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Experimental investigation for failure analysis of steel beams with web openings

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Abstract. This paper presents an experimental study on the behaviour of steel beams with different types of web openings. Steel beams with web openings became progressively more accepted as a well-organized structural form in steel construction since their existence. Their complicated design and profiling method provides better flexibility in beam proportioning for strength, depth, size and location of holes. The objective of this study is to carry out the experiments on steel beams with different types of web openings and performed non-linear finite element (FE) analysis of the beams that were considered in the experimental study in order to determine their ultimate load capacity and failure modes for comparison. Ten full scale models of steel beam with web openings have been tested in the experimental investigation. 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. FE model of each specimen that is utilized in the experimental studies is carried out. These models are used to simulate the experimental work to verify test results and to investigate the nonlinear behaviour of failure modes such as local buckling, lateral torsional buckling, web-post buckling, shear buckling and Vierendeel bending of beams.

Keywords: experimental study; steel beams with web openings; non-linear finite element analysis; failure modes; web post buckling

1. Introduction

The structural use of steel in the construction industry is perhaps increasing across the world, despite seeming to have reached maturity in some countries. New challenges in the structural use of steel are arising all the time, and research is being called upon to provide appropriate solutions. In such situations the used of steel beams with web openings is one of the suggested possible solution. Open web-expanded steel beams was initially used in structures for building, bridges, industrial structures and ship construction in different countries of the world like the U.S.A, U.K, Japan, Germany and other European countries during World War II to decrease the cost of steel structures.

Previously, researchers Redwood and Uenoya (1979) have treated the problem of webs as a stability problem of a perforated plate with simplified edge loadings and support conditions. Based on their experimental studies Coull and Alvarez (1980), have proposed an empirical method for determining the lateral buckling capacity of beams with a number of openings, either circular or rectangular. Nethercot and Kerdal (1982) and Kerdal and Nethercot (1984) investigated the performance and stability of castellated beams, in which they provided quantitative data on the lateral torsional buckling strength of castellated sections, and the similarity in the behaviour of castellated and plain-webbed beams was shown. The results of their study showed that web opening has a slight influence on the overall lateral torsional buckling behaviour of these beams. Thevendran and Shanmugam (1991) and Shanmugam and Thevendran (1992) proposed a numerical method to calculate the elastic lateral buckling load of narrow rectangular and I-beams containing web opening and subjected to single concentrated load applied at the centroid of the cross-section using the principle of minimum total potential energy. In an additional study by Mohebkhah (2004), the numerical procedure has been conducted to investigate the inelastic lateral torsional buckling behaviour of castellated beams.

Corresponding information may be found in Sweedan (2011), where propositions for the determination of the critical bending moment Mcr in cellular and castellated beams are given. Other investigations associated to instabilities in cellular or castellated beams may also be found in Sweedan (2011) and Verwij (2010), such as for flexural buckling behaviour. Main difficulties that have arisen with the use of perforated beams relate to the position of openings along the span of the beam, the shape the openings should have, how large the openings should be, and the closeness of the openings to each other. Chung *et al*. (2003), Tsavdaridis and D'Mello (2011, 2012) and Morkhade and Gupta (2015) has made significant experimental and theoretical research on steel beams with web openings in the last decade with the aim to maximize the web opening area and minimize the self-weight of the beam.

Various other aspects of structural behaviour of steel

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beams with web openings have been studied theoretically as well as experimentally by Kiymaz *et al*. (2010), Bayramoglu (2012), Erdal (2015), Durif *et al*. (2015). The failure mechanism of steel beam having plain and corrugated web with openings under shear, bending and compression are the main topics of investigations undertaken by most of the above researchers.

Considering all of this, it seems that no fully satisfactory experimental investigation showing failure modes of steel beams with web openings. Therefore, in this paper an attempt is made to perform a through experimental investigation for failure analysis of steel beams with web openings.

Fig. 2 White washing of the test specimen

2. Experimental investigation

Steel beams with web openings with two aspect ratios (defined as the ratio of length of opening to depth of opening), one beam having oval shape openings, one cellular beam, five different spacing to diameter ratios (defined as the ratio of center to center distance of openings to the diameter of openings, S/D_o), and one plain-webbed beam were tested to failure. The models tested of each category are mentioned in Table 1. For all beams, overall depth was maintained at 100 mm with nominal top and bottom flange width of 55 mm and the corresponding nominal thickness of flange 5 mm and that of web is 4.7 mm. Transverse stiffeners were made of flat plates 25 mm wide and 5 mm nominal thickness. Fig. 1 shows the cross section of the beams studied. All the test specimens were white washed by means of lime as depicted in Fig. 2 in order to identify the yielded and stress concentration zone properly. The reason is that as the yielding occurs the dry lime falls down from the sections and identification of stress concentration zones becomes easier. The details regarding the position of proving ring, loading jack, and dial gauge are highlighted in Figs. 3 and 4 respectively.

