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# **SEISMIC EVALUATION OF REDUCED WEB SECTION (RWS) MOMENT CONNECTIONS**

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## **1. ABSTRACT**

This paper presents a study of fully-fixed (welded) perforated beam-to-column connections, used as strengthening techniques to code-deficient steel frames. The effect of reduced web sections (RWS) using non-standard novel opening shapes on of variable depths and positions is investigated. The improvements on the structural behaviour foreshadow the enhancements gained using such perforated members. It is concluded that using large isolated perforations is an effective way of improving the behaviour of connections enhancing their ductility, rotational capacity and their energy dissipation capacity. Moreover, the connections with novel openings outperform the conventional ones; therefore they can be suitably used in the seismic-resistant design of steel frames.

## **2. INTRODUCTION**

### **2.1 Background and RBS**

Since the earthquakes of Northridge in 1994 and Kobe in 1995 and the observation of brittle fractures in connections, numerous studies were deployed to find the best methods in improving the seismic behaviour of steel beam-to-column connections.

A number of connections have been proposed in FEMA 350 [1], such as the Bolted Flange Plate (BFP), the Bolted Unstiffened (BUEEP) and Stiffened Extended End-plate (BSEEP), and the so called CONXTECH CONX and KAISER Bolted Bracket (KBB) moment connections, and their satisfaction degree has been determined in numerous tests. In general, two concepts were introduced for achieving high levels of ductility and assured operation in connections: (i) connection reinforcement/strengthening and (ii) beam weakening by reducing the cross-sectional area of the beam locally at a certain distance from the connection in order to prevent the catastrophic damage of the connection.

Reinforced connections increase costs, and excess reinforcement leads to new problems including increasing welding and bolting processes, increasing connection resistance and hence stronger panel zone which attracts stresses, as well as increasing the weight of the structure and thus the seismic effects. On the other hand is the idea of weakened beams, which was developed the last decade, based on the design technique of trimming away steel parts from the region adjacent to the column connection without reducing dramatically the beams' load bearing capacity. These parts are reduced from the flange resulting to what is known as Reduced Beam Section (RBS) or "Dogbone" connection. Weakening the beam instead of reinforcing the connections has proved to be more economical. While reducing the cross-sectional properties, the demand in panel zone capacity of a strong column-weak beam requirement has been minimised too. Vast experimental and analytical tests have been examined this solution, and following parametric studies on the actual shape of the flange cut (eg. constant cut; tapered cut; radius cut, etc.). The RBS connection with radius cut was evaluated to be the most suitable and hence introduced in FEMA 350 [1] and EC8 [2] regulations.

## 2.2 Perforated beams

Up to date, researchers are mainly focused on the performance-based design of solid webbed steel beam-to-column connections. However, the last decade there is a dramatic increase of use of perforated beams in the steel construction industry as they offer numerous advantages [3~5]; namely the ease to integrate services within the floor-to-ceiling zone and maintaining a shallow structural depth; the reduction of the material volume without reducing the structural strength; the potential to span longer without resulting to heavy sections, hence they do comply with the serviceability requirements; and therefore the need for fewer columns and consequently foundations.

## 2.3 The new RWS connections

The present study aims to introduce the seismic evaluation of beam-to-column welded connections using novel perforated beams. Similarly to the RBS connections, an effective method in designing seismic-resistant connections is by using the reduction of the beam's web cross-section, and developing a fuse mechanism which dissipates the energy, while the rest structural elements remain elastic. Such connections can be called Reduced Web Section (RWS) connections and they can also be easily used as a retrofitting technique to code-deficient steel buildings. Yang et al. [3] studied the aseismic behaviour of a steel moment resisting frame with isolated circular web openings of two different diameters while they were placed at two different positions along the length of the beam. Hedayat and Celikag [6] proposed a different beam end configuration for post-Northridge connections. Through FE analyses they designed two parallel horizontal long voids in the beam web close to the connection which was considered as an effective solution. The use

of link-to-column connections in eccentrically braced frames having web section connections with various sizes and number of small web penetrations on welded link-to-column connections was studied by Prinz and Richards [7]. Later, Kazemi and Hoseinzadeh [5] developed a link element to study the behaviour of frames with reduced web section connections. A comparison was then established against frames with RBS connections. It was revealed that the frame with the new connections has provided at least the same level of seismic enhancement with that of the frame with RBS connections.

