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Strain Measurements in Skewed Reduced Beam Section Special Moment Frame Connections

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Strain Measurements in Skewed Reduced Beam Section Special Moment Frame Connections

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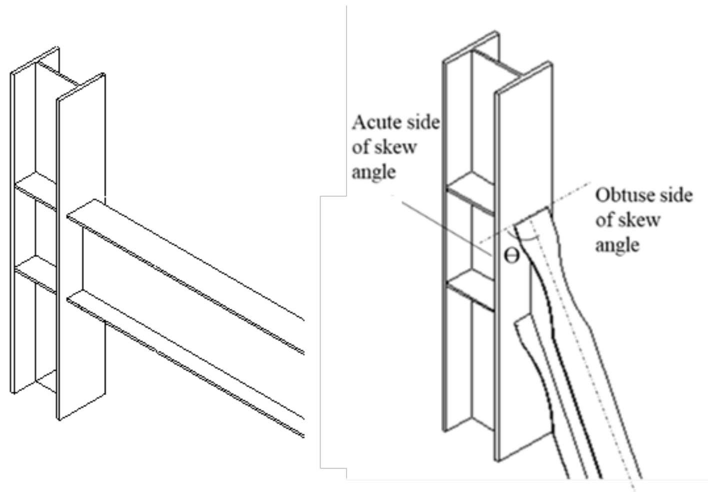
I. Introduction and Background

As architectural desires of steel buildings evolve and become more intricate, the structural design of framing is often constrained by connection requirements. In high seismic areas, steel special moment-resisting frames (SMFs) are often used to resist flexural, axial, and shearing actions that result from the displacement in a building because of the ground shaking [4]. These connections provide brace-free spaces in a building that accommodate many architectural features. However, these connections are limited to conform to some architectural designs because of the skew that develops at the beam-column connection due to the building's features they are intended to accommodate. A skew connection can either be in-plane, out-of-plane, or a combination of the two. Figure 1 depicts the beam-column connection oriented orthogonally compared to skewed. Existing SMF connection design procedures and codes do not consider skew, or how it should be taken into account in design.

A steel building frame is designed to withstand the inelastic behavior of an earthquake as a building sway. Steel frames consist of horizontal beams that resist lateral loads and vertical columns that transfer compressive loads. In high seismic areas, these components are welded together to create SMFs capable of transferring large moment or shear forces that develop in the beam to the column connection [4]. A reduced beam section (RBS) is a common, prequalified SMF connection detail in which a section of the beam flange is removed. A typical RBS cut is depicted in Figure 2. This detail is used to prevent failure from developing at the beam-column connection welds during a seismic event, and forces failure of the beam instead. The purpose of using this type of detailing is to force the structural member to yield and accumulate damage in a specified location to minimize damage during an earthquake and control the failure mode. Typical SMF connections with RBS detailing have been validated for seismic design with experimental procedures. Current design codes only consider orthogonal configurations of SMF connections in which the longitudinal beam is connected perpendicularly to the column flange. However, this connection type has its limitations when it comes to certain architectural designs. For some architectural features, moment frames develop skew at the beam-column connection in order to conform to the design. Current design protocols do not consider skew or the structural effect it might have on the structure in a seismic event. SMF with skew connections have been investigated through finite-element (FE) modeling, as they can reasonably predict the global response, local stress fields, local buckling, and locations likely to fracture [6]. Experimental procedures have not been conducted to determine if out-of-plane skew in RBS connections is acceptable, and in the case that they are, how much skew is acceptable. Experimental verification is required to determine if beam skew is applicable for steel building frames.

A series of experimental tests were conducted in the Civil Engineering Research and Education Center (CEREC) at the University of Arkansas to evaluate the effect of beam skew on a reduced beam section. Various degrees of skew on deep and shallow column depths were tested following a cyclical loading protocol, established by the AISC Seismic Provisions, to analyze the capacity of the out-of-plane skew connection [1]. Using the prequalified cyclical loading protocol allows for the evaluation of SMF connections in skew configurations against seismic events. Strain distributions throughout the RBS section, the welded beam-column connection, and the column flange were recorded throughout the cyclical loading procedure for each specimen. Strain gauges were placed on five specimens to measure the strain of various areas of interest during the tests. The scope of this research is narrowed to the evaluation of the strain distribution at the RBS cut for varying degrees of skew configuration for both shallow and deep column depths.



(a) Orthogonal (b) Skewed

Figure 1: Comparison of Beam-Column Connections

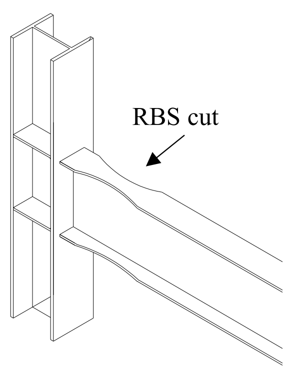


Figure 2: AISC 358-16 Prequalified RBS Flange Detail

II. Experimental Setup and Instrumentation

A total of six beam-column specimens were used for the testing of RBS moment connections in skewed configurations using the prequalified loading protocol. Skew angles of 10-, 20-, and 30-degrees were investigated each with column depths of 14- and 24-inches, to evaluate what effect column depth has with varying degrees of skew. Shallow column sizes consisted of typical W14x132 members, and deeper columns consisted of W24x131 members. Strain data was not collected for the shallow column specimen with a 20-degree skew angle, as it was used as a trial for the loading protocol. Typical RBS cuts were applied to each skewed specimen connection at the top and bottom flanges. The beam flange was connected to the column flange following AISC 358 requirements for welding connections [5] All specimens used a W24x76 beam to satisfy compactness requirements. All members were constructed by a commercial fabricator and made of ASTM A992 Grade 50 steel.

