Experimental study for steel arch beams of compact section with circular web openings

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Abstract: An experimental study for the behavior of steel arch beams with and without web circular openings, non-strengthened and strengthened using steel stiffeners had been investigated. Seven models of simply supported I shape steel compact section arch beams have been tested in laboratory. One of the models was without opening as control beam and the other six models were with openings and divided into two groups: Group (1) consist of three arch beams with different numbers of non-strengthened circular openings in various locations, Group (2) consist of three arch beams with circular opening and strengthened with steel stiffeners. There are four parameters considered in the test: existence of circular opening, location of opening, number of openings and strengthening effect using steel stiffeners. The test results showed that the presence of openings in the web at midspan of steel beams decrease the ultimate load capacity by about (12%) while edges openings had no significant effect on ultimate strength with same opening diameter.

Key Words: Steel Beam, Arch, Web circular Openings, stiffeners

1. Introduction

Arch beam can be characterized as a bended girder having convexity upwards, and constrained at its edges. In the past, the arches had been the backbone of the important buildings. The essential aim of arch is to improvement the load carrying capacity, which may come from the stiffening behavior due to membrane action. However, because of relatively littler values of tensile stresses and bending moments generated in the arch beam compared with the straight beam, it is preferred to employment arched girders in structural purposes. Also, this characteristic enabled structural engineers to getting large spans in buildings roofing and bridges decking [1]. The structural use of steel in the construction is perhaps increasing across the world,
Despite seeming to have reached maturity in some countries [2]. With the development of buildings, organize of pipes and conduits within construction is essential to achieve basic requirements like water supply, air-conditioning, sewage, telephone, electricity, and computer network. Usually, these pipes and conduits are set under the beam and, for aesthetic reasons, are covered by a suspended ceiling, in this way making a dead space. Passing these conduits through transverse opening within the floor beams leads to a decrease in the dead space and result in a more compact plan. For little buildings, the saving in this way accomplished may not be remarkable, but for multistory buildings, any saving in story rise multiplied by the stories number can represent a remarkable saving in total rise of the building [3]. Practically, the most popular shapes of openings are rectangular and circular. Circular openings are desired to passing service pipes, such as for water pipes, whereas rectangular openings are provided to accommodate air-conditioning conduits that are generally rectangular.

Lian and Shanmugam (2003), presented ultimate load capacity tests on plate girders arched in plan with centrally placed circular openings. Girders, built up of Grade 43A rolled steel plates, were tested to failure and variables investigated involve degree of curvature and opening diameter. Test outcomes indicated that the ultimate strength of the girders decrease linearly with the increasing opening diameter [4]. Abdul Gabar (2012), investigated three steel plate girders under shear load. The first one is reference without web opening, and the second one contains central circular web opening with diameter 60% of the web height, whereas the third girder is with strengthened strip welded around the circular web opening. The comparison between the three girders shows that the decrease in ultimate shear load for plate girder with opening is 51% and for the girder with strengthened web opening is 35% [5]. Morkhade and Gupta (2015), Conducted an experimental investigation on seven straight hot rolled steel girders of ISMB 100 with web openings to study the maximum load behavior and the deflection. The openings shapes considered in the study are rectangular and circular. Test outcomes indicated that the ultimate strength and the stiffness reduce with increase in opening size. [6]. Morkhade and Gupta (2017), presented an experimental study on the behavior of straight steel I-section beams with different shapes of web openings. Test results showed that circular openings found to be very effective when compared to equivalent square or rectangular openings. Rectangular shape of web openings found to be very critical as it shows very high concentration of stress around the corners’ regions [2]. Siwowska and Siwowski (2017), tested steel straight beams of I-section prestressed with plates of CFRP to evaluation of flexural behavior of strengthened steel beams. The beams contained vertical stiffeners on each side in depth of the web at the position of the applied loads and at the supports to prevent local yielding or web crippling through the tests. The obtained results showed that steel beam strengthened with plates of CFRP does not increase the stiffness while improve the ductility of steel beam in the plastic stage [7]. Zaher et al (2018), presented a search related to the behavior of arched-shape cellular beams with two-hinged supports. The perforated steel arch beams of I section were tested under a vertical concentrated load at mid-span of the beam. The experimental search was performed to investigate the effects of radii of curvature and cellular web openings. The test results showed that an obvious lowering in the ultimate strength of cellular beams in comparison with the solid beam [8]. A surveying, on experimental investigation of steel arch beam of compact I section with openings, shows that it is truly scarce. Hence, to filling this shortage in the scientific field; seven steel arch beams prepared and tested experimentally under two-point load. The main objectives of the present work are to study the influences of different position, different number of openings and strengthening by steel stiffeners on the full performance of such structures.
2. Experimental program
This section presents details of the experimental program.

