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FE parametric study of circular Reduced Web Section (RWS) connections subjected to cyclic loading

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Abstract

Circular reduced web section (RWS) openings provide a practical weakening strategy for retrofitting welded steel moment connections by relocating inelastic demand away from the beam-to-column interface. This paper defines a compact suite of performance metrics for cyclic assessment of fully restrained circular RWS subassemblies subjected to AISC 341 cyclic loading protocol. A validated three-dimensional finite element model is used to generate a database of 7,575 numerical specimens spanning European IPE sections, steel grades S235, S275, and S355, and span-to-depth ratios $2L/h=6$ to 14. Backbone-based ordinates and hysteresis-derived measures are proposed to quantify strength retention, high-drift stability. Database-level trends show that opening geometry primarily governs post-yield behaviour, with larger web openings and close to the column face most detrimental at low span to depth ratios. In addition, robust geometry corridors meet AISC criteria for special moment frames with less than 20% strength degradation while preserving stability. Selected well-proportioned openings can match or exceed solid web stability and high drift.

Keywords

reduced web section, circular web opening, welded moment connection, cyclic loading, performance metrics, backbone curve, seismic retrofit, finite element analysis

1 Introduction

New steel construction can contribute to climate change impacts. The World Steel Association estimates that steel production is responsible for roughly 7 to 9% of global direct CO₂ emissions [1]. In many cases, retrofitting existing steel buildings offers a more sustainable and cost-effective alternative to demolition and replacement [2]. Accordingly, a substantial body of research has investigated retrofit strategies that enhance the performance of existing structures rather than reconstructions, leading to the development of approaches based on joint strengthening and beam weakening [3] [4].

These advancements have culminated in the development of prequalified beam-to-column connections, which are a codified common practice in the United States [3], while specifications regarding prequalification are being developed in Europe [4]. European retrofit guidance for earthquake resistance promotes ductile mechanisms and stable rotation capacity [5]. On the other hand, following the 1994 Northridge earthquake, extensive research refined steel moment connection behaviour and detailing [6]. Within this context, RWS connections with circular openings provide a practical weakening strategy by relocating

inelastic demand away from the column face via Vierendeel action in the surrounding tee-sections; cyclic response is strongly governed by opening size and offset, with local instability as a common limiting mechanism [7] [8]. The primary goal of this study is to understand performance metrics for screening circular RWS geometries under a qualification-style cyclic loading. The overall geometry of a welded RWS connection with RWS geometry parameters is shown in Figure 1.

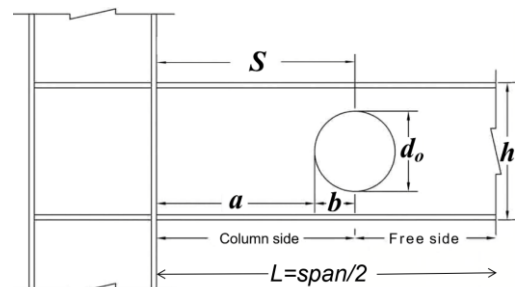


Figure 1 Circular RWS geometry and definition of non-dimensional parameters S/h , d_o/h and $2L/h$.

2 Numerical framework and FE database Outline

The FE framework was verified against five full-scale cyclic

four plastic hinges forming in the upper and lower tee sections and transferring the shear V_{sd} across the opening under the applied moment M_v .

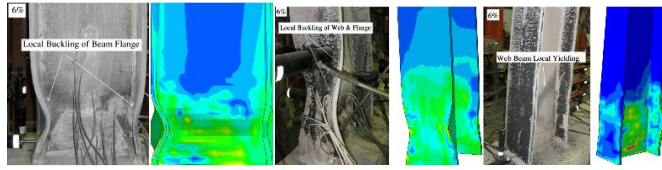


Figure 10 Experimental photographs adapted from Saneei Nia et al. [9] and corresponding FE deformation and von Mises patterns of DC specimens at 6% drift: DC-S, DC-M and DC-L.