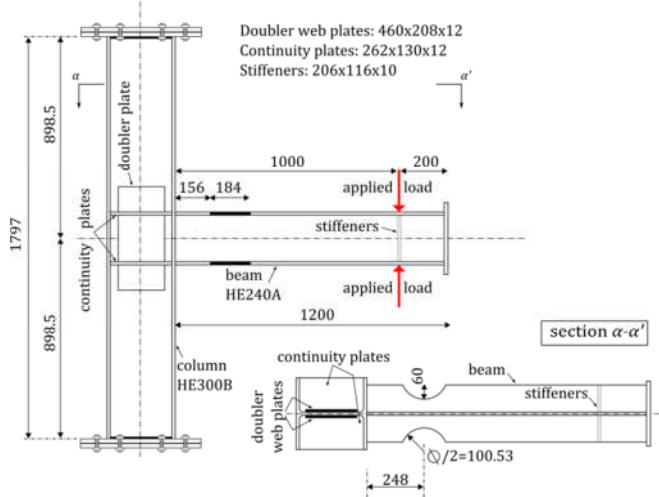
Yet, limited research has been conducted on the behaviour of moment connections with isolated web openings to date.

## 2.4 Aims and methodology

This work studies the behaviour of RWS connections with isolated web openings as the first step to introduce non-standard web opening shapes which have been proven to be efficient for the design of economic perforated steel beams used in steel and composite buildings from floor to roof applications. A computational parametric Finite Element (FE) analysis is performed as the fully rigid moment connections are imposed to cyclic loading to gain the complete understanding of the stress distribution and their hysteretic behaviour. Traditional circular web openings are replaced with novel patented elliptically-based web openings proposed and extensively studied in complementary papers [8~10]. The suitability of these new patented perforated beams is now going to be evaluated, for the seismic-resistant design of lightweight steel frames.

## 3. VALIDATION OF THE FE MODEL

The experimental specimen RBS1 (*Fig. 1*), as tested by Pachoumis et al. [11], was modelled to validate the FE model. A three-dimensional FE model was employed using shell elements to model the beam-to-column connection. A nonlinear (geometric and material) analysis was performed and the numerical results obtained were compared with the experimental results.

