Numerical Study for Steel Arch Beams of Compact Section with Circular Web Openings

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Abstract: This study presents a numerical simulation of the behaviours of compact steel arch beams, with and without openings, using the commercial finite element software ABAQUS. Numerical model was firstly validated against under-publishing research to verify the accuracy of FEA results and then used to conduct a parametric study to investigate the effects of several parameters on the load - deflection curve of the arch steel beams with openings such as opening area, opening shape, openings number, yielding stress of steel material, radius of arch beam and effect of adding steel stiffeners. The results from the numerical investigation showed that the FEA results gave a good agreement with the experimental results in terms of ultimate strength, maximum deflection, load-deflection curves, and failure mode. The parametric study further showed that the ultimate failure loads for arch beams with openings decreased with the increase in the opening diameter from nearly 2 to 21% for openings of diameters 50mm and 125 mm, respectively, located at the centre of the web, while the ultimate load capacity of steel arch beams with edge openings decreased by about 26% in comparison with the control beam when the diameter increased to 125 mm. Also, the increase in the radius of the arch beam using radii of (537.3, 797.5, and $\infty$) mm resulted a decrease in ultimate load capacity about 17% and 40% for radii (797.5 and $\infty$ mm) respectively, compared with the control beam of radius 537.3 mm.

Key Words: ABAQUS, FEA, Steel Beam, Arch, Web Openings, stiffeners

1. Introduction

Arch beams can be characterised a bent girders with upward convexity and constrained at its the edges. In the past, such arches have been the backbones of many important buildings, and the essential aim of these arches is to improve the buildings’ load carrying capacity, which may come from the stiffening behaviours due to membrane action. The reduced values of tensile stresses and bending moments generated in arch beams as compared with straight beams make them preferable for many structural purposes. In particular, these characteristics enable structural engineers to generate large spans for building roofing and bridge decking [1]. The structural use of steel in construction is generally increasing across the world, despite having reached maturity in some countries [2]. With the development of buildings, the organisation of pipes and conduits within construction is essential to achieve basic requirements like water supply, air-
conditioning, sewage, telephone, electricity, and computer network. Such pipes and conduits are generally set under the beams and, for aesthetic reasons, covered by suspended ceilings, which creates a dead space. Passing such conduits through transverse openings within the floor beams can decrease such dead space and result in a more compact plan. For small buildings, the savings of this type may not be remarkable, but for multi-storey buildings, each saving in storey rise is multiplied by the number of storeys, potentially representing a remarkable saving in the total rise of the building [3]. The most popular shapes of openings are rectangular and circular, for practical reasons: circular openings are useful for service pipes, such as water pipes, whereas rectangular openings are provided to accommodate air-conditioning conduits, which are generally rectangular.

Shanmugam et al (2002) presented a finite element (FE) model to study the behaviours of steel plate girders with web opening. ABAQUS software was used in this analysis to produce a model for a steel plate girder with opening, and the accuracy of the FE model was evaluated by comparing it to a plate girder tested by previous researchers. The comparison between the numerical results and the available experimental results showed a good agreement for yielding, ultimate strength, and load-deformation behaviours [4].

Abdul Gabar (2012) investigated three steel plate girders under shear load, the first one without any web opening, the second one with a central circular web opening with a diameter of 60% of the web height, and the third with a strengthened strip welded around a circular web opening. The comparison between the three girders showed that the decrease in ultimate shear load for the plate girder with opening was 51%, while for the girder with the strengthened web opening, it was 35% [5].

Morkhade and Gupta (2015) conducted an experimental and numerical investigation of seven straight hot rolled steel girders of ISMB 100 with various web openings in order to study the maximum load behaviours and deflection. The openings shapes considered in the study were rectangular and circular, and the test outcomes indicated that the ultimate strength and stiffness both reduced with increases in opening size [6].

Al-Khafaji and Al-Abbas (2016) presented a numerical investigation of behaviours of steel straight beams with openings strengthened using CFRP plates using ANSYS V.14.5. The parameters considered were shape, location of opening, and the number of CFRP layers, and the outcomes showed that the ultimate strength reduced with the increase in the area of the opening. Circular openings in the shear section of the steel specimens resulted lower reductions in the ultimate strength due to the minimal concentration of stress around the web opening, whereas specimens with rectangular openings had smaller ultimate strength values [7].

