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STRUCTURAL BEHAVIOR AND DESIGN CRITERIA FOR BRIDGE STRENGTHENING BY TIED ARCH - COMPARISON WITH NETWORK ARCH BRIDGES

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Abstract: *This study focuses on a new strengthening method of continuous bridges with several spans that present extensive damage in their foundation/piers due to scour and erosion. The method consists on the construction of a new upper steel arch with a network hanger's arrangement over the original deck with the aim to hang the existing deck to the new arch. The deck is acting as a tie in the new structural configuration. This allows to remove the damaged foundations/piers, deriving on an arch bridge with a span-length similar to the total length of the strengthened bridge and avoiding future problems related to scouring. The paper discusses the resisting mechanisms that control the structural optimization process and therefore define the design criteria. The main target of this process is different for each case, namely: the optimization of the arch in traditional network bridges; the limitation of maximum and minimum stresses in the deck in the case of strengthened bridges. Finally, it allows the comparison of each case, setting the differences between them and providing a new line of research on the topic of the tied arch method.*

1 INTRODUCTION

The network arch bridges are a typology where hangers are inclined and cross over other hangers at least twice. This bridge type has developed in the 40´s of the XX century looking to improve the structural behavior of the tied arch bridges with vertical and Nielsen hanger arrangement, due to the reduction of the amount of material and economic costs.

The optimization of this typology allows to reduce the dimensions of the arch and deck, provoking a slender structure, with a high aesthetic appearance and an adequate integration with the environment.

These characteristics just have been recognized in the last decades, generating a development related to research, design and construction of these bridges at many locations in Europe, USA, Asia and Latin America [1].

The research on new network bridges is focused on the structural behavior, parametric design, buckling analysis, dynamic behavior, earthquake resistance and construction method by locations [2].

The new lines of research are focused on strengthening and rehabilitation of bridges, using the tied arch as an element applied over the old decks. This technique is applied when it is necessary to eliminate a pier due to problems of scour/erosion or when the location condition requires to increase the horizontal clearance.

2 GENERAL BEHAVIOR OF TIED ARCH BRIDGES

The tied arch bridges are composed by an arch, acting as an upper chord, a deck as a lower chord and a hanger arrangement, connecting both chords, producing a behavior similar to a truss system.

The main internal force in the bridge is the axial compression in the arch, without inducing a horizontal reaction at the abutments due to the use of the deck as a tied system, from the edge of the arch along the entire element (rigid longitudinal diaphragm).

This condition produces vertical reactions at the support system (abutments), allowing a simple and traditional design of support, quite similar to simply supported bridges.

The system behavior in Nielsen and Network Bridge is very similar to a truss bridge. However, this condition is not achieved when the hanger arrangement loses tension, causing significant bending moments in the arch and deck.

3 TARGET DESIGN

The main target design of tied-arch bridges is the optimization and reduction of usable material. The cost is reduced significantly when the hanger arrangement has been modified from vertical type to network. This process minimizes bending moments in the arch and deck, allowing to reduce the arch profile. Therefore, an adequate control of in and out plane buckling, and an efficient stiffness in the plane allow to optimize the structure.

For that reason, the design of a new tied-arch bridge, at any state (construction and service) and any load scenario, should focus on reducing the bending moments in arch and deck.

The network arch bridge achieves, adequately, this purpose, due to the action of the cross hangers producing: a) Small length between supports, at the arch and deck; b) Reduced buckling length; c) Continuous support system quite similar to Winkler type, avoiding problems of concentrated loads (truck effects) and losing of tension in the hanger.

Therefore, in new design tied-bridge, the focus of the optimization process is the reduction of internal forces (mainly bending and shear) in the arch.

4 STRENGTHENING BRIDGES USING TIED-ARCH

One of the main problems in bridges is the scour at its piers, especially when the bridge is located over torrential rivers. The study of [3], presents an alternative of strengthening by placing a bowstring arch with a mixed arrangement of hangers (vertical and sloped). In such a manner, the original deck is conserved being lifted by the vertical hangers, allowing unlink the deck from the piers. This situation allows to remove the piers, generating a unique free span between abutments, avoiding future scour or undermining problems (Figure 1).

