Experimental study and rotational capacity of steel beams with web openings

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ABSTRACT

This paper presents an experimental and analytical study on rotational behaviour of steel beams with web openings. An experimental study was performed on a prototype model of steel beams with web openings. Four specimens of hot rolled steel beams of ISMB 100, with different spacing to diameter ratio ($S/D_o$) were tested to investigate the failure mode and ultimate strength of steel beams with web openings. The beams were simply supported at the ends and subjected to a concentrated load applied at the mid span. After performing experimental study, all the beams were analyzed by the elasto–plastic finite element method by using general finite element analysis software ANSYS and the results were compared with those obtained experimentally. The test results indicate that the load-carrying capacity decreases with the increase in the openings area as well as position of the openings. The finite element results for deformation and ultimate strength shows good agreement with the corresponding values observed in the experiments. At last a parametric study was carried out by using finite element method to study the rotational capacity of steel beams with web openings. The result of parametric study shows that, web openings reduce the beam ductility till 68%.

Keyword: Steel beam with web openings (SBWO), Experimental study, Beam ductility, ANSYS, Finite element method.

1. Introduction

Now a day high-rise buildings of steel structure are of huge attention due to their many advantages, such as, ductility, fast construction etc. Since the construction cost of high-rise building steel structures is generally more than that of a concrete one, decrease of the construction cost of high-rise steel structures is of great importance for designers as well as builders. Many attempts have been made by engineers to decrease the cost of steel in buildings. Steel beams with web openings (SBWO), either hexagonal or rectangular, were first introduced into building technology in 1910 (AgIan et al., 1974), and then beams with circular web openings, referred to as cellular beams, were invented. The main purpose of providing openings in the web is that it can allow service pipes to pass through and thus the floor height is reduced (Chung et al., 2003). The use of such types steel beams has resulted in lightened and longer-span structures. Their recognition has also increased because of an architectural emphasis on exposed structures, with cellular, castellated and elongated web openings being typical in structural sections (Erdal et al., 2013). Sections having webs penetrated by large closely spaced openings over almost the full span are now common. According to experimental tests, there were 8 possible failure modes in steel beams with web openings (Kerdal and Nethercot, 1984; Mohebkah, 2004; Zirakian and Showkati, 2006). These failure modes are caused by beam geometry, web slenderness, type of loading, and
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provision of lateral supports. Under applied load conditions, failure is likely to occur due to one the following modes

1. Formation of a Vierendeel mechanism;
2. Lateral torsional buckling of the entire span;
3. Lateral torsional buckling of the web post;
4. Rupture of the welded joint;
5. Web post buckling due to shear force;
6. Web post buckling due to compression force;
7. Formation of a flexure mechanism;
8. Distortional buckling.

Considering the high usage of steel beams with web openings, particularly in high-rise buildings, study of their behavior is essential. Many investigations have been conducted regarding the behavior of these beams. The information available on beams with web openings does not cover optimum spacing to diameter ratio for circular openings which should be adopted safely without web post failure. The present study is, therefore, concerned with steel beams with web openings with varying the ratio of spacing to diameter ratio of openings. An experimental study on such beams consists of testing of four full scale models is described herein and the results from the experiments are compared with those obtained from finite element analysis. The intention of this study is of dual. First, the experimental results are used to calibrate the finite element modeling of steel beams with web openings using finite element analysis software ANSYS. Secondly, the parametric study was carried out to study the rotational behaviour of steel beams with circular openings subjected to constant moment. The test results are expected to provide an understanding of the behaviour of these beams in general. From experimental study, failure modes, load–deflection behaviour and ultimate load-carrying capacity are considered in the present investigation. Considering all these factors, steel beams with web openings (circular or rectangular) which is one of the suggested possible solutions for integration of technical utilities in buildings were tested up to failure. Geometric details for the design of these beams with web openings shapes are given in Table 1. The present work is predominantly experimental oriented, and experiments have been performed on models up to failure. The parametric study consists of the moment–rotation behavior of simply supported steel beams with web openings was compared with that of the corresponding plain-webbed beams. Simply supported steel beams with web openings subjected to constant moment have been modeled to study the rotational capacity of this type of beams.

