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FE ANALYSES OF RWS COMPOSITE CONNECTIONS UNDER CYCLIC LOADING

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ABSTRACT

This study investigates the behaviour of the composite beam-column connection through a comprehensive finite element (FE) analysis using a perforated beam with a circular web opening; the so-called reduced web section (RWS) connections. Results showed that the existence of a web opening can be effective as the stresses are mobilised away from the column face, thus, the ductility and the energy dissipation of the connection can improve significantly. In the previous research, the composite action was not considered with scope to account for the severest case in terms of the load carrying capacity. However, this study proves that the composite effect should be included since it has a detrimental effect on the ductility and the rotational capacity of the RWS connections. It was also concluded that the contribution of the composite action to the load carrying capacity increases with the increase in the web opening diameter. Therefore, the calculated negative capacity tends to be very conservative if the composite effect is neglected when the large opening diameter is used.

Keywords: RWS connection, Plastic hinge, Vierendeel mechanism, Circular web, Composite beam-column connection.

1 INTRODUCTION

As a result of its good ductility and load carrying capacity, composite structures are increasingly considered in the building design particularly in earthquake-prone regions. The input energy dissipates mainly by the plastic deformation of the structure. Such deformation takes place at high stress concentration regions such as the beam-column connections. Before the 1994 Northridge earthquake in California and 1995 Kobe earthquake in Japan, structural engineers and researchers believed that fully welded connections provide the optimum combination of strength and ductility. However, unexpected brittle fractures at the region of the welded beam-to-column connections were spotted during these earthquakes [1 and 2]. Therefore, the ductility and strength of the beam-column connection inevitably halt the climax of steel and composite structures in case the selected parameters of the connection fail to achieve ductility that tallies with the system level.

2 REHABILITATION METHODS

2.1 Strengthening of the connection

Previous studies carried out on reinforcing connections concluded that retrofitted connections such as the use of triangular haunch, cover plate, or side plate method delivered an outstanding performance by achieving significant plastic rotation before the fracture was initiated [3 and 4]. However, in most cases it is required to breaking parts of the concrete slab before adding the new steel parts for strengthening. Therefore, the strengthening of the connection is usually the most expensive method in terms of time-consuming, required material, and inspection.

2.2 Reduced beam section (RBS)

Another approach developed during the last decade was weakening the beam by trimming away steel parts at designated locations so that the structural fuse is formed in the beam while the stress of weld and heated regions remain at low stress levels. The parts can be trimmed from the beam flange resulting the so-called Reduced Beam Section (RBS) connection. Many previous studies proved that the plastic hinge was formed at the RBS location while high ductility was achieved [5 and 6]. However, the RBS method is relatively costly as it is also required to break some concrete parts at the location of cutting the flanges as well as the cuts from the top and bottom steel flanges of the beam should be precise and symmetrical to avoid out-of-plane instability of the web.

2.3 Reduced web section (RWS)

Instead of reducing the section by trimming steel parts away from the flanges, an alternative way is to cut a steel plate away from the beam web introducing what is now known as Reduced Web Section (RWS) connection. The shear strength of the beam at the reduced section is decreased depending on the size of the web opening and the shear force transfers across the opening results in secondary moments known as the Vierendeel moments (Vierendeel mechanism). Eventually, the global shear plastic hinge is formed at the tee section (reduced section) due to the interaction between these moments and the major beam moments.

This connection configuration has received limited attention compared with the other types of retrofitting. However, the performance of the RWS connections showed its capability to achieve the required ductility and to avoid the brittle failure of the connection [7 and 8]. Yang et al. [9] studied the aseismic behaviour of a steel moment frame with web openings that have different diameters placed at a specific position away from the column face. It was concluded that the Vierendeel mechanism formed at the weakened areas resulted in high dissipated energy due to the local deformation and thus the brittle weld fracture was avoided.

3 SCOPE OF THE STUDY

Yet, there have been no studies reported on the composite RWS connections. The composite downstand beams are widely used in engineering practice since they have considerable higher strength and stiffness compared with the non-composite beam. The composite action may increase the non-composite beam's strength by 1.5 times under positive bending moment [10]. However, the existence of the slab may be detrimental in certain cases. One of the main reasons, which led to the premature failure of steel connections due to the past earthquakes, was the high strain demand of the bottom flange as a result of the upward shift of the neutral axis due to the composite action. In this paper, the RWS connection with the composite beam was investigated through a comprehensive FE analysis, which firstly validated using an experimental test from the literature. Also, non-composite RWS connections with same opening configuration and parameters assigned to the composite connections were considered. The behaviour of both connections (with and without the composite beam) was compared to discern the effect of the composite action on RWS connections.

