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Reducing column-face demands in circular Reduced Web Section (RWS) connections

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Abstract

Brittle fracture in welded steel moment connections is often initiated by concentrated stresses and low-cycle strain demands at the column face, particularly in the groove weld and adjacent heat-affected zone. Circular reduced web section (RWS) openings can act as ductile fuses within the beam web and relocate inelasticity away from the beam-to-column interface when opening diameter and offset are properly proportioned. A validated three-dimensional finite element model is used to analyse 7,575 welded subassemblies covering IPE270 to IPE600 beams, steel grades S235 to S355, span-to-depth ratios $2L/h = 6$ to 14, and geometry ratios d_o/h and S/h . Two indicators are extracted from a defined column-face region: normalised von Mises stress η_σ and accumulated equivalent plastic strain PEEQ at column face. The results show that d_o/h dominates demand relocation. Column-face yielding is typically avoided for $d_o/h \geq 0.60$, while complete suppression of column-face plasticity (PEEQ at column face = 0) is achieved consistently for $d_o/h = 0.75$ with $S/h \approx 0.8$ to 1.4. These corridors provide a practical screening basis for circular RWS retrofit detailing.

Keywords

circular reduced web section, column-face demand, demand relocation, von Mises stress, equivalent plastic strain (PEEQ), seismic retrofitting, finite element analysis

1 Introduction

Brittle fracture in welded steel moment frames has been closely associated with severe inelastic straining at or near the column face, including the groove-weld region and adjacent heat-affected zones [1]. European retrofit guidance and assessment procedures promote mechanisms that shift plastic hinging away from the column face and develop stable rotation capacity in designated dissipative regions [2]. Qualification concepts based on storey drift angle demand and cyclic testing protocols are codified in modern seismic provisions [3], while prequalified connection families are documented separately for several connection types [4]. Following the 1994 Northridge earthquake, extensive research refined the understanding of steel moment connection damage and mitigation strategies [4]. Flange-reduction strategies such as Reduced Beam Section (RBS) connections are widely used and have been investigated in many configurations [4] [5] [6]. Circular RWS openings provide an alternative weakening strategy to relocate demand by mobilising Vierendeel action in tee-sections around the opening; the effectiveness of this mechanism depends on opening diameter and offset, which govern whether demand is relocated into the

reduced web region or remains concentrated at the column face [7] [8] [9]. Recent studies have similarly shown that opening size and offset govern cyclic strength retention, drift capacity, and the ability to confine inelasticity to a protected beam zone under AISC341-16 cyclic loading [10] [11]. While global moment-rotation response and energy dissipation indicate overall cyclic robustness, the present paper focuses on local demand at the column face quantified by von Mises stress and accumulated equivalent plastic strain (PEEQ). PEEQ index is a commonly used FE indicator of local plastic-strain demand and plastic-hinge location under cyclic loading [12] [13] [14]. Higher PEEQ at a given location indicates higher local inelastic strain demand and a greater propensity for tearing, damage, or permanent deformation in that region [14]. In parallel, column-face von Mises stress provides a complementary indicator of demand localisation. FEMA 350 further notes that when plastic hinging develops at the beam face adjacent to the column, the weld metal and surrounding heat-affected zone can be subjected to very high inelastic strain demands, which may promote brittle failure [1]. In the present study, PEEQ distributions and column-face von Mises stress are therefore examined to verify whether inelasticity initiates within the intended protected zone of the beam, away from the column face, thereby limiting

inelastic demand on welds and other fracture-sensitive components. Accordingly, suitable combinations of opening diameter (d_o) and distance from the column face (S), shown in Figure 1, are expected to suppress inelastic action at the beam-to-column interface and result in low PEEQ values at the column face (CF).

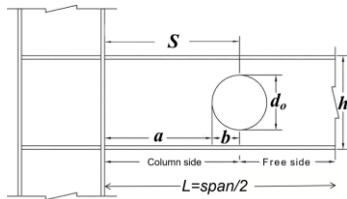


Figure 1 Circular RWS geometry and definition of non-dimensional parameters d_o/h , S/h and $2L/h$.

2 Numerical framework and FE database outline

The FE framework was verified against five full-scale cyclic subassemblies reported in the literature, including three WUF-W moment connection tests of different scales (DC-S, DC-M, DC-L), for each one, two identical specimens were tested by Saneei Nia et al. [13]. Similarly, Davarpanah et al. investigated the cyclic performance of fully welded RWS connections incorporating elliptical web openings. Two identical specimens, denoted HE-RWS-1 [14] and HE-RWS-2 [15], were tested. HE-RWS-1 was subjected to the standard AISC 341-16 loading protocol [3], while HE-RWS-2 was examined under an extended AISC 341-16 protocol plus two additional cycles at 7% drift. Details of these connections, along with test set-up for the experimental programme are illustrated in Figure 2.