The other parameters are such as dimensions and location of stiffeners. The depth of the girder was kept constant in order to study the behaviour of the web post exclusively. In the fifth model the stiffeners were not provided whereas in remaining all specimens the transverse stiffeners were provided at locations where concentrated forces are likely to occur, i.e., at the center of the span and at supports, in order to prevent local buckling of the flange. All tested beams during experimental and numerical analysis having no lateral restrain i.e., laterally unrestrained beams.

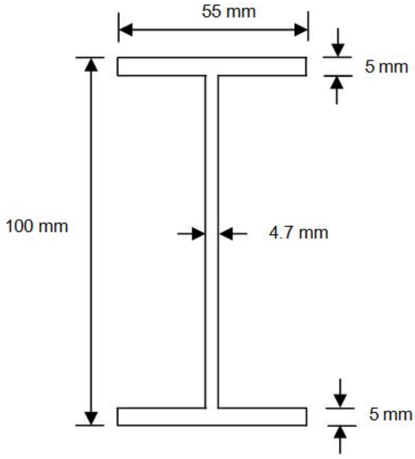


Fig. 1 Cross sectional details of ISMB 100

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 carrying 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 behaviour of failure modes such as web-post buckling, shear buckling and Vierendeel bending of steel beams with web openings. A 3-D finite element model is developed to simulate the behaviour of steel beam with web openings having an I-shaped cross-section using the finite element package ANSYS v12. The summary of the finite element procedure which was used for the comparison of the experimental work is as follows:

- In the present study, four noded shell 181element with reduced integration points having six degrees of freedom per node is used;
- Geometric as well as material non-linearity are considered in beams model;
- Solver by iterations according to Newton-Raphson;
- The material properties obtained as per coupon test are used in the analysis;
- A bilinear stress-strain curve with a Young's modulus, E of 210 GPa and a Tangent modulus, E_T, of 5000 MPa was used in material modelling of steel together with the von Mises yield criterion and the kinematic hardening rule, which is suitable for steel;
- The large deformation effects has been considered in the analysis to accounts for geometrical non-linearity present in the models;
- The initial imperfection of L/1000 was used in the analysis;
- The load was applied stepwise as pressure.

