DESIGN OF SLENDER AESTHETICAL CONCRETE BRIDGES - CHALLENGES AND CONSIDERATIONS

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ABSTRACT

Reinforced concrete (RC) has the advantage that the material can be freely shaped to accommodate architectural design with complex curved surfaces and slender elements resulting in elegant bridges with high focus on aesthetics. It is very common that midrange to major bridges are designed together with architects which may challenge the design engineer due to the key role of the visual appearance of the bridge.

The consulting engineering company COWI has designed several midrange RC box girder bridges and cable-stayed bridges, e.g. Aarsta Bridge, Sweden created by the architect Sir Norman Foster (opened in August 2005 by His Majesty King Carl XVI Gustaf) and recently a cabled-stayed bridge in Constantine, Algeria (Constantine Viaduct, also known as Viaduc Transrhumel, currently under construction) designed together with the architects from Dissing+Weitling. Common to both Aarsta Bridge and the Constantine Viaduct are the throughout use of cross-sections consisting of curved lines. For the Aarsta Bridge, a very slender girder with double curved soffit was a structural challenge. For the Constantine Viaduct, a slender bridge deck with curved soffit and rib structure required increased need for analyses and reinforcement detailing. In addition, the pylons have been made slender with the lower part designed with corbels embracing the deck. This has resulted in harmonic, beautiful and elegant pylons.

With the Aarsta Bridge and Constantine Viaduct Bridge as case studies, this paper presents the main challenges in the design of slender bridges where aesthetical requirements governed the design. Careful attention has to be given to the arrangement of post-tensioning and the reinforcement details in connection with the slender elements.

Keywords: Constantine Viaduct, Aarsta, Concrete bridges, aesthetical, slender

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1. INTRODUCTION

Since the middle of the 20th century reinforced concrete (RC) bridges have proven to be an economic choice for midrange bridges where one of the advantages is that local resources in terms of material and labour can be utilised. Traditionally, concrete bridges have been associated with a bulky design with poor aesthetical appearance. The introduction of computer based design and the corresponding continuous development of advanced analysis programs has made it possible to design RC bridges with complex curved surfaces and slender elements which nowadays are highly requested by bridge owners and architects.

Despite that architectural design results in some structural challenges, it is possible to built elegant RC bridges with high focus on aesthetics (see e.g. Bridges Aesthetics around the World 1991; Niroumand et al. 2011). This was also realised by the internationally known and respected engineer Leonhardt (Leonhardt 1984) which defined some guidelines/rules for aesthetic design which can be summarised as 1) Fulfilment of purpose, 2) Proportion, 3) Order, 4) Refinement of form, 5) Integration into the environment and 6) Surface texture.

Fulfilment of the purpose of the bridge is of course essential. The bridge should be able to carry a road or a railway across a stretch of water or a valley fulfilling the comfort of bridge users with sufficient safety to resist imposed loads. The second rule, proportion, plays a key role to create an elegant bridge. The most important aspects with regards to proportioning are ratios of span length to navigational clearance or deck height above terrain, girder depth to span length, girder width to bridge length and pier dimensions to pier heights. In addition, attention should be paid to the effects caused by the sunlight where light and darkness must be anticipated because this influence the viewers sense of proportion. At night, architectural lighting can provide strong visual identity to a bridge. The third rule, order concerns lines and edges where it is important to limit the numbers. In addition, it is recommended to utilise symmetry and repetitions. For cable-stayed bridges, a central cable plane has a high advantage in this context due to limited lines and stay cables separating two traffic directions without blocking the view for the users. The fourth guideline, refinement of the form, could for instance be to haunch the girder instead of a straight appearance or the detailing of handrails. The reason is that parallel straight lines appear stiff and static. Another option is to use curved surfaces. To create a masterpiece of a bridge, integration into the environment is important. In that connection choice of alignment and bridge type is paramount, whereas detailing such as surface texture of the bridge may be a parameter to modify, e.g. the colour of the bridge. The bridge ends are often curved in plan to match up with connecting roads. This has the aesthetical advantage that the bridge is seen from various angles when approaching while the drawback is complicated geometry.

