The Analytical Study of Strengthening the Bottom Flange of Steel I-Section Simply Supported Horizontally Curved Beams

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Abstract

This research is devoted to study the effects of strengthening the bottom flange of steel I-section simply supported horizontally curved beams on the behavior and maximum strength of these beams under concentrated static load. The strengthening includes increasing the thickness of bottom flange at finite region (**angle of strengthening**,(φ)), thus the volume of steel will be increased. Three dimensional nonlinear finite element analyses done utilizing computer program called **NFHCBSL**, incorporate 20-node isoparametric brick element used to represent the steel elements. The study incorporates five **angles of horizontal curvature** ($0=5^o,10^o,15^o,30^o$ and 45^o). For each angle of horizontal curvature(θ), eight regions of strengthening investigated, thus forty case had been studied. The results show that by strengthening the bottom flange of this type of beams the ultimate strength of beam can be increased about 35%, while the maximum vertical and the horizontal deflections can be reduced by 67% and 69% respectively, when the angle of strengthening (φ = $55\%\theta$,i.e. the increment in the volume of steel is equal to 15.7%). Also, when the angle of horizontal curvature(θ) increases the ultimate strength of beam decreases for any value of angle of strengthening (φ), but this decrement increase rapidly if the angle of strengthening (φ) was increased.

الخلاصة

هذا البحث كرَّس لدراسة تأثيرات تقوية الشفة السفلى للأعتاب الحديدية ذات المقطع I– ،الأسناد البسيط والمنحنية أفقياً على تصرف هذه الأعتاب و تحملها الأقصى تحت تأثير أحمال استاتيكية مركزة. التقوية تضمنت زيادة سمك الشفة السفلى عند منطقة محددة **(زاوية التقوية**، (φ))، لذا فإن حجم الحديد سوف يزداد. تحليلات العنصر المحدد اللاخطية ثلاثية الأبعاد تمت بالإستفادة من البرنامج الحاسوبي المسمى **NFHCBSL**، المتضمن استخدام العنصر الطابوقي ذي العشرين عقدة لتمثيل العناصر الحديدية. تضمنت الدراسة خمسة قيم **لزاوية الأنحناء الأفقي** $(\theta = 5^{\circ}، 10^{\circ}، 15^{\circ}، 30^{\circ}$ و $45^{\circ})$ لكل زاوية انحناء افقي (θ) ثمانية مناطق تقوية بحثت، لذا أربعين حالة تم دراستها. النتائج بيّنت انَّ بتقوية الشفة السفلى لهذا النوع من الأعتاب يمكن زيادة التحمل الأقصى للعتب تقريبا 35%، بينما الهطولات العمودية والأفقية القصوى يمكن تخفيضها 67% و69% على التوالي، عندما تكون زاوية التقوية (φ = θ%55، اي انَّ الزيادة في حجم الحديد تساوي 15.7%). كذلك، عندما تزداد زاوية الأنحناء الأفقي (θ) فإنَّ التحمل الأقصى للعتب يتناقص لأي قيمة من زاوية التقوية (φ)، لكن هذا التناقص يزداد بسرعة اذا تزايدت زاوية التقوية (φ).

