PARAMETRIC STUDY OF SLOPED REDUCED BEAM SECTION (RBS) STEEL CONNECTIONS

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Abstract: In modern architectural design, the use of non-orthogonal connections is inevitable, where the beam is connected to the column at an angle other than 90°. In this paper, a parametric study is conducted to evaluate the sensitivity of the cyclic response of Reduced Beam Section (RBS) connections with a focus on the effect of beam slope angle. To this goal, a finite element model is developed and verified using an experimental study. The verified model is then used to carry out a statistical sensitivity analysis. Twenty design factors, which are either material or geometry related, are considered. The performance of the connection is assessed by comparing different response variables, including initial stiffness, rupture index, equivalent plastic strain index, moment capacity, and hysteretic energy dissipation. The results show that beam depth and slope angle are the most significant factors in RBS connections. The rupture and plasticity indices are highly sensitive to the slope angle, and therefore, a higher slope angle can result in greater potential for brittle fracture and greater plasticity within the reduced beam section. In addition, panel zone related factors, including doubler plate, column web, and continuity plate do not significantly affect the cyclic behavior of RBS connections.

Keywords: Steel structures; Sloped reduced beam section (RBS) connections; Finite element modeling; Cyclic response; Sensitivity analysis; Analysis of variance (ANOVA).

1   Introduction

Reduced Beam Sections (RBS) connections were proposed after the Northridge (1994) and Kobe (1995) earthquakes (Iwankiw and Carter 1996). The idea was to weaken part of the beam so that the plastic hinge location is shifted from the beam-to-column interface to a region where the structural behavior is more reliable and predictable (AISC 2016; FEMA 2000).

The performance and behavior of the RBS moment connections are dependent on various factors, notably the configuration of the RBS cut. Thus, a large number of tests were dedicated to the configuration of RBS cutout (Chen, Yeh, and Chu 1996; Iwankiw and Carter 1996; Zekioglu, Mozaffarian, and Uang 1997; Jones, Fry, and Engelhardt 2002). Among tested shapes of RBS cutouts, the radius-cut showed a better performance. After several numerical and experimental studies, the RBS connection was introduced by AISC 358 (AISC 2016) as a prequalified connection.

The design codes (AISC 2016; CISC 2017) provide valuable recommendations for steel connection design especially RBS connections. Nonetheless, they are implicitly limited to orthogonal connections. Moreover, modern architectural design needs non-orthogonal and more complex connections; and therefore, the use of non-orthogonal connections, i.e. sloped or skewed connections, is inevitable.

Based on AISC-358 (AISC 2016) in sloped RBS connections, a small deviation from orthogonal angle does not change the performance of RBS connection significantly, while for bigger slope angles, e.g. 28 degrees, some adjustments should be made to avoid adverse impact of slope angle. The adverse effects are fracture at beam flange welds and increasing strain demand at the connection heel location.

In this paper, the effects of twenty different design parameters, including the beam slope angle, on the cyclic response of RBS connections are evaluated by performing a sensitivity analysis in a design of experiment framework. The effect of slope angle on stress demands and unequal yielding in the beam flanges, i.e. significant yielding in top flange and limited yielding in bottom flange, has been studied in previous study (Kim et al. 2016). A factorial analysis, however, is required to evaluate the influence of different design factors and interactions.

2   Finite element modeling

The cyclic response of RBS connections is simulated using ANSYS software (ANSYS 2018). A sloped RBS connection is chosen to validate the accuracy of the developed models. All components, such as the beam and column are modeled using 3-D 8-node structural solid elements (*SOLID 185*). For increased accuracy, finer meshes are generated within the panel zone and RBS region. The developed finite element model is shown in Figure 1. Material properties for this specimen are listed in Table 1.
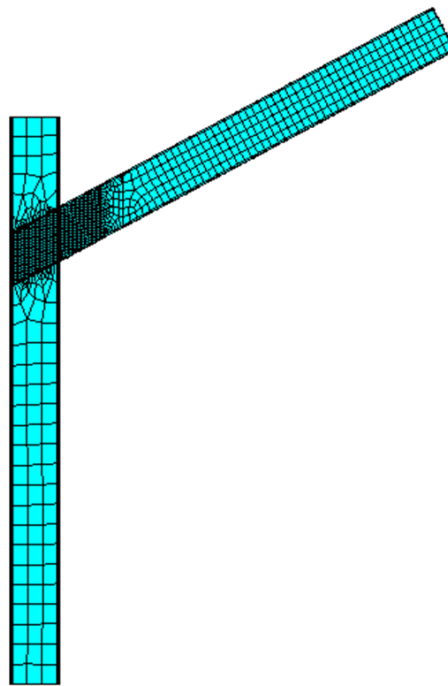