Tudjono et al (2017) analysed castellated steel straight beams to evaluate the optimum size and shape of opening. An experimental and numerical investigation was carried out by using software package (ABAQUS /CAE 6.12). The outcomes of the finite element analysis in ABAQUS showed good compatibility with experimental results [8].

El-Dehemy (2017) analysed a finite element model of IPE 400 steel straight beam with openings using ABAQUS software. The variables of this research were boundary conditions (fixed or hinged supports) and the number and locations of openings. The FE analysis produced outcomes close to those obtained by Jichkar et al [9], with the deflection value of steel straight beams increasing with increases in openings numbers [10].
Zaher et al (2018) presented a study of the behaviours of arched-shape cellular beams with two-hinged supports. The perforated “I” section steel arch beams were tested under a vertical concentrated load at the mid-span of the beam and a finite element model search was performed to investigate the effects of radii of curvature and cellular web openings. ABAQUS was used to produce an FE model, and the results showed an obvious lowering in the ultimate strength of cellular beams in comparison with solid beam. The model showed good agreement with experimental results [11]. However, numerical investigation of steel arch beams of compact “I” sections with openings are scarce, and to address this shortage, the current work developed a finite elements models in ABAQUS/Standard 2017 software based on experimental tests [12] in which, seven simply supported steel arch beams, with and without circular web openings, were prepared and tested experimentally under two-point loading to observe the effects of changes in location and number of openings. This research also includes a study of several new parameters such as changes in the radius of beams, yielding stresses, and the addition of stiffeners, in addition to size, shape and number of web openings.

2. Experimental study
The steel arch beams that experimentally tested by Hemzah et al in-under-publishing research [12] were simulated in this research using ABAQUS software. All experimental beams had the same radius, span, and section (“I”-section) and were tested under the same load type and boundary conditions. The steel beams were built-up from steel plates, and the width and thickness of the flange plates were 80 mm and 5 mm respectively, while the height of the web plates was 150 mm, with 4 mm thickness. The span of all specimens was 1049 mm, calculated between two supports as shown in Figure 1, with radius (R) and angle (α) of 537.3 mm and 154.8°, respectively, measured to the centre of the arc. One of these specimens, which was without an opening, and this was marked as a reference beam, while the other six specimens were divided into two groups:
- Group 1, which consisted of three arch beams with different numbers and locations of circular openings, and
- Group 2, which consisted of three arch beams with circular openings, as in group (1), strengthened using steel stiffeners. The diameter of each web circular opening was 80 mm (50% of beam depth) for all specimens. Details of the specimens are offered in Figure 1 and Table 1.
Figure 1: Geometric Details of Experimentally Tested Specimens
Table (1): Details of Tested Specimens

| Group          | Reference beam | Group (1) | Group (1) |
|----------------|----------------|-----------|-----------|
| Specimen       | AR             | AMO       | AEO       | AEMO      | AMOS     | AEOS     | AEMOS     |
| Location of opening | _              | At middle | At edges  | At middle and edges | At middle | At edges  | At middle and edges |
| Number of openings | _              | 1         | 2         | 3         | 1         | 2         | 3         |
| Strengthening using vertical steel stiffeners | _ | _ | _ | _ | 2 of 5mm thickness at 80mm from opening edges on two sides | 2 of 5mm thickness at 80mm from stiffener under loading points on two sides | 2 of 5mm thickness at 80mm from middle opening edges and 2 of 5mm thickness at 80mm from stiffener under loading points on two sides |

3. Finite elements modelling

To simulate the experimentally tested arched beams, the same measurements used for the experimental specimens were used in a finite elements model to achieve adequate accuracy. Table 2 shows the steel properties used in the experimental study. The steel can be considered as a homogeneous material that exhibits a similar stress-strain relationship in tension and compression.

