PERFORMANCE OF STEEL BEAMS WITH CIRCULAR OPENINGS UNDER STATIC AND DYNAMIC LOADINGS

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Abstract. In modern structural constructions and high rise buildings, one of the most important consideration is the efficient design of long span floor composite system and girder beams with web opening. For minimizing the cross sectional of these members, reducing the dead load and cost wise of construction steel beams, web openings are necessary and the floor beams acts compositely with slabs. This study is focused on the performance of floor steel beam with circular web perforation subjected to line loading and on the evaluation of shear buckling capacity for such beams under the effects of static and dynamic loadings. The adopted parameters are web to thickness ratio and web perforation size. Numerical analysis method as finite elements approach by ANSYS software is taken to simulate all models and presented as three dimensional problems. The analysis results indicate that the presence of web perforations reduced the shear strength capacity and increased the deflection, and the configuration of tension field were changed. In case of dynamic loadings, the study showed that the magnitude of deflections is effected by the frequency of the applied external load and varied with respect to the magnitude of the frequency.

1. Introduction
The aims of using girder steel beam with web perforations in different locations and sizes are to reduce the height of beam web, passing services through the openings and reducing the dead loading. Chung et al. [1] for steel beams and Chung and Lawson [2] for composite beams stated that services that require web openings up to 75% of the beam height are not uncommon. These openings could lead to a significant decrease of the beam load carrying capacity depending on the adopted openings shape, size and location. Hagen et al [3] presented a design model based on the numerical study that accounts for the reduction in web shear area, shear buckling of the web and the effect of opening position. Rodrigues et al. [4] presented finite element models using the ANSYS software to investigate the structural response of steel beams with web openings in terms of stress distributions, collapse load magnitude and associated failure modes. It was proved the structural efficiency of unstiffened steel beam with circular web openings when compared to their equivalent unstiffened solutions with square and rectangular openings. Thepchatri and Limkatanyu [5] proposed a design method to check for the Vierendeel failure of non-composite symmetric cellular steel beams, circular or elongated circular openings. The method simultaneously offered the combined global bending from flexure, shear and Vierendeel, thus facilitated safe and cost effective design of beams with openings. Morkhade and Gupta [6] presented an experimental and numerical study of evaluating the strength of steel beams with different web openings’ configurations and web opening area. Circular web openings were found to be very effective in all respects. Limazie and Chen [7], [8] studied numerically the structural behavior of shallow cellular composite floor beam. The FE models were developed based on the flexural bending test specimens and including nonlinear contact modelling. It was found that the concrete topping above the steel beam has a great influence on the performance of these beams. Najafi, and Wang [9] studied the behaviour of steel beams with web openings under combined axial compression, bending
moment and shear force through numerical simulation modelling. It showed that when dealing with the general situation of a beam under combined axial compression, bending moment and shear force, the effect of compressive force and consequent tee-section buckling should be included to reduce both the bending moment and shear resistances of the perforated section. El-Dehemy [10] presented an ABAQUS finite element models software to achieve the structural response of steel beams with web openings for static and dynamic analysis. It was confirmed that the presence of openings in the web of steel beams decreases stiffness of the beam and introducing a larger deflection than in the steel web opening with solid opening. Yanling et al [11] carried out an experimental research on the dynamic responses of the steel-concrete composite beams under the dynamic harmonic loadings, and they stated the sources of harmonic loadings are the machine action and the moved vehicle loads. It was found that the mid span dynamic deflection and mean value of slip were most influenced by the static load components, the slip amplitude was most influenced by the load amplitude, and the mid-span accelerate is mainly affected by the load frequency and amplitude.

In present paper, the performance of floor beam with central circular openings was considered under static and dynamic loadings. Different parameters such as web to thickness ratio and web perforation size are discussed. The effect of multiple openings is also investigated which certainly increase the deflection of steel beams due to the loss of flexural and shear stiffness. Web (shear) buckling next to or between the openings is normally the critical design condition.

2. Structural configuration

The steel section of floor beam is (254 × 254 × 73 UB) "Universal Beam" that means a broad flanged rolled joist for stanchion (bending load), with different size of openings and locations. The reference beam was made without any openings to make comparisons with other beam layouts. The first type is with central opening of diameter to web ratio (0.55). The second, two web openings as (0.55) ratio while the third, three circular openings of (0.55) as shown in Figure (1). Same configurations mentioned but with ratio of (0.45) and (0.33) were also considered. The mechanical properties of steel section are (0.33) as Poisson ratio, (200000 MPa) as elastic modulus, (420 MPa) as yielding strength and (590 MPa) as ultimate strength. The static load was applied at the top of the flange as uniformly distributed line loading.

