Steel Structures Research Update

Seismic Performance of Nonorthogonal Special Moment Frame Beam-to-Column Connections

JUDY LIU

INTRODUCTION

Ongoing research on the seismic behavior of nonorthogonal special moment frame beam-to-column connections is highlighted. Featured is a comprehensive experimental and computational study under way at the University of Arkansas and led by Dr. Gary Prinz, Associate Professor in Structural Engineering. The research team includes PhD students Hossein Kashefizadeh and Damaso Dominguez. Dr. Prinz's research interests include mechanics and simulation of ductile fracture, seismic design solutions for steel structures, and computer simulation of structures under dynamic loading. He received a National Science Foundation Faculty Early Career Development (CAREER) award to investigate a new micromechanics-based approach to ductile fracture simulation in additively manufactured steels for improved seismic structural fuse design. Dr. Prinz has also been awarded AISC's Milek Fellowship. The four-year Milek Fellowship is supporting this research on the seismic performance of skewed special moment frame (SMF) connections. The research team is partway through the third year of the four-year study. Selected results from the computational parametric study are highlighted along with a preview of the experimental investigation.

BACKGROUND AND MOTIVATION

Architectural flexibility and knowledge gaps for the seismic behavior of skewed SMF connections motivate this study. The architectural form and building envelope geometry of an SMF building might require a beam-to-column connection with a lateral beam skew angle, θ, as shown in Figure 1. However, only orthogonal configurations ($\theta = 0°$) are included in the AISC *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications* provisions (AISC, 2020). This limitation would preclude placement of an SMF connection such as a reduced beam section (RBS) or welded unreinforced flange–welded web (WUF-W) at such a location. Furthermore, research on skewed SMF connections under cyclic loading is limited and has not considered the influence of the composite floor slab. This research seeks to develop new knowledge and guidelines to improve architectural flexibility in SMF buildings.

Prior nonorthogonal SMF research focused on effects of skew angle and column axial load on the seismic performance of bare-steel RBS connections. The numerical investigations demonstrated adequate flexural capacity. Up to a 20° skew angle, increases in column twist and column flange yielding were minimal (Prinz and Richards, 2016; Desrochers et al., 2018). At a 30° skew angle, the torsional demands and yielding effects were more pronounced. The AISC *Prequalified Connection* Commentary cites Prinz and Richards (2016) with the acknowledgment that seismic performance of RBS connections with low skew angles (e.g., less than 5° to 10°) might be acceptable (AISC, 2020).

Prior studies on orthogonal SMF beam-to-column connections with composite slabs provided relevant results while highlighting potential issues for the behavior of nonorthogonal SMF connections. Increased moment capacity and delayed connection strength degradation under cyclic loading were observed for RBS connections with slabs (Zhang et al., 2004; Zhang and Ricles, 2006). Jones et al. (2002) demonstrated that the slab effects were more pronounced for shallow beam sections than for relatively deep beam sections. Dominguez and Prinz (2020) observed from the literature that for "skewed connections, increases in beam flexural strength through the addition of a concrete slab may have negative consequences, as increased beam-flange forces transmitted to the column may result in

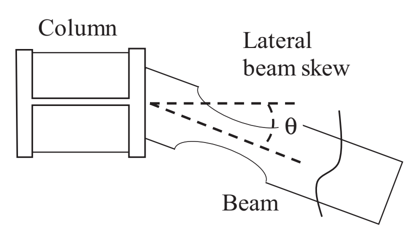

Fig. 1. Skewed reduced beam section (RBS) connection.

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increased column twisting due to eccentricities between the beam-line and column centroid created by the skew.”

