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Prosthetic Engineering: "Le Pont des Etudiants" in Constantine

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Abstract

This paper illustrates the prosthetic reconstruction of a historic masonry viaduct in Algeria. Two of the viaduct arches on the left bank that collapsed because of soil instability have been replaced with a stayed girder that allows for future soil kinematics while restoring the compression in the remaining masonry arches on the right bank. The numerical simulations of the viaduct wreckage needed to assess the integrity of the standing portion and the main issues in the subsequent design and construction of this pioneering intervention are discussed.

Keywords: arch masonry bridge; stayed bridge; structural rehabilitation; numerical modelling.

Fig. 1: The Student Bridge in 2014

Introduction

The "*Student Bridge*" (*Fig. 1*) in Constantine is a beautiful stone masonry viaduct built across the Rhumel River few hundred metres downhill from the Constantine University. The bridge, built during the French colonial period for the railway line connecting Constantine to Guelma, became a favourite pedestrian crossing when the railway line was dismissed. In 2004, due to soil instability of the left bank, the first two arches collapsed. The remaining three arches were left there as a remainder of the damage caused by rapid and unsustainable industrialization. Constantine, in the meanwhile, was becoming a city devoured by traffic and sprawling urbanization with resurfacing soil instabilities that, although congenital to the city subsoil, have been greatly enhanced by the lack of a proper land and water management. It happen that the bridge is also on the way to the airport and therefore the first author routinely cast his eyes on the structure in the numerous trips to Constantine, also known as "*la ville des ponts*," where other historical bridges have also been in need of repair and strengthening.[1,2] In 2013, after few enquires and meetings with the local authorities, it was decided to repair the *Student Bridge* and restore the pedestrian crossing over the Rhumel River. The main concern with repairing the bridge was that the budget did not allow for a thorough stabilization of the unstable left bank. Soil instability has historically plagued Constantine as the city subsoil is made of a layer of marnes and argillites resting on calcareous bedrock. These top layers of soft soils tend to slip over the bedrock; the movements are scattered in time and space, activated and reactivated depending on the ever-changing filtration patterns of the meteoric water and aqueduct leaks. It is now few years that a comprehensive plan for the solution of this problem is in the making, but a final decision is yet to be made, and to date, the major interventions have been specifically addressed to preserve two of the main city bridges, the historic Sidi Rached one[2] and the most recent trans-Rhumel,[3] which are threatened by a large slippage of an hillside on the right bank of the Rhumel River, just opposite to the city historic centre. The instability that caused the collapse of the first two arches on the left bank of the *Student Bridge* is smaller and less perilous compared to the above said one. The *Student Bridge* has been standing there for over 100 years without any problem, and no other significant signs of soil instability have been recorded in the buildings standing in the nearby area. Ten years ago, the heap overlooking the left bank must have slipped few decimetres, causing the first two stiffer arches to collapse. The foundations of the other arches are outside the unstable slope that seems to be confined to a relatively small area, the one where the morphology allows for enough gravitational energy to trigger the slippage.

Although limited, the unstable area discouraged the reconstruction of the bridge with stone, bricks and mortar because the resulting structure would be too sensitive to further movement of the bank which may restart any time. A reinforced concrete solution would not be much better because although more ductile, it would simply shift the problem to the existing masonry portion.

It was therefore decided to replace the two collapsed arches with a stayed composite girder. The stays would introduce a healthy compression in the remaining masonry portion of the bridge, the one now missing because of the collapsed portion. This force is balanced by two concrete blocks placed on the right bank where the back stays are anchored (*Fig. 2*).

The stayed girder is rigidly connected to the masonry portion and free to slide in both the longitudinal and transverse directions at the abutment should the latter creep following a reactivation of the soil instability. In the vertical direction, displacements should be limited by the abutment foundation that is made of three D:1200mm diameter, 20 m long piles. A shock transmitter restrains the deck end in the lateral direction in case of very strong winds or seismic events.

