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Review on Steel Beams with Web Openings

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***Abstract:*— Modern multi-storey buildings have limitations in floor height because of economic concerns and architectural considerations. Utilities like air ducts, water pipes, etc. require a large space thus compromising the headroom. Steel beams having openings in web are found to be very effective in providing for the loss of this headroom. Lately, the structural designers have been providing such beams to accommodate building services within the construction height as it reduces material volume without affecting strength of the structure or serviceability requirements. According to research, there is a tendency to use building services which require the openings to be upto almost 75% of depth of beams. Rigorous research is carried out on the load carrying capacity of structures having beams with web openings. Experiments have been performed and numerical analyses have been carried out to determine the effectiveness of such beams. This review endeavours to present the research in a collective manner with particular emphasis on behaviour of steel I beams with openings of various shapes under shear and flexure.**

***Index Terms* - buckling, flexure, load carrying capacity, openings, shear.**

I. INTRODUCTION

Steel beams having openings in web are broadly used for various types of structures in, automobile industry, storages, commercial and industrial buildings, warehouses, towers, crane girders, multi-storey residential buildings, etc. The openings in web facilitate the proper access for inspection, maintenance and repair work. Apart from providing head- room and accommodating the services like plumbing, air- ducts, etc. it also reduces the overall weight of the struc- ture. However, there are certain drawbacks to use of such a system since load carrying capacity is reduced and the shear area is compromised because of the part of the web being cut. These losses can be compensated by providing maximum possible web opening area for service integration while keeping the self weight and section capacity losses to the minimum. Fig.1 shows the applications of steel beams with web openings. Optimization problem is discussed in terms of sizing, shape and topology optimization using FEA package[1]. The objective was to show that a significant reduction in overall weight of the structure is realized by providing web openings without compromising strength of the structure or serviceability. A rigorous review covering many aspects of thin walled structures having web open- ings, which are very significant in aircraft industries, ship building and nuclear industries [2].

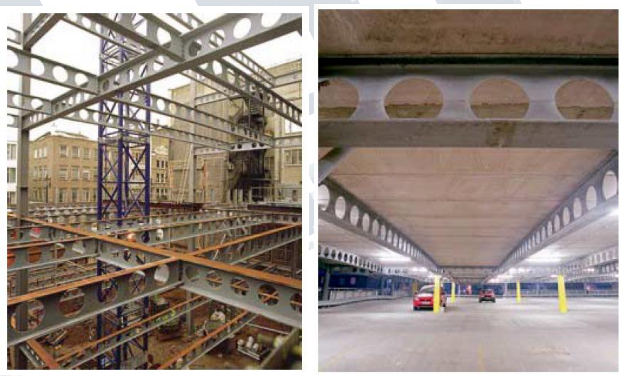

Figure 1: Applications of beams with web openings

For a given I-section with an opening in the web, the cross section suffers a loss of shear area leading to severe reduction of shear strength of the section. However, the second moment of area does not reduce as drastically and so the moment capacity reduction is not as severe. Various hypotheses have been proposed and tested so as to com- pensate for the loss of strength because of the punch-out. Experiments were performed by researchers and numerical models were proposed which modelled them accurately. Fi- nite element packages were used to study and model the experiments.

II. SHEAR AND FLEXURE

This section describes the research on cold formed and hot rolled steel sections with web openings. It mostly con- cerns the actions under shear and bending.

A. Cold Formed Sections

Experimental and analytical investigations of the struc- tural behaviour of cold-formed steel C-sections with and without web openings subjected to pure bending, pure shear and a combined bending and shear were performed [5]. It was claimed that the presence of a web punch out would re- sult in a measurable decrease in the structural performance of the web. Based on the findings of studies of the be- haviour of sections with web openings subjected to uni- form shear force, the nominal shear strength was found to be determined by applying a strength reduction factor to strength calculations for a cross section without web punch outs. Both linear and non-linear reduction factors were de- veloped, which when applied to the nominal shear strength determined by the present American Iron and Steel Institute (AISI) design provisions gave reliable design strengths.

The influence of web openings on strength of compres- sive elements and web-crippling strength of cold formed sections was investigated [3]. Considerable research has been done on the behaviour of cold formed steel and on comparison with hot-rolled sections, it has been very well established to be equally effective. Three main parameters considered for this study were opening size, shape and slen- derness of the web. For this analysis, the author used the provisions of Canadian standards, which do not specify con- ditions for beams with web openings. Intense experimental program was carried out on C-shaped lipped channel sec- tion. On the basis of the experimental results, the author de- rived equations for the influence of the web openings using a non-linear curve fitting technique. The influence on com- pressive strength was predicted by the authors via a simple empirical equation.