RESEARCH OBJECTIVES AND PLAN

Building upon prior work on bare-steel skewed SMF connections and orthogonal connections with composite slabs, the primary research objectives are (1) to characterize the cyclic behavior of skewed SMF connections with composite slabs and (2) to develop comprehensive seismic design guidelines for skewed SMF connections. The research scope includes reduced beam section (RBS) and welded unreinforced flange–welded web (WUF-W) connections. Specifically, the research team is exploring “the effectiveness of RBS and WUF-W design procedures for limiting fractures near the beam-column connection welds of skewed SMF connections, as well as composite frame slab effects and the effects from column axial loads on column twisting/yielding.” (Dominguez et al., 2020)

The team is achieving these research objectives through an integrated analytical-experimental investigation. Advanced finite element modeling is used for a parametric investigation into skewed SMF connection response to cyclic loading, as well as analyses to evaluate susceptibility to low-cycle fracture and dynamic system-level performance. Composite connection behavior is explored through the analytical parametric study. Experiments will include cyclic testing of bare-steel, skewed SMF connections, and detailed fracture investigations. The fracture investigations following testing will include nondestructive inspections within the beam-to-column weld regions (die penetrant, magnetic particle testing) to identify potential brittle fracture issues. Additionally, destructive weld-region sectioning and metallographic investigations will help identify crack formations (if any) within the beam-to-column weld regions.

ANALYTICAL INVESTIGATION

The comprehensive analytical investigation includes evaluation of skewed SMF connection response to cyclic loading, susceptibility to low-cycle fracture, and dynamic system-level performance. A six-story earthquake time-history simulation has been used to study system-level performance. For cyclic behavior of skewed SMF connections, the analysis matrix includes 64 double-sided RBS prequalification-type simulations, 48 double-sided WUF-W simulations, and 12 RBS connection with composite slab simulations. The low-cycle fracture susceptibility of the RBS and beam-to-column weld regions is being investigated with 124 submodels. Some results from the parametric study are highlighted.

Parametric Study

An in-depth computational investigation explored the behavior of skewed SMF connections with and without a composite slab. A three-story SMF subassembly was modeled with appropriate boundary conditions to capture the behavior at the middle pair of SMF connections (Figure 2). RBS and WUF-W connections were investigated, along with shallow, medium, and deep column configurations and beam-column skews ranging from 10° to 30° (Table 1). Column axial loads of 0, 10, 25, and 50% of the design compressive strength were considered. The different axial loads were investigated to isolate the effect of column axial load on column flange yielding because increased column twist resulting in column-flange yielding was observed in early analyses. Results for 12 composite models were compared to those for nine bare-steel RBS models. Three of the 12 composite models used a higher compressive strength. Additional details can be found in Dominguez and Prinz (2020).

Modeling Approach, Loading, and Validation

The modeling of the steel and concrete components, boundary conditions, and loading provided realistic representation of the cyclic behavior of skewed SMF connections subjected to cyclic loading. Shell elements used for the steel sections captured local buckling and aided local connection stress and strain measurements. The floor slabs, modeled with solid elements and embedded truss elements for the reinforcing bars, utilized the existing concrete cracking constitutive models in ABAQUS (HKS, 2014). Shear studs were modeled using embedded beam elements. As shown in Figure 2, a three-story frame assembly was modeled to focus on the behavior of the middle-story connection. Dominguez and Prinz (2020) explain that this was done “in order to simulate realistic torsional boundary conditions within the columns of the skewed frame geometries” and to remove the connections of interest from boundary support effects. Figure 3 shows the cyclic loading protocol as specified by the AISC *Seismic Provisions* for SMF connection prequalification (AISC, 2016). The cyclic loading was applied as displacements at the beam ends in the model, which represented the beam mid-span inflection points in an SMF. The modeling approach was validated against cyclic tests of RBS connections (Jones et al., 2002). Additional details can be found in Dominguez and Prinz (2020).

