6th International PhD Symposium in Civil Engineering
Zurich, August 23-26, 2006

POSSIBILITIES FOR STRUCTURAL IMPROVEMENTS IN THE DESIGN OF CONCRETE BRIDGES

Ana Spasojevic[1]

Abstract

This paper presents the concept and the current state of a research investigating possibilities for further evolutions in medium span concrete road bridges. The main parameters of the study are the structural shape, the type of materials used and their disposition. The study will provide an optimisation of the design of various systems of concrete bridges, with the perspective of introducing new advanced cementitious materials, such as ultra high performance fibre reinforced concrete, UHPFC. Feasible directions for improvement will be indicated by means of parametric analyses of the structural response.

Keywords

Concrete bridges, structural shape, optimal design, UHPFC.

1 Introduction

The improvement of the performance and efficiency of bridges is a constant task of engineering design. Recent developments in concrete material properties have renewed the research interest for this topic. In the context of this research, efficient structures are defined as structures that satisfy the design requirements with a minimum amount of materials, enabling easy and rational construction. Existing structures are investigated to identify the most successful shapes combining these properties.

Topological optimisation is applied as a procedure to find efficient structural shapes with respect to the maximum stiffness achieved for a given volume of material. This method allows observing the relationship between the amount of the material and the stiffness as a function of the shape.

The resulting and other predefined shapes will be further optimised, taking into account the constrains of concrete bridge design. The solution is controlled by the ultimate limit state, by the serviceability limit state requirements or by constructive constrains. In addition, the actual material behaviour of concrete and steel is included.

An example of the application of this approach to the classical case of a continuous bridge girder with a box section is presented in the paper.

[1] PhD candidate, Ecole Polytechnique Fédérale de Lausanne, ana.spasojevic@epfl.ch

2 Evolution of structural types

2.1 Learning from history

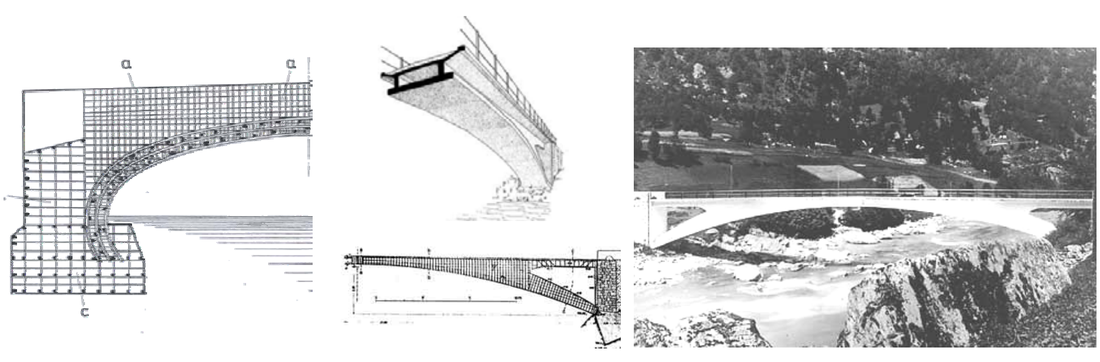
An important source of ideas on possibilities for improvement of bridges can be gained by studying existing structural systems and historical cases. Throughout history, the design of structures has been based on the principles of functionality, strength, durability, economy, and aesthetics. These basic design principles do not change, which allows to draw analogies between known ancient structures and contemporary ones. Another interesting aspect of ancient systems is the possibility of rediscovering a structural system which becomes interesting again because of the availability of new materials. This is the case of under-spanned bridges, developed in the beginning of the 19th century and rediscovered in the last decades.

The most significant progresses in the development of structures are related to inventions in the field of materials and their application in an appropriate form. Because it is a multidisciplinary task, bridge design is also influenced by the progress in other domains, such as structural analysis, numerical methods and technological developments, notably in construction techniques. It must be noted, however, that a substantial time lag is usually observed between the introduction of a new component and its wide-spread application in designs that fully exploit its properties. The drive towards a decrease in material consumption while keeping a sufficient strength and a suitable stiffness is a constant force throughout this evolution.

2.2 Concrete material and structural development

In the development of reinforced concrete bridges, important phases of evolution were the invention and application of forms specifically conceived for this material and the invention of prestressing. The 19th century is the beginning of the modern era of concrete. In 1875 the first reinforced concrete bridge is designed by J. Monier in Chazelet, France, almost two decades after the first patent for reinforced elements was awarded. The structural shape is strongly influenced by traditional massive masonry arches (fig. 1a).

It was not until the beginning of 20th century that the first structural shapes specifically conceived for reinforced concrete structures were designed by R. Maillart (fig. 1b). The mechanical properties of concrete did not evolve significantly over that time period. An important potential of evolution for concrete structures was introduced in the 1920's with the invention of prestressing by Freyssinet in France, and by Dischinger in Germany. The first bridge with this technology was built in 1928 in Alsleben, Germany, spanning 68 m. The widespread of application of prestressing did not start until after the Second World War.



a) The first RC bridge, J. Monier,1875,Chazelet, Fr.

b) Tavanasa bridge, R. Maillart, 1905, Switzerland

Figure 1 Steps in the evolution of reinforced concrete bridges

A new era of concrete started in the 1970's with rapid developments of the material properties. Starting with introduction of fiber reinforcement, superplasticizers, and various pozzolanic additives, concrete performances improved constantly.

