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A Proposal in Steel Arch Bridge Design: The Stayed Lonely Arch-Rib

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Summary

In the paper we suggest a new way to secure the arch-ribs of bridges of the Langer-girder type against transversal wind and spatial buckling. In analogy with the stayed-column design concept, the load capacity of curved slender rods subjected to high compressive stresses can be increased by equipping them of an assemblage of prestressed stays and rigidly connected crossarm members. We present many possible patterns of stay and crossarm arrangement. A representative arch-bridge structure with single central stayed arch-rib is analysed up to the collapse by a nonlinear elasto-plastic finite element method.

1. Introduction

The deck-stiffened tied arch, in its through-type version, is an attractive and efficient device for highway and railway bridges, in the medium-span range up to the bottom of the large-span range (about 300 m). It is particularly suitable and may offer the best engineering solution if the site is wide-sweeping and the subsoil conditions are rather difficult and could be preferred in terms of costs, ease of erection, short construction time and minimised environmental impact. Many impressive realisations in the last decades and recent years (e.g. [1], [2], [3], [4]) confirm the validity of the solution in satisfying, with different configurations, the requirements of strength, feasibility, aesthetics and economy.

The continuing success of the tied-arch bridge in the modern engineering is strongly influenced by aesthetic purposes: the intrinsic beauty of the elegant sweep of the arches, the spatial arrangement of the slender suspenders, the clean-lined appearance of the thin girders have a great potential to lead to striking pieces of structural Architecture.

However, the pronounced trend toward lighter bridges, with more slender arches, and the increasing traffic demands, both of number of traffic lanes and size of traffic loads, make the problems of the overall stability of such bridges more acute.

Since the in-plane stability of the arches is not usually of concern, the main challenge for the designers lies in creating a lateral bracing system rational, reliable and not overwhelming. Really, the least satisfactory aspect of the trough-type arch bridges is sometimes the boring impact of the overhead structural mass visible from the deck, a tunnel-effect unattractive as well as unsafe for

drivers.
The aim of this paper is to suggest a new type of wind-bracing of the arches: cross-arms cantilevering from the arch-core and taut, high strength, cables generate a their own spatial truss, *the cable-stayed arch*, a new structural form that express lightness.
Our proposal is for a synthesis of a tied arch, carrying the vertical load, and of a cable stayed system, for the horizontal stabilisation of the arch-rib, with a natural visual elegance.
The innovative system could also be used to upgrade many existing bridges to deal with increased vehicular loading following changes in road transport.
We will give a first insight into the behaviour of the proposed lateral bracing system, attempting to clarify its true role through an elasto-plastic spatial analysis, considering the influence of finite deflections and inevitable structural imperfections.

2. The Stayed Arch Bridge

The earliest form of the "Langer girder" [5] has been subjected to several refinements, with primary concern in finding handsome solutions for the stiffening of the arch ribs against wind and buckling.
A determinant improvement of competitiveness has been attained by the adoption of self-standing arches, located in the central strip of the bridge or laterally to the deck. The arches obtain the necessary transverse stiffness through stocky cross section, either flat rectangular or tubular twinned, and the result is an awkward visual impact at the bridge access ([2], [3]).
A new impetus, mostly centred in Japan, took place in the last years with bridges of "basket-handle" type [4]. A number of long span "Nielsen-Lohse" bridges have been constructed, in which the deck is carried by a lattice of crossed hangers and the twin lateral arches are inclined inwardly and connected by few – or just one or two – bracing struts near the crown. In spite of the obvious advantages of the solution, the appearance of the bridge is rather cumbersome.
Seeking to find new paths for the lateral bracing of arches rising above the deck, we propose an innovative conception of the arch itself, which is planned as *self-braced.*
It has been shown that the strength of a centrally loaded slender column may be increased many times by reinforcing it with three or four identical planar stay frames, evenly spaced around and rigidly connected to the core by simple radial spokes or bipods ([6], [7]).
Arch bridge ribs are spatially curved slender rods subjected to high compressive stresses: hence their load capacity can be enhanced, in analogy with the columns, by equipping them of an assemblage of prestressed stays and rigidly connected crossarms members (stayed column concept towards stayed-arch concept). The preloaded stays, placed side by side to the arch, integrate its transversal and torsional stiffness.
Many patterns of stay and crossarm arrangement are possible, for a variety of structural forms.