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1- Introduction

1.1 Previous Researches

Horizontally curved beams are frequently used in construction of bridges, interchange facilities and balconies, because the constraints of existing land use. In 1970, **Heins** and **Spates** carried out experimental tests on a curved I-girder subjected to a combination of concentrated loads and torsional moments. The model constructed by them was embedded in concrete blocks to prevent the movements at ends and provide a fixed support, and loaded in the elastic range only. A series of experimental investigations to study the effect of curvature on the ultimate load behavior of prismatic curved I-beams, was reported by **Fukumoto et al.** in 1981. They tested six simply supported curved I-beams under a concentrated load at mid span. During the tests the beams were restrained at their supports against twist. In 1985, **Hasebe et al.** studied the effects of curvature and the effects of cross section dimensions on the effective width of horizontally simply supported curved beams of box and channel cross section under uniformly distributed loads. The authors concluded that the effective width ratio is independent on the cross sectional dimensions of the curved beam under uniform loading but it is dependent for concentrated loading. **Al-Shaarbaf**, 1990 presented a three dimensional nonlinear finite element model suitable to analyze the steel and reinforced concrete structures under static loads. In 1995, **Shanmugham et al.** tested ten steel curved beams. The results obtained from experiments on two sets of curved I-beams. The objectivity of this paper is to determine the ultimate load carrying capacity of steel I-beams with intermediate lateral restraint and to examine the effect of curvature on the behavior of these beams under bending loads. **Sennah** and **Kennedy** In 1998, summarized the results from an extensive parametric study, using the finite element method in which 120 simply supported curved bridge were analyzed to evaluate the shear distribution in the web due to truck loading as well as dead load. The parameters considered in the study are: cross bracing system, aspect ratio, number of lanes, number of cells and degree of curvature. In 2001, **Young-Lin** and **Bradford** investigated the nonlinear elastic-plastic behavior of steel I-section beams curved in plan under vertical loading. The material and geometric nonlinearity are included in this study. Three types of simply supported I-section steel curved beam (continuously braced, centrally braced, and unbraced) under mid-span concentrated load were investigated analytically. Comparisons with rational finite element results and existing experimental results show that the proposed interaction equations give a good lower bound for the design of horizontally curved beams (steel I-section). **Al-Mutairee** in 2008, presented a three dimensional finite element computer program called NFHCBSL to analyze a horizontally curved beams (steel, concrete and composite) subjected to static loads. His investigation was proved that the plastic zone initiated under the concentrated load at extreme web edge of the simply supported horizontally curved beam, as shown in Fig.(1). **Raad** in 2009, was used the NFHCBSL computer program to study the effect of the width to depth ratio (bf/d) and the curvature of the steel I-section horizontally curve beams on their ultimate strength. The research adopts three dimensional nonlinear finite element analyses of steel I-section horizontally curved beams under static load. The 20-node isoparametric brick element has been used to represent the steel element. The results appear that the (bf/d) ratio equal to 1.5-2 is optimum for diff

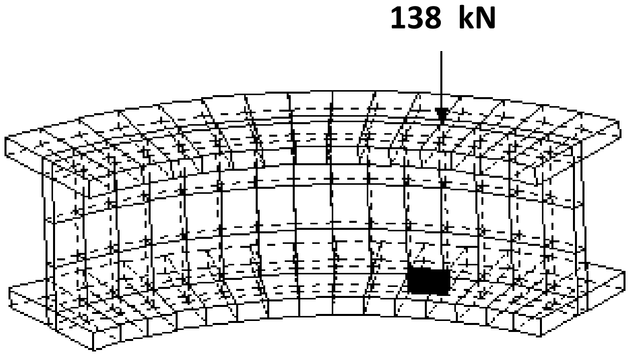


Fig.(1): Initiation of Plastic Zone, Al-Mutairee

1.2 Research Objective

All previous investigations and studies did not show the effects of strengthening the bottom flange of steel I-section simply supported horizontally curved beams on the behavior or ultimate strength of these beams. Therefore, the main object of this research is to study this effect which is important to improve the strength and performance of steel I-section horizontally curved beam.

2- Nonlinear Finite Element Program

The analyses done utilizing the computer program coded **NFHCBSL** (**N**onlinear **F**inite element analysis of **H**orizontally **C**urved **B**eam under **S**tatic **L**oad) presented by [Al-Mutairee, 2008].

2.1 Steel Idealization

In the present study, the 20-node quadratic brick element has been adopted for describing the steel elements. The element has its own local coordinate system, r, s ,t as shown in Fig.(2), with the origin at the center of the element, hence each local coordinate ranges from (-1) to (+1). [William and Paul, 1987].

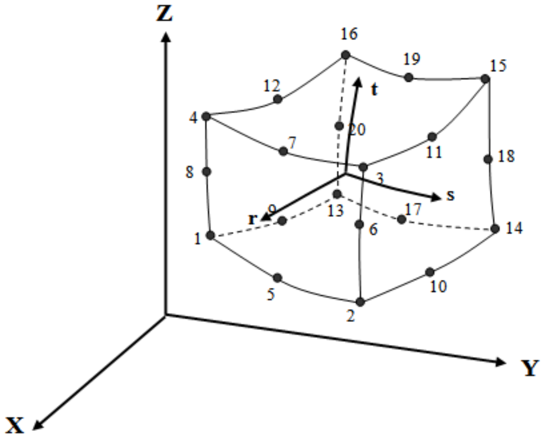


Fig.(2): The 20-Node Brick Element in Cartesian Coordinates.

2.2 Modeling of Steel Adopted in the Analysis

The elastic – perfect plastic relationship, shown in Fig.(3), based on von-Mises, Chen 1982, yield criterion is used for steel elements.

