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The Kamoro Suspension Bridge in Madagascar

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Abstract

The government of the Republic of Madagascar has been granted a funding by the International Development Association (IDA) for the Projet d'Urgence pour la Préservation des Infrastructures er la Réduction de la Vulnerabilité (PUPIRV). Part of the project consists in renovating the country's main infrastructures. The Madagscar Roads Authority is in charge of managing the subsequent activities. The Kamoro suspension bridge is the most prominent civil engineering site in Madagascar and has been the subject of an important study realized by the present authors. The study consisted in assessing its state of conservation, its residual capacity and providing solutions for guaranteeing its efficiency. The article synthesizes the conducted studies and the structural choices made. Such decisions must absolutely take into account the territorial context in which they will be carried out.

Keywords: Suspension bridge, Cable-stayed Bridge, low-medium span bridge.

1 Introduction

The Madagscar Roads Authority (ARM) is being funded by the World Bank in order to rehabilitate certain strategic bridges along the National Road 4 (RN4). The RN4 links the province and city of Mahajanga in the North-West of the country to the capital Antananarivo. Proceeding in the direction of Antananarivo, a few kilometers after having encountered the traffic coming from the RN6 that comes from the north, there are two major civil structures. After 5 km, there is the Kamoro suspension bridge (Fig.1) and 65 km further there is the truss beam viaduct that crosses the rocky rapids of the Betsiboka river.

The present authors have participated in the assessment and rehabilitation of the Kamoro suspension bridge.

2 The existing Kamoro Bridge

The Kamoro suspension bridge was designed and built in the nineteen thirties by the company led by the French engineer G. Leinekugel Le Cocq (Fig.2), son-in-law of the famous designer and constructor Ferdinand Arnodin (1845-1924), author of many patents in the field of construction [1].

Figure 1. The Kamoro Suspension Bridge

The scheme of the structure was very common at the time, with spans that are nowadays considered small, i.e. between 100 and 250 meters (2). The Kamoro Bridge has a central main span of 206.5 m and a lateral span of 54 m, which is also suspended. The deck has a net width of about 4 m, the two parapet beams are truss structures made of standard I-profiles made by Krupp in the early decades of last century. A ratio equal to 1/100 links the main span of the bridge and the deck height (2m) giving a pleasant slenderness to the structure. The carriageway is made of a metal sheet patented by Arnodin, composed of very thin (4-5mm) tiles displayed side by side, provided with stiffening elements and rested on the transverse beams, which are themselves supported by the main beams in correspondence with the hangers. The suspension system is composed of a range of 12 cables displayed in three layers. The cables are discontinuous and anchored on each tower. Towers are also made out of steel with a pinned base. The hangers are arranged with a regular step of 1.3 m. All the cables and hangers are made from spiral ropes protected by a coat of pitch (cables: 127 wires ϕ3.8mm, hangers: 37 wires ϕ4.1mm). The main cable terminals are made of standard sockets and high strength bars (Fig.3). The bridge (suspension cables) anchorages are realized by underground concrete ballasts.

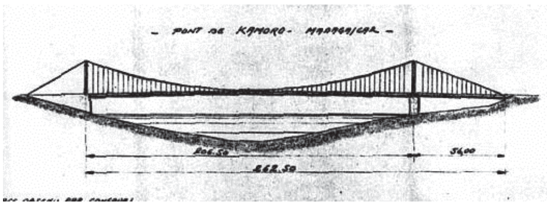

Figure 2. Original sketch of the Kamoro Bridge.

The geometric relation between span/height of the cable is equal to 10, hence the towers are about 22 m high from the bottom of the deck. The cable in the central part of the bridge is practically at the same level as the upper chord of the parapet beams.

The structure of the Kamoro Bridge, the Arnodin sheets apart, is in a rather good condition considering that it is almost 90 years old. The steel deck framework, the parapet truss beams and the transverses only show signs of superficial corrosion, more prominently on the underneath of the bridge, where stagnating water persists abated by the humidity of the river.