2.1 Geometry of tested arches
The experimental program involved manufacturing and testing of seven simply supported steel arch beams specimens. All beams have the same radius, span, section (I-section) and tested under the same load type and boundary conditions. The steel beams were built-up from steel plates, the width and thickness of the flange plates is 80mm and 5mm respectively, while the height of the web plates is 150mm with 4mm thickness. The span of all specimens was (1049 mm) calculated between two supports as shown in Figure (1), with radii and angle of (537.3 mm) and (154.8°) respectively, measured to center of arc. One of these specimens, which was without opening, marked as reference beam while the other six specimens were divided into two groups as follow:
Group (1): which consists of three arch beams with different numbers and locations of circular openings.
Group (2): consist of three arch beams with circular openings, same as those of group (1) with strengthening using steel stiffeners.

The diameter of web circular openings was 80 mm (50% beam depth) for all specimens. The details of the specimens are explained in Table (1) and Figure (1).

| Group | Reference beam | Group (1) | Group (1) |
|-------|----------------|-----------|-----------|
| Name of Specimen | AR | AMO | AEO | AEMO | AMOS | AEOS | AEMOS |
| Web height (hw) [mm] | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Web thickness (tw) [mm] | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Flange breadth (bf) [mm] | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| Flange thickness (tf) [mm] | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Arc length (L) [mm] | 1703 | 1703 | 1703 | 1703 | 1703 | 1703 | 1703 |
| Span (S) [mm] | 1049 | 1049 | 1049 | 1049 | 1049 | 1049 | 1049 |
| Arc rise (h) [mm] | 420 | 420 | 420 | 420 | 420 | 420 | 420 |
| Opening diameter (D) [mm] | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| 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 opening edges on two sides | 2 of 5mm thickness at 80mm from stiffener under loading points on two sides |
Fig. (1) Geometric Details of Tested Specimens
2.2 Manufacturing

The flanges and webs of all arched beams were cut off from 5mm and 4mm thick plates, respectively. The webs of the beams were cut from the plates in a curved shape, and then the flanges were welded to the arched web. Circular openings of 80mm diameter were created in its specified locations. A laser-cutting machine used to cut all parts of the steel arch beams (webs, flanges, openings, and stiffeners). The cutting process was controlled by (computer numerical control) to achieve high accuracy in the required dimensions. The arched flanges were formed by bending (curving) the straight flanges plates to satisfy the desired arch shape, this process was carried out by using roller machine. In order to collect different parts of the built-up steel arched-beams, manual fillet welds were used to have full strain compatibility between the parts in the steel beam. The welding procedure was carried out as follows:

1. Plates of two flanges were spot welded to the web at distance of 300mm between two adjacent welding spots.
2. Bottom flanges were welded first to the web, then top flanges.
3. For both bottom and top flanges, the process of welding was carried out by welding from the edges to the middle.

2.3. Material properties

In order to find properties of the steel plates that utilized in manufacturing arch beams, three tensile coupons were cut from the 5 mm and 4 mm thickness flange and web plates, respectively. The measurements of coupon coincided to the ASTM-A370 for the tensile testing of metals, based on a gauge length of 200mm, Figure (2) shows specimens used in tensile testing. The values of yield stress, ultimate stress, and modulus of elasticity are presented in Table (2).

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        |

Fig. (2) Tensile Testing Specimens
2.4. Instrumentation

Tests were performed on the beams up to failure by using hydraulic testing machine with ultimate capacity 2000 kN. All tested arches were constrained by simply supported as shown in Figure (3). Two different devices were used for measuring the central deflection to ensure the validity and accuracy of measurements, the first one was a dial gauge with 0.01 mm accuracy, while the second device was an LVDT which was linked to a computer. Another LVDT was used to measure the lateral displacement in the end of arched beam at the roller support. Figure (4) shows typical vision of the experimental test set-up. All specimens of the steel arches were tested under two-point concentrated load. The load has been applied progressively up to failure of the specimen.

