Stay simple, stay nice at Ostellato

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Summary

The Ferrara waterway, connecting this historic town with *Comacchio* on the Adriatic Sea is being upgraded: section widening and straightening as well as higher clearance has called for the replacement of most of the existing bridges. On the outskirt of Ostellato the conditions were appropriate for a medium span stay cable road bridge having the peculiarity of a curved girder with a plan and crest radius of 1000 metres. The structure had to be cost efficient, because it was offered as an alternative design to an awkward but smaller tender solution within the same budget. Concrete towers had to be of the inverted Y shape to resist lateral forces given by the horizontal radius, steel frames have been cast into the upper concrete section of the towers to facilitate positioning and erection of the 48 stays. The 14m wide deck sports the classical composite design with plated girders running at both sides and transverse beams at 4 metres centre; with an height of 1.5m circa for the 130 metres span, the resulting slenderness is considerable and associated with the double curvature gift the structure with elasticity and lightness.

Keywords: Stay cable bridges, fibre reinforced concrete, stay anchorages, pylon design.

1. Introduction

Small to medium stay cable bridge have been the main target of the "*make it strange*" fashion that has contaminated structural engineering in the last 20 years. Contrary to suspension bridges where extreme fanciness is not possible because of size but also because suspension cables must oblige to the force of gravity and there is no way to arrange them in fancy configurations, stays can go from here to wherever you want provided that you have enough money to make it. Wannabe architects become structural engineers have proposed all sorts of stay configurations relaying on the fact that a steel girder can self support itself over 100 plus metres span and stays can then be added without any particular static function.

As a matter of fact, designing a nice looking stay cable bridge of small to medium size is not an easy task because stay anchorages are quite cumbersome and consequently towers and deck cannot be made as slender as global stability would allow. For larger spans the problem vanish because anchorage size becomes negligible compared to tower and deck cross section dimensions [1][2].

The only solution to reducing the impact of anchorages on the aesthetic of the bridge is to use ropes with cast sockets possibly pinned to gusset plates welded to the steel tower and deck. This is the arrangement of choice for small architectural stayed structures that have sprung around our cities in the last decades. For these structures white paint finishing is generally "*de rigueur*".

For the Ostellato bridge, fashionable solution and other fancy arrangements had to be ruled out because of severe budget constraints and therefore a different approach, one of structural and economic efficiency, had to be undertaken to obtain a nice looking stay cable bridge. The paper presents the main feature of the design and the construction stages up to stays erection undergoing at the time of going to print with the finished bridge is due to open in fall 2015.

2. The bridge layout

The Ferrara waterway, connecting this historic town with *Comacchio* on the Adriatic Sea is being upgraded: section widening and straightening as well as higher clearance has called for the replacement of most of the existing bridges [3]. On the outskirt of Ostellato the conditions were appropriate for a medium span stay cable road bridge having the peculiarity of a curved girder with a planimetric and altimetric radius of 1000 metres.

The authors were asked to devise an alternative solution to the tender design, a small and awkward stay cable bridge with a symmetric configuration with two H shaped pylons placed at 95 m distance inside the waterway main embankments plus two other access spans for a total length of 250 m circa. The stay solution had to be retained although spans and all other elements could be changed within the same budget.

Fig. 1: A render of the bridge with artist intervention

To start with, the road alignment has been modified so as to obtain a curve of constant radius that bypass the old bridge and smoothly rejoin the existing alignment. This solution makes the variant much more appealing from the road user point of view but also requires the new stay cable bridge deck to be built with a horizontal radius of 1000m contrary to the tender solution where the bridge was placed along a straight section followed by two curves of smaller radius. Secondly, the towers have been displaced out of the main embankments increasing the span to 130m circa and eliminating the access spans. The shape of the tower had also to be modified so as to resist the horizontal (centripetal) pull caused by the deck radius of curvature that gives, for the central span only, a middle ordinate of 2m circa.

2.1 Geology and foundations

The new Ostellato bridge is located in the large Po River alluvial plain, about 25 km upstream of the river mouth. The subsoil of the alluvial plain is constituted by several hundred meters thick alluvial deposits. The surface portion of the alluvial sediments, directly interested by the bridge foundations, is formed by thin layers and lens of mainly clayey and sandy silts soils, with thin peat intercalations. Some small methane deposits, trapped in silty sediments, have been encountered during the investigation drillings. A thick layer of very dense, coarse sands underlies the fine sediments at 40 m depth. Due to the poor geotechnical characteristics of the fine alluvial sediments encountered up to 40 m, piles heads are bored into this sandy layer.