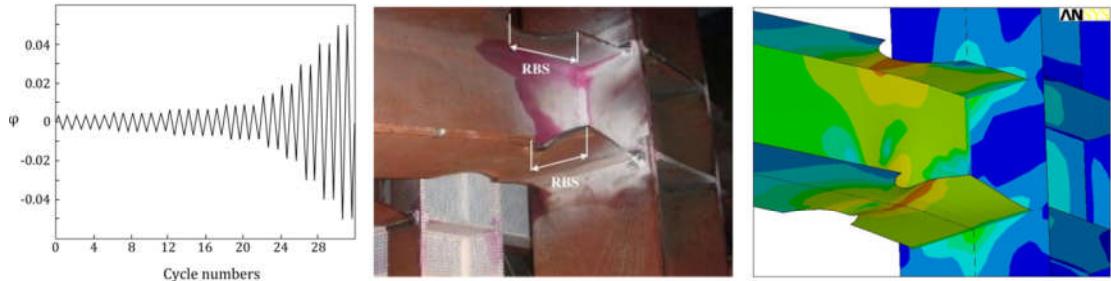


*Fig. 1: Test set-up (all dimensions in mm)*

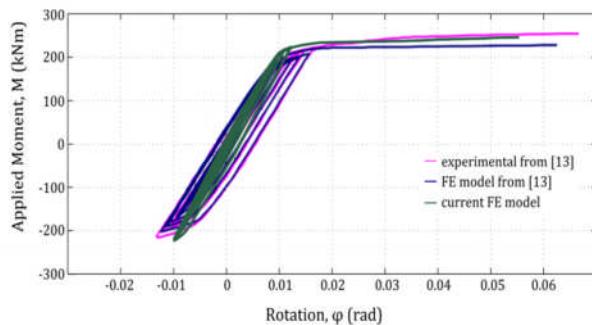
The quadrilateral 4-node shell element (SHELL181 plastic), with 6DOF at each node, material plasticity, large deflection and large strain modelling capabilities, was employed. The fillet-welds were considered continuous and did not model separately in the FE model,

similarly to the literature [11]. All 6DOF were restrained at both ends of the column to be in agreement with the experimental test setup where the supports were considered fixed, using extended end plate connections. The free-end of the beam was fixed against translation normal to the beam web. Material nonlinearities were accounted for using a bilinear kinematic rate independent hardening rule. To predict the onset of yielding the Von-Mises yield criterion was activated. The material properties for the beam and the column were uniformly selected as: Young's Modulus  $E=207\text{GPa}$ , ultimate stress  $f_u=510\text{MPa}$  and yield stress  $f_y=305\text{MPa}$ . The tangent Modulus was assumed  $E_T=1000\text{MPa}$ .

The specimen was loaded cyclically through beam end displacement in accordance with the SAC loading protocol recommended in FEMA350 [1] (*Fig. 2 - left*). The results of the FE model were compared against the experimental work (*Fig. 3*). The local buckling of the beam flange and the yielding of the RBS region shown in the FE model are in agreement with the experimental specimen (*Fig. 2 - right*). The comparison of the moment-rotation curves between the FE models and the test data from RBS1 recorded at 4cm away from the face of the column. The rotation was computed by dividing the deflection at this point over the length from this point to the column centre-line. The maximum applied moment that the experimental specimen experienced is 220kNm, while the numerical corresponding result of the FE model is 223kNm, which is only 1.4% different. The comparison of the hysteretic curve and the buckling behaviour presents a similar performance.



*Fig. 2: SAC protocol (left) and Correlation between FE model and RBS1(right)*



*Fig. 3: Moment-rotation curves*

## 4. RECOMMENDED REDUCED WEB SECTION (RWS) CONNECTION

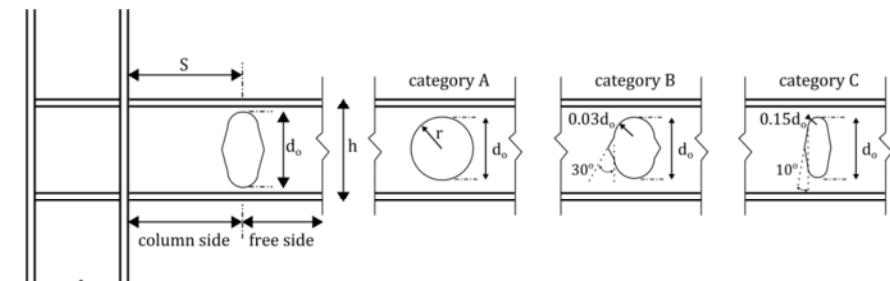
### 4.1 Geometric parameters

For the purpose of the current study three opening shapes were considered; one conventional circular and two novel web opening shapes. In addition to RWS connections, a beam-to-column connection with a non-perforated solid webbed beam was modelled as a reference point, to compare and evaluate the structural performance of the new type steel