A series of experiments on such sections under the given loading conditions was conducted at the University of Missouri-Rolla (UMR) [4]. In addition to web-crippling, research has been done on the behaviour of cold formed steel in response to other types of loading like bending, shear and their combinations. According to the authors, the plastic moment capacity of the section can reduce by 40% because of a web opening and the shear capacity would re- duce by an empirical quantity called shear reduction reduc- tion factor, proposed by [5]. The shear failure was seen diagonally around the corners of the opening whereas the bending failure occurred at the midspan as shown in Fig.2. These two patterns occurred almost simultaneously leading to the conclusion that this was the mode of failure because of combined shear and bending.

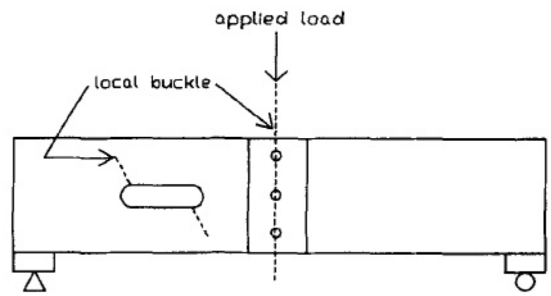

Figure 2: Combined bending and shear failure mode

The authors concluded that the interaction equation em- ployed by the American Iron and Steel Institute (AISI) spec- ification did provide an adequate strength prediction, pro- vided that the shear and bending capacities were modified to account for the influence of the web opening.

B. Hot Rolled Sections

A rigorous study of Vierendeel mechanism in beams with web openings was performed [6]. Such beams are also known as perforated beams (or cellular beams in case of circular openings). Openings in the web are bound to reduce the load carrying capacity of the section via three different modes of failure at perforated section viz. shear failure due to reduced shear capacity, flexural failure due to reduced moment capacity and the 'Vierendeel' mecha- nism, as shown in Fig.3, due to the formation of four plastic hinges in the tee-sections above and below the web open- ings under the Vierendeel action, i.e. transferring of lateral shear force across a web opening. The term Vierendeel mechanism seems to be coined from a type of truss known as Vierendeel truss, a structure where the members are not triangulated but form rectangular openings, and is a frame with fixed joints that are capable of transferring and resist- ing bending moments.

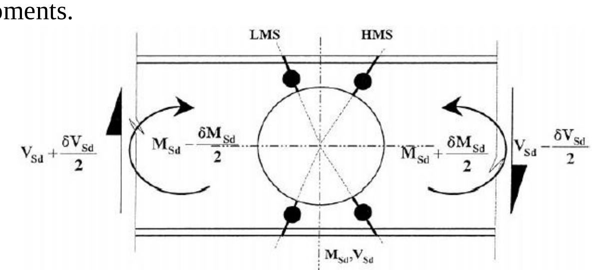

Figure 3: Vierendeel Mechanism

In order to determine the load carrying capacity of the perforated beam, the Steel Construction Institute, SCI's publication gives a linear interaction relation between shear and moment. It assumes that the capacity of the section is reached when plastic hinges are formed at the top tee sec- tions at the low moment side of the web opening. This method was regarded as conservative and instead claimed that

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the beams can carry load until the formation of four plastic hinges at critical sections of the beam which form the 'Vierendeel' mechanism. Authors investigated the said mechanism in steel beams with circular openings based on analytical and numerical studies. To simulate the actual be- haviour of steel beams with web openings under co-existing actions, a finite element model was prepared with material non-linearity and bilinear stress-strain curve and geometric non-linearity was also incorporated in order to accurately predict large deformations. An empirical relation was de- rived from the results of the FE analysis given. It was ob- served that the load carrying capacity of steel beams with circular web openings are 5-10% higher than those obtained from the linear interaction equation. Also, the presented formula gave an enhanced strength assessment on the mo- ment capacities of tee sections under co-existing axial and shear forces [6].

A provision of a modified design method [7] which used a generalised moment-shear interaction for steel beams with large web openings of various shapes and sizes was devel- oped. Another empirical model was developed this time keeping into view various kinds of shapes of openings. For this purpose, a 'vierendeel' parameter which is governed by critical opening length, was established as a part of the empirical relation. Eight shapes and three sizes were con- sidered for a FE analysis and it was found that moment- shear interaction curves for all models were similar in pat- tern, which confirmed the suitability and hence the need of a generalised curve. All the curves converged to the same x-intercept, i.e. having the same moment capacities under zero shear force provided that the web openings have the same depths. Also, all the curves had different y-intercepts, i.e. different shear capacities at perforated sections under zero moment possibly due to the different local Vierendeel moments acting onto the tee-sections above and below the web openings.It was observed that increase in the opening depth, do , reduced both the shear and the moment capac- ities of the perforated sections, and thus, both shear and flexural failures of perforated sections were known to be primarily controlled by the magnitude of do and an increase in the opening length, c, directly increased the 'Vieren- deel moments acting onto the tee-sections thus promoting the 'Vierendeel mechanism in the perforated sections. A generalized empirical model was developed by the authors which could be used for various shapes of openings. For web openings with small opening lengths under high shear force, shear failure was found to be apparent in the perfo- rated section; for web openings with large opening lengths under high shear force, 'Vierendeel mechanism was dom- inant in the perforated section and for web openings with large opening depths under low shear force, flexural failure in the perforated section was found to be critical. To quan- tify the 'Vierendeel' mechanism, the Vierendeel parameter, vi , was established and was governed by critical opening length.