This paper presents some of the structural challenges and solutions in the design of slender bridges where aesthetical requirements govern the design. The paper focus on two specific concrete box girder bridges, namely the Aarsta bridge in Sweden (opened in 2005) and the cable-stayed bridge Constantine Viaduct bridge in Algeria (currently under construction). The Aarsta bridge and the Constantine Viaduct bridge have been created by the famous architect companies Foster+Partners and Dissing+Weitling respectively. Both bridges are situated in prominent urban locations demanding high attention to aesthetical appearance.

The Aarsta bridge is a continuous haunched concrete box girder bridge with eleven spans (nine interior spans of 78m and two end spans of 48m and 65m respectively) carrying dual track railway, pedestrian/cycle traffic as well as service/rescue vehicles across Aarstaviken, see Figure 1 (left). The Constantine Viaduct bridge is a cable-stayed concrete box girder bridge with a main span of 259m, central cables and central pylons. The bridge is intended for four lane traffic and pedestrian walkways in each side of the bridge, see Figure 1 (right). The Aarsta bridge and the Constantine Viaduct bridge follow many of the guidelines for aesthetic design addressed by (Leonhardt 1984). Both bridges have been designed by the engineering company COWI. Details will be given in sections 3 and 4.

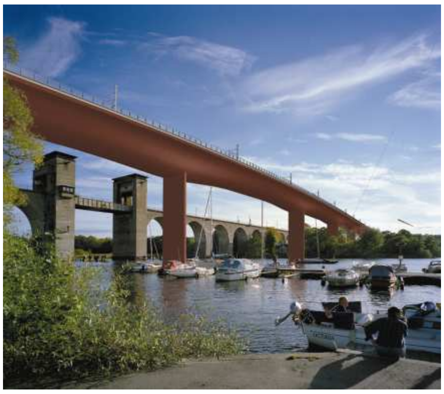

Figure 1: Renderings of Aarsta Bridge, Sweden (left) and Constantine Viaduct, Algeria (right)

2. CONSIDERATIONS IN DESIGN OF SLENDER BRIDGES

The girder depth is the most important key parameter to obtain a slender appearance. The girder depth can be reduced by minimising the self weight to be carried (use thin slabs and webs) and provide significant post-tensioning cables. Thin slabs often require transverse post-tensioning in the deck slab, diaphragms, thin cover and high ratios of mild reinforcement. Thin slabs in combination with small girder depth however often do not provide sufficient flange area and space for longitudinal post-tensioning. Therefore, slender girders are often characterised by thick flanges in local areas and high ratio of reinforcement and post-tensioning. For both the Aarsta bridge and the Constantine Viaduct bridge, the advantages of prestressing have been utilised in order to minimise the dimensions and the amount of mild reinforcement. For the Aarsta bridge, longitudinal internal post-tensioning cables have been applied in the top and bottom slab. For the Constantine bridge longitudinal post-tensioning cables, both internally and externally, have been introduced. In addition, the top slab has been prestressed transversely typical approximately every meter (closer in special areas). Moreover it is worth noting that diagonal post tensioning cables have been provided in the diaphragms to transfer the vertical component of the stay force to the girder cross-section. Finally the pylon walls in the anchorage zone of the stay cables have been prestressed horizontally to be able to resist the horizontal component of the stay forces.

Another factor that plays a key role in order to obtain slender concrete elements is the concrete compressive strength. High compressive strength is needed to limit the dimensions and is also required in order to resist the compression forces introduced from the prestressing cables.

In table 1 the key figures for the Aarsta and the Constantine Viaduct bridges are tabulated. It can be mentioned that for the Aarsta bridge, the superstructure in average contains 220 kilos of mild reinforcement per cubic metre of concrete (kg/m^3) and the Constantine Viaduct superstructure contains 310 kg/m^3. These figures are both high and are the consequences of designing slender RC elements.