Two investigation campaigns, related to different project stages, have been conducted on site with core recovery boreholes (up to 50 m deep), SPT tests and undisturbed sample collecting for laboratory tests. A complete laboratory campaign has been conducted, with triaxial, shear and oedemeter tests, as well as physical properties determination. In order to have a complete geotechnical model of the subsoil, five cone penetration tests, with pore pressure measurements (piezocone –dissipation tests) have also been carried out.

Based on this reconnaissance campaign, 1.5 m diameter bored piles have been chosen for both towers and abutments foundations. These large diameter piles provide a satisfactory lateral resistance and allow a better and safer execution of the piles boring down to 45m circa so as to have the piles heads few metres into the sandy layer.

During the design it has been found that, due to the fine grained layers of the sediments, the subsoil would have significant settlements after embankment construction and these settlements would take up to few years to fully develop. For this reason several prefabricated vertical drains have been driven into the ground following a 1.5m square grid.

As far as seismic behaviour is concerned, several sand liquefaction phenomena were reported during the last earthquake which stroke the provinces of Modena and Ferrara in May 2012. Following specific analyses and investigations, the actual bridge site was found to be immune to the risk of soil liquefaction.

2.2 The towers

Since the road platform is a two lanes single carriageway of 10 m circa, the towers legs had to be placed outside the deck. Standard H shape is not particularly suited to the case under consideration because it suffer from horizontal force (centripetal) arising from the deck curvature and does not allow for a symmetric anchorage layout as better discussed in the following paragraph.

Fig. 2: Detail of the tower leg

The design therefore focused on finding the optimal inverted Y configuration that could provide lateral resistance and sufficient space for anchoring the 6 rows of 4 stays (a zero torque configuration). Once the overall shape had been defined, numerous simulations were carried out to find the most appropriate cross section shape for the legs and the crowning element where the stay anchorages are placed. For the legs, a T or H section does increase resistance while reducing weight. These sections do also have a slenderer look compared to rectangular ones because of the shadows projected by corners and recesses. For the uppermost element, a full rectangular section was better suited instead because any type of groove or corner would subtract space to the 24 stays anchorages.

The final shape of the towers could only be finalised after extensive computer simulations and once it was decided that the towers would be made of reinforced concrete and therefore section shape and variation had to be compatible with a single formwork that could be piecewise modified while rising from the foundations to the top anchorages. Use of steel was in fact investigated in the early stages of the project since it was perceived to be quicker to built and less labour intensive then concrete. This situation is now changing because of the severe economic crisis of the last 5 years that makes manpower cheap and abundant and has therefore changed the way site works are organised. Reinforced concrete elements, even with elaborated shapes and complex reinforcing are now seen in a new perspective.

2.3 Stays and anchorages

As mentioned in the introduction, small stay cable bridges benefit from the use of ropes with cast sockets because this technology allows for the reduction of anchorage size thus improving the structure silhouette. This technology has various drawback though, especially when compared to stays made of individually protected strands. The latter are often cheaper, easier to erect and stretch to the desired length and are better protected against weathering agents.

For all of the above reasons, the 48 stays of the Ostellato bridge are made of 19 to 31 individually gained 06” super compacted strands anchored in concrete at both towers and deck. For larger bridges where towers can have an hollow section and still retain a slender look, stays can be anchored inside the towers. While this solution is probably the best in case of large bridges with tower section in excess of 5 m, in case of small to medium size bridge it becomes cost inefficient and architecturally awkward.

For the Ostellato bridge, stays at tower are anchored in a symmetric fashion, 4 each rows, 2 each side in a zero torque disposition. This configuration is the simplest and the cheapest since stays simply run through the full concrete section with the anchorages placed on the outside as in a standard postensioned element. The only drawback of this arrangement is the need to cast steel tubes inside the concrete towers in their exact positions and then making sure that they do not move during concrete casting. In order to facilitate their positioning and firmness during casting, they have been welded to steel frames (2 each tower) that have been cast into the tower top segments. The solution proved to be economic (steel frames are not structural although do contribute) and easy to install since the frames were welded in shop with absolute precision and once correctly placed in the towers eliminated any possible mistake in the positioning of the 24 anchorages that otherwise had to be trimmed individually at each tower.

