explored for their effects on the connection moment capacity. Specimen S-LS lacked continuity at the column line, with a longitudinal seam in the metal decking, as shown in Figure 3(a). Specimen W-CC included crack control reinforcement at the column, as shown in Figure 3(b).

In specimen S-LS, the seam was able to transfer some tensile stresses at low drifts but began to fail at the deck-to-beam puddle welds at approximately 2.5% drift. By 5% drift, the negative moment capacity for specimen S-LS had approached that of specimen W-SC, as shown in Figure 7. The higher positive moment capacity for specimen S-LS as compared to specimen W-SC is attributed to the increased contribution of the concrete in compression.

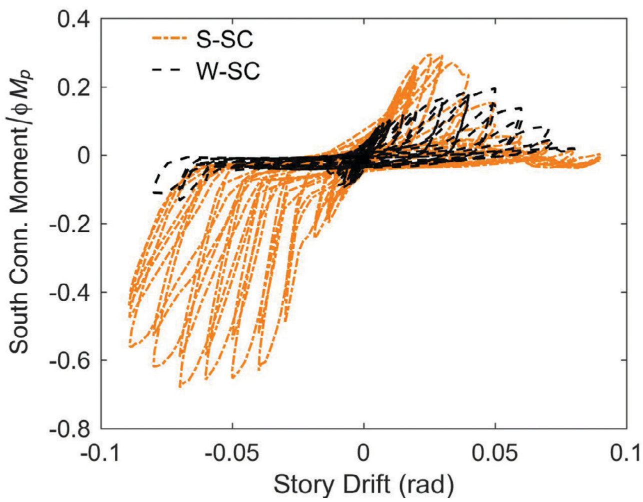


Fig. 6. Comparison of composite test specimens with deck ribs parallel (S-SC) and perpendicular (W-SC); normalized moment vs. story drift.

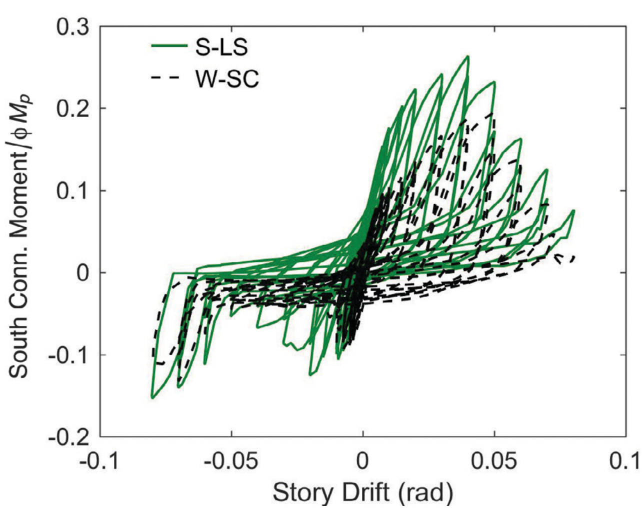


Fig. 7. Comparison of strong direction–longitudinal seam (S-LS) and weak direction composite test specimen (W-SC); normalized moment vs. story drift.

Specimen W-CC was nominally the same as specimen W-SC aside from the crack control reinforcement at the column line. As noted earlier, the weak orientation of the deck resulted in a negative moment capacity for W-SC that was comparable to that of the bare steel specimen. Specimen W-CC did see an initial increase in the negative bending connection resistance. However, cracking in the concrete at the ends of the reinforcement began by 1% drift, and by 3% drift, the reinforcement was considerably less effective in transferring tensile forces. Figure 8 shows a comparison of normalized moment versus story drift for the specimens with and without crack control reinforcement.