Table 1: The Aarsta and the Constantine Viaduct bridge figures

Item		*Aarsta Bridge (Railway bridge)*	*Constantine Viaduct cable-stayed bridge (Roadway bridge)*
Total length		833m	756m
Structural height		Min 3.5m, max 5.2m	3.75m
Width		19.5m	Varies, typically 28.3m
Typical slab thicknesses	Girder, Top	323mm	250mm
	Girder, Bottom	500mm-700mm	250mm-1100mm
	Girder, Web	300mm	400mm-800mm
	Pylon, walls	-	700mm
Diaphragms		Only at piers	Transversely every 7m
Post-tensioning girder	Long. internal	VSL 19Ø15.7	Freyssinet 12C15 / 9C15
	Long. external	-	Freyssinet 27C15
	Transverse	-	Freyssinet 4F15
	Diaphragm	-	Freyssinet 13C15
Material strength	Concrete	42.5MPa	50 MPa (piers 40MPa)
	Reinforcement	500MPa	500MPa
Concrete cover		50mm	45mm outer faces, 35mm inner faces
Surface texture	Colour	Red	none
Quantities, Total	Concrete	29000m^3	34000m^3
	Reinforcement	5200 ton	7600ton
	Prestressing	1100 ton	340ton

3. AARSTA BRIDGE, SWEDEN

The Aarsta Bridge consists of a slender continuous concrete girder with curved soffit both in the transverse and longitudinal direction. The piers have elliptical shape. In the paper by (Jakobsen and Eriksson-Vanke 2005) it is noticed that the evaluation committee justified their choice of the winning proposal (Figure 1) by highlighting its slenderness, elegance and simplicity. The unique red colour was obtained by adding iron oxide pigments to the concrete mix.

3.1. Superstructure cross-section

The cross-section of the Aarsta Bridge is illustrated in Figure 2, where the two rail tracks are located in a trough in the centre part and the roads for pedestrians, cyclists and service vehicles are located on the cantilevered wings. Here it is seen that the overall depth of the cross-section varies between 3.5m and 5.2m corresponding to depth-to-span ratios of 1/22 to 1/15. However in the centre part of the cross-section the depth varies from only 2.2m to 4.0m corresponding to depth-to-span ratios of 1/35 to 1/20. The depth of the cross-section was from the beginning of the project restricted by the architects. Especially the narrow section between the wing and the centre part of the girder was challenging to verify structurally. Detailed FE shell models were developed by use of COWI's in-house bridge program called IBDAS in order to prove the capacity of the structural elements (Jakobsen and Eriksson-Vanke 2005).

One of the optimisations COWI came up with was to reduce the dead load of the superstructure by applying a direct fixation of the rails instead of the traditionally applied ballasted tracks. Longitudinal prestressing was also used extensively throughout the cross-section to keep the small dimensions. This can be seen in Figure 2 (right) where a typically anchorage of post-tensioned cables in the bottom slab is shown. This also confirms that the bridge girder is heavily prestressed (see quantities, Table 1).

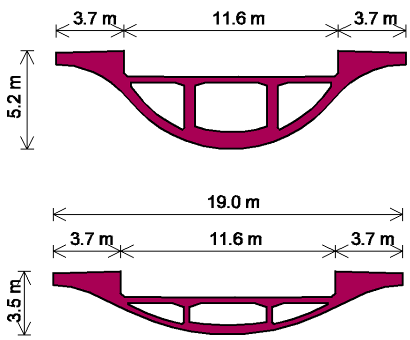

Figure 2: Aarsta Bridge cross-section (left), Post-tensioning anchorage (right)

It can also be mentioned that the optimal orientation of the diaphragms was consider carefully. The analysis showed that it was most beneficial to have two longitudinal diaphragms instead of transverse diaphragms. Therefore, the Aarsta bridge only contains transverse diaphragms at the piers.