Table 2: Steel Plate Properties

| Plate thickness (mm) | fy (N/mm²) | Es (N/mm²) | fu (N/mm²) |
|----------------------|------------|------------|------------|
| 4                    | 328        | 200000     | 365        |
| 5                    | 328        | 200000     | 405        |

The S4R element, (a 4-node thin shell element) was used for modelling the steel material of all seven beams. In general, the modelling of an “I”-section beam involves six parts: top flange, web, bottom flange, support plates, angles for loading, and stiffeners. Each part was drawn separately, then these were assembled to form the specimen model, as illustrated in Figure 2.
4. Convergence Study

Mesh size selection is an essential step in finite element modelling, and several attempts with different mesh sizes were made to determine the best element size for the desired accuracy. Good convergence is achieved in the result when the beam is divided into an adequate number of elements. For this purpose, in the current FEA, a convergence study was done to determine a suitable mesh size by choosing the element sizes of the model (AR) from a range of (40, 20, 15, and 10 mm). As shown in Table 3, the ultimate load capacity and maximum deflection values are more accurate when the mesh size is decreased to 15, based on the experimental results for the control beam. The 15 mm mesh size was thus selected for all tested beams. Figure 3 shows the changes in the load-vertical midspan deflection behaviours and load-lateral deflection behaviours with varying mesh sizes.

Table 3: Effect of Mesh Size on Ultimate Load and Maximum Deflection

| Mesh size (mm) | Ultimate Load (kN) | Maximum Deflection (mm) |
|---------------|--------------------|-------------------------|
|               | EXP. | FEA. | EXP. | FEA. | EXP. | FEA. |
| 10            | 160  | 151.87 | 16.02 | 13.25 | 10.78 | 6.97 |
| 15            | 160  | 153.36 | 16.02 | 15.99 | 10.78 | 8.54 |
| 20            | 160  | 153.75 | 16.02 | 19.74 | 10.78 | 14.10 |
| 40            | 160  | 153.00 | 16.02 | 29.30 | 10.78 | 16.72 |
5. Comparison between numerical and experimental results

Figure 4 presents a comparison between the FE analysis results and the experimental study results based on load-vertical midspan deflection curves and load-lateral deflection curves at roller support. The modes of failure in all models were as in the experimental tested beams; local buckling and yielding in the top flange at the maximum bending zone in the midspan of beams. It can be observed from Table (4) that there are small differences between the experimental and numerical results for ultimate load capacity and maximum deflection values, such differences are almost inevitable and the important factor is the general behaviour of the load-deflection curve; as seen in Figure 4 shows only small differences between the numerical and experimental behaviours of load-deflection curves.
Figure 4 Experimental and Numerical Load-Vertical Mid Span Deflection and Load-Lateral Deflection Curves for AR, AMO, AEO, AEMO, AMOS, AEOS and AEMOS
Table 4: Experimental and Numerical Results

| Specimen | Ultimate load (kN) | Maximum deflection (mm) |
|----------|--------------------|-------------------------|
|          | Experiment | Abaqus | Abaqus | Deference | Experiment | Abaqus | Abaqus | Deference | Experiment | Abaqus | Abaqus | Deference |
| AR       | 160        | 153.3  | 4.18   |           | 10.78      | 8.54   | 20.77  |           | 16.02      | 15.99  | 0.18   |
| AMO      | 140        | 142.2  | 1.57   |           | 7.43       | 5.64   | 24.09  |           | 10.71      | 10.22  | 4.57   |
| AEO      | 145        | 151.2  | 4.27   |           | 8.70       | 7.43   | 14.60  |           | 14.56      | 14.13  | 2.95   |
| AEMO     | 139        | 141.8  | 2.01   |           | 7.38       | 5.57   | 24.52  |           | 10.70      | 10.20  | 4.67   |
| AMOS     | 144        | 142.7  | 0.90   |           | 7.74       | 5.66   | 26.87  |           | 11.46      | 10.25  | 10.55  |
| AEOS     | 147        | 152.0  | 3.40   |           | 9.45       | 7.46   | 21.05  |           | 14.61      | 14.18  | 2.94   |
| AEMOS    | 142        | 142.3  | 0.21   |           | 7.66       | 5.61   | 26.76  |           | 11.38      | 10.23  | 10.10  |