Figure 3. Cable anchorages on towers.

The towers' steel structures have a very good state of preservation with only very localised rust stains. The cables' state, on the other hand, is less satisfactory, especially at mid-span where water that trickles down the cables stagnates with oxides and dirt [2] (Fig.4). Lastly, the hangers are generally in a fair state of conservation and show only mild signs of corrosion, mainly located near the lower sockets, due to the accumulation of water in those parts.

As far as the substructures are concerned, (base of the pillars and ground anchorages), the conducted inspections did not reveal notable critical situations.

In order to evaluate the mechanical characteristics and the residual resistance of the suspension system a number of non-destructive structural tests were undertaken, of which the most significant are synthesised below.

For the supporting cables, the goal was to find out the type of steel used and the extent of the corrosion penetration into the steel wires. To do so, some samples of steel wires were collected and subjected to tensile tests (the samples were collected close to the ground anchorages from an already broken wire, most likely damaged due to a mechanical impact given no signs of environmental deterioration was noticed). The results of the tests showed a tensile strength above 1300 MPa with a linear elastic response up to 1000 MPa.

The authors investigated further on the visual aspect of the state of preservation of the cables, it was decided to dismantle a hanger clamp at mid-span, where oxidation tends to occur. As expected, the state of preservation of the steel cables underneath the clamp was worse than on the outer parts. In fact, the covering of the clamp induces a greater deterioration due to stagnant humidity resulting from the water that runs down the cables, and maintains the situation. The investigation showed a clear cortical oxidation state of the steel wires but no ruptured ones.

Regarding the hangers, it was decided to remove an entire element, that is to say, the cable with upper and lower sockets and U shaped connecting bars Once dismantled, the hanger was tested in a laboratory, reproducing the same bearing conditions as the in situ links. The element was submitted to a force 3 times larger than the maximum service tension (15tons) obtaining a perfectly linear -elastic response. Based on the tensile strength found for the main cable wires, the maximum resistance of these hangers may well be above the 30 tons but the authors did not want to perform a destructive test but return the original hanger to the bridge.

Finally, the static analysis was conducted on finite element models of the whole structure. These brought to light satisfactory margins of security concerning the maximum expected overweight. In particular, as far as the steel cables are concerned, assuming the degree of corrosion close to 30%, a security factor superior to 2.5 was obtained; similar results were found concerning the hangers as well as for the main girders.

Figure 4. Detail of corroded cables.

Figure 5. The underneath of the orthotropic deck.

According to the above findings, the proposed rehabilitation aimed at a possible restructuring of the bridge which maintained unaltered the suspension system intervening exclusively on the secondary elements of the deck, the “platelage” which is unrecoverable as is (Fig.5). As far as the main cables and hangers are concerned, an anti-corrosion treatment consisting of the extensive application of a layer protective coating, to counter the further progress of oxidation, has been planned. Clearly, such an intervention does not generate a resolution of the problems for the bridge, in fact the oxidation present on the cables can be removed but they cannot be returned as good as new, one can only attempt to lengthen their lifespan slowing the progress of the corrosion. To definitely solve it, it would be necessary to consider changing all of the cables and hangers. This hypothesis however, due to the geometrical configuration of the cables disposed on three levels, would result in a costly and rather extensive operation, as it is not possible to free one cable at a time from the hangers.

As such, the renovation of the cables of the Kamoro Bridge could only take place with the following two different schemes:

1. Create a provisional supporting grid to hold up the bridge while the whole suspension system is removed and replaced.

2. Create a parallel suspension system to the existing one before removing it.

The first alternative would be expensive and would very likely have a major impact on traffic during the replacement works (there are no viable alternative routes to the Kamoro crossing). Also, the river Kamoro is subject to flooding during the cyclone season, which lasts for a large part of the year. Thus it would only be possible to work over a limited amount of time during the year, with the strong possibility of not being able to complete the works in such a short span of time.