**Table 1** Description of various beams

<table>
<thead>
<tr>
<th>Beams</th>
<th>Type of openings</th>
<th>Span of Beams (mm)</th>
<th>Diameter of Openings (mm)</th>
<th>Spacing/Diameter (S/D₀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBWO 1</td>
<td>Circular</td>
<td>1000</td>
<td>75</td>
<td>1.07</td>
</tr>
<tr>
<td>SBWO 2</td>
<td>Circular</td>
<td>1000</td>
<td>75</td>
<td>1.33</td>
</tr>
<tr>
<td>SBWO 3</td>
<td>Circular</td>
<td>1000</td>
<td>75</td>
<td>1.50</td>
</tr>
<tr>
<td>SBWO 4</td>
<td>Circular</td>
<td>1000</td>
<td>75</td>
<td>2.0</td>
</tr>
</tbody>
</table>
2. The experimental procedure

The beam having simply supported boundary conditions was set up in the loading frame with sufficient care taken to ensure that the specimen was correctly positioned in the loading frame and the midpoint of the beam was in line with the centre line of the loading hydraulic jack. The specimen was heavily gauged, as shown in Fig. 1, in an attempt to identify a primary mode of failure i.e. either buckling load for the web post, the formation of plastic hinges, or were calibrated properly. Before the actual test, a small preload not exceeding 5 percent of the expected ultimate load was applied slowly and removed in order to eliminate any slack in the support system so that the specimen would be properly seated on the supports. The loading and unloading process was repeated a few times and this procedure also helped to check whether the dial gauges functioned properly. Readings were initialised after ensuring that all instruments worked satisfactorily. The specimen was loaded first up to 20% of the expected failure load and then unloaded to zero value. It was observed that the deflection readings reached the initial values when unloaded. The procedure was repeated up to 35% of the expected failure load and the specimen was finally loaded to failure by increasing the load gradually by a predetermined increment. The five dial gauges were installed, three for measurement of vertical deflection placed at L/4, L/2 and 3L/4 respectively and two for measurement of lateral deflection of top and bottom flange respectively as shown in Fig. 1. The beam was then tested to failure. After the maximum load was attained and unloading occurred with increase in beam deflection, the load was then removed. The ultimate load and the mode of failure for each of the specimens were noted. The same test procedure was adopted for all the specimens.

![Figure 1: Experimental Test Arrangement.](image)

2.1 Materials properties

Tensile test coupons cut from the flange and web plates of the section segments were tested in order to determine the material properties required for the numerical modeling of the steel beams with web openings. For all of the test specimens, only four tensile coupons, i.e. two from the flange plate and two from the web plate, were cut out for the material test, as all test specimens made from the same section. The results, yield stress, ultimate stress and modulus of elasticity obtained from the coupon tests are given in Table 2.
Table 2 Material properties of the test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Actual Width</th>
<th>Actual Thickness</th>
<th>σy (MPa)</th>
<th>σu (MPa)</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1F</td>
<td>20</td>
<td>5</td>
<td>376</td>
<td>487</td>
<td>1.98 x 10^5</td>
</tr>
<tr>
<td>S2F</td>
<td>22</td>
<td>5</td>
<td>352</td>
<td>495</td>
<td>2.10 x 10^5</td>
</tr>
<tr>
<td>Overall average values</td>
<td></td>
<td></td>
<td>364</td>
<td>491</td>
<td>2.04 x 10^5</td>
</tr>
<tr>
<td>Web</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1W</td>
<td>20</td>
<td>4.7</td>
<td>322</td>
<td>450</td>
<td>1.96 x 10^5</td>
</tr>
<tr>
<td>S2W</td>
<td>20</td>
<td>4.7</td>
<td>337</td>
<td>430</td>
<td>2.01 x 10^5</td>
</tr>
<tr>
<td>Overall average values</td>
<td></td>
<td></td>
<td>329.5</td>
<td>440</td>
<td>1.99 x 10^5</td>
</tr>
</tbody>
</table>