connections. The parametric study focuses on the effects of the opening depth,  $d_o$ , and the distance between the web opening centreline and the column's face,  $S$ . The three different configurations investigated are shown in *Fig. 4*. Also, three different values were chosen for  $d_o$  and  $S$  geometric parameters as follows: (i)  $d_o$  is equal to 0.5h, 0.65h, and 0.8h, and (ii)  $S$  is equal to 0.87h, 1.30h and 1.74h; where  $h$  is the total beam height (230mm). The alteration of opening depths and shapes produces different Web Opening Areas (WOA), the magnitude of which could be crucial to the beams' performance. Therefore, it was envisaged that assessing the WOA would provide a good understanding on the structural behaviour of the joints with perforated beams under cyclic loading. To distinguish the specimens considered, the configurations were categorised as A, B and C according to *Fig. 4*. Category A: Circular openings with radius  $r$ ; Category B: Novel web opening with  $R=0.30d_o$  and  $\theta=30^\circ$ ; Category C: Novel web opening with  $R=0.15d_o$  and  $\theta=10^\circ$ . Each specimen is represented with a specific three field identifier; for example: C2-300; is the RWS connection with web opening C,  $d_o$  of 0.65h and located at 300mm away from the column's face (i.e.  $S=0.87h$ ).

#### 4.2 Analysis and FE results

The same cyclic loading as the one used in the validation study was applied to all beams. The hysteretic curves were determined based on the moment capacity at the column centreline and the total rotation of the beam at 750mm away from the face of the column. Undoubtedly, the moment capacity of all beam-to-column connections using perforated beams is decreased due to the presence of openings. This reduction is significantly affected by the opening depth as well as the shape of the perforation. The use of RWS connections with circular web openings in steel frames results the decrease of rotational stiffness, which further results the decrease of initial lateral frame stiffness. This might be of concern if damage limitation requirements (i.e. the design of moment resisting frames according to EC8) for low intensity earthquakes are considered. It is observed that the rotational stiffness of the connection using a circular opening was significantly reduced by 40% when the opening depth,  $d_o$ , was increased from 0.5h to 0.8h (*Fig. 5*), while the connections using configurations B and C with similar  $d_o$ , lost 30% and 16% respectively, of their rotational stiffness. Generally, although the position of the opening did not affect the connections' stiffness significantly, the reduction of the web opening depth resulted in stiffer connections. Moreover, it was established that the moment capacity of the perforated beams with large WOA is reduced gradually as the number of rotations increased, followed the yielding point. Conversely, when smaller openings were used, significant strength degradation was detected during the final cycles.



*Fig. 4: Geometric parameters  $d_o$  and  $S$  with opening configurations*

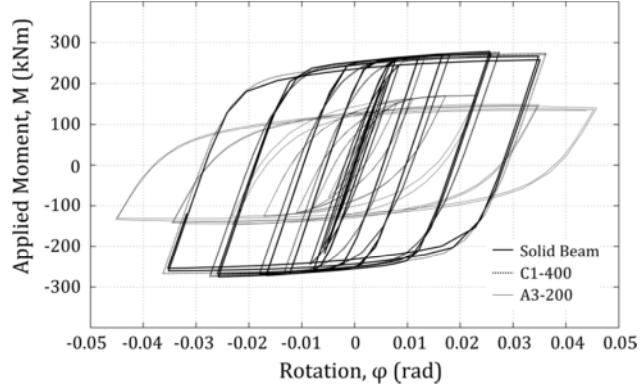


Fig. 5: Moment-rotation curves of solid beam, C1-400 and A3-200 (at 30 cycles)

The effect of the WOA on the rotational ductility of the connection was also studied, elucidating the importance of the geometric parameters characterising the opening configurations; further observations are synopsised in Tsavdaridis et al. [12]. The rotational ductility was increased together with the WOA. However, certain comparisons indicate that similar level of ductility can be achieved regardless of the difference in the WOA and visa-versa. It is concluded that the use of C3 openings in perforated beams is ideal and that depth,  $d_o$ , is the dominant controlling parameter for the rotational ductility of a connection together with the web opening shape.