Table 1. Beam, Column, and Connection Configurations for Parametric Study						
No. of Models	Connection	Column Section	Beam Section	Beam Skew Angles (degrees)	Column Axial Load (% capacity)	Concrete* Compressive Strength (ksi)
10	RBS	W14×193	W24×76	0, 10, 20, 30	0–50	4, 6
4	RBS	W18×143	W24×76	0, 10, 20, 30	0–50	Not applicable
7	RBS	W24×131	W24×76	0, 10, 20, 30	0–50	4
7	RBS	W33×291	W36×150	0, 10, 20, 30	0–50	4
4	WUF-W	W14×257	W24×76	0, 10, 20, 30	0–50	Not applicable
4	WUF-W	W24×162	W24×76	0, 10, 20, 30	0–50	Not applicable
4	WUF-W	W33×354	W36×150	0, 10, 20, 30	0–50	Not applicable

* For 10°, 20°, and 30° skew angle models only.

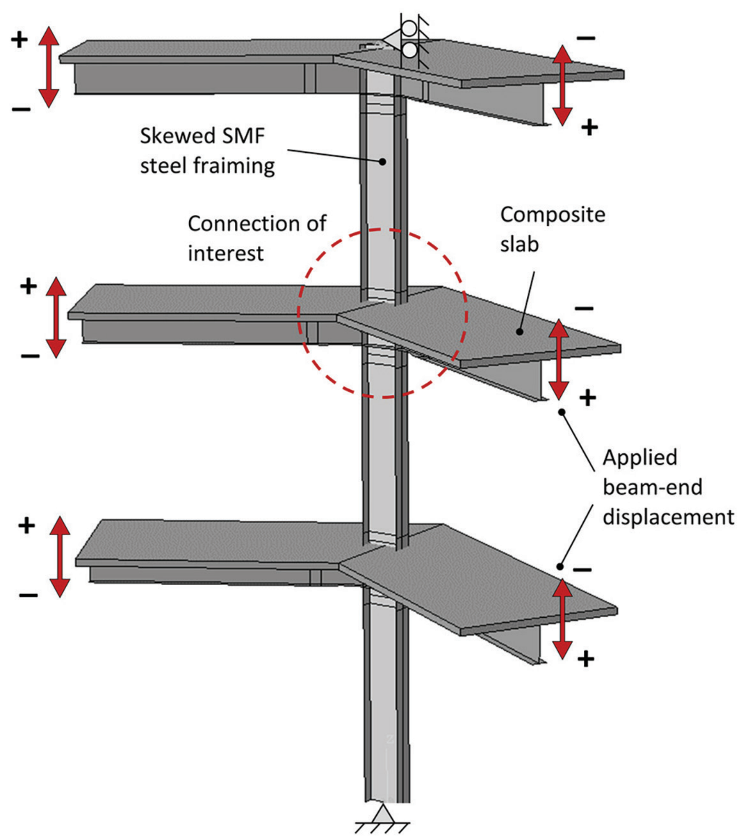

Fig. 2. SMF subassembly for parametric study.

Effects of the Composite Floor Slab

Results from the parametric study included insights into the effects of the concrete slab on moment capacity and column twist. Figure 4 compares moment-rotation responses for bare-steel and composite sections at 10° and 30° skew for shallow (W14×193) and deep (W33×291) columns. The presence of the composite slab did not result in any discernable increase in the connection negative moment capacity. A limited increase was observed for the positive moment capacity when the concrete slab was in compression. More significant was the delay in the post-peak degradation for the composite sections. Dominguez and Prinz (2020) observed that the "improved moment degradation behavior under the positive moment cycles is likely due to increased confinement of the beam top-flange delaying the onset of flange local buckling." For both bare-steel and composite sections, loss of moment capacity occurred more rapidly with an increase in skew angle. However, all connections satisfied the criterion of at least 0.04 radian of drift before 20% reduction in plastic moment capacity (AISC, 2016). Meanwhile, the composite slab reduced column twist until large skews; an increase in column twist was observed at 30° skew. The increase was attributed to the larger flexural demands from the beam combined with the larger eccentricity between the beam-line and the column centroid. Additional details and results, include the effect of the composite floor slab on connection plastic strain demands, can be found in Dominguez and Prinz (2020).