The second possibility, already experimented by the present authors, for the rehabilitation of a similar structure in Algeria [3], plans to place the new suspension system on a vertical plane slightly shifted towards the exterior from the existing suspension system. This requires, though, to modify the deck x-section, having to widen it, which could be profitable for inserting a pedestrian lane.

Both solutions were regarded as too expensive for the small added value they would confer to the bridge. It seemed likely that a 260m one-way bridge, located on the main route between the capital and the north-west of the island, would soon be inadequate for the traffic demand of a fast developing country.

3 The new Kamoro Bridge

In accordance with the considerations reassumed in the previous paragraph, the road management authority of Madagascar has decided to maintain the existing bridge in service by refurbishing it with the minimal required intervention and to make, alongside it, a modern bridge that can efficiently satisfy long term traffic increase.

The designers considered the suspension bridge as being the best choice for the new crossing, eliminating the other solutions on the basis of the considerations written here above.

Eliminating a beam bridge solution, whatever its type, seemed obvious. Considering that the Kamoro bridge is the most important civil engineering structure of the country, it was clear that one couldn’t diminish it by placing alongside it a girder of medium-small span. The solution was also eliminated because of the necessity of foundations in the river bed.

Moreover, the possibility of making a long span beam was pushed aside as the budget didn’t cover the cost of bringing in the equipment which would be necessary for its launching. The deck would also be a lot higher in comparison to the slenderness of the 2m deck (barrier and parapet included).

The only considerable choices were hence the cable stayed and suspension bridges. The cable stayed was finally discarded for two reasons, the first regarded esthetics, and the second technicality. Indeed, the new structure would have presented very high showy towers (nearly double the size of the current ones) which would have hidden the current Kamoro Bridge. Then, it was seen that the construction of a cable stayed bridge required heavier on site equipment for the construction of the deck, whether it was in steel or concrete. Considering the fact that the necessary equipment could be unavailable on the island and that the site accessibility is difficult (the Kamoro bridge is about 150 km away from the nearest port and 500 km away from the main one of Antisiranana - Diego Suarez), the cable stayed bridge didn’t seem right for the dimension of the project. Even though the typology for such spans is nowadays cable stayed (see next paragraph), the choice narrowed into a suspension bridge which can indeed be made with a lot lighter equipment [4] keeping in mind that the Kamoro river can be crossed on foot during dry season.

The design choices were made keeping in mind the following structural criteria. The structure must:

- Be Functional for the future road traffic development/increase;
- Guarantee a long lifespan with the possibility of changing, individually, each element;
- Be easy to plan, i.e. in accordance with the delivery of material and flexible with the installation of the structures;
- Be in keeping with the available budget.

The result gave birth to a structure with the same longitudinal and vertical dimensions as the existing bridge (Fig.6) with 8m wide deck a standard bi-directional two lanes carriageway (Fig.7). Considering the proximity of the existing bridge which is kept in service for light traffic and pedestrians, the absence of sidewalks on the new bridge isn't an issue.

The suspension system will be made with cables placed on a single plane so that they can be replaced separately (the operation was carried out by the authors for a bridge that presented the same type of cable layout [5]). In order to do so, it is also necessary to design clamps which allow the replacement of a single cable without having to release the whole hanger.

Finally, the whole suspension system was designed to allow the use of standard strand cables which are nowadays cheaper and easier to procure compared to spiral ropes that need to be manufactured to measure. For this reasons the hangers are placed perpendicular to the main cables (radial configuration instead of vertical) so as to zero the tangential forces that the clamp must transfer to the main cables. The resulting compression force in the deck is negligible if not beneficial for spans up to few hundred meters. The deck steel framework is formed by a truss structure. The main beams are designed with the exact same height as the existing Kamoro Bridge (2.00m). Unlike the existing bridge, the carriageway is placed above the actual framework. A reinforced concrete slab is used for supporting the carriageway guaranteeing a simpler, convenient and tougher solution compared to an orthotropic steel one.

