FEA Validation on the Degree of Composite Action of Composite Reduced Web Section (RWS) Connections under Cyclic Loading

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ABSTRACT
This study is part of a large research campaign that studies experimentally and numerically the effect of the degree of composite action to the performance of the extended end-plate RWS connections. The experimental tests involve full-scale testing of three composite connection specimens using demountable bolted shear studs subjected to cyclic loads with positive and negative bending moments. This paper presents detailed FE models capable of simulating the behaviour of the experimental test. Validated models were used for a parametric study, the aim of which is to better understand composite bolted RWS connections with demountable bolted shear studs under cyclic loadings. Based on the results, it is apparent that the composite RWS connections can also be employed, alike bare steel RWS connections, to improve the seismic performance of steel structures engaging the strong column – weak beam approach, despite the type of shear studs and the local strengthening in the vicinity of the web opening due to the concrete slab, which is the opposite of the web reduction locally.

KEYWORDS
RWS connections; Seismic-resistant MRF; Composite action, Metal Deck; Demountable Shear Studs; Ductility.

1 INTRODUCTION

The Reduced Web Section (aka RWS) connection where the material is reduced from the web of the beam has been proven to function as ductile fuses under seismic loading, while limiting out-of-plane movements that found in RBS connections [1]–[15]. In seismic applications, the main purpose of RWS connections is to develop a ductile Vierendeel mechanism by localising the failure to the yielding and buckling of the Tee sections within the web opening while keep other members of moment-resisting frames (MRFs) in elastic state. A Vierendeel Mechanism

(VM) induces additional rotation at the joint, thereby enhancing the ductility and energy dissipation in MRFs. Recent experimental and FE campaign on composite RWS connections have indicated that the VM could be triggered when the perforation is located in a high shear region [5], [6]. However, the efficiency of RWS connections depend on both the size and location of the web opening to fully exploit the benefits of the VM which also complies with the strong column weak beam concept [1]–[6], [8]–[15].
The literature review revealed the lack of experimental data on steel-concrete composite RWS connections. Well-validated finite element analysis (FEA) provides a reliable method to further investigate their seismic behaviour. The objective of this paper is to develop a comprehensive parametric FE study to analyse the effect of the presence/absence of bolted shear studs (composite action) over the web opening on the behaviour of steel-concrete composite RWS connections subjected to cyclic loading. It is worth noting that the low composite action means the absence of bolted shear studs (composite action) over the web opening. All composite RWS connections in this study complied with SCI-P355 [16] and SCI-P428 [17].