Figure 1: Finite element model for the experimental specimen

All nodes at top and bottom of the column are restrained to simulate a fixed support. Regarding the loading procedure, a displacement-controlled loading is applied to the end of the beam (Kim et al. 2016). To reduce the computational cost, a symmetry condition was considered. That is, half of the specimen model is simulated while out-of-plane displacements are set to zero. In an ongoing research study (Mohammadi Nia and Moradi 2019), we are using full models instead to assess the response sensitivity of RBS connections.

In order to validate the finite element modeling, the load-drift response of the beam is plotted alongside the experimental response. Figure 2 shows that the finite element analysis result agrees well with the experimental response.

Table 1: Material properties of reference connection (Kim et al. 2016)

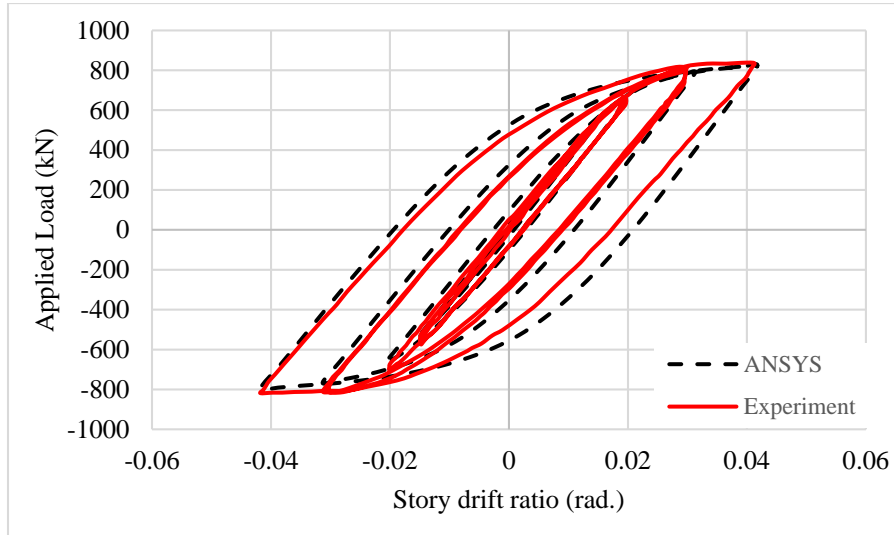| Member	Yield Stress (MPa)	Young's Modulus (GPa)
Beam (W36× 231)	436	200
Column (W36×302)	383	

Figure 2: Analytical model versus experimental response in (Kim et al. 2016)

3   Sensitivity analysis

The effect of different factors and their interactions on the cyclic response of RBS connections is determined in the sensitivity analysis. Twenty design factors are considered in this study. Table 2 lists these factors and their high (+) and low (-) levels. The high and low levels for the factors are selected to create a wide range while being practical.

Factor combinations for sensitivity analysis are developed by Design-Expert commercial software (DX11 2018). A total of 64 experiments are created and analyzed (Mohammadi Nia and Moradi 2019). Five response variables are chosen for the assessment of the cyclic behavior of RBS connections. These response variables include initial stiffness (K_i), rupture index (RI), equivalent plastic strain index ($PEEQ$), moment capacity (M_{max}), and hysteretic energy dissipation (HED).

A wide range of cyclic response is observed because of the variability in the design factors. Figure 3 shows the moment-rotation curves for models 7, 17, 48, and 64.