3.2. Elliptically shaped piers

The elliptically shaped solid piers are shown in the photos in Figure 3. The maximum length and width of the cross-section are 7.0m x 2.5m. The superstructure is supported on bearings placed on the top of the piers. The slender appearance of the piers influenced the required reinforcement amount. In the Aarsta piers the reinforcement percentage was up to 2.7% in the extreme locations.

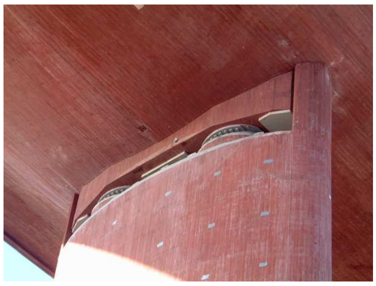

Figure 3: Elliptically shaped pier

4. CONSTANTINE VIADUCT, ALGERIA

In the paper by (Hansen 2013) it is stated that a cable-stayed bridge for the Constantine Viaduct bridge was chosen for aesthetical reasons compared with a girder bridge which due to the relative short span would have been an alternative, competitive option. The relative short main span introduces the possibility to design the girder in concrete. In this section some of the challenges introduced by a slender concrete cable-stayed bridge are given.

4.1. Post-tensioned box girder with curved bottom slab

The cross-section of the Constantine Viaduct bridge is shown in Figure 4. The depth of the cross-section is 3.75m, the typical top and bottom slab thickness is 250mm and the web thickness is typically 400mm (cf. Table 1). As seen, the bottom slab and the ribs have been designed curved.

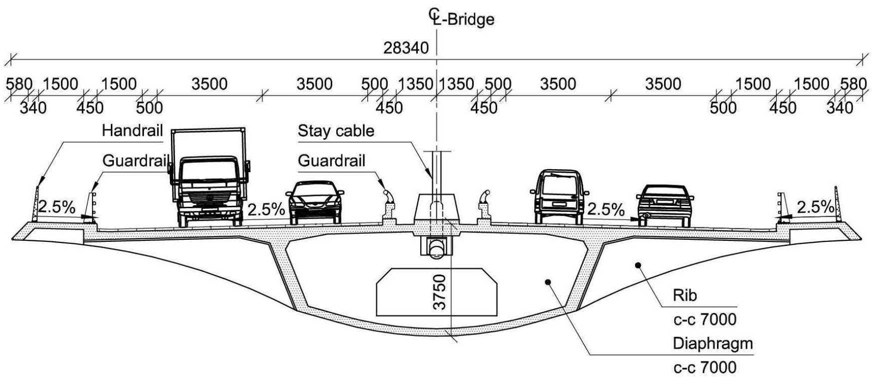

Figure 4: Typical cross-section of Constantine Viaduct

The thin, curved bottom slab has some structural consequences. Compared with a horizontal bottom slab, the curved slab reduces the depth of the webs significantly. The shear forces are mainly carried by the webs and when the depth of the webs is reduced, the concrete contribution to the shear capacity will be smaller. Consequently, more shear reinforcement is necessary and in the Constantine Viaduct, typically Ø20-Ø32 stirrups placed per 150mm have been provided as shear reinforcement (corresponding to a reinforcement ratio of 1%-2.7%). Another impact by the curved shape is that the transverse in-plane forces in the bottom slab will introduce bending moments in the bottom slab. This additional moment requires extra reinforcement. Finally, the inclination of the bottom slab at the webs caused fillets to be too steep to be cast without top form. The contractor therefore requested the fillets to be eliminated with higher demands on transverse reinforcement as consequence.

As mentioned previously, the top and bottom slab are heavily prestressed in the longitudinal direction. It has been necessary to supplement the internal, longitudinal post-tensioning cables with external post-tensioning cables placed inside the box girder of the approach spans. There are both advantages and disadvantages with external prestressing. However for the Constantine Viaduct bridge it was necessary to apply external post-tensioning cables due to the limited space in the slender elements.

