Effect of Depth and Flange to Web Thickness Ratio on Structural Behaviour of Corrugated RC Section Used in Arch Bridge

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***Abstract*—Arch structures is one of the oldest structural form in bridge engineering. Due to its surprisingly durability and aesthetic value, it is widely used as crossing over valleys and rivers nowadays. Closed spandrel arch bridge is one type of arch bridges that have been produced using precast concrete technology since 1965. Various cross-sectional shapes for precast concrete bridge have been proposed. Corrugated shape is a relatively new section which was introduced in 2008 in Malaysia. In this paper, the effect of depth, flange to web thickness ratio and slenderness ratio on structural behavior of this new corrugated arch section is presented. Computational analysis is carried out using analysis software PLAXIS and LUSAS. A total of 25 models with various flange to web thickness ratio and overall depth is proposed. The clear rise and clear span of the bridge is 5.8m and 20.6m, respectively. It was found that high slenderness ratio of the corrugated section result in lower stress in the section at crown but higher stress in the section at haunch. The flange to web thickness ratio contributes insignificantly to the maximum stress resulted on the corrugated section.**

***Index Terms*—precast concrete closed spandrel arch bridge, corrugated section, flange to web thickness ratio, slenderness ratio**

I. Introduction

Countless arches have been developed with outstanding performance as early as 3000 B.C. by the ancient Egyptians [1], 800 B.C. by the Assyrians [2], 100 B.C. by the Romans and 610 A.D by the Chinese [3]. Arch structures are widely used for bridge structures due to its aesthetic value and durability. Arch structures have the advantages of transferring transverse load via axial action and resist compressive axial force effectively. As a result, section of arch structure can be more efficiently utilized. Such more efficient usage of material of section will lead to relative lighter section in comparison with bridge structures without curvature such as girder bridges.

Due to the existence of curvature in arch structure, the associated construction process will be more complicated than straight members. In comparison with cast-in-situ method, the use of precast method will lead to better control of arch segments especially the curvature of the arch segments. With the advancement in precast concrete technology, precast concrete arch bridges have been widely used for short to medium span bridges from 25.6m to 50m.

This study focuses on closed spandrel precast concrete arch bridges. Various cross-sectional shapes for precast concrete bridge have been proposed. Among the variety of cross-sectional shapes, corrugated shape is a relatively new section. It has the following advantages: unique aesthetic value, high stiffness to self-weight ratio, 40% lighter compared with solid rectangular section and ability to span beyond limit of 25.6m (possibly up to 50m for short to medium span) [4], [5]. Patent has been granted for this new corrugated arch segment in 2008 [6]. Fig. 1 shows the typical arch geometry with corrugated section.

Figure 1. Precast concrete arch a) parabolic arch profile b) corrugated section

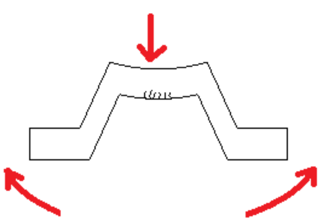

Figure 2. Shape distortion of corrugated shape

In the effort to produce an even more economical corrugated section, the aspect of dimensional stability of

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the sectional shape needs to be considered. In comparison with solid and closed cross-sectional shape, corrugated shape suffers from the problem of shape distortion as shown in Fig. 2. This is due to the fact that corrugated shape is an open section.

As arch bridge is typically used to span a wide clear span, it is crucial that efficient sectional shapes to be used. In this way, the self-weight of the whole bridge can be reduced. This will then lead to more economical way of construction as machinery with lower capacity can be used.

