Movable and launched bridges: recent realizations and improved techniques

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Abstract

Most bridges are fixed structures designed to provide continuity in roads, railways or any other kind of network systems. Nevertheless in some cases the design of the bridge or traffic requirements at the bridge’s location involves some level of mobility to the structure. In this paper, two examples of non fixed structures, namely movable bridges and launched bridges, are described. In both cases several examples are posed and the circumstances related to the conception and the design of these constructions are described.

Keywords: movable structures, launched bridges, innovative bridge design, design optimization.

1 Introduction

Most bridges are fixed constructions, designed to provide continuity in highways, railways or any other class of network systems. Nevertheless in some cases these structures are required to modify their geometry to allow some traffic below or across them. This circumstance complicates the design process as the structure needs to be stable and safe not only in its usual shape but also in its modified position.

These kinds of bridges, entitled movable bridges, have been erected in several countries in recent decades. There are several means to design a movable bridge and they will be described in the following paragraph.

Another class of bridge that contains the necessity of being translated before it stands in its final location is the so-called launched bridge. These structures are built not far from their position but they have to be rotated or translated from the construction site to their definite spot. Due to the capability of these structures
they have captured the interest of practitioners and researchers [1–4] with the aim of using the most up to date design methodologies in the design of these structures.

2 Movable bridges

There are several classes of movable bridges [5], depending on the type of displacement carried out to modify the location of the bridge. The more frequently used versions are:

- Bascule bridges
- Swing bridges
- Vertical lift bridges
- Tilt bridges
- Convertible bridges
- Folding bridges

a) Bascule bridges: These bridges move because they have hinges at both ends that allow a rotation from a horizontal axis perpendicular to the traffic direction of the bridge. They are very usual in harbors. Some examples are the Leon de Carranza Bridge in the bay of Cadiz (Spain) or the Galata Bridge in Istanbul (Turkey). Also, two more bascule bridges recently built in Spain are presented in Figure 1.

![Figure 1: Examples of bascule bridges: a) Barcelona Harbour, b) Valencia Harbour.](image)

b) Swing bridges: These bridges rotate with respect to a vertical axis. It can be located at one end of the structure or in the middle. Sometimes the span of the movable bridge can be very long. The El Ferdan Bridge over the Suez Canal has a main span of about 300 m. More recently the floating and swing bridge in the Osaka Harbour in Japan has a main span of 280 m. Other examples are the Sungai Prai River Bridge (Malaysia) or the Shatt-Al-Arab Bridge (Iraq). Figure 2 shows some pictures of this class of bridges.
c) Vertical lift bridges: These bridges modify their regular geometry by lifting vertically one or more spans. The Guaiba River Bridge at Porto Allegre (Brazil) and the Hawthorne Bridge (USA) belong to this typology. Recent examples include the Chaban Delmas Bridge, shown in Figure 3 and inaugurated in 2013 in Bordeaux (France) with a very innovative design.

Figure 3: Example of vertical lift bridge. Chaban Delmas Bridge: a) view of the bridge, b) bridge after central span lifting.

d) Tilt bridges: This version of movable structures rotates with respect to a horizontal axis in the longitudinal direction of the bridge. Such movement produces a drastic change in bridge geometry. A recent example can be found in the Millennium Bridge in Newcastle (U.K) shown in Figure 4.
Figure 4: Example of a tilt bridge. The Millennium Bridge in Newcastle (UK): a) bridge view, b) bridge in tilted position.

e) Folding bridges: They are draw bridges with some hinges at intermediate locations of the span that allow segments of the bridge to fold. They are not very common but the visual impact produced by the folding mechanism is astonishing. Figure 5 shows a bridge of this kind in Kiel (Germany).

Figure 5: Folding footbridge in Kiel (Germany): a) view of the bridge, b) bridge during folding.

Figure 6: Elevable footbridge at Duisburg (Germany): a) deck after elevation, b) footbridge view.
f) Elevable bridges: This version of movable bridges differ from vertical lift bridges. Instead of translating vertically the span a constant magnitude each point of the bridge is displaced a different value and thus changing the longitudinal shape of the elevable span. An interesting example in the footbridge at Duisburg, shown in Figure 6. That structure is a suspension footbridge with two pylons at each end that are hinged at the bottom. By introducing an additional force at the cables the pylons rotate and raise the main cable what leads to a vertical displacement of the footbridge deck as shown in the figure.

3 Launched bridges

Bridge construction by launching procedures is a usual solution when the structure crosses over deep valleys or not accessible locations, in general. In that case the bridge is built in one side, or half bridge is made at each end. Then the structure is translated longitudinally until placing it in its final location. The most common version of launching is the Incremental Lauching Method (ILM) that consist on building a segment of the bridge deck and afterwards moving forward the structure. The procedure is repeated several times until the full bridge is completed.

