CONTEMPORARY CONCRETE ARCH BRIDGES

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SUMMARY

Concrete arch bridges are regaining their place in public works, responding to a society that values aesthetics, that provides ever more powerful construction equipment, that knows better the behaviour of high capacity concrete and that is able to monitor with great precision the construction of bridges.

A brief history of concrete arch bridges built in the 19th and 20th Centuries is presented before addressing the mains features and successes of concrete arch bridges at the turn and beginning of the 21st Century.

Keywords: *Concrete arch bridges, construction technology.*

1. INTRODUCTION

Concrete arch bridges are again getting their deserved place in the options of both public authorities and structural designers, first because society values very much natural landscape, second because construction equipment are more and more powerful, third because rheological behaviour of high capacity concrete are better known and duly taken into account, and fourth because structural monitoring technology has evolved tremendously.

Construction methods and technologies in arch bridge construction were mostly developed in the second half of the 19th Century and in the first half of the 20th Century, respectively for iron and steel bridges and for concrete bridges. Names of Gustave Eiffel, Robert Maillart and Eugène Freyssinet may be highlighted, but many other brilliant constructors and designers are present in our minds.

All materials resist more to compressive stresses, unless if forming a structural element liable to instability. Obviously, instability is not present in structural elements under tension. Typically, instability is well controlled by increasing the instability efficiency of the cross-section of the structural element. Instability is also controlled by limiting the free length of that individual structural element. It is in “playing” with those two ways of instability control, together with the choice of the most convenient structural material for every structural element, that different types and geometries of arch bridges were developed. Obviously, the ideal structural material would be that displaying high resistance both to compression and to tension, at the same time being inexpensive and durable. If it were not for its higher cost, steel would be the “ideal” structural material, especially since modern paintings overcome partially the steel corrosion weakness. However, for structural elements under compression, concrete is clearly the winner because of its much lower cost, in spite of its complex rheological behaviour. Notwithstanding, these conclusions become questionable when construction conditions, site requirements and construction time are called into the decision.

Those are the arguments and contra-arguments implicit in the evolution of arch bridges. In this keynote, only concrete arches under the deck are considered.

2. THE STRUCTURAL ARCH

Regardless of the structural material, arches aim at working solely in compression when under permanent loads. This objective requires the study of the arch “optimum” shape (antifunicular geometry) and, in the case of a concrete arch, the minimization of the imposed deformation effects (elastic deformation, shrinkage and creep).

Three-hinged arches are isostatic structures that secure the latter objective, but the arch geometry is difficult to sustain as designed. Two-hinged arches are better for their geometry persistence, but they are no longer isostatic structures and imposed deformation effects develop. Hinged concrete arches were the common solution in the first half of the 20th century, but because durability and maintenance of hinges were serious shortcomings, no-hinged arches took over as soon as the reinforced concrete technology improved sufficiently.

Freyssinet designed the three arches of the Veurdre-sur-Allier Bridge (Fig. 1) as three-hinged arches. The bridge, built in 1912 and destroyed in the Second World War, is a superb masterpiece. However, important deformations were identified in the first year of service. The shortening of the semi-arches were compensated with jacks, and the central hinges were eliminated.

Fig. 1. *Veurdre-sur-Allier Bridge (72.50 m central span, built in 1912).*

Live loads inevitably generate bending moments in the arch, but their values in the case of heavy concrete arches do not create problems, and several concrete arches were built with no reinforcement (Fig. 2).

Fig. 2. *Bridge over River Tua – Portugal, 80 m span, designed by Franco e Abreu and built in 1939.*

3. CLASSICAL CONSTRUCTION METHODS

Concrete arches were built initially over temporary timber structures, either supported on the ground or masterly supported on the slopes (Fig. 3).

