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Numerical Modelling of Solid and Perforated Horizontally Curved Steel Plate Girders

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***Abstract*: Through last decades, the behaviour of the curved steel plate girder has been tested either curved vertically or horizontally in order to study the failure modes and how to increase its ultimate strength and its capacity. Horizontally curved steel bridges have been fabricated and designed commonly in many countries for decades to support more efficiently. Furthermore, curved steel plate girders were used to present a beautiful shape in the buildings. Even though, the usage of curved girders faces some difficulties in their fabrication because of the high cost related to its construction, raw materials and erection. Besides, this type of girders is difficult in stability specially during lifting. For many decades, massive experiments and finite element models were carried out to predict design guidelines for horizontally curved steel plate girders (HCSPGs). Horizontally curved plate girders are subjected to different failure mechanisms such as: torsion (warping), large deflection, local torsional buckling of the flanges, shear buckling at the web panels, tension field action (TFA) of the web and lateral torsional buckling (LTB). According to the AASHTO specification [1], many researchers have investigated the behaviour of HCSPGs in order to improve their shear resistance and their torsional moment capacity as well and to enhance the ultimate bearing capacity and the girder's strength. In this paper, two finite element (FE) models have been developed using Abaqus software [2] to verify the experimental tests implemented by other studies and to compare these experimental results with the developed FE results.**

***Keywords*- Horizontally curved steel plate girders, Torsional behaviour, Lateral torsional buckling, Tension field action, Vertical stiffeners, Finite element model, Perforated web.**

I. INTRODUCTION

Many years ago, plenty researchers were attracted to study and carry out many tests in the steel plate girders curved vertically [3] or horizontally [4] – [8]. In 1961, some researchers like Basler presumed the diagonal tension field developed in small parts of the web [9], while others have supposed it to expand all over the completely web, their studies were continued and developed to study shear in many failure modes as it was represented in the tension field action (TFA) at straight PGs [10] and at the HCSPGs [11]. Other researchers performed tests on composite curved steel bridges [12] and high strength steel used in modern highway systems [13]. Recently, in many implementation fields these girders are located in the on and off-ramps with suitable curved radius and are identified by composite of horizontal and vertical geometries. Many researchers like Zureick et al. [14] and Kala et al [15] carried out experimental tests and analytical studies to create the exact size of curved girders bridge system components. After overcoming the disadvantages of the girder's construction, in the second half of the 20th century, the influence of HCSPGs on their behaviour were examined to use it as a perfect option in curved buildings due to its architected shape as well as its speed of erection, besides its serviceability performance in the bridges [16][17][18]. Frankl and Linzell [11] studied the impact of horizontal curvature on the shear strength of the plate girders (PG) because its ability to improve shear capacity.

From other hand, Lian and Shanmugam [19] tested eight (HCSPGs) in order to investigate the ultimate strength and to increase the shear resistance of these girders. They studied the influence of the curvature amount for these girders as well as the effect of the web openings size which was validated in this study.

A. Research Importance and Motivation

As mentioned before, there are many possible failure mechanisms for HCSPGs like: - Torsional buckling of the flanges, lateral torsional buckling [20] and tension field action (TFA) [10] at the web panels. Besides, shear failure mode, which is studied intensively in this paper, to enhance the shear strength and raise the shear resistance in the web, the curved plate girder (CPG) is stiffened with vertical stiffeners located at specific places to prevent or delay the shear failure.

II. NUMERICAL MODELS AND VALIDATION STUDY

2.A. Horizontally curved steel plate girder without web openings

2.A.1. Description of the model

A simple horizontally curved plate girder was modelled, to determine the highest shear strength of the P.G including transverse stiffeners as indicated in Figure 1, by a 3D finite element model designed and monitored using the Abaqus program [2].

