The Chiani Suspension Bridge: A Complete Overhaul

Marco Petrangeli, Prof., INTEGRA S.r.l., Rome, Italy and **Marcello Petrangeli,** Eng. Tensacciai SpA Via F. Milano, Italy.
Contact: marco@integer.it

Summary

The paper presents the rehabilitation works carried out on the Chiani suspension bridge in Algeria. The bridge, designed by the French engineer Arnodin at the beginning of the last century, has a main span of 105 m and a mixed cable supporting system with a stayed deck portion near the towers. The bridge was designed and built before the similar Sidi M'Cid one in Constantine, Algeria. The strengthening works carried out on this bridge by the same authors during the 1990s was reported in *Structural Engineering International* (4/2000).[4] Following the successful experience of the Sidi M'Cid bridge, the authors have been asked to engineer a complete overhaul of the Chiani bridge, a beautiful structure completely abandoned and closed to traffic because of its severe state of degradation. The works included the complete substitution of the suspension system, the widening of the superstructure with new pedestrian sidewalks moved out of the parapet girders and a new concrete deck to allow for unrestricted vehicular traffic to transit on it. Works have been carried out without supports from below, with the deck weight transferred from one suspension system to the other while the bridge remained open to pedestrian, motorbikes and herds. An innovative suspension system with resin-encased strands has been used for main cables, stays and hangers in lieu of ropes and steel bars. New saddles, made of welded plates following a concept originally developed for the third generation suspension bridges, have been placed over the existing ones with the two systems working in parallel during the load transfer.

Keywords: suspension bridge; cable substitution; deck widening; strands; saddle; clamps.

Introduction

Various existing small to medium span suspension bridges built in the late 19th and early 20th centuries are now in need of strengthening and repair.[1–3] Very often it is now time to replace the main suspension cables that given their reduced diameter and lack of proper protection are more prone to corrosion compared with larger ones.

Replacement of the suspension system is not a simple task though. Large displacements, deformations and elastic energy are accumulated into these structures during construction making it difficult to perform the release and replacement of the various components, especially the suspension cables.

The Chiani Bridge (*Fig. 1*) is a small suspension bridge designed by the French engineer F. Arnodin at the beginning of the last century. The bridge spans over the Chiani River at the outskirts of the homonymous village, located near Annaba in northeastern Algeria. The bridge was built few years before two similar ones were erected by the same engineer in Constantine, the Sidi M'Cid[5] and the Perregaux bridge.

Fig. 1: The Chiani Bridge before the repair works

The bridge uses a mixed system (popular among French engineers during that period[5] and adopted few decades later by Dischinger) with both suspension cables and stays as shown in *Fig. 2*. The main suspension cables and the backstays are anchored into four concrete pits excavated into the rocky ground.

The bridge showed extensive signs of corrosion in the suspension and stay cables (*Fig. 3*) and in the deck stiffening girders and transverse beams. The wooden plank resting on the transverse beams was completely rotten leaving for the pedestrian crossing only two narrow kerbs made of corrugated steel.

The Bridge Suspension System

The Chiani bridge was supported by two cables, each one made of six ropes of 75 mm diameter. The six ropes are not bundled together but run adjacent one to another and so rest over the saddle at pier top and at the anchorages. Each suspension rope was individually clamped with inverted U-shaped rods and nuts to small steel castings