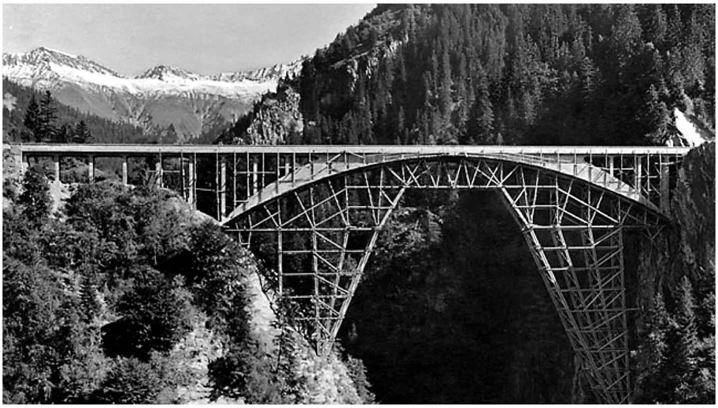


Fig. 3. *Salginatobel Bridge – Switzerland, 90 m span, designed by Robert Maillart and built in 1930.*

The “navigating” scaffolding conceived by Freyssinet for the construction of the Albert Louppe Bridge (Fig. 4) deserves to be evoked, for it is a masterpiece by itself.

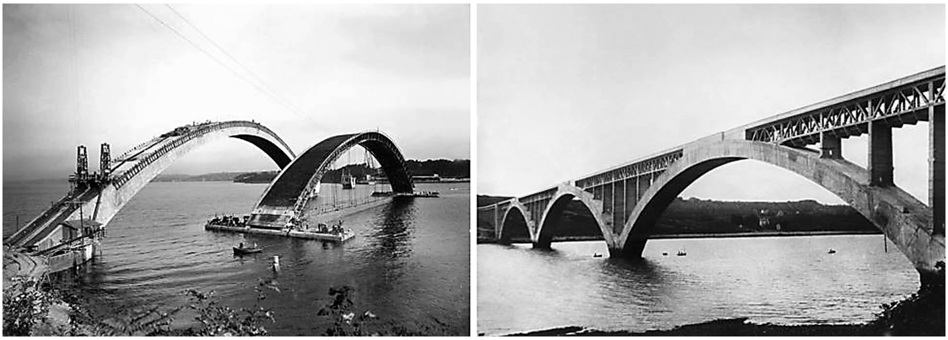


Fig. 4. *Albert Louppe Bridge – France (3 spans of 186 m, built in 1930).*

Construction methods used in iron or steel arches (Fig. 5) were logically “imported” into the construction of concrete arches, initially, for the erection of scaffoldings and later for the concrete arch itself.

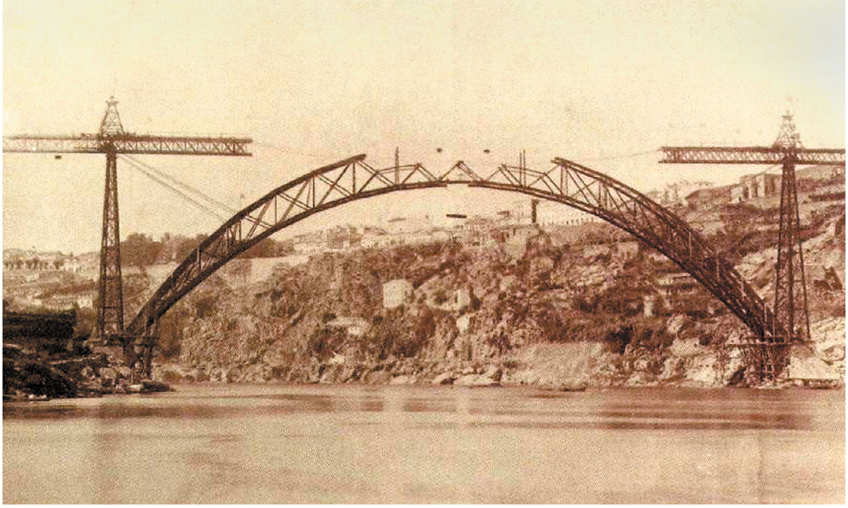


Fig. 5*. Maria Pia Bridge – Portugal, 160 m span,*
designed by Théophile Seyrig and built in 1877 by Gustave Eiffel.

In 1952, Freyssinet came up with another innovation (Fig. 6). A pair of scaffoldings advanced from both sides until they were 80 m apart. Next, a scaffolding segment for those remaining 80 m span was lifted into place.

