

Effect of circular web openings on dynamic behaviour of cantilever steel thin-walled tapered I - beams

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Abstract. In this study, free and harmonic vibration analyses of cantilever steel thin-walled tapered beams without and with web openings are performed. The analyses are carried out based on finite element method with the help of ANSYS. SHELL 63 element is used for the analyses. Tapered I - beams with symmetric and un-symmetric cross-sections are considered. Initially, free vibration analysis is performed for tapered beams without and with circular web openings to find out the effect of web openings on natural frequencies. The free vibration analysis is then followed by the harmonic analysis. The peak amplitudes and corresponding frequency ranges are presented for the considered cases. Web tapered beam of symmetric cross-section with circular web openings resulted in maximum fundamental natural frequency on performing free vibration (modal) analysis and resulted in peak amplitude at higher frequency on performing harmonic analysis among the considered cases of beams with and without web openings. Thus web openings and type of cross – section affect the dynamic behaviour.

1. Introduction

Steel tapered beams are commonly used in modern era of steel structures. They are economical when compared with the prismatic members. Recent advancement in engineering design enabled the structural designer to provide web openings in the tapered beams for further increase in economy and to meet the functional requirements. These beams are quite commonly used for roofing in stadiums and other metal structures. The presence of web openings may influence the dynamic behaviour and is worth to be studied.

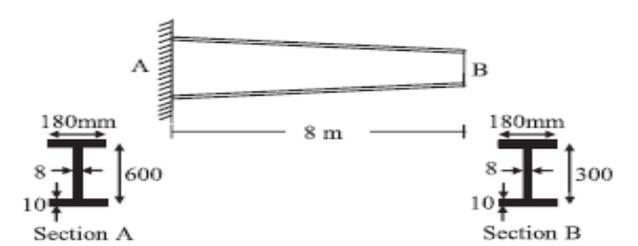
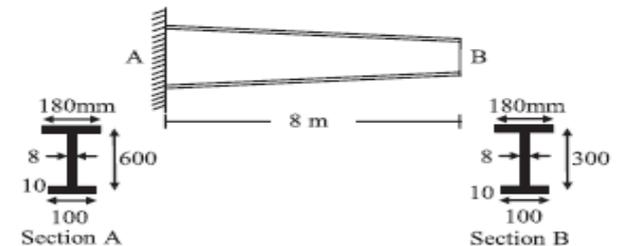
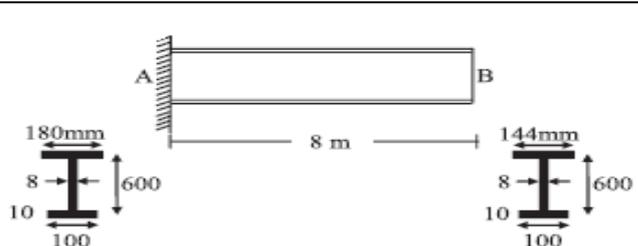
Lot of research on dynamic behaviour of non – prismatic / non – uniform beams was carried out by previous researchers [1-6]. Improved formulation for free vibration of thin – walled tapered beams was proposed by researchers Kim and Kim [7]. Free vibration analysis of tapered I-beams for various tapered ratios and boundary conditions using power series method and ANSYS was performed and the results were presented by Soltani and et al.[8]. From the brief literature review, it is evident that the effect of web openings on dynamic behaviour of tapered beams is worth to be studied. In this paper, the effect of circular web openings on free and harmonic vibration of tapered beams is discussed.



2. Validation

Free vibration analyses of tapered steel beams without web openings were previously performed [8]. For validation, three cases of cantilever tapered beams are modelled and again free vibration analysis is performed with the help of ANSYS. The results obtained from present analysis are presented in the Table 1, along with results of the previous study [8]. SHELL 63 element (four noded element) is used for analysis. The material is modelled as linearly elastic isotropic. Young's modulus (E) = 210 GPa; Poisson's ratio (ν) = 0.3; Density = 7800 kg/m³. Block Lanczos method is used for finding out the natural frequencies. The obtained results from present study are in good agreement with the previous values of previous study [8].

