Serrería Bridge – A Calatrava-designed Cable Stay Bridge in Valencia, Spain

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ABSTRACT

Located in the south of Valencia, the City of Arts & Sciences is made famous by the designs of architect Santiago Calatrava and has become one the most interesting points of the city. In the middle of this site featuring many of Calatrava’s bridges and buildings, Puente Serrería rises with its 126m pylon height as the highest point of the City.

Puente Serrería, also known as L’Assud de l’Or, is a stay cable bridge comprising a steel pylon and deck, with a 155m long main span. The backward-inclined steel pylon towers above the bridge and supports 29 front cable stays comprising between 31 and 61 strands and the 4 back stays with 85 strands each, support more than 1,800 tonnes of steel used for the bridge deck. The bridge features the new BBR HiAm CONA stay cable system where each strand is individually guided and sealed leak tight. All anchorage components of the BBR HiAm CONA have been designed for a stress ranges greater 300 MPa. The stays are furthermore equipped with the advanced BBR Square Damper system to prevent stay cable vibration.

KEY WORDS
Parallel strands system, high fatigue resistance, durability, corrosion protection, fast installation.
INTRODUCTION

During the last 20 years, stay cable bridges have become more and more popular in Spain, and are now a common solution chosen by designers. A high priority is placed on aesthetic aspects as bridges are no longer considered only functional structures, but also works of art. There are many stay cable configurations in use and larger bridge structures commonly use the parallel strands system. Serrería Bridge, designed by Santiago Calatrava, illustrates the versatility of these stay cables, and demonstrates that the installation can be adapted to almost any kind of structure requiring high performance structural elements.

RIGOROUSLY TESTED SYSTEM

The BBR HiAm CONA stay cable system for strand stay cable bridges has been rigorously and successfully tested for fatigue and leak tightness tests – with testing provisions and test results exceeding the provisions stipulated in the fib recommendation, Bulletin 30 'Acceptance of stay cable systems using prestressing steels.'

PREPARATORY WORK AND CABLE INSTALLATION

During pylon construction, three provisional front stays were installed to bear the weight of the inclined pylon. The work took place from the middle of March 2008 to the first week of May. Starting from the end of May, the installation of the BBR HiAm CONA system was performed on site using the strand-by-strand installation method, which is comprised of four basic steps:

- Installation of the upper (pylon) and lower (deck) BBR HiAm CONA anchorage.
- The preassembled compact BBR stay pipe is hung between the two anchorages using two master strands. The stay cable outer duct is now used as a guide and passage from anchorage-to-anchorage.
- The strand is positioned at deck level and pulled up through the stay pipe and the upper anchorage and inserted into the lower anchorage.
- Each strand is tensioned immediately after the installation, using the BBR ISOSTRESS tensioning method, ensuring an equal stress distribution among the strands of an individual cable.

Before beginning the installation, numerous preparatory tasks have to be carried out. The tasks can be summarised into 3 groups: strand pre-cutting and peeling, duct butt-welding and anchor head positioning.
**Strand pre-cutting and peeling**
The prestressing strand that makes up the stays in Serrería Bridge comprise is a galvanised, waxed and HDPE co extruded strand with an ultimate tensile strength of 1860 MPa and a steel cross section of 150mm$^2$. Each strand has to be prepared individually, taking into account the length between anchor heads, deformation expected in the structure during stay tensioning and extension of the strand during tensioning. Each strand is cut to a predetermined length on a workbench equipped with rollers, and then the HDPE sheathing is stripped for a short distance at each end to allow wedge gripping at the anchorages.

**Duct butt-welding**
Each of the stay cable ducts had a different length and must be accurately assembled from relatively short sections of specialist co extruded PE pipe sections. Thermal effects are very important as almost 3 meters of deformation can be expected during the lifetime of the longest stays for Serrería Bridge. The correct welding process is highly critical and the duct ends need to be cleaned and levelled to ensure correct alignment. Heat is applied to each side of the duct to be joined and then the duct is pressed together using hydraulic jacks which maintain constant pressure during curing of the joint. An inner lip is formed as a result of the butt welding and this is removed with a debeader in order to avoid the strands catching on the pipe joint during strand pushing.