![Figure 1: Central, two and three circular web perforations (75, 199, 125 mm) in diameter](image)

The performance of steel beam with web perforations under predominantly shear loading classified in three stages [12], pre-buckling, post buckling and the final stage is failure. The ratio of scaled beam to the depth is greater than unity, so that the shear buckling coefficient for perforated web is [12]:

\[ k_p = k_w (1 - \frac{d}{h_w}) \]

...(1)
Where, \((d)\) is the diameter of opening, \((h_w)\) is the depth of web, \((k_o)\) is the shear buckling of the unperforated web plate for (simply supported beam) which is calculated as follow:

\[
k_o = 5.35 + 4 \left( \frac{h_w}{L_w} \right)^2
\]  
...(2)

In which \((L_w)\) is the span of the steel beam. The shear buckling stress \((\tau_s)\) is calculated as follow:

\[
\tau_s = k_p \frac{\pi^2 E}{12(1-\nu^2)} \left( \frac{t_w}{h_w} \right)^2
\]  
...(3)

The tensile membrane stress that developed in the web in the post – critical stage \((\sigma_m)\) as follow:

\[
\sigma_m = \frac{3}{2} \tau_s \sin(2\alpha) + \left[ \tau_s^2 + \tau_s^2 \left( \frac{3}{2} \sin^2 \alpha \left( 2\alpha \right)^2 - 3 \right) \right]^{1/2}
\]  
...(4)

Where, \((\sigma_m)\) is the yield stress of the web plate. Therefore, the shear load that causes the web plate to buckle is given by:

\[
V_{cr} = \tau_s h_w t
\]  
...(5)

In case of steel beam without openings, the assumed inclination of the tension field \((\alpha)\) is approximately to two third of the inclination of the panel diagonal \((\alpha_d)\) as follow [13]:

\[
\alpha_d = \tan^{-1} \left( \frac{h_w}{L_w} \right)
\]  
...(6)

\[
\alpha = \frac{2}{3} \alpha_d
\]  
...(7)

And in case of web opening [12], the inclination of the tension field \((\alpha)\) is:

\[
\alpha = 0.75 \alpha_d \left( 1 - 0.71 \left( \frac{d}{h_w} \right) \right)
\]  
...(8)

3. Dynamic analysis

Dynamic analysis by using the same applied static load as amplitude with frequency range (0-40 Hz) with frequency step as (2 Hz) for models M1, M4 and M10 is carried out to check out the performance of steel beams and the full performance of deflection-frequency for all models. Dynamic loads as harmonic sin wave was applied. The general form of the harmonic load as sin wave may be expressed as follow:

\[
P(t) = P_{am} \sin(\omega t)
\]  
...(9)

In which, \(P(t)\) is the total applied load, \(P_{am}\) is the amplitude load and \(\omega\) is the frequency.

4. Finite element modeling

The finite element analysis FEA is adopted in present study for simulating all models. The purpose is to develop accurate and reliable FEA models that matching with the real problem. The FEA models were established using ANSYS software, taking into accounts all aspects that would likely influence the quality or state of being correct of the formal or systematic examination or research such as mechanical properties, element type, mesh size, boundary conditions and applied loading. The steel
section is modelled by SOLID185 element type with (20) nodes and three degrees of freedom at each node [14]. The mesh size is selected in which (25 mm) square element with ratio equal to unity. The linear solution of the shallow beam with constant modulus of elasticity was run and the deflection, stress and strain were calculated the nonlinearity material was assumed that the stress – strain behaviour of steel section is bilinear as shown in Figure (2). Figures (3) to (6) represent the finite elements mesh for all models taking (125, 100 and 75 mm) diameter openings at centre, edges and combined.

5. Analysis results and discussions
The analysis results from the numerical analysis by ANSYS are listed in Table (1) for maximum displacements under the effects of static loading. Figures (7, 8, and 10 to 15) show the shear stress distributions along the web for all cases and the vector shear stress. The non-symmetry of shear stress distributions because of the boundary conditions of supports as show in Figure (1), where the left is roller support and the right is pinned support. Figures (9, and 16 to 18) represent the whole deflection
and showed that symmetry because of the two supports symmetry in vertical direction. Figures (19) and (20) show the performance of beam as central deflection and shear stress at final stage of analysis with the number of web openings. While Figure (21) represents the shear stress in web vs. diameter to web depth (d/hw) ratio.