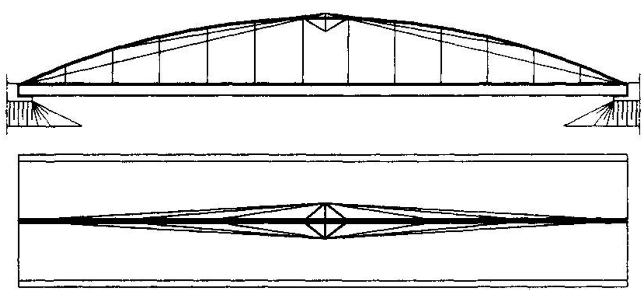

Fig. 1

The simplest but effective staying system presents a double three-dimensional arrangement of the stays fanning from "tripods" (spatial trusses) cantilevering from the crown of the arch (fig. 1). Also with a width-to-span ratio as low as 1:20, by the connection of the top of the arch with the ends of the stiffening girder at bearings, the out of plane rigidity is considerably increased and the propension of the

arch to buckle out-of-plane is contained by the torsional restraint of the mid cross-section.
If the crossarms provide intermediate supports to the stays in many sections along the central line of the arch (fig. 2), we achieve a good lateral supporting with little bending in the arch and the tie in consequence of the tensioning of the cables.
A totally innovative unusual shape – structurally quite plausible – presents arches tilting from the vertical outwardly while crossarms inclines inwardly (fig. 3) so that visual flight lines are balanced.

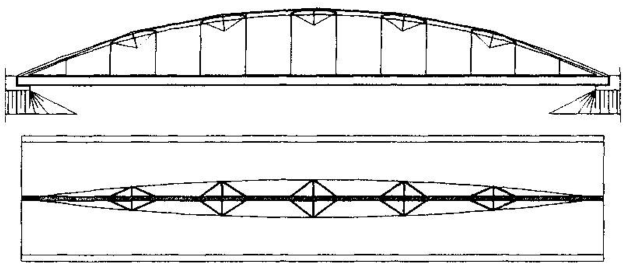

Fig. 2

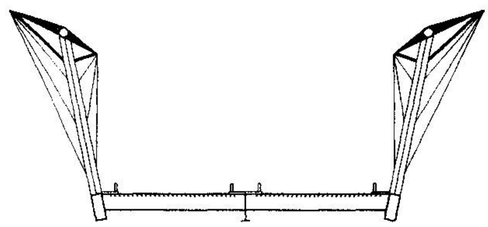

Fig. 3

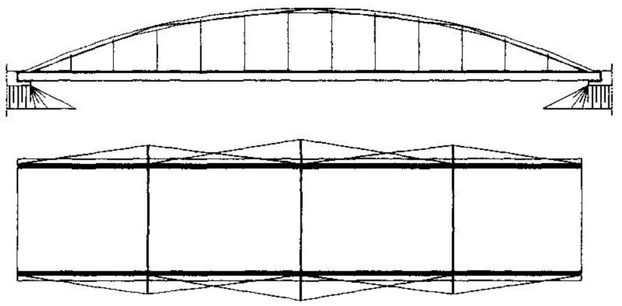

Fig. 4

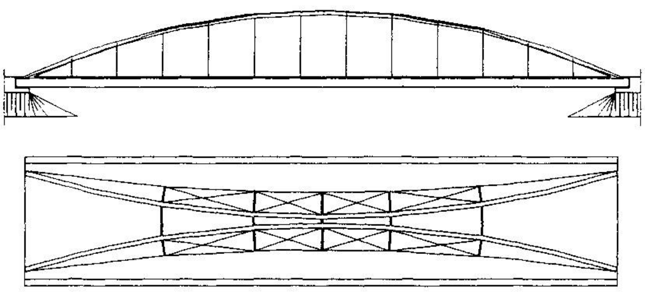

Fig. 5

For twin ribs, upper lateral bracing of Vierendeel type becomes very light when integrated by lateral staying (fig. 4), leading to a better acceptance of structural members above the carriageway.
In the basket-handle type bridges, the outward concavity of the horizontal projection of the arch ribs naturally receives the stay bracing (fig. 5) for an optimum location and rigidity of wind bracing.
It is noteworthy to point out that a peculiar characteristic of the tied-arch bridges is the possibility to adjust, during the erection, the axial forces in hangers, in order to control the bending moment diagrams [2]. Since the staying of the arches increases the internal statical indetermination of the structure, it is apparent that the cable-force adjustment calls into play further degrees of freedom for the load balancing operations.