6. Parametric study

This section discusses the study of multiple parameters and their effects on the behaviours of steel arch beams:
1- Opening diameter
2- Opening shape
3- Openings number
4- Add stiffeners
5- Steel yielding stress
6- Arch beam radius

6.1 Effect of opening diameter

In order to study the effect of changing the circular web opening diameter on the load-deflection response, two opening locations were selected with different diameter/depth ratios of 31.25%, 46.8%, 62.5%, and 75% (50, 75, 100, and 125 mm) diameters, respectively. The first location was in the mid-span of the web of the arch beam, while the second was near to the supports of the beam. Figure 5 shows the effect of opening diameter changing on load-midspan deflection curves.

![Figure 5: Effect of Opening Diameter Changes on Load-Vertical Midspan Deflection Curves](image-url)
As seen in Figure (5-a) the beams showed only small differences in the behaviours within the elastic range for all diameters. When yielding began, the behaviours differed, as the load increased, the beams with higher diameters showing lower stiffness, and the difference between the curves becoming clearer with increasing load. Generally, with increases in the diameter of the opening, a reduction in the ultimate load occurred. Figure 5-b shows that the curves of beams with opening diameters 50 mm, 75 mm, and 100 mm showed identical stiffness and no distinctive differences from that of the beam without an opening, while the curve with diameter of 125 mm created a remarkable difference in the load-deflection response, and a significant reduction in the ultimate load occurred. This indicates that the arch beam with two openings near to the supports was not greatly affected by variation of the opening diameter below 125mm because of small values of bending moment and shear force at the edges of the arch. Table 5 shows the ultimate strength and maximum deflection values for arch beams with midspan openings and beams with edge openings of different diameters.

Table 5: Ultimate Load and Maximum Deflection Values for Arch Beams with Circular Openings of Different Diameters

| Beam                        | Opening diameter (mm) | Ultimate load (KN) | Decrement ratio in ultimate load (%) | Maximum deflection (mm) | Comparison in maximum deflection (%) |
|-----------------------------|-----------------------|--------------------|--------------------------------------|-------------------------|-------------------------------------|
| Beam without of opening     |                       | 153.36             | -                                    | 8.54                    | -                                   |
| Beam of middle opening      | 50                    | 149.54             | 2.5                                  | 6.66                    | -22.0                               |
|                             | 75                    | 143.71             | 6.3                                  | 5.69                    | -33.4                               |
|                             | 100                   | 134.49             | 12.3                                 | 5.11                    | -40.2                               |
|                             | 125                   | 120.88             | 21.2                                 | 4.14                    | -51.5                               |
| Beam of edge openings       | 50                    | 153.36             | 0                                    | 8.67                    | 1.5                                 |
|                             | 75                    | 152.14             | 0.8                                  | 8.19                    | -4.1                                |
|                             | 100                   | 151.13             | 1.5                                  | 7.41                    | -13.2                               |
|                             | 125                   | 114.12             | 25.6                                 | 5.55                    | -35.0                               |

6.2 Effect of Opening Shape Changes

To study the effect of opening shape on the load-deflection behaviours of steel arch beams with midspan web opening and arch beams with edge openings, five opening shapes (circle, hexagonal, square, triangular, and rectangular), with a constant area of 7850 mm², were applied. Figure 6 shows the opening shapes used in this study. For the rectangular shape, four height to length ratios [1:1.27 (78.5*100mm), 1:1.83 (65.416*120mm), 1:2.49 (56.071*140mm) and 1:3.26 (49.063*160mm)] were selected. Figure (7-a), demonstrates that the beams with middle web opening of circular, square, hexagonal, and rectangular shapes had identical stiffness, while the beam with a triangular middle opening showed a significant difference in load-deflection curve comparing to other beams, with a smaller stiffness of about 12 KN/mm; for comparison, the control beam stiffness was nearly 18 KN/mm, as shown in Figure (7-a). It can be concluded from Figure (7-b) that the beam with an edge opening was not affected significantly by the
opening’s shape. Table 6 illustrates the effect of opening shapes on the ultimate strength and maximum deflection.