Even in the worst-case scenario of significant vertical and horizontal displacement, the stayed portion can accommodate for additional compliance, hopefully preserving the masonry part.

The Structural Analysis

Before taking the final decision on the bridge reconstruction, some numerical analyses have been performed in order to assess the structural integrity and residual resistance of the standing portion of the bridge. A finite element model of the structure has been set up using the Midas Fea finite element code. The model is made of 12 664 nodes and 9810 brick elements (six and eight nodes ones). The constitutive behaviour of the elements is a smeared rotating crack model where the compression behaviour is based on the Thorenfeldt expression,[4] and the postpeak tensile one (softening) is linear with the softening modulus calculated according to the specified fracture energy.[5]

The bridge was built using three main materials, the stone of the arches (barrel), that of the spandrel walls and the piers and the filling; their assumed material properties are summarized in *Table 1*. These material properties have been fixed according to visual inspection and literature.[6] Boundary conditions were kept as simple as possible by pinning all the nodes at the pier bases. In order to avoid local failure, a pier basement fascia with enhanced material properties has been introduced to simulate plinth confinement (see *Fig. 3*).

The first analysis to be performed has been the simulation of the collapse caused by the soil displacement. From a topographic survey, we knew that the abutment on the left bank, which is the foundation of the first small arch, slipped 0.12 m inwards (parallel to the bridge axis) and 1 m circa perpendicularly to the bridge axis. The above-mentioned displacement is the total displacement calculated with respect to a symmetric and straight configuration that the bridge had at the time of construction. No info is available concerning speed and exact timing of the displacement.

The first analysis therefore consisted in applying the self-weight (8000 ton circa) and then an imposed displacement to the first two foundations. From a visual inspection of the collapsed bridge, it could be noticed that a differential displacement did take place between the first two foundations although we do not dispose of an exact measure of the second foundation displacement because the collapsed masonry obstructed a proper topographic reading of it. In the numerical analyses, it has been assumed that this foundation has moved in the same direction but with a 70% amplitude compared to the first one.

The analyses seem to properly capture the failure mechanism which led to the collapse of the bridge as shown in *Fig. 4*. The finite element model shows two distinct failure zones developed: the collapse of the smaller arch that involved the majority of it and that of the larger arch that localized at quarter span.

The very good match between the failure mechanism depicted by the finite element model and the actual collapse of the structure provided a proof-check of the model and the numerical simulations. The same numerical simulations while properly depicting the failure mechanism also showed that the rest of the bridge was not particularly stressed neither damaged as also confirmed by close visual inspection of the remaining arches.