In order to diminish the value of bending moments in the bridge deck during launching a device named launching nose is placed in front of the deck. This device is a steel structure much lighter than the bridge deck and its proper size is very important for the efficiency of the construction procedure. Examples of bridges built by ILS system with concrete and composite decks are presented in Figure 7.

![a)  
Figure 7: Examples of bridges built using ILS: a) concrete deck bridge, b) bridge with composite deck.

A recent example of launched bridge is the Millau viaduct, in France. It is a continuous cable stayed bridge with seven towers and spans of 342 m length. The bridge has steel deck and was built from both sides of the valley by assembling deck segments and launching the structure over neoprene-Teflon bearings on the top of the intermediate piers. A short launching nose was
installed at the front of the bridge because the tip of it was connected to the top of a tower that was built at the beginning of the bridge construction and collaborated in decreasing bridge deflections and bending moments distribution. Some details of the bridge after completion and at different stages of the construction are shown in Figure 8.

![Figure 8: Millau Viaduct: a) view of the bridge, b) launching nose at a temporary pier, c) towers on temporary and final piers, d) bridge under construction with only two towers.](image)

### 4 Launching nose optimization is prestressed concrete bridges

The problem of finding out an efficient length for the launching nose was first studied by Rosignoli [6]. The problem was formulated defining the following parameters:
- \( q_n \): launching nose unit weight,
- \( E_n I_n \): launching nose bending stiffness,
- \( L_n \): launching nose length,
- \( q \): deck unit weight,
- \( E J \): deck bending stiffness,
- \( L \): deck span length.
In the literature, $L$ is commonly considered to be same for all bridge spans. Defining the launch progression by the distance $x$ measured from the front end of the deck to the foremost pier $B$ and the dimensionless parameter $\alpha = x/L$, two phases are established during each launching stage as presented in Figure 9:

- **Phase 1 (Figure 9.a):** $0 \leq \alpha < l - L_n / L$
  During this phase, the frontal part of the deck and the launching nose constitute a cantilever, and the bending moment at support $B$ can be calculated as a statically determinate structure.

- **Phase 2 (Figure 9.b):** $l - L_n / L \leq \alpha \leq l$
  During this phase, the launching nose reaches and passes over a new pier $A$, which is ahead of support $B$. The bending moment at support $B$ must be calculated by solving the statically indeterminate nose-deck structural system. As an approximation, the number of equal spans behind support $C$ is assumed to be very large to assimilate the system to a continuous beam with infinite spans.

![Figure 9: Phases in launching procedure: a) cantilever phase, b) continuous beam phase.](image)

For the specific case when $q_n/q = 0.1$, Rosignoli found out using a trial and error method that the best length for the launching nose was $L_n/L = 0.65$ as it made equal the maximum value of bending moment at point B in both launching phases as it can be seen in Figure 10.

![Figure 10: Bending moment MB during launching procedure.](image)
It can be observed in this figure that the relative stiffness between launching nose and bridge deck must be \( \frac{E_n \cdot I_n}{E \cdot I} > 0.2 \) or other ways the maximum value of bending moment during the second phase of launching will appear before the end of the procedure which is undesirable.

The same problem has been solved as an optimization problem as follows:

- **Design variables:** \( \alpha = \frac{x}{L} \), \( \alpha_L = \frac{L_n}{L} \), \( \alpha_{El} = \frac{E_n \cdot I_n}{E \cdot I} \)

- **Objective function:** \( \min \max [M_B^{\text{phase1}} (1 - \alpha_L) = M_B^{\text{phase2}} (\alpha)] \), where \( M_B^{\text{phase1}} \) and \( M_B^{\text{phase2}} \) are the evolution of bending moment at support \( B \) in Phase 1 and 2 respectively.

This optimization problem can be solved by an equivalent formulation as

\[
\min F = [f_1 - f_2]^2
\]

subject to constraints

\[
1 - \alpha_L \leq \alpha \leq 1 \quad \begin{cases} g_1 = 1 - \alpha_L - \alpha \leq 0 \quad 0 \leq \alpha_L \leq 1 \quad 0 \leq \alpha_{El} \leq 1 \\
0 \leq \alpha \leq 1 \end{cases}
\]

where

\[
f_1 = M_B (1 - \alpha_L) / q \cdot L^2 \quad f_2 = M_B (\alpha) / q \cdot L^2 \quad 1 - \alpha_L \leq \alpha \leq 1
\]

The solution obtained is presented in Figure 11 and corresponds to the following numerical values

\[
\alpha = \frac{x}{L} = 0.924 \quad \alpha_L = \frac{L_n}{L} = 0.666 \quad \alpha_{El} = \frac{E_n \cdot I_n}{E \cdot I} = 0.323 \quad \frac{M_B}{q \cdot L} = 0.1003
\]

**Figure 11:** Optimum values of MB for \( q_n/q = 0.1 \).
Insight considerations on this problem allowed to find that the formulation stated by Rosignoli could be improved because:

- Perhaps the optimum could be obtained just by diminishing the maximum bending moment during the launching.
- Perhaps the formulation needed to include the value of bending moment at support C.
- Perhaps the formulation should be made considering not the values of the bending moments but the stress values top and bottom fibres in the concrete deck.
- Perhaps the formulation should include the distribution of bending moment inside the bridge front span, that have values of opposite sign to the bending moments at the supports.
- Perhaps the formulation should include a relationship between the unit weight and the length of the launching nose.