Each beam-column specimen is identified by their column depth and the applied skew angle. Naming convention for individual specimens is consistent throughout this analysis. The shallow column specimens connected at 10- and 30-degree skews are identified by “W14-10” and “W14-30,” respectively. Similarly, the deeper column specimens connected at 10-, 20-, and 30-degree skews are identified by a naming convention of “W24-10,” “W24-20,” and “W24-30,” respectively. Table 1 outlines the naming convention of the specimens used in this research.

Table 1: Specimen Naming Convention

Column Depth (inches)	Connection Skew Angle (°)	Specimen Identification
14	10	W14-10
14	30	W14-30
24	10	W24-10
24	20	W24-20
24	30	W24-30

A total of 19 uniaxial strain gauges were applied to each of the five specimens in various locations. The locations of the strain gauges were based on the stress concentration areas determined from modeling [3]. Figure 3 shows the configuration of the strain gauges on the RBS of the beam flange. Three strain gauges were applied to either side (top and bottom) of the beam flange at the RBS cut in a vertical orientation. The illustration in Figure 3 is consistent throughout the results, with a respective identification of the location of the strain data for each analysis.

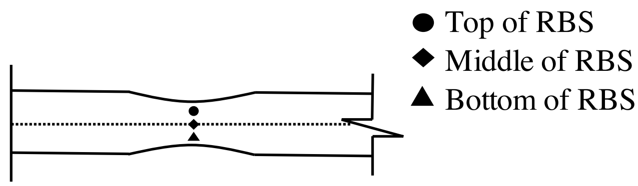


Figure 3: Strain Gauge Configuration on RBS Cut

The strain gauges were applied using a methodical procedure using a chemically hardening glue to adhere the gauge to the steel member. The strain gauges were removed from their casing using tweezer tongs and placed upright onto a cleaned mirror. Tape was placed directly onto the gauges for easy application. The area of application of the steel member was cleaned using Acetone before applying the adhesive. The powdered bonding material was mixed with an activator to create a chemically hardening glue, and then thinly applied directly on to the steel member. The strain gauges were carefully placed onto the area of application and secured with the glue. This methodical procedure is important in ensuring accurate data collection. Strain gauges were spaced evenly and placed to determine the strain at the top, middle, and bottom of the RBS cut. Because this is where the member is expected to fail in seismic events, measuring the strain at these locations on the RBS cut is critical.

A reaction frame is connected to each specimen, which is then connected to the strong floor through pre-tensioned, high strength, all-thread rods. Bolted skewed wedges were used to connect the column to the reaction frame, while ensuring the specimen remained horizontal. The specimens were oriented parallel to the strong floor and connected at the column ends with a pin-connection at the top and a roller-connection at the bottom. The boundary conditions are in accordance with AISC 358-16 prequalification requirements [2]. Figure 4 illustrates the orientation of the experimental setup. The beam was attached to a hydraulic actuator at the end and laterally supported at two locations. Displacements were applied to the beam ends in accordance with the AISC Seismic Provisions protocol [5]. The loading protocol for beam-to-column SMF connections is illustrated in Figure 5. Wires were attached to the strain gauges prior to testing and connected to a computer to record the strain distribution during each loading phase. All five specimens endured the same loading protocol, and the strain at the RBS was measured to evaluate the effect of skewed connections on the section. The AISC loading protocol that was determined for an orthogonal orientation of SMF connections of beams and columns was used to compare with the results of skewed connections.