3. Finite element analysis

The objective of this section is to carry out non linear finite element analysis of the steel beams with web openings that were considered in the experimental study in order to determine their ultimate load capacity for comparison. The finite element method has been used to predict their entire response to increasing values of external loading until they lose their load carrying capacity. These finite element models are used to simulate the experimental work in order to verify the test results and to investigate the nonlinear behavior of failure modes such as web-post buckling, shear buckling and Vierendeel bending of steel beams with web openings. In the present study, four noded shell 181 element with reduced integration points having six degrees of freedom per node is used. Nonlinear finite element models of these steel beam with web openings specimens are built to determine maximum values and locations of ultimate load, stress, strain and displacement concentrations under point loading. The objective of these analysis is to determine ultimate load, stress, strain and displacement in the steel beam with web openings and to compare experimental results with the results of observed nonlinear finite element analysis.

4. Results and discussion

The values of ultimate loads obtained from the experiments and finite element analysis are presented along with the comparison between the two values for all beams in Table 3. It has been observed from the experiments that stiffness and ultimate load of the steel beam with web openings decrease with an increase in the openings area (i.e. decrease in the S/D_o). Comparison between the ultimate loads obtained experimentally and those predicted by the finite element modeling presented in Table 3, shows that the finite element solutions are relatively close to the corresponding experimental results. It can therefore, be concluded that ANSYS analysis is reliable in predicting the ultimate strength of steel beams with web openings. Comparisons between experimental and finite element load-deflection curves have shown in figures 2, 3, 4 and 5 shows a satisfactory agreement between the analytical and experimental curves. It is clear from the figures that the experimental and finite element results are close in most beams except SBWO1 in which the two curves do not match well. The discrepancy between the two curves might be due to the inability of the ANSYS program. Fig. 6 shows the photograph during actual testing of the specimen SBWO2. Fig. 8 shows the von-misses stress distribution for SBWO1.
Table 3 Comparison of experimental and finite element ultimate load.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Spacing/Diameter (S/D₀)</th>
<th>Ultimate load Pu (kN)</th>
<th>Pu_{Ansys}</th>
<th>Pu_{Exp.}</th>
<th>Pu_{Ansys}/Pu_{Experimental}</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBWO1</td>
<td>1.07</td>
<td>09.00</td>
<td>14.25</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>SBWO2</td>
<td>1.33</td>
<td>29.00</td>
<td>31.50</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>SBWO3</td>
<td>1.5</td>
<td>30.00</td>
<td>31.00</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>SBWO4</td>
<td>2.0</td>
<td>30.96</td>
<td>32.50</td>
<td>0.95</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Load Vs mid span deflection graph for SBWO1

Figure 3: Load Vs mid span deflection graph for SBWO2
Figure: 4 Load Vs mid span deflection graph for SBWO3.

Figure: 5 Load Vs mid span deflection graph for SBWO4.

Figure: 6 Photograph showing actual testing of the specimen SBWO2
4.1 Parametric study based on rotational capacity of steel beams with web openings