FUTURE WORK

Future work includes the experimental investigation and development of seismic design guidelines for skewed SMF connections. A total of 12 connection assemblies will be experimentally tested, providing a comprehensive data set for estimating demands in skewed RBS moment connections during cyclic loading. These 12 connection assemblies represent skewed geometries at three different angles (10°, 20°, and 30°) and two column depths (typical W14× column sections and deeper W18× column sections) with replicates for each (Table 2). The two column sections will be used to explore web depth effects on column twisting and flange-tip yielding. All test specimens will use a W24×76 beam, which has a flange width-thickness ratio that narrowly satisfies compactness requirements. The columns for the one-sided connection assemblies will be supported at each end (Figure 5), the beams will be laterally braced, and the cyclic loading protocol will be applied at the beam end (Figure 6).

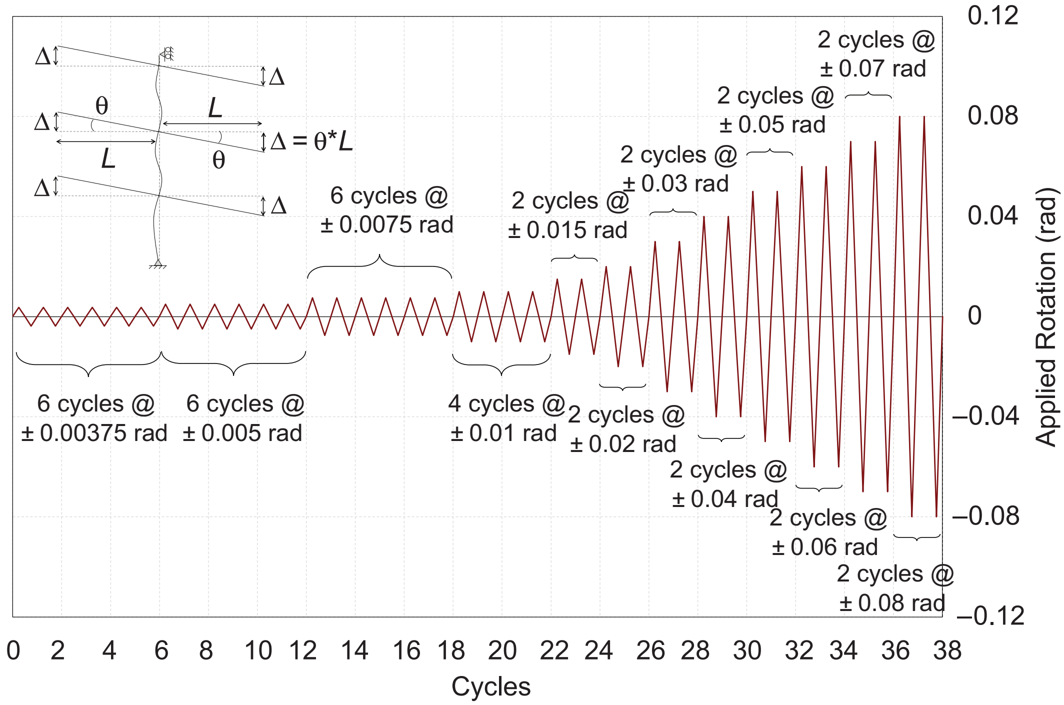

Fig. 3. Cyclic loading protocol for parametric study.