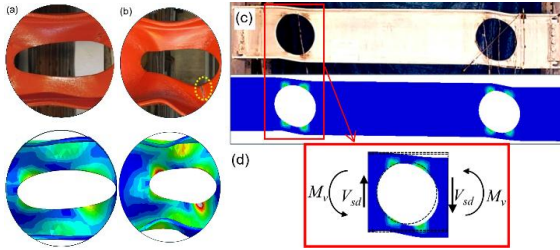


Figure 11 Experimental deformation patterns and corresponding FE PEEQ contours: (a) HE-RWS-1 at 6% drift [10]; (b) HE-RWS-2 at 7% drift [11]; and (c) Specimen 1 at 4% drift [15].

Implemented as a single dynamic Python script in ABAQUS, the FE model reproduces the moment-rotation hysteretic curves, including peak strengths and cyclic degradation, and the local failure modes across five experiments. In addition, the comparison with Specimen 1 from Shin et al. [15] in Figure 11(c) provides a sixth, independent validation of the four plastic hinging patterns around web openings (Vierendeel mechanism) and local deformations for a different beam configuration, supporting the application of the FE model to a wider range of web opening geometries, including circular openings. This approach is consistent with previous finite element studies on RWS connections i.e. [16], where the FE models were first validated against the available experiments and then used to investigate modified web opening geometries, including circular and other novel shapes, given the limited experiments for RWS connections.

3 Parametric Study

The primary objective of this study is to quantify the influence of geometric parameters ($2L/h$, S/h and d_o/h), material properties (steel grade), and beam profile (IPE sections) on the moment capacity of RWS connections. The response is characterised using key performance measures, including the yield moment (M_y), peak moment (M_c), ultimate moment (M_u), and the moment capacity at 4% and 6% drift ($M_{0.04}$ and $M_{0.06}$), together with compliance against AISC prequalification criteria. European steel grades S235, S275, and S355 are adopted in the parametric study based on the experimental database reported in [17], and the corresponding mean material properties are summarised in Table 1.

Table 1 Mechanical properties of steel grades for the parametric study

Property	S235	S275	S355
E (GPa)	197.48	206.47	205.67
σ_y (MPa)	301	324	395
$\sigma_{y,0.2}$ (MPa)	301	324	395
σ_u (MPa)	440	477	529

ϵ_y	0.0015	0.0016	0.0019
ϵ_u	0.31	0.30	0.28

Metrics are extracted from the hysteretic curves and backbone envelope depicted in Figure 12, consistent with SMF qualification concepts in ANSI/AISC 341 [12]. To explicitly address the rotation capacity requirements associated with ANSI/AISC 358 prequalified moment connections, the imposed storey drift angle is also treated as the connection chord rotation. For special moment frames, the target total rotation demand is 0.04 rad (equivalent to 4% drift), while intermediate moment frames are associated with 0.02 rad (2% drift). In addition to strength checkpoints at prescribed drift angles, an ultimate rotation capacity θ_u is reported as the chord rotation at which the backbone moment degrades to $0.8M_c$, representing 20% strength degradation from the peak.

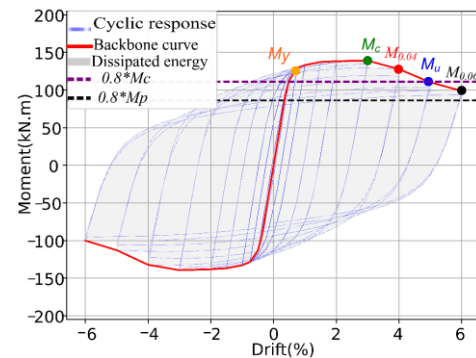


Figure 12 Schematic representation for characterising the responses

3.1.1 Parametric FE database

The parametric database comprises 7,575 analyses organised in 75 batches (5 beam sizes $\times$ 3 steel grades $\times$ 5 span-to-depth ratios). Each batch includes 100 circular-opening configurations tabulated in Table 2 plus the corresponding solid-web reference (C100: $d_o/h = S/h = 0$). Beam sections are IPE270, IPE330, IPE400, IPE500 and IPE600 in grades S235, S275 and S355. The span-to-depth ratios considered are 6, 7, 9, 12 and 14. All response quantities are normalised by the solid-web reference of the corresponding batch to isolate the effect of opening geometry. Specimen classification is illustrated in Figure 13.