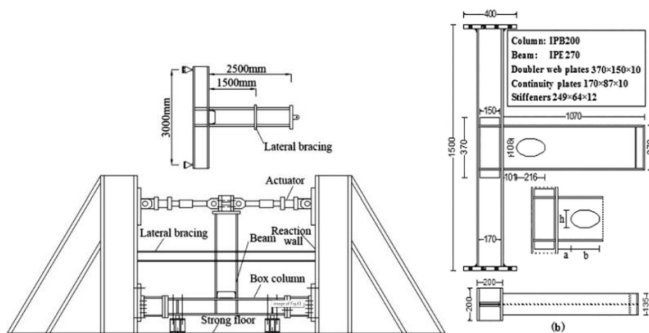


Figure 2 (Left) DC-S, DC-M, and DC-L test setup experiments [13]. (Right) HE-RWS-1 and HE-RWS-2 test set-up [15].

2.1 Finite element model

A three-dimensional solid finite-element (FE) representation of a welded beam-to-column subassembly was developed in ABAQUS/Standard. To isolate the influence of the RWS geometry on cyclic flexural response, the column and panel zone were idealised as rigid, and the beam end was fully restrained at the column face. This produces a conservative upper bound on plastic rotations and drift demands by eliminating any beneficial effect the panel zone could have on drift capacity, consistent with other studies [16] [17] [18] [19]. This ensures that changes in response are due to alterations in RWS geometry, providing clear insights into its behaviour under seismic cyclic loading. Lateral restraints were provided at the loading and support points to suppress out-of-plane instability. The true stress-strain relationship used in the finite element analyses of

this study was derived by converting the experimental engineering stress-strain data. Additionally, the steel behaviour of the DCS, DCM, DCL, and HE-RWS-1 assemblies is modelled using a trilinear stress-strain relationship, while the HE-RWS-2 assembly is modelled using a multilinear stress-strain relationship. The isotropic component was defined using these monotonic data, and the kinematic component was automatically calibrated in Abaqus via the Half Cycle method, which derives the Chaboche backstress parameters from the initial unloading-reloading branch (ABAQUS v6.6, Section 18.2.2). This standard combined hardening formulation captures cyclic effects such as the Bauschinger phenomenon. The same approach is used later in this study for the parametric analysis, supplemented by values found in the literature to describe other behavioural phenomena. Twenty-node reduced-integration brick elements (C3D20R) were used globally with a maximum element size of 20 mm, while ten-node tetrahedral elements (C3D10) with 10 mm sizing were adopted locally around the opening to capture curvature and local buckling. Welds were represented using tie constraints; accordingly, the weld metal and the heat-affected zone were not modelled as separate material regions, and direct crack initiation or propagation in those regions is outside the scope of the present model. Instead, within the validated framework, column-face PEEQ is used as an indicator of local plastic-strain demand and plastic-hinge location [12] [13] [14], while column-face von Mises stress provides a complementary indicator of demand localisation. Higher PEEQ is associated with greater tearing-prone demand [14], and FEMA 350 notes that plastic hinging at the beam face can impose very high inelastic strain demands on the weld metal and adjacent heat-affected zone [1]. Accordingly, low column-face PEEQ and low von Mises stress, including the weld-access-hole vicinity, are interpreted here as surrogate indicators that inelasticity has been shifted into the reduced web protected zone and away from fracture-sensitive weld and heat-affected-zone regions. Initial geometric imperfections were introduced from the first eigenmode of an elastic buckling analysis, scaled to $t_w/200$, as adopted in related research [7] [20] [21]. Geometric nonlinearity was included. The cyclic loading history followed the qualification-style protocol in AISC 341 [3] depicted in Figure 3. Figure 4 shows the general finite-element model used in this numerical study.

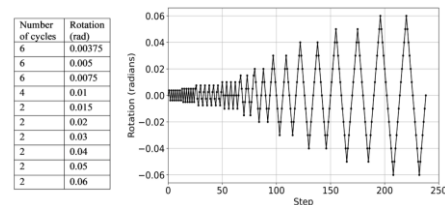


Figure 3 AISC 341 loading protocol [3] with incrementing q in steps of 0.01 radians, recommended by FEMA 350 [1].