4 FINITE ELEMENT MODELLING AND VERIFICATION

One of the connections experimentally tested by Lee et al. [11] was modelled using the general-purpose FE software ABAQUS 6.10 [12]. The FE models were developed using three-dimensional continuum (solid) elements. The computational outputs were compared against the experimental results in order to validate the FE models. The selected specimen was conventionally the composite beam-column connection type (bolted web-welded flanges), often referred to as a Pre-Northridge connection (Figure 1).

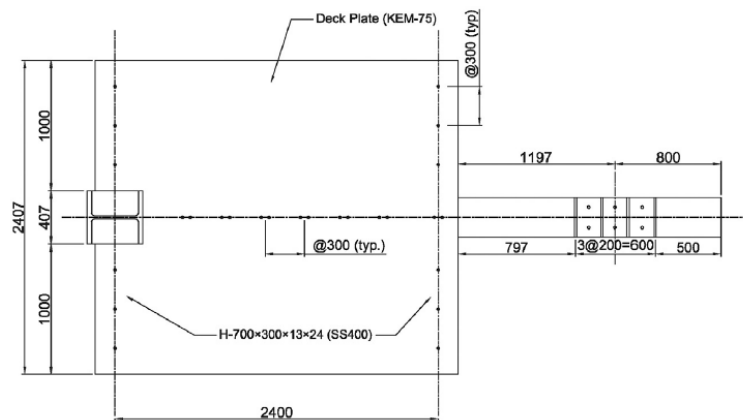


Fig. 1. Geometry of the specimen [11]

Embedded element technique in ABAQUS was used to model the interaction between the slab-reinforcement and slab-studs. In the embedded element technique, the nodes' translational degrees of freedom of the reinforcement and studs are constrained to the interpolated values of the corresponding degrees of freedom of the concrete slab. To simplify the model, the interface between the welded parts in the experimental test (such as the column and the beam) was modelled as tie constraint (perfect bond) in the FE models. The interface between the slab and the steel (beam and the column) was considered as frictionless formulation and the sliding between the beam and the slab was resisting by the connection of the shear stud. The normal contact behaviour was defined by using a hard contact in ABAQUS which does not permit the transfer of the tensile stress across the interface and constraint the nodes on one surface so as not to penetrate the other surface.

Cyclic displacement load was applied at the beam end (at 3,597mm from the column face). The applied displacement followed the AISC [13] cyclic seismic loading protocol. The geometric nonlinearity was considered in the analysis. The analysis was carried out on the imperfect model to trigger various failure modes. In order to introduce an imperfection in the geometry, the buckling mode shapes were computed in prior in separate buckling analysis and then the first buckling mode was implemented to perturb the geometry of the perfect model.

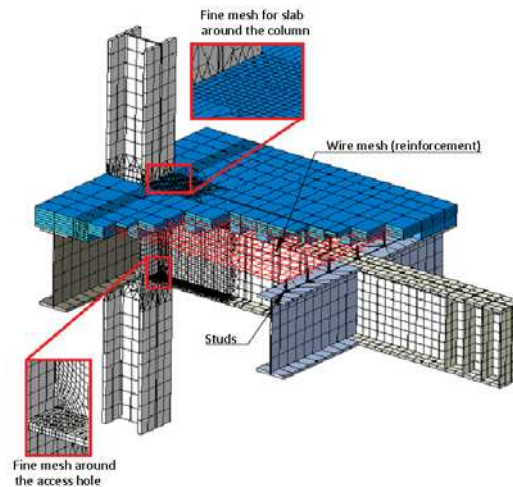


Fig. 2. Finite element mesh

The FE mesh of the validated model is shown in Figure 2. 8-node linear brick elements with reduced integration (C3D8R) was mainly adopted for the solid parts (beams, the column, the slab, plates, and studs) considering that a fine mesh was assigned for parts expecting to receive high-stress concentration and a coarse mesh for other parts.

The material nonlinearity of the steel beams ($f_y=304\text{MPa}$ and $f_u=455\text{MPa}$) and the column ($f_y=343\text{MPa}$ and $f_u=512\text{MPa}$) was considered during the analysis by adopting bilinear stress-strain relation. The tangent modulus was assumed $E=1000\text{MPa}$. The elastic modulus 200GPa and Poisson's ratio 0.3 were assigned for the steel material in the elastic range. The constitutive model concrete damage plasticity (CDP) in ABAQUS was adopted. The CDP model is capable of representing the concrete crushing and formation of cracks.