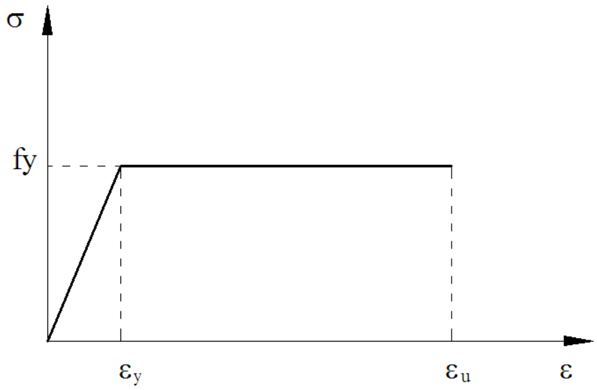


Fig.(3): Idealization of Stress-Strain Curve for Steel Beams.

2.3 Numerical Integration

The Gaussian-Legender quadratic numerical integration technique has been used to evaluate the stiffness matrix, Zienkiweixz 1977. The (3x3x3) Gauss quadratic integration rule was used for concrete elements representation.

2.4 Nonlinear Solution Technique

To consider the material nonlinearity problem, the incremental-iterative method is used in this study. The load applied as a series of increments, at each increment the stiffness matrix (within each increment, the stiffness matrix updating or recomputed after each fifth iterations) computed and iterative solution is carried out to achieve the true response. Within the increment of loading, if the difference between the external and the internal forces becomes negligibly small, the convergence is assumed to be obtained. The displacement convergence criterion was adopted in this research and the tolerance was equal to 0.3%.

3- Reliability of Program

To evaluate the reliability of the program NFHCBSL, a steel I-section simply supported horizontally curved beam analyzed by Shanmugam et al. in 1995, coded (CB1) will be analyzed. The initial stresses considered as shown in Fig(4). The boundary conditions is assumed such that nodes 1-3 on the bottom flange at support(A), as illustrated in Fig.(5), are constrained in X, Y and Z directions and nodes 15-17 at support(B) are allowed to move only in Z direction. While the nodes 4-8, 9-14 and 18-22, are assumed to be restrained only in the X-direction. All geometry, properties of materials, loading conditions and the parameters adopted in the analysis are shown as in Fig.(6). The nodes located at the perimeter of the ends will be considered fixed, while the nodes located at mid-span will be restrained in the tangential direction only. A convergence study of this curved beam (CB1) was done by [Al-Mutairee, 2008] including five different meshes involving a total of 90, 180, 270, 360, and 450 elements. The results show that the difference between any successive meshes decreased until it is reached to about 0.6% between 360 element and 450 element meshes. Thus the mesh of 360 is adopted in current analyses, see Fig.(7).

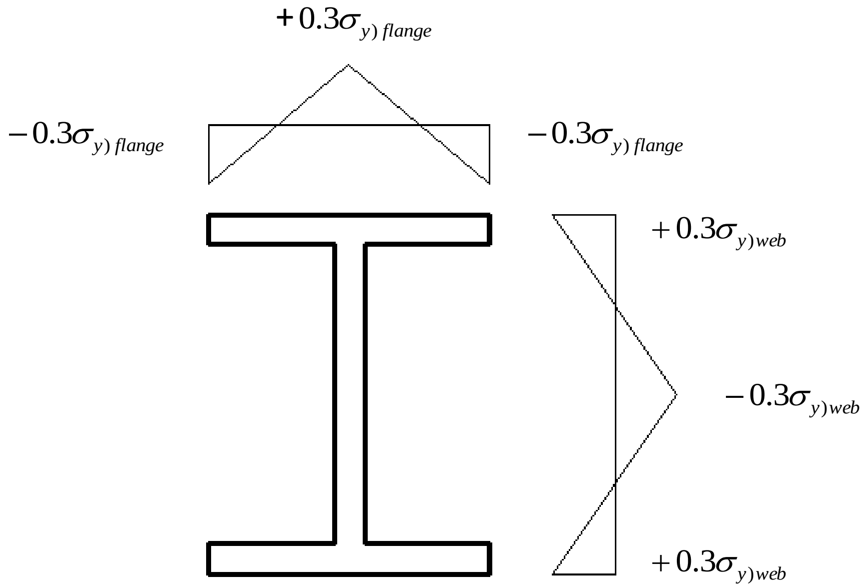
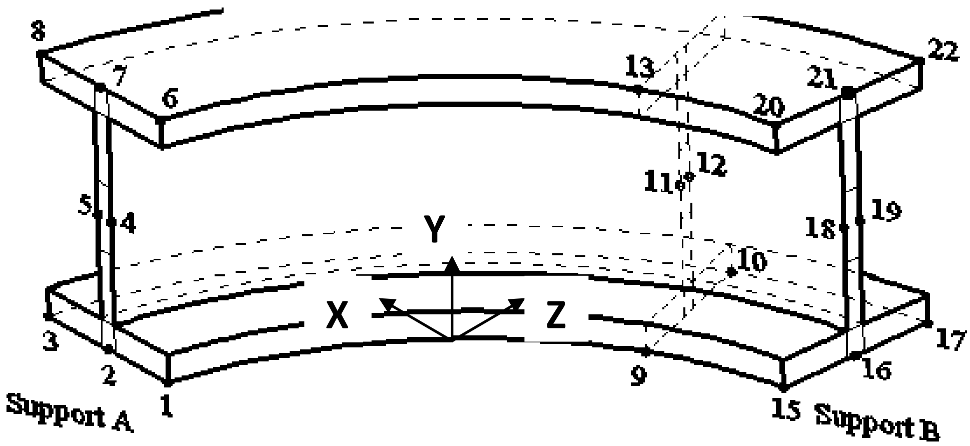


