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Full Length Article

Effect of (B/D) ratio on ultimate load capacity for horizontally curved box steel beam under out of plane concentrated load

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ABSTRACT

The intended of this research is to prepare an analytical study to investigate the best width to depth section ratio (b/d) of horizontally curved steel box beam with constant cross-sectional area (without stiffeners) under single concentrated load at mid-span of the beam. The research adopts three – dimensional nonlinear finite element analysis of steel box -section horizontally curved beams exposed to static load. The isoparametric brick element of twenty-node has been used to represent the steel element; also, the yield criterion used to compute the stress level of plastic deformation is Von-Mises. The simulation model of the behavior of steel under tension and compression stresses is elastic-perfect plastic. A semi-circular two-span continuous horizontally curved steel box beam was fabricated and tested under two point loads at midspan of the beam, the results was compared with the results of the computer program (NFHCBSL) used in this study. In general, it is found that the adopted finite element model to predict the structural response of horizontally curved steel box beam has a good agreement with the test results concerning estimate load-deflection response.

The effect of b/d ratio is considered by taken different values (20–100) % with the identical area of cross-section. Also, the effect of curvature was studied by considering different values from beam with half circle to straight beam. The results appear that the best (b/d) ratio is in between (0.3 and 0.4) at curvature between (0° and 90°) and the best (b/d) ratio is in between (0.4 and 0.5) at curvature between (90° and 180°). Also, the result showed that the decrease in carrying load capacity as the beam curvature increased is independent on the value of b/d ratio.

1. Background and previous research

The background information in this work focused on the previous studies on numerical and experimental modeling of steel box beams which are very commonly used in constructions especially in curved bridges.

Culver and Christiano [1] derived influence coefficients from curved beam governing differential equations used in a computer program that uses flexibility method. The predicated deformations from computer program was compared with results obtained from static tests of scale-model two span continuous I-girder curved bridge. Brennan [2,3] developed a three-dimensional computer program to analyze curved steel bridge. A comparison was made between the results obtained from the computer program with the experimental results as a deflections and moments. Mozer et al. [4] performed a static test on scale model of eight curved steel plate girders bridge. The girders were tested under high shear, high bending and combined high bending and shear forces. The evaluation of a developed computer program modeled the structure as a grid was accomplished through comparisons to test results. Fam and Turskstra [5], conducted experimental test of a simply-supported curved Plexiglas single-cell box girder bridge. The results were used to evaluate analytical data from finite element program. The study showed a good agreement between experimental and analytical solution. Heins and Oleinik [6] used finite difference approach to solve Vlasov's differential equations to analyze single and continuous curved box Girder Bridge. The forces and the corresponding stresses that were calculated included bending moment and shear, warping torsion, pure torsion, and bi-moments. Sisodiya et al. [7] used finite element method to analyze skew curved bridges of single box girder. They used rectangular elements for webs and triangular or parallelogram elements for flanges. Fukumoto and Nishida [8] carried out experimental study on six simply supported curved I-beams. The study aims to investigate the effect of the cross sections dimensions, radii of curvature and span lengths variations were tested under three-point bending. A computer program developed for analyzing inelastic and elastic curved girder large deformations behavior. The results of the computer program were had a good agreement with those of the laboratory tests. Yoo