Figure 6: Opening Shapes

Figure 7: Effect of Opening Shapes on Load-Vertical Midspan Deflection Curves

(a) Arch Beam with Middle Opening      (b) Arch Beam with Edge Openings
### Table 6: Ultimate Load and Maximum Deflection Values for Arch Beams with Different Opening Shapes

| Location of opening | Opening shape | Dimension (mm) | Ultimate load (KN) | Decrement ratio in ultimate load | Maximum deflection (mm) | Comparison in maximum deflection |
|---------------------|---------------|----------------|-------------------|---------------------------------|------------------------|---------------------------------|
| Without opening     | -             | -              | 153.36            | -                               | 8.54                   | -                               |
| Middle of the web   | Circular      | D = 100        | 134.49            | 12.3                            | 5.11                   | -40.2                           |
|                     | Hexagonal     | S = 54.96      | 135.5             | 11.6                            | 4.77                   | -44.1                           |
|                     | Triangular    | B = 134.64, h = 116.6 | 134.2        | 12.5                            | 11.22                  | 31.4                            |
|                     | Square        | L = 88.6       | 135.64            | 11.6                            | 5.54                   | -35.1                           |
|                     | Rectangular   | B = 100, h = 78.5 | 137.88        | 10.1                            | 5.79                   | -32.2                           |
|                     | Rectangular   | B = 120, h = 65.416 | 139.17        | 9.3                             | 7.54                   | -11.7                           |
|                     | Rectangular   | B = 140, h = 56.071 | 138.38        | 9.8                             | 8.08                   | -5.4                            |
|                     | Rectangular   | B = 160, h = 49.063 | 137.59        | 10.3                            | 9.15                   | 7.1                             |
| Edges of the web    | Circular      | D = 100        | 151.13            | 1.5                             | 7.41                   | -13.2                           |
|                     | Hexagonal     | S = 54.96      | 152.05            | 0.9                             | 7.74                   | -9.4                            |
|                     | Triangular    | B = 134.64, h = 116.6 | 151.05        | 1.5                             | 7.59                   | -11.1                           |
|                     | Square        | L = 88.6       | 151.62            | 1.1                             | 8.25                   | -3.4                            |
|                     | Rectangular   | B = 100, h = 78.5 | 151.41        | 1.3                             | 7.65                   | -10.4                           |
|                     | Rectangular   | B = 120, h = 65.416 | 151.51        | 1.2                             | 7.43                   | -13.0                           |
|                     | Rectangular   | B = 140, h = 56.071 | 151.50        | 1.2                             | 7.57                   | -11.4                           |
|                     | Rectangular   | B = 160, h = 49.063 | 151.49        | 1.2                             | 7.25                   | -15.1                           |

### 6.3 Effect of opening numbers

In order to study the effect of the number of openings along arch beam on the load-deflection behaviours, six cases with different numbers of openings were investigated along the path of the arch beams. The cases were: one opening at mid-span; two openings at the edges of the beam; three openings, one at mid-span and two at the edges; four openings, two at mid-span and two edge openings; five openings, one at mid span, two near to the point loads, and two at the edges; and, finally, six openings, two at mid-span, two near to the point loads, and two at the edges. Figure 8 shows that the ultimate load capacity was reduced by about 7% in the beam with one middle opening as compared with the arch beam without opening, while the presence of two openings at the edges of the beam had less effect on the ultimate load, so identical curves for arch beams with one, three, and four openings were observed. The arch beam models with five and six openings were the critical cases due to the presence of two openings at the maximum shear zone.
shows the ultimate load capacity and maximum deflection values for arch beams with different number of openings along the beam.