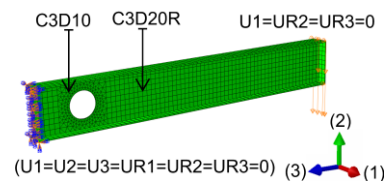


Figure 4 Typical FEM considered in this study

2.2 FE model validation

Figure 5 to 9 compare the hysteretic curves predicted by the finite-element model employed in this study with experimental results for DC-S, DC-M, DC-L, HE-RWS-1, and HE-RWS-2. In all validation plots, the current FEM results are represented by the black curves.

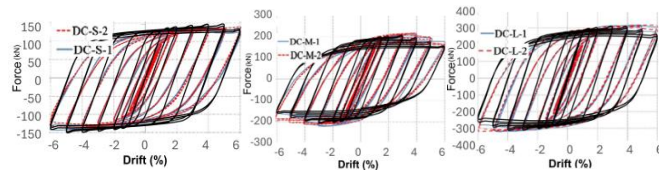


Figure 5 DC-S

Figure 6 DC-M

Figure 7 DC-L

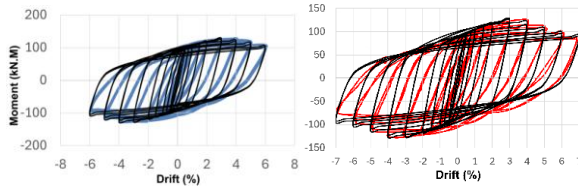


Figure 8 HE-RWS-1

Figure 9 HE-RWS-2

In addition to the global response, the numerical model was checked against local deformations. Figure 10 and Figure 11 compare the experimentally observed deformation patterns with the FE contours at similar drift levels. Consistent with the tests, the FE model reproduces the Vierendeel mechanism around the circular opening, with 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 .

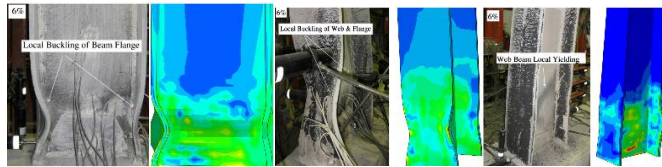


Figure 10 Experimental photographs adapted from Saneei Nia et al. [13] and corresponding FE deformation and von Mises patterns of DC specimens at 6% drift: DC-S, DC-M and DC-L.

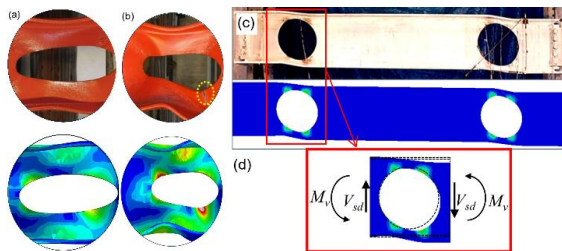


Figure 11 Experimental deformation patterns and corresponding PEEQ contours: (a) HE-RWS-1 at 6% drift [14]; (b) HE-RWS-2 at 7% drift [15]; and (c) Specimen 1 at 4% drift [8].

Implemented using an automated 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. [8] 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 [22] [23] [15] [24], 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 goal of this study is to understand how geometric parameters ($2L/h$, S/h and d_o/h), material properties (steel grade), and beam profile (IPE sections) influence moment capacity expressed as yield moment (M_y), peak moment (M_c), Ultimate moment (M_u), and moment capacity at 4% ($M_{(0.04)}$) and at 6% drifts ($M_{(0.06)}$) as well as AISC 358 prequalification criteria. European steel grades S235, S275, and S355 were adopted for the parametric study, based on the comprehensive experimental database obtained in [25], and the values presented in Table 1 represent the mean values derived from this dataset.

Table 1 Mechanical properties of steel grades S235, S275, and S355 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 [3].