Table 1. Natural frequencies ω (rad/sec)

	Data case [8]	Mode	Previous study[8]	Present study
1		1 2 3	11.06 33.98 65.001	11.0654 33.5240 66.6143
2		1 2 3	8.86 29.41 50.45	8.8499 29.0742 50.1769
3		1 2 3	7.14 19.93 37.31	7.1264 19.8165 38.5876

3. Methodology

Circular openings are provided for the beams considered in above cases. The openings are provided such that (i) Web opening is away from the support by twice the beam depth, (ii) Clear spacing between openings greater than depth of beam and (iii) The diameter of circular openings is limited to 0.5 times the depth of beam [9].

As one end of the beam is free (cantilever beam), shear force and moment are zero at the free end for uniformly distributed / concentrated load. Hence near the free end, a circular opening is provided. From supported end (fixed end at A, Figure 1), the distance of first opening is 1.2 m for beam. Diameter of circular opening is taken as 0.125m and spacing between the (centre to centre distance)

adjacent holes is taken as 0.8m. For 8 m length beam, a total number of nine web openings are provided. Modelled image of case 1 beam is shown in Figure 1. Likewise case 2 and case 3 beams are modelled. Linear elastic material behaviour of steel is considered. Modulus of Elasticity (E) is taken as 210 GPa. Poisson's ratio (ν) = 0.3. Density is assumed to be 7800 kg/m³. SHELL 181 which is a four noded isoparametric element is considered for proper meshing near the holes. The element has six degrees of freedom (translations along X, Y and Z axes along with rotations about X, Y and Z axes at each node). The element is well suited for both linear and non-linear analyses. Fine meshing is provided with a total of around 705 elements for analysing the tapered steel beam with circular web openings. Figure 1 also depicts the image of meshing. Beams with and without circular cut outs corresponding to data cases 1 – 3 (Table 1) are analysed.

Block Lanczos method is used for free vibration analysis to find out the natural frequencies. For performing harmonic analysis, a vertical point load of -10 kN is applied at top tip of web and flange near free end as shown in Figure 2. Sparse solver method is chosen for solving the dynamic equations. The harmonic frequency is taken as 1 to 800 Hz. The load is divided into 50 sub steps. Stepped condition is assumed. The beams without and with circular web openings are analyzed.

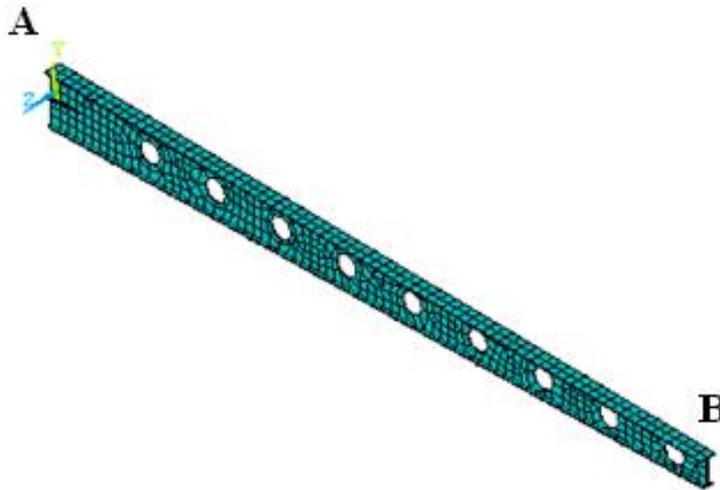


Figure 1. Model of case 1 beam in ANSYS

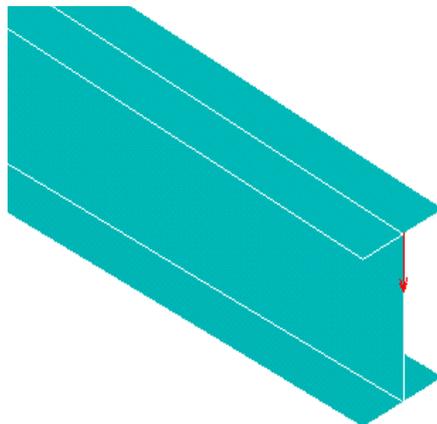


Figure 2. Application of point load 10 kN at free end

4. Results and Discussion

4.1 Free Vibration Analysis

Natural frequencies of for the first six modes are presented in the Table 2 for beams of cases 1-3 with and without circular cut out. The mode shapes are same for beams of all cases considered. Mode shapes 1-6 are depicted in Figures 3 – 8. Flexural-torsional vibration of the beams occurred for mode shapes 2, 3, 5 and 6. Flexural vibration of the beam occurred for mode shapes 1 and 4.

