CYCLIC RESPONSE OF PERFORATED BEAM IN STEEL COLUMN JOINTS

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Abstract - *A structure is an assembly of various elements or components which are fastened together through some type of connections. Connections of most steel moment frames are vulnerable to brittle failure. According to the studies, great damages are mainly due to formation of plastic hinges followed by cracking of the weld between the beam flange and the column face. Shifting of the plastic hinge formation away from the joint is one possible remedy for this problem which will increase the energy dissipation of the frame. A useful approach to reduce the stress concentration at the panel zone is the use of reduced web section (RWS) which ensures the formation of plastic hinge under loading, which will occur at the beam and not at the column. This project intent a parametric study on the cyclic performance of steel moment-resisting connections with RWS under finite element analysis consisting the effect of opening location, opening depth, opening length, opening corner radii, on energy dissipation capacities of steel beam with circular and elongated circular web openings and to find out the location of plastic hinge carried out by using a commercial finite element software ANSYS v.17.*

Key Words: Reduced web beam section, Cyclic loading, Energy dissipation, Nonlinear analysis.

1. INTRODUCTION

Design connections play an important role in multi-story buildings with structural steel frames. In these buildings unexpected damage occurs generally at the panel zone which causes brittle failure in the structures. Steel frames which are subjected to external loading experience the largest stress and strain demands in their most vulnerable locations i.e. at the beam-column joints where the connection welds and heat-affected zones are located.

It was observed that in many earthquakes, the major drawback in steel framed structures is the presence of crack in the panel zone followed by a brittle type of failure. After initiation, cracks propagate from the weld into other parts of the joint, depending on loading and connection characteristics. In some cases, it was found that the crack moves through entire weld and in other cases, the propagation will be through the flanges of column and in the worst case, extends to the column web and travels across the panel zone which results in total fracture across the column section. Once the beam column connection subject to fracture, it will undergo large reduction in strength and rigidity to resist the external force to open up the cracks. Presence of these cracks will leads to a large reduction in strength and stiffness of beam-column connection and will decrease the amount of dissipated energy within a loading cycle. Many factors are believed to contribute to the occurrence of brittle fracture; they are excessive beam strength, weld defects and notch effects, fracture toughness of deposited weld metal, low temperature, high stress triaxiality due to severe structural restraint conditions residual stresses, geometry of access holes and stress distribution on the flange of beam.

A schematic view of the typical failure modes of the welded beam-to-column connection is shown in Fig 1.

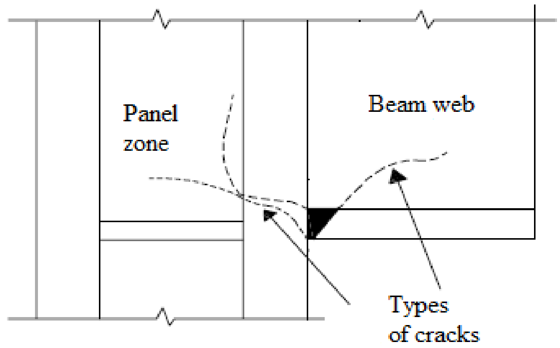

Fig 1.1: A schematic view of the typical fracture paths

The joints should be made with adequate strength and considerable stiffness to resist the external force like earthquake and wind loadings and internal forces by the framing members itself. It is essential for the connection to be sufficiently strong enough and robust, mobilizing the stresses to a desired location along the length of the beam away from the connection assembly, creating the "weak beam-strong column" mechanism with the formation of plastic hinges.

2. FINITE ELEMENT VALIDATION

The results of the FE model were compared with the experimental work conducted by D.T Pachoumis et al. on "Cyclic performance of steel-moment resisting connections with reduced beam sections – experimental analysis and finite element model simulation". The maximum applied moment that the experimental specimen experienced is 109 kNm, while the numerical corresponding result of the FE model is 112 kNm, which is only 2.7% different and when comparing the area of moment rotation curve for the last cycle it was found 8.77% different. The energy dissipated, E, is equivalent to the area under the hysteretic curve which is computed using the trapezoidal rule .The values thus obtained were nearby to the referred journal values. Hence validation of the software is considered okay.