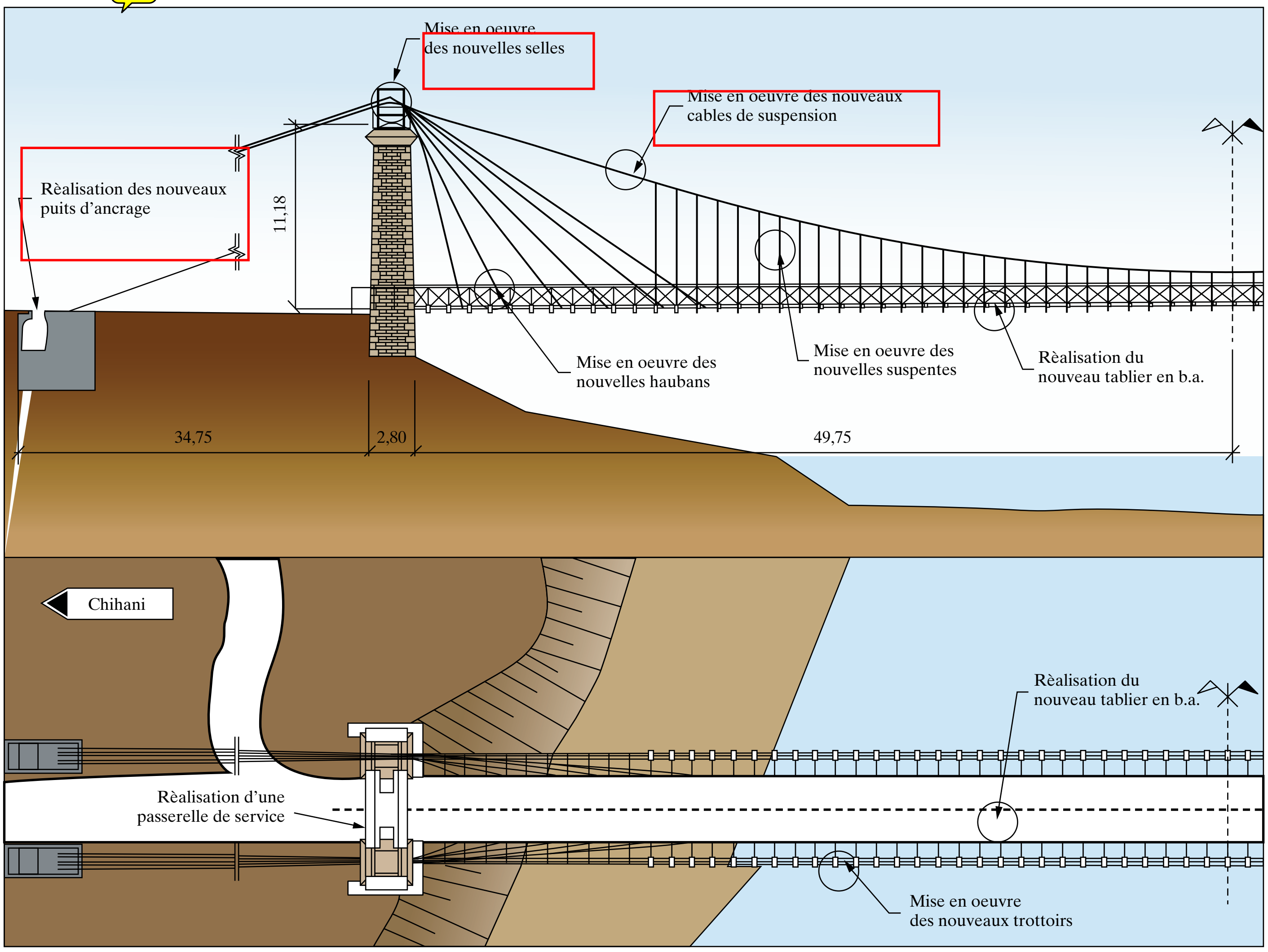

Fig. 2: The bridge layout

Fig. 3: Cables, clamps and hangers

(*Fig. 3*) connected to the hangers made of 33 mm diameter rods. The 57 hangers each side of the deck are closely spaced (1,25 m) and directly connected to the I-type steel cross beams supporting the deck.

Twenty metres each side of the towers the deck was supported by six plus six stays made of 35 mm diameter ropes. These six stays were made of three ropes looping around three pulleys at the saddles. Their force was balanced by a backstay made of a 42 mm diameter rope (*Fig. 4*). The stays are anchored to stiffening I-beams that run beneath the stayed portion of the deck under the parapet girders. The horizontal force component of the stays is balanced by two ropes (traction ropes), running below the deck along the suspended part and connecting the above-mentioned I-beams at the two sides of the bridge. This configuration allows the deck to swing longitudinally because the horizontal stay component is self-equilibrated and the deck does not push against the abutments (towers).

