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The Effect of Degree of Composite Action on RWS Connections Subject to Cyclic Loading

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Abstract. Concerns have been raised over the presence of concrete slab and resulting composite action in jeopardising the concept of strong column and weak beam seismic design. This comprehensive finite element analysis (FEA) aims to study the effect of the degree of composite action and other two parameters; namely, size and location of the web opening, on the performance of steel-concrete composite extended end-plate RWS connections subjected to cyclic loading. It is apparent that the degree of composite action of RWS connections is an important factor in their seismic-resistant design. In particular, the low degree of composite action in RWS connections can result in the mitigation of the bottom flange fracture damage and the crushing and cracking of the concrete slab. It is concluded that extended end-plate RWS connections can be used in retrofitting existing and in new buildings in seismic areas.

Keywords: RWS connections; Seismic-resistant MRF; Composite action, Concrete slab; Ductility.

1 Introduction

Extensive studies have been conducted on the seismic performance of steel beam-to-column reduced web section (RWS) connections as shown in Fig. 1, where the material is reduced from the web, have been proven to have satisfactory aseismic performance, limiting out-of-plane movements that found in RBS connections [1]–[6] and economic benefits in terms of both fabrication and maintenance. An additional benefit of RWS connections is the onset of Vierendeel mechanism due to the shear force transfer across the opening [7] which results in secondary moments (Vierendeel moments) and thus dissipates energy. This mechanism also introduces additional rotation which leads to the increase of the ductility and local deformation of connection [7]. However, the literature review revealed concerns over the presence of composite slab leading to poor seismic performance of RWS beam-to-column connections [8]–[10]. The higher bending moment capacity that is developed by a composite beam, and the asymmetric behaviour that depends on the direction of the moment, jeopardise the concept of strong column and weak beam seismic design, which deserves further investigation. That could lead to the strengthening rather than weakening of the beam and the premature fracture of the bottom beam flange due to the increase in the strain demand on the bottom flange due to shift of neutral axis [9] [10].

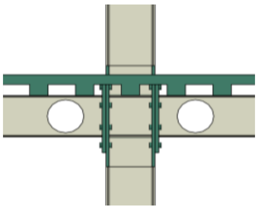

Fig. 1: Reduced Web Section

Studies of [9] [10] have concluded that the concrete slab with high composite action kept contributing to the strength of the connection even when the slab is crushed and cracked. On the other hand, several studies on the haunch and RBS connections with a low degree of composite action showed little negative impacts of the composite action and alleviate strength degradation as well as the strain demand on the beam bottom flange [11], [12]. The literature review however revealed the lack of experimental and FE studies of steel-concrete composite RWS connections. The ones that do exist [5] [9], demonstrated that composite action should be considered due to its effect and confirmed the contribution of composite action in the overall strength capacity of the connection. Consequently, the aim of this project is to develop a comprehensive parametric FE study to analyse the effect of the degree of composite action to the performance of a steel-concrete composite bolted extended end-plate (BEEP) RWS connections subjected to cyclic loads.

2 Finite Element Modelling and Verification

The experimental test of Chaudhari et al. [13] was modelled using ABAQUS to initially validated the FE model. The test was an interior steel-concrete composite stiffened BEEP connections consisting of two main beams connected to single column in cruciform shape (Figs. 2a) and designed according to the NZ3404 [14]. The applied displacement follows control loading regime of ACI report T1.1-01 [15].

Geometric and material nonlinearities were considered, by applying the first Eigen mode shape, and adopting a bilinear stress-strain relation using a combined material-hardening model from ABAQUS [16] for steel elements. While concrete damaged plasticity model was utilised for concrete, using the constitutive law in accord with EC2 [17] and exponential tension softening model [18] to simulate the concrete crushing and cracking. It is worth to note that assumptions of mechanical properties of materials were made based on the material grades (nominal values), due to the absence of tensile test results for some steel elements.

The combination of shell (S4R) and solid elements (C3D8R) was adopted to model the experimental test [13] as shown in Fig. 2b. The reinforcement steel bars were adopted using truss elements (T3D2). The metal decking was not modelled to simplify the FE model and avoid numerical instabilities, which can lead to early termination of the analysis, as also stated by [19]. The absence of metal decking affects the pattern of cracks in the concrete slab [20]. However, it does not affect the connections' strength as the degree of shear connection mainly governs the maximum capacity of the connection [9]. Embedded element technique was used for concrete slab and steel rebars, and shear studs. Tie constraint was used to simulate the welded parts. Normal and tangent interaction were defined introducing hard contact and friction formulation with a coefficient equal to 0.2 and with finite sliding approach between steel-to-steel elements and frictionless with small sliding approach steel-to-concrete elements.