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and Carbine [9] investigated experimentally the ultimate load of horizontally rolled curved I-section steel wide flange beams of differing cross-sections and radii of curvature. The load applied in three points and the results compared against computer-generated results. Shanmugam et al. [10] carried out experimental test of a series of isolated curved I-beam. The aim of the test to investigate the ultimate load capacity of the I-beam. The results obtained from experiments compared to finite element data using ABAQUS package program. Luo and Li [11] established the equation of equilibrium of thin-walled curved box-girder based on thin-walled curved bar theory and potential variation principle considering shear lag, bending and torsion. A cubic parabolic curve used to approximate the displacement function of longitudinal warping of Reissner's method. Luo et al. [12] investigated the effect of shear lag for box girders. For this purpose, conducted experimental test of Perspex glass model of continuous three-span box girder of varying depth. The experimental results were examined to verify a developed finite segment model. Generally, reasonable agreement between the experimental results and numerical data. In order to evaluate the current AASHTO guide specifications, Huang [13] carried out field test on the Veteran's Memorial curved steel-box Girder Bridge. The test and analytical data showed that the spacing of the first transverse stiffener at the end of simply supported curved girder may be very conservative. Jerad [14] conducted analytical and experimental investigation for four horizontally curved steel, I-girder bridges with semi-integral and integral abutments. The experimental work was focused to monitoring and finding the short and long-term response of the bridges. The analytical work employed using commercial finite element analysis software to modeling the bridge. The main conclusions were the live load moment distribution factors were primarily influenced by the degree of curvature. For extreme girder the axial stresses under thermal loading was 6.4 ksi, while the corresponding value was 11.6 ksi under other total loading. Al-Mutairee and AbdulAbbas [15] performed analytical investigation of strengthening of horizontally curved steel, I-girder with CFRP laminates. A computer program NFASAC (Nonlinear Finite Element Analysis of Steel-Adhesive-CFRP) was made to analyze data theoretically. The static parametric studies showed that increase in CFRP thickness lead to significant increase in elastic and ultimate loads. The CFRP laminates using can confine steel curved beam and decrease the angle of twisting and lateral deformation.

2. Research objective

The main object of this study is to explore the optimum width/depth ratio (b/d) of horizontally curved steel box beam with constant cross-sectional area (without stiffeners) which is important in manufacturing of the section. Also, to study the effect of the beam curvature on (b/d) ratio, ultimate load and deflection.

3. Finite element idealization

3.1. Steel representation

The horizontally curved box steel beam is divided (discretized) in its length, width and depth into brick elements. In the current study, three-dimensional 20-node isoparametric quadratic brick elements are used to model the steel, each node have three degrees of freedom.

4. Idealized behavior of steel

Elastic-perfectly plastic relation used to simulate horizontally curved steel box beam behavior based on Von-Mises criterion as shown in Fig. 1.

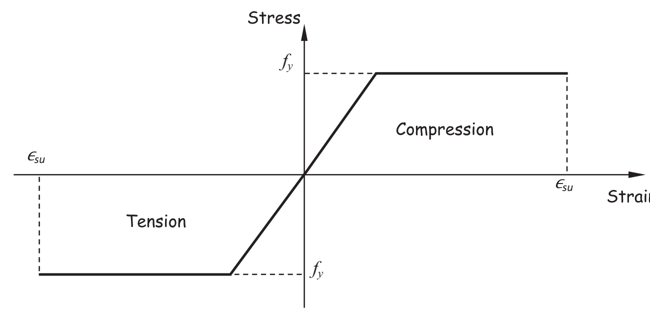

Fig. 1. Idealized bilinear stress-strain relationship for steel.

5. Numerical integration

In most finite element analyses, the element stiffness matrix cannot be obtained analytically. Thus, to accomplish the integration required to evaluate the element stiffness matrix, a suitable scheme of numerical integration has to be used. The 27 ($3 \times 3 \times 3$) -point Gauss-quadrature integration rule is employed in computer program.

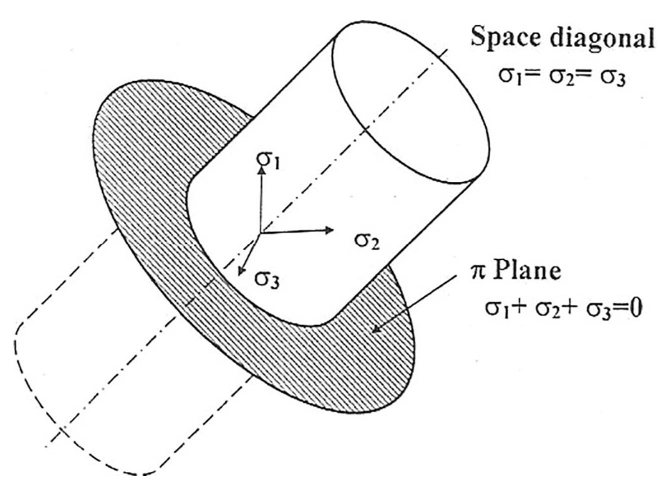

Fig. 2. Three – Dimensional representation of Von-Mises yield surfaces in principal stress space.