The saddles could slide on rollers (*Fig. 4*); this mechanism, although showing extensive sign of deterioration, must have been still effective at the time of rehabilitation judging from the perfect condition of the stiff masonry towers.

Fig. 4: The old saddles

All the elements of the suspension system showed severe signs of deterioration. Stays had quite a few broken wires hanging loose, cables were still locked but close inspection after their removal showed corrosion had reached the inner wires with localised pitting phenomena.

The Deck Widening and Strengthening

The metallic part of the existing deck was made of two parapet stiffening girders and the transverse I-beams directly supported by the hangers. Both elements showed extensive but still superficial corrosion. The running surface of the deck was made of wooden planks and was in a very poor state (*Fig. 5*), falling apart and leaving wide openings so that the bridge was officially closed to traffic, although still providing factual crossing for pedestrians, small motorbikes and herds along two steel clad kerbs running besides the two parapet girders.

In order to open the bridge to vehicular traffic, it was decided to cast a concrete slab on top of the transverse beams in between the two parapet girders. While providing a firm surface for vehicular traffic, the slab would also strengthen significantly the bending and axial behaviour of the superstructure.

Fig. 5: The existing deck

Thickness of the slab has been kept to a minimum (140 mm) so as to reduce its weight. The slab was cast onto corrugated steel sheeting for increased punching and bending resistance. Still, the new concrete slab provided 100% increase of the deck self weight with respect to the original configuration.

In order to allow for vehicular traffic to run onto the new deck, two other aspects had to be addressed, namely: transverse beams had to be strengthened and kerbs displaced (*Fig. 6*) to make place for a single lane carriageway in between the parapet girders (see also Ref. [6]).

Strengthening of the transverse beam was obtained by welding an additional plate onto the bottom flanges and stud connectors on the top ones so as to obtain composite action with the concrete slab.

Sidewalks were moved outside of the parapet girders. This displacement required the transverse beams to be extended with additional steel plates bolted onto the transverse beam web so as to support the new pedestrian corridors positioned in between the parapet girders and the new hangers.

The hangers had also to be displaced half a metre outwards thus swinging the suspension cables from the slightly inward original position, to their new position, 3° outwards.

Because deck concreting displaced the centroid of the bridge transversal cross section downwards, while strengthening the transverse beams, additional plates were welded onto the upper chord of the parapet girders. This operation was simple and very straightforward allowing an increase in the strength of the parapet girder and especially in the buckling load of the parapet because the additional plates did increase the lateral and torsional resistance of these members.

The New Suspension System

Two options were available for the suspension system replacement.

The first option was to replace the main suspension cables and stays one by one, retaining the existing saddles. This approach was used for the partial