3. Case Studies

We present in some detail two expressive examples of staying to horizontal straightening of tied arches: bridges studied are representative of typical arch structures actually constructed.
To visualise a comparison between the existing bridges and their proposed enhancement, we created computer renderings with almost photographic level of realism.

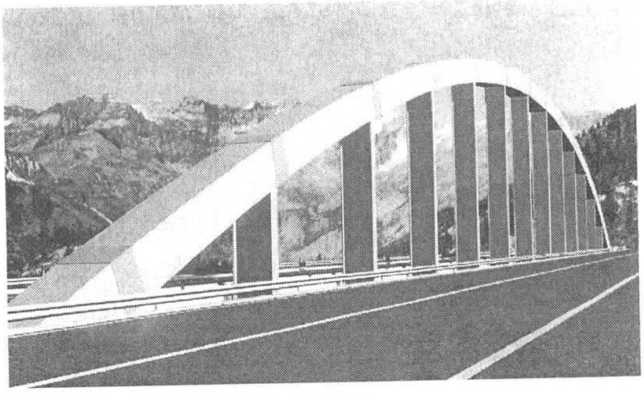

Fig. 6

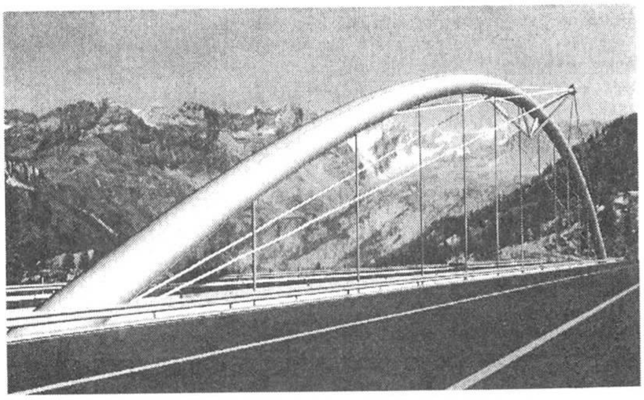

Fig. 7

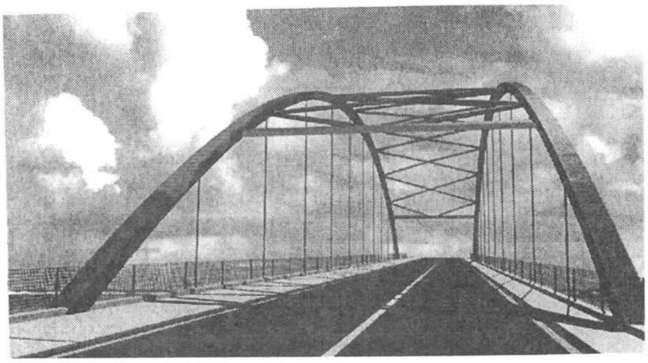

Fig. 8

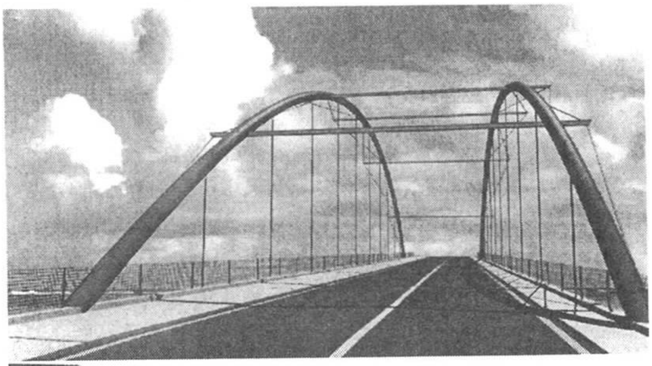

Fig. 9

The first case focuses on a highway bridge of the central-arch-girder type [8]. The heavy requirements for eight lanes of traffic resulted in a relevant beam depth and stocky cross-section of the arch-rib (fig. 6). Broad steel plate hangers seemed necessary to ensure the out-of-plane stability of the arch: looking at the structure while crossing the bridge shows little of anything but masses of columns.