The normalised moment at the column face against the story drift rotation curve obtained from the FE modelling are plotted in Figure 3 together with the test data from Lee et al. [11] for a direct comparison. The normalised moment was calculated based on the actual plastic

moment of the steel section only. The initial stiffness and post-elastic behaviour were well matched for the FE model and the experimental test. Therefore, it might be concluded that the FE model was appropriate to carry out the parametric analysis.

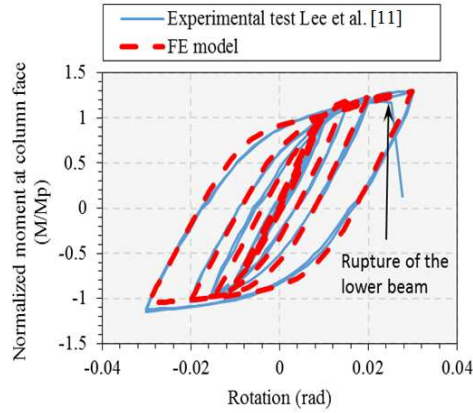


Fig. 3. Comparing between analytical and experimental results

5 AREA OF INTEREST

In order to understand the effect of opening on the behaviour of the composite connection, a perforated beam with one circular web opening but various parameters was considered. Furthermore, similar non-composite connection (without concrete slab) with same opening parameters as before were examined and the results were compared against the connection with the composite beam. This paper focuses on the effect of opening depth, d_o , and the distance between the face of the column to the centreline of the web opening, S , (Figure 4). Three different values for d_o and five values for S parameters were investigated as follows: $d_o=0.5h, 0.67h, \text{ and } 0.75h$
 $S=0.5h, 0.75h, 1.25h, \text{ and } 1.5h$ where h is the overall section height of the steel beam.

Three specific field identifiers, as illustrated in Figure 4, identify the specimen. The first identifier represents the type of the beam (non-composite or composite). The second identifier represents the diameter of the opening as a percentage of the beam depth. The third identifier indicates the end distance as a percentage of the beam depth.

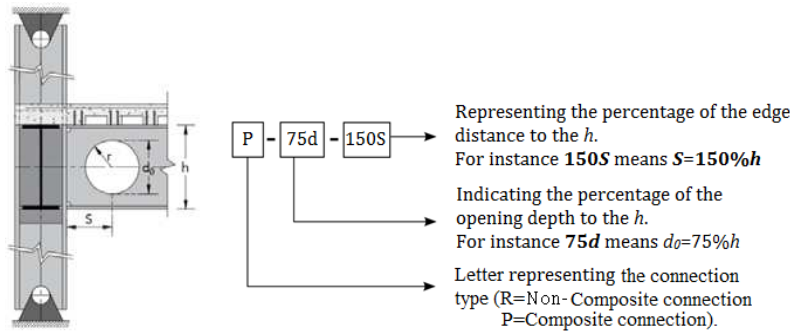


Fig. 4. Parameters and specimen's identification

6 RESULTS OF PARAMETRIC STUDY

6.1 Ductility and failure mode

The fracture of the flanges at heated zones can be predicted when the equivalent plastic strain (PEEQ) exceeds the critical limit [14]. The rupture of the flange was the main failure mode for the composite connection without web opening. The composite action resulted in the upward shift of the neutral axis which led to the concentration of the stress and the strain on the bottom flange (Figure 6). This was one of the main failure reasons of steel structures during the previous major earthquakes [1 and 2]. The failure modes of the RWS connections with composite beams were more complex due to the weakened local shear stiffness at the opening location, which results in a Vierendeel moment. This evidently caused the different failure modes that were observed for the RWS connections depending on the geometric parameters of the opening.