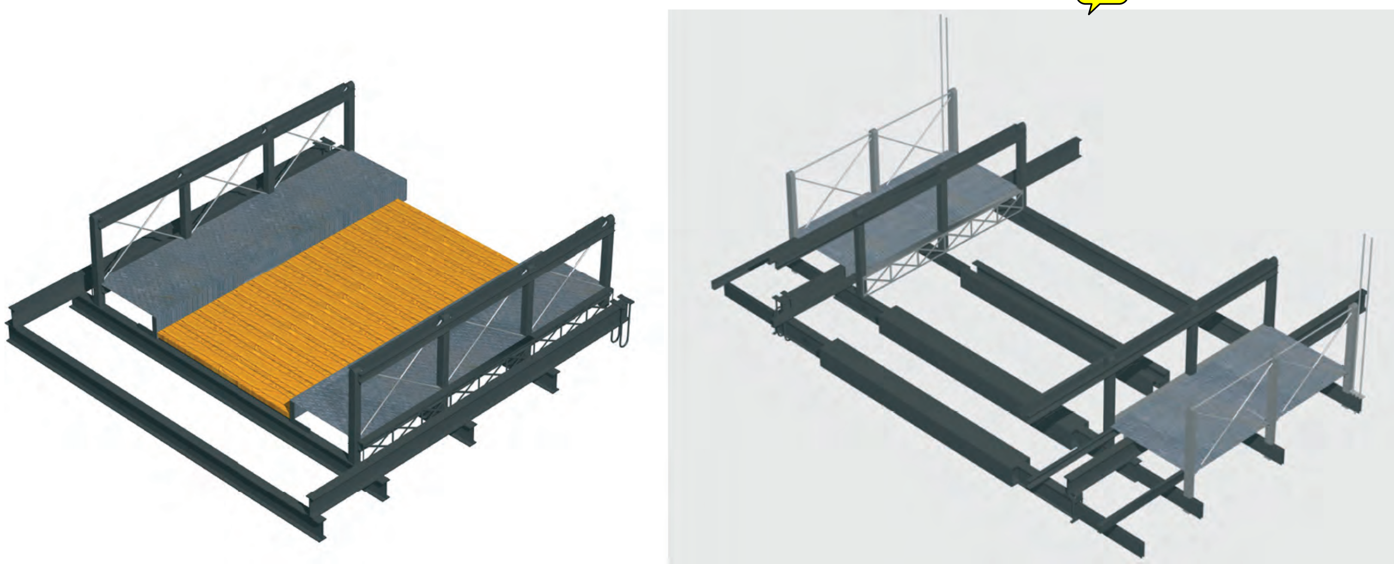

Fig. 6: Deck three-dimensional view. Before (left) and after

replacement of the Sidi M'Cid suspension cables in Constantine.[4] This approach has few drawbacks though: the works are slow and cumbersome with a maximum of two suspension cables at the time to be replaced followed by the stays and the hangers; the existing saddles would have to be retrofitted, especially the sliding support beneath them now jammed because of extensive rollers corrosion. This latter problem was particularly difficult to solve because access to the bottom of the existing saddles would require their lifting, that is to say, lifting of the entire deck.

The second option was to build an entire new system, independent of the existing one, made with state of the art materials and technologies.

This second option was retained because it was more efficient, durable and economic with respect to the former. The only problem with this second solution being the challenging operations required for transferring the load from the old system onto the new one, with the two systems working in parallel before the old one was completely unloaded and removed (see also Ref. [7]).

The key elements of the new system are the new saddles (*Fig. 7*). These elements were designed following a philosophy developed for larger bridges by William Brown (1928–2005) where the saddles are an assemblage of smaller components made of rolled and welded plates instead of being made of a single casting.

The old saddles have been encased in a steel box, cement grouted once the old cables and stays were removed. The new saddles are placed on top of these encasings on steel–teflon bearing pads that allow longitudinal displacements.

Main suspension cables are made of epoxy-coated prestressing strand arranged in three ropes of 13 strands on each side. Clamps are made of two parallelepiped castings bolted together. Hangers are made of two strands each fixed to the clamps with standard monostrand prestressing anchorages. Between hangers and deck, a tensioning road has been interposed to allow for easier and finer tensioning in the last project stages.

A number of tests (*Fig. 8*) were carried out in Italy to assess the clamp capability to resist the tangential component of the hangers pull that increases towards the towers up to 25% of the vertical force. The tests showed a surprisingly good capability of the clamps to resist tangential forces. Short-term resistance was, on average, 50% of the clamping force (eight D12mm bolts each clamp). No significant reduction of this resistance could be detected for long-term load application although some loss can be expected after prolonged exposure to the Algerian sun. Still, the design maximum tangential force for the clamps (5 kN) is less than 10% of the resistance (50 kN) found in the laboratory on a prototype clamping only one cable, out of three, with four bolts, out of eight of the final clamp.