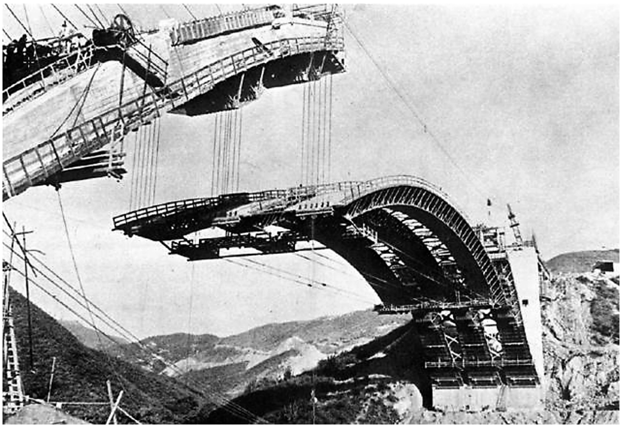


Fig. 6. Central scaffolding in the three Guaira Viaducts – Venezuela (136 m to 152 m spans).

Very cleverly, load capacity of the lateral partial arches were increased by concreting their lower slabs before the lifting of the central arch segment of the scaffolding.

The Arrábida Bridge (Fig. 7) was built a few years later, in 1963, with a steel scaffolding that was first used to build one arch and then moved sideways to build the twin arch. That steel scaffolding was planned to be used in the construction of a second bridge upstream in the River Douro, but, sadly, it was left to rotten along the riverbanks.

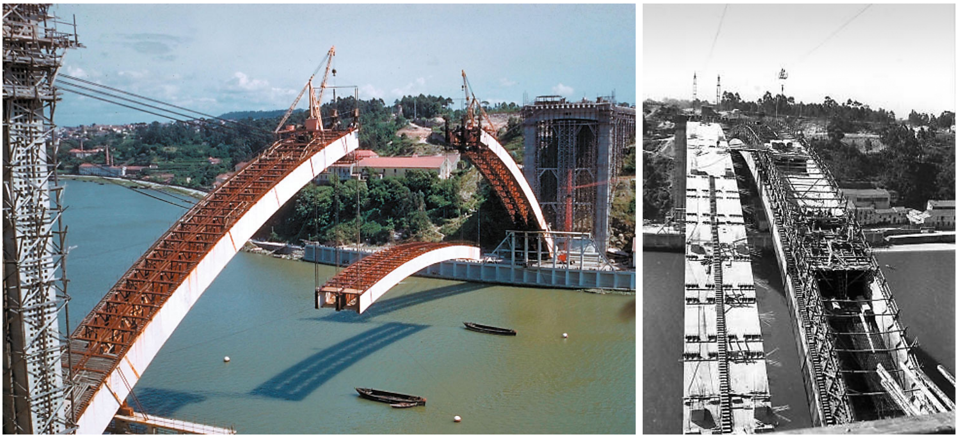


Fig. 7. Arrábida Bridge – Portugal (270 m span, designed by Edgar Cardoso).

The high cost of arch scaffoldings was always a shortcoming in the construction of concrete arch bridges. The entire scaffolding was needed because concrete arches had to be complete in order to sustain themselves and provide support for the construction of the deck (Fig. 8).

Fig. 8. Arrábida Bridge – Portugal.

An interesting construction method had been advanced well before, still in the 19th Century, by Joseph Melan, where the formwork was supported from inside by an iron lattice arch which became the reinforcement of the finished concrete arch. The first bridge built with this method was the Schwimmschule Bridge, in Steyr, Austria, and many others followed with steel lattices (Fig. 9).

Fig. 9. Echelsbach Bridge over River Ammer – Germany (HaTe photo), 130 m span, designed by Heinrich Spangenberg and built in 1929.

The Melan method requires an amount of steel for the scaffolding that is much higher than the reinforcement needed for the final concrete arch. However, merits of this classical construction method explain its present use in record braking arch bridges in China, as are the Wanxian Bridge (Fig. 10) over the Yangtze River and the Beipanjiang Bridge (Fig. 11), the latter one being presently the concrete arch World Record [1].