Table 2: Factors considered in the sensitivity analysis

| Factor	Symbol	Low Level	High Level	Unit
Beam depth	A	533	934	mm
Beam flange thickness	B	17	43	mm
Beam web thickness	C	11	24	mm
Beam flange width	D	179	281	mm
The distance from face of column flange to start of the RBS cut	E	130	215	mm
The length of RBS cut	F	425	560	-
Depth of cut at center of RBS	G	30	50	-
Span length	H	6535	8744	mm
Slope angle	J	0	45	mm
Column depth	K	386	948	mm
Column web thickness	L	21	60	mm
Column flange thickness	M	20	97	mm
Column flange width	N	281	437	mm
Column height	O	6000	11000	mm
Story ratio	P	0.3	1	-
Continuity plate thickness	Q	0	25	mm
Doubler plate thickness	R	0	44	mm
Strain hardening ratio	S	0.001	0.03	-
Yield strength of beam	T	248	436	MPa
Yield strength of column	U	248	436	MPa
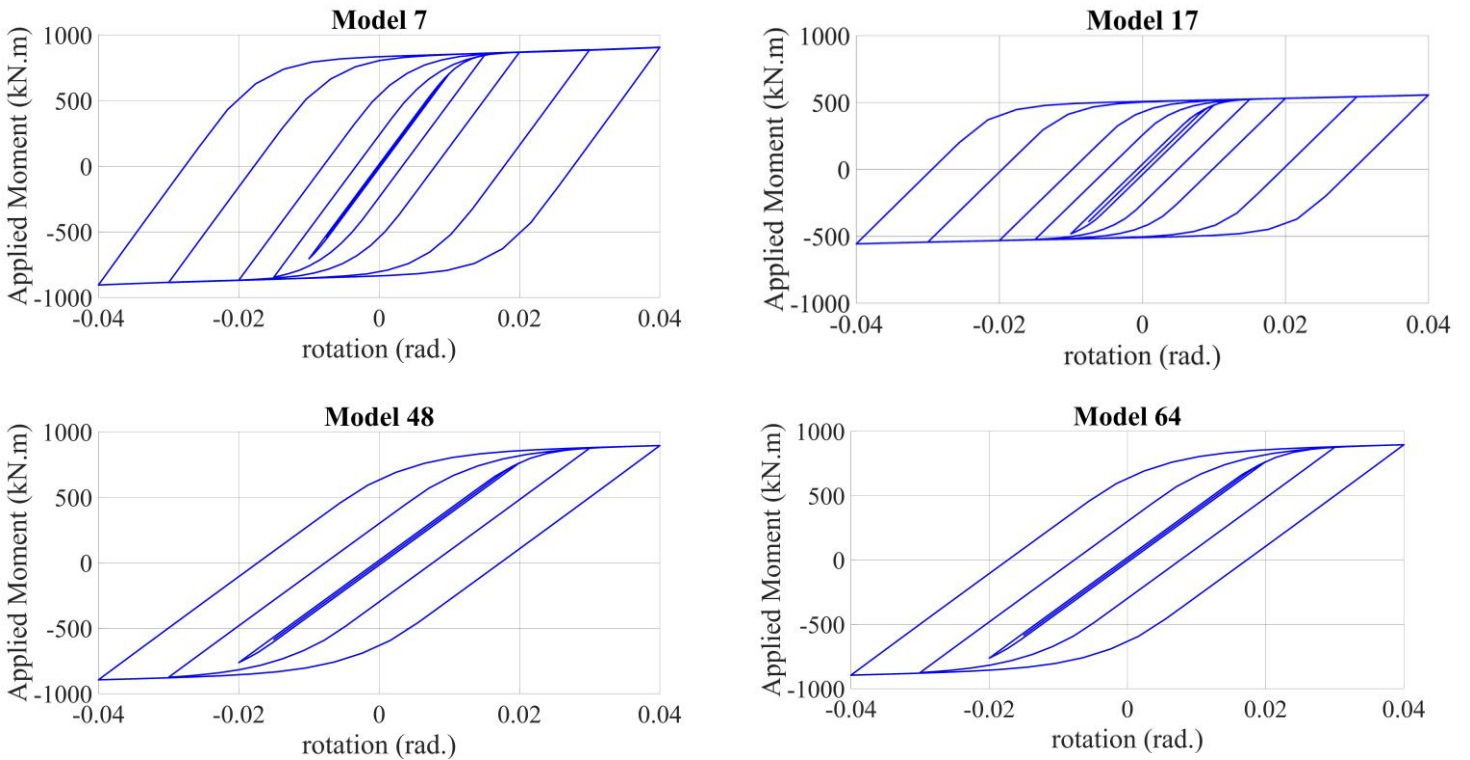
Figure 3: Moment-rotation curves for models 7, 17, 48, and 64