![Graph showing ultimate load capacity and maximum deflection values for arch beams with different number of openings.](image)

**Figure (8):** Effect of Opening Numbers on Load-Midspan Vertical Deflection Behaviours

**Table 7:** Ultimate Load and Maximum Deflection Values for Arch Beams with Different Numbers of Openings

| Number of openings | Opening location                     | Ultimate load (kN) | Decrement ratio in ultimate load | Maximum deflection | Decrement ratio in maximum deflection |
|--------------------|--------------------------------------|--------------------|----------------------------------|--------------------|---------------------------------------|
| Without opening    | -                                    | 153.36             | -                                | 8.54               | -                                     |
| 1                  | Mid-span                             | 142.2              | 7.3                              | 5.64               | 34.0                                  |
| 2                  | Edges                                | 151.2              | 1.4                              | 7.43               | 13.0                                  |
| 3                  | 1 at Mid-span + 2 at edges           | 141.8              | 7.5                              | 5.57               | 34.8                                  |
| 4                  | 2 at mid-span + 2 at edges           | 140.9              | 8.1                              | 5.08               | 40.5                                  |
| 5                  | 1 at mid-span + 2 near to points-load + 2 at edges | 137.5              | 10.3                             | 8.10               | 5.2                                   |
| 6                  | 2 at mid-span + 2 near to points-load + 2 at edges | 137.0              | 10.7                             | 7.94               | 7.0                                   |
6.4 Effect of adding steel stiffeners

To observe the effect of adding stiffeners on load-deflection behaviours in the arch beam without opening, four different numbers of stiffeners (2, 4, 6, and 9) were added to the weaker regions of the arch beam, at the maximum shear and maximum bending moment zones on each side of the beam. Figure 9 shows that the ultimate load capacity and stiffness of the beam slightly increased with the addition of stiffeners. Table 8 illustrates the effect of adding stiffeners to the arch beam without opening.

![Figure 9: Effect of Adding Stiffeners on Load-Midspan Vertical Deflection Behaviours for Arch Beam without Opening](image)

**Table (8):** Ultimate Load and Maximum Deflection Values for Arch Beam Without Opening with Different Numbers of Added stiffeners

| Number of add stiffeners at each side of beam | Location of add stiffeners | Ultimate load (KN) | Increment ratio in ultimate load (KN) | Maximum deflection (mm) | comparison in maximum deflection (%) |
|---------------------------------------------|----------------------------|--------------------|--------------------------------------|------------------------|--------------------------------------|
| Without add stiffeners                      | -                          | 153.36             | -                                    | 8.54                   | -                                   |
| 2                                           | Maximum bending moment sections | 154.51             | 0.7                                  | 7.99                   | -6.4                                |
| 4                                           | Maximum bending moment sections | 156.16             | 1.8                                  | 6.50                   | -23.9                               |
| 6                                           | Maximum bending moment sections | 156.88             | 2.3                                  | 4.58                   | -46.4                               |
6.5 Effects of yielding stress of the arch steel beam

Increasing yielding stress leads to an increase in ultimate load capacity; this parameter was thus studied to show the rate of effect of yielding steel stress and to give an indication to researchers as to whether this increase is beneficial or not. Two cases were thus studied: an arch beam without opening and an arch beam with one web circular opening at midspan. Three values of yielding steel stress, 248, 360, and 450 N/mm², were numerically investigated for this case. Figure 10 shows that an increase in ultimate load and stiffness of the load-deflection behaviours is associated with increases in yielding steel stress. The load-deflection curves show matches in the elastic range, with differences beginning after yielding. Table 9 shows the ultimate strength and maximum deflection values for the specimens with regard to this parameter.

| Yielding Stress (N/mm²) | Ultimate Load (kN) | Maximum Deflection (mm) |
|-------------------------|--------------------|-------------------------|
| 248                     | 165.024            | 7.6                     |
| 360                     | 10.60              |
| 450                     | 24.1               |