Table 2 Parametric combinations of (S/h) and (d_o/h) in each batch of analysis

$(S/h)_w$	$(d_o/h)_w$									
	30	35	40	45	50	55	60	65	70	75
60	C00	C10	C20	C30	C40	C50	C60	C70	C80	C90
80	C01	C11	C21	C31	C41	C51	C61	C71	C81	C91
100	C02	C12	C22	C32	C42	C52	C62	C72	C82	C92
120	C03	C13	C23	C33	C43	C53	C63	C73	C83	C93
140	C04	C14	C24	C34	C44	C54	C64	C74	C84	C94
160	C05	C15	C25	C35	C45	C55	C65	C75	C85	C95
180	C06	C16	C26	C36	C46	C56	C66	C76	C86	C96
200	C07	C17	C27	C37	C47	C57	C67	C77	C87	C97
220	C08	C18	C28	C38	C48	C58	C68	C78	C88	C98
240	C09	C19	C29	C39	C49	C59	C69	C79	C89	C99

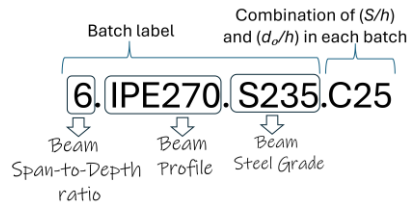


Figure 13 Specimen classification

4 Results and discussion

4.1 Yield Moment (M_y)

The results indicate that the normalised yield moment $M_y/M_{y,FS}$ is generally close to unity, with the most pronounced reductions and dispersion observed at low span-to-depth ratios 6–7, particularly when combined with larger d_o/h regardless of steel grades. This pattern is evident on the response surfaces (i.e., for IPE270.S235 in Figure 14). In addition, as the span-to-depth ratio increases to about 12 to 14, the 5×15 normalised M_y boxplots in Figure 15 show a clear contraction of the interquartile range and a shift of the median towards 0.95–1.0, evidencing reduced sensitivity to web openings. The data further suggest a profile-depth effect, with deeper IPE sections exhibiting smaller variability at a given opening configuration, consistent with increased flexural reserve and reduced local demand concentration. It was observed that the span-to-depth ratio acts as a first-order moderator of yield-moment degradation: lower span-to-depth ratios require stricter limits on d_o/h and opening location, whereas higher span-to-depth ratio configurations maintain M_y near the baseline even for relatively large openings.

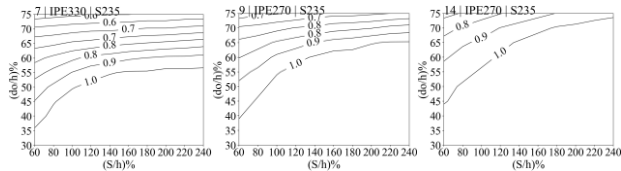


Figure 14 $M_y/M_{y,FS}$ plots for batches: 7.IPE270.S235, 9.IPE270.S235, and 14.IPE270.S235

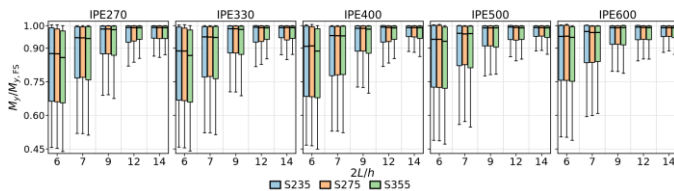


Figure 15 Boxplots $M_y/M_{y,FS}$ for profiles: IPE 270, IPE 330, IPE 400, IPE 500, IPE 600

4.2 Peak Moment (M_c)

The peak moment ratio $M_c/M_{c,FS}$ shows the most significant deterioration at low span-to-depth ratio (6–7) when combined with large opening ratios, as indicated by the response surfaces in Figure 16; the minima in the IPE270 examples fall to roughly one-half to two-thirds of the baseline, and the normalised M_c boxplots in Figure 17 exhibit wide spreads with numerous low outliers. As the span-to-

depth ratio increases to 12–14, the distributions become tighter, and the medians approach 0.9–1.0, indicating a markedly reduced sensitivity to the opening. A consistent depth effect is evident across profiles: IPE330 to IPE600 display progressively narrower interquartile ranges at comparable opening configurations, suggesting greater reserve and less localisation of demand in deeper sections. It is observed that controlling opening size and position is critical for smaller span-to-depth ratios. In contrast, higher span-to-depth ratios provide a practical buffer that keeps the peak strength near its reference value.