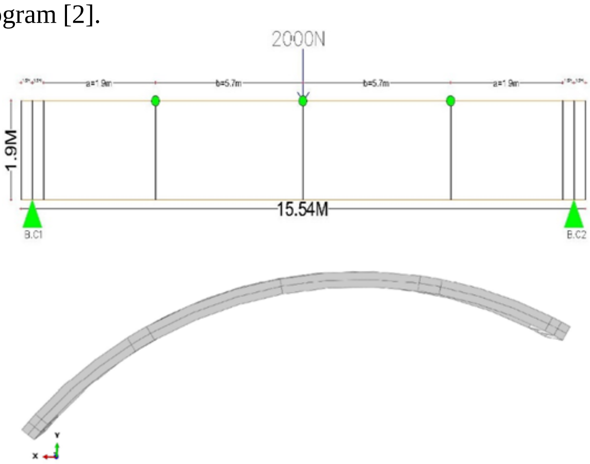

Figure 1: Steel plate girders curved in plan with solid web

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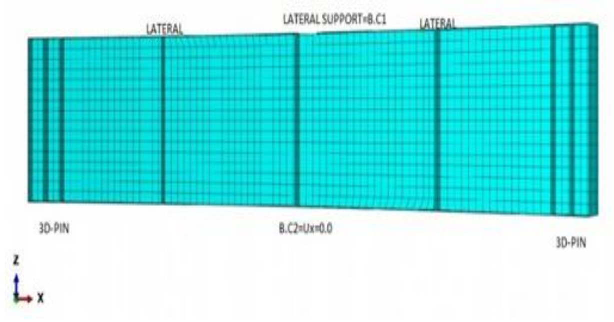

Figure 2: UNL1 model in ABAQUS with the location of boundary conditions

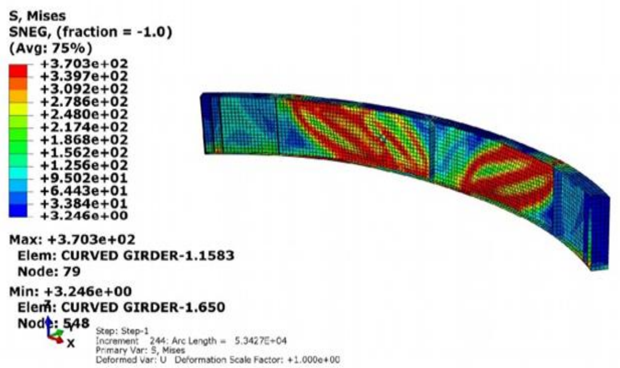

Figure 3: The deformed shape of the girder UNL1 in 3D view

The FEM was carried out by using trilinear stress strain curve for the material properties as indicated in the validated paper. Frankl and Linzell [11] investigated these studies to prove that the horizontal curvature parameter (z) has significant impact on the ultimate load capacity by its relationship with the curvature radius and the slenderness ratio (D/tw). A series of girders were examined to study the influence of the horizontal curvature on the shear capacity and to enhance the ultimate bearing capacity and the shear strength in turn [20][21].

2.A.2. Loading & Initial imperfections

Plate girder elements as the previous tested girder in this paper were merged (weld) using Abaqus software [2]. The tested PG was modelled with an applied load concentrated on the top flange at the mid span with 2000N. The elastic buckling occurs obviously in pure shear due the parameters mentioned earlier and causes bulges at the plastic buckling. Therefore, the initial imperfection was taken as a percentage of the web thickness according to the structure welding code(0.1-3) t_w [22] in order to study the deformed shape of the girders due to shear stress.

2.A.3. Boundary conditions

Simply supported girder with two types of boundary conditions used in the FEM (3D-PIN and lateral). Vertical stiffeners were located as indicated in Figure 2. The lateral supports are used to restrain y-displacement in order to resist lateral torsional buckling. The 3D-PIN was at the ends of the girders.