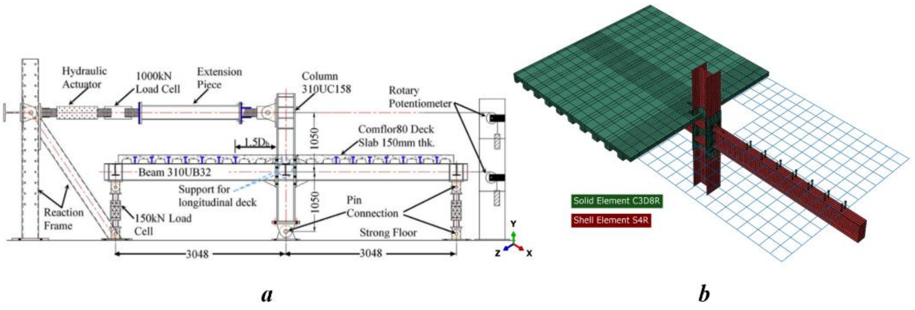

Fig. 2: a) Test setup [13] and b) 3D FE model.

The load-rotation hysteretic curve of the column obtained from the FE analysis was compared against the one in the experimental test [13] as shown in Fig. 3. The initial positive and negative stiffnesses and plastic behaviours compare well between the experimental test and the FE model. The maximum loads recorded in the experimental test [13] were +211.4 kN and -215.93 at 3% lateral drift, and at the same lateral drift they were +207.9 kN and -208.8 kN, respectively, obtained in the FE analysis. The mismatch between the two curves of around 1.7% and 3.3% in positive and negative maximum capacities, respectively, was reasonable due to the lack of experimental data on the inelastic properties of rib stiffeners, extended end-plate and bolts.

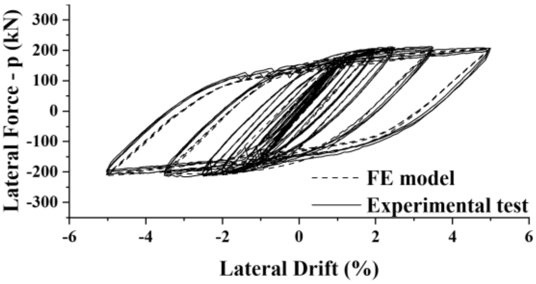

Fig. 3: Comparing between analytical and experimental results.

3 **Parametric Study**

3.1 Model Description

A 3D FE model was then employed to conduct the parametric study and examine the effect of the degree of composite action on the performance of steel-concrete composite BEEP/RWS connections subjected to cyclic loads. Four modifications were made in the validated FE model, namely; European beam IPE300 and column HEB320 sections were used instead of the New Zealand sections; Unstiffened bolted extended end-plate was used (i.e. no rib stiffeners); 6 mm web supplementary plates were used in both sides; and AISC cyclic loading protocol [21] was used.

In detail, three parameters were considered: namely, circular web openings with diameter (*d*) 0.8*h* (where *h* is the steel beam section height), five end-distances (*S*) = 0.5*h*, 0.65*h*, 0.80*h*, *h* and 1.2*h*, and the degree of composite action - both high degree (H) and low degree (L). A total of 18 models, including the three solid (unperforated) models (specifically high composite action, low composite action and bare steel) were considered in this FE parametric study. Each model was identified by a specific five-field identifier as the following:

1. R represents BEEP/RWS and NR represents BEEP (without web opening);
2. C represents composite slab and NC represents non-composite slab;
3. L represents low degree and H represents high degree;
4. d represents web opening diameter, for instance 80*d* means *d*=80% of *h*;
5. S represents end-distances from the connection face to the centreline of the web opening, for instance 80*S* means *S*=80% of *h*.