Effects of Slab Confinement

In specimen W-RB, a ring beam around the floor slab simulated restraint to frame expansion (i.e., beam growth) that might inherently be present in a real building with many bays. The resulting confinement to the concrete increased the flexural strength of the composite connection. Recall that the standard composite specimen with deck ribs perpendicular (W-SC) had low negative moment capacity relative to the composite specimen with continuous, parallel deck

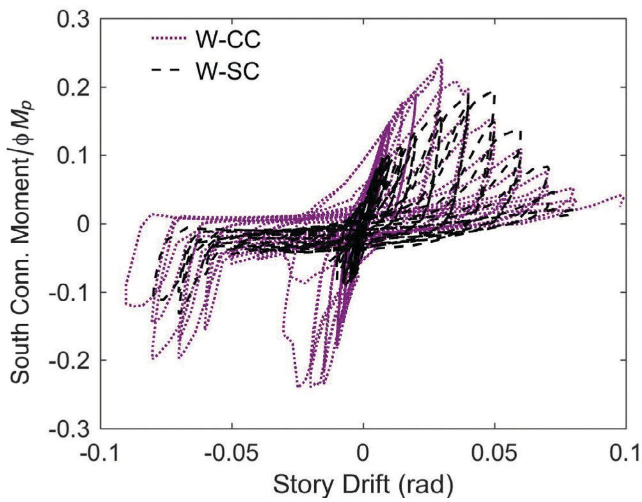


Fig. 8. Comparison of weak direction composite test specimens with and without crack control reinforcement (W-CC and W-SC); normalized moment vs. story drift.

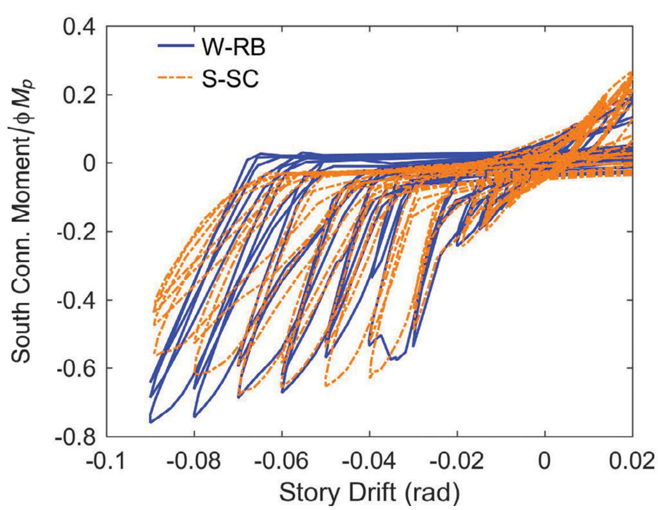


Fig. 9. Comparison of composite test specimens, strong direction (S-SC) and weak direction with ring beam (W-RB); normalized moment vs. story drift.

ribs (S-SC), as shown in Figure 6. Figure 9 shows that with prevention of the frame expansion and deck ribs unfolding in the weak direction, the negative moment capacity of the confined slab specimen (W-RB) approaches that of the specimen with deck ribs continuous and oriented in the strong direction (S-SC).

SUMMARY AND FUTURE WORK

Consistent with findings from previous experimental research programs, these tests have shown that the presence of the composite concrete slab has a major impact on the gravity connection response. Additionally, the direction and detailing of the metal decking has a significant effect on the flexural resistance of the connection. This finding suggests that the additional resistance provided by the presence of the composite slab may not only be attributed to the concrete compressive strength, as was assumed in past studies, but that the tensile resistance of the metal decking plays an important role in the flexural resistance of the connection. These tests also highlighted the importance of the test specimen boundary conditions, particularly related to the effects of unrestrained frame expansion observed in cruciform subassembly test set-ups. When frame expansion is restrained, which may be more representative of the boundary conditions in a multibay gravity framing system, the flexural capacity of the gravity connection can increase significantly.

Ongoing research efforts include development of numerical connection models of varying levels of complexity from more detailed finite element models to simpler component spring-based models. These models will be used to explore system-level behavior, including investigation of restraint to frame expansion in a multibay, multistory system that may affect gravity connection capacity and, ultimately, seismic performance of the steel building.

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