Fig. 3: The stay anchorage frame (2 each towers)

Stays at the deck are anchored into concrete blocks that are attached to the deck slab and connected to the outer beams webs with standard headed studs. The only problem that can arise with this solution is concrete cracking due to the concentrated forces applied to these anchorages that not only cause splitting tensile stresses but also shear and torque because these blocks are eccentric with respect to the longitudinal beams webs (the main load carrying members). Making these anchorages in steel has various and possibly more severe drawbacks compared to concrete ones. Steel anchorages are expensive, prone to fatigue and do not allow for significant geometric tolerance, a desirable feature for a curved stay cable bridge where each stay has a different angle of attack. In order to overcome the risk of cracking and keeping standard reinforcement within an acceptable level, these anchorage blocks have been cast using FRC with 50 kg/m^3 of steel fibres type DRAMIX BG 80/50 BG.

The increase of strength and toughness (ductility) of concrete with this limited amount of fibres is amazing as demonstrated by the 3-point bending test [4] results plotted in Fig. 4. Specimens were cast using the same standard concrete class C32/40 with f_{ck} = 40 MPa used for the deck slab. Equivalent tensile strength at peak load of the FRC specimens is 8 MPa circa. With this increase of the tensile properties and ensuing bond capabilities, reinforcing and casting of these anchorage blocks proved to be quite straightforward. With a toughness that is an order of magnitude greater than that of similar blocks made of standard concrete, cracking simply cannot take place.

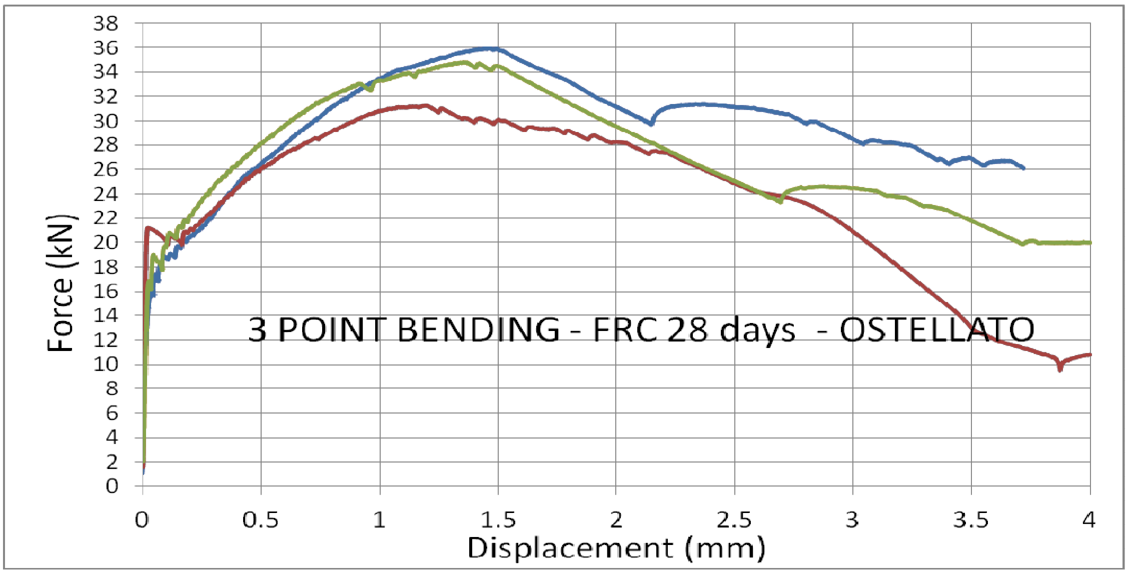

Fig. 4: Test result of FRC notched beams

2.4 The deck

Fig. 5: The steel deck

The deck is a standard composite design with two edge beams 14 metres apart and transverse beams every 4 metres. Weathering SJ355 steel has been used to reduce cost of construction and maintenance. The deck thickness had to be kept to a minimum because the underneath clearance had to be dramatically increased with respect to the existing bridge. Main longitudinal beams are therefore only 1200mm high giving the deck a slenderness ratio of approximately 100. Since the concrete deck slab is slightly larger than the steel deck so as to incorporate the anchorage blocks that are cast against the outer face of the longitudinal beam webs, all of this protruding part of the concrete slab has been cast using shop fabricated steel formworks welded onto the steel structure.