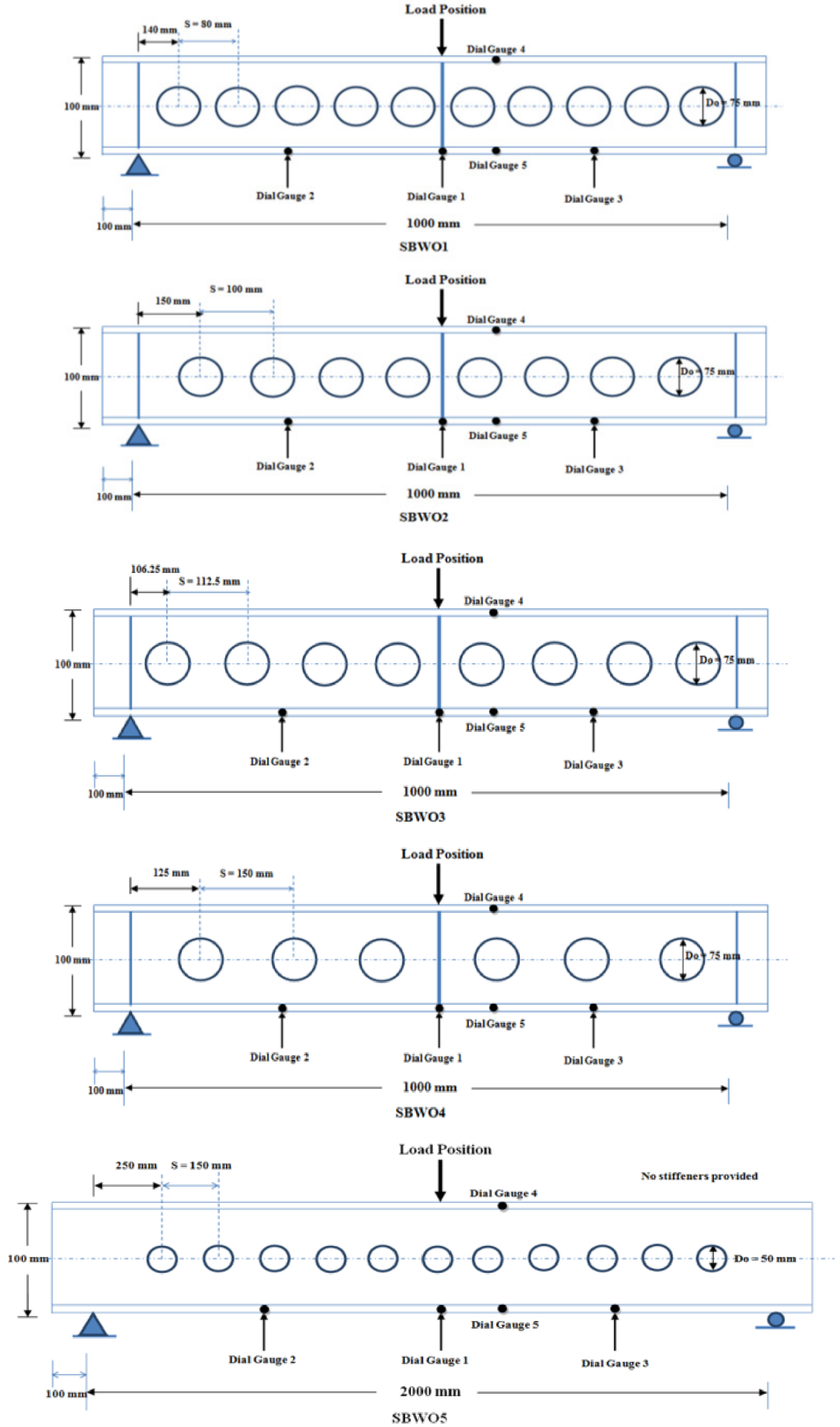


Fig. 3 Geometrical details of steel beams with web openings

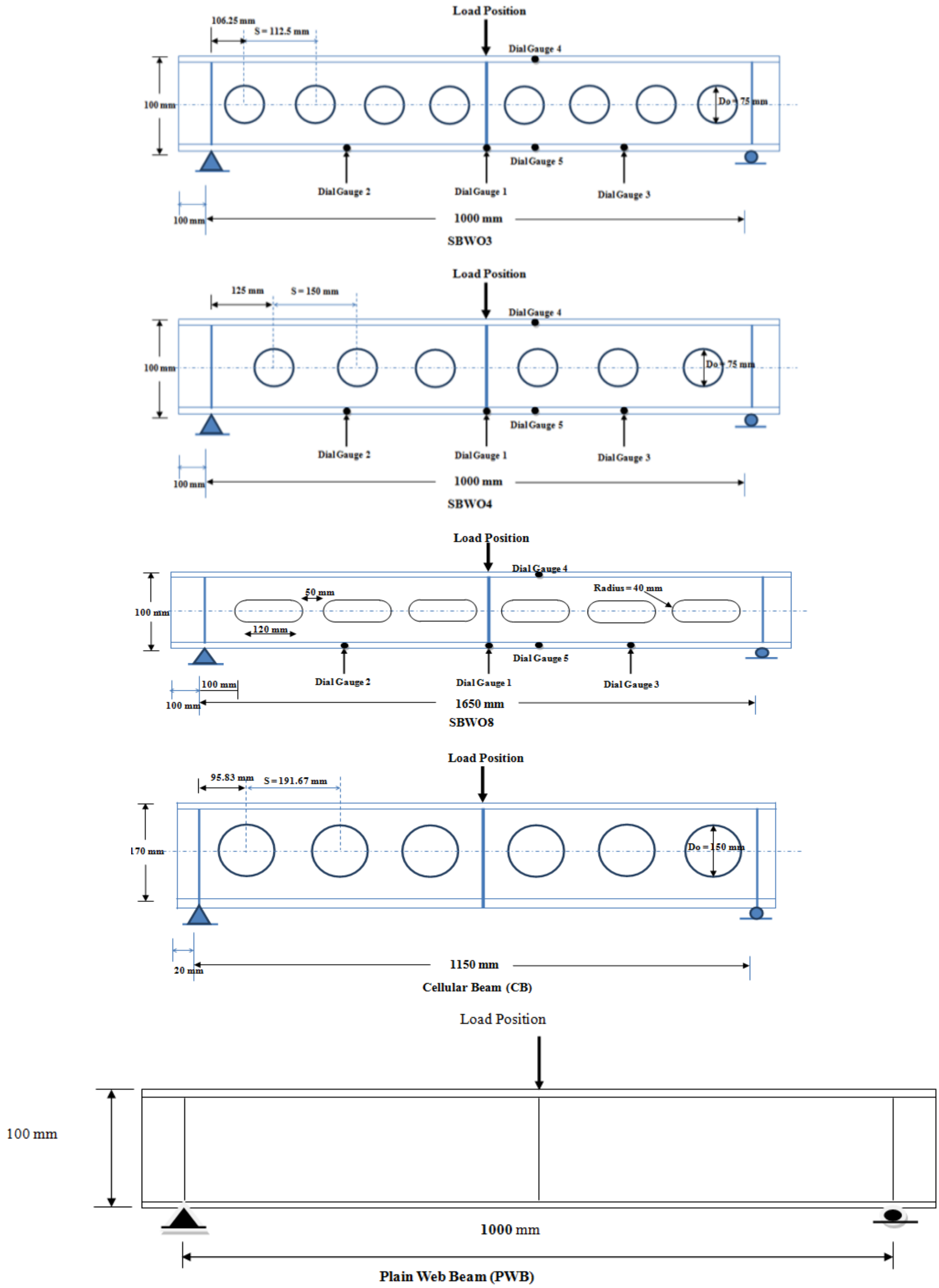


Fig. 3 Continued

Fig. 5 shows the finite element model of plain-webbed steel beam and steel beams with circular, rectangular and oval shape web openings. Nonlinear finite element models of these steel beams with web openings specimens are built to determine maximum values and locations of stress, strain and displacement concentrations under point loading. The objective of these analyses is to determine the ultimate load, stress, strain, displacement and different failure modes in