**Anchor head positioning**
Anchor heads are composed of an externally threaded body and an outer load distribution nut. As bearing plates are reached through the guide pipes, the anchor head body is introduced from the outside of the form pipe thus protecting the thread. When it is lowered so that it protrudes out of the bearing plate beneath the deck, the nut is threaded into place (its initial position depends on the tolerance required) and fixed with centralisers. Correct positioning of the anchor head is crucial, as a misalignment could obstruct the final stay cable tuning and adversely affect the required tolerances (strength and geometry) of the stay.
With the preparation work complete, the installation of the duct and strands can be commenced.

**Strand pushing and stressing**

The first step is installing the outer HDPE duct and installing and tensioning the 2 initial strands to align the duct between the anchorage points. These operations are shown in Figures 3 and 4.

![Figure 3: Raising of the outer stay pipe using two strands](image)

![Figure 4: Tensioning of the initial strands to align the outer stay pipe](image)

With the stay pipe installed and aligned, the operations relating to installation of the remaining strands comprise:

- A wire-pushing machine is situated on the top of the pylon and a 5.4 mm diameter wire is passed through the next hole of the anchor head and run down the outer PE duct until it exits at the bottom anchorage location. The 7-wire strand is trimmed so that the central king wire is left protruding to allow the connection to be made as small as possible.
- When the wire arrives at the deck, the strand to be raised is connected to the guiding wire using a small coupling device. Figure 5 shows the coupling device being attached to the strand at the bottom anchorage.
- The wire-pushing machine then winches the strand back up and it is carefully guided through the top anchor head when it reaches the pylon.
- The anchor wedge is then fixed to the strand and the coupler holding the guiding wire removed. Figure 6 shows the top anchorage with the wedges placed.
- At this point, the bottom extremity of the strand is guided into the deck's anchor head using another guiding wire.
Stressing of each individual strand is carried out using a mono-strand jack, immediately after each strand is placed. This systematic approach guarantees that all strands in each stay are parallel. Every strand in a single stay is stressed with a slightly different tension load due to the small deformations that occur in the deck during tensioning. The pylon deformations also have to be taken into account and some tuning is carried out on individual strands to finally ensure the same tension in every strand of a stay.

**Final tuning**

Final tuning of the cable stay is done with a multi-strand jack and is carried out from the inside of the deck. Depending on the project’s specific requirements, the multi-strand jack can adjust the geometry, modify the cable tension or perform a check loading function. The active anchor heads in Serrería Bridge are designed to allow a +30mm adjustment (stressing) and a -70mm adjustment (destressing).

Space conditions are very important inside the deck, as the hydraulic jack has a weight of about 3 tons and a diameter of approximately 1m. A common method to facilitate the positioning and movement of the jack is a chariot, which can be inclined to approximate the alignment of the anchorage. Figure 7 shows the system as used inside the deck on Serrería Bridge.
BACK STAY CABLE INSTALLATION

Serrería Bridge has 4 back stays with 85 strands each positioned in a near-vertical orientation (2% inclined) each side of the pylon. Refer Figure 8. The design and installation of the back stays was quite a challenge for many reasons. In order to understand the installation complexities, a number of technical requirements have to be explained.

The back stays are not inside a HDPE duct as with the front stays, but inside a steel pipe which is approximately 750mm in diameter with a wall thickness of 36mm. This pipe was completely installed before the strands were installed. It was an important design requirement that all the strands of a stay and the outer steel pipe worked as one structural element, whilst preserving the option of removing one strand for maintenance or replacement should it become necessary during the lifetime of the bridge. Another condition was that no access to the inside of the anchorages was available (as the pipes were in their final position), so working “windows” had to be created artificially. Finally, stressing requirements demanded that the 4 back stays had to be tensioned simultaneously in 4 steps (up to 1,250 tonnes in each stay). Following tensioning of all stays, an important part of the load (about 800 tonnes) had to be transferred from the strands and into each steel pipe.