(a) Arch Beam Without Web Opening

(b) Arch Beam with Middle Web Opening

Figure 10: Effect of Yielding Stress on the Load-Vertical Midspan Deflection Curve
Table 9: Ultimate Load and Maximum Deflection Values for Arch Beams with Different Values of Yielding Stress

| Beam without opening (EXP.) | Yield stress (MPa) | Ultimate load (kN) | Comparison ratio in ultimate load (%) | Maximum deflection (mm) | Comparison ratio in maximum deflection (%) |
|-----------------------------|--------------------|--------------------|--------------------------------------|-------------------------|-------------------------------------------|
| 328                         | 160                | -                  | 10.78                                | -                       | -                                         |
| 248                         | 116.31             | -24.2              | 7.27                                 | -14.9                   |                                           |
| 328                         | 153.36             | -                  | 8.54                                 | -                       |                                           |
| 360                         | 167.90             | 9.5                | 8.73                                 | 2.2                     |                                           |
| 450                         | 208.30             | 35.8               | 8.93                                 | 4.6                     |                                           |
| Beam with middle opening (EXP.) | 140                | -                  | 7.43                                 | -                       |                                           |
| 248                         | 108.28             | -23.9              | 5.38                                 | -4.6                    |                                           |
| 328                         | 142.2              | -                  | 5.64                                 | -                       |                                           |
| 360                         | 156.09             | 9.8                | 6.08                                 | 7.8                     |                                           |
| 450                         | 193.89             | 36.4               | 7.05                                 | 25                      |                                           |

6.6 Effect of arch beam radius

This parameter was studied by changing the radius of arch beam, with radii of 537.3, 797.5, and \( \infty \) mm investigated for an arch beam without opening, an arch beam with a middle opening and an arch beam with edge openings, with the opening diameter fixed at 80 mm in the arch beams with openings. Figure (11) indicates a significant difference in the stiffness of the beams, where the stiffness of all beams decreases with the increase in the radius of beam. Meanwhile, a remarkable increase in maximum deflection of the arch beam without opening and the beam with edge openings is seen due to the increase in the radius of arch beam, as illustrated in Figures 11-a and 11-c. It also can be seen from Figure 11-b that the arch beam with middle opening has a small value of ductility as compared to that of the other beams. Table 10 shows the ultimate load capacity and maximum deflection values for arch beams of different radii.
Figure 11: Effect of Radius of Arch Beam on Load-Midspan Vertical Deflection

Table 10: Ultimate Load and Maximum Deflection Values for Arch Beams with Different Values of Arch Beam Radii

| Beam                        | Radius of arch beam (mm) | Ultimate load (kN) | Decrement ratio in ultimate load (%) | Maximum deflection (mm) | Incremental ratio in maximum deflection (%) |
|-----------------------------|--------------------------|--------------------|-------------------------------------|-------------------------|--------------------------------------------|
| Beam without opening        | (EXP.)537.3               | 160                | -                                   | 10.78                   | -                                          |
|                             | 537.3                    | 153.36             | -                                   | 8.54                    | -                                          |
|                             | 797.5                    | 126.50             | 17.5                                | 12.91                   | 51.2                                       |
| Beam with edges openings    | (EXP.)537.3               | 145                | -                                   | 8.70                    | -                                          |
|                             | 537.3                    | 151.2              | -                                   | 7.43                    | -                                          |
|                             | 797.5                    | 126.43             | 16.4                                | 13.65                   | 83.7                                       |
|                             | ∞                        | 92.30              | 39.0                                | 15.72                   | 111.6                                      |
Beam with middle opening

| Beam with middle opening | (EXP.)537.3 | 140 | - | 7.43 | - |
|--------------------------|-------------|-----|---|------|---|
| 537.3                    | 142.2       | -   | 5.64 | -    |
| 797.5                    | 117.64      | 17.3| 6.18 | 9.6  |
| $\infty$                 | 84.16       | 40.8| 6.37 | 12.9 |

7. Conclusions

The main conclusions arising from the numerical investigation of steel arch beams with and without web openings, with different locations, shapes, and numbers of openings, both strengthened using steel stiffeners and without such stiffeners, are offered below:

1- The FEA results for steel arch beams with and without web circular openings and both non-strengthened and strengthened using steel stiffeners offer good agreement with the relevant experimental results in terms of ultimate strength, maximum deflection and load-deflection curves. These are thus suitable for studying additional parameters.

2- The ultimate load capacity of the steel arch beam with a middle web opening was decreased with the increase in opening diameter by 2.49%, 6.29%, 12.30%, and 21.17% for opening diameters (50, 75, 100, and 125mm) respectively, as compared with the control beam.