Fig. 4 Typical view of the experimental test set-up

the steel beam with web openings and to compare experimental results with the results of observed nonlinear finite element analysis.

4. Experimental observations

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 1. Variations of mid span deflection with the applied load for typical beams are as shown in Figs. 6-15.

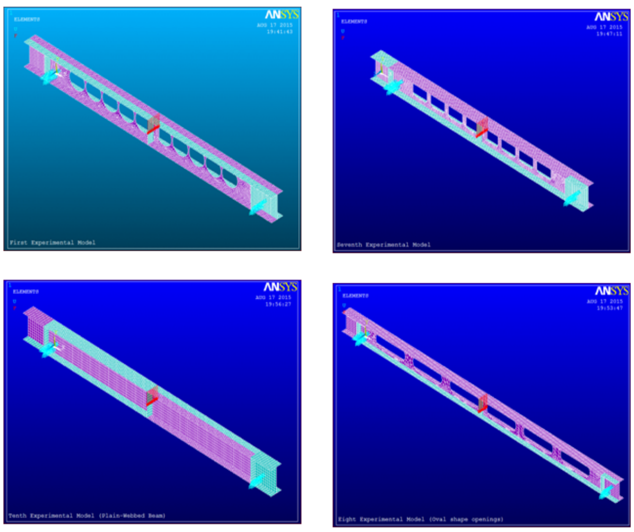


Fig. 5 Finite element models of beams

It has been observed from the experiments that the stiffness and the ultimate load of the steel beam with web openings