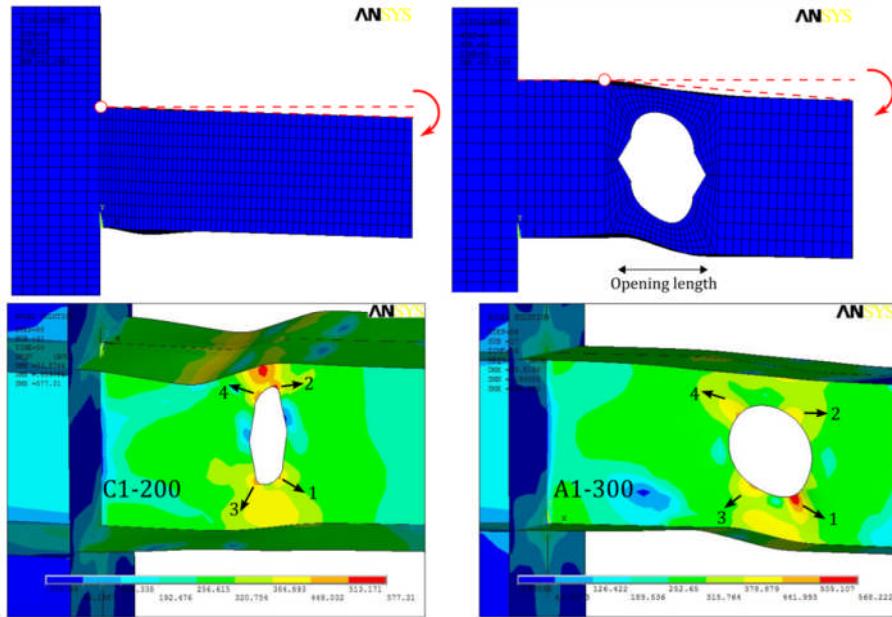
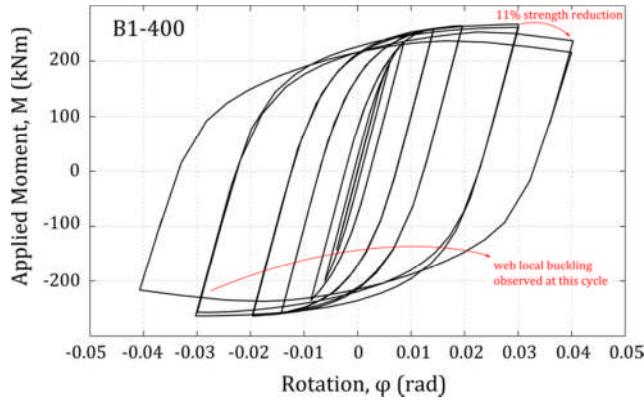


Fig. 6: Source of rotation in solid and perforated beams and Von-Mises stress contour plot and Plastic hinge formation; left: at cycle 29, right: at cycle 27



*Fig. 7: Strength degradation after web local buckling*

The Vierendeel deformation is introducing additional rotation to the RWS connections at the position of the opening, unlike to the connections with solid beams (*Fig. 6 - top*). It is well-known that the Vierendeel mechanism is controlled by the critical opening length [8~10], meaning that any increase of the opening length will result an increase of the local Vierendeel moments acting at the tee-sections. Perforated beams with traditional circular openings showed a premature formation of plastic hinges compared to beams with those novel web openings. Specimens of category A1 ( $d_o=0.5h$ ) developed four plastic hinges in the vicinity of the opening by the end of the cycle 27 (*Fig. 6 - bottom*), while specimens with configurations B1 and C1 developed four plastic hinges two cycles later, while providing higher Vierendeel capacity. It is further concluded that in most cases the effect of the distance  $S$  is minimal on the ultimate rotation capacity of the connection. It was further established that openings with depth,  $d_o$ , equal to  $0.8h$  are more successful in distributing stresses locally, around the perforation, allowing plastic deformation to develop only in the controlled region, away from the welded area or the beam flanges. As the displacement increased, the specimens experienced local web buckling on the edges of the opening as well as flange local buckling at large plastic rotations. Moreover, the initiation of local web buckling resulted in higher strength degradation (*Fig. 7*).