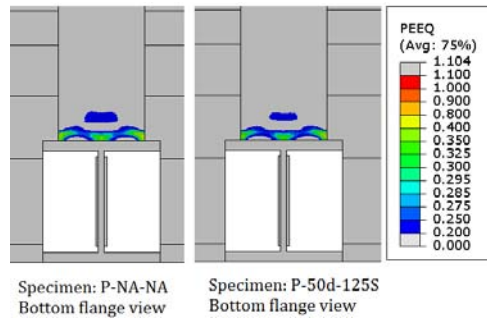


Fig. 6. Rupture of the flange

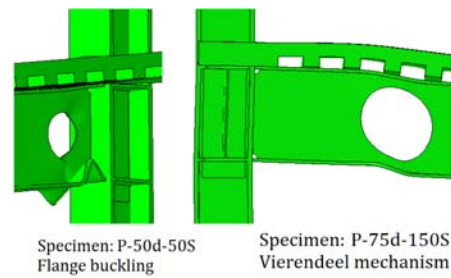


Fig. 7. Failure modes

Generally, for connections with small opening diameters (e.g., $0.5h$), local buckling of the beam was captured as it is shown in Figure 7. However, the use of web opening with a small diameter and large end distance (e.g., specimen P-50d-125S) was not effective to mobilise the stress away from the column face and the failure mode was the rupture of the beam's bottom flange as demonstrated in Figure 6. The connections with a large opening diameter (e.g., $0.75h$) suffered a high Vierendeel moment, which exceeded the Vierendeel capacity of the tees. Accordingly, the predominant failure of the connections with large web openings was the Vierendeel mechanism, independent of the end distance (Figure 7).

The composite effect was responsible for the deterioration of the conventional composite section due to stress concentration and premature rupture of the flange. The ductility was decreased from 4.21 to 3.09 (26.6%) when the slab was added to the unperforated non-composite connection. However, the use of the web opening such as in model P-50d-50S enhanced the ductility in the positive and the negative directions by 29% and 50%, respectively. This enhancement had a great positive effect on the dissipated energy which was increased by 135% without affecting the negative ultimate strength significantly (less than 5%). In previous studies, the composite effect was neglected in order to represent the severest case in terms of ultimate capacity. However, the composite effect should be considered during the study of RWS connections since its effect may determine their ductility and rotational capacity.

6.2 Composite effect

Table 1 illustrates the contribution of the slab in the positive and negative directions. It is obvious from the table that the positive and negative capacities of the composite RWS connections were higher than the non-composite connections. However, the composite effect

was significantly affected the moment capacity of connection in the positive direction. Furthermore, the composite effect was not similar for all examined opening depths. While the average contribution of the composite in the positive direction was 26% for the small opening diameter, it changed to 66% when the large opening diameter was used.

Connection notation	Composite contribution		Average contribution	
	$\frac{M_p^{+ve}}{M_R^{+ve}}$	$\frac{M_p^{-ve}}{M_R^{-ve}}$	+ve	-ve
P-50d-50S	1.30	1.02		
P-50d-75S	1.27	1.05	1.26	1.03
P-50d-125S	1.22	1.04		
P-50d-150S	1.25	1.01		
P-67d-50S	1.41	1.11		
P-67d-75S	1.43	1.15	1.43	1.16
P-67d-125S	1.45	1.19		
P-67d-150S	1.44	1.20		
P-75d-50S	1.64	1.26		
P-75d-75S	1.62	1.30	1.66	1.32
P-75d-125S	1.68	1.35		
P-75d-150S	1.69	1.35		

M_p^{+ve} and M_p^{-ve} : capacity for the composite RWS connections.
 M_R^{+ve} and M_R^{-ve} : capacity for the non-composite RWS.

Table 1. Contribution of composite action

The capacity of the composite RWS connection can be estimated accurately under negative moment without including the composite effect when small opening depth is used since the average effect of composite found to be only 3.0%. However, the average effect of the composite action when larger web opening introduced was found to be significant. For instance, the increase in negative capacity of the composite RWS was 32% against the non-composite connection, when the opening depth was 0.75h. Therefore, the calculated negative capacity tends to be very conservative if the composite effect is neglected when large opening diameter is used.

6.3 Stress and strain distribution

Figure 8 depicts the stress and the strain distribution for unperforated and RWS connections. The stress and PEEQ were concentrated mainly in the welding zone and the column panel zone for the connection without web opening. In the case of using the perforated beam, the yielding was promoted in the vicinity of the web opening and there was no stress or strain concentration observed at the weld location. More specifically, an example is demonstrated through specimen P-50d-50S which experienced stress concentration in the top flange at the weld area. However, the PEEQ in the top flange at this location was very small which revealed that the rupture of the flange did not occur.