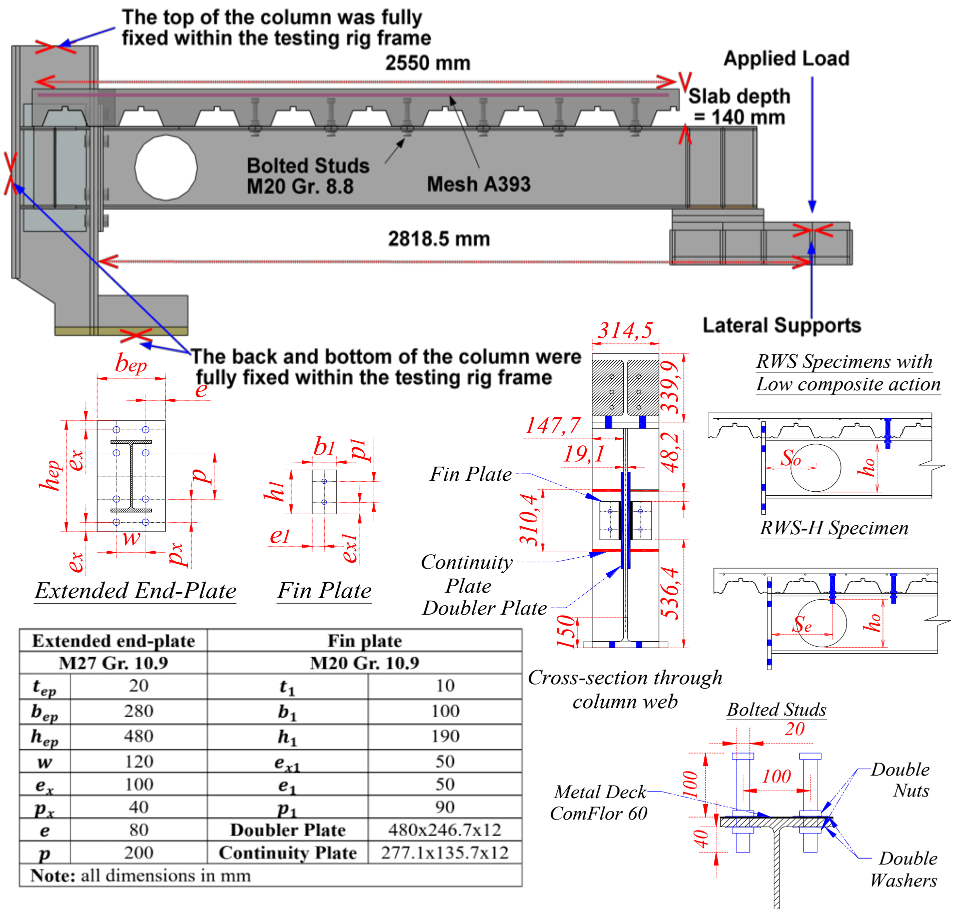
2 VALIDATION OF FINITE ELEMENT MODEL

The FE models were initially modelled using ABAQUS [18] to simulate the findings of two identical demountable steel-concrete composite connections in terms of sizes and material connections (Table 1 and Fig. 1) [6]. The difference between the two identical composite connections was the presence of composite action above the web opening as illustrated in Table 1. The boundary and loading conditions including the gravity load and bolts preloading, were assigned in FE models to simulate the ones in the experimental tests [6]. The AISC-341 loading protocol under displacement control was followed [19]. Solid elements (C3D8R) for concrete slab, bolts, and bolted shear studs were adopted to model the experimental tests [6]. Shell (S4R) and truss elements (T3D2) were adopted for all other elements and for the reinforcement steel bars, respectively.
Eigen buckling analysis was initially performed in order to introduce a geometric imperfection and scaled by the recommended factor of $t_w/200$ in accordance with [20]. Material nonlinearity was adopted by using a trilinear stress-strain relation with a combined material-hardening model from ABAQUS [18] for all steel elements including bolts and bolted studs. A bilinear stress-strain relation was adopted for metal deck and steel reinforcements. The nominal values of materials properties were taken from the manufacture's specifications for steel, except the beam web and flange, the average values of coupon tests were considered. The ultimate strains (ε_u) were equal to $15\varepsilon_y$ and $10\varepsilon_y$ for steel elements and bolts, respectively. The ultimate strain of bolted shear studs was equal to $10\varepsilon_y$ as well. The rupture strain (ε_r) was set to 0.2 for all steel elements and to 0.05 for the bolts and bolted shear studs. The ductile damage option was applied from ABAQUS [18] to consider the cracks' effect that developed in the vicinity of the web opening during the experimental tests [6]. Concrete damaged plasticity model was utilised for concrete using the constitutive law of EC2 [21] and the exponential tension softening model [22] to replicate the concrete crushing and cracking, respectively. The compression cylinder tests were considered for concrete with the axial tensile strength f_t was assumed as 10% of compressive strength of f_{ck} 31.28 MPa [23].

Specimen ID	RWS-L	RWS-H
1) Diameter d_o and 2) End-distance S_o	1) $0.8h$ and 2) $0.8h$	
1) Primary and secondary beams and 2) Column	305x165 UB 54 - 305x305 UC 198	
Bolts - M27 Gr. 10.9 and	Preloading force of 321kN	
Slab with ComFlor 60 Metal deck	Thickness = 140 mm and width = 1250mm	
Two rows of bolted shear Studs - M20x160mm - Gr. 8.8 -	Preloading force of 40kN	
# of lines of bolted shear studs	6	7

Note: All connections are extended end-plate. Low (L) = low composite action where the studs are avoided over the protected zone. High (H) = high composite action where the studs are placed over the protected zone.

Table 1: Specimen test matrix [6].