3. Experimental results

The results obtained from experimental test of seven arched steel beams were discussed herein. The beams behavior was studied and discussed in term of load-vertical displacement behavior at mid-span, load-lateral displacement behavior at roller-support, ultimate load capacity, ultimate deformation and failure modes.
3.1 General observations and summery of test results

An exhaustive analysis of the experimental test results showed that the web circular openings of the perforated beams weakened the steel arched beam, as predictable. The arched beams in group one (AMO, AEO, and AEMO), and group two (AMOS, AEOS, and AEMOS) were failed at ultimate load less than of beam (AR). It also can be seen from table (3) a slight increase in ultimate load of (2.86%, 1.38%, and 2.16%) was found when using stiffeners in beams of group two (AMOS, AEOS and AEMOS) respectively, if compared with beams of group one (AMO, AEO and AEMO).

| Table (3): Experimental Results of Tested Beams |
|-----------------------------------------------|
| Group | Reference beam | Group one | Group two |
| Beam | AR | AMO | AEO | AEMO | AMOS | AEOS | AEMOS |
| Yielding load (Py) (kN) | 140 | 128 | 133 | 126 | 133 | 135 | 128 |
| Ultimate load (Pu) (kN) | 160 | 140 | 145 | 139 | 144 | 147 | 142 |
| Comparison in ultimate load | With AR | - | -12.50% | -9.38% | -13.13% | -10.00% | -8.13% | -11.25% |
| Strenthe ned vs unstrengthen | - | - | - | - | +2.86% | +1.38% | +2.16% |
| Yielding deformation at mid-span (Δy) (mm) | 5.38 | 4.96 | 5.35 | 4.69 | 4.88 | 5.35 | 4.88 |
| Ultimate deformation (mm) | Vertical deformation (Δv) | 10.78 | 7.43 | 8.70 | 7.38 | 7.74 | 9.45 | 7.66 |
| Horizontal deformation (Δh) | 16.02 | 10.71 | 14.56 | 10.70 | 11.46 | 14.61 | 11.38 |
| Ductility (Δv /Δy) | 2 | 1.49 | 1.62 | 1.57 | 1.58 | 1.76 | 1.56 |

It also could be observed from these results that the effect of middle openings on ultimate strength of the specimen is larger than that of edges opening with same opening size, this is because maximum bending moment occurs at mid span section. The edges openings had minimal effect on ultimate strength because of small values of bending moment and shear force at the edges of the arch, Figure (5) shows the bending moment and shear force diagrams for simply supported arch beam under two-point load.
Generally, deflections of the control beam (AR) and beams with edge openings, non-strengthened and strengthened with steel stiffeners (AEO, AEOS) increase at ultimate load if compared with strengthened or unstrengthen beams with middle opening (AMO, AMOS) and beams which have middle and edge openings (AEMO, AEMOS). The modes of failure of all tested beams were local buckling in top flange at maximum bending moment section as shown in Figure (6).
3.2. Load-deflection curves for arched specimens

In the Figures. (7) to (9), a load-midspan vertical deflection and load-lateral deflection at roller support are showed for all tested arched specimens.
(a) Load-Vertical Midspan Deflection  
(b) Load-Lateral Deflection

Fig. (8) Load-Deflection Curves for Beams with Opening at Edges (AR, AEO, and AEOS)

(a) Load-Vertical Midspan Deflection  
(b) Load-Lateral Deflection

Fig. (9) Load-Deflection Curves for Beams with Opening at Midspan and Edges (AR, AEMO, and AEMOS)
4. Conclusions

The main conclusions observed from experimental investigation test of steel arch beams with and without web openings, with different locations and numbers of openings strengthened or unstrengthen using steel stiffeners are:

- The existence of circular web opening which has a diameter to height ratio of 0.5 in midspan for arched beam minimize the ultimate strength nearly 12%, if compared with beam without opening.
- The web openings at edges of arched beam had minimal effect on ultimate strength, nearly 9%, if compared with reference beam without opening.
- The strengthening of the openings region by steel stiffeners, slightly increased the ultimate strength nearly (1% to 3%) if compared with non-strengthen beams.
- The results showed that using vertical steel stiffeners as a strengthening technique had insignificant effect on ultimate load capacity and deflection values of arch beams.
- Presence of opening and/or stiffeners didn’t change the mode of failure of all specimens which was local buckling and yielding in top flange of the midspan zone.

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