3. ANALYTICAL STUDY

Modelling of structure had a prime importance in the software analysis. Each element in structure like beams, columns, slabs etc. are modelled as solids and their properties are assigned to them for its realistic nature. These are done using ANSYS Workbench 17 software. A simulation similar to the structure is thus modeled in the software before analysis to obtain accurate results. The Fig 2 shows specimen modelled with holes and the corresponding dimensions of the connection is shown in Table 1 and Fig 2.

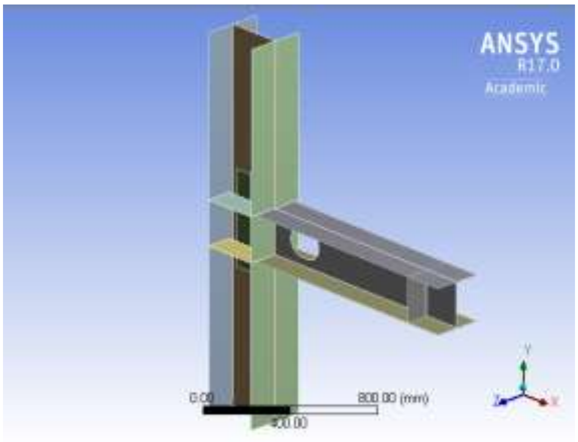

Fig 2: Specimen modeled with holes

Table -1: Dimension of the connection (All in mm)

Beam (HE300B)		Column (HE240A)		Continuity Plates		Doubler Plates	
h_b	300	h_c	230	h	262	h	460
b_b	300	b_c	240	b	130	b	208
t_{fb}	19	t_{fc}	12	t	12	t	12
t_{wb}	11	t_{wc}	7.5				

Figure 3 shows the beam and column cross sections

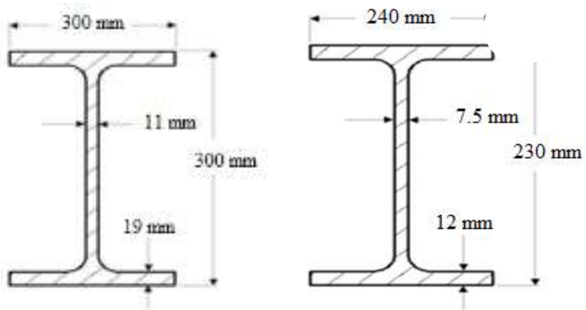

Fig.3: Cross Sections of (a) Beam (b) Column

The material properties of the specimen are shown in table 2.

Table 2: Material properties of steel

No	Property	Value	Units
1	Density	7850	Kgm^{-3}
2	Young's modulus	2.1E+05	MPa
3	Poisson's Ratio	0.3	
4	Bulk Modulus	1.725E+11	Pa
5	Shear Modulus	7.9615E+10	Pa
6	Multilinear Isotropic elasticity		

The analyses were conducted by applying cyclic variable amplitude displacement at the top of the beam at a distance of 1.00 m from the face of the column. The cyclic displacement amplitude followed the loading protocol in the AISC Seismic Provisions (AISC 2002), which is the same as the SAC loading protocol 1997. The specimen was loaded cyclically following the SAC loading protocol in order to identify its main cyclic response characteristics. The loading protocol is shown in Fig. 4