To study the rotational behavior of standard ISMB100 a plastic section as per IS800-2007 (2007) beams with circular web openings were used and a parametric inelastic finite element model has been developed. The beam lengths were considered as a parameter. The simply supported beams are investigated under two point loading (pure bending) applying concentrated load at the each quarter point from the support. The results of steel beams with web openings models are compared with corresponding conventional plain-webbed I-shaped steel beams, to have a better understanding of moment-rotation behavior of steel beams with web openings. Full-depth stiffeners of 5 mm thickness were used in both sides of web at supports and under concentrated load. To compare the results with those of plain-webbed beam behaviour, the loading and boundary conditions similar to the simply supported beam. Fig. 8 shows the finite element model of the specimen, showing the boundary condition and applied load.
The two terms used herein, namely normalized moment and normalized rotation, for presenting the beam moment – rotation behavior. Based on the definition, normalized moment is equal to \( M/M_y \), where \( M \) is the moment applied on the member section at each instant and \( M_y \) is the moment causing the extreme cross-sectional fiber to yield. The normalized rotation is equal to \( \theta/\theta_y \), where \( \theta \) is the member section rotation at each instant and \( \theta_y \) is the cross-sectional rotation resulting in the yield of the extreme fiber. General information of the specimens is listed in Table 4. The rotation capacity of specimens is calculated using Equation (2), as given in AISC-2005 (2005), where \( \theta_u \) is the rotation when the moment capacity drops below \( M_p \) on the unloading branch of the \( M-\theta \) plot and \( \theta_p \) is the rotation at which the full plastic capacity is first achieved. \( L_p \) in the table denotes the length of plastic hinge needed for plastic buckling of the beam, \( M_y \) and \( M_p \) are the yield moment and plastic moment capacity of the plain-webbed beam, respectively. \( R_p \) and \( R_{SBWO} \) are the rotation capacity of plain-webbed and steel beams with web openings respectively.

\[
R = \left(\frac{\theta_u}{\theta_p}\right) - 1
\]  

(2)

A Figure 9, 10, 11, 12 and 13 shows the moment-rotation graphs for different lengths.

### Table 4: General properties of beam specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Beam Length (m)</th>
<th>( L_p ) (mm)</th>
<th>( M_y ) (kN-m)</th>
<th>( M_p ) (kN-m)</th>
<th>( R_p )</th>
<th>( R_{SBWO} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB1</td>
<td>1.2</td>
<td>523</td>
<td>9.15</td>
<td>10.42</td>
<td>9.2</td>
<td>3.96</td>
</tr>
<tr>
<td>SB2</td>
<td>2.0</td>
<td>523</td>
<td>9.15</td>
<td>10.42</td>
<td>8.36</td>
<td>3.12</td>
</tr>
<tr>
<td>SB3</td>
<td>2.5</td>
<td>523</td>
<td>9.15</td>
<td>10.42</td>
<td>10.5</td>
<td>5.16</td>
</tr>
<tr>
<td>SB4</td>
<td>3.0</td>
<td>523</td>
<td>9.15</td>
<td>10.42</td>
<td>16.2</td>
<td>8.26</td>
</tr>
<tr>
<td>SB5</td>
<td>4.0</td>
<td>523</td>
<td>9.15</td>
<td>10.42</td>
<td>14.34</td>
<td>9.67</td>
</tr>
</tbody>
</table>

**Figure 9:** Moment-rotation curve for length 1.2 m.
Figure: 10 Moment-rotation curve for length 2 m

Figure: 11 Moment-rotation curve for length 2.5 m

Figure: 12 Moment-rotation curve for length 3 m
5. Conclusions

In this study, moment-rotation behavior of simply supported steel beams with circular web openings was compared with that of plain-webbed beams. Based on the results of the investigation, the following findings and conclusions are presented for steel beam with web openings:

1. Test results show that the ultimate load capacity and the stiffness decrease with increase in openings area. Failure modes are similar for all the beams with web openings.

2. A comparison of the experimental and finite element ultimate loads shows that the finite element analysis using the ANSYS software is capable of predicting the elastic and ultimate load behaviour of steel beams with web openings with reasonable accuracy. The load–deflection curves obtained by finite element analysis also compare well with the corresponding results from the experiments.

3. It was clear that the web openings reduce the ductility of beams to a great extent, i.e. 68%.

4. Circular web openings found to be very effective in all respect i.e. show a very less stress concentration at the web openings, easy to fabricate and architectural appearance etc.

6. References