Fig. 7: The new saddles

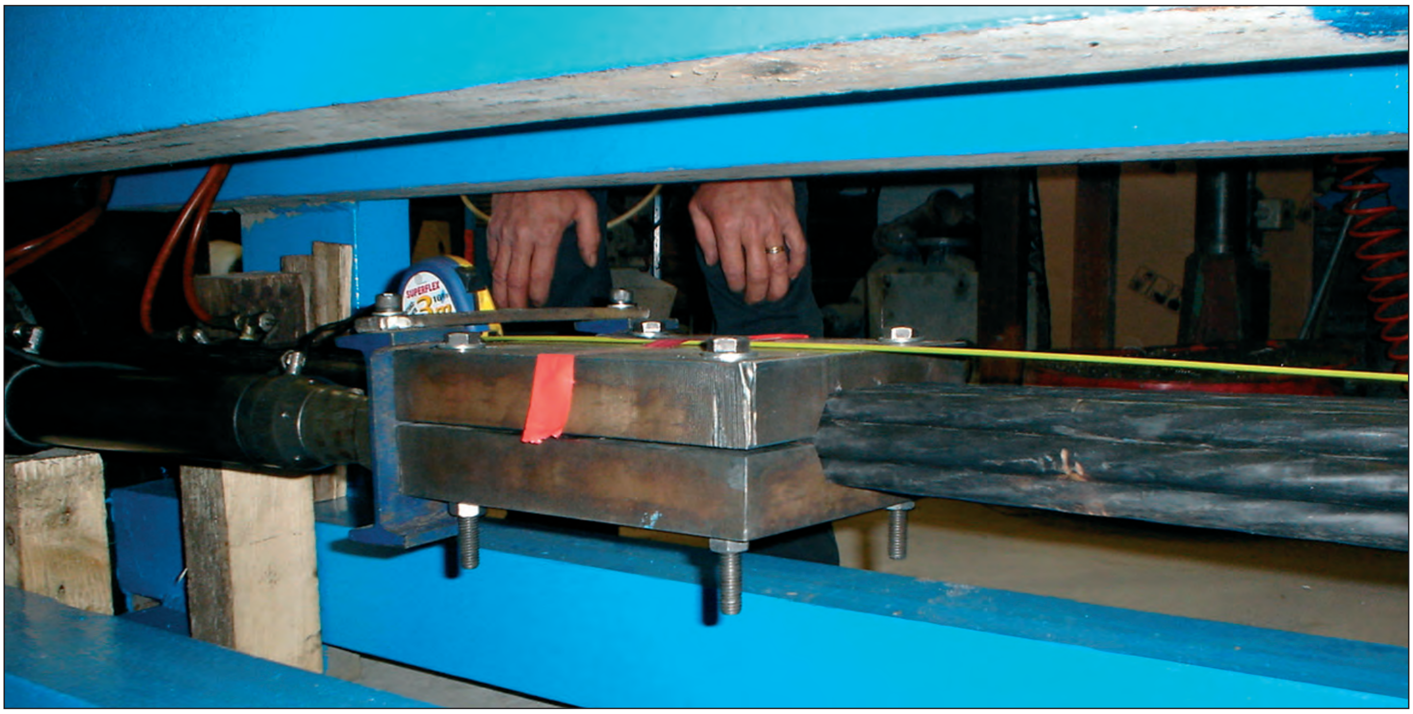

Fig. 8: Test loading of the clamps tangential behaviour

All the suspension system components (*Fig. 9*) were therefore made in Italy and shipped to Algeria together with the epoxy-coated prestressing strands.

The Anchorages

The new suspension cables and stays were anchored in cast *in situ* reinforced concrete blocks connected to the existing anchorages (*Fig. 10*). These anchorages were made of lean concrete, cast inside pits bored in the rocky ground. The original cables were deviated at the entrance by steel clad concrete saddles and anchored vertically inside these pits.

The anchorage chambers were large enough to make room for the new reinforced concrete castings. The additional weight of the new anchorage blocks, firmly connected to the existing ones by means of reinforcing bars drilled and grouted into it, provided sufficient strength for the increased weight of the suspension bridge.

Fig. 9: The clamps

The Work Phasing

The works commenced with the complete removal of the wooden deck planks and sandblasting of the existing steel deck components. The superstructure was then reinforced by welding additional plates to the transverse beams and parapet girder upper chords and widened by bolting extensions to each transverse beam (*Fig. 11*). A total of 2,5 kN/m of structural steel was added to the deck during this stage. Corrosion protection, by means of epoxy primer coating, was then applied to the whole of the structure.