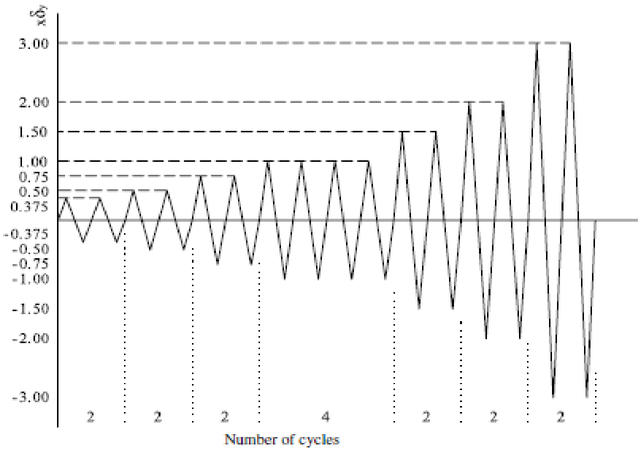

Fig.4: Loading Protocol

Once the mesh generation is complete, loading and supports are supposed to be given. For the analysis of beam column joint under cyclic loading in ANSYS, the top and bottom end of the column was fixed, displacement degrees of freedom in 1,2,3 directions (U1, U2, U3) as well as rotational degrees of freedom in 1,2,3 directions were restrained to be zero. The cantilever end of the beam was kept free. Cyclic load is applied for all the different models. The loads are applied at a distance of 1000mm from the column face where a stiffener is placed.

Large number of parameters should be considered in analysis to evaluate the complex behavior of steel beams with web openings. Using finite element model a parametric study were carried out to find the behavior of circular and elongated circular web opening model subjected to cyclic loading. The parametric study mainly focuses on the effects of the opening location ratio, opening depth ratio, opening length ratio, and ratio of opening corner radii.

From the literature study conducted in the earlier chapter it is clear that beam with round openings perform better than rectangular openings when considering connection rigidity, stiffness, and formation of local buckling that can occur on the opening corners. This improved performance helps to decrease concentration of stresses at beam column joint and also helps the availability of larger web regions in the remaining tee-sections that are helps to carry shear. Therefore, in this present study, the parameter, λ, ie, opening corner radii is considered as unity which helps to obtain circular or elongated circular openings.

The specimens are labeled in such a way that, opening location ratio, opening depth ratio and opening length ratio can be identified from the label. For example in the label D2 300 indicated web opening of category D (change β) in with second combination of opening depth and length ratio at a distance 300 mm from column face.

2.1 Effect of a/H and b/H ratios on energy dissipation

The choice of the opening depth and length can alter stress and strain distributions around the web opening and connection welds. To analyse the variation of energy dissipated for openings with different length and width a total number of 20 models were created with making value of a/H constant as 0.5, 0.6, 0.7, 0.8, and 0.9 while varying b/H from 0.5 to 0.8 with a difference of 0.1. The following graphs show the variation of energy dissipation with respect to the a/H and b/H ratio.

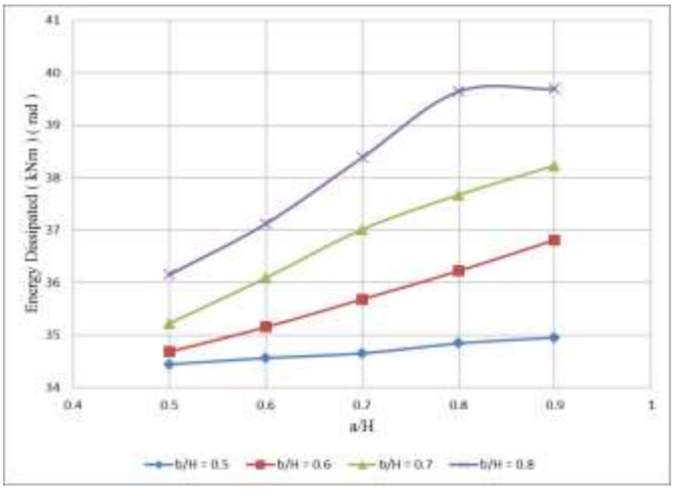

Fig 6: Energy dissipated vs a/H when b/H=0.5,0.6,0.7,0.8

According to the figure, as the opening size increases, the contribution of RWS to the overall energy dissipation of connection increases, in which larger openings dissipates more energy during cyclic loading. For larger openings as the dimensions increase the magnitude of total dissipated energy increases gradually and then become nearly constant. It is worthy to note that for openings with small length, almost the entire area above and below the hole yields, while for the openings with greater dimension plastic hinges are formed at the tee sections which helps to dissipate more energy.