Proper ratio of flange to web thickness should be used in order to ensure the rigidity of the sectional shape. When considering the ratio of flange to web thickness, the overall slenderness of the arch segment should also be considered. Slenderness ratio is defined as:

$$Slenderness\ Ratio = \frac{L}{D} \quad (1)$$

where, L = Length of actual arch segment

D = Overall depth of the section

The rigidity of the cross-section under transverse loading acting on the arch segment will lead to a secondary effect. Such secondary effect will lead to crack developing in the longitudinal direction of the arch segment. This secondary effect will impede the structural capacity of the concrete and this may result in structural failure of the concrete bridge which is an unfavourable condition. Therefore this study is needed to determine the influence of section parameter on the behaviour of the corrugated section.

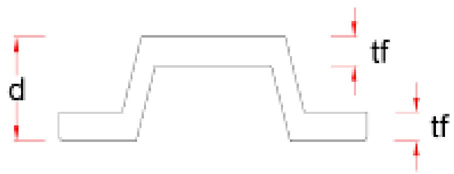

Figure 3. Notation used for the corrugated section

II. Computational Linear Analysis

Linear analysis using program PLAXIS and LUSAS are carried out to analyse and compare these closed spandrel arch with corrugated section in terms of structural capacity under different loading with different ratio of flange to web thickness. Fig. 3 shows the notation used for the corrugated section. The notation 'd' indicates the overall depth of the section while 't_f' indicates the thickness of the flange.

A. *Model of Arch Structure*

The arch section is designed as a single element with both ends pinned. Different flange to web thickness ratios of the corrugated section models is considered. In this study, the web thickness is fixed as 100mm. The flange thickness and overall depth of the corrugated section is manipulated as shown in Table I. The flange thickness are divided into five categories – A to E. In this study, the total longitudinal length of the corrugated arch is fixed at 25.63m. The slenderness ratio shown in Table II is defined as the ratio of length to depth.

TABLE I. Model with Various Flange Thickness and Overall Depth

Category	Flange thickness, t_f (mm)	Ratio of flange to web thickness	Model	Overall Depth, d (mm)
A	135	1.35	A1	475
			A2	500
			A3	525
			A4	550
			A5	575
B	140	1.4	B1	475
			B2	500
			B3	525
			B4	550
			B5	575
C	145	1.45	C1	475
			C2	500
			C3	525
			C4	550
			C5	575
D	150	1.5	D1	475
			D2	500
			D3	525
			D4	550
			D5	575
E	155	1.55	E1	475
			E2	500
			E3	525
			E4	550
			E5	575

TABLE II. Various Slenderness Ratios

Overall Depth (mm)	Slenderness Ratio
475	53.97
500	51.27
525	48.83
550	46.61
575	44.58

B. *Load Cases*

This corrugated closed spandrel arch bridge is designed to withstand the loading as specified in BS 5400: Part 1 & 2 (1978) [7], [8], BD 31/01 [9] and BD 37/01 [10] for a design period of 120 years. Primary live loads considered for the design of the bridge are as follows: (a) HA-UDL + HA-KEL and (b) HB-45 unit guided at the centerline of the deck. The dead load of the precast arch panel is resisted initially by a three-pinned arch system. Once the crown is connected, the ring of the precast arch panel acts as a two-pinned arch system to resist loads. They are modelled accordingly in design and analysis for all possible loading stages.

C. *PLAXIS Model*

Generally, Plaxis Software is used in the linear analysis of precast concrete arch bridge. The arch is modeled as beam element which backfill material is loaded on the arch layers by layers. Besides, soil-structure interaction is modeled. The material properties for arch concrete, backfill materials and premix are shown in Table III, Table IV and Table V.