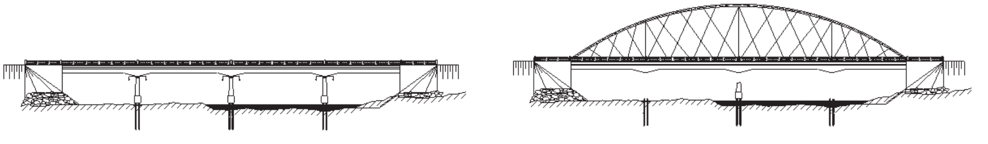

Figure 1: Initial and Final stage of strengthening process

Currently, the line research is focused on the short to medium span continuous concrete beam bridges (very common in Latin-America), with a design optimization on the conservation of the deck.
The method of strengthening considers: the placement of a steel arch over the deck; the unlink between deck and piers; application of external prestressing on the deck; placement and sequential tensioning of the vertical hangers located over the original supports; placement of sloped hangers (network type); lifting of the deck and tension adjustment of the sloped hangers.
This method looks to keep stress state quite similar to the original condition, i.e., positive bending moments at the spans and negative bending moments at original supports. This is most relevant when the reinforcement details of the existing load-bearing elements are unknown.
The load-bearing system is very similar to a bowstring bridge, i.e., the arch and deck acting as upper and lower chords, respectively, generating a closed resistance system. For this, the hangers are responsible to transmit the forces between chords, in order to produce a static system of simple support.
Despite similar geometry and overall aspect, some differences arise between the structural performance of new design or strengthened bridges, mainly due to the presence of the vertical hangers in the location of the removed piers to lift the deck.

5 STRUCTURAL BEHAVIOR: STRENGTHENED AND NEW BRIDGES

The load-bearing mechanisms between new and strengthened bridges are different, mainly due to the construction process and the goal of the optimization procedure, namely:

a) New bridge: arch profile optimization.
b) Strengthened bridge: deck optimization, in order to keep the original stress state. The internal forces in the strengthened deck should be as similar as possible to the original multi-span continuous deck

The analysis of these two cases summarizes and compares the final results obtained in [1] and [3] for new and strengthened bridges respectively.

5.1 Main load-bearing mechanisms: Internal forces at arch and deck

a) Axial force in the arch

New bridge: The axial compression force in the arch depends on the sag ratio. It is steady when uniform loads are applied.

Strengthened bridge: The axial force is influenced by the sag of the arch, being more significant than in the case of the new bridge due to the presence of the vertical hangers.

The presence of the vertical hangers generates variable axial forces, with abrupt changes at the location of these hangers. This situation is quite similar to a new network bridge with a non-symmetric load permanently applied. It generates a non-uniform bending moment with increased values at the location of the vertical hanger. The maximum value of bending moment occurs when a concentrated load, during service, acts at the location of the vertical hangers.

b) Bending moment in the deck

New bridge: The internal forces are similar to the behavior of a beam supported on elastic bearings.

Strengthened bridge: The internal forces in the deck are similar to the behavior of vertical fixed supports of a continuous beam, with a distributed elastic support between them (Figure 2). The axial force in the arch is different than in the deck. This difference is more pronounced at the areas of vertical hangers.

For this reason, at the strengthened bridge tension should be applied to the network hangers after lifting the deck. This process allows adjusting the structural behavior, as a new bridge, due to a more homogenous distribution of the hangers, allowing a reduction of the bending moment at the chords location.

On the other hand, the network arrangement reduces the peaks of the negative and positive bending moments. When the axial force at a network hanger is increased, the bending moment is disturbed (steps) following the path of a continuous beam system.

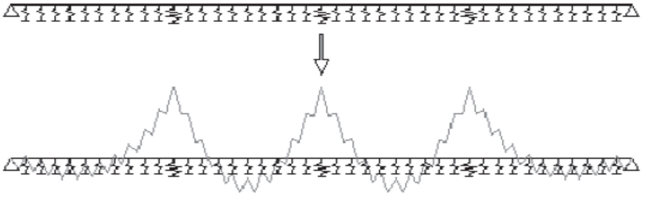

Figure 2: Bending moments of a continuous beam system strengthened by tied arch.