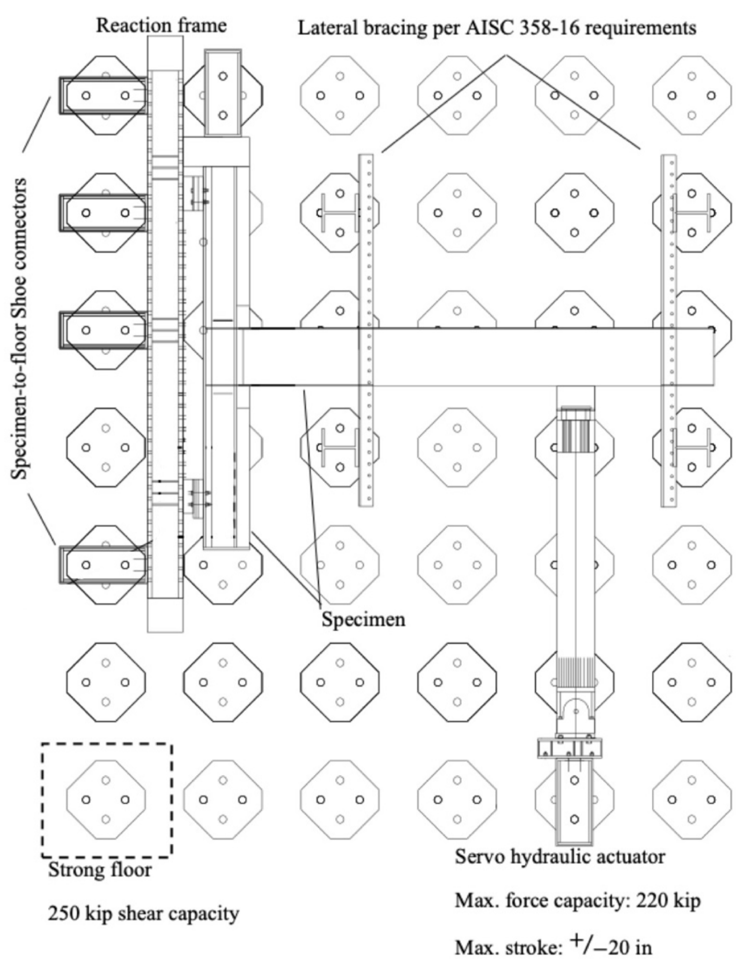


Figure 4: Experimental Setup of Specimen to the Strong Floor

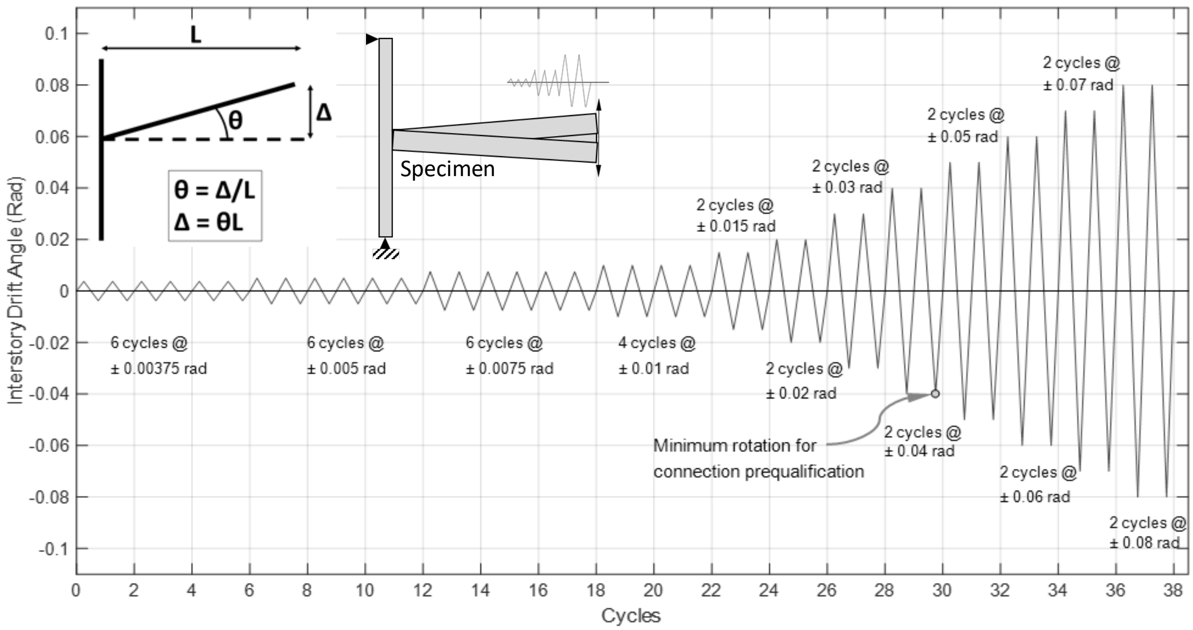


Figure 5: AISC Prequalifying Cyclical Testing Procedure for Beam-To-Column SMF Connections

For SMF connections oriented orthogonally, a successful test is indicated by the connection enduring a 4% story drift, or 0.04 radians, while retaining 80% of the plastic moment capacity of the beam [1]. This value was also used as the reference value when testing specimens with skewed connections. Since the scope of this research is narrowed to discuss the impacts of skewed connections and column depth on the strain at the RBS cut, the results of drift endurance encountered at this location will not indicate a failed or successful test.

It is expected that for the shallow column specimens, the strain will increase as the skew becomes larger. Conversely, the strain is expected to be larger with smaller degrees of skew for the deeper column specimens. With larger degrees of skew, more twisting occurs, allowing for the deeper column specimens to alleviate the strain through the RBS. Overall, the deeper column specimens are anticipated to have less strain overall with increasing skew geometries than shallower column specimens because the deeper columns will dissipate more energy through column twist. Additionally, the strain gauges on the RBS closer to the acute angle of the skew are expected to report higher strain values than those further away from the skewed angle.

III. Results and Discussion

The strain distribution was recorded for each specimen for the duration of the displacement-controlled test. Most strain gauges recorded data for the entirety of the loading protocol, but some were unable to record data due to breakage from extreme strain exposure. The effect of the column depths on the RBS strain is illustrated by Figures 6 and 7. The effect of skew on the RBS strains is illustrated by Figures 8 through 17. Figures 8 through 11 compare the effect varying skew angles have on the beam at the acute and obtuse sides of the skew. Figures 12 through 17 compare the effect varying skew angles have on different locations of the RBS for both the deep and shallow columns specimens.

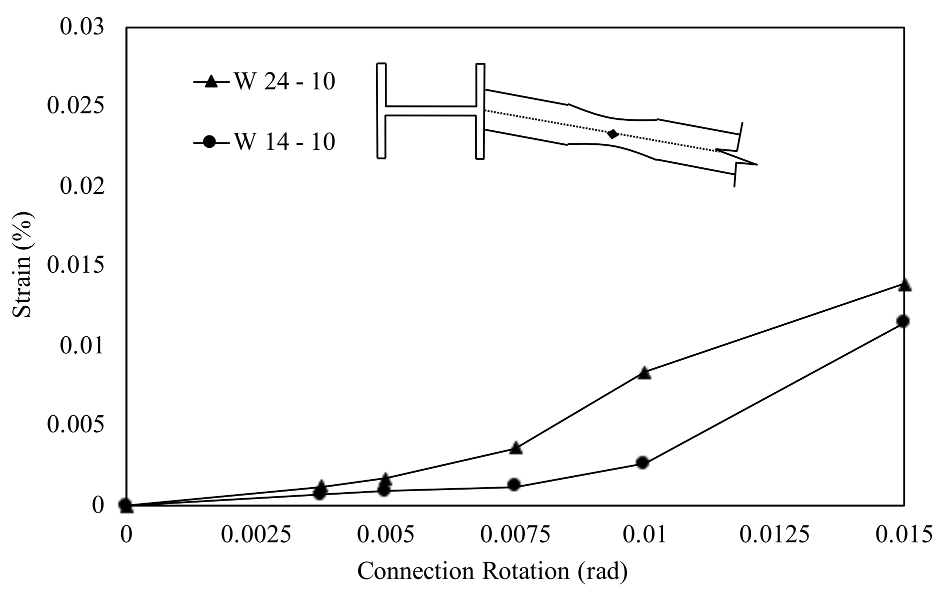


Figure 6: The Effect of Column Depth on the Strain Evaluated at the Center of the RBS Cut at 10 Degrees