Extended end-plate		Fin plate	
M27 Gr. 10.9		M20 Gr. 10.9	
t_{ep}	20	t_1	10
b_{ep}	280	b_1	100
h_{ep}	480	h_1	190
w	120	e_{x1}	50
e_x	100	e_1	50
p_x	40	p_1	90
e	80	**Doubler Plate**	480x246.7x12
p	200	**Continuity Plate**	277.1x135.7x12
Note: all dimensions in mm			

Fig. 1: Dimensions of test specimens (mm) [6].

2.1 Results of FE Model and Comparison with Experimental Test

The moment-rotation hysteretic curves at the column face, obtained from the FE analysis were compared against the ones in the experimental test [6] as shown in Fig. 2. The initial positive and negative stiffnesses, as well as the plastic behaviours compare well between the experimental tests and the FE models. The maximum sagging and hogging moments in the RWS-L test were +339.4 kNm and -293.4 kNm at 0.03 rad and -0.04 rad, respectively. At the same rotations, they were +319 kNm and -293.5 kNm, respectively, in FEA. The difference was around 6% and 0.04% in sagging and hogging moments, respectively. For RWS-H test and FE model, the maximum sagging moments were +328.7 kNm and +318.6 kNm, respectively. While the maximum hogging moments were -290.2 kNm for RWS-H test and -301.8 kNm for FE RWS-H model. The differences were 3.1% in sagging and 4% in hogging moments. The FE models showed similar performance to the experimental tests in terms yielding, stiffness degradation, and energy dissipation (Fig. 2) as well as the failure modes as shown in Fig. 3.

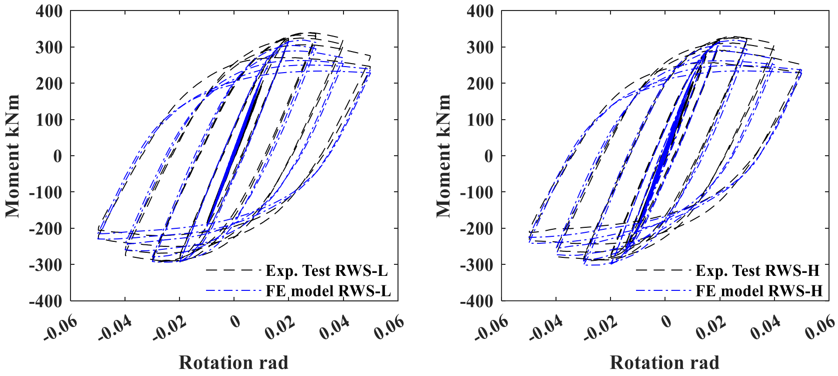


Fig. 2: Comparing between FE and experimental results.

a) Failure of RWS-L *b) Failures of RWS-H* *c) Failures of Studs in RWS-H*

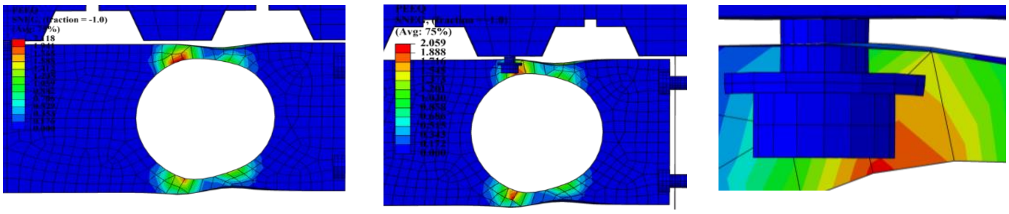


Fig. 3: Comparison between tests and FE models.

3 PARAMETRIC STUDY

FE models were employed to conduct the parametric study and examine the effect of the presence of composite action on the performance of steel-concrete composite BEEP/RWS connections subjected to cyclic loading. A total of 16 models were considered in this FE parametric study. In detail, circular web openings with eight diameters d_o equal to $0.5h$, $0.55h$, $0.60h$, $0.65h$, $0.7h$, $0.72h$, $0.75h$ and $0.8h$ (where h is the steel beam section height) were examined herein. The end-distance S_o was kept constant, equal to S_o = $0.8h$ to identify the effects of composite action with different diameters. The presence and absence of composite action over the web opening were studied. A 25 mm gap between steel parts and concrete slab were provided for all models similar to the validated experimental tests [6] in this study and according to EC8 [24].