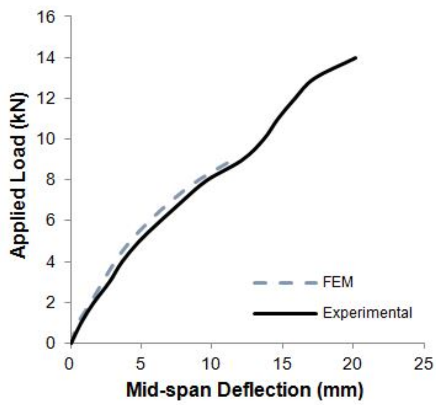


Fig. 6 Load vs mid span deflection graph for SBWO1

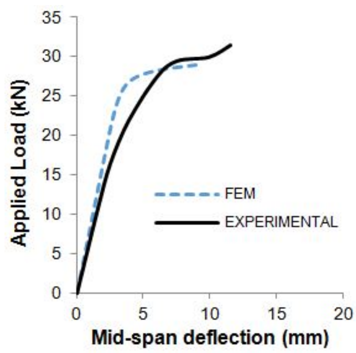


Fig. 7 Load vs mid span deflection graph for SBWO2

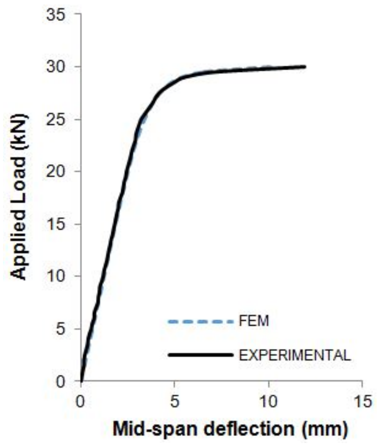


Fig. 8 Load vs mid span deflection graph for SBWO3

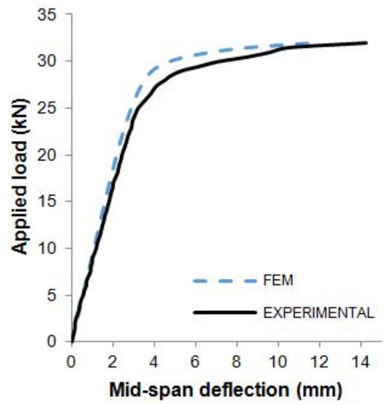


Fig. 9 Load vs mid span deflection graph for SBWO4

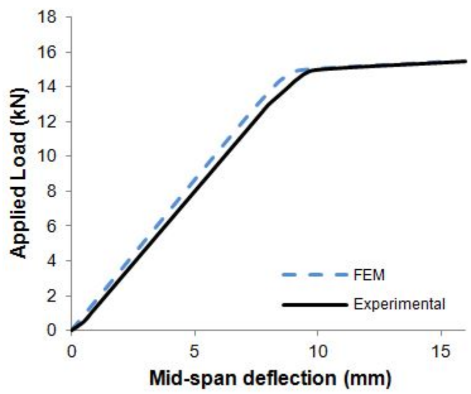


Fig. 10 Load vs mid span deflection graph for SBWO5

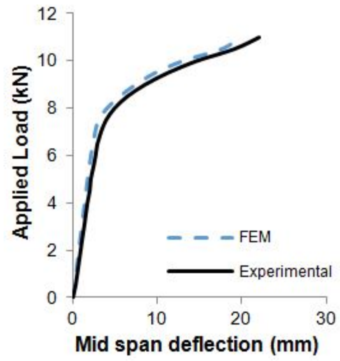


Fig. 11 Load vs mid span deflection graph for SBWO6

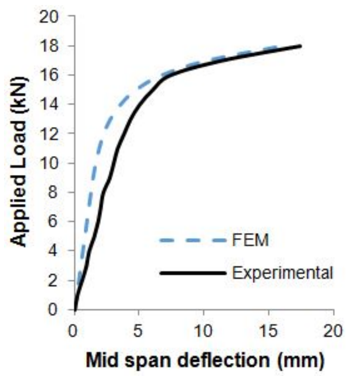


Fig. 12 Load vs mid span deflection graph for SBWO7

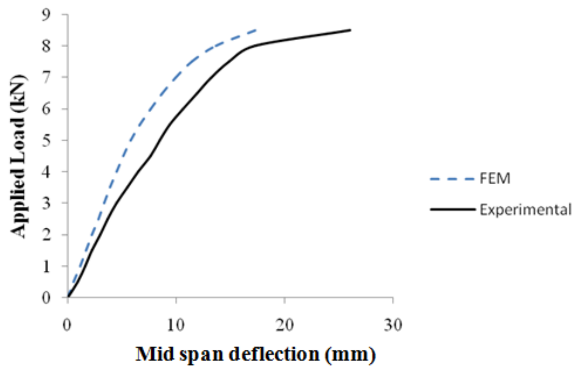


Fig. 13 Load vs mid span deflection graph for SBWO8

decrease with an increase in the opening area (i.e., decrease in the S/D_o ratio) for steel beams with circular web openings. Comparison between the ultimate loads obtained experimentally and those predicted by the finite element modeling presented in Table 1, 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 showed in Figs. 6-15 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 in some cases (SBWO1, SBWO6, and SBWO7) in which the two curves do not match well. The main reasons which are responsible for difference in experimental and numerical failure loads is mainly due to human error in experimental work, variation in material properties and stiffness of members. Fig. 16 shows the deformed shapes found in experimental and finite element studies for SBWO1 having S/D_o equal to 1.07. The SBWO1 is failed by web-post buckling before the formation of the plastic hinges, since the width of the web-post in this case was not sufficient to carry shear at the supports. A similar failure mode as in case of SBWO1 was found in SBWO2. Fig. 17 shows the excessive stress