Works on the tower and existing saddles followed, with temporary steel platforms erected on top of the towers, encasing of the old saddles and erection of the new ones. In order to keep the encasings of the old saddles within acceptable weight (plate thickness), the encasings were tailored so as to transfer the load to the old saddles along multiple contact lines. Upon removal of the old cables and stays, grouting of the four encasings provided additional strength and solidity to these bases supporting the new saddles.

Replacement of the suspension system followed. The new cables were spun across one strand at the time (78 strands) using the catwalks erected on the existing cables. The freestanding position of the new cables was, at midspan, 3,5 m *circa* above the deck and therefore 3 m higher than the old cables (*Fig. 12*). This choice allowed,

Fig. 10: The new anchorages cast inside the existing ones

Fig. 11: Strengthening and widening the transverse beams

after loading the new cables, a minimum clearance of 2,2 m at midspan for pedestrians.

First tensioning of the new system was carried out with the new hangers shortened to a given length so as to take over roughly 50% of the deck weight. This operation was rather unusual because the stay technology and equipment used for the new suspension system are designed for stiffer configurations and higher loads.

Tensioning started from the midspan hangers, shortened by 0,5 m *circa*, with a tensioning force of few kilonewtons. Tensioning then moved symmetrically towards the two towers with the main cables gaining tension and stiffness thus simplifying the tensioning operations.

Because of this first tensioning taking place after a prolonged summer stop due to environmental and minor technical adjustments, significant errors were committed when shortening (tensioning) the hangers to the predefined length. A plot of this error is shown in *Fig. 13*. Hanger length was topographically measured after first tensioning. Because tension in the hanger was negligible, topographically measured length is very close to actual length. Plotted error is therefore the difference between measured and project lengths.

Error in hanger tensioning could be easily verified by manually checking the tension in the hangers. According to the above graph, few hangers were almost slack, other significantly stiffer than the others.

Nonetheless, the bridge deck proved to be sufficiently strong and flexible to withstand the uneven load distribution resulting after the first hanger tensioning. Given the very light deck configuration and strength reserve of both deck and hangers, it was therefore decided to proceed with the next phase leaving the correction of the first tensioning to a later stage.

Next phase was the complete unloading of the old suspension system. Old hangers were released one by one leaving the deck hanging from the new cables. The old suspension ropes, standing under self weight only, were temporarily clamped, sawn at midspan and removed from both sides. The operation required the ropes to glide over the old saddles, previously greased to facilitate the operation.

Finally, the second tensioning of the new hangers could be performed. This second tensioning was performed before concreting of the new deck slab. Because concreting of the deck would increase the deck weight by 100%, the second tensioning had to significantly raise the deck to make up for the subsequent sagging of it. While doing this, the following other issues were to be tackled:

- correct first phase tensioning errors
- adjust small geometric tolerance in the initial cable setup
- allow for the third and final tensioning to be performed from the bottom rods only
- adjust rod lengths so as to obtain a constant height of the anchorage plate between hangers and roads after final tensioning

After the second tensioning, strand anchorages were pushed to lock, the strands cut to measure and the anchorages greased and closed with their metallic cap. After second tensioning, error between design and measured value reduced significantly as shown in *Fig. 14*.