The back stays were very challenging in terms of aerodynamics and BBR Headquarters in Switzerland developed and analysed a special configuration, where the whole 116m long back stay pipe was injected with special grout to add extra mass, which enhances the overall aerodynamic behaviour. Furthermore, to ensure that any single strand could be replaced, a 100m long PE duct (25 mm diameter) was placed over each strand in order to keep it isolated from the grout. The dimensional tolerances were carefully selected to prevent significant vibrations of the individual strand assembly.
Strands were installed one by one, without stressing, but with careful controls on the length to make sure that no strand would take more load than the others. Refer Figure 9. Auxiliary steel frames were installed on the top of the pylon and at the bottom, to provide a temporary bearing surface for the anchor heads to initially isolate the load from the outer steel pipe. Temporary bearings were installed at the top anchorage, which would be removed at a later stage to transfer the load into the outer pipe making the pipe and stay cable strands act as a single structural element.

Stressing was done simultaneously with 4 multi-strand jacks capable of stressing to 1,250 tonnes each. Figures 10 and 11 illustrate the jack positioning at the top of the pylon and a close-up of a single jack location.

The transfer of load into the outer steel stay pipe was carried out by removing the temporary bearings under the upper anchor head and destressing the stay, with the wedges fixed, transmitting the entire load into the outer steel pipe.

ADVANCED CABLE DAMPING

Despite the wide use of cable-stayed bridges, there are still areas of great concern, particularly the effects and elimination of cable vibration phenomena such as vortex shedding, galloping, parametric excitation and wind and rain induced vibration. Various countermeasures are available – for example, the use of helical rib on the cable surface or cross ties. Supplemental damping devices add damping to the cable – hence achieving sufficient total damping as an efficient measure against cable vibrations.

Standard techniques such as helical ribs on the stay pipes and rubber centralisers were used on the Serrería Bridge cables. In addition, an advanced cable damping solution was implemented which involved installation of BBR Square Dampers.
The BBR Square Damper is based on friction and is essentially an adaptation of the braking system of an automobile. The device can be used as an internal damper, where it is installed inside the steel guide pipe or alternatively as an external damper, attached to the free cable length using a damper housing and external brace. A schematic view of the friction damper is shown in Figure 12.

![Figure 12: Schematic view of BBR Square Damper inside stay pipe](image)

The basic characteristics of the BBR Square Damper are:

- The damper is not activated at low and non-critical vibration amplitudes and avoids constant working thus reducing maintenance requirements.
- Damping efficiency is independent of the acceleration and mode of cable vibration.
- The cable is free to move longitudinally to allow temperature elongation and force variations without constraints.
- Damping characteristics can be adjusted at any time by changing the ‘clamping’ force.

On Serrería Bridge, all front stays terminating at the pylon are equipped with a rubber centraliser while all deck stay cable connections (longer than 100 m) have BBR Square Dampers to prevent important vibrations during the lifetime of the bridge. All elements of the centralisers and dampers can be inspected individually and are replaceable if required (due to external damage, vandalism, etc). Figures 13 and 14 show the BBR Square Dampers installed into the guide pipe at the deck level. Note the split pipe arrangement in Figure 13 to permit initial installation and future removal if required.

![Figure 13: BBR Square Damper with split guide pipe to assist installation](image)

![Figure 14: Damper inside completed guide pipe](image)
FINAL DETAILING AND FINISH

At completion, corrosion protection of the anchor head is guaranteed by a double wax injection process which firstly encapsulates any section of bare strand through the anchor head and then a secondary level of protection comprising a wax filled protective cap.

The balance of finishing work involves placing the covers and anti-vandalism pipes in the deck, sealing of neoprene transition boots (between cable ducts and guide pipes) to avoid water entering through the duct to the anchor head and installing upper covers at the pylon connections. As can be seen by the Figures 15 and 16, the final protection and finish of the completed stay cables are durable, robust and visually attractive.

CONCLUSIONS

The parallel strands stay cable system comprising BBR HiAm CONA configuration presents high durability and fatigue resistance and the system is able to be adapted to multiple construction processes such as cantilever bridges, precast segmental construction, incremental launching method and even as support cables for large roof structures.
Serrería Bridge shows the important versatility shown by this stay cable system, allowing different ways of installation, stressing and damping utilising light additional equipment and for a structure requiring high performance. The installation of the first stay cable began the 26th of May 2008, and the load test was successively passed on the 20th of August 2008 – in time for the Formula 1 Grand Prix weekend in Valencia and the opportunity to showcase to the world another legendary structure designed by Santiago Calatrava in the celebrated City of Arts and Sciences.

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- Stay Cable Technology: BBR VT International Ltd

REFERENCES