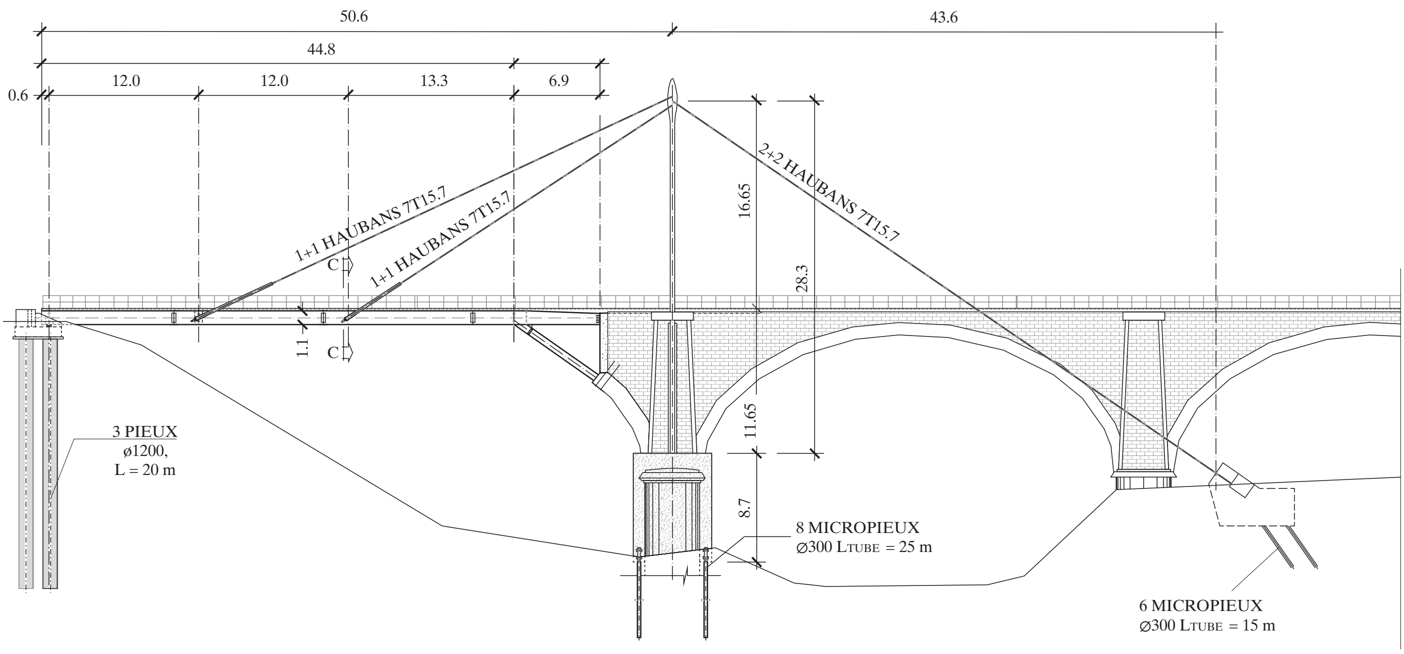

Fig. 2: The longitudinal profile of the new Student Bridge (unit : m)

Element	Material	Young Modulus, E_m[GPa]	Poisson Modulus, ν [–]	Compressive peak stress, f_c [MPa]	Tensile peak stress, f_t [MPa]	Fracture energy [N/mm]
Arch barrel	Hard limestone	12	0.25	38	0.5	0.026
Pier and spandrel walls	Limestone	8	0.25	34	0.5	0.026
Fill material	Cemented granular	0.5	0.25	5	0	0