3. Deck boundary conditions and seismic behaviour

The Ferrara region was not considered to be particularly seismic until an earthquake of Magnitude 5.9 with a PGA of 0.3 g hit the area in May 2012 causing diffuse damage to the masonry building heritage. Since the tender design was developed before this seismic event with looser specs, it did not satisfy the new stricter rules and higher design seismic action. The new bridge had to make up for this deficiency with the design being scrutinized with a much more severe stance in the aftermath of the event under an emotional backslash that typically makes the pendulum swing to the opposite extreme.

The seismic response of a stay cable bridge is typical driven by the deck inertia forces which in turn are a function of its boundary conditions and stiffness. Towers also have a response of their own, especially in the transverse direction that may trigger significant inertia forces but in this specific case their moderate size and A shaped configuration made this contribution almost negligible.

When it comes to deck boundary conditions, a symmetric configuration is always the best which means fixing the deck longitudinally at both towers. Unfortunately, the distance between deck and foundations is too short for the towers to have enough compliance to avoid serious thermal stresses when the deck expand and contract under daily and seasonal temperature oscillations. Fixing the deck on a single tower and coupling it with some sort of seismic device to the other tower and abutments was considered to be too fancy, expensive and maintenance intensive for an area where moderate earthquake typically came every few hundred centuries and only cause damage to masonry structures.

Finally, elastic (rubber) fenders will be installed at both towers making the deck free to expand and contract symmetrically under temperature load and float and bump with a 1 sec main longitudinal period under seismic action. This solution is structurally efficient, economic, easy to built and does not require a particular maintenance. Certainly, damping is not as high as you can get with viscous seismic devices, but installing these devices in a structure whit a few percent possibility of them to be activated during their life time (20 years roughly) is highly inefficient. Unfortunately, elasto-plastic (metal) devices that are simpler and cheaper could not be used because of thermal expansion is to large and tower compliance too small.

In the transverse direction the deck is constrained at the two towers and at the abutment. At the tower the deck is laterally restrained with rubber fenders although shallower (stiffer) then the longitudinal ones, at the abutment instead, standard uni-axial pot bearings have been used.

4. The erection procedure

While casting the towers, the deck as been assembled in place by welding longitudinal and transverse beams together. The deck has been erected onto temporary supports placed every 30 metres circa except for the navigational channel crossing where a 40 metres span was required. This solution was preferred to the balanced cantilever construction because is simpler, cheaper and eliminates the risk of geometrical errors that may arise when cantilevering out with extremely slender decks as the one under consideration. The solution could be adopted because traffic on the existing waterway is still scarce and channel widening postponed until the temporary supports could be removed. This put a lot of pressure on the erection timing because the channel excavation could not be delayed nor it could be partitioned waiting for the temporary supports to be removed. These supports have been founded on 5, 20 m long wooden piles easily driven into the ground and even more easily demolished once the support had to be removed for channel widening.

Stay tensioning was carried out in 3 stages. An initial force controlled pre-tensioning at 1 ton each strand followed by 2 displacement controlled shortenings of the stays, the first one before casting of the deck slab, the second one before applying road surfacing and other finishing works onto the platform. A graph of the stays shortening to be applied in the two phases is plotted in the following figure.