3.2 Discussion

The introduction of a circular web opening with a diameter equal to *0.8h* in the beam-to-column connections led to a significant reduction in the strength capacity of the connections compared to the composite solid models, NR-C-L and -H and -NC (Fig. 4 and Table 1). The reduction in the maximum strength capacity of the RWS models with high composite action was up to 30.7% compared to the composite solid model (NR-C-H), in line with [4] [6] [9]. For the RWS models with low composite action in comparison with the composite solid model (NR-C-L), the reduction was not more than 28.9%. The RWS models with high composite action and end distance in accord with SCI P355 [22], had lower strength reduction, that was less than 16% compared to the composite solid model (NR-C-H). This is an indication that the suggestion of the end distance proposed by SCI P355 [22] could be considered when designing a cellular beams in seismic areas. When the web opening is closer to the face of the connection, the strength reduction is larger. The difference in strength capacity reduction between the model with the longest end distance of *1.2h* and the shortest *0.5h*, is 29.2% and 5.8% for high and low composite action, respectively. The lower difference in strength capacity reduction in the case of models with low composite action is due to the different number of shear studs between the models. In particular, RWS models with end distances (*S*) equal to *1.0h* and *1.2h* had fewer shear studs than the RWS models with *S* equal to *0.5h*, *0.65h* and *0.8h* due to shorter plastic zone. Thus, when the opening was located to the face of the column, the number of shear studs increased and the strength capacity reduction was lower.

The introduction of a web opening with a diameter equal to *0.8h* in beam-to-column connections substantially enhanced the ductility of the connection in all models between 20% and 97% (Table 1). RWS models with low composite action have higher ductility values than those with high composite action, except the RWS model with *S=0.5h*. This is attributed to an earlier yielding of R-C-H-80d-50d than R-C-L-80d-50d, due to high composite action. The energy dissipation greatly improved in all RWS models in comparison to composite solid models (NR-C-L and -H) due to the early brittle bolt failure in the solid models, and while RWS models experienced ductile failure. However, the bolts exceeded their ultimate strength in the composite solid models (NR-C-L and -H) and two of the RWS models with high composite action (R-C-H-80d-100d and R-C-H-80d-120d). In models NR-C-L and -H, the ultimate strength of bolts was reached at a rotation of 0.05rad and 0.04rad, respectively, while in models R-C-H-80d-100d and R-C-H-80d-120d, it was reached later at a rotation of 0.06rad and 0.05rad. Despite the bolt failure in models R-C-H-80d-100d and R-C-H-80d-120d (RWS models), the energy dissipated was higher than in the solid models due to the early formation of the Vierendeel mechanism, which delayed bolt failure.

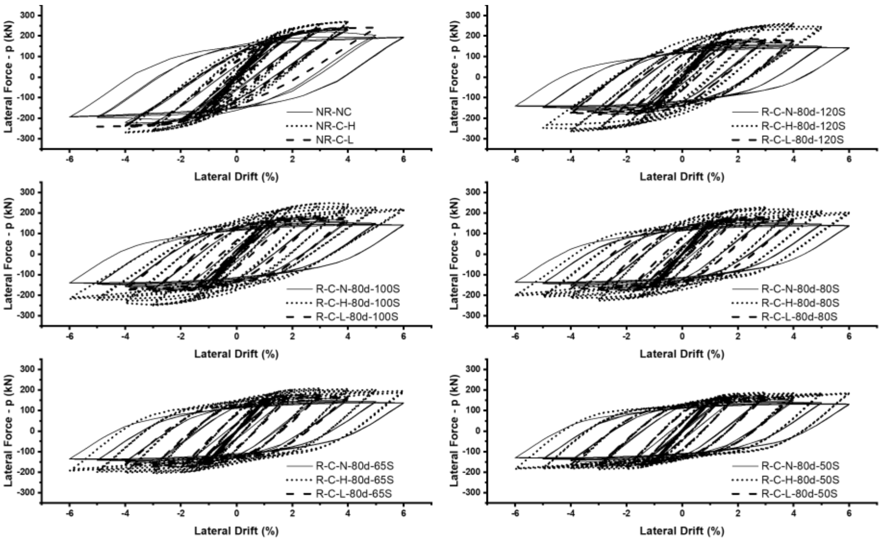

Fig. 4; Moment-Rotation Curves.

Three failure modes were captured, namely the Vierendeel mechanism, bolt failure, and bending of extended end-plate. The failure modes of solid models were critical due to a combination of severe failures. Ductile failure occurred in all RWS models due to the formation of the Vierendeel mechanism, and four plastic hinges were formed above and below the web opening. This mechanism helped to mobilise the stresses away from the connection and shear panel zone. Regarding the crushing and cracking of the concrete slab, the solid models experienced significant spread of cracking, while the crushing is less for the solid model with low composite action. Consequently, the use of a large web opening equal to 0.8*h* could mitigate the crushing and cracking of the concrete slab by dissipating all energy due to an early plastic deformation in the vicinity of the web opening (Vierendeel mechanism), as shown in Fig. 5. This conclusion could be applied to RWS connections with either low or high degree of composite action.