Fig.(4): Residual Stresses Pattern, Shanmugam et al.



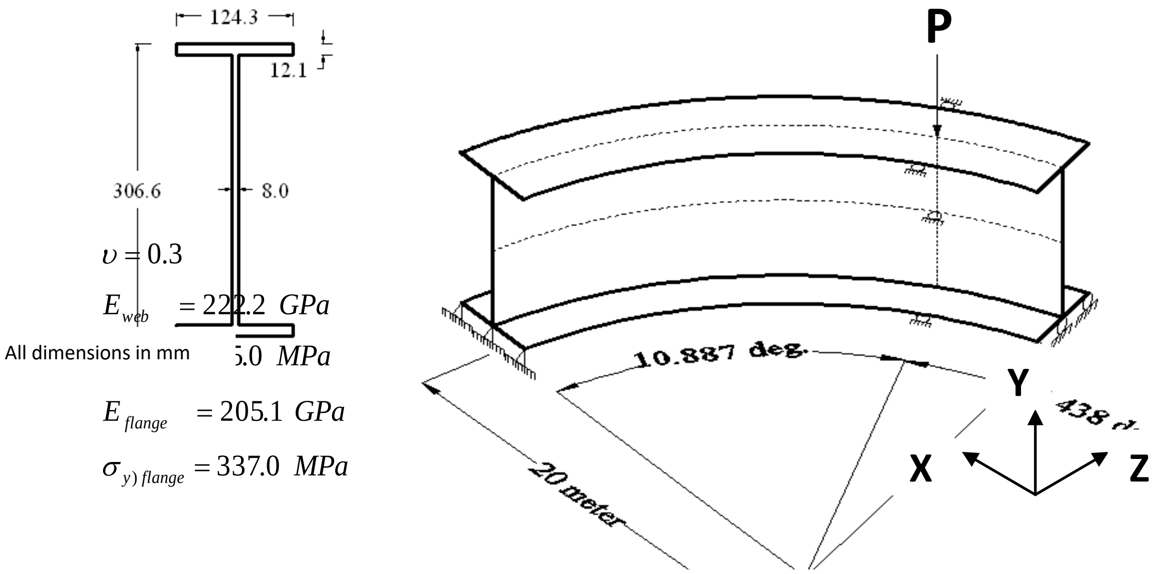


Fig.(6): Geometry, Properties and Loading Conditions of the Shanmugam Curved Beam(CB1).

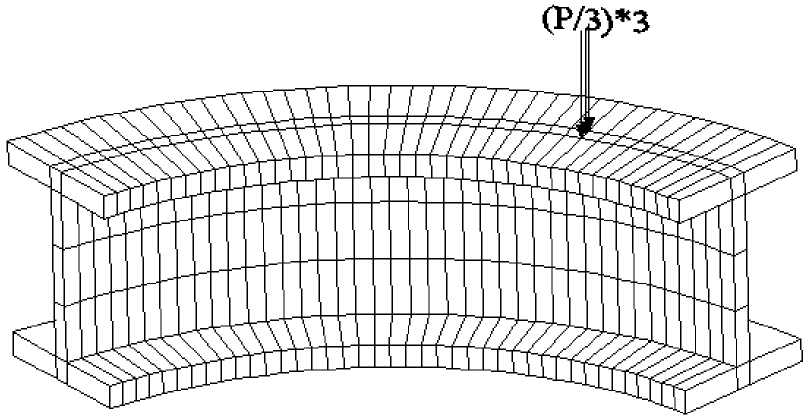


Fig.(7): Finite Element Mesh of 360 Brick Elements of CB1, Al-Mutairee

The deflected profile in the vertical direction obtained from NFHCBSL numerical results and the experimental results are graphed in Fig.(8). This figure reveals good agreement between the experimental and the predicted load-deflection curves throughout the entire range of behavior of the tested specimen. The computed ultimate load (197.27 kN) was slightly higher than the experimental (192 kN), hence, the difference between them is 2.7%.