Table 2. Natural Frequencies ω (rad/sec)

Data case	Mode	Without opening	With opening
1	1	11.0654	11.4612
	2	33.5240	33.0759
	3	66.6143	68.7820
	4	66.8405	68.9203
	5	109.7987	108.7808
	6	180.9369	186.3530
2	1	8.8499	9.2086
	2	29.0742	28.7783
	3	50.1769	51.5083
	4	64.8299	67.0981
	5	94.9326	94.9955
	6	121.4288	123.2447
3	1	7.1264	7.3520
	2	19.8165	19.4848
	3	38.5876	39.5231
	4	64.7105	66.4824
	5	77.4340	77.0633
	6	96.9190	98.8282

From Table 2 and Figures 3 – 8, the following inferences may be drawn

- Fundamental natural frequency of the web tapered beam of symmetric cross – section (case 1) along with circular web openings is greater than the fundamental natural frequency of the web tapered beam of symmetric cross – section without circular web openings by 3.45%.
- Fundamental frequency of the web tapered beam of un- symmetric cross – section (case 2) along with circular web openings is greater than fundamental frequency of the web tapered beam of un- symmetric cross – section without circular web openings by 4.05%.
- Fundamental frequency of the flange tapered beam of un-symmetric cross –section (case 3) with circular web openings is greater than fundamental frequency of the flange tapered beam of un-symmetric cross –section without circular web openings by 3.166%.
- Web tapered beam of symmetric cross-section (case 1) resulted in higher fundamental natural frequency when compared with web tapered beam of un-symmetric cross-section and flange tapered beam of un-symmetric cross-section either with / without web openings.

Thus, presence of circular web openings resulted in increase of fundamental natural frequencies for web / flange tapered beam with symmetric / un-symmetric cross sections and also among the considered cases, web tapered beam of symmetric cross-section resulted in higher fundamental frequency either for with / without circular web openings. Hence, type of cross-section also affects the dynamic behaviour.