Table 1 Comparison of experimental and finite element ultimate load

Specimen	Span of beams (m)	Spacing/diameter (S/D_o)	Aspect/ratio (L/D)	Ultimate load Pu (kN)		Pu_{Ansys}/ $Pu_{\text{Experimental}}$	Primary failure modes
				Pu_{Ansys}	$Pu_{\text{Exp.}}$		
SBWO1	1.0	1.07	-	09.00	14.25	0.63	WPB
SBWO2	1.0	1.33	-	29.00	31.50	0.92	WPB
SBWO3	1.0	1.5	-	30.00	31.00	0.96	WPY
SBWO4	1.0	2.0	-	30.96	32.50	0.95	WPY
SBWO5	2.0	3.0	-	15.98	16.50	0.96	FLB/LTB
SBWO6	1.0	-	1	18.00	25.00	0.72	Vierendeel Mechanism
SBWO7	1.0	-	1.33	11.00	14.50	0.76	Vierendeel Mechanism
SBWO8	1.65	-	-	9.50	12.0	0.80	Vierendeel Mechanism & Bending at load application point
CB9	1.15	-	-	32.0	36.0	0.89	WPB / Vierendeel Mechanism
PWB10	1.0	-	-	45.0	49.0	0.92	Bending at load application point

* SBWO: steel beam with web openings FLB: flange local buckling PWB: plain-web beam
LTB: lateral torsional buckling WPY: web posting yielding WPB: web post buckling

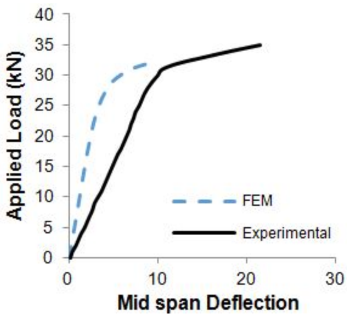


Fig. 14 Load vs mid span deflection graph for SBWO9

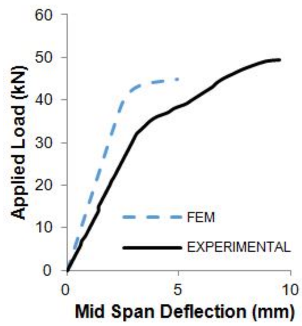
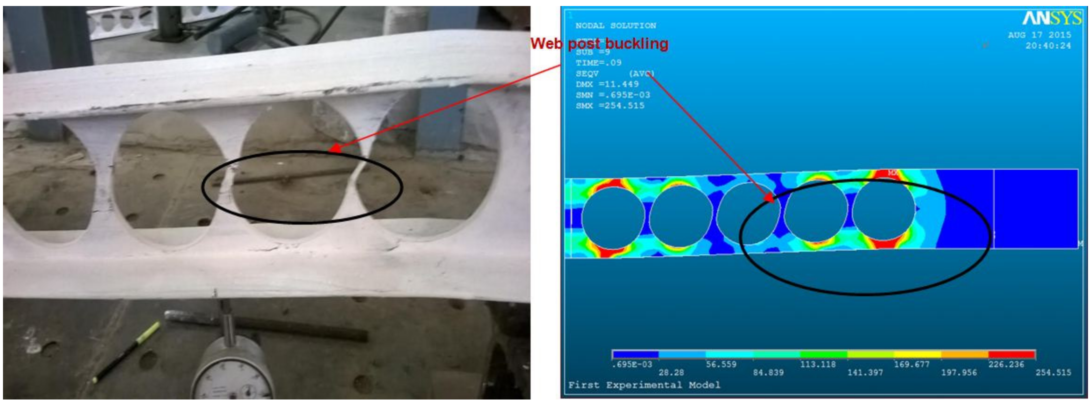


Fig. 15 Load vs mid span deflection graph for SBWO10



(a) (b)