TABLE III. PROPERTIES OF CONCRETE

Young's modulus	28 GPa
Poisson's ratio	0.3
Density	2400kg/m^3
Compressive strength	40.0MPa

TABLE IV. PROPERTIES OF BACKFILL SOIL

Material model	Mohr-Coulomb
Material type	Drained
Unsaturated unit weight	18.5 kN/m^3
Saturated unit weight	19.0 kN/m^3
Young's modulus	35 MPa
Poisson's ratio	0.3
Initial friction angle	30^o
Final friction angle	30^o

TABLE V. PROPERTIES OF PREMIX

Material model	Linear elastic
Material type	Non-porous
Unsaturated unit weight	25 kN/m^3
Young's modulus	28 MPa
Poisson's ratio	0.2

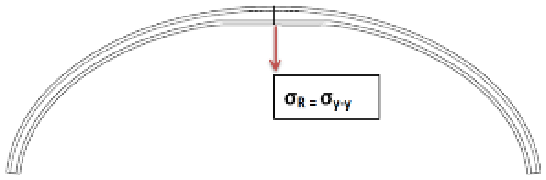

Figure 4. Resultant distributed load at crown

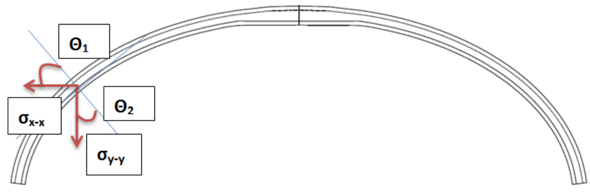

Figure 5. Resultant distributed load at haunch

D. LUSAS Model

The section analysis at crown and haunch is done using LUSAS software. The distributed load applied perpendicular on the corrugated section is taken as the resultant stress in x-direction and y-direction (σ_{x-x} and σ_{y-y}) acting on the arch bridge. At crown, σ_{y-y} is considered only for corrugated section analysis as shown in Fig. 4. At haunch, σ_{x-x} and σ_{y-y} are resolved to the normal axis of the corrugated section and the resultant distributed load is computed as shown in Fig. 5.

The support condition of the corrugated section is applied to the bottom of lower flange by spring stiffness, K in y-direction. Spring stiffness is defined as:

$$k = \frac{F}{\delta} \quad (2)$$

where,
k = Spring Stiffness
F = Force applied on the body
δ = Displacement produced by unit force along the same degree of freedom

The spring stiffness is determined by applying 1 kN load on the arch segment perpendicular to the crown and haunch respectively and obtaining the vertical deflection perpendicular to both crown and haunch. Fig. 6 and Fig 7 show the example of determining the spring stiffness at crown at haunch respectively in LUSAS.

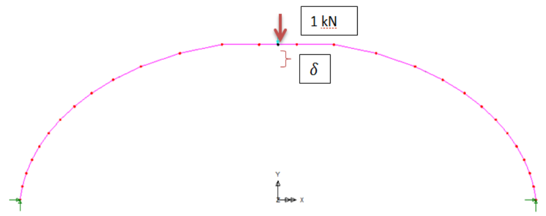

Figure 6. Example of determining spring stiffness at crown

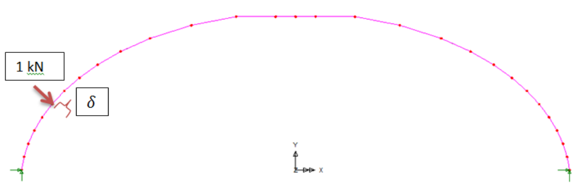

Figure 7. Example of determining spring stiffness at haunch

Fig. 8 shows one of the examples of the corrugated section modelled in LUSAS for analysis.