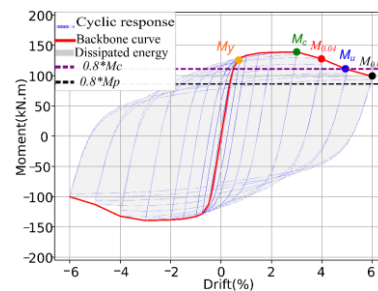


Figure 12 Schematic representation for characterising the responses

3.1 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

$(S/h)_{\%}$	$(d_o/h)_{\%}$									
	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

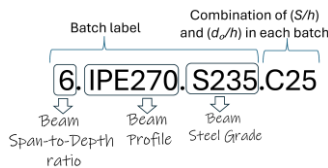


Figure 13 Specimen classification

4 Column-face demand indicators and demand-reduction measures

Two finite element response quantities are used to characterise demand localisation at the column face: von Mises equivalent stress and the equivalent plastic strain (PEEQ). Both are evaluated within a defined column-face region adjacent to the beam-to-column interface, including the vicinity of the weld access hole. Demand-reduction factors are expressed relative to the solid-web reference specimen in each batch: $r_{\sigma} = \sigma_{vm,CF} / \sigma_{vm,CF,FS}$ and $r_{\epsilon} = PEEQ_{CF} / PEEQ_{CF,FS}$. Values below unity indicate demand reduction, while $r_{\epsilon} = 0$ corresponds to a fully elastic column-face response under the imposed cyclic history.

4.1 Normalised von Mises and PEEQ_{CF} ratio

Von Mises stress in the column-face region, $\sigma_{vm,CF}$, is normalised by the nominal yield strength F_y to define $\eta_{\sigma} = \sigma_{vm,CF} / F_y$. Values $\eta_{\sigma} > 1$ indicate yielding at or near the column face, including the weld access-hole vicinity. Such response is contrary to the intended mechanism of relocating inelasticity into a ductile beam region away from the beam-to-column interface. Representative η_{σ} heatmaps across the investigated opening-geometry space are shown in Figure 14.

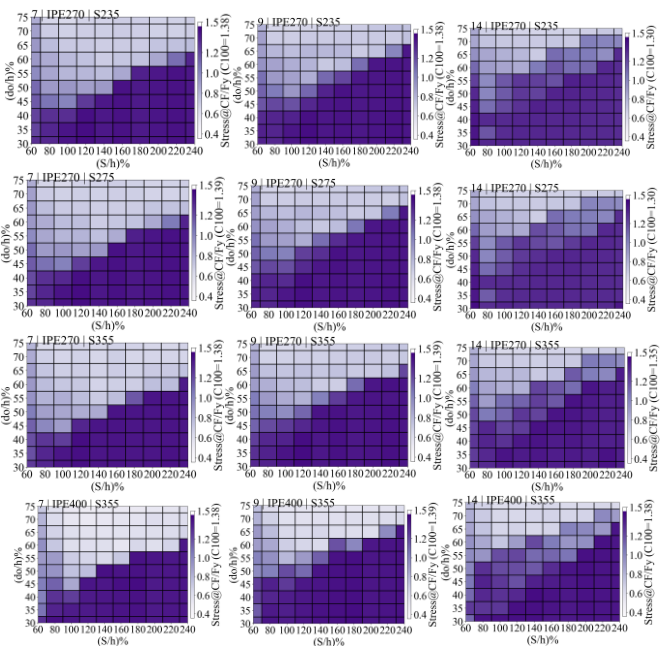


Figure 14 Representative heatmaps of η_{σ} response, illustrating

sensitivity to d_o/h and S/h , with secondary modulation by $2L/h$, steel grade, and beam profile.

Maximum accumulated PEEQ in the column-face region, $PEEQ_{CF}$, quantifies plastic strain accumulation. A strict no-plasticity criterion $PEEQ_{CF} = 0$ is adopted to identify geometries that keep the column face elastic throughout the imposed cyclic history. Across the database, $PEEQ_{CF}$ was observed to decrease sharply with increasing d_o/h , consistent with relocation of the plastic hinge into the reduced web region. Similarly, as shown in Figure 15, d_o/h governs column-face plasticity far more strongly than S/h , with $PEEQ_{CF}$ decreasing sharply as d_o/h increases and approaching zero for the largest openings (typically $d_o/h \approx 0.70$ to 0.75), indicating effective relocation of the plastic hinge into the reduced web region. For intermediate opening sizes (approximately $d_o/h = 0.55$ to 0.65), S/h provides secondary modulation, where moderate offsets ($S/h \approx 0.8$ to 1.4) minimise $PEEQ_{CF}$, whereas large offsets ($S/h \geq 1.8$) can produce localised pockets of elevated $PEEQ_{CF}$, and increasing $2L/h$ and section depth generally reduce the overall demand level.