Table 1: Material proprieties

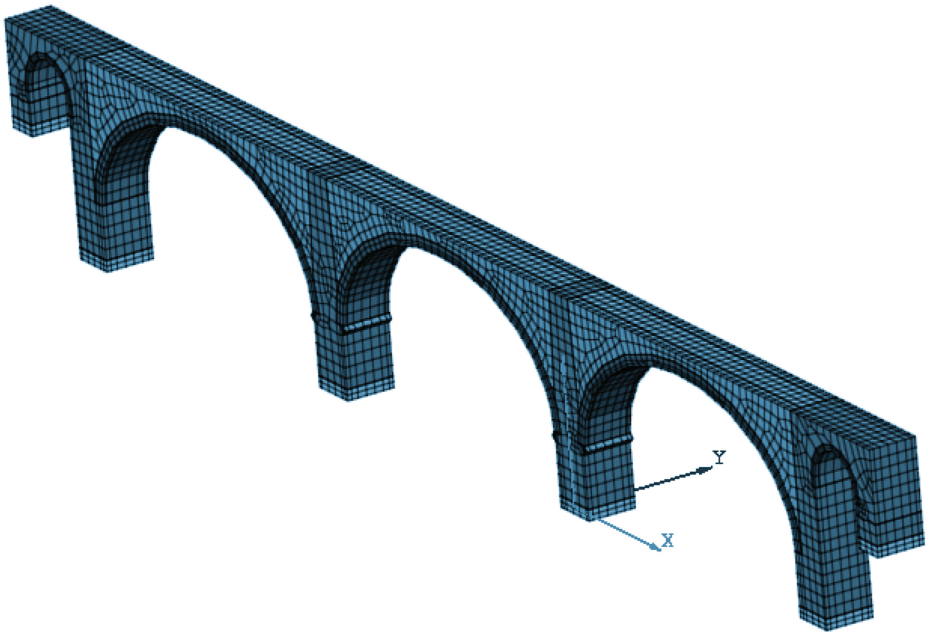

Fig. 3: The finite element model of the Student Bridge before the collapse

Finally, in order to assess the seismic resistance of the original structure, response spectrum and pushover analyses were performed using the same finite element model. The modal analysis shows the fundamental modal shapes in the longitudinal and transverse directions to have a period of 0.27 and 0.62 s, respectively. If the response spectrum specified by the Algerian code for the city of Constantine is applied, a spectrum with a PGA_{475} equal to 0.15 g and a plateau up to 0.5 s, one can see that the bridge remains almost in the elastic regime with some moderate cracking (tension) in the arches when the seismic action is applied in the longitudinal direction and at the pier base for the transverse one.

These stress–strain states are still a long way from the collapse of the structure as demonstrated by the nonlinear push-over analyses carried out with the same model. These masonry structures have significant ductility resources, at least three in the longitudinal direction and five in the transverse one. This is something the authors could experience first-hand while rescuing and repairing the famous Sidi Rached bridge, located only few hundred metres downstream.[2,7] The bridge underwent huge displacements (more than 0.2 m) and still serving the city chaotic traffic.

As far as the repaired bridge is concerned, only the elastic analyses were performed. These analyses show that the prosthetic girder reduces the stresses in the masonry part as long as the

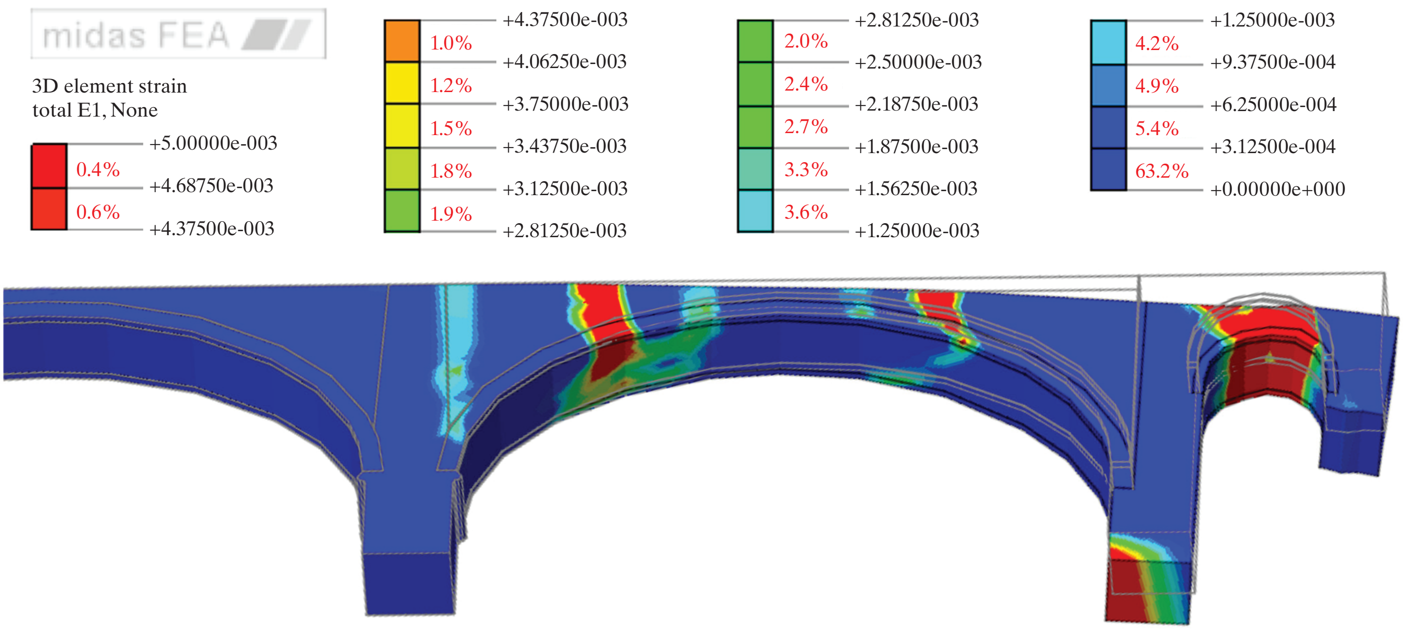

Fig. 4: Total positive (traction) strains, with finite elements percentage, caused by the imposed foundation slippage (Units: [–])