2.A.4. Material properties of the tested model

Grade 50/345 steel was identified as material properties of the girders with yield stress (345MPa), ultimate strength (448MPa), elastic modulus (200000MPa), failure strain 18.64 % , strain hardening 1.33% and poisson's ratio value was chosen ν = 0.3. Using static-RIKS method step for nonlinear analysis by Von Mises approach in order to investigate the ultimate shear stress and the tension field action that occurred in web panel as well.

2.A.5 Results and discussions

The current FE model analyses could predict the mode of failure accurately as shown in Figure 3. The analytical test showed approximate values for the maximum load strength results. It is observed that the results values were higher than those with web opening (See Table 1). It is obvious that the validated specimen [11] had the same mode of failure in the analytical testing comparing to the numerical simulations. Note that from Error! Reference source not found. the contours represent the out-of-plane shear failure (TFA) [10]**,** Besides that, Figure 4 presented the comparison between the tested girder and the validated girder load deflection curves with high accuracy.

Table 1: The Pu results comparison

Girder	P_u (kN) Analtical. (B)	P_u (kN) Verification(A)	A/B
UNL1	728.42	770.42	1.06

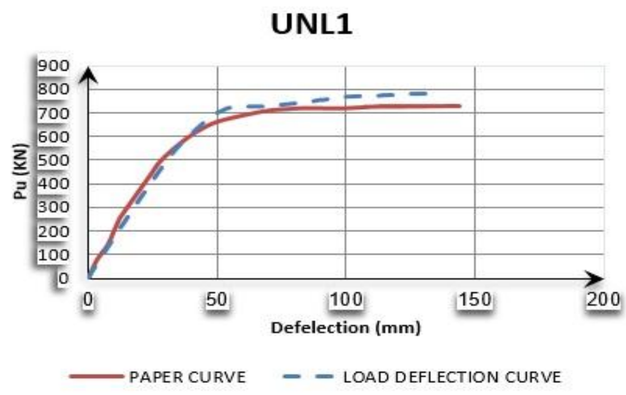

Figure 4: Load and deflection curves comparison of UNL1

2.B. Horizontally curved steel plate girder with web openings

2.B.1. Description of the model

The horizontally curved steel plate girders are simply supported with web openings were modelled according to decreased integral shell element S4R, which is recommended intensively for eigen mode value and nonlinear finite element analyses in the form component library [2]. The proper 3D model involves geometrical and material nonlinearity. A mesh control confirmed reasonable accuracy with 2 sizes (30 mm × 30 mm) & (40 mm × 40 mm) - The mesh size was free element type. The tested girders were examined with two different degrees of curvature (30° & 45°) (curvature angle) as in

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[8][19], the ratio of girder span (arc length through the middle line of the curved PG) L to curvature radius R, with circular openings in the webs' center having four various sizes. The curvature angle was 0.784 (45°) as seen in Figure 5, and the span length (L) = 2250 mm. For the tested girder, insignificant total depth of the girder = 567 mm and 2 mm thickness of web with top and bottom flanges of symbolic width =150 mm and the flanges thickness 8 mm. The slenderness ratio value (d/t) = 283.5 with web panel aspect ratio b/d = 1.5 where *(b)* refers to width of the panel, and *(d)* the depth of the web. The tested dimensions of the girder are presented in Table 2.