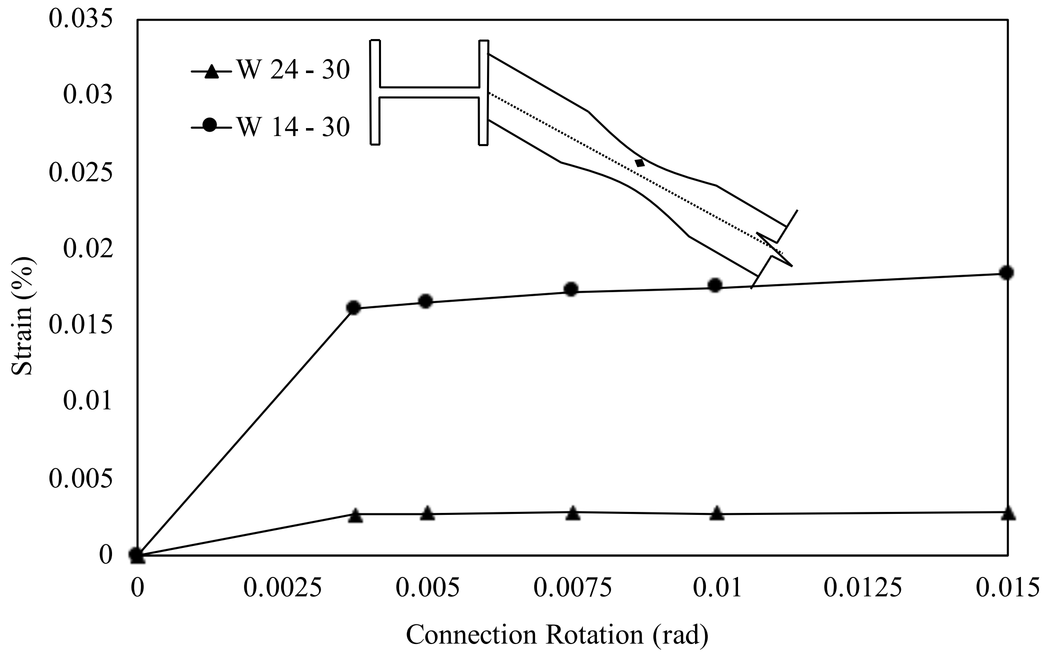


Figure 7: The Effect of Column Depth on the Strain Evaluated at the Top of the RBS Cut at 30 Degrees

Figures 6 and 7 define the impact of column depth on the strain at the RBS cut. In Figure 6, the strain for both column depths are compared for a 10-degree skew. The strain data was recorded at the center of the RBS cut for both column depths. Further comparison of the strain distribution at the top and bottom locations on the RBS cut cannot be made, as some strain gauges failed to record data due to breakage. For a 10-degree skew, as the column depth increases, the strain was observed to increase as well. This observation was expected to occur as specimens with deeper columns should experience higher amounts of strain at lower degrees of skew. The strain distribution for the specimens at a 20-degree skew cannot be compared, as data was only recorded for the 24-inch column depth. The strain comparison at the top of the RBS cut for both column depths at a 30-degree skew is illustrated by Figure 7. As anticipated, the strain was the largest for the specimen with a shallower column depth. At higher degrees of skew, the deeper column can dissipate more energy through column twist. The results for the effect of column depth on the RBS strain are consistent with the expectations. Specimens with shallow columns experience more strain at larger degrees of skew. Conversely, specimens with deeper columns proved to experience more strain at smaller degrees of skew.