Figure 3. Mode shape 1

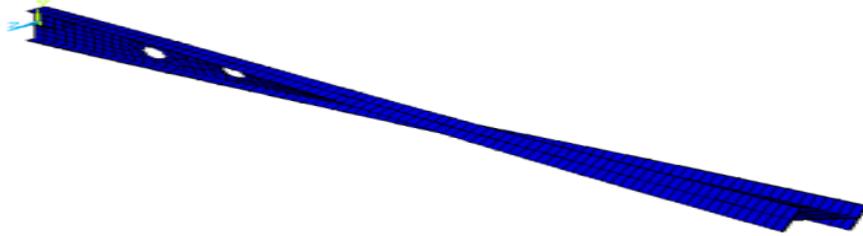


Figure 4. Mode shape 2



Figure 5. Mode shape 3

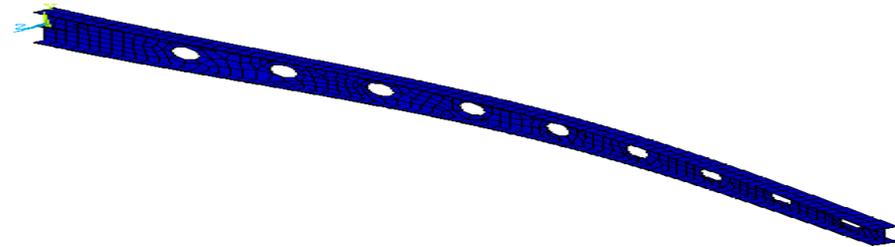


Figure 6. Mode shape 4

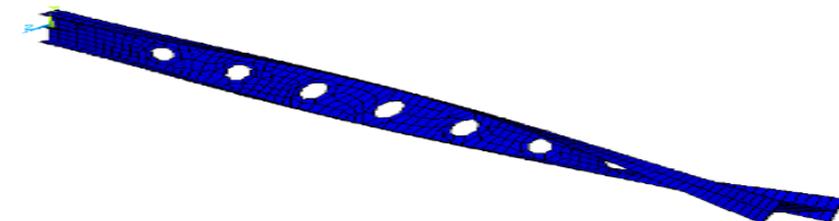


Figure 7. Mode shape 5

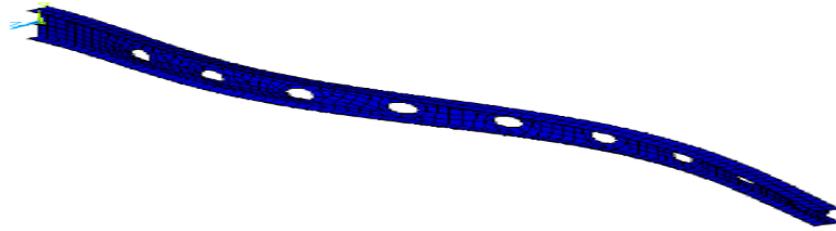


Figure 8. Mode shape 6

4.2. Harmonic Vibration Analysis

Plot between harmonic frequency and amplitude – UY (VALU) at the top junction of web and flange is plotted for data cases 1-3 with web openings as shown in Figures 9 - 11.

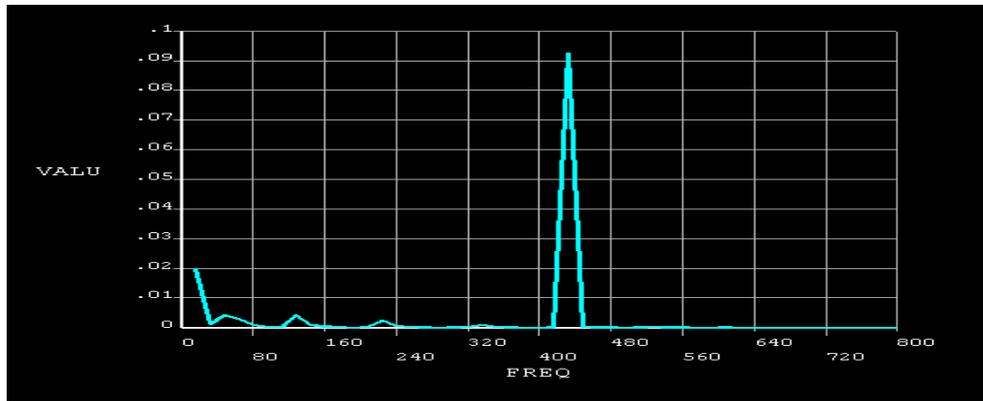


Figure 9. Harmonic frequency (FREQ) vs Amplitude UY for case 1 beam with web opening