The deflection of the deck is controlled by the tension of the network hangers, using as base line the deflection produced in the lifting process of the deck (according to sequence and magnitude).

c) Continuity between arch and deck

An edge effect occurs when an embedment (continuity) between arch and deck is provided, avoiding a relative rotation between them. The arch limits the downward rotations of the deck, producing a negative bending moment in the deck and a positive bending moment in the arch.
New bridge: The bending moments in the arch control the design. The effects in the deck are not significant.
Strengthened bridge: The design criterion of the arch is controlled by the bending moments ensuing in the vicinity of the vertical hangers, not at the edge of the arch.
The deck is the controlling element. It should be verified according to the resistance provided in the original deck. If this is not known, it is necessary to avoid exceeding the threshold tension of the original deck.
The edge effect produces a stress problem in the deck (fixed parameter) due to its original design as continuous beam system (therefore with bending moment equal to zero in the abutments). For that reason, this effect is critical and controls the strengthened bridge design. Finally, it is required to construct an alternative joint between arch and deck in order to reduce this effect.

d) Transverse beams

The transverse beams are located over the supports, when an adequate transversal distribution of the concentrated loads or lateral loads (wind, earthquake, others) is necessary. In both cases (new and strengthened bridge), these beams are an active and principal element. No major difference exists between newly designed and strengthened bridges.

e) Frame effect

The frame effect produces a bending moment at the joint between the arch and the deck.
New bridge: The arch is a critical element due to the slenderness of the arch profile. Therefore, the use of an exempt arch (without transversal bracing) is not recommended.
Strengthened bridge: The design of the arch is not critical. The load induced by the vertical hangers for the lifting operation requires a sturdy arch profile. Therefore, the design criteria are defined by the lateral loads.
In the strengthened case, the mass of the deck is bigger, reducing the effect induced by the lateral loads (seismic), due to the greater collaboration of the mass inertia of the deck.
Additionally, this type of deck stabilizes the system against the overturning due to the lowering of the gravity center of the structure.

f) Network hangers

The axial force in network hangers follows a uniform behavior for symmetrical loads.

New bridge: Solely the hangers located at the ends of the arrangement have different axial force.
Strengthened bridge: A uniform axial force in hangers is obtained after the "network tension phase" is applied. This phase corresponds to a tension process in the hangers with forces obtained by the code TEMEGA [4], once the lifting process is completed.
During the lifting phase, the strengthened bridge resists asymmetrical and symmetrical loads, so that only the hangers placed at the end of the arrangement remain active.

g) Concentrated loads

A concentrated load applied at the mid-span of the deck produces tension increase in some hangers and relaxing of others (passive condition). The tensioned hangers are those which are positioned on the deck close to the applied concentrated load.
New bridge: The applied load is gravitational during construction and controlling that all network hangers remain in tension is an easy task.
Strengthened bridge: The vertical hangers, during the lifting phase, produce an upward concentrated load on the structure. Due to these vertical loads some hangers are tensioned (active) and others are in passive condition (loss of tensioning force).

h) Truss Effect

The truss effect is induced by the network hangers. It is possible to simulate the deck and arch as the upper and lower chord of a truss, with bending moment's resistance of the deck greater than that of the arch. The hangers act as diagonals, transferring the flow of forces produced by concentrated loads.
New bridge: The maximum and minimum axial forces of hangers are conditioned by the deformation of the arch, depending on the relative displacement between the arch and deck. This condition is the design criteria for choosing the hanger's cross-section area.
Strengthened bridge: The truss effect considers a deflection of arch and deck. The deflection is bigger during the lifting process, inducing maximum tension in the network hangers. The hangers near the longitudinal edge of the bridge have the larger forces. However, this increase is not critical. The design criteria is controlled by the ratio between the vertical and network hanger's areas.