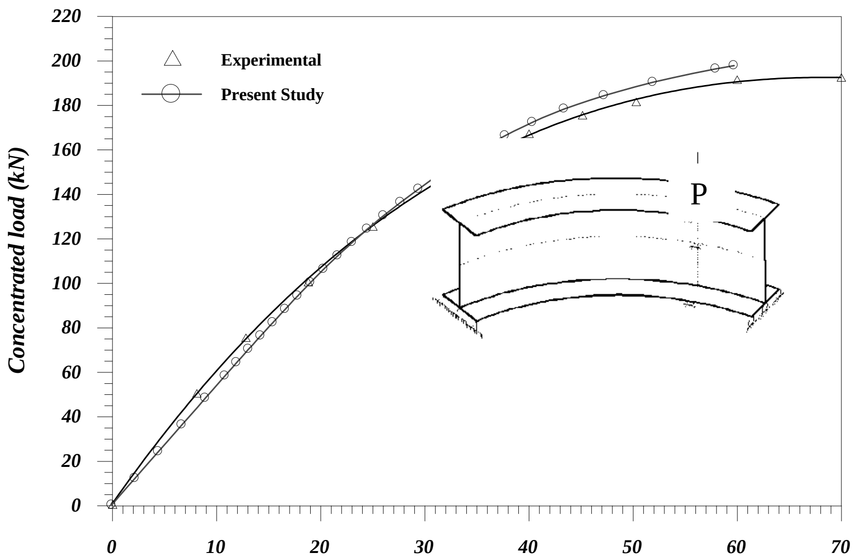


Fig.(8): Load-Deflection Curves for Shanmugam et al. Curved Beam CB1.

4- Parametric Study

Parametric studies incorporate strengthening the bottom flange of steel I-section horizontally curved beam at specific region had been done. The values of angle of curvature (θ) that studied were 5^o, 10^o, 15^o, 30^o and 45^o. For each value of θ eight values of angle of strengthening (φ) investigated (φ = 0% θ, 5% θ, 15% θ, 25% θ, 35% θ, 45% θ, 55% θ and 65% θ), thus forty case studied. The curved beam was prismatic when φ = 0% θ, and non-prismatic for other values of (φ). The concentrated load applied at mid span and divided on the existed seven nodes equally, see Fig.(9). The lateral restraints are not considered while the boundary conditions at ends, properties of material and dimensions of cross section as defined previously. The additional strengthening layer takes the same thickness of bottom flange. The incremental scheme of loads shown in Table (1) is used. When the value of (φ) is grater than zero, the volume of steel increases according to the value of this angle and as tabulated in Table (2). It is nice to note that each case study required between 19164 input data (when φ = 0% θ) and 22499 input data (when φ = 65% θ).

Table (1): The Incremental Analytical Scheme of Applying the Loads.

Number of Increments	≤ 14	≥ 15	≥ 35
The Applied Load ΔP(kN) for θ = 5°, 10°, 15°	**4.0**	**2.0**	**1.0**
The Applied Load ΔP(kN) for θ = 30°, 45°	**2.0**	**1.0**	**0.5**

Angle of Strengthening (φ = %θ)	**0**	**5**	**15**	**25**	**35**	**45**	**55**	**65**
Additional Elements	**0**	**6**	**18**	**30**	**42**	**54**	**66**	**78**
Increment in Volume of Steel %	**0**	**1.43**	**4.28**	**7.14**	**9.99**	**12.9**	**15.7**	**18.6**

Table (2): Increments in Volume of Steel of Curved Beam Due to Strengthening.