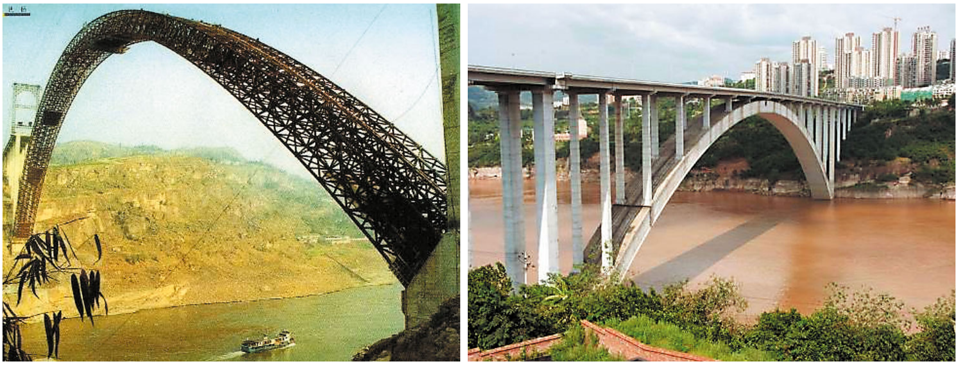


***Fig. 10.** Wanxian Bridge – China, 420 m span, built in 1997.*

***Fig. 11.** High-speed train Beipanjiang Bridge – China, 445 m span, built in 2016.*

4. CONTEMPORARY CONSTRUCTION METHODS

Reduction in the construction cost of concrete arch bridges has to be achieved either by making cheaper the construction of the scaffolding or by the elimination of the entire scaffolding. In 1943, the wooden scaffolding for the construction of the second Longeray Bridge over the River Rhône were put in place by the rotation of the scaffolding semi-arches first built almost vertically over the abutments. The same technique was adopted in the construction of the Saboya Bridge over the same River Rhône, but it was Riccardo Morandi who first did it with concrete semi-arches of the Lussia Footbridge (Fig. 12).

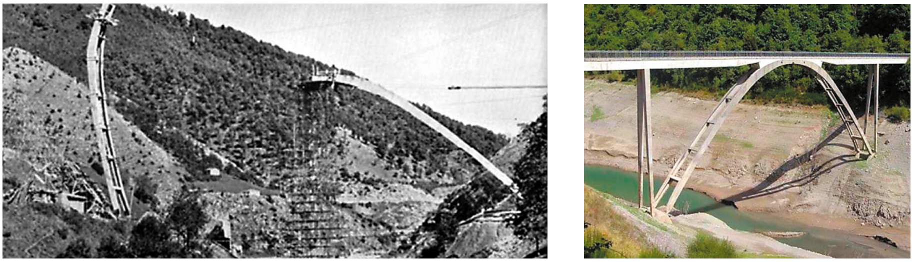


Fig. 12. *Lussia Footbridge – Italy (70 m span, built in 1953).*

This “rotational method” was applied with several ingenious assembly procedures in the construction of the Bridge Arcos de Alconétar (Fig. 13), spanning 220 m over River Tagus, at the Alcântara Reservoir. The two longitudinal beams of the deck, columns supported by the arch and the arch itself are made in weathering steel. Quite clearly, this method is not interesting for concrete arches.

Fig. 13. *Arcos de Alconétar Bridge – Spain,*
designed by J A Llombart, J Revoltós and S Wőrner, and built in 2006.

The cable-stayed cantilever launching of the arch alone is quite common nowadays, but the method of simultaneous construction of arch, deck and columns, together with provisional diagonals to materialize a cantilever truss, is becoming quite competitive. This last method was first used in 1974, in Japan, in the construction of the Hokawatsu Bridge, with an arch spanning 170 m. Just five years later, Ilija Stojadinovic, in cooperation with Vukan Njagulj and Bojan Možina, designed the outstanding Krk Bridges (Fig. 14), in Croatia. The arch of the East Bridge spans 390 m and it is still today a European Record.

Fig. 14. Krk Bridges – Croatia.

In fact, the tension chord of the advancing trusses of the Krk East Bridge was not provided by the deck but by cables, thus reducing the weight of the cantilever trusses (Fig. 15).

Fig. 15. Krk East Bridge under construction.

Both the method of erection by cable-stayed cantilever launching, with or without provisional towers, and the “truss method”, generate increasing compression in foundations and in the advancing half-arches. Elastic deformation, shrinkage and creep are thus significantly compensated during construction. The cable-stayed cantilever launching is better for geometry control but compression is introduced only partially. The “truss method” is not so efficient in geometry control but compression is introduced almost entirely, unless the deck is built afterwards, like in the Krk Bridge option. However, if the deck is built simultaneously and is the tension chord of the advancing trusses, extra prestressing is needed in the deck.