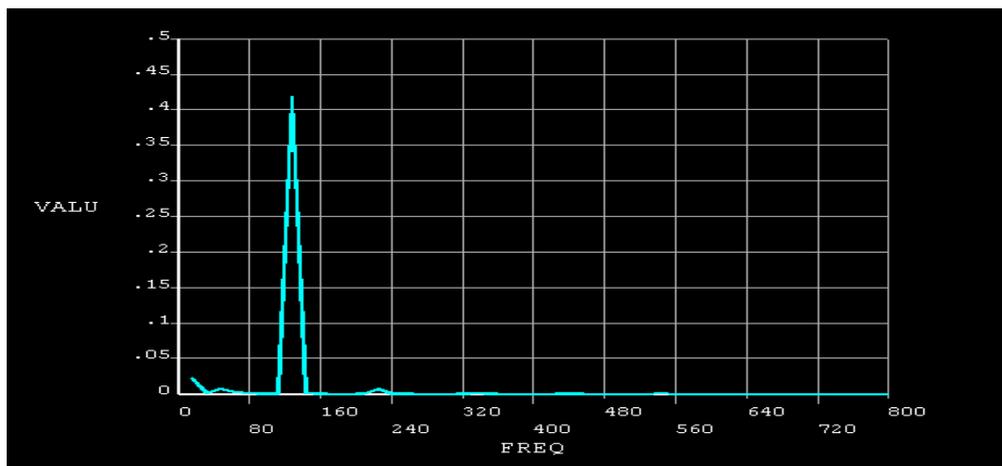


Figure 10. Harmonic frequency (FREQ) vs Amplitude UY for case 2 beam with web opening

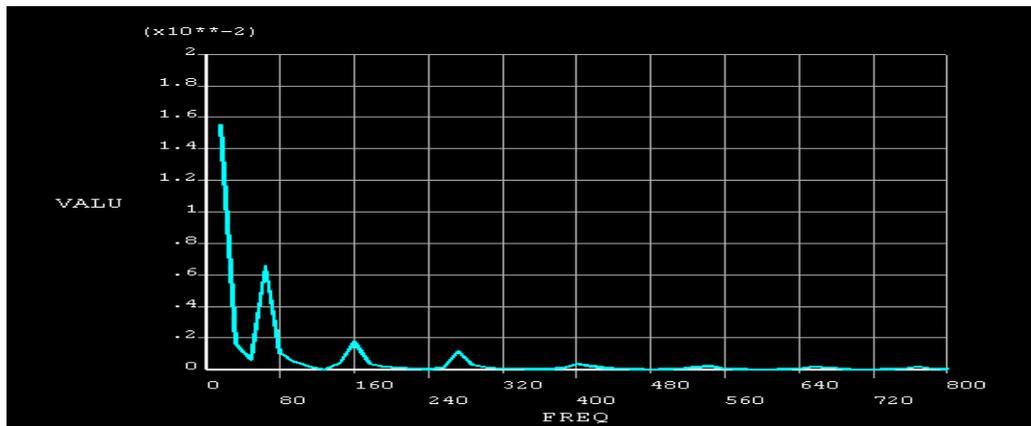


Figure 11. Harmonic frequency (FREQ) vs Amplitude UY for case 2 beam with web opening

Table 3. Peak Amplitude UY vs Frequency Range

Data Case	Peak Amplitude UY (m)		Frequency Range (Hz)	
	Without Web Opening	With Web Opening	Without Web Opening	With Web Opening
1	3.4×10^{-2} (avg.)	0.095 (avg.)	320-400	400-480
2	1.9×10^{-2} (avg.)	0.425 (avg.)	0-80	80-160
3	1.4×10^{-2}	1.45×10^{-2} (avg.)	0-80	0-80

From Figures 9-11 and Table 3, it can be observed that beams with web openings resulted in higher amplitudes at greater frequency ranges for beams of cases 1 and 2. For case 3 beam there is not much difference in the dynamic behaviour when subjected to harmonic loading.

5. Conclusions

Dynamic analyses of cantilever steel tapered I beam with and without circular web openings are performed with the help of ANSYS based on finite element method. SHELL 181 (4 noded isoparametric element) is considered for meshing. Linear – Elastic material behaviour of steel is assumed. Both symmetric and un-symmetric sections are considered. The obtained natural frequencies and mode shapes are presented. From this study it is evident that the provision of circular web openings resulted in increase of fundamental natural frequencies. The main inferences from the study are as follows

- 1) Presence of circular web openings resulted in increase of fundamental natural frequencies for web / flange tapered beam with symmetric / un-symmetric cross sections.
- 2) Web tapered beam of symmetric cross-section (Case 1) resulted in higher fundamental frequency for either with / without circular web openings when compared with the web tapered beam of un-symmetric cross-section (case 2) and flange tapered un-symmetric cross-section (case 3).
- 3) Web tapered beam of symmetric cross-section (Case 1) resulted in higher amplitude at greater harmonic frequency for either with / without circular web openings when compared with the web tapered beam of un-symmetric cross-section (case 2) and flange tapered un-symmetric cross-section (case 3).

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