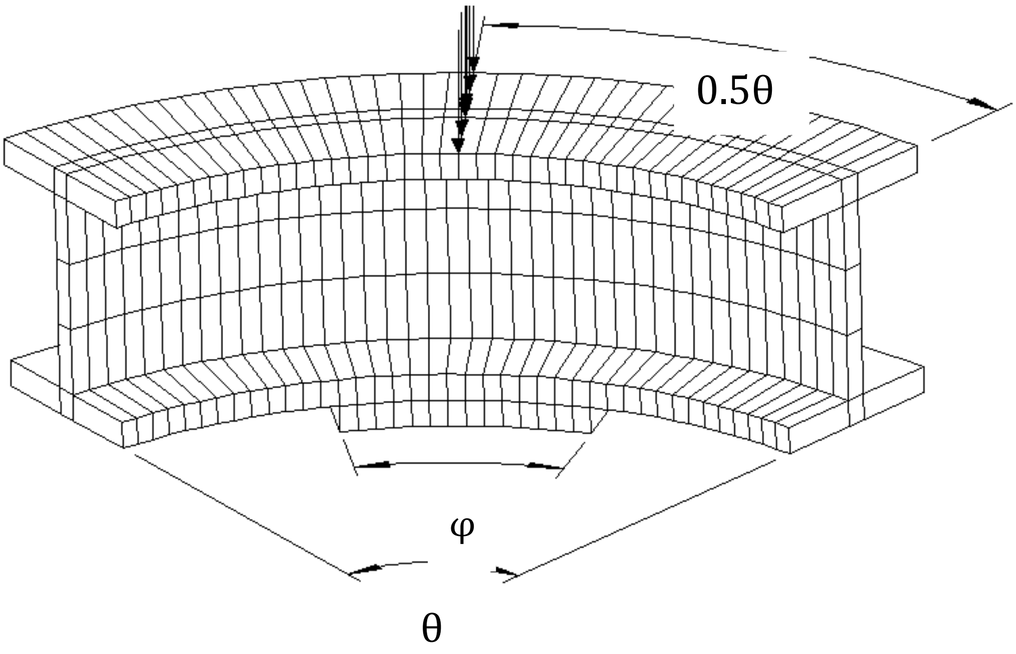


Fig.(9): Details of Strengthening the Bottom Flange

4.1 Discussion of Results

The analytical results had been drawn in Figs.(10) to (15). The ultimate strength of steel I-section curved beam increases when the angle of strengthening (φ) increases at $\theta = 5^{\circ}$, see Fig.(10), the maximum ultimate load is equal to 164 kN and 221 for φ = $0.0\%\theta$ and φ = $55\%\theta$ respectively, i.e., the increment in the ultimate strength of beam is reached to 34.8% when increasing the volume of steel 15.7%, see Table (2). If the angle of curvature increased to be $\theta = 10^{\circ}$, the maximum increment in the ultimate strength of beam is reached to 27.6% corresponds the value of angle of strengthening φ is equal to $65\%\theta$, i.e., increment in the volume of steel is equal to 18.6%, as shown in Fig.(11). The results proved that the increment in the ultimate strength of beam decreases when the angle of curvature increases, for example when $\theta = 45^{\circ}$, the maximum increment in the ultimate strength was 7% at $\varphi = 65\%\theta$, see Fig.(14), this is due to the torsional effect which will be more critical than bending effect and control on the behavior of curved beam when the angle of curvature increases. Thus, it is not economical to strengthening the bottom flange only, if the angle of curvature (θ) is larger than 13° because the increment in the volume of steel will be larger than the increment in the ultimate strength of horizontally steel I-section curved beam.

Without looking to the ultimate strength of the beam, all results show improvement in the behavior of steel I-section horizontally curved beam against deformations. The maximum vertical deflection at mid span of prismatic ($\varphi = 0.0\%\theta$) steel curved beam was 57.25mm at the ultimate load of 164 kN, for $\theta = 5^{\circ}$ as shown in Fig.(10), this deflection reduced to be 32.42mm at the same value of load when ($\varphi = 65\%\theta$), also the horizontal deflection decreased form 32.70mm to 10.83mm, thus when the increment in the volume of steel equal to 18.6% ($\varphi = 65\%\theta$), the vertical and horizontal deflection reduced by 43% and 67% respectively, as appeared, the horizontal deformation are more effected by strengthening than the vertical deformation. Also, this improvement increases when the angle of curvature increases, for example, at ($\theta = 45^{\circ}$, $\varphi = 0.0\%\theta$) the vertical and horizontal deflection at mid span were 552mm and 89.8mm respectively at ultimate load which was equal to 43 kN, but when the bottom flange strengthened ($\theta = 45^{\circ}$, $\varphi = 65\%\theta$) these two deformations were equal to 182.6mm and 27.6mm at the same load, i.e. reduced 67% and 69% respectively, as shown in Fig.(14).

It is interesting to note that the analytical study incorporated the effect of angle of horizontal curvature on the behavior and ultimate strength of steel I-section horizontally curved beam. The obtained ultimate loads for prismatic curved beams ($\varphi = 0.0\%\theta$) were 164 kN, 145 kN, 107 kN, 58 kN and 43 kN for $\theta = 5^{\circ}, 10^{\circ}, 15^{\circ}, 30^{\circ}$ and 45° respectively. The ultimate load was decreased 74% when the angle of curvature increased from 5° to 45°, this decrement increases when the angle of strengthening increases as revealed in results and illustrated in the following figures.