deck is transversally constrained at the left abutment. For this reason, two viscous shock transmitters (couplers) have been installed in the transverse direction on this abutment so as to accommodate further soil instabilities but retaining the deck under dynamic loading.

Thanks to the above numerical diagnoses, we could finally conclude that the reconstruction of the bridge could be structurally feasible and economically convenient, let apart the historical value of the structure, possibly a reason in itself for its preservation and reconstruction.

The Structural Design

The new stayed girder had to be slender and light. The heavier the new deck, the greater the reaction onto the existing structure, both vertical at the pier and horizontal against the standing portion of the masonry deck. The stiffer the new deck, the less it would accommodate for further displacement and the greater the moment it would transmit to the masonry portion.

The new composite deck (*Fig. 5*) is therefore made of two 1.1 m high steel beams. The walking platform is provided by a reinforced concrete slab of 0.12 m only cast on corrugated sheets. This slab is extended 12 m onto the existing masonry deck so as to provide a ductile connection between the new and existing parts of the deck.

Connection of the steel beams to the masonry part is obtained by welding these beams to a 20 mm thick steel plate (flange) concreted and nailed onto the re-profiled end section of the masonry bridge. Although the connection of the steel plate to the masonry portion has been enhanced by 24 steel bars drilled into the masonry part, it can only take limited tangential and traction forces because these rods are drilled only few centimetres into the existing masonry. A longer nailing was deemed unnecessary and difficult to achieve, thus leaving to the overlapping concrete slab the task of providing the additional resistance in case of extreme conditions such as large displacements of the abutment, strong earthquake or failure of the stay system.

The stay system consists of three main elements: the new masts, the stays and the anchorages.

The masts are erected adjacent to the existing pier and are supported on two small plinths founded on micropiles. The masts are made of double T welded steel profiles that are connected to the masonry pier up to the deck level. This allows these masts to be extremely slender as the axial force is small and instability prevented by the connection to the masonry part. In the free standing portion, from deck level to the stay top anchorages, the section is boxed to reduce slenderness and prevent buckling. The two masts are connected to each other via a curved steel x-bracing featuring an Arab arch.

The stays are made of seven galvanized and individually sheathed 0.6″ strands placed inside a PHDE tube. Each stay is anchored at both ends (tower, deck, anchorage blocks). In order to minimize the visual impact of the anchorages on top of the masts, the latter are crowned with a flame-shaped pinnacle.

The stay anchorages could not be attached to the standing portion of the bridge because this would have introduced unacceptable localized stresses in the structure. As a matter of fact, temporary post-tensioning used to secure and strengthen the existing masonry arches during construction has been anchored into the right abutment but the location was geometrically unfeasible for the final anchoring of the stays. Two independent concrete anchoring blocks have been cast on the right bank, each weighing 150 tons. The anchorage resistance was provided by gravity and friction of the blocks themselves plus the pull-out resistance of six D300 mm micropiles drilled 15 m into the ground. A total capacity of 350 tons has therefore been obtained against a maximum stay force (SLE) of 120 tons.