All steel framework elements have practical sizes i.e. easy to transport even with reduced means (6m maximum length). The bridge will be constructed by segments, each segment being assembled on site by bolted joints. Segments will then be transported to its position at ground level and finally lifted up to the planned deck level. This construction method is permitted when the river becomes very shallow during dry season allowing one to access the river bed easily. The maneuverability of segments is ensured thanks to their small weight (2-2.5 tons). The first segment is lifted at mid-span and the construction proceeds from there towards both banks.

The planned towers are in reinforced concrete providing an economical solution compared to a steel structure. The same concrete towers, crowning with properly shaped and steel plated pier caps do function as saddles for the main suspension cables avoiding costly iron castings. The tower foundations are planned to be supported on micro-piles (60 D300 20 metre long each tower) because of surfacing sandstone formations although large diameter piles cannot be ruled out based on more comprehensive geotechnical investigations to be carried out before the detailed engineer design.

The lateral span, unlike the existing bridge, isn't suspended and is hence supported by two intermediate piers. The presence of these piers doesn't have a significant impact on the river flow capacity since during the rainy season the river flood the whole valley making the section reduction due to these piers negligible. The proposed truss structure for this span is nearly identical to the one used for the main span even though the static scheme is different (22m spans). Lastly, such a solution provides an economical advantage; indeed, the material and construction costs required for the piers are less to the cost of the equivalent suspension system (hangers, clamps, etc.).

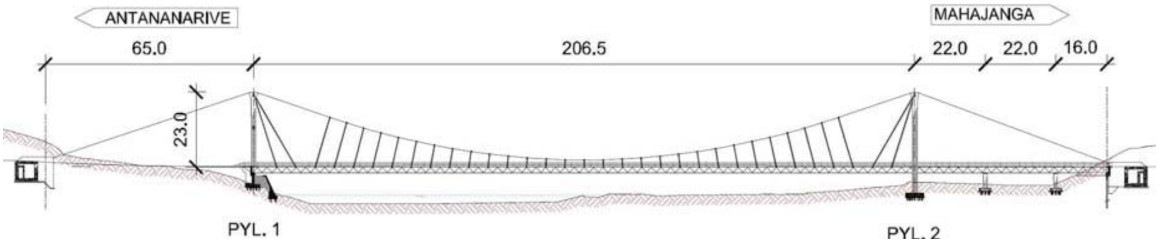

Figure 6. Longitudinal view of the new Kamoro Bridge.

Onshore cable anchorages are gravity type ballasted reinforced concrete caissons dug into the sand and limestone. They are provided with an access to the anchorage jacking chambers in order to always be able to inspect the state of the cable anchorages which are of the standard post-tensioning type.

To conclude, the construction costs of the new Kamoro Bridge should be around 10M USD which corresponds more or less to the available budget granted by the World Bank for this project which is part of a larger development plan for the whole island of Madagascar.

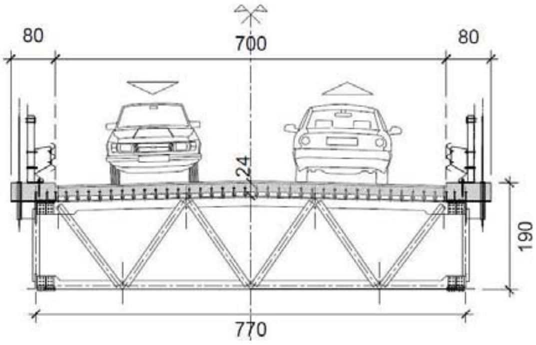

Figure 7. Deck of the new Suspension Bridge.

4 Suspension Bridge vs Cable-stayed Bridge of small-medium span

The following paragraph presents an introduction to the studies the authors are currently carrying out on the performance and cost comparison between cable stayed and suspension bridges. The study aims to assess the performance of the static models and evaluate their material cost. Hereafter are only shown the results of the structural behaviour of bridges with up to 400m long spans, as the full study is still in progress.