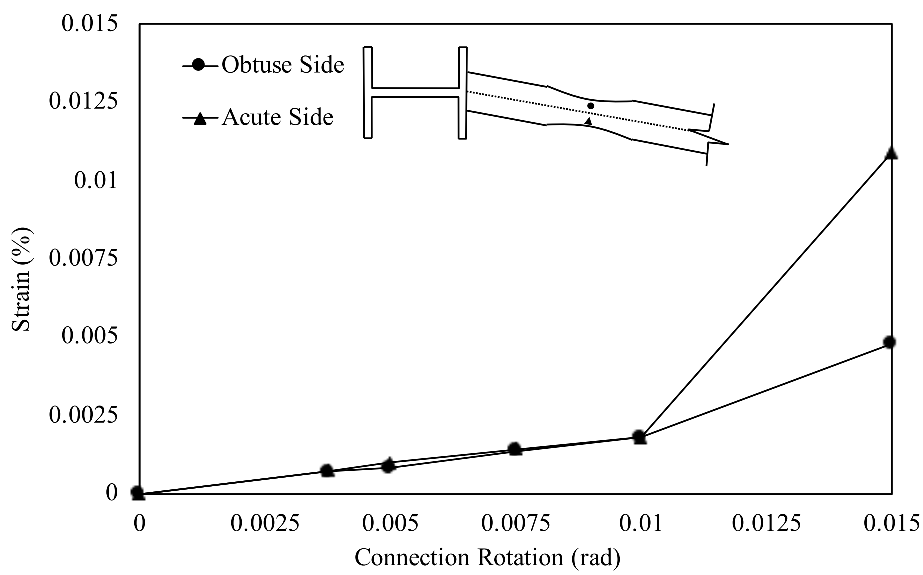


Figure 8: The Effect of Skew on RBS Strains Evaluated on a W14–10 Specimen

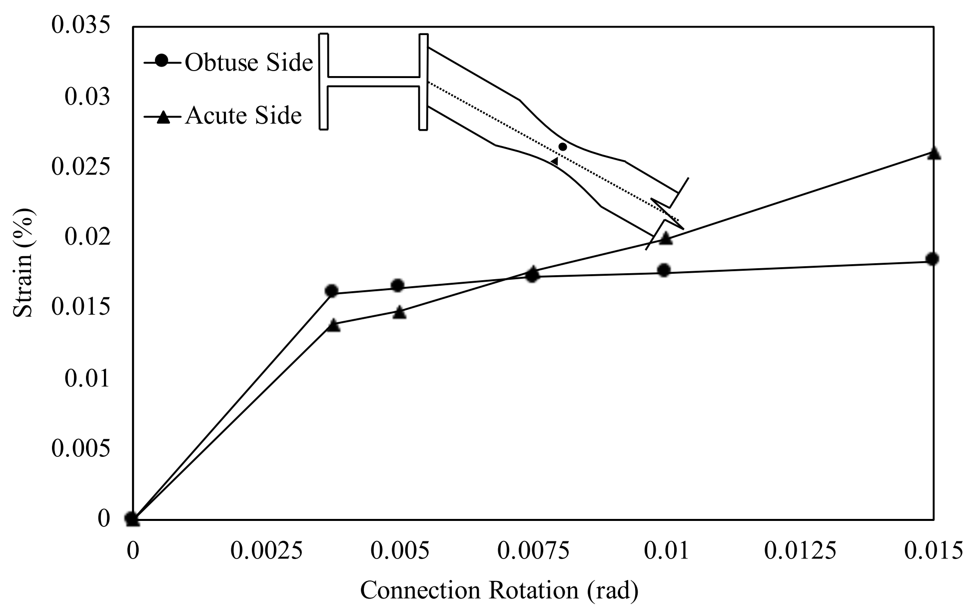


Figure 9: The Effect of Skew on RBS Strains Evaluated on a W14–30 Specimen

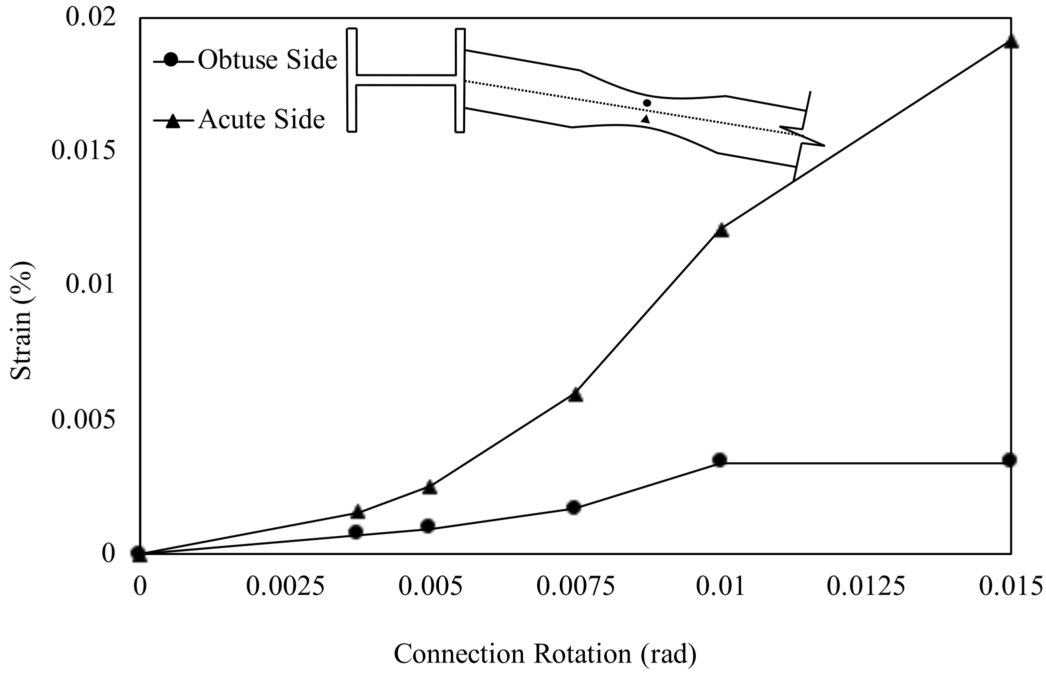


Figure 10: The Effect of Skew on RBS Strains Evaluated on a W24–10 Specimen

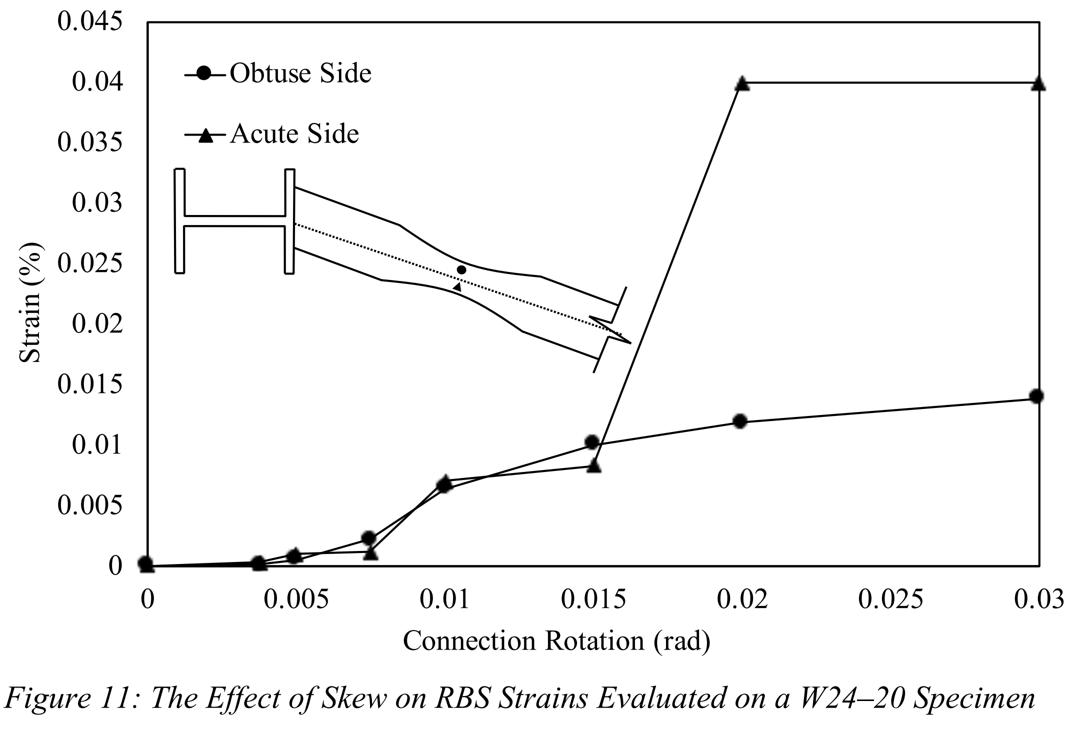


Figure 11: The Effect of Skew on RBS Strains Evaluated on a W24–20 Specimen

The effect of increasing skew angle on the strain on the obtuse side and the acute side of the skew at the RBS cut is compared by Figures 8 through 11. The “obtuse side” refers to the strain gauge at the top of the cut, closest to the obtuse angle formed by the beam-column connection. Similarly, the “acute side” refers to the strain gauge at the bottom of the RBS cut, closest to the acute angle formed by the beam-column connection. The W24-30 specimen does not have comparisons between the obtuse side and the acute side of the skew due to unrecorded strain values of the acute side.