Following the second tensioning, stays were replaced, two at a time, with the

Fig. 12: The two suspension systems before the load transfer

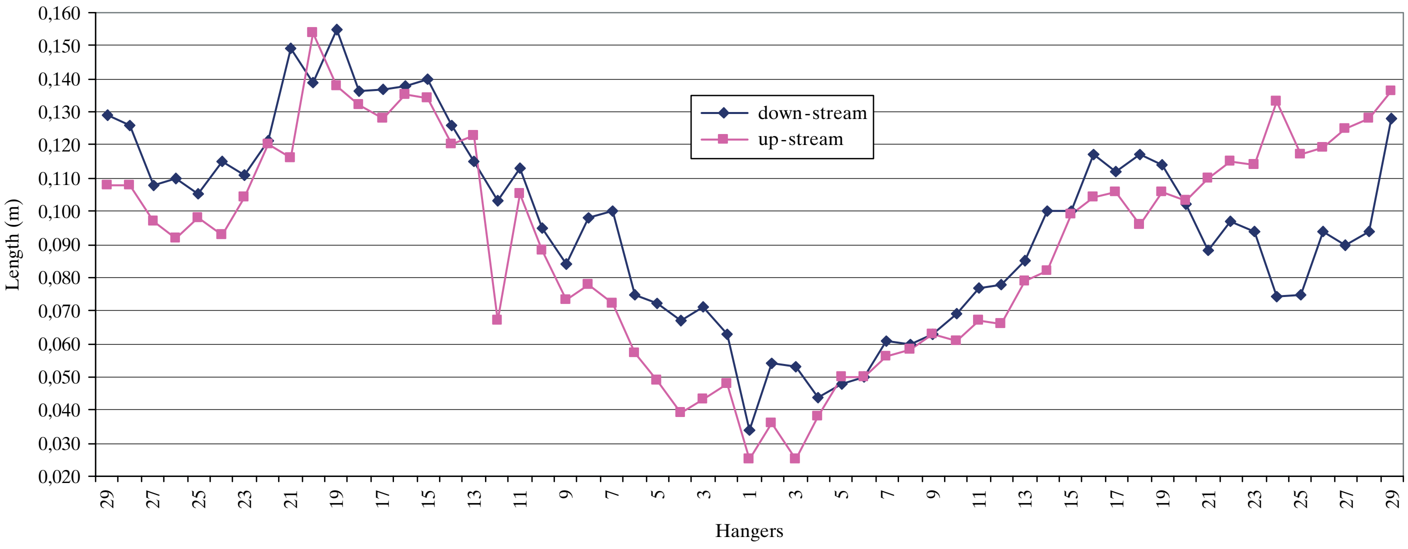

Fig. 13: Hanger's length difference between design and measured value after first tensioning

new ones made of the same strands used for the main suspension cables. Contrary to hanger tensioning, carried out under geometry (length) control, stays have been tensioned to pre-defined force values.

With the suspension system fully replaced, concreting of the deck slab was performed. The slab was cast over corrugated steel sheeting discontinuous over the transverse beams where stud connectors were welded to obtain composite action with the concrete deck slab. The concrete top surface slab was then immediately waterproofed with acrylic painting.

During this phase, 80% of the deck weight increment was applied to the bridge, with the deck camber of 700 mm after second tensioning reducing to 350 mm. Because of the cable tension increments, saddles displaced 100 mm *circa* towards central span partially recovering the initial set back imposed during cable erection.

After deck concreting, the third hangers tensioning and the second stays tensioning took place. Once again, hangers tensioning was carried out with a displacement-controlled