In the deck slab, transverse prestressing has been introduced by post tensioning cables placed in flat ducts (duct thickness 22mm). In total 789 flat duct cables are foreseen to be installed in the Constantine Viaduct bridge. Moreover, one single post-tensioned cable has been placed in every diaphragm and diagonal post-tensioning cables have been installed, with anchorage in the stay blocks and in the bottom of the diaphragms, to transfer the stay force. The stay block anchorage is illustrated in Figure 5.

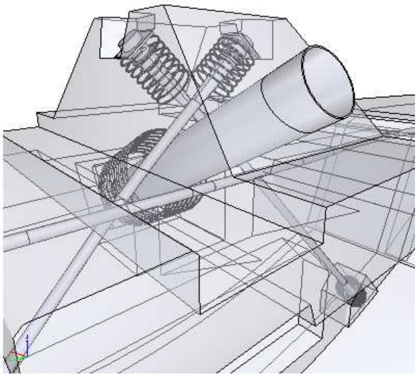

Figure 5: Stay anchorage with diagonal and transverse post tensioning in the diaphragm

4.2. Pylons

The two pylons of the Constantine Viaduct consist each of a central, hollow leg approximately 130m high. Minimised dimensions and a slender appearance have been obtained by tapering the faces of pylons in both directions, see Figure 6. The girder is monolithically connected to the pylons with corbels embracing the deck soffit.

Figure 6: Pylon during construction (March-April 2013)

Especially in the stay anchorage zone where the outer dimension of the pylon is approximately 2700mm x 4600mm, the space to place reinforcement, which can resist the action from the stays, is limited. For that reason, horizontal post-tensioned bars (bar diameters 36mm-50mm) have been installed in both directions, see Figure 7.

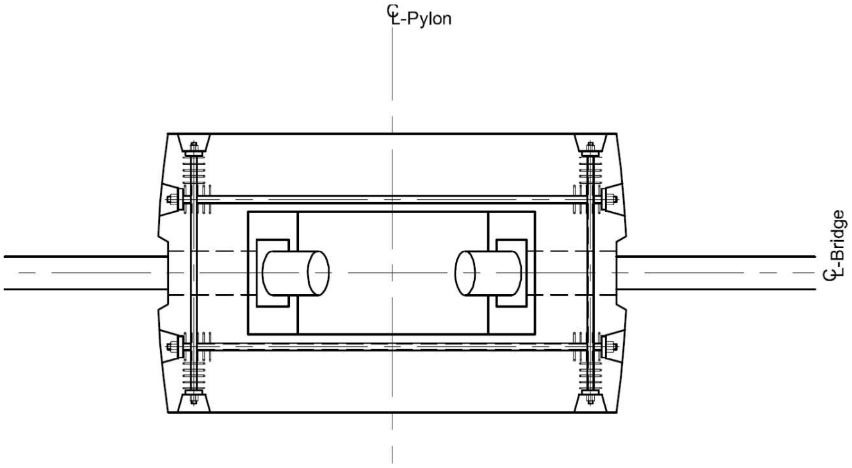

Figure 7: Post-tensioning bars layout, pylon

5. CONCLUSIONS

The purpose of this paper has been to present RC bridges which both fulfil the structural requirements and are elegant. This has been demonstrated by two examples, namely the Aarsta bridge and the Constantine Viaduct bridge designed by the engineering company COWI. In both examples, the RC elements are very slender and this has only been structurally possible by introducing a significant amount of post-tensioning cables in the design, by using concrete with high compressive strength and by utilising the capabilities of COWI's advanced FE analysis program IBDAS.

For slender RC bridges, it can be concluded that a design which optimises aesthetic, design and constructability requires a close cooperation between architects, design engineers and contractors starting from the conceptual phases. Many structural challenges imposed by e.g. slender elements and curved surfaces can be overcome if they are thought into the design from the beginning.

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