4 Results and discussions

The results of the sensitivity analysis are summarized in this section. In order to determine significant factor effects and interaction effects, Design-Expert software (DX11 2018) is used to generate half-normal probability plots. In a half-normal probability plot, insignificant factor and interaction effects are normally distributed with a mean of zero. Therefore, insignificant effects lie on a straight line in a half-normal probability plot. The half-normal probability plot for the initial stiffness response is shown in Figure 4. Based on this figure, slope angle (J), beam depth (A), column depth (K), and beam flange thickness (B) are the most influencing factors on the initial stiffness.
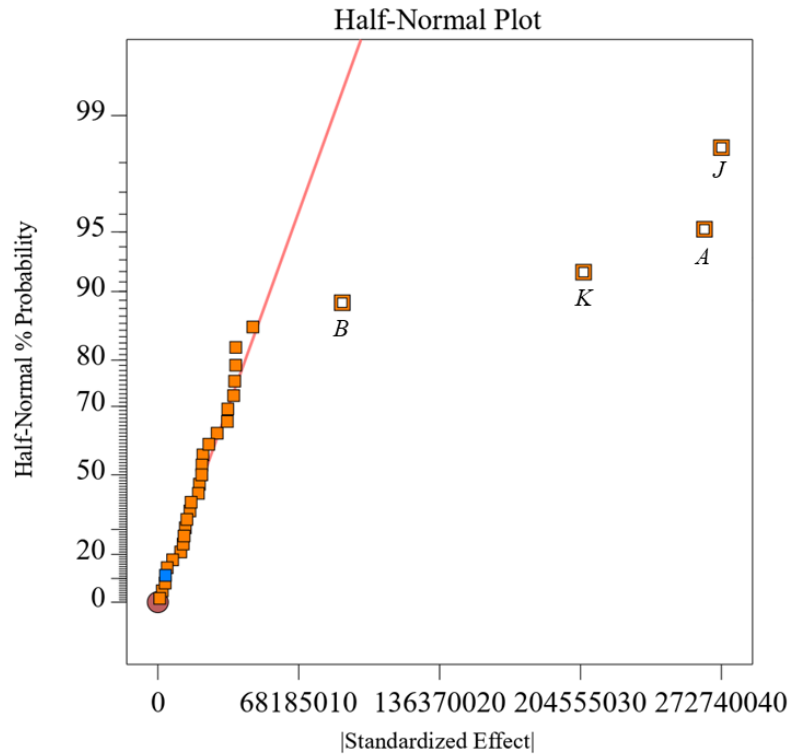

Figure 4: Half-normal probability plot for the initial stiffness

Analysis of variance (ANOVA) is performed to determine statistically important (significant) factors and also confirm the results from half-normal probability plots. ANOVA is a statistical tool to test the null hypothesis (H_0) of no significant effect (Montgomery 2017). In this study, the probability that a null hypothesis is true, i.e. significance level, is considered as 5%.

The initial sensitivity analysis results (from running 32 models, i.e. half of the total factor combinations) are listed in Table 3. By examining Table 3, significant factors are determined. On the other hand, after checking all the underlying factors, N (column flange width) is identified as an unimportant factor that has no significant influence on the response variables.

The interaction between slope angle and beam web thickness is shown in Figure 5 for RI response. In this 3D plot, the positive effect of the slope angle and negative effect of the beam web thickness are observed where increasing the slope angle and decreasing the beam web thickness result in higher RI.

In the fractional factorial design used in this study, main factor effects are aliased with two-factor interactions. As an example, for the RI response, there exist active interactions between beam depth (A) and other factors, such as AC, AD, AH, and AL. From the initial sensitivity analysis, it is not possible to distinguish which interaction is actually affecting RI. Therefore, a complete fold-over technique is applied by which a secondary factorial design is generated and then added to the initial factor combinations to de-alias the effects.