3.1 Discussion

The Ibaraa-Medina-Krawinkler (IMK) [25] model was employed to define the hysteresis characteristic points as shown in Fig. 4. The plastic moment strength of the connection ($\boldsymbol{M_{j,Rd}} = \boldsymbol{M_{ye}}$) is defined as the point of intersection where the tangent line drawn at the point of maximum moment strength ($\boldsymbol{M_{m,Rd}} = \boldsymbol{M_m}$) intersects with the line representing the initial stiffness. $\boldsymbol{M_{j,Rd}}$ and $\boldsymbol{M_{m,Rd}}$ are compared to the applied moments at column face ($\boldsymbol{M_f}$) from parametric FE models. The difference between $\boldsymbol{M_{m,Rd}}$ and $\boldsymbol{M_{j,Rd}}$, is considered as the additional capacity developed by the connection due to strain hardening.

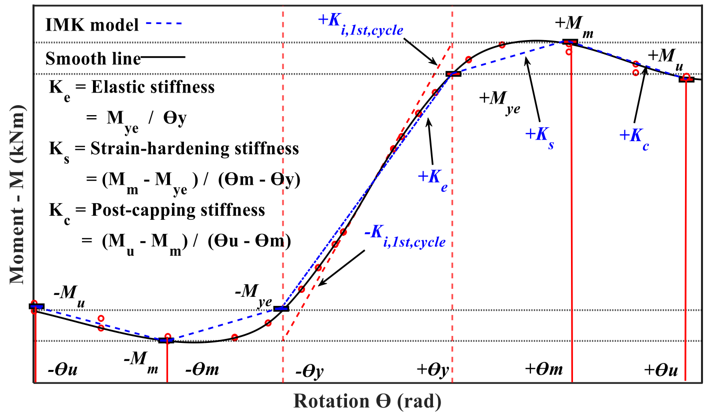


Fig. 4: Backbone curve for hysteretic models using IMK

All RWS models were designed based on the nominal plastic bending capacity $\boldsymbol{M_{pl,a,Rd}}$, of the connected steel solid-webbed beam of a partial-strength connection, without considering the composite action contribution according to EC3, EC4, and EC8 [24], [26]–[28]. Thus, the incorporation of web opening alters the strength category of the connection from partial to full-strength due to the reduced section. In partial-strength connections, the deformations occur in the connection, which lead to the pinching effect associated with the development of the gap between the end-plate and column flange [29]. In Fig. 5, it can be seen that the pinching phenomenon occurred in models with diameters equal to $0.5h$, $0.55h$, $0.60h$, and $0.65h$. Moreover, it has been noticed that when the diameter increased the pinching effects were vanished. This is in line with the findings of Almutairi et al. [5] that proved the efficiency of the incorporation of a web opening to alter the strength category and make the reduced section in the beam the main element to dissipate the energy by developing the plasticity. Table 2 also demonstrates the effect of the web opening as the strength ratio of $\boldsymbol{M_{j,Rd}/\ M_{pl,a,Rd}}$ decreases with the increase of the diameter.