Main features of the suggested variant are (fig. 7): a more slender tubular arch-rib – with slower drag coefficient for wind load -, thin high-strength hangers made of parallel wire strands and a "diamond shaped" crown lattice that supports the spatial fan of stays, of the type of fig. 1, for the lateral bracing of the arch. The total effect is obviously much more handsome.

Fig. 8 shows a beautiful town-arch-bridge carrying four lanes and walkways [9]. An upper lateral bracing of the twin arches of the double Warren truss type were adopted, with flat box sections for the end-portal-frame and tubular sections for the diagonals.

Although the upper truss appears a refined solution, it is busy with its diagonal members extending over most of the span. The modified design (fig. 9) adopts a transparent wind bracing without diagonal members, high lateral stiffness being provided by the side stays. The mainly aesthetic choice leads to a dynamic spatial structure.

4. Ultimate Strength of Stayed Arches

The strength of unbraced or traditionally braced steel arches is an intricate problem to which only recently several important researches have been devoted with almost exhaustive conclusions. In particular, the Japanese school of arch-bridges designers developed comprehensive numerical studies and parametric analysis on the load carrying capacity of actual arch-bridges by an accurate F. E. approach ([10], [11], [12]). Design recommendations and formulas have been proposed for the prediction of the ultimate strength of through-type steel arches that fail by lateral instability.

The mayor findings that are brought out by such numerical analysis, with respect to the general behaviour of stiffened arch-bridges loaded to the ultimate state, can be summarised as follows:

i. Bifurcation approach to the out-of-plane stability is inadequate: linearized buckling load appears almost as a purely mathematical concept;
ii. The only possible accurate approach to the safety assessment against ultimate load is an elasto-plastic and finite displacement analysis of a three-dimensional model, taking account of initial out-of-plane imperfections, residual stresses, tilting loads of the hangers, horizontal loads. With it, the behaviour of the system may be traced from the erection stage until the maximum load capacity, determinate by deflection divergence, in a complex interaction of in-plane and out-of-plane instability.

Nearly unexplored is the field of the design concepts of prestressed load-bearings curved bars in compression, in which hogging frames and tension ties introduce at several points along the length of the central core restraints against lateral translations and rotations.

A lot of problems still remain unsolved also for the simplest case of stayed columns. From a literature review ([6], [7]), again it appears that an elastic stability analysis, linear or nonlinear, produces uncertain results, while the large displacements nonlinear elasto-plastic analysis (considering the initial core crookedness, errors in stay prestressing, the possibility of stay slackening, residual stresses and lateral loads) is an indispensable tool.

On the ground of these considerations, it seems obvious to infer that the load carrying capacity of arch-ribs stiffened by stay frames can only be understood and accurately determined by finite element analysis, including geometrical-mechanical changes in the structure until the collapse.

We present here an example of such ultimate strength analysis, applied to the central-arch girder bridges of figures 6 and 7. With the aim of a comparison of the performances of the existing bridge and of the proposed stayed-arch variant, we used the standard finite element package ADINA [13], containing all the features needed to manage an efficient nonlinear frame analysis. The bridges are idealised as three-dimensional framed structures (fig. 10); in the simulation, the

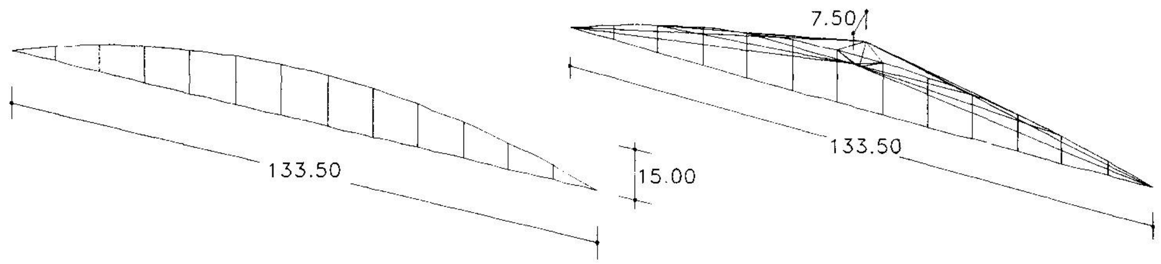

Fig. 10

arch ribs and the I-shaped hangers have been modelled by beam-elements in which elasto-plastic and large displacements behaviour can be taken in consideration, the stiffening girder by large displacement elastic beam elements ([12]) and the cables as truss nonlinear elastic elements supporting tensile but not compressive loading.