Fig. 16 Comparison of deformed shaped for SBWO1: (a) FEM; (b) Experimental

concentration in the web-post found during the experimental investigation for SBWO4. The specimen SBWO5 was failed by flange local buckling (which was occurring due to absence of load bearing stiffener under the load) and lateral torsional buckling. Fig. 18 shows the small lateral deflection observed during the testing of the fifth model (SBWO5). Rectangular openings were found to be very critical as it shows very high stress concentration around the corner regions of openings. To avoid this high stress concentration there is a practice of providing corner radius of five times the thickness of web. Figs. 19 and 20 shows the stress concentration observed during the experimental and finite element analysis for SBWO6 and SBWO7. This is one the prime failure mode in perforated beams, which is due to the formation of four plastic hinges around the corners of openings, is called as Vierendeel mechanism. The SBWO8 having the oval shape web openings is also failed due to the formation of plastic hinges around the

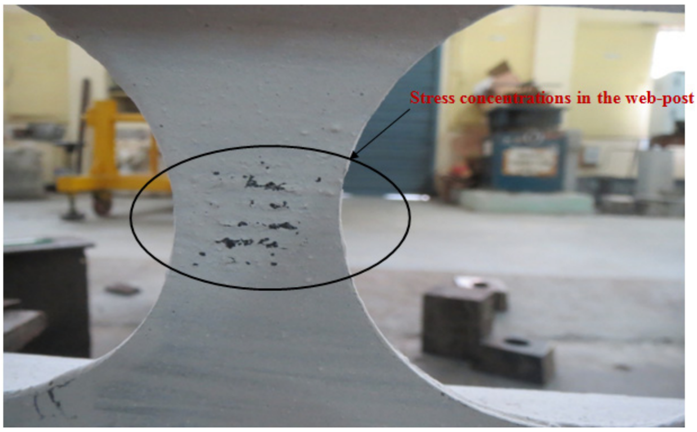


Fig. 17 Stress concentrations in the web-post SBWO4

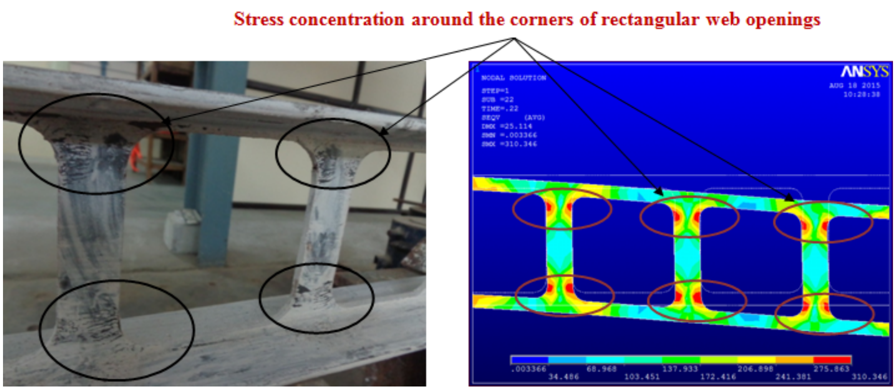
Fig. 18 Lateral movement of SBWO5 during experiment

corners of web openings as shown in Fig. 21. Figs. 22 and 23 show the deformed shape for cellular beam (CB9) and plain-webbed beam respectively.

5. Conclusions

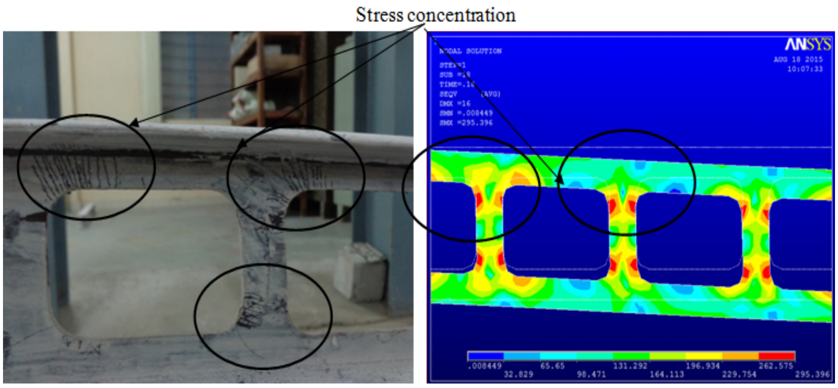
This paper presented an experimental and finite element study examining the static behaviour of steel beams having different web openings configuration. Ten full scale simply supported beam specimens were tested in loading frame. Based on the experimental and finite element study the following conclusions can be made:

- From the present investigation, it can be concluded that circular openings found to be very effective when compared to the equivalent with square or rectangular openings.
- Openings depth up to 75% of the depth of the section found to be effective.
- Adopt spacing to diameter ratio of openings (S/D_o) in the range of 1.5 to 2.0, so that there should be sufficient width of a web-post is available to carry the vertical shear.
- Web–post buckling failure modes found to be predominant when spacing to diameter ratio (S/Do) are in between 1.07 to 1.4, in such cases the perforated beams can fail by web-post buckling



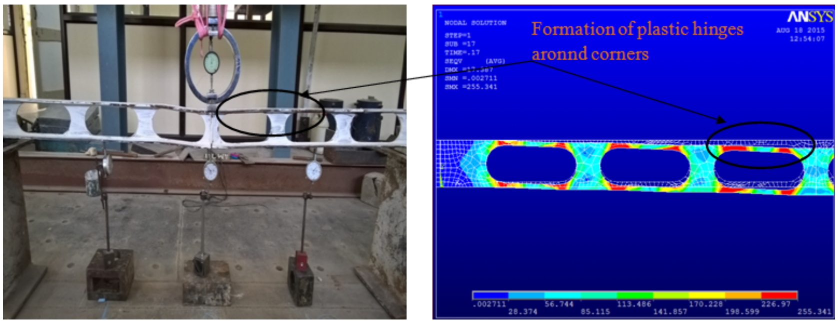
(a) (b)

Fig. 19 Stress concentrations around the corners region of rectangular openings SBWO6 (Vierendeel mechanism failure): (a) Experimental; (b) FEM



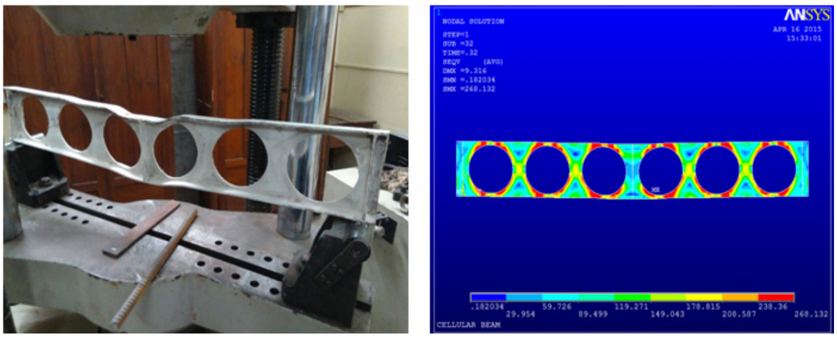
(a) (b)

Fig. 20 Stress concentrations around the corners region of rectangular openings SBWO7 (Vierendeel mechanism failure): (a) Experimental; (b) FEM



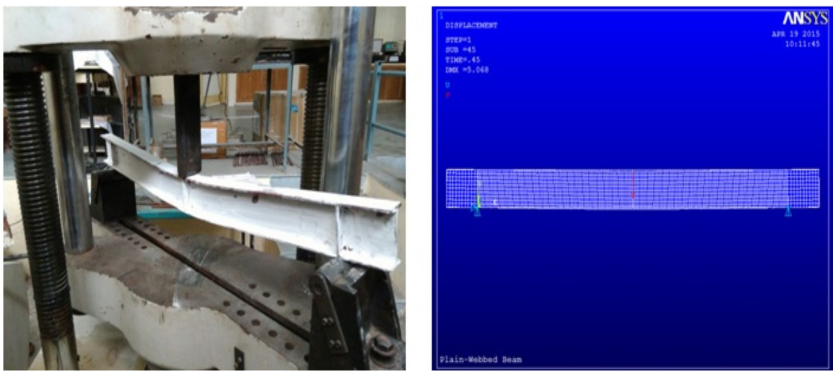
(a) (b)

Fig. 21 Comparison of deformed shaped for SBWO8: (a) Experimental; (b) FEM



(a) (b)

Fig. 22 Comparison of deformed shaped for CB9:(a) Experimental;(b) FEM



(a) (b)

Fig. 23 Comparison of deformed shaped for PWB10:(a) Experimental;(b) FEM before formation of four plastic hinges around the corners regions of openings (Vierendeel mechanism).

- Rectangular openings found to be very critical as it shows very high stress concentration around the corners regions. To avoid this use of appropriate corner radius equal to five times the thickness of web in beams with square and rectangular openings is preferable.
- For better performance of beams with square, rectangular and oval shape web openings, it is advisable to go for horizontal stiffeners above and below the openings, which enable a better stress redistribution around the openings and increase of the ultimate load carrying capacity of steel beams with web openings.

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