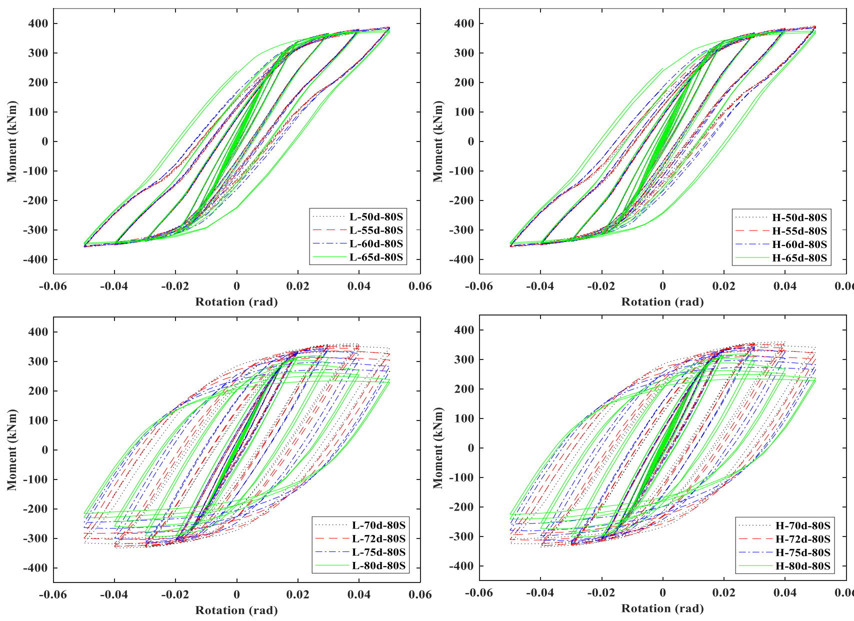


Fig. 5: Moment-Rotation curves for all FE models.

The increase of web opening into the beam enhanced the ductility of the connection compared to the solid-webbed beam connections. The ductility ratios of the solid-webbed beam connections ranged between 3.38 to 3.63 under sagging and 3.48 to 3.78 under hogging. All RWS and solid-webbed connections reached the ultimate rotation of 0.05 rad in both directions. Therefore, the ductility relies on the yielding rotation of the connections, as earlier yielding results in higher ductility. Table 2 and Fig. 5 demonstrate not only the relationship between the increase in the web opening diameter and the elimination of pinching phenomenon, but also the increase of the ductility. The increase in the diameter leads to the increase in the ductility due to the early yielding in the beam Tee sections in the vicinity of the web opening. The yielding is caused due to the efficiency of large web openings in developing four plastic hinges around the web opening. This is in line with what found in the literature [1]–[15], that shows the ability of medium to large opening in developing VM. However, the studies of Shaheen et al. [7] and Almutairi et al. [5] showed the benefit of using small to medium opening in improving the connections in certain cases. These cases are when: i) when high "degree" of composite action near the connection is present [7] and ii) when the strength ratio of $\boldsymbol{M_{j,Rd}/\ M_{pl,a,Rd}}$ needs to be changed due to unaccounted composite slab contribution [5].
The use of composite slabs affects positively the performance of RWS connections in providing lateral stability to the beams. Table 2 shows the contribution of the composite slab to the overall strength of the connections under sagging, unlike when the connection is under hogging. This was expected as the top section of the composite beam is under compression is the latter case. However, the maximum capacities of the connections were similar between the RWS models with and without bolted studs over the plastic zone (web opening) as shown in Table 2 and Fig. 6. This was due to the elimination of contact between the concrete slabs and the extended end-plates and columns (i.e., 25mm gap) in all models. This 25 mm gap withholds the force transfer from concrete slab to the extended end-plates and columns. Thus, the extra row of bolted shear studs that provided in the RWS connections with high composite action, has no effect on the overall strength of the connection. However, it had an impact on other aspects such as ductility in which the presence of composite action led to an early yielding. Finally, Fig. 6 shows that when the diameter increases, the strength degradation becomes visible.

Models	$\boldsymbol{M_{j,Rd}/M_{pl,a,Rd}}$		**Ductility** $\boldsymbol{\theta_u/\theta_y}$		**Max composite contribution**	
	+ve	**-ve**	**+ve**	**-ve**	**+ve**	**-ve**
H-50d-80S	0.97	-0.89	3.57	3.71	1.06	0.98
L-50d-80S	1.00	-0.92	3.35	3.44	1.05	0.98
H-55d-80S	0.97	-0.89	3.56	3.69	1.05	0.98
L-55d-80S	1.00	-0.92	3.33	3.43	1.05	0.98
H-60d-80S	0.97	-0.89	3.56	3.69	1.05	0.97
L-60d-80S	1.00	-0.92	3.34	3.43	1.04	0.97
H-65d-80S	0.94	-0.88	3.64	3.72	1.03	0.97
L-65d-80S	0.98	-0.90	3.40	3.47	1.04	0.97
H-70d-80S	0.92	-0.86	3.75	3.79	1.03	0.98
L-70d-80S	0.95	-0.88	3.51	3.59	1.03	0.97
H-72d-80S	0.91	-0.85	3.79	3.82	1.02	0.98
L-72d-80S	0.94	-0.87	3.56	3.63	1.03	0.97
H-75d-80S	0.89	-0.83	3.87	3.87	1.03	0.99
L-75d-80S	0.92	-0.85	3.63	3.69	1.03	0.98
H-80d-80S	0.84	-0.79	4.06	4.03	1.04	1.01
L-80d-80S	0.85	-0.79	3.83	3.90	1.04	0.98