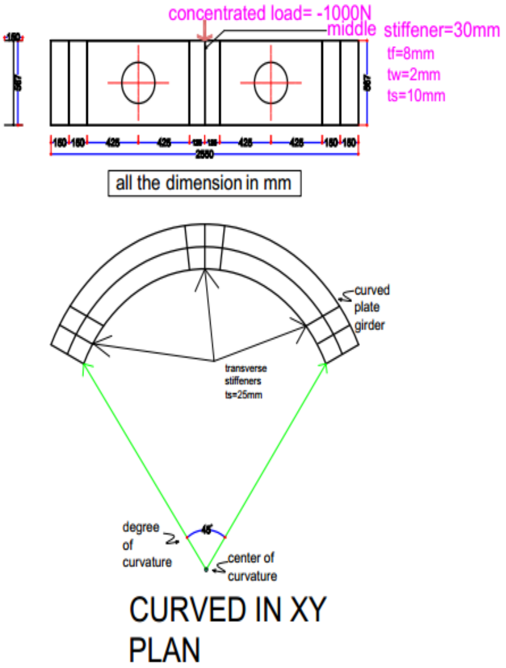

Figure 5: The curved girder specimen with the tested dimensions

Table 2: Dimensions of tested girder

Girder	Span	Θ^o	R	b_f	t_f	t_w	d_o/d	Depth	Size of openin
	mm	degree	mm	mm	mm	mm		mm	mm
PC45 D2	2250	45°	2870	150	8	2	0.2	567	114

All dimensions in mm

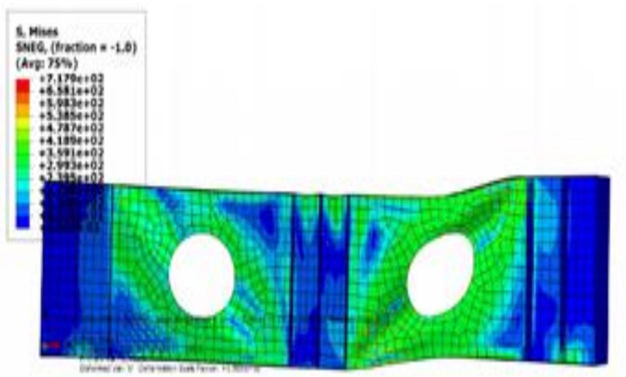

Figure 6: Tension field action failure mode

A simple (HCSPG) was modelled, to get the ultimate shear strength of the plate girder including circular webs openings which were placed at the web centre and transverse stiffeners are suitably located. Figure 7Figure 8 indicated the curvature of the HCSPGs in XY plan and 3D plan. The effects of curvature and opening size, load-deflection curves, the failure mechanism were investigated in the verified FE mode in conjunction with Lian and Shanmugam [8] experimental studies. The key parameters affecting the behaviour of the curved plate girder with web openings were then determined. The girders with openings placed in the high shear zone were noticed to collapse at considerably lower loads than girders with holes in the zone of higher bending and lower shear. The obvious failure mode was the tension field action [10] located round the holes of the web girder as indicated in Figure 6.

Table 2 displays the detailing of the tested girder. The web openings diameters = 114 mm. Transverse stiffeners, having symbolic width = 75 mm and 10 mm stiffeners' thickness, and the inclined angle of the girder (Θ^o) =45° were located at the ends of tested girder with distance between them = 150 mm and at 125 mm from the mid-span on each side of the web to prevent buckling and to bear the reaction forces in addition to turn away the anchor shear forces because of TFA of the web panel and the shear force in turn [21].

2.B.2. Loading and Initial imperfections

In the model, HCSPG parts including flanges, webs, and stiffeners were welded [2] to behave as one part. The studied PG was modelled with applied concentrated load of 1000 N on the top flange at the mid span. According to the Eurocode 3 [23] an initial imperfection of $h_w/200$ was applied.

2.B.3. Boundary conditions

Simply supported boundary conditions (BC) were performed at the end supports. Hinge and Roller were emulated in the tested model by restricting proper degrees of freedom at points on correspondent positions to avoid out-of-plane movement of the upper flange and the lateral support to prevent the lateral torsional buckling (See

Table 3).

Table 3: Boundary conditions

Support*	U_Y	U_Z	U_X	θ_Y	θ_Z	θ_X
Hinged	1	1	1	0	0	1
Roller	1	1	0	0	0	1
Lateral	1	0	0	0	0	0

*1 = restrained, 0 = free.