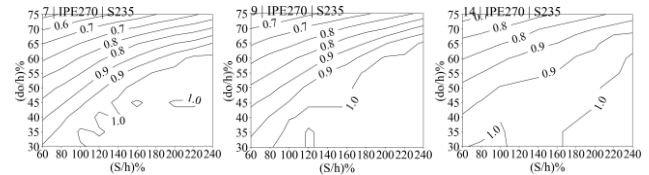


Figure 16 $M_c/M_{c,FS}$ plots for batches: 7.IPE270.S235, 9.IPE270.S235, and 14.IPE270.S235

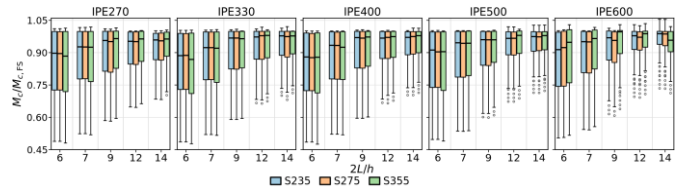


Figure 17 Boxplots $M_c/M_{c,FS}$ for profiles: IPE 270, IPE 330, IPE 400, IPE 500, IPE 600

4.3 Prequalification Criteria

4.3.1 Strength at 4% drift ($M_{0.04}$)

The flexural strength of a connection in SMFs at 4% drift needs to be at least 80% of the nominal beam plastic moment (M_p) [12]. In the present study, this full-section check, expressed as $M_{0.04} \geq 0.8M_p$, is used as the principal prequalification-style benchmark. Across the 7,575 models, 6,927 satisfy this requirement (91.45%), while 648 fall below it. The failing cases are concentrated in very large openings, predominantly $d_o/h \geq 0.65$ and especially $d_o/h = 0.75$, combined with low span-to-depth ratios, primarily $2L/h = 6$ to 7. This indicates that the 4% drift benchmark is generally achievable for moderate opening sizes, but unfavourable opening geometries should be screened out in design. A broad corridor around $d_o/h \approx 0.30$ to 0.50 and $S/h \approx 0.80$ to 1.20 achieved universal compliance.

4.3.2 Rotation capacity (θ_u) and strength degradation

While the $M_{0.04}$ benchmark provides a direct comparison against the AISC acceptance strength at 0.04 rad, rotation capacity can also be characterised by the onset of post-peak degradation. Using θ_u as a consistent indicator, 640 out of 7,575 models reach 20% strength degradation before 4% drift, 5,615 reach it at or beyond 4% drift, and 1,320 models do not reach 20% degradation by 6% drift. For the models that reach $0.8M_c$ within the analysed range, the median θ_u is 4.89% drift (interquartile range 4.39% to 5.41%).

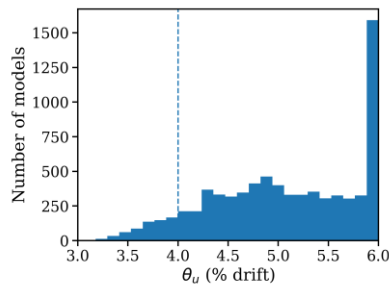


Figure 18 Distribution of θ_u , defined as the chord rotation at which the backbone degrades to $0.8M_c$ (20% strength loss). Values that do not reach $0.8M_c$ by 6% drift are plotted at 6% drift (censored).

4.3.3 Moment at 6% drift ($M_{0.06}$)

It was observed that the normalised moment at 6% drift, $M_{0.06}/M_{0.06,FS}$, increases with span-to-depth ratio and becomes less sensitive to web opening geometry: For instance, as shown in Figure 19, IPE270(S235), the mean rises from 0.854 at span-to-depth ratio = 7, to 0.892 at span-to-depth = 14. The surface plots show the lowest values around $S/h \approx 60\%$, and $d_o/h \approx 75\%$. In addition, it was observed that when the web opening exceeds about $0.40h$ and the end distance is short, the normalised 6%-drift, $M_{0.06}/M_{0.06,FS}$ drops below unity (lower than the solid beam counterparts).