Analysis results for equivalent stress for beams with perforations β = 0.8 H, γ = 0.8H is shown in fig 7

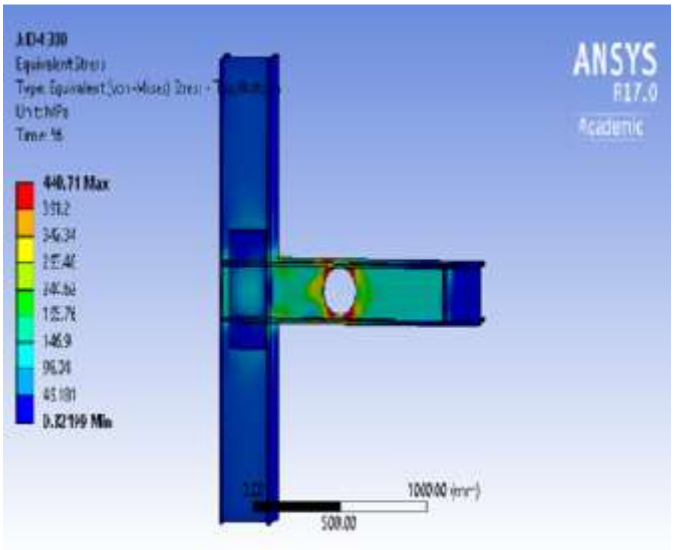

Fig 7: Equivalent von-Mises stress formation for D4 300 (β = 0.8 H, γ = 0.8H)

From the figure it is clear that the value of energy absorption increases with increase in radius. As the size of the opening increases, the plastic hinges action takes place which helps to dissipate seismic energy and circular web opening with diameter equal to 80% of beam depth ideally relocate plastic hinge from beam column joint to web opening.

2.2 Moment-rotation curves of solid beam and D4 300

The moment–rotation (M–θ) curves were derived from each analysis to present the hysteretic performance of the beam-to-column connections and particular characteristics of the amount of energy dissipated.

The hysteretic curves were determined based on the moment capacity at the column center line and the total rotation of the beam at 1000 mm away from the face of the column.

The rotations were defined from the vertical displacement of the beam divided by the distance to the column center line and the moment can be defined as the force reaction multiplied to the distance from column centerline to load application.

The Fig 8 below shows the hysteretic curve of solid beam and D4 300 (configuration having highest energy dissipation capacity).

The value of energy dissipation is obtained from the area under the moment rotation curve. Thus from the above graph it is clear that with the introduction of web opening will leads to the increase of energy dissipation when compared to solid beam (without any opening).

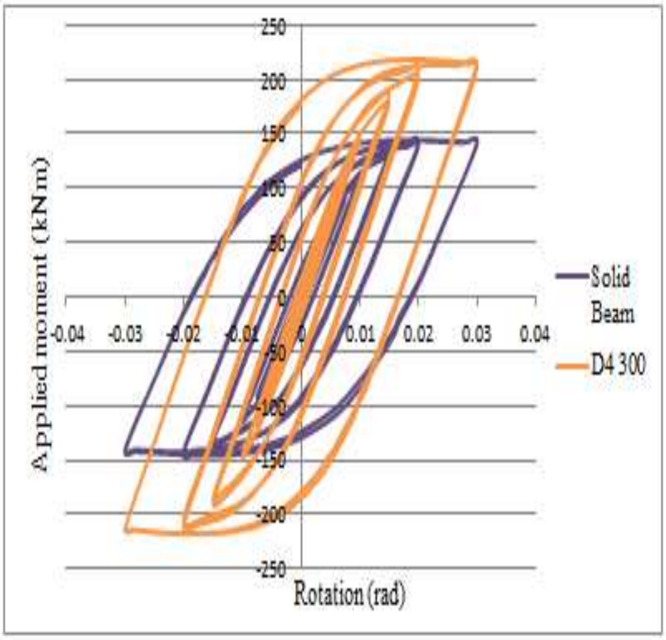

Fig 8: Hysteretic curve for solid beam and D4 300

Table 3 shows energy dissipation corresponding to solid beam and D4 300

Parameter	Solid Beam	D4 300
Energy Dissipated (kNm)(rad)	33.41	39.64

The table above typically shows the amount of energy dissipated in beam column joint with and without web openings.