The arch members of the actual bridge have been modelled with thin walled circular cross section having about the same cross-sectional properties as the original ones; the cross section of the arch rib and the central "diamond shaped" spoke in the variant have been designed with pipe sections. The characteristics of the various members are summarised in table 1.

The material properties were represented by steel stress-strain curves from EC3, part 2: Steel Bridges (for the girder and the arch ribs Steel Grade S 355 H).

Imperfections in initial geometry of the arch ribs similar to the first buckling mode, derived from a linearized buckling analysis, has been introduced, with a value of the horizontal eccentricity at the crown of 1/1000 of the span. Moreover, an initial configuration with very reduced bending moments in the upper and lower chords of the bridge has been heuristically realised in the numerical models, subjected to dead load and prestress forces introduced in the hangers and the stays, by the ADINA "initial strain" option: from this configuration began the incremental nonlinear analysis under increasing live loads.

	Arch rib	*Girder*	*Hangers*	*Stays*
Actual bridge	50 / 1650	$J_x = 1.2254\ m^4$	$J_x = 0.00037\ m^4$ $J_y = 0.01771\ m^4$	
Proposed bridge	60 / 1550	$J_y = 68.1990\ m^4$ $J_t = 0.4159\ m^4$	PWS 163 ϕ 7.11	PWS 121 ϕ 7.11

Table 1

Traffic loads on bridges were assumed in agreement to Eurocode 1, Part 3, as in fig. 11 (eight notional lanes on the carriageway, load model 1 over the full span, each tandem system having an axle at midspan).

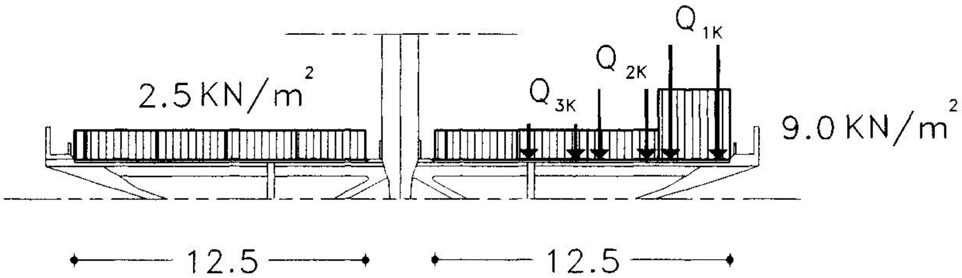

Fig. 11

The structure is examined subjected to both vertical and horizontal loads: the service wind load is 1.0 kN/m^2 on exposed surfaces. Two loading paths are investigated in checking for ultimate limit state: 1) dead load, increasing road traffic load proportionally to a load parameter, wind load; 2) dead load, increasing wind load proportionally to a load factor.
The calculated load parameter versus deflections curves at the crown of the arch-rib in the two cases are shown in figures 12 and 13.
At the ultimate state, extended plastic zones are present, spreading from the springing of the arch-rib; diagrams confirm the remarkable effect of the stays on the ultimate strength of the stayed arch.
The stay-stresses and load-factor relationship is shown in fig. 14 for load combination 1): it is noteworthy that to the evanescent tension in some stays does not correspond the maximum load carrying capacity; it is evident, also, the complex and unpredictable spatial interaction of the various members of the structure.