It was anticipated that as skew increased, the strain should be greater on the acute side regardless of column depth. The results from all specimens indicate similar strain effects on either side at the beginning of the cyclical test, but a significant increase in the strain on the acute side towards the end of the test. The results indicate a greater strain on the acute side regardless of skew angle or column depth. Overall, the observed higher strain values on the acute side of the skew are consistent with the predicted results of the test.

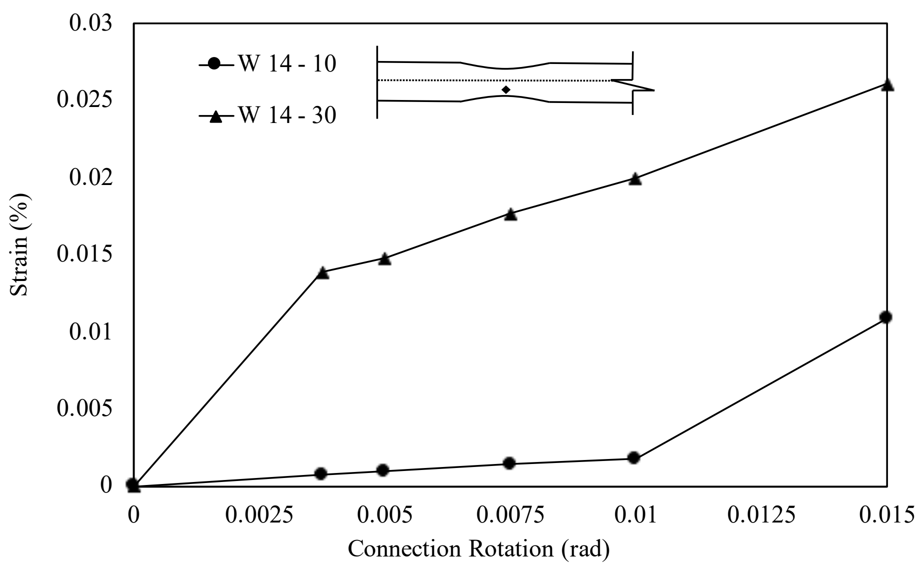


Figure 12: The Effect of Skew on RBS Strains on a W14 Member with Varying Degrees of Skew Evaluated at the Bottom of the RBS Cut

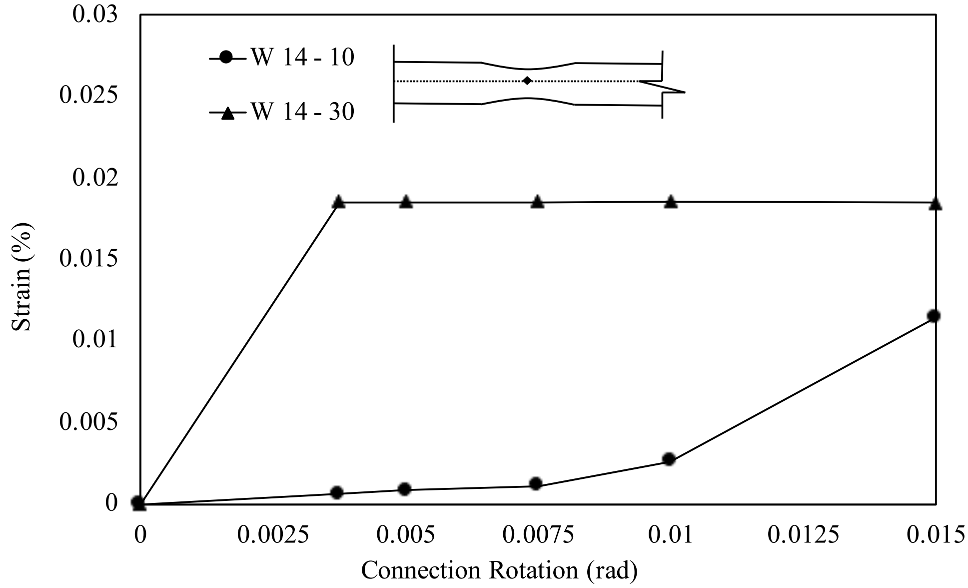


Figure 13: The Effect of Skew on RBS Strains on a W14 Member with Varying Degrees of Skew Evaluated at the Middle of the RBS Cut