Note: $M_{pl,a,Rd}$ = nominal plastic bending capacity for steel solid-webbed section. Max composite contribution = $M_{m,Rd,RWS,comp}$ / $M_{m,Rd,RWS,non-comp}$. Non-composite FE models' results were not included in this table due to the page limitation.

Table 2: Summary of FE results.

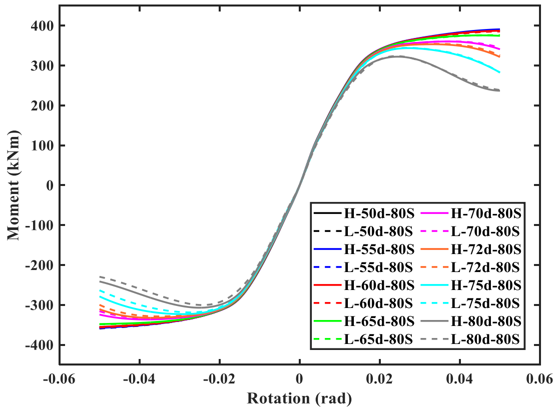


Fig. 6: Skeleton curves for all FE models.

4 CONCLUDING REMARKS

Based on this study and the previous research campaign carried out by the group [5]–[7], the following conclusions can be drawn:

- Composite RWS connections behave in an acceptable manner and provide an ideal structural performance in terms of stress distribution under cyclic loading without significantly compromising the connection capacity, providing that a suitable location for the web opening is chosen.
- The composite action should be considered in the design of RWS connections, as it plays a critical role in the seismic performance.
- When the web opening diameter of the RWS connections is increased the pinching effects were vanished.
- When the web opening diameter of the RWS connections is increased, the strength degradation becomes visible.

In conclusion, the results of the study of extended endplate RWS systems could be used in retrofitting existing as well as in constructing new buildings located within seismic zones.

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ΣΥΝΟΨΗ
Η μελέτη αποτελεί μέρος ενός μεγαλύτερου ερευνητικού έργου που εξετάζει πειραματικά και με μοντέλα προσομοίωσης την επίδραση του βαθμού σύνδεσης μεταξύ μεταλλικής δοκού και της σύμμικτης πλάκας στην απόδοση των κοχλιωτών συνδέσεων με διάτρητη δοκό (γνωστές και ως RWS συνδέσεις). Οι πειραματικές δοκιμές περιλαμβάνουν τρία δοκίμια στα οποία νέα ελάσματα διάτμησης από αποσυναρμολογούμενα μπουλόνια χρησιμοποιήθηκαν. Τα δοκίμια υποβλήθηκαν σε κυκλικά φορτία με θετικές και αρνητικές ροπές κάμψης. Αυτή η εργασία παρουσιάζει τα μοντέλα πεπερασμένων στοιχείων που είναι ικανά να προσομοιώσουν τη συμπεριφορά της πειραματικής δοκιμής. Με βάση τα αποτελέσματα, είναι προφανές ότι οι συνδέσεις RWS με σύμμικτες πλάκες μπορούν επίσης να χρησιμοποιηθούν, όπως και οι συνδέσεις RWS από χάλυβα μόνο, για τη βελτίωση της σεισμικής απόδοσης των μεταλλικών κατασκευών που σχεδιάζονται με την προσέγγιση ‛ισχυρού υποστυλώματος - ασθενούς δοκού’, παρά τον νέο τύπο των ελασμάτων διάτμησης και την τοπική ενίσχυση στην περιοχή του ανοίγματος του κορμού της δοκού λόγω της σύμμικτης πλάκας, που είναι ως αρχή ενάντια στην μείωση της δοκού τοπικά.

KEYWORDS
RWS connections; Seismic-resistant MRF; Composite action, Metal Deck; Demountable Shear Studs; Ductility.