**Table (1):** Analysis results for all models by ANSYS

| Model mark | M1  | M2  | M3  | M4  | M5  | M6  | M7  | M8  | M9  | M10 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| %Reduction in shear strength (per one hole) | Control | 44.44 | 44.44 | 44.44 | 55.60 | 55.60 | 55.60 | 67  | 67  | 67  |
| Maximum central deflection (mm) | 7.11 | 7.83 | 8.37 | 8.75 | 7.56 | 7.86 | 7.99 | 7.35 | 7.65 | 7.85 |
| Maximum shear stress (MPa) | 755  | 821  | 1025 | 1083 | 785  | 855  | 922  | 766 | 771 | 781 |
Figure (12): Shear stress – 100 mm opening

Figure (13): Shear stress vector - 100 mm opening

Figure (14): Shear stress – 75 mm opening

Figure (15): Shear stress vector - 75 mm opening

Figure (16): Deflection for 125mm opening
Figure (17): Deflection for 100 mm opening

Figure (18): Deflection for 75 mm opening

Figure (19): Central deflection vs. number of openings

Figure (20): Shear stress in web vs. number of openings
Table (2) depicts some models that are taking into account to check out the response of the steel beam under the effect of dynamic loadings. Figures (22-24) represent the deflection, longitudinal displacement and bending stress with frequency that ranges between 0-40 Hz and a step of 2 Hz. The performance of control model gave higher deflection than other models because of no hole that make discontinuity of cumulative deflections due to the applied load for the top to the bottom at the central point of the steel beam. The maximum deflections for all models vary in magnitude because of the models differ in time that continuing effect on the beam. The maximum longitudinal displacements for all models occur at the frequency range 2-4 Hz. The maximum bending stress-frequency for all load frequencies range occur at high frequency for control model M1 because of the flexural stiffness is high due to absences of openings. Generally speaking, the deflection varies with frequencies for each specific amplitude and all performance are same in behaviour.

Table 2: Analysis results for harmonic loading

| Loading case | Frequency (Hz) [ ] - Maximum deflection (mm) | Frequency (Hz) [ ] - Maximum longitudinal strain | Frequency (Hz) [ ] - Maximum bending stress (MPa) |
|---------------|---------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| M1            | [8] 0.710                                   | [4] 0.046                                     | [30] 663                                      |
| M4            | [2] 0.062                                   | [2] 0.075                                     | [14] 165                                      |
| M10           | [8] 0.033                                   | [4] 0.020                                     | [10] 154                                      |

Figure (21): Shear stress in web vs. diameter to web depth (d/hw) ratio

Figure (22): Deflections-frequency performances for selected models
6. Conclusions

- The finite elements Approach proved to be a valuable tool for evaluating structural response of steel beams with web openings. It demonstrated to be reliable for estimating stress distributions, load capacity and accompanying failure modes.
- Due to the existence of shear stress intensity at the supports, it is not recommended to make a hole near the supports to avoid shear failure of beam and, the web opening should be away from the support by at least twice the beam depth. The clear spacing between such opening equal or greater than the opening diameter to avoid the shear stress concentration and overlap.
- The ultimate shear of web panel may be affected significantly by the size of the web opening.
- The width of membrane stresses developed along a diagonal band, which carries the applied load in the post-critical stage, is reduced by the largest dimension of the opening.
- The position of the maximum shear stress is mainly concentrated in zones close to the flange and in the central length of the tee sections above and below the web opening.
- The presence of web openings increased the deflections as (10, 17.7 and 23%), (6.3, 10.5 and 12.3%), (3.5, 7.6 and 10.4%) for (125, 100 and 75 mm) openings series respectively.
- The presence of web openings increased the shear stress because of a reduction in sectional area as (8.7, 35.7 and 43.4%), (3.9, 13.2 and 22.1), (1.5, 2.2 and 3.5%) for (125, 100 and 75 mm) openings series respectively.
- The deflection and shear stress are increased as the opening size is increased (higher diameter to depth ratio) due to the loss of flexural and shear stiffness as the reduction in area of web and moment of inertia of a member.
• The maximum bending stress for all load frequencies range occur at high frequency for control model because the flexural stiffness is the maximum due to the absence of openings.
• In case of dynamic loadings, the magnitude of deflections is influenced by the frequency of the applied external load and varied with respect to the magnitude of the frequency.

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