It is important to note that the ultimate strength of non-prismatic curved beam ($\varphi \neq 0.0\%\theta$) affected by increasing angle of curvature and decreases more rapidly when the angle of strengthening increases, as shown in Fig.(15).

5- Conclusion

Depending on the analytical results obtained from forty study cases the following conclusion can be drawn for simply supported steel I-section horizontally curved beams:

1- The ultimate strength of such type of beams can be increased about 35% by strengthening the bottom flange of beam by ($\varphi = 55\%\theta$, increment the volume of steel is equal to 15.7%) if the angle of horizontal curvature ($\theta \leq 5^{\circ}$).
2- The benefit from strengthening the bottom flange of this type of beams decreases when the angle of horizontal curvature increases.

3- By strengthening the bottom flange, the vertical deflection at mid span of beam can be reduced by 43% at ($\theta = 5^{\circ}$, $\varphi = 65\%\theta$), this improvement increases when the angle of curvature increases, for ($\theta = 45^{\circ}$, $\varphi = 65\%\theta$), the decrement in the vertical deflection reaches to 67%.

4- The maximum horizontal deflection at mid span decreases with increasing the angle of strengthening of bottom flange (φ) and designer can achieve decrement in this deflection equals to 67% if ($\theta = 5^{\circ}$, $\varphi = 65\%\theta$), this decrement approximately is not effected by angle of curvature, for example when ($\theta = 45^{\circ}$, $\varphi = 65\%\theta$) the decrement in the maximum horizontal deflection at mid span was 69%.

5- Finally, when the angle of curvature(θ) increases, the ultimate loads of beam decrease for any value of angle of strengthening (φ), but this decrement increases rapidly if (φ) increases.

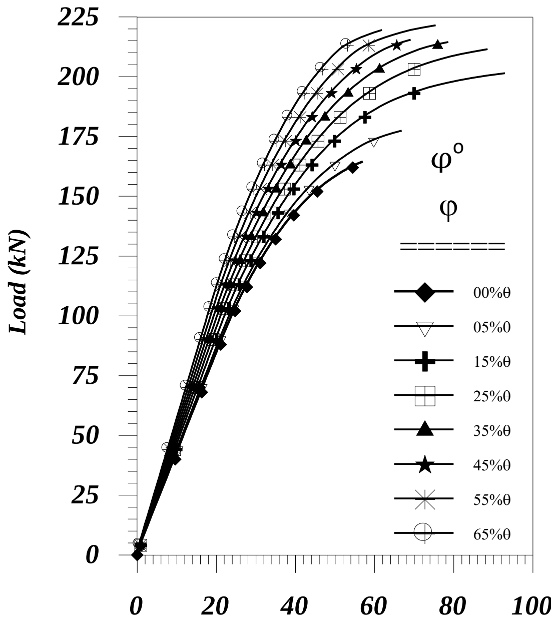


Figure (10): Load-Deflection

Curves for $\boldsymbol{\theta} = 5^{\circ}$.