Table 2. Experimental Test Matrix				
Test No.	Test ID	Skew (degrees)	Column Section	Beam Section
½	SC-1	10	W14×132	W24×76
¾	SC-2	20	W14×132	W24×76
⅚	SC-3	30	W14×132	W24×76
⅞	DC-1	10	W18×86	W24×76
9⁄10	DC-2	20	W18×86	W24×76
11⁄12	DC-3	30	W18×86	W24×76

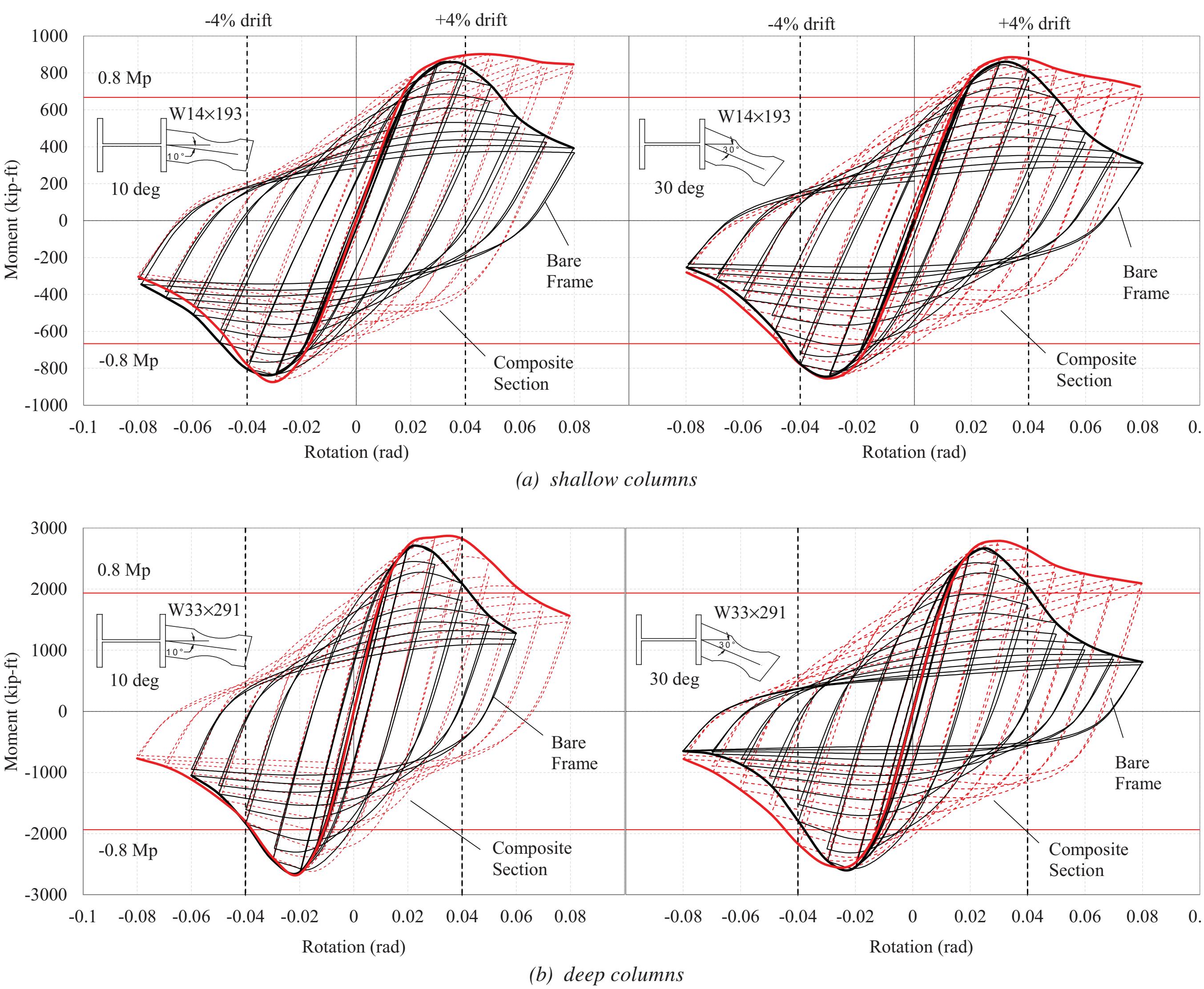

Fig. 4. Moment-rotation response for bare-steel and composite sections at 10° and 30° skew.