Table 3: Results of initial sensitivity analysis

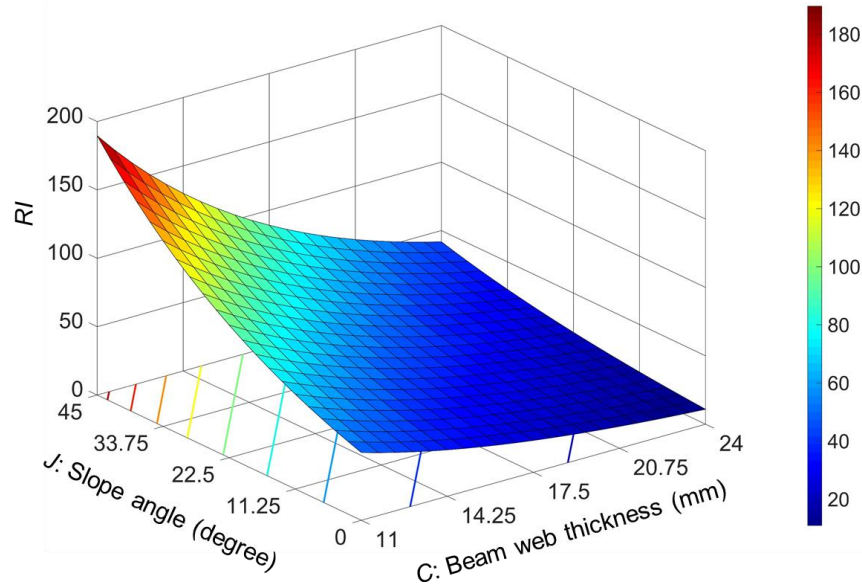| Response Variable	Influential Factors
Initial stiffness	*A, B, J, K*
Rupture index	*B, E, F, G, J, M, O, P, R, S, AC, AD, AH, AL*
Equivalent plastic strain index	*C, J, K, O, P, Q, R, T, AD, AL*
Moment capacity	*A, B, C, D, J, S, T*
Hysteretic energy dissipation	*A, B, C, J, K, L, AG*

Figure 5: Interaction between slope angle and beam web thickness influencing the *RI* response

The alias between the main factors and their interactions is eliminated by applying a complete fold-over method. For the factor combinations generated from the complete fold-over method, finite element models are developed and analyzed. Table 4 lists the significant factors based on a total of sixty-four models.

Table 4: Significant factors based on a total of sixty-four models

Response Variable	Significant Factors
Initial stiffness	*A, J, B, K, AJ, AK*
Rupture index	*J, K, C, T, R, JK, AL*
Equivalent plastic strain index	*J, T, C, R, K, AQ*
Moment capacity	*A, T, B, C, D, J*
Hysteretic energy dissipation	*A, J, K, B, C, AK*

For the significant factors and interactions associated with each response, percentage contributions are calculated. Percentage contribution is defined as the ratio between sum of squares for each factor to the total sum of squares (Montgomery 2017). Figure 6 depicts the percentage contribution of different factors and interactions on the response variables. Positive and negative effects are shown in blue and red colors, respectively. The results show that the beam depth, slope angle, and column depth are the most significant

factors. The rupture and plasticity indices are highly sensitive to the slope angle. A higher slope angle can result in greater potential for brittle fracture and greater plasticity within the reduced beam section.