Table 1: **Summary of FE results.**

Model	**Peak Strength at column tip (kN)**	**Dissipated Energy *E* (kN.rad)**	**Ultimate Rotation θ_u (%rad)**	**Ductility ($D = \theta_u / \theta_y$)**
NR-C-L	242.2	15.27	5.00	2.79
NR-C-H	269.9	13.95	4.00	2.52
NR-NC	231.1	27.26	6.00	2.80
R-C-L-80d-120S	184.6	23.26	6.00	4.32
R-C-L-80d-100S	182.4	23.00	6.00	4.44
R-C-L-80d-80S	179.6	23.22	6.00	4.80
R-C-L-80d-65S	177.7	22.74	6.00	4.84
R-C-L-80d-50S	172.2	22.25	6.00	4.44
R-C-H-80d-120S	262.7	21.55	5.00	3.05
R-C-H-80d-100S	248.5	27.86	6.00	4.00
R-C-H-80d-80S	226.7	28.15	6.00	4.32
R-C-H-80d-65S	206.2	27.73	6.00	4.55
R-C-H-80d-50S	187.0	23.50	6.00	4.96
R-NC-80d-120S	181.1	23.54	6.00	3.64
R-NC-80d-100S	177.9	23.49	6.00	3.65

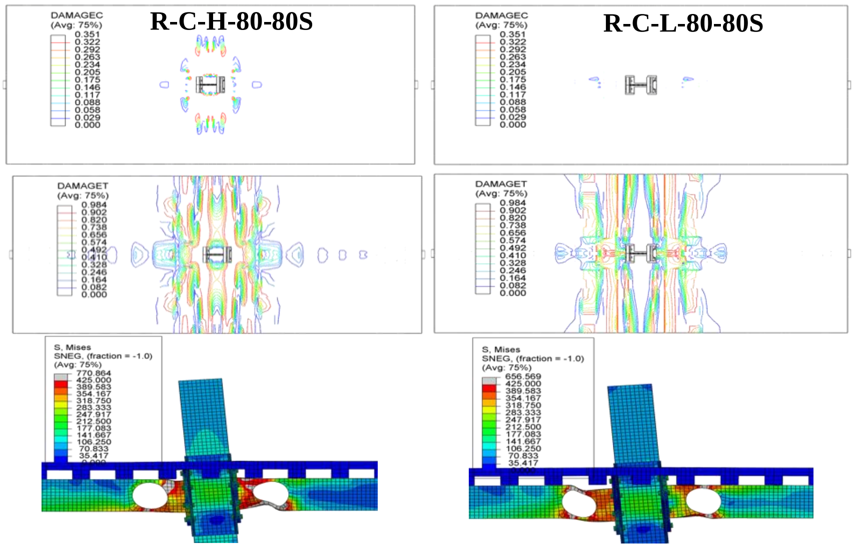

Fig. 5: Cracking, Crushing, Stress distribution.

The presence of the concrete slab has a positive effect in limiting the strength degradation. In solid models with composite action, there was almost no strength degradation with 0% to 0.6% for high and low degrees of composite action, respectively. All RWS models with high and low composite action demonstrated relatively low strength degradation up to 13%, while all RWS and solid models with non-composite action experienced larger strength degradation of up to 22% due to the absence of lateral stability which makes them susceptible to lateral-torsional buckling. In particular, all non-composite models with $d_o = 0.8h$ experienced strength degradation between 20% to 22%, but all of them reached 6% story drift. It can be concluded that all models show satisfactory strength degradation through all cycles before 4% story drift, thus satisfying the requirements of EC8 [23] and AISC 341 [21]. In addition, the composite action (high or low) improved lateral (out-of-plane) stability of the beams which in turn enhanced the performance of RWS connections.

4 Conclusions

The findings agree with previous research carried out [4] [6] [7] [9], now adding the effect of composite action. The composite RWS connection provides satisfactory seismic behaviour in terms of forcing the stresses to concentrate away from the column face and shear panel zone without significantly compromising the connection capacity, provided that the proper size and location of the web opening are selected. Moreover, the elimination of composite action behaviour over the plastic zone in the RWS connections with low composite action, led to the standard formation of the Vierendeel mechanism, alike bare steel beams-to-column connections. On other hand, RWS connections with high composite action have demonstrated different behaviour due to the high contribution of the composite slab to the overall strength. The use of low composite action is preferable to avoid high strain demand on the bottom flange of the beam as well as cracking and crushing of the concrete slab, while it is not jeopardising the strong column-weak beam concept. It can be concluded that the composite action should be taken into account in the design of RWS connections, as it plays a critical role in the ductility.

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