Two outstanding concrete arch bridges are being finalized for the high-speed railway over the Alcântara Reservoir, in Spain.

The bridge designed by the Carlos Fernandez Casado office, led by Javier Manterola Armisen, flies over the River Tagus with a 324 m span arch rising 70 m (Fig. 16), built with concrete grade C70. Geometry of the curved arch was obtained after a detailed process of optimization of the dead load bending stresses, looking for an approximation to the antifunicular curve of the those permanent actions [2].

Fig. 16. Bridge over River Tagus, at Alcântara Reservoir (to be finished in 2016): construction sequence and rendering of the final bridge.

The cable-stayed cantilever launching of the arch was implemented with long backstays anchored directly in the ground, followed by the construction of the columns supported by the arch and by the deck over the arch with two gantries travelling each from each side of the bridge, to guarantee loading symmetry.

The other bridge was designed by the Arenas & Asociados office under the leadership of Juan Arenas del Pablo, with an arch also rising 70 m but spanning 384 m over the River Almonte (Fig. 17). The high strength concrete C80 helped to achieve a very elegant curved arch bridge [3]. The arch was built also by the cable-stayed cantilever method and the deck by travelling gantries. In all these construction methods, a quite stiff arch is required in order to ensure instability does not occur at any stage of the construction.

Fig. 17. *Bridge over River Almonte, at Alcântara Reservoir (finished in 2016): construction sequence and rendering of the final bridge.*

Beautiful slender arches were designed by Robert Maillart (Fig. 18) in the first half of the 20th Century.

Fig. 18. *Schwandbach Bridge – Switzerland (37 m span, built in 1933).*

Later, already in the second half of the same Century, Christian Menn also designed some outstanding slender arches (Fig. 19).

Fig. 19. *Cascella Bridge – Switzerland (96 m span, built in 1968).*

Obviously, a slender arch is only capable of resisting small bending moments. Therefore, a slender arch under live loads requires "outside" help to guaranty generated bending moments are kept small. A stiff deck accomplishes this, for it capable of distributing loads "cleverly" by the various columns. The bridge is said to be a deck-stiffened reinforced concrete arch bridge.

Construction of slender arches has always been very audacious. Robert Maillart and Christian Menn used always a complete scaffolding that was taken away only after the bridge was complete and the "pair" arch/deck could interact. The cable-stayed cantilever launching is not appropriate for very slender arches because the required stiffness of the system is difficult to ensure with deformable stays under temperature variation. Differently, the “truss method” has already proved to be a suitable solution. Because the deck is the “outside” stabilizing element of the arch, construction of the deck needs to go in ahead of the arch. The first time this method was deployed was in the construction of the Nakatanigawa Bridge, in Japan, with the arch spanning 100 m and rising 19 m.

Already in the present Century, the author, together with J.A. Fernández Ordoñez and Francisco Millanes, designed an World Record slender and shallow arch bridge (Fig. 20 and 21) over River Douro, between Porto and Gaia.

Deck construction ahead of arch construction can be seen in Fig. 21, as well as the triangulation with temporary diagonal cables.

Fig. 20. *Aerial view of Maria Pia, Infant Dom Henrique (built in 2003) and Luiz I Bridges.*