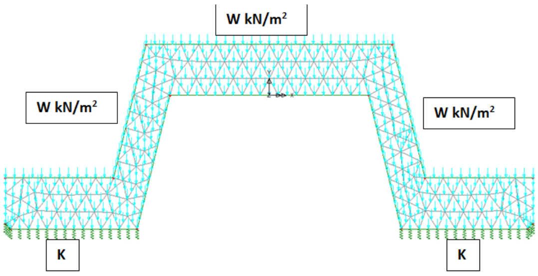

Figure 8. Example of corrugated section modelled in LUSAS

III. RESULT AND DISCUSSION

A. Maximum Tensile Stress at the Crown and Haunch

Fig. 9 shows that the maximum tensile stress at crown increases with the overall depth of the corrugated section. This is due to the increasing self-weight of the section. The increase in percentage of maximum tensile stress at crown is in the range of 2% to 8% for every increasing 25mm overall depth. Fig. 10 shows that for the same overall depth with different ratio of flange to web thickness, the maximum tensile stress fluctuates in the range of 0% to 6.5% for every increase of 0.05 in ratio. Whereas Fig. 11 shows that the increasing slenderness ratio, the decreasing maximum tensile stress at the crown. On the other hand, Fig. 12 shows that the maximum stress at haunch decreases as the overall depth increases. Hogging moment is induced at the haunch of the arch segment due to the arch deformation therefore the stress acting upward at the haunch counteract with the increasing self-weight of the corrugated section. The decrease in percentage of maximum tensile stress at haunch is in the range of 10% to 29% for every increasing of 25mm overall depth. Fig. 13 shows that for the same overall depth with different ratio of flange to web thickness, the maximum tensile stress fluctuates in the range of 0% to 15.6% for every increase of 0.05 in ratio.