An analytical study to study was performed by [8] the behaviour of perforated steel beams with different shape configurations and sizes of openings and investigate their moment-shear interaction behaviour. FE models were cre- ated in ANSYS with two large isolated openings. A total of 11 forms of opening were considered; circular, square, rect- angular, hexagonal, elliptical and 45o rotated elliptical. The critical opening length 'c' is the main dimensional param- eter since the width of the web opening influences the load carrying capacity of the perforated sections. The geomet- ric configurations of web openings along with the opening depths are shown in Fig.4. The FE model included both material and geometric non-linearity; for the material mod- elling of steel, a bi-linear stress-strain curve and the Von- Mises yield criteria was used. The analyses were performed on simply supported beams of 5m span under a uniformly distributed load. The FE model was calibrated against ex- perimental data [9]. The plastic hinge formation near the web openings was observed by Von Mises stresses. Since the web opening width for vertical and rotated elliptical openings is lower, their performance was found to be better than circular and hexagonal openings.

New design equations were developed empirically which were claimed to be an improvement over the previous ver- sion [10]. The previous versions were found to be upto 40% conservative when compared to the empirical formula which clearly concluded the cost-effective nature of pro- posed formula. Various FE models were developed with simply supported beams with circular openings of various sizes and at various locations in order to study the modes of failure. Steel beams having openings in web are very well known to reduce weight of the structure substantially and thus analysing those for different support conditions under different types of loading conditions was of great impor- tance.

A parametric study on a FE model of ISMB300 of 5.0m span was performed [12]. Three types of opening shapes were studied viz. circular, square and hexagonal. Also, sup- port conditions were kept variable with a constant ratio of depth of web opening to depth of beam and a constant value of uniformly distributed load on the beam. Value of buck- ling load was found to be nearly same for square and hexag- onal shapes but more for circular openings for any support condition. Also, buckling load was found to be more in case of beams with restrained support conditions than those

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with unrestrained and simply supported conditions. Experiments were performed [13] on 7 different models of such beams in order to identify maximum load behaviour

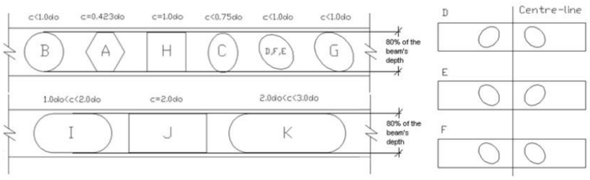

Figure 4: Geometric configurations of web openings

and deflection. Vertical loads were applied on samples of laterally unrestrained ISMB100 beams, which were simply supported with a concentrated load at the centre. Circular and rectangular openings were punched in the beam sam- ples for experimentation. Numerical models were devel- oped in ANSYS to study the non-linear behaviour of fail- ure modes. Material and geometric non-linearity was in- corporated in the model and a bilinear stress-strain curve was adopted for steel. From both the experimental and FE results, it was concluded that the ultimate load carrying ca- pacity is inversely proportional to the opening area and that the rectangular openings prove to be a critical case because of the stress concentration around its corners. In general, it was found that the results from numerical model accurately agreed with the experimental results. Owing to this valida- tion of the numerical model, it was used for a parametric study for an efficient opening type among circular, rectan- gular, hexagonal and octagonal. It was concluded from the parametric study that circular openings are best among all since there is no stress concentration; also, those are easy to fabricate and enhance the aesthetics [13]. The hexagonal and octagonal openings gave almost similar results for the load carrying capacity.

The bending strength of steel beams with corrugated webs was investigated [14] wherein the beams were tested to failure under uniform bending. The failure was observed as sudden and due to vertical buckling of the compression flange into the web. The test results indicated that the web offered a negligible contribution to the moment carrying ca- pacity of the beam. Non-linear finite element analysis was conducted in FEM package ABAQUS with bilinear elastic perfectly plastic material properties, and the model was cal- ibrated using test results. The numerical results agreed very well with the experimental results. Parametric studies were performed to examine the effect of the ratio between the flange and web thickness and yield stress, the corrugation configuration, the panel aspect ratio, and the stress-strain re- lationship. From the parametric study, it was concluded that the contribution of the web to the ultimate moment capacity of a beam with corrugated web is negligible, and the ulti- mate moment capacity would be based on the flange yield stress. The stress in the web due to bending were equal to zero except for very close to the flanges where the web was restrained.