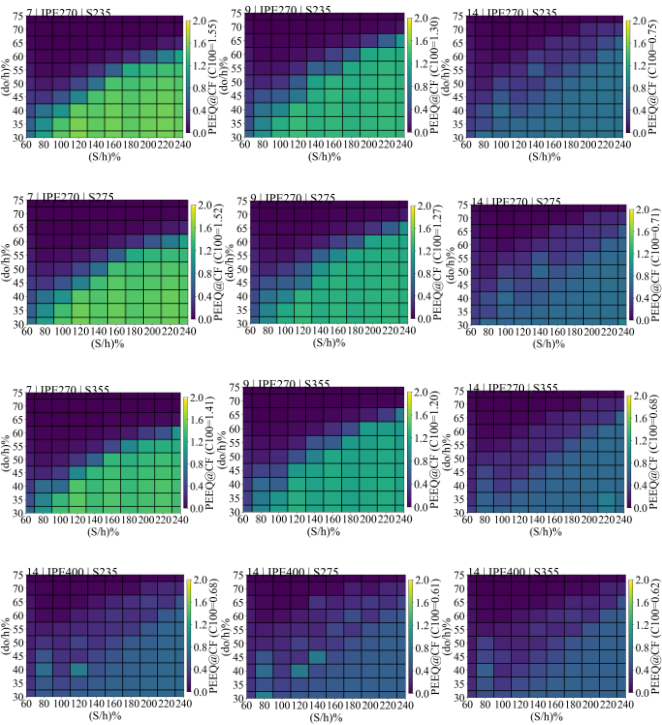


Figure 15 Representative heatmaps of $PEEQ_{CF}$, illustrating sensitivity to d_o/h and S/h , $2L/h$, beam profile and beam steel grade.

Taken together, the η_{σ} and $PEEQ_{CF}$ indicators provide a rational screening basis for verifying whether demand is effectively relocated away from the beam-to-column interface.

4.1.1 Mean stress patterns and response contour maps across all batches of analyses

Mean demand patterns indicate that d_o/h governs column-face stress reduction, while S/h modulates local peaks. Small openings provide limited stress relocation, whereas larger openings activate Vierendeel action and shift demand into the reduced web region. Database-wide mean column-face stress contours across the geometry space are shown in Figure 16.

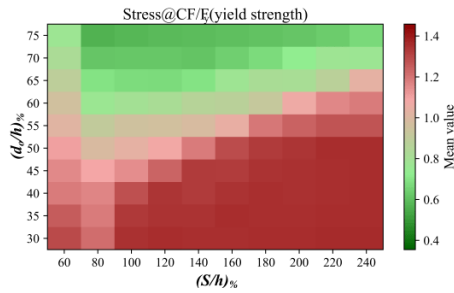


Figure 16 Von Mises stress ratio at the column face ($\eta_\sigma = \sigma_{vm,CF}/F_y$). Green indicates sub-yield demand and red indicates yielding at the column face.

The strict no-plasticity screen $PEEQ_{CF}=0$ is satisfied by 14.9% of the database and occurs only for $d_o/h \geq 0.60$. Full (100%) satisfaction is achieved for $d_o/h=0.75$ combined with S/h in the range 0.8 to 1.4, where η_σ remains well below unity (median $\eta_\sigma \approx 0.60$). A relaxed numerical tolerance $PEEQ_{CF} \leq 0.02$ was also considered. Under this tolerance, the protection corridor expands from $d_o/h=0.75$, $S/h=0.8-1.4$ to include $d_o/h=0.70$ with $S/h=0.8-1.2$.

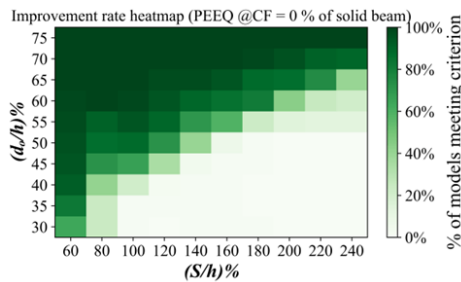


Figure 17 Improvement-rate heatmap for column-face protection: percentage of models with $PEEQ_{CF} = 0$.

As shown in Figure 18, the database-wide median $PEEQ_{CF}$ is high for $d_o/h \leq 0.50$ irrespective of S/h but decreases sharply for $d_o/h \geq 0.60$ and is near-zero for $d_o/h=0.70$ to 0.75 with $S/h \approx 0.8$ to 1.4. For intermediate openings ($d_o/h \approx 0.55$ to 0.65), very large offsets ($S/h \geq 1.8$) increase $PEEQ_{CF}$ and reduce column-face protection.