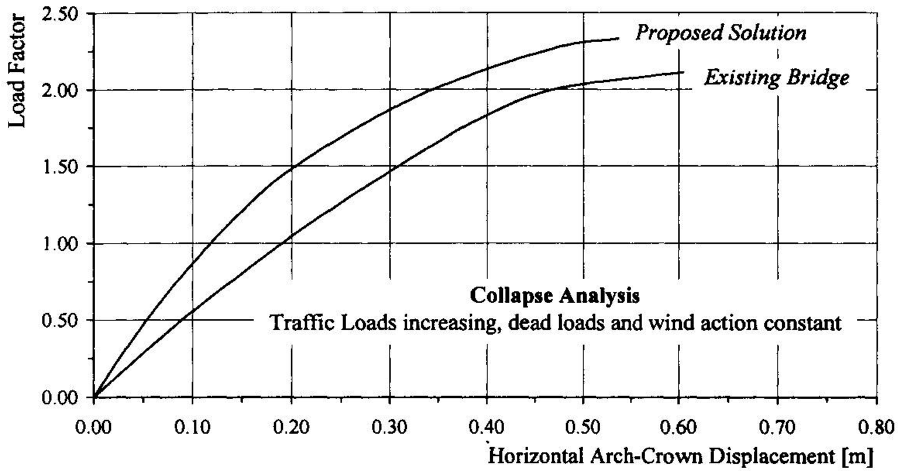

Fig. 12

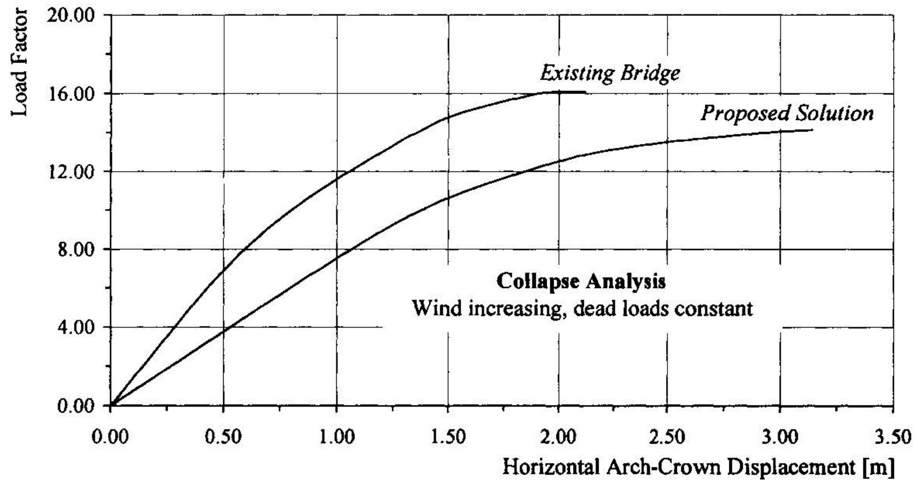

Fig. 13

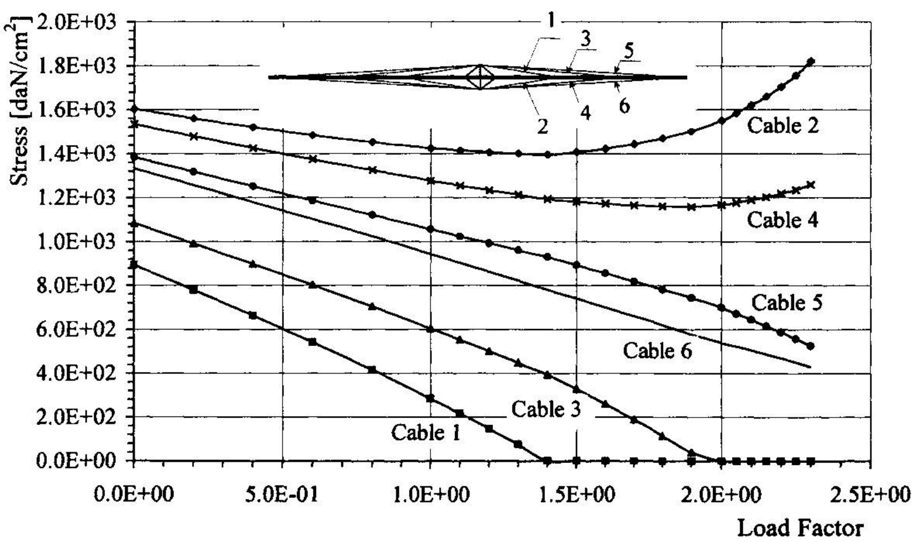

Fig. 14

5. Conclusions

The proposed stayed-arch is a composite structure in which a curved slender beam-column (the arch-rib) is stiffened against overall out-of-plane buckling by high strength prestressed stays, supported by crossarms cantilevering from the core.
Technically, such combination of elemental components results in a good design concepts; aesthetically, in a through-type arch-bridge this arrangement, which substitutes the cluttering traditional wind-bracing, leads potentially to an elegant appearance.
The ultimate load-carrying capacity of a representative example of stayed central-arch-bridge has been studied: the development of the structural idea needs obviously deeper researches and field verifications.

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