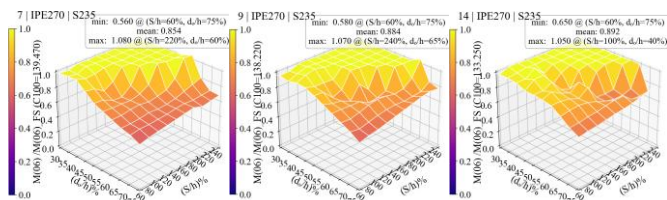


Figure 19 Surface plots, $M_{0.06}/M_{0.06,FS}$ for batches: 7.IPE270.S235, 9.IPE270.S235, and 14.IPE270.S235

Figure 20 is an illustration where a well-proportioned RWS outperforms the solid beam at high drift: For IPE600 with $d_o/h \approx 0.45$ and $S/h \approx 2.4$ (C39), the curve at $\sim 6\%$ drift sits above the Full section ($M_{0.06,RWS} > M_{0.06,FS}$). The moderate opening and large end distance redistribute the stresses, enabling a higher moment at 6% drift.

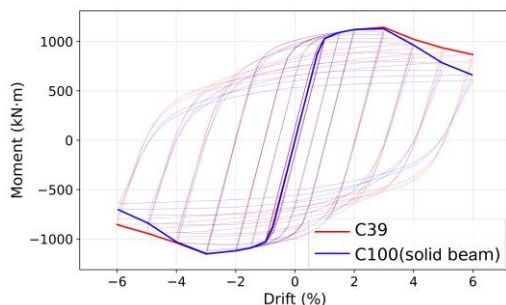


Figure 20 C39_VS_C100_ $M_{0.06}$ in batch: 14.IPE600.S235

5 Conclusions

This study aimed to quantify how RWS geometry governs the cyclic response of welded RWS beam-to-column connections when used as a seismic retrofit strategy for European IPE beams. A finite element model was developed

and validated against five full-scale experiments with satisfactory accuracy, and its local deformation patterns were further checked against an independent sixth test. Together, these comparisons confirmed that the analyses capture the Vierendeel mechanism, and the associated local deformation demands around a circular web opening. The validated model was subsequently used to generate and interrogate a database of 7,575 welded RWS beam-to-column connection specimens subjected to the AISC 341 cyclic loading protocol. The parameter space was defined across IPE270 to IPE600 sections, span-to-depth ratios of 6, 7, 9, 12 and 14, and three European steel grades S235, S275, and S355, with opening diameter and end distance parameterised and expressed by d_o/h and S/h . The response measures considered were M_y , M_c , M_u , $M_{0.04}$, and $M_{0.06}$, all normalised by the corresponding solid section reference. Across the database, the opening geometry primarily influences post-yield behaviour. The dispersion of the normalised yield moment is generally lower than that of the peak moment, while large openings combined with short end distances penalise M_c most severely, especially for stocky systems. As span-to-depth ratio increases, sensitivity to opening size reduces and the median $M_c/M_{c,FS}$ approaches 0.9 to 1.0. For the principal AISC 4% drift benchmark based on the full-section plastic moment, 6,927 of the 7,575 models satisfy $M_{0.04} \geq 0.8M_p$, while 648 fall below this threshold. These results indicate that the 4% drift requirement is generally achievable for moderate openings, but unfavourable combinations still exist and should be screened out in design. A broad corridor around $d_o/h \approx 0.30$ to 0.50 and $S/h \approx 0.80$ to 1.20 achieved universal compliance. At higher drift demand (6%), selected well-proportioned RWS geometries can exceed the solid section reference by improving post-peak stability, consistent with the intended redistribution of yielding. Overall, within a screened geometry range, RWS connections offer a viable and code-consistent option for seismic retrofitting of steel moment frames, provided that the RWS geometry is well proportioned. This conclusion is in agreement with earlier studies on fully restrained RWS connections [18] [19] [20].

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