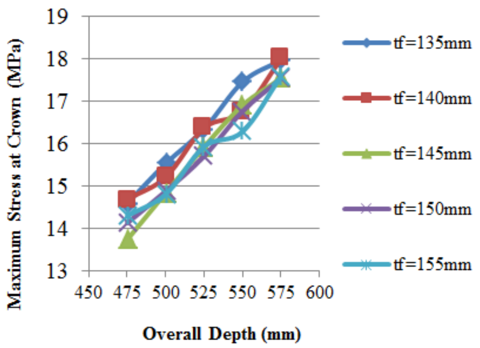

Figure 9. Maximum stress at crown versus overall depth

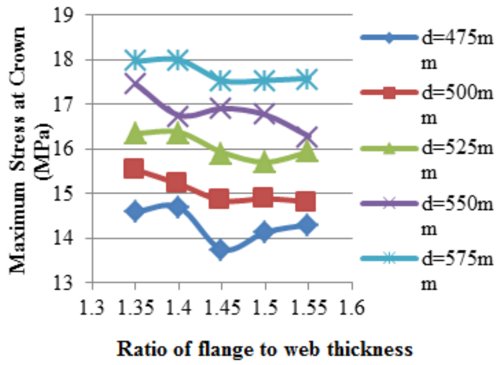

Figure 10. Maximum stress at crown versus ratio of flange to web thickness

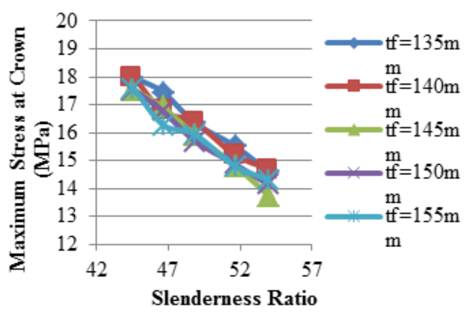

Figure 11. Maximum stress at crown versus slenderness ratio

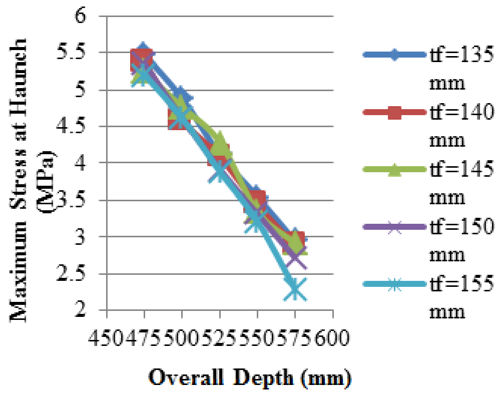

Figure 12. Maximum stress at haunch versus overall depth

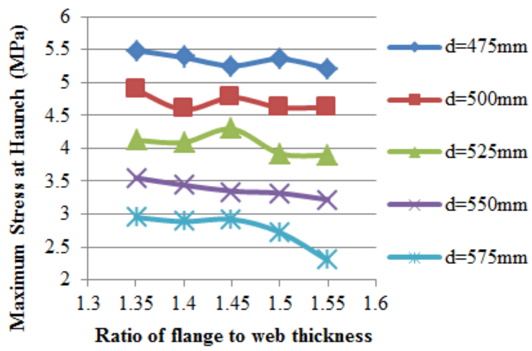

Figure 13. Maximum stress at haunch versus ratio of flange to web thickness

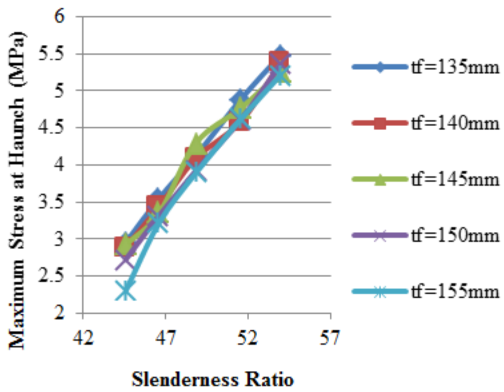

Figure 14. Maximum stress at haunch versus slenderness ratio

For this study concrete C40 is used therefore the maximum allowable stress is 4MPa. From the data obtained, the maximum stress at crown all exceeded 4MPa. This is because rebar is not provided to the section. For the haunch, the maximum tensile stress for C3 (d = 525mm, t_f = 145mm) is 4.272MPa which exceeded the allowable stress of 4MPa. Fig. 12 shows that corrugated section with overall depth of 550mm and 575mm does not require any rebar because the maximum tensile stress is less than 4MPa. Besides, C4 (d=525mm, t_f = 150mm) and C5 (d=525mm, t_f = 155mm) also does not require any rebar.

The maximum tensile stress at crown is inversely proportional to the slenderness ratio of the arch segment Fig. 11 shows that as the slenderness ratio increases, the maximum tensile stress decreases at crown in the range of

2.2% to 8%. On the other hand, the maximum tensile stress at haunch is directly proportional to the slenderness ratio of the arch segment. Fig. 14 shows that as the slenderness ratio increases, the maximum tensile stress increases in the range of 10% to 29%.

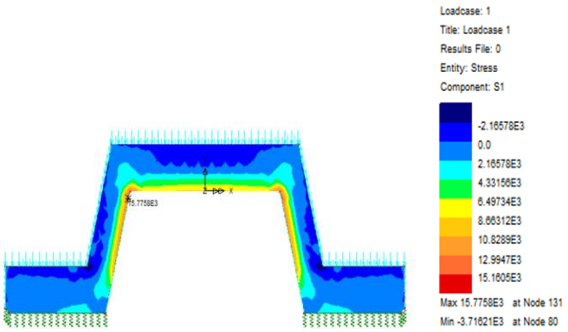

Figure 15. Example of stress distribution of corrugated section (d=525mm, t_f=145mm) at crown

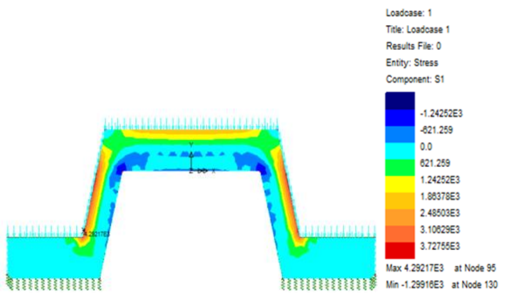

Figure 16. Example of stress distribution of corrugated section (d=525mm, t_f=145mm) at haunch

The location of maximum tensile stress is determined so that we can identify where the corrugated section will start to fail. Fig. 15 and Fig. 16 shows an example of stress distribution of corrugated section (d=525mm, t_f=145mm) at crown and haunch respectively.