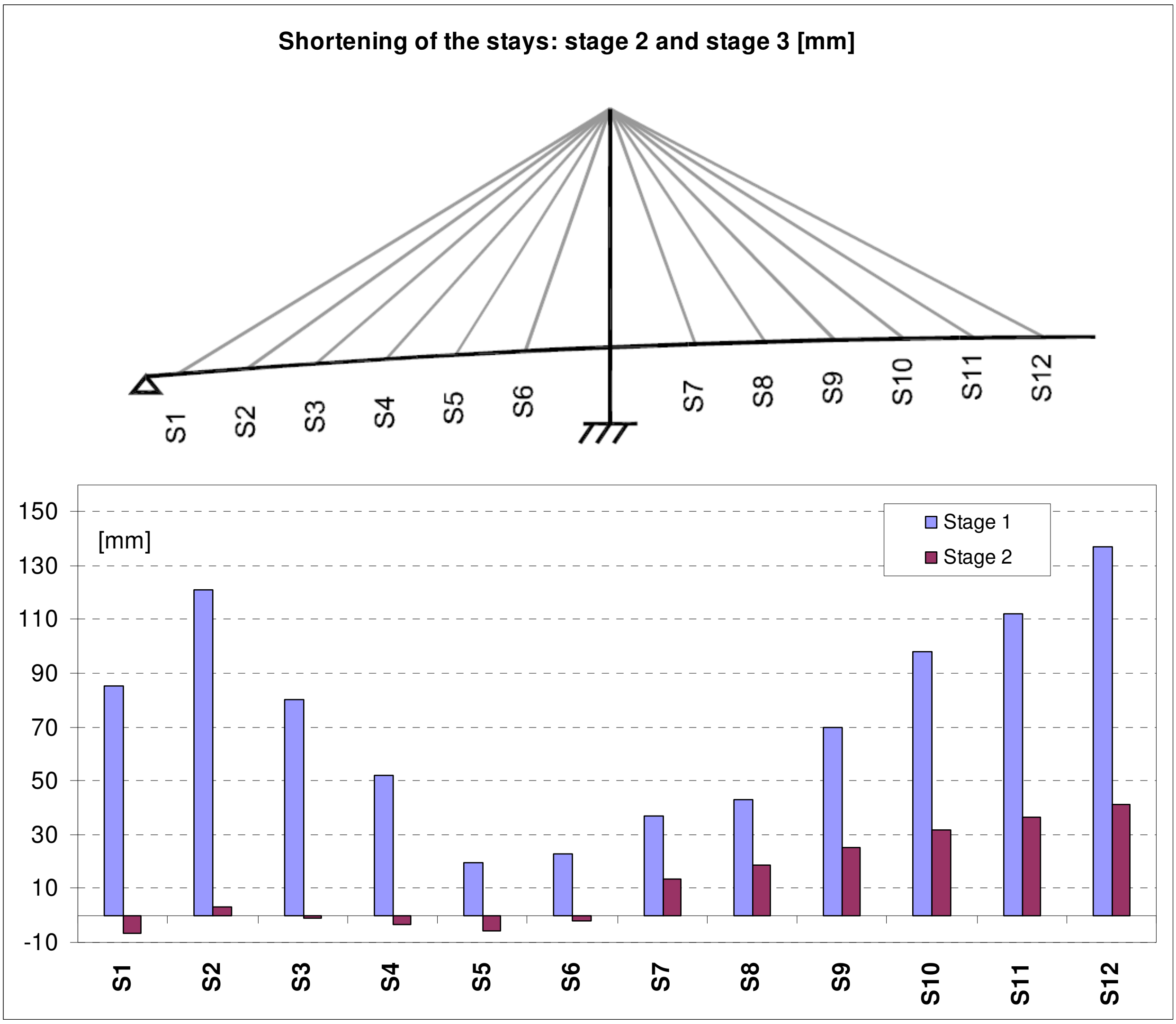

Fig. 6: Shortening (mm) of the stays for stage 2 and 3 (half bridge).

5. Conclusions

Cable-stayed bridges for medium and short spans may not be able to compete with conventional girder systems from a cost point of view, but there might be many occasions where the benefits warrant the extra cost. For the Ostellato bridge, the following aspects had to be taken into account. A limitations in deck thickness due to the required vertical clearance, an environmental concerns that suggested to move the piers out of the river embankments and the aesthetics requirement that called for a signature structure.

Designing and building a signature stay cable bridge can be reasonably cost efficient if only some basic optimization is carried out at the design stage. The following components need to be carefully evaluated and optimized:

- Composite decks may be particularly efficient and easy to erect.

- Tower design and material need to be efficient otherwise these elements are simply a cost addition with respect to a girder scheme. Concrete is certainly economic and efficient.
- Anchorages need to be optimized because they are typically expensive and awkward to built.
- Stays cost need to be comparable to that of a post-tensioning system since the two are similar and have the same structural function.

Fig. 7: The deck slab under construction

6. References

[1] WALTER R., HOURIET B., ISLER W., MOIA P. and KLEIN J.F. *Cable-Stayed Bridge,* Second Ed., Thomas Telford Ltd, London, 1999.

[2] GIMSING N.J., “History of Cable Stayed Bridges”*, IABSE Conf., Cable-Stayed Bridge – Past, present and Future*, Malmo, Sweden , 1999.

[3] PETRANGELI M., ANDREOCCI C. and PIETRANTONI M. “Phoenix taking of at Comacchio”. *Elegance in Structure*, *IABSE Conference*, Nara, 2015.

[4] EN 14651:2005 “Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual)”.