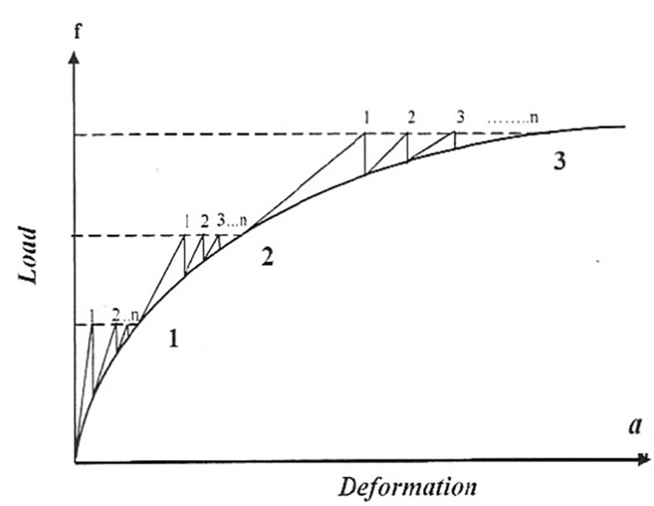

Fig. 3. Iterative – Incremental technique.

Fig. 4. Loading Machine Used in the Test.

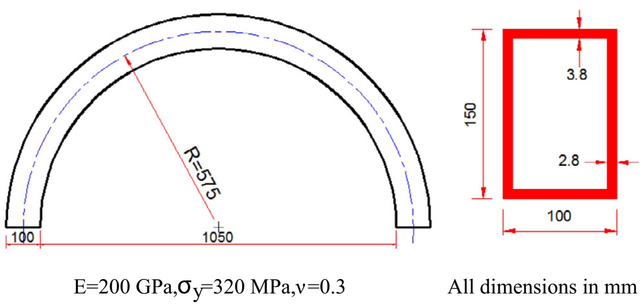

Fig. 5. Geometry and properties of the tested beam.

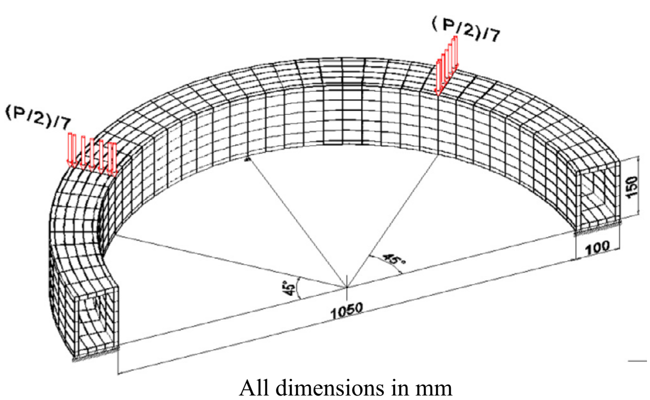

Fig. 6. Finite element mesh of 880 brick Elements of the tested beam.

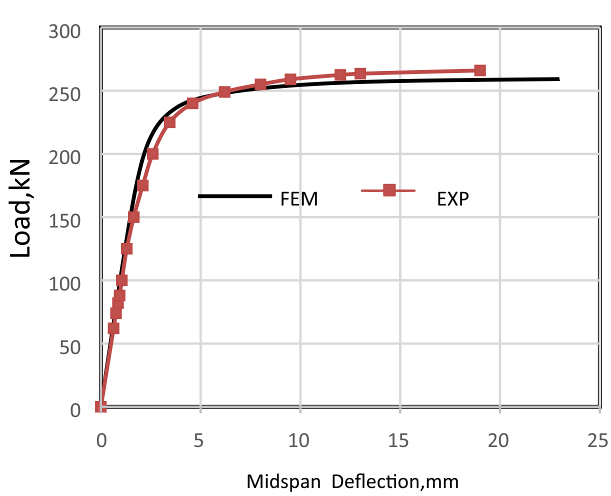

Fig. 7. Comparison between experimental and theoretical load-deflection curves for tested beam.