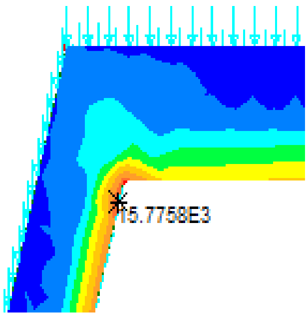

Figure 17. Maximum tensile stress at the edge of the corrugated section at crown

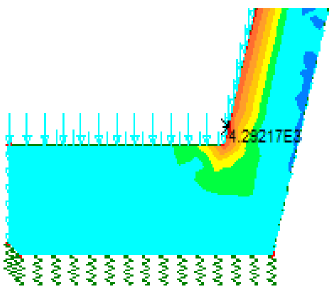

Figure 18. Maximum tensile stress at the edge of the corrugated section at haunch

From the Fig. 17, the maximum stress of corrugated section at the crown occurs at the interior part of the web and top flange due to sagging moment. As for the corrugated section at haunch, the outer part of the web and top flange shows maximum stress as a result of hogging moment as presented in Fig. 18. Fig. 17 and Fig. 18 show that the maximum tensile stress always occurs at the edge of the corrugated section.

B. *Deformed Shape of the Corrugated Section under Maximum Stress*

At crown, the stress acting downward resulting in sagging moment on the corrugated section therefore the section is pushed downward as shown in Fig. 19. At haunch, hogging moment occurs. The corrugated section at haunch is pushed upward as shown in Fig. 20.

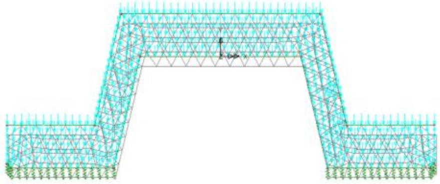

Figure 19. Example of deformed shape of corrugated section (d=525mm, t_f=145mm) at crown

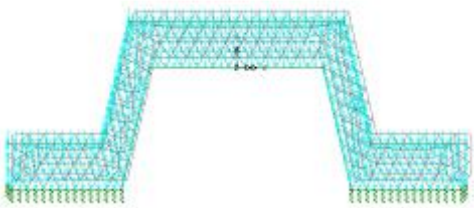

Figure 20. Example of deformed shape of corrugated section (d=525mm, t_f=145mm) at haunch

In general, higher overall depth or lower slenderness ratio results in higher tensile stress at crown. On the other hand, higher overall depth or lower slenderness ratio results in lower tensile stress at the haunch. Higher flange thickness reduces the tensile stress acting on the arch which means the higher flange thickness to web thickness ratio, the lower the resulting maximum tensile stress. However the result is insignificant.

IV. Conclusion

This study is carried out with the objective of studying the effect of ratio of flange to web thickness on the rigidity of the corrugated section and also the effect of slenderness ratio on precast concrete arch segment with corrugated section on its structural behaviour. Finite element analysis was carried out. A total number of 25 models consisting 5 different overall depths and 5 different flange thicknesses have been considered. They have been analysed using PLAXIS and LUSAS softwares.

Analysis results show that the lower slenderness ratio results in lower tensile stress at the haunch of the arch segment. The increasing ratio of flange to web thickness will reduce the maximum stress on the corrugated section at both crown and haunch insignificantly. The overall depths of the corrugated section have more significant effect on the structural behaviour of the corrugated arch. The research shows that higher overall depth increases the bending moment, axial force and shear force but reduces the vertical displacement resulting on the arch segment. High slenderness ratio with constant arch length reduces the maximum tensile stress on the corrugated section at the crown while high slenderness ratio with constant arch length increases the maximum tensile stress on the corrugated section at the haunch.

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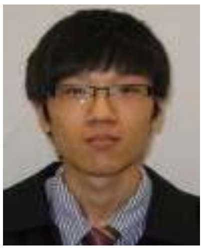

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