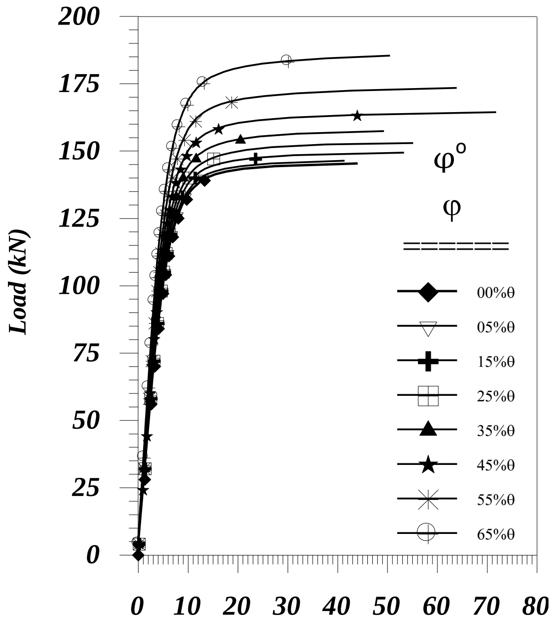
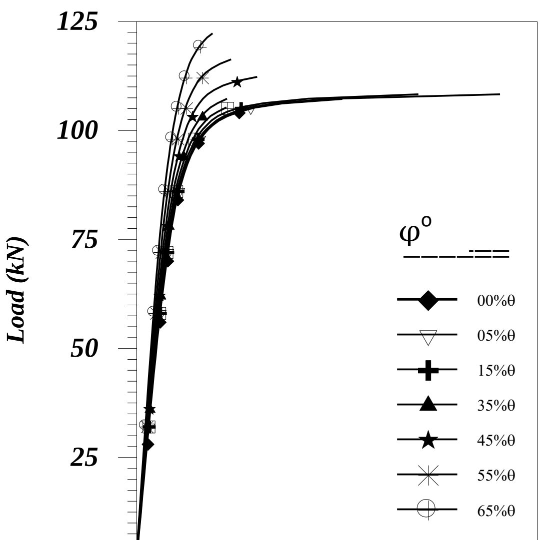
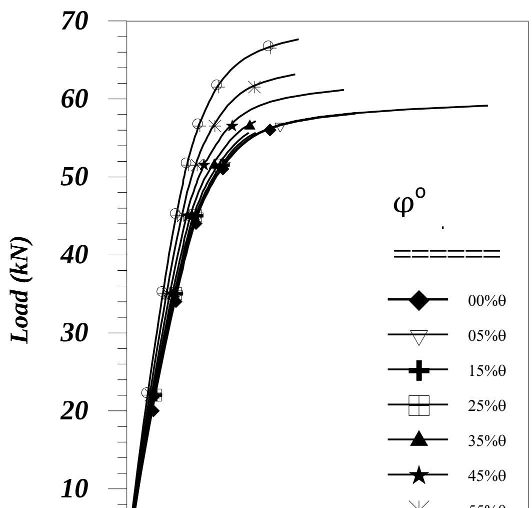


Figure (11): Load-Deflection

Curves for $\boldsymbol{\theta} = 10^{\circ}$.





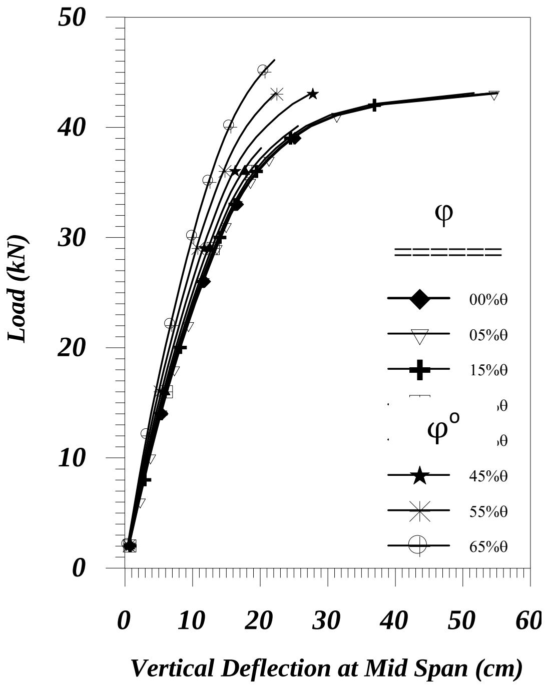


Figure (14): Load-Deflection Curves for θ=45°

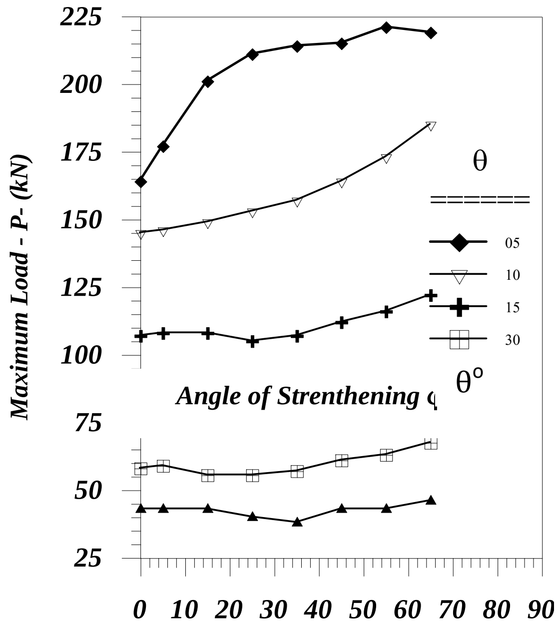


Figure (15): Ultimate Loads-Angles of Strengthening Curves.

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Notations

θ	= angle of horizontal curvature of horizontally curved beam, degree.
φ	= angle of strengthening, degree.
ε_u	= ultimate strain of steel.
ε_y	= yield strain of steel.
f_y	= yield stress of steel, MPa.
σ_y	= yield stress of steel, MPa.
v	= Poisson’s ratio.
E	= modulus of elasticity, GPa.