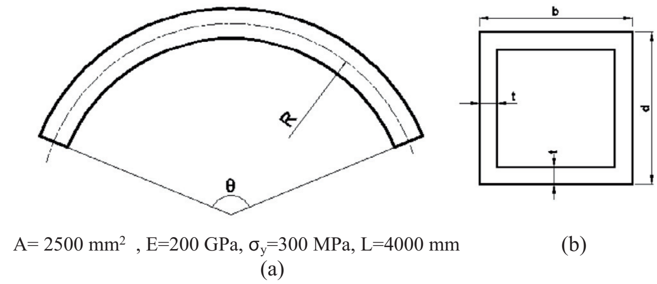

Fig. 8. Geometry, Properties, and Section Details of the Curved Beam (a):Plan view of the curved beam; (b):Cross section of the beam.

6. Yield criterion used for steel

The Von-Mises yield criterion (Fig. 2) has been used to observe the stress value at the beginning plastic deformation for steel material [16]. Yield criterion may be written as

$$f(\sigma) = \sqrt{3J_2} = \sigma_0 \quad (1)$$

Table 1
Values of (b_f/d) considered in the present study.

b/d	d,(mm)	b,(mm)	t,(mm)**
0.2	231	46.2	4.6665
0.3	221	66.3	4.4913
0.4	212	84.8	4.3384
0.5	200	100	4.2893
0.6	197	118.2	4.0709
0.8	185	148	3.8424
1.0	175	175	3.6474

**$t = \frac{2(b+d) - \sqrt{4(b+d)^2 - 16A}}{8}$, A = 2500 mm^2, b = (b/d)d.

Table 2
Values of (θ) and R in the present study.

θ	R (mm)
45°	5092.96
90°	2546.48
135°	1697.65
180°	1273.24
Straight Beam	∞

*R = L(4000 mm)/θ.

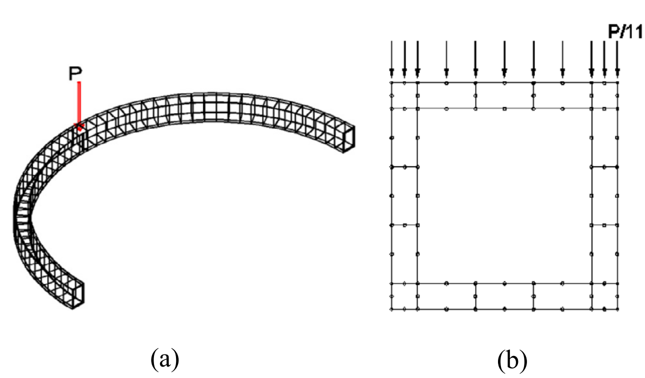

Fig. 9. Finite element mesh of 784 brick elements of the beam. (a):Mesh along the beam; (b): Mesh of cross-section.

where J_2 is equal to:

$$J_2 = \frac{1}{3}\left[\left(\sigma_1^2 + \sigma_2^2 + \sigma_3^2\right) - \left(\sigma_1 \cdot \sigma_2 + \sigma_2 \cdot \sigma_3 + \sigma_3 \cdot \sigma_1\right)\right] \quad (2)$$

6.1. Nonlinear solution technique

In this study, the incremental-iterative technique is used to conduct the nonlinear finite element analysis, Fig. 3. The external