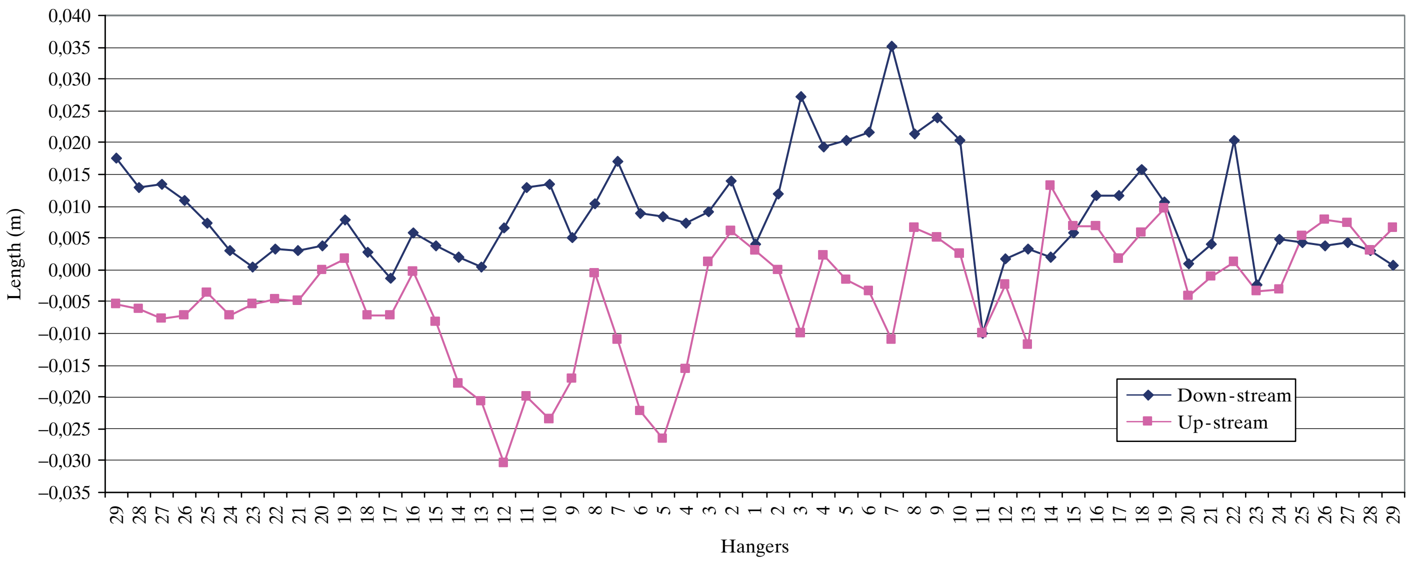

Fig. 14: Hanger's length difference between design and measured value after second tensioning

procedure, whereas stays with a force-controlled one.

Finishing works then followed, with a 30 mm bituminous wearing course cast on the deck slab and the external railing erected using the hangers as supports (*Figs. 15 and 16*).

Conclusion

Rehabilitation and strengthening of small to medium span suspension bridges built in the late 19th and early 20th centuries around the globe is finding growing interest from the structural engineering community as these bridges are now in need of extensive repairs and upgrade. On the basis of the field experience gained from the rehabilitation of the Algerian suspension bridges designed by French engineer Arnodin, the following recommendations can be made.

Fig. 15: The new Chiani bridge platform

– Small suspension ropes used in these bridges are economically and efficiently replaced by cables made of prestressing tendons. Epoxy-encased strands increases life span but also allows for efficient clamping.
– Replacing of the existing suspension system can be carried out with the two system (old and new) in parallel, provided the two are cinematically independent at the towers, that are likely to be made of masonry or concrete and therefore stiff and prone to cracking under unbalanced forces from the suspension cables.
– The suspension system replacement must be conducted under a displacement-controlled procedure. Any procedure based on force specification is likely to be translated, on site, into displacement (elongation). This simple truth is often ignored in the design of contemporary small to medium cable (stay) supported bridges. With a stiff girder and a reduced number of cables (stay), a force-controlled procedure may still work but with a flexible deck and a large number of supporting cables, as the case under consideration, displacement control is always simpler and safer, especially in developing countries where topographic stations are more popular than pressure gauges.
– Hanger spacing and number is better kept as in the original configuration for aesthetic and structural reasons. Increasing hanger spacing and reducing their number modifies the mechanical behaviour of the steel stiffening girder. Again, prestressing strands and stay technology can be used as they are cheaper, easier to erect and adjust and, most important of all, simpler to replace in the future.
– Concreting of the deck is often a simple and efficient system to strengthen the bridge provided the towers and the foundations have enough strength reserves. Additional weight can be accounted for when designing the new suspension system thus obtaining a stiffer structure

Fig. 16: The Chiani bridge

(via the increased tension in the cables) but also a tougher and more ductile response of the deck under the increased live loading of today traffic.
- New saddles at towers can be easily made of welded and rolled plates instead of cumbersome and expensive castings.

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SEI Data Block

Owners:
Willaya de Tarf

Consulting Engineer:
Integra

Main Contractor:
SAPTA, Alger, Algeria

Suspension system supply and erection:
Tensacciai Milano, Italy

High strength steel (t):	25
Steel (t):	40
Concrete (m^3):	50
Total Cost (EURO million):	2
Service Date:	April 2008