The beams with web openings shows 18.65% increment in energy dissipation compared to one without holes.

2.3 Effect of orientation of opening

To evaluate the complex behavior of steel beams with web openings, the orientation of openings in beam web should be considered. In the table given below the first geometry indicates the elongated circle with longer side is parallel to the web axis and the second geometry have elongated circle with longer side perpendicular to the total depth of the beam.

The Table 4 and Fig 9 indicate energy dissipation corresponding to orientation of opening.

Table 7.4: Energy dissipated corresponding to various geometric parameters

Sl.no.	Specimen Name	Geometric parameters	Energy Dissipated (kNm)(rad)
1	A2	β = 0.5 H, γ = 0.6H	34.56
	B1	β = 0.6 H, γ = 0.5H	34.68
2	A3	β = 0.5 H, γ = 0.7H	34.65
	C1	β = 0.7 H, γ = 0.5H	35.22
3	A4	β = 0.5 H, γ = 0.8H	34.84
	D1	β = 0.8 H, γ = 0.5H	35.85
4	B3	β = 0.6 H, γ = 0.7H	35.78
	C2	β = 0.7 H, γ = 0.6H	36.09
5	B4	β = 0.7 H ,γ = 0.8H	36.22
	D2	β = 0.8 H, γ = 0.7H	37.12
6	C4	β = 0.7 H ,γ = 0.8H	37.67
	D3	β = 0.8 H ,γ = 0.7H	38.38

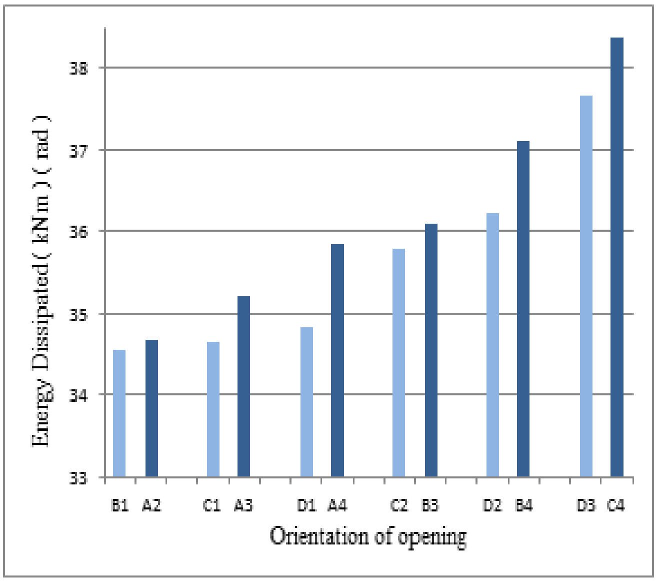

Fig 7.25: Energy dissipation vs orientation of opening

From the figure it is clear that the elongated circle with depth of opening lies across the depth of beam dissipated more energy during cyclic loading compared to the other.

3. CONCLUSIONS

- As the opening dimensions increases the magnitude of total dissipated energy increases gradually.
- When considering circular perforations as radius increases, the value of energy dissipation also increases and shows better performance when the depth of perforation is about 80% of the depth of

beam which ideally relocate plastic hinge from beam column joint to web opening.

- For beams with elongated circular web openings, the one with longer side lies across the depth of beam perform better due to the formation of plastic hinge in the two tee sections which helps to dissipate more energy.

- Comparing all models it is concluded that larger perforated beam perform better than smaller ones.

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