The main problem is finding a way to compare such different objects where so many parameters come into play. The author's aim was to fix a large number of these parameters by using standard values taken from representative examples and common experience.

Bridge performance is an easy to obtain and significant numerical value that one can predict in a theoretical way. All other aspects such as foundations, geometry, and aesthetics include too many factors (location, geology, function, personal taste) and so their influence on cost is unpredictable.

The main assumptions are the following:

- To be comparable bridges must have the same geometry (length), the same material (steel) and equal stress state for each element type (e.g. deck, towers)
- The deck cross-section is an idealized I-beam. Its height only depends on the bridge span and is constant along the deck.
- The tower cross-section is an idealized I-beam. Its height depends on its own dimensions.

Overall 4 bridge models were analysed: 2 cable stayed bridges and 2 suspension bridges of respectively 200, 400 main spans (Fig.8).

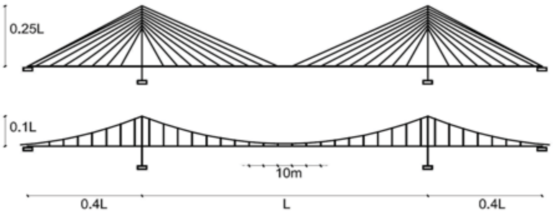

Figure 8. Geometry of models.

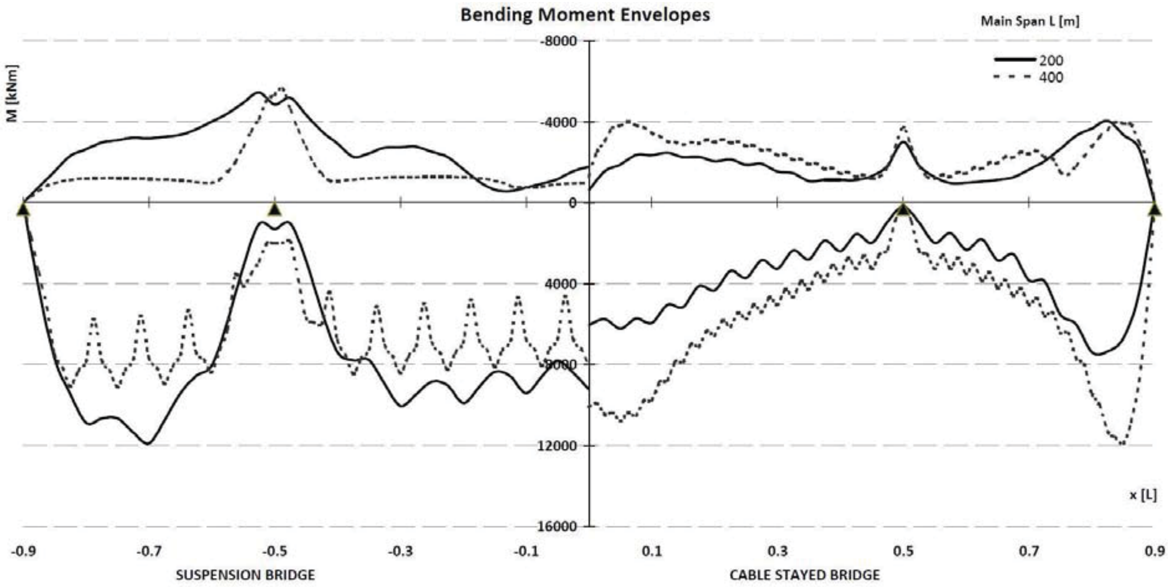

Figure 9. Deck bending moment.

An iterative process allowed us to define cross-sectional properties for the decks and towers that provided equal stress states. An arbitrary value of 200 MPa was set as the maximum stress observable, cable elements apart. The exact same analysis was performed on these models i.e. the response to a moving load of 2000kN distributed over 30m. The obtained results allowed the authors to graph the bending moment envelopes for decks and antennas of each bridge (Fig.7 and 8).