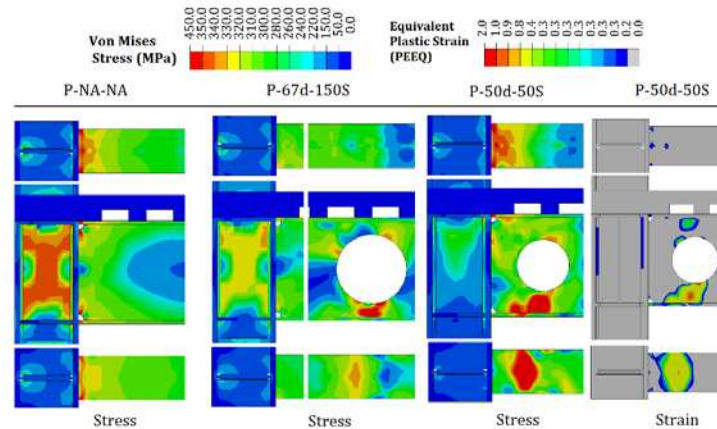


Fig. 8. Stress and strain distribution

Both opening parameters (d_o and S) had substantial influence on the stress distribution at the web opening location. The stress was concentrated in the beam's flanges when small opening diameter was used. On the other hand, the Vierendeel behaviour was clearly observed (i.e., fully formed) when large web opening used while the stress mainly concentrated in the vicinity of the web opening at four specific angles (i.e., formation of plastic hinges) from the centre of the opening (specimen P67d-150S).

7 CONCLUDING REMARKS

A computational study was carried out to investigate the behaviour of the composite beam-column connection using an isolated circular web opening. The FE model used in the parametric analysis was firstly validated against an experimental test found in the literature. This paper focuses on the effect of the opening diameter d_o and the distance between the face of the column to the centreline of the web opening S under cyclic FE analysis. Based on the analysis of the parametric models, the following conclusions can be drawn:

- In the literature, the concrete slab was neglected during the study of the RWS connections in order to represent the severest case in terms of ultimate capacity. However, the current study proves that the composite effect should be included since it has a severe effect on the ductility and the rotational capacity.
- The use of the circular web opening with certain parameters (d_o and S) improves the performance of the connection significantly, while the position of the plastic hinge is mobilised away from the column flange to the location of the opening. For instance, in specimen P-50d-50S, the dissipated energy was increased by 135% comparing with the non-composite unperforated connection without affecting the load carrying capacity of the connection.
- The contribution of composite action to the load carrying capacity tends to be higher under negative bending moment when larger openings are considered. Therefore, the calculated negative capacity tends to be very conservative in case the composite effect is neglected while using large web openings. Consequently, it is highly recommended to consider the composite effect during the design stage.

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ΣΥΜΠΕΡΙΦΟΡΑ ΑΝΤΙΣΕΙΣΜΙΚΩΝ ΣΥΜΜΕΙΚΤΩΝ ΣΥΝΔΕΣΕΩΝ RWS ΥΠΟ ΚΥΚΛΙΚΗ ΦΟΡΤΩΣΗ

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ΠΕΡΙΛΗΨΗ

Η παρούσα εργασία ερευνά τη συμπεριφορά σύμμεικτων συνδέσεων δοκού-υποστυλώματος μέσω πεπερασμένων στοιχείων (FEA) χρησιμοποιώντας διάτρητες δοκούς με μεμονωμένο κυκλικό άνοιγμα κορμού γνωστές και ως RWS συνδέσεις. Τα αποτελέσματα έδειξαν ότι η χρήση διάτρητης δοκού είναι αποτελεσματική καθώς οι υψηλές τάσεις συγκεντρώνονται μακριά από τα πέλματα της κολόνας. Με αυτόν τον τρόπο, η ολκιμότητα τη σύνδεσης ενεργεί ως μέτρο απόσβεσης ενέργειας. Στην βιβλιογραφία, σύμμεικτες συνδέσεις δεν έχουν ληφθεί υπόψιν με σκοπό να κατανοηθεί η χειρίστη περίπτωση (μεταλλικές συνδέσεις χωρίς σύμμεικτη πλάκα) όσον αφορά το φορτίο αντοχής. Η μελέτη αποδεικνύει ότι η σύμμεικτη συμπεριφορά της σύνδεσης πρέπει να συμπεριλαμβάνεται, καθώς έχει αρνητική επίδραση στην ολκιμότητα και στην ικανότητα περιστροφής των συνδέσεων RWS. Εξήχθη επίσης το συμπέρασμα ότι η συμβολή της σύμμεικτης δράσης στο φορτίο αυξάνεται με την αύξηση της διαμέτρου του ανοίγματος κορμού της δοκού. Επομένως, η υπολογιζόμενη μείωση ικανότητας φορτίου λόγω των ανοιγμάτων του μεταλλικού κορμού τείνει να είναι πολύ συντηρητική εάν η σύμμεικτη συμπεριφορά παραληφθεί όταν χρησιμοποιείται άνοιγμα μεγάλης διαμέτρου.