A case with the following numerical values was used by Fontán and Hernández [7] to formulate the optimization problem considering the full set of considerations aforementioned.

$L = 50m; \; q = 150kN \div m; \; W_i = 5.01m^3; \; W_s = 7.58m^3; \; k_m = 0.018; \; k_M = 0.030$ \tag{5}

being $W_i$ and $W_s$ the strength modulus at the bottom and top fibers of the deck

$$k_m \leq \frac{q_n}{L_n^2} \leq k_M$$ \tag{6}

The formulation of the problem becomes

- Design variables: $\alpha = x / L , \; \alpha_L = L_n / L , \; \alpha_E = E_n \cdot I_n / E \cdot I , \; \alpha_q = q_n / q$
- Objective function:

\[
\text{min max} \left[ \frac{M_B^{\text{phase}1}(0)}{W_s}, \frac{M_B^{\text{phase}2}(\alpha)}{W_s}, \frac{M_C^{\text{phase}1}(0)}{W_s}, \frac{M_C^{\text{phase}2}(\alpha)}{W_s}, \frac{M_{BC}^{\text{phase}1}(0)}{W_s}, \frac{M_{BC}^{\text{phase}2}(\alpha)}{W_s} \right] 
\tag{7}
\]

This $\text{min max}$ problem, is solved by defining a new design variable $\gamma$:

$$\min \alpha_{\gamma}$$ \tag{8}
subject to the followings constraints:

\[ g_1 = \frac{f_1}{W_s} - \alpha_\gamma \leq 0 \quad g_2 = \frac{f_2}{W_s} - \alpha_\gamma \leq 0 \quad g_3 = \frac{f_3}{W_s} - \alpha_\gamma \leq 0 \quad g_4 = \frac{f_4}{W_s} - \alpha_\gamma \leq 0 \]

\[ g_5 = -\frac{f_5}{W_i} - \alpha_\gamma \leq 0 \quad g_6 = -\frac{f_6}{W_i} - \alpha_\gamma \leq 0 \quad g_7 = -\frac{f_7}{W_i} - \alpha_\gamma \leq 0 \quad 10^{-2} \leq \alpha_\gamma \leq 10^2 \]

\[ 1 - \alpha_L \leq \alpha \leq 1 \quad g_8 = 1 - \alpha_L - \alpha \leq 0 \quad 0 \leq \alpha \leq 1 \quad g_9 = \frac{k_m}{q} \cdot (L \cdot \alpha_L)^2 - \alpha_q \leq 0 \quad 0 \leq \alpha_q \leq 1 \]

\[ g_{10} = \alpha_q - \frac{k_M}{q} \cdot (L \cdot \alpha_L)^2 \leq 0 \quad 0 \leq \alpha_L \leq 1 \quad 0 \leq \alpha_{EL} \leq 1 \]

where \( f_1 \) and \( f_2 \) are as defined in Eq. (3), with:

\[ f_3 = \frac{M_C(0)}{q \cdot L^2} \quad f_4 = \frac{M_C(\alpha)}{q \cdot L^2} \quad f_5 = \frac{M_{AB}(0)}{q \cdot L^2} \quad f_6 = \frac{M_{BC}(0)}{q \cdot L^2} \quad f_7 = \frac{M_{BC}(\alpha)}{q \cdot L^2} \]

The solution is presented graphically in Figure 12. The numerical results are

\[ \alpha_L = 0.748 \quad \alpha_{EL} = 0.092 \quad \alpha_q = 0.168 \]

\[ \frac{M_B}{q \cdot L^2} = f_2 = 0.1103 \quad \text{at} \quad \alpha = 0.588 \quad \frac{M_C}{q \cdot L^2} = f_3 = 0.0931 \quad \text{at} \quad \alpha = 0 \]

Figure 12: Optimum values of \( M_B \) in the enhanced formulation of optimization.
5 Conclusions

In some circumstances bridges are not fixed structures standing in the same location. Traffic requirements may lead to the design of movable bridges. In fact this class of structures has become more usual and fashionable in recent years. Some examples have been included in this paper.

Bridge launching is a procedure that contains the idea of translating the structure from an initial construction site to the final location of the bridge. This procedure requires temporary devices, namely the launching nose that must be optimized to make efficient bridge sizing for bending moments.

References