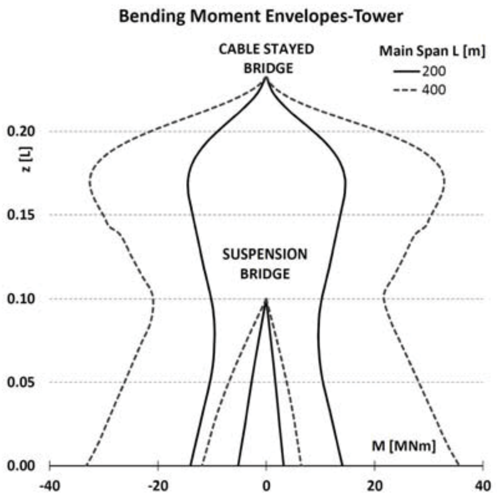

Figure 8. Tower bending moment.

By analysing the behaviour of the deck one observes that until 200m spans suspension bridges have higher bending moments. When one reaches 400m long spans one sees that the situation has reversed. In fact, the increase of the span for the suspension bridge scheme isn't accompanied by an increase of stress. This can be explained by the fact that the cable/deck stiffness ratio increases giving the observed envelope diagram. However its not the case for the cable stayed scheme where dimensions and stress increase together. The behaviour of the suspension then tends to be more uniform than that of the cable stayed bridge. This indicates that a constant deck cross-section is the optimal solution for a suspension bridge.

The most critical point is always located on the lateral span, whether we're looking at the suspension or the cable stayed bridge, where the efficiency of the structure is lower, though for different reasons.

Lastly, observing the towers' diagram one notices how the elevated (nearly double the height of the suspension ones) cable stayed towers are always penalized. The suspension bridge towers for these heights don't exhibit significant second order P-δ effects and behave more like cantilever beams. This however is linked to the initial assumptions made for modeling the structures.

5 Conclusions

One can draw many conclusions from the Kamoro Bridge project whether they are of general nature or about more precise subjects. The old Kamoro bridge is in a very decent state of conservation given its nearly ninety years of age without having had any significant refurbishment interventions except for steelworks painting renewal. It is true the bridge is located in a favourable environment (absence of salinity and substantially dry climate). Such an example is a testimony of how suspension bridges can represent long term solutions for modest needs of up keeping if positioned in the correct environment. Yet, nowadays, thanks to the development of steel protection technologies the environmental conditions don't represent an obstacle to durability.

The construction of small to medium span suspension bridges can a provide a good alternative to cable stayed bridges. Even though the structural performance of cable stayed bridges might be superior, undoubtedly, the suspension scheme offers a relatively simple construction and is aesthetically more slender and pleasant to look at (restrained tower height and bridge span ratio). In developing countries, where the carriageway can still have a small width and it is possible to design light weight decks, suspension bridges represent the only alternative on spans that cannot be made with continuous girders (L>100-150m).

The cost optimization of suspension bridges, considering both construction and maintenance costs, can be controlled by a careful design of constructive details. To sum up, it is, especially desirable to use cables that can be made of standard stay type parallel strands, to display the supporting cables on a unique horizontal plane to facilitate replacement, to make deviation saddles which take advantage of the concrete towers, to limit the weight of the steel deck segments and finally to make the vehicle carriageway by means of a reinforced concrete slab.

The new Kamoro bridge reassumes all these aspects and is a positive example of designing in harmony with the territorial facts of a developing country and proposes real solutions to the encountered challenges.

Finally, the first results of the comparative study between suspended and cable stayed schemes which the authors are currently carrying out, have shown that there isn't a clear structural superiority of one type on the other for small to medium spans. However, today, cable stayed bridges are preferred. One can hence conclude the preferences are more due to esthetical aspects than for purely structural and economical reasons. In the authors opinion though, the softness and transparency of a suspension bridge are and always will be present and pleasant to the eyes of the observer.

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