Fig. 5. Specimen in test frame.

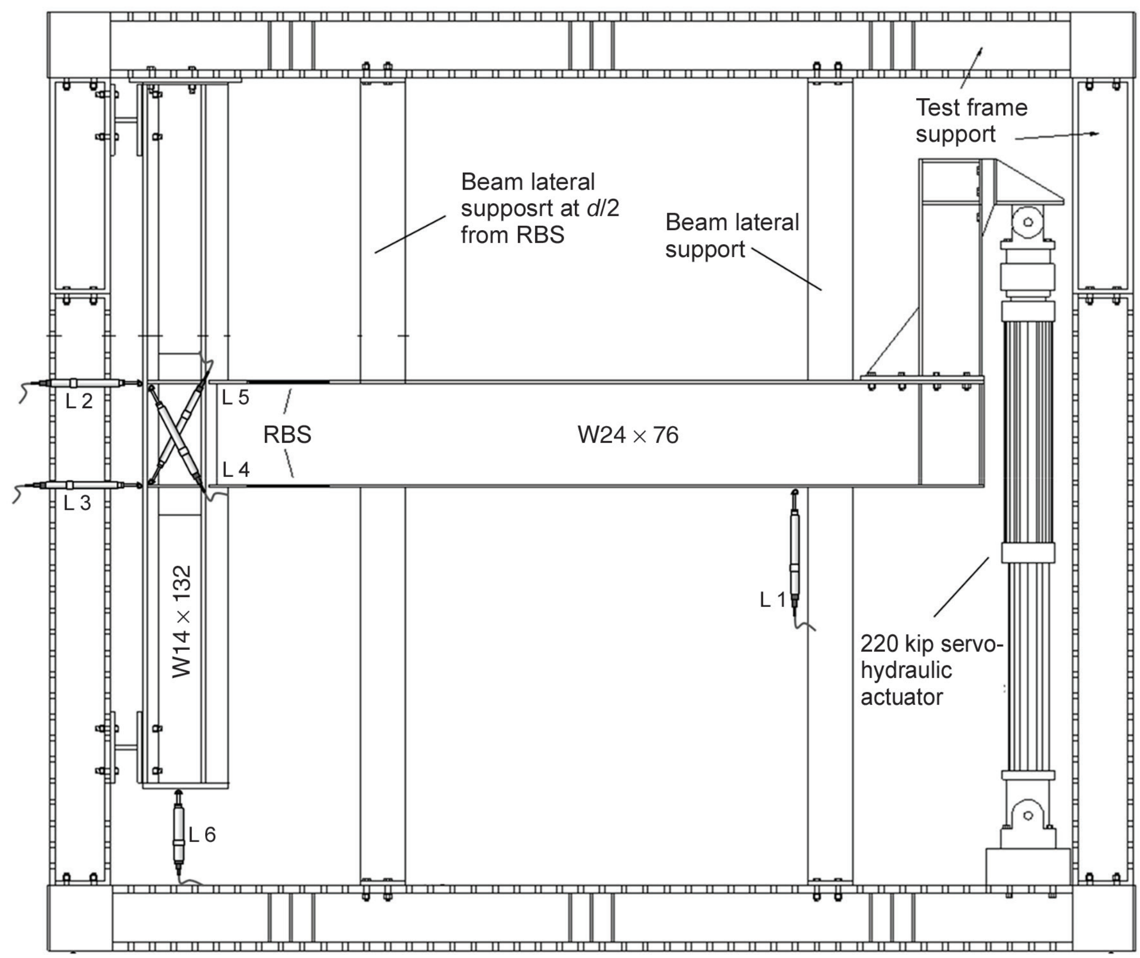

Fig. 6. Schematic of experimental setup.

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