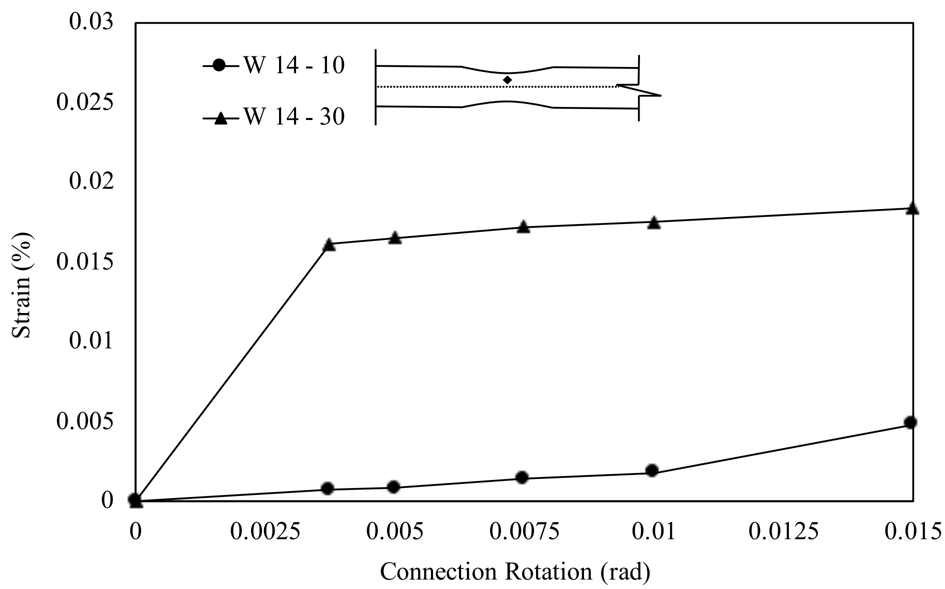


Figure 14: The Effect of Skew on RBS Strains on a W14 Member with Varying Degrees of Skew Evaluated at the Top of the RBS Cut

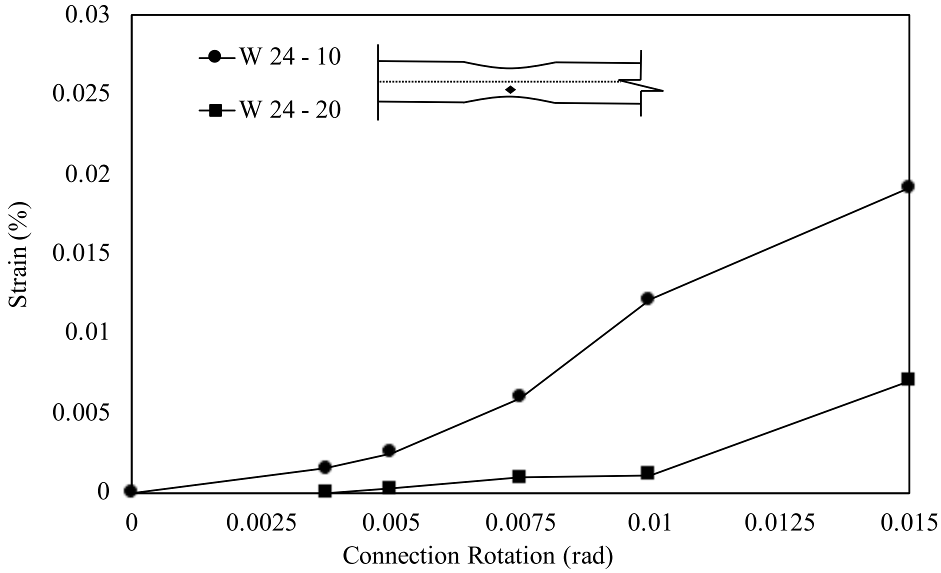


Figure 15: The Effect of Skew on RBS Strains on a W24 Member with Varying Degrees of Skew Evaluated at the Bottom of the RBS Cut