### 3. CONCLUSIONS AND RECOMMENDATIONS

A major drawback of RBS connections, especially if this is used as a retrofit technique in existing structures, is that by reducing the flange size where the floor slab sits, the time and cost of rehabilitation is increased, and the longitudinal shear interaction between the steel beam and the metal deck of the slab is jeopardised. On the other hand, RWS connections can be more practical and easy to implement, even if they are used as a “strengthening” technique. The desirable behaviour under cyclic loading, with sufficient energy dissipation without substantial loss of strength and stiffness, could be achieved with appropriate selection of the opening shape, depth and position. This study in combination with Tsavdaridis et al. [12] has presented that the use of RWS with novel perforated beams is an excellent replacement for the traditional RBS or RWS with circular openings, since adequate moment capacity is provided, while high rotational ductility and energy absorption is achieved. RWS connections achieved higher inelastic rotation capacity in comparison to the RBS1 connections, and they are capable of reaching beyond 0.035 radians rotation, hence such connections can be employed in special moment frames.

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## **ΣΕΙΣΜΙΚΗ ΑΠΟΤΙΜΗΣΗ ΔΙΑΤΟΜΩΝ ΑΠΟΜΕΙΩΜΕΝΟΥ ΚΟΡΜΟΥ ΣΕ ΣΥΝΔΕΣΕΙΣ ΡΟΗΣ**

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### **ΠΕΡΙΛΗΨΗ**

Η παρούσα ερευνητική εργασία εξετάζει με την βοήθεια υπολογιστικών μοντέλων την αντισεισμικότητα μιας σειράς πρότυπων συνδέσεων δοκού-υποστυλώματος οι οποίες συμπεριλαμβάνουν διατομές δοκών διάτρητου κορμού με μη-συμβατικά ανοίγματα. Οι νέες αυτές λύσεις πιστές στη βάση του μοντέρνου ικανοτικού σχεδιασμού διατηρούν την αρχή του “ισχυρού υποστυλώματος - αδύναμης δοκού” αλλά σε σύγκριση με τις υπάρχουσες μορφές παρόμοιων προτάσεων αντιπαραβάλονταν επιπλέον πρακτικά οφέλη που τις καθιστούν ελκυστικές σαν μια γρήγορη, ευέλικτη και σχετικά εύκολα υλοποιήσιμη παρέμβαση ιδιαίτερα για την περίπτωση υφιστάμενων κατασκευών. Εστιάζοντας στη μηχανική απόκριση αυτών των νέων συνδέσεων, το κύριο μέλημα όσων ακολουθούν είναι να παρουσιαστεί με σαφήνεια η ολιστική ανωτερότητα τους και η επιπλέον ικανότητα που μπορεί να αποφέρει η εφαρμογή μεθόδων βελτιστοποίησης σε γνώριμες κατασκευαστικές μορφές που απαντώνται για χρόνια τώρα σε κτίρια με πρόβλεψη σεισμικών δράσεων. Αναλυτικά εξετάζεται μια σειρά πρότυπων διατομών έναντι κοινών διατομών απομειωμένου πέλματος και διατομών απομειωμένου κορμού με κυκλικά ανοίγματα. Για μια τυπική γεωμετρία συγκολητής σύνδεσης δοκού-υποστυλώματος, το πεδίο της έρευνας επικεντρώνεται στην ικανότητα απόσβεσης ενέργειας κατά τη διάρκεια ψευδοστατικής ανακυκλιζόμενης κάμψης. Λεπτομέρειες σχετικές με την πλαστιμότητα και την οριακή αντίσταση προσφέρουν σαφείς ποσοτικές αποδείξεις των πρόσθετων αρετών που απορρέουν από την χρήση των συγκεκριμένων προτεινόμενων συνδέσεων.