Fig. 21. *Infant Dom Henique construction.*

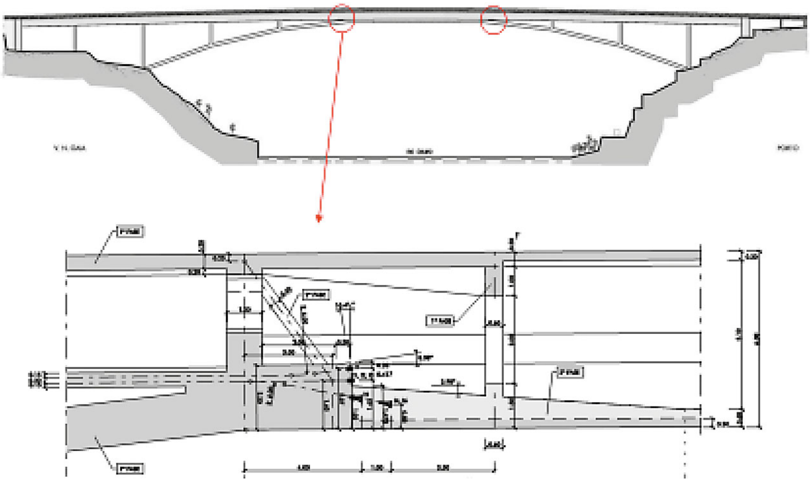
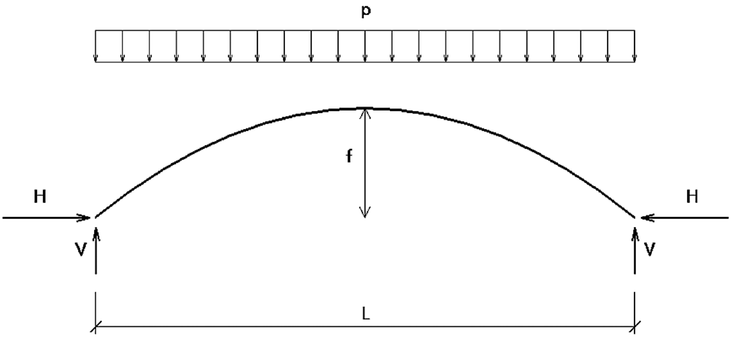


Fig. 22. Detail of the arch-deck linking triangulation of the Infant Dom Henrique Bridge.

Geometrically, the arch is independent of the deck even when in fact "united" with the deck (Fig. 22) in the central 70 m long segment of the bridge. This unifying link in very shallow arches is very tricky and it was resolved with an internal triangulation to allow the transfer of forces in between the distinct structural elements.



$$H = \frac{p}{8} \times \left(\frac{L^2}{f} \right)$$

Fig. 23. Structural response of a "perfect arch".

The Infant Dom Henrique Bridge [4] exhibits high technical and aesthetic qualities and represents an important technological advance in construction, because it demanded advanced monitoring systems, because of the magnitude of its dimensions, and because of the following set of relevant facts (see Fig. 23):

- It is the fourth largest concrete arch in Europe; with a span L = 280 m;

- It holds the world record for shallow deck stiffened arches; with a constant thickness of 1.50 m (= L/187), it stands out for being extremely slender in relation to the usual thicknesses used in conventional rigid arch solutions (between L/40 and L/60);
- The rise of f = 25 m means a shallowness (L/f = 11.2) for the arch that has no parallel in the field of large span arch bridges;
- Its "static coefficient" (L2/f > 3000), which is directly proportional to the axial force existing at the crown of the arch, is the largest of any arch built to date (Fig. 24).

Indeed, the arch of the Infant Dom Henrique Bridge is the most loaded and the most "delicate" in the World.

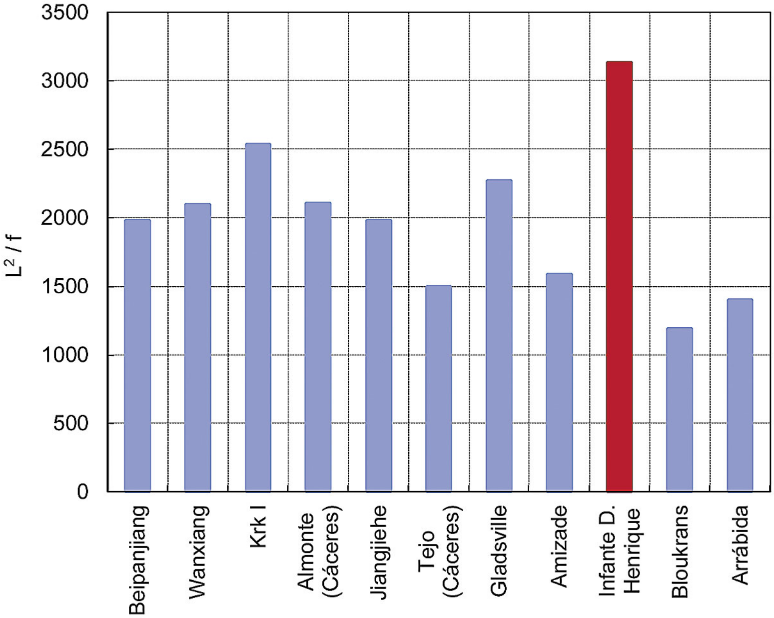


Fig. 24. *"Static coefficient" of world arch bridges with long spans.*

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