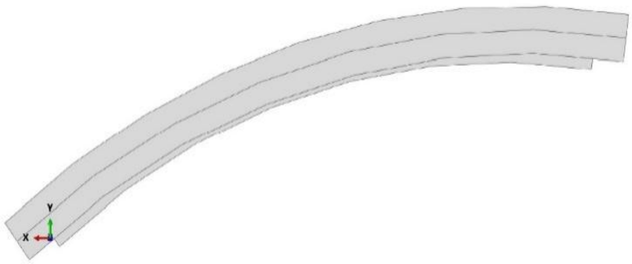

Figure 7: PC45D2 curved horizontally in XY PLANE

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Figure 8: The X.Y.Z Directions for the curved P.G

2.B.4. Material model

The steel material has been applied as a von Mises material with isotropic hardening. The elastic modulus and the yield stress were indicated in Table 4 and Poisson's ratio value v =0.3, with static-RIKS method. The material properties were assigned in Abaqus [2] according to elastic-plastic perfect curve [24[.

Table 4: Material properties for tested girder

Girder	Flange Material		Web Material	
	f_y (N/mm^2)	E (kN/mm^2)	f_y (N/mm^2)	E (kN/mm^2)
PC45D2	302	206	343	205

2.B.5 Results and discussions

The ultimate strength loads presented in the paper (P_u) are compared with the ultimate strength loads of the finite elements model ($P_{u, FEM}$) and ($P_{u, EXP}$) in Table 5 confirming the high accuracy of the model [8].

The finite element analysis modelled both tension field action and shear failure of the studied girder as seen in Figure 9. The impact of curvature as well as the opening size on maximum load capacity is observed from the results shown the load deflection curve with P_u in Figure 10.

Table 5: Experimental results and verification with analytical results

Girder	P_u (kN) Exp. (B)	P_u (kN) Anal. (C)	P_u (kN) Verification (A)	A/B	C/A
C45D2	192	193	199	1.036	1.031

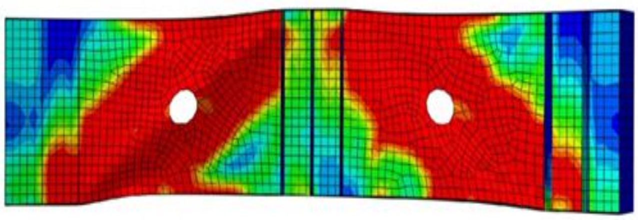

Figure 9: The deformed shape for girder PC45D2

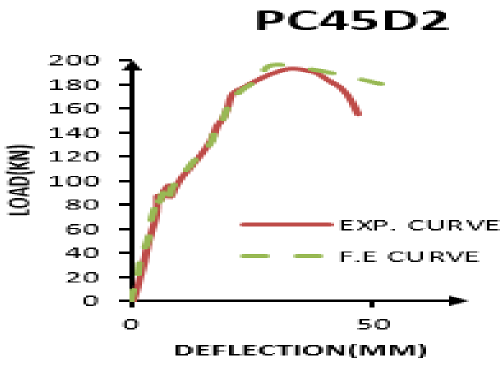

Figure 10: Load deflection curves comparison

III. Conclusions

The comparison between tested HCSPGs and the FE results show a high accuracy for the results even for the horizontally curved steel plate girders with or without web openings which were tested to failure under shear load applied at the mid-span. The load deflection curves comparisons in addition, to the F.E results display great enhance in the ultimate strength without web opening. It's noticed from the results that the loss of shear strength due to the presence of web openings, the results show a significant increase in the ultimate loading capacity higher by 25% than the HCSPGs with openings. The webs were strengthened by vertical stiffeners at the mid span under the applied load and above the applied boundary conditions to improve the shear strength of the tested girders and to raise the resisting against the torsional stress (warping). The most observed failure was shearing failure represented in tension field action (TFA) with great buckling impact at the web and the top flanges.

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Conflicts of Interest: There is no conflict of interest, according to the Authors understanding.

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