[16] performed a Vierendeel bending study of perforated steel beams with various novel web opening shapes through non-linear finite-element analyses. A theoretical study of Vierendeel mechanism was done and the steel beams were studied for effect of opening shape and effect of position of web opening. Finite element study was performed in which different geometric parameters were isolated and studied to understand their effect. A comparison of global V-M interaction curves was done and accurate position of plastic hinges, critical opening length and Vierendeel parameter were determined. The main objectives of the study were to introduce web opening shapes with maximum depth of 0.8 times beam depth, propose an effective novel non-standard opening shape, study Vierendeel mechanism with respect to standard and non-standard opening shape as shown, per- form parametric studies on mid-range steel beams and com- pare structural behaviour of novel beams with typical per- forated beams.

The efficiency of longitudinal stiffeners welded at open- ing areas was investigated [18] via finite element analysis and studied the usage of edge concordance radius in beams with circular and rectangular openings. The presence of web opening in steel beams introduces three different fail- ure modes, i.e., shear, bending and Vierendeel collapse. The Vierendeel collapse, occurs due to the formation of four plastic hinges on the 'Tees' generated by the lateral shear force transmitted along the web opening. An increase of the web opening height reduces the beam shear and bending capacities whereas an increase on the web opening length do not significantly affect the beam shear and bending ca- pacities but increases the local Vierendeel bending moment acting on the Tees, reducing the perforated section Vieren- deel collapse capacity. Based on these observations, authors conducted rigorous FE simulations calibrated against nu- merical and test results. Further, a comprehensive paramet- ric analysis of beams with web openings was performed, which focussed on the profile size and web opening loca tion. It was observed that the beams with rectangular open- ings had smaller ultimate loads, almost 30% less than corre- sponding beams with square or circular openings. In these samples, the Vierendeel collapse mechanism was observed in all the beams with rectangular openings and was inde- pendent of the beam opening position on the span. A good agreement between the numerical and experimental results was also observed.

A parametric study of steel beams with web openings was conducted [19], wherein slender cantilever beams and simply supported beams with no openings, rectangular openings and circular openings were considered. Two soft- ware packages viz. ANSYS and SAP2000 were used to compare the results of the parametric study. The consid- ered specimens were investigated for lateral buckling capac- ity of beams with doubly symmetric I sections. Cantilever and simply supported beams were studied for the following cases: no opening, one rectangular opening at three differ- ent locations, 3 rectangular openings, 6 rectangular open- ings and 3 circular openings. The values of critical buckling load obtained from ANSYS and SAP showed a variation of 0-5% for cantilever beams and 0-6.5% for simply sup- ported beams. It was concluded from the parametric study that at the web opening, interaction between bending and shear is found to be weak. The authors suggested that the opening can be placed in the neutral zone which originates in midspan and stretches in the direction of beam support where shear force is maximum. It was also observed that as the location of openings changes from fixed support towards free end, buckling resistance increases and out of plane dis- placement decreases. The circular openings performed bet- ter than rectangular openings in all the cases.

An experimental study and a numerical study for rota- tional capacity of steel beams with web openings was per- formed [20]. The specimens under study were simply sup- ported steel beams with concentrated load at the midspan. From the experimental study, a few results were considered like, failure modes, load deflection behaviour and ultimate load carrying capacity. On obtaining the experimental re- sults, an elasto plastic finite element study was performed in ANSYS, which was calibrated accordingly. Moment curva- ture profile for simply supported beams was observed for beams with circular openings and compared with that of plain webbed beams. On comparing the results for steel beams with web openings with corresponding conventional plain webbed beams it was observed that ultimate load ca- pacity and the stiffness decrease with increase in opening area. The load deflection plots obtained from FE results compare well with experimental results. It was also ob- served that circular web openings were very effective in all respects since they show very less stress concentration at the web openings and are easy to fabricate and in ar- chitectural appearance. A parametric study was also per-

formed to study rotational behaviour of steel beams with circular web openings subjected to constant moment. Beam length was varied which involved investigation of simply supported beams under two point loading (pure bending). From the parametric study, authors reported 68% reduced ductility because of the presence of web openings.

III. CONCLUSION

Steel beams having openings in web have been analysed till date and remarkable progress has been made with re- spect to the shear and moment capacity as well has various types of buckling failures. Experimentation has also been done extensively and numerical models developed to deter- mine the effects of various other components like stiffeners, etc. Further research related to buckling of such beams un- der transverse loading needs to be studied and in future.

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