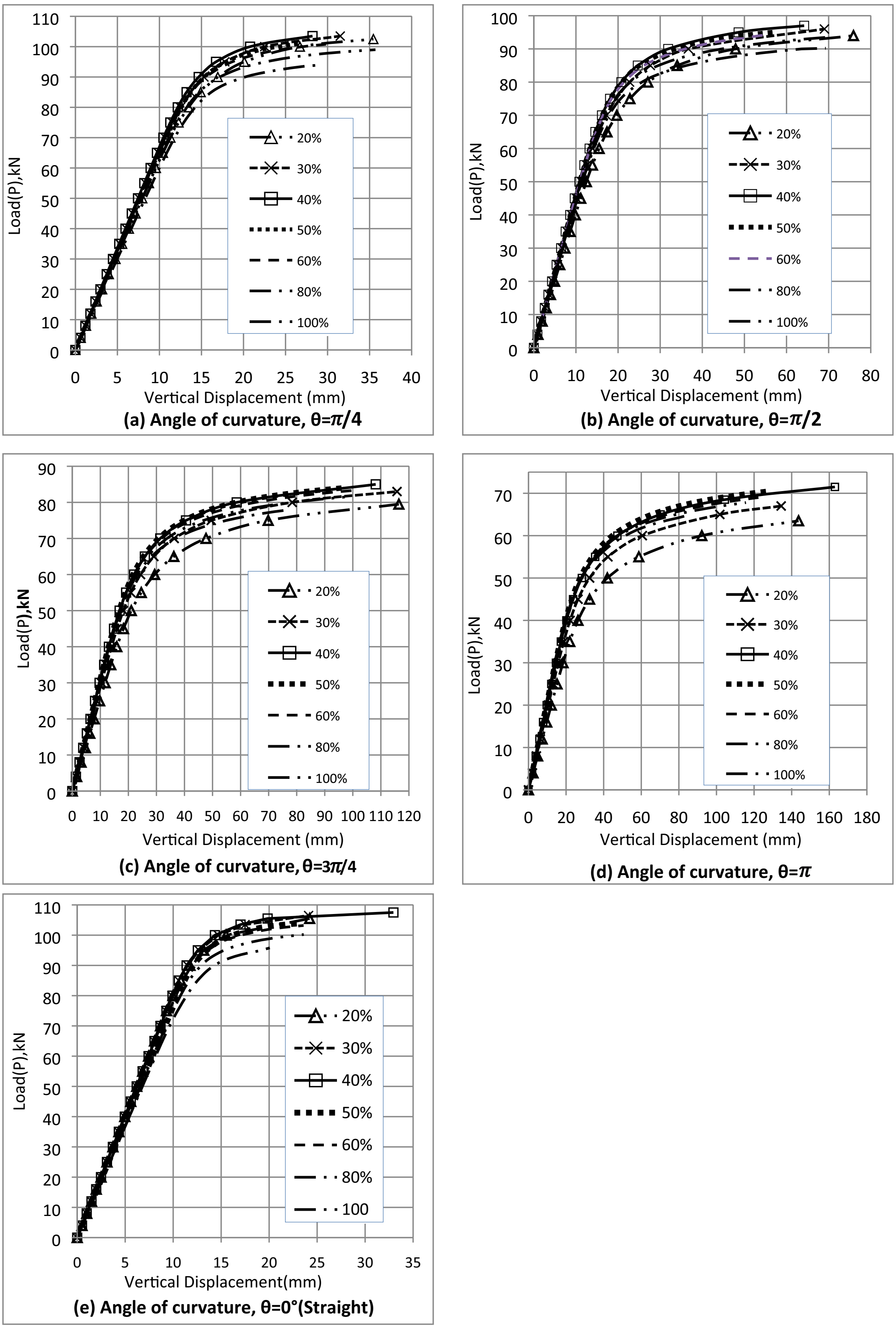

Fig. 10. Load-Deflection curve at midspan of beam (a) $\theta = \frac{\pi}{4}$; (b) $\theta = \frac{\pi}{2}$; (c) $\theta = \frac{3\pi}{4}$; (d) $\theta = \pi$; (e) Straight beam.

load is applied gradually, and the duplicates are performed to obtain a corresponding solution that corresponds to the load stage under consideration. The stiffness matrix is formed at each iteration, which may give more accurate results, but it may take a great deal of arithmetic effort to form and analyze the stiffness matrix.