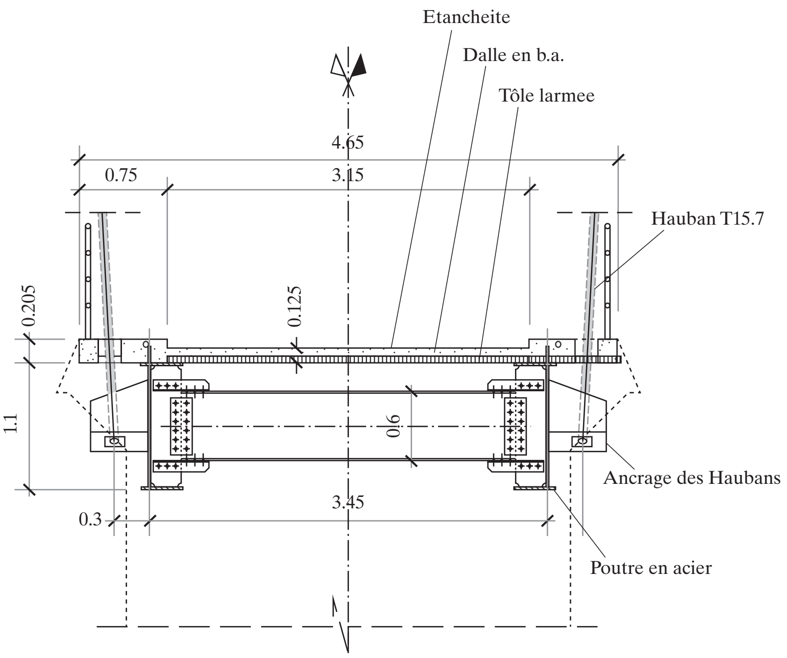

Fig. 5: Cross section of new composite deck (Units: [m])

The Bridge Reconstruction

The steel beams and concrete deck were built using two temporary supports over the 50 m span. No much surprise there as the works could be carried out with an easy access and the possibility to amend the final details of the interface between the stayed steel beams and masonry portion after cleaning and removal of debris. Very interesting is the erection of the stays as the stayed structures can have the characteristics varying from very stiff to extremely flexible. The former are better erected with a force-based approach, similar to the post-tensioned ones, and the latter are better tensioned following a displacement controlled procedure (*Fig. 6*).

The stayed portion of the Student Bridge is extremely flexible and therefore stays tensioning was carried out imposing a tendons shortening and tower tip displacement controlled

Fig. 6: The repaired bridge

schedule. An initial tie back of the mast was imposed by tensioning the back stays (from the anchorage blocks) followed by a subsequent tensioning of the stayed girder. An intermediate control of reactions and stiffness was carried out lifting the deck at the abutment before a final tie back from the anchorages lifted the deck in place.

It should be noticed that tensioning with a force-based approach is always easier since force is what we get at the pressure gauge throughout the whole operations. Unfortunately, a force-based approach cannot be used in flexible structures as there it may lead to severe unbalance and geometry faults but nonetheless checks and force instructions need to be feed to the operator. Therefore, a force-controlled operation is only force controlled, but a displacement-based one is both.

Conclusions

Masonry bridges are very nice structures worth preserving as it is highly unfeasible we will be building much more of them, nor to the technical prowess and architectural grandiosity of the "European Heritage," from "Roman to French Empire," as in the city of Constantine. Masonry bridges are also delicate, especially when subjected to foundation unsettling, be that soil instabilities or riverbed scouring. Interventions aiming at preserving these structures when partially collapsed may be expensive and risky.

The paper presented a solution where an extremely slender stayed prosthesis is added to the remains of a stiff masonry viaduct. Structurally, it makes sense to place yourself at the other end of the spectrum so as to reduce the redundancy and clearly identify the different mechanisms. On site, the solution proved easy to install and erect and it is also economically sound.

There remains the question whether it will last and survive to further soil instabilities, lack of maintenance, vandalism to pure robbery or any other action that comes with time and changing habits. There the effective resilience of the proposed scheme will be told and we will know if it is worth using in similar situations, many indeed, especially because of local riverbed scouring across the European continent.

Acknowledgements

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SEI Data Block

Owner/Client:
Constantine Municipality/Direction Travaux Publics
Designer:
INTEGRA s.r.l., Rome, Italy
Execution:
SAPTA, Algiers, Algeria

Total length of bridge (m):	137
Length of new stay girder (prosthetic) (m):	51
Completion date:	December 2016