The sensitivity analysis results presented in Table 4 and Figure 6 show that the panel zone related factors, including doubler plate, column web, and continuity plate do not significantly affect the cyclic behavior of RBS connections.
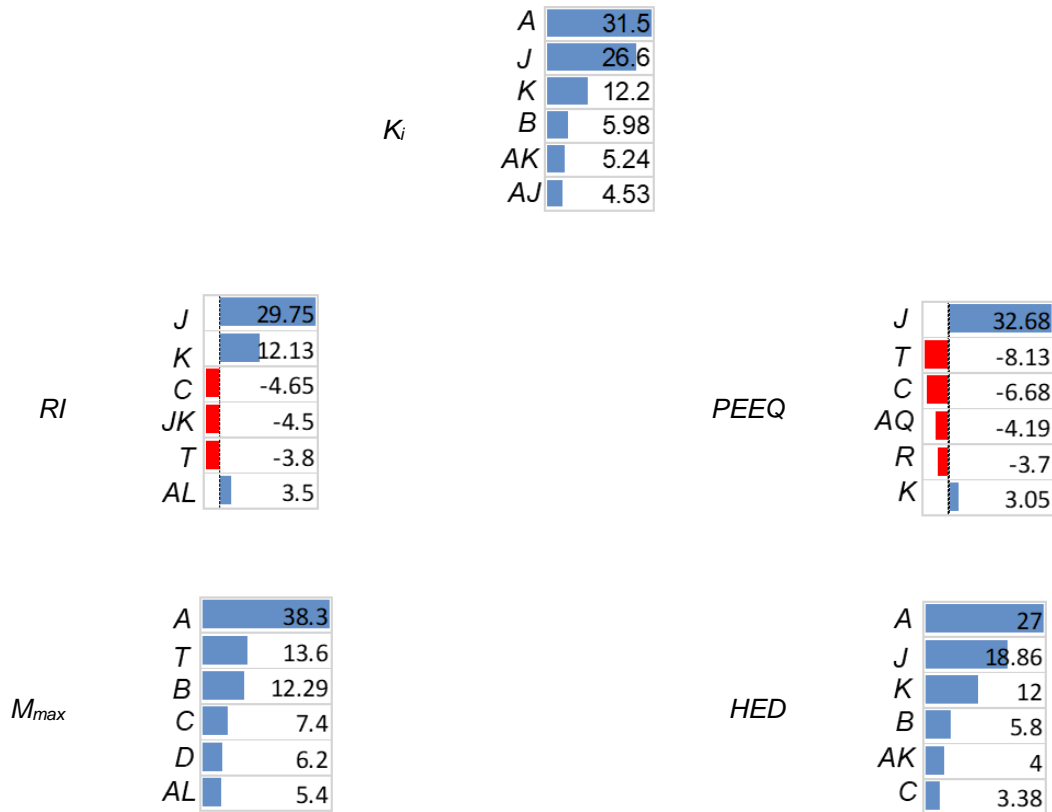
K_i

A	31.5
J	26.6
K	12.2
B	5.98
AK	5.24
AJ	4.53

RI

J	29.75
K	12.13
C	-4.65
JK	-4.5
T	-3.8
AL	3.5

$PEEQ$

J	32.68
T	-8.13
C	-6.68
AQ	-4.19
R	-3.7
K	3.05

M_{max}

A	38.3
T	13.6
B	12.29
C	7.4
D	6.2
AL	5.4

HED

A	27
J	18.86
K	12
B	5.8
AK	4
C	3.38

Figure 6: Percentage contributions of different factors and interactions on the response variables

5   Conclusion

The effects twenty different design factors (including the beam slope angle) on the cyclic response of RBS connections are assessed in this study. A fractional factorial design-of-experiment framework is used to perform two series of sensitivity analyses. The effect of each factor and any possible interaction between factors on the cyclic response of RBS connections is evaluated. It is worthy to note that the results in this study are based on a half model assuming symmetry conditions; however, in an ongoing research study (Mohammadi Nia and Moradi 2019), full finite element models are used to assess the response sensitivity of RBS connections. The following conclusions are drawn from the present paper:

- Beam depth and slope angle are the most significant factors. Initial stiffness, moment capacity, and hysteretic energy dissipation are affected by beam depth as the most significant factor. Slope angle has a direct (positive) effect on the initial stiffness, rupture index, equivalent plastic strain index, and hysteretic energy dissipation. Beam web thickness (influencing rupture index, equivalent plastic strain index, moment capacity, and hysteretic energy dissipation) and column depth (influencing initial stiffness, rupture index, equivalent plastic strain index, and hysteretic energy dissipation) are the next two important factors.

- The initial stiffness of RBS connections is sensitive to the beam depth, slope angle, column depth, and beam flange thickness. These factors account for 76% of total variability of the initial stiffness response.
- The rupture and plasticity indices are highly sensitive to the slope angle. A higher slope angle results in greater potential for brittle fracture and greater plasticity within the reduced beam section.
- The moment capacity of the RBS connection is highly affected by beam properties. These factors account for 78% of the moment capacity response variability of RBS connections.
- Panel zone related factors, including doubler plate, column web, and continuity plate do not significantly affect the cyclic behavior of RBS connections.

6   Acknowledgements

7   References

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