7. Convergence criteria

The force convergence criterion which considered in the present work. The redistribution of the out of balance forces is observed directly. The termination of equilibrium is estimated by the amount of the residual unbalanced nodal forces. The convergence criteria may be expressed in as:

$$\frac{\sqrt{\{r(a)\}^T \cdot \{r(a)\}}}{\{f\}^T \cdot \{f\}} \leq Specified\,Tolerance$$

Where {r(a)}, is the out of balance residual force vector , {f} is the vector of external loads.

8. Comparison with experimental work

In order to check the validity and accuracy of the NFHCBSL computer program written by [17]to simulate horizontally curved steel box beam behavior, a semi-circular two-span continuous horizontally curved steel box beam was fabricated and tested under two point loads at midspan of the beam. The test was carried out using hydraulic testing machine with capacity of 2000 kN, as shown in Fig. 4. The specimen was of inner diameter 1050 mm and outer diameter 1250 mm, and had cross-section dimensions of 150 mm overall depth, 100 mm width and 2.8 mm, 3.8 mm web and flange thickness, respectively. The properties of steel material was 200,000 MPa, 320 MPa, 0.3 for elasticity coefficient, yield strength and Poisson ratio, respectively. Fig. 5, shows the geometry, properties and loading for curved beam. The convergence of the results of the midspan deflection is obtained when the curved beam is divided into 880 elements, shown in Fig. 6. The finite element method results compared with experimental results through load-deflection curve and ultimate load. In general, it can be noted a good agreement between the finite element analysis results and the experimental results within specified range of behavior as shown in Fig. 7. The maximum difference in ultimate load between experimental and NFHCBSL results about 2.3%.

9. Parametric study

In order to find optimal (b/d) ratio for horizontally curved steel box beam, a thirty-five beams with constant (cross-sectional area = 2500 mm^2, length = 4000 mm and fixed boundary conditions for both ends) are studied. The values of (b/d) ratio are (0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0). Each value of (b/d) ratio are investigated for (θ = 45°, 90°, 135°, 180° and straight beam) as shown in Fig. 8. The properties of the material for the steel section are fixed for each parametric study, assumed to be 200,000 MPa, 300 MPa, 0.3 for the elastic coefficient, yield strength and the Poisson ratio, respectively. The information of cases studied, can be summarized in Tables 1 and 2.

A convergence study on mid span deflection for b/d = 1.0 and degree of curvature (θ = 45°) showed that the present horizontally curved steel box beam was divided into 784 elements with 20-node isoperimetric brick element, as shown in Fig. 9, where the difference between the last two meshes is 2.6%. Then the NFHCBSL computer program is adapted to analyze the thirty-five beams.

10. Results of parametric studies

As shown in Figs. 10, for angles of curvature ($0 \leq \theta \leq 90°$), it's found that the optimal value of b/d ratio lying between (0.3) and (0.4), while the optimal value of b/d ratio for angles of curvature ($90° < \theta \leq 180°$) lying between (0.4) and (0.5). Also, the carrying load capacity of curved beam decrease as the degree of curvature increased (due to increase of torsional moment) regardless the value of b/d ratio. For θ = 45° the carrying load decreased by 3% of that of straight beam whereas decreased by 33% for θ = 180°.

11. Conclusions

1. Comparison of numerical and experimental results confirmed the validity of numerical analysis to simulate the behavior of horizontally curved steel box beam where the difference ratio in ultimate load was 2.3%.
2. The optimal value of b/d ratio lying between (0.3) and (0.4) for curved steel box beams have angles of curvature ($0 \leq \theta \leq 90°$) while the optimal value of b/d ratio sited between (0.4) and (0.5) for angles of curvature ($90° < \theta \leq 180°$).
3. The decrease in carrying load capacity as the beam curvature increased is independent on the value of b/d ratio.

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