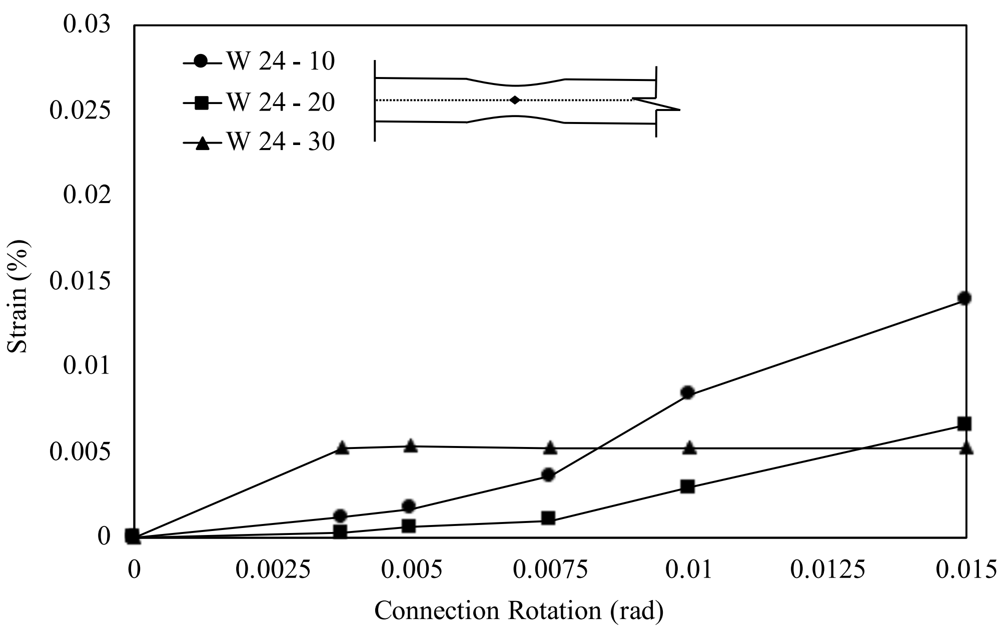


Figure 16: The Effect of Skew on RBS Strains on a W24 Member with Varying Degrees of Skew Evaluated at the Middle of the RBS Cut

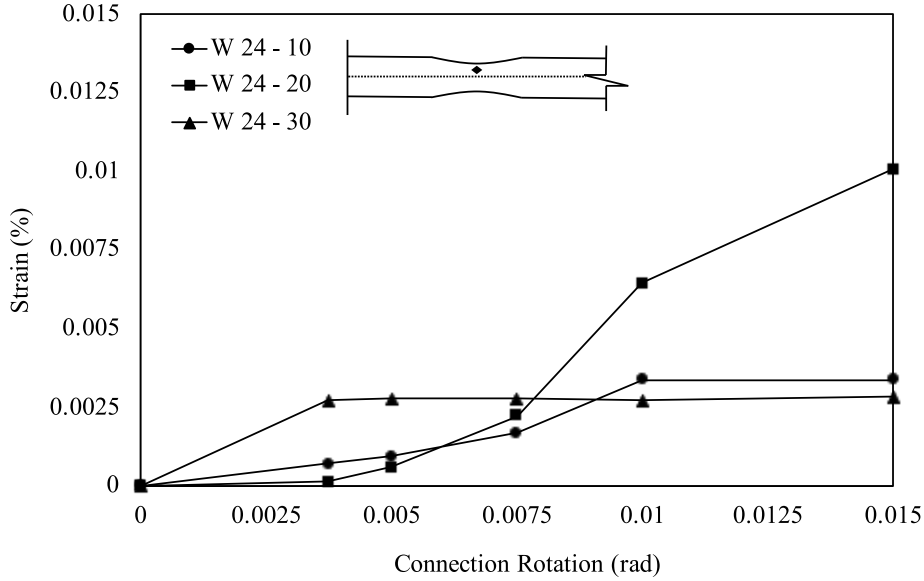


Figure 17: The Effect of Skew on RBS Strains on a W24 Member with Varying Degrees of Skew Evaluated at the Top of the RBS Cut

Figures 12 through 17 analyze the effect of skew on strain values at the bottom, middle, and top of the RBS cut. Each figure compares the same column depth and same data recording location with increasing skew. Figures 12, 13, and 14 compare skew angles of 10-degrees and 30-degrees on a shallow column specimen. Figures 15, 16, and 17 compare skew angles of 10-, 20-, and 30-degrees on a deeper column specimen. The strain gauge located at the bottom of the RBS cut on the 24-inch column specimen connected at a 30-degree skew did not record any data. It was expected that with increasing skew, the strain distribution would be observed to increase for shallow column specimens and decrease for deeper column specimens. For all locations on the RBS cut, the results conclude that shallow column specimens will experience greater strain at larger degrees of skew. For all locations on the RBS cut, the results conclude that deeper column specimens will experience greater strain at smaller degrees of skew. Figure 17 illustrates that a 20-degree skew produces the largest amount of strain for a W24 column, however, both strain gauges at this location for 10- and 30-degree skews broke off before the conclusion of the test. It can be expected that reproduction of this procedure would produce supporting evidence as well.

Overall, the skewed connections met the minimum acceptance criteria established by the AISC Seismic Provisions, indicating a successful test. All five specimens yielded at the anticipated RBS cut regardless of skew angle. Some comparisons could not be made to analyze column depth effect or skew effect on the strain distribution at the RBS cut because of damage during the cyclical test. Reproduction or repetition of these tests are expected to produce similar results for those whose data could not be analyzed.

IV. Conclusions

This study experimentally evaluated strain distributions within SMF RBS connections containing skew. In this study, 6 full-scale SMF connections instrumented with strain gauges within the beam-to-column connection region, and were subjected to the AISC cyclic prequalification protocol. Three different skew angles and two different column depths were considered in the testing. The following conclusions result from the local strain measurements taken within the SMF connections:

1) Increasing beam skew angle within an SMF connection increases the strain within the RBS during cyclic beam loading, however, more column twist due to the increasing beam skew angle allows for alleviation of the strain.
2) Increasing the column depth produces larger strain at the RBS cut with smaller degrees of skew and smaller strain with larger degrees of skew. The W24 column had a smaller strain distribution than the W14 column at a 30-degree skew but had a larger strain distribution at a 10-degree skew.
3) All specimens, regardless of skew or column depth, experienced larger strain at the acute skew-angle side of the RBS.

V. References

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[6] G. S. Prinz and P. W. Richards, "Demands on Reduced Beam Section Connections with Out-of-Plane Skew," *J. Struct. Eng. (United States)*, vol. 142, no. 1, pp. 1–9, 2016, doi: 10.1061/(ASCE)ST.1943-541X.0001360.