i) Longitudinal deflection

As in a new bridge, a strengthened bridge presents a longitudinal deflection bounded by the elongation stiffness of the deck. This deflection induces tension in the deck due to the application of gravitational loads. For that reason, it is necessary to place an external prestressing cable in the deck in order to get a tied response, allowing to close and balance the system of forces in the bridge. This element avoids the horizontal reactions at the abutments, reducing their dimensions. However, the accidental loads (earthquake) are not well countered by the tie, provoking thrust at abutments and longitudinal movements at the bearing supports.

j) Shortening of the arch

New bridge: Larger compression in the arch produces a longitudinal shortening of the bridge with a movement to mid-span, with maximum at the quarters of the bridge. Additionally, it generates a vertical movement with its maximum at the crown of the arch.
Strengthened bridge: The behavior is similar to new bridges. However, these displacements are overlapped with the lengthening of the arch and the deflections obtained in the lifting process. For that reason, the maximum horizontal displacement is not located at the quarters of the bridge span, but rather at the position of the vertical hangers.

k) Deflection

New bridge: The behavior under live loads is quite similar to an isostatic beam with maximum vertical displacement at mid-span and zero at the supports.
Strengthened bridge: The vertical deflection is overlapped with the deflection obtained in the lifting process. Consequently, the maximum vertical deflection is defined by the sum of deflections during the construction process (optimized by TEMEGA code) and deflections due to service loads (live loads), provoking a higher reduction of deflection at mid-span, than in new bridges.

5.2 Secondary Resisting Mechanisms

Some secondary mechanisms in new bridges become principal mechanisms (controlling criteria) for the case of strengthened bridges.

a) Axial forces in hangers

New bridge: The variation of tension between hangers generates a non-continuous variation of the axial force in the arch and deck. The distribution depends on the slope of the hangers. However, this effect is not relevant due to the reduced horizontal component of the force.
Strengthened bridge: The effect induced by tension of network hangers is similar to new bridges. However, the variation of axial effort on the arch and deck is larger, because the network phase generates an increase of the axial forces in hangers. Additionally, there is an overlapping effect of vertical hangers in the distribution of the axial forces, inducing significant disturbances in internal forces with a stepped path.

b) Shear Effect

Shear effect in hangers occurs when a concentrated load is applied. For this reason, it induces in the arch a mixed load state (concentrated and distributed load). This generates a bending moment with alternating sign.
This effect is significant in strengthened bridges during the lifting process, resulting in only a few active hangers before network phase. In the same manner, when the network phase is applied, it induces tension in the network hangers, provoking bending moment distribution in the arch modified over the line path defined by the action of the vertical hangers.
This explains the superposition effect, namely, the main internal forces are defined by the vertical hangers and the secondary effect is produced by the shear of the network hangers, quite similar to individual loads within the structural system of a new network bridge.

6 CONCLUSIONS

It has been shown in the paper how, despite many similarities in the shape of new and strengthened network arch bridges, important differences should be considered. As example:

- The design criteria and structural behavior of a strengthened bridge by tied-arch are controlled by the strength capacity of the existing deck. The reuse of the deck from a continuous beam and the construction method (lifting the deck and tension of the hanger) converts the deck, and not the arch, as the main element of the structural system and controls the optimization process.
- The strengthened bridge, following the continuous beam system, presents significant bending moments, negative at vertical hangers and positive in span.
- It is recommended to use two groups of hangers, namely: vertical, in order to produce the lifting of the deck and inducing the negative bending moments in the deck, replacing the original supports (piers zone); network, in order to resist the service loads and modulate the bending moment in the arch.
- This condition defines the structural behavior of the strengthened bridge. It requires placing an arch (centered or two lateral according to the width of the deck) with size profiles greater than in a new original network bridge, due to the increase of the in-plane bending moments, similar in magnitude to transverse bending moments of a centered arch.
- The joint system between hangers and arch is the same in original network and strengthened bridge, however the joint between hangers and deck is different, due to the reuse of the original deck.
- The tensioning of network hangers is developed in order to optimize the use of elements. This tension induces a disturbance of the bending moment distribution in the deck, that resembles a beam resting on elastic supports (network hangers), with a few rigid supports (vertical hangers).

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