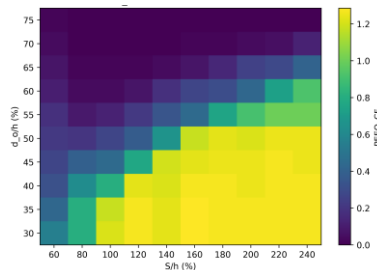


Figure 18 Database-wide median $PEEQ_{CF}$ at the column face (all batches) mapped over d_o/h and S/h .

5 Trade-offs with cyclic strength

Reduction of column-face demands should not be achieved at the expense of global cyclic robustness. Accordingly, column-face screening is most effective when applied alongside global acceptance checks (for example, strength retention at 0.04 rad) and complementary cyclic energy measures. Within the database, a limited subset of deep-section, long-span configurations (for example, IPE600 with $2L/h=14$ in S355) was observed to achieve simultaneous column-face protection and enhanced cumulative energy dissipation. In these cases, ($PEEQ_{CF}=0$ and

$r_o \leq 0.71$) coincided with $E_{cum}/E_{cum,FS} > 1$ (up to ≈ 1.15), albeit with a reduction in peak strength, expressed by $M_c/M_{c,FS} \approx 0.75$ to 0.83. However, only 8 out of 7,575 models (0.11%) achieved $E_{cum}/E_{cum,FS} > 1$ while maintaining $PEEQ_{CF} = 0$, all within the IPE600, S355, $2L/h=14$ subset. Figure 19 compares the solid-web reference (C100) with two representative circular RWS configurations for IPE600, S235, and $2L/h = 14$. Configuration C92 reduces column-face demand but also lowers peak moment and cumulative energy dissipation relative to C100. By contrast, C48 retains a stronger global cyclic response, but at the expense of higher column-face demand. This comparison highlights the trade-off between local demand reduction and global cyclic robustness.

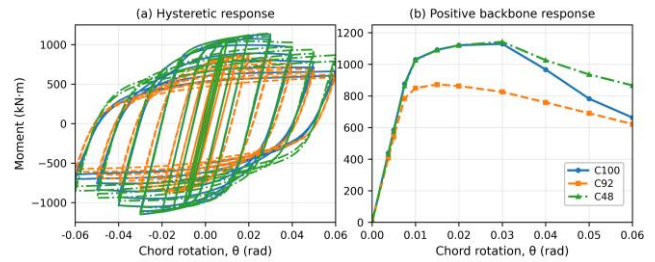


Figure 19 Representative cyclic response for IPE600, S235, and $2L/h=14$: (a) hysteretic response and (b) positive backbone response for the solid-web reference (C100) and two circular RWS configurations (C92 and C48).

6 Conclusions

Column-face demand reduction in circular RWS connections has been quantified using yield-normalised von Mises stress and accumulated equivalent plastic strain indicators. Improvement-rate maps and demand distributions identify geometry corridors that support capacity-design intent to relocate yielding away from the welded beam-to-column interface. The proposed indicators provide a practical basis for screening for circular RWS retrofit details. The results support a practical screening sequence for circular RWS geometries aimed at protecting the column face. Mean demand patterns across all batches of analyses indicate that d_o/h governs column-face stress reduction, while S/h modulates local peaks. Small openings provide limited stress relocation, whereas larger openings activate Vierendeel action and shift demand into the reduced web region. In addition, the opening ratio d_o/h was observed to be the dominant demand reduction variable, with $\eta_\sigma \leq 1$ typically achieved for $d_o/h \geq 0.60$, while more stringent suppression of inelasticity at the column face required larger openings, most consistently at $d_o/h \geq 0.70$. Demand control was ensured by enforcing $\eta_\sigma \leq 1$ at the target drift level, indicating that yielding at the column face can be avoided when this criterion is satisfied. Where weld protection is critical, complete suppression of local inelasticity, expressed as $PEEQ_{CF}=0$, was observed robustly for $d_o/h=0.75$ with S/h approximately 0.8 to 1.4, and with high likelihood for d_o/h around 0.70 at S/h close to 1.0. Substantial stress reduction was also demonstrated when $r_o \leq 0.71$, corresponding to roughly a 29% reduction relative to the solid web reference. The offset ratio S/h was found to provide a secondary means of shaping demand patterns and accommodating service penetrations, with moderate offsets (S/h approximately 0.8 to 1.4) generally favourable, although offset alone was not sufficient to

guarantee column face protection. Finally, the findings indicate that local demand reduction should be accompanied by verification of global cyclic acceptance, including strength retention, stability, and energy dissipation, to mitigate premature deterioration elsewhere in the connection.

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