3- The ultimate load capacity of the steel arch beam with edge openings decreased by about 26% as compared with control beam when the diameter increased to 125 mm.

4- The shapes of opening (circular, square, triangular, hexagonal, and rectangular) had no clear effect on the load-deflection behaviours of the steel arch beam with openings near to its supports, while the arch beam with a middle triangular opening had a remarkable decrease in the stiffness of the beam to about 12 KN/mm, as compared with the control beam stiffness of nearly 18 KN/mm.

5- As expected, the increase in yielding stress of steel increases the ultimate load capacity for all types of beams, in which the ultimate strength of the arch beam without opening and arch beam with middle opening reaching 153.36 and 142.2 KN, respectively, at a yielding stress of 328 MPa and decreased by about 24% at 248 MPa and increased by about (10%, 36%) at (360, 450 MPa) respectively.

6- Adding steel stiffeners at maximum bending moment and maximum shear zones leads to an increase in stiffness and ultimate load capacity of the arch beam by (0.7%, 1.8%, 2.3%, 7.60%) for 2, 4, 6, and 9 stiffener at two sides of the beam, respectively, as compared with the arch beam without added stiffeners.

7- Increase in the radius of the arch beam using (537.3, 797.5 and $\infty$) mm decreases ultimate load capacity, while the maximum deflection is increased with increases in the radius of the arch beam by (51.2%, 83.7% and 9.6%) for a radius of 797.5mm and (81%, 111.6% and 12.9%) at straight beam for a beam without opening, beam with edge openings, and beam with middle opening, respectively.
References

[1] Hamza, B. H., “Behavior of RC Curved Beams with Openings and Strengthened by CFRP Laminates,” Ph.D. Thesis in Civil and Structural Engineering, University of Basra, 2013.

[2] S. G. Morkhade and L. M. Gupta, “Experimental investigation for failure analysis of steel beams with web openings,” Steel and Composite Structures, Vol. 23, No. 6, pp. 647–656, 2017.

[3] Mansur, M. A., “Design of Reinforced Concrete Beams with Web Openings,” Proceeding of the 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006), 5-6 September, Kuala Lumber, Malaysia, 2006.

[4] N. E. Shanmugam, V. T. Lian, and V. Thevendran, “Finite element modelling of plate girders with web openings,” J. Thin-Walled Structures, vol. 40, pp. 443–464, 2002.

[5] A Abdul Gabar M. S. "Steel Plate Girders with Web Opening Loaded in Shear" M. Sc. Thesis, University of Technology, Iraq, 2012. (Cited by D. H. Al-Saffar, 2014).

[6] S. G. Morkhade and L. M. Gupta, “An Experimental and Parametric Study on Steel Beams With Web Openings,” Int. J. Advanced Structural Engineering, no. 7, pp. 249–260, 2015.

[7] A. G. A. Al-khafaji and B. H. Al-abbas, “Numerical Study on the Effect of Openings in Steel IPE Beams Strengthened by CFRP Plates,” Journal University of Kerbala, vol. 14, no. 4, pp. 213–227, 2016.

[8] S. Tudjono, Sunarto and A. L. Han, “Analysis of castellated steel beam with oval openings,” IOP Conf. Series: Materials Science and Engineering, Vol. 271, 2017.

[9] R. R. Jichkar, N. S. Arukia, and P. D. Pachpor, “Analysis of Steel Beam with Web Openings Subjected To Buckling Load,” Int. Journal of Engineering Research and Applications, vol. 4, pp. 185–188, 2014.

[10] H. El-dehemy, “Static and Dynamic Analysis Web Opening of Steel Beams,” World Journal of Engineering and Technology, Vol. 5, pp. 275–285, 2017.

[11] O. F. Zaher, N. M. Yossef, and M. A. Dabaon, “Structural Behavior of Arched Steel Beams With Cellular Openings,” J. Constructional Steel Research, vol. 148, pp. 756–767, 2018.

[12] S. A. Hemzah, Z. M. R. Abdul Rasoul and Z. A. Naser, “Experimental study for steel arch beams of compact section with circular web openings” (under-publishing research)