2.3 Application of ultra-high performance concrete

In the mid 1990's, a new class of a concretes appeared, called ultra-high performance concrete, UHPC, reaching more than 200 MPa of compressive strength. So far, this development has not been followed by significant improvements in the design of bridges at the conceptual level.

The latest development in cement-based materials is ultra high performance fibre reinforced concrete (UHPFC). From a material point of view, UHPFC is an advanced cementitious material characterized by a very dense microstructure compared to conventional concretes. This leads to a very high compressive strength, a low porosity and a high durability. The brittleness of the matrix is decreased by the addition of steel or polymeric fibers. This combination of superior properties makes this material interesting for applications in bridge design.

From a structural point of view, the application of UHPFC is a challenge. It is being investigated worldwide at the material and element scale. But the transition from this knowledge to the structural level is not straightforward. The first application of UHPFC to road bridges was in 2001, in France (Simon, Hajar, 2002). The chosen structural solution is typical of ordinary prestressed concrete bridges. In this context, the highly improved mechanical strength led to a decrease of sectional dimensions compared to classical solutions. This decrease is accompanied by a corresponding decrease in stiffness. If the structure is flexible, this may lead to sections that are designed to limit deflections and thus do not use the full ultimate limit strength of the material. Optimizations of structural elements for the application of UHPFC behavior mostly concentrate on sizing problems, with predefined classic shapes (Park et al. 2002).

The idea of the present study is that for a more competitive application of the advanced properties of UHPFC, new structural concepts need to be investigated.

3 Form finding by topological optimisation

Structurally efficient shapes can be defined, in a first approximation, as the shapes that, for a given stiffness or a given strength, use the least amount of material or, conversely, for a given amount of material lead to the largest stiffness or strength.

Expressing the structural stiffness as a function of the structural shape allows optimising the stiffness with the structural shape as a design variable. This approach is made possible by the means of topological optimisation (Bendsoe 1995, Sigmund 2001). The results obtained allow identification and a quantitative comparison of various structural types.

3.1 Problem statement

Topological optimization is a domain of structural optimization in which no structural shape is initially prescribed. This gives *a priori* more freedom in the search of the best suited shape.

The problem is formulated as that of finding the material distribution leading to the largest global structural stiffness for a given amount of material, *V*, on a given design domain. The boundary conditions and portions of the design domain that need to be kept intact for functional reasons are predefined.

Based on the assumptions of a linear elastic behaviour, after meshing of the observed volume in finite elements, the structural response needs to satisfy the equilibrium and compatibility conditions, $\boldsymbol{K}\, U = F$, where $\boldsymbol{K}$ is the global stiffness matrix, U and F are the displacement and load vectors respectively. The global structural stiffness is considered through the strain energy and, consequently, the problem of maximisation of the stiffness is defined as:

$$\min C = \sum_{i=1}^{N} u_i^T k_i u_i \qquad (1)$$

where C is the structural compliance, k_i and u_i are local stiffness matrices and displacement vectors and N is number of elements. To express the compliance as a function of the disposition of the material, a variable η_i with values $0 < \eta_i \leq 1$, is assigned to each element as its relative density parameter (pseudodensity). The stiffness of an element is represented as: $k_i = \eta_i \cdot k_0$, where k_0 is the stiffness of the initial elastic solid.
Finally, the objective function of the problem is expressed in a function of the design variables, η_i :

$$C = f(\eta_i, k_0, u_i) \tag{2}$$

A set of design variables satisfying constrains, $V \leq V_0 - V^*$, where V_0 is the initial volume and V^* is the volume to be removed, forms a feasible region in which the minimum of the objective function is found.

3.2 Application to the shape of a bridge superstructure

This procedure was applied to a variety of design domains and boundary conditions that correspond to families of bridge superstructures. This led to the identification of families of structural shapes with a maximal stiffness for the given conditions. *Figure 2* shows examples of design domains on which the topological optimisation was performed.

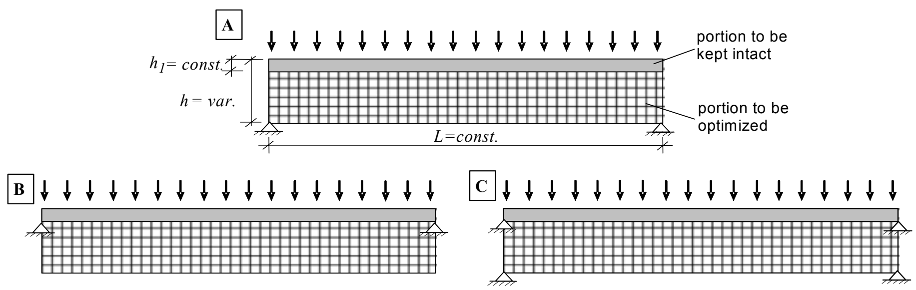


Figure 2 Geometry of the initial body: 2D continuum with portions to be kept intact for three sets of boundary conditions

The optimised structural shapes are shown in the density distribution plots obtained as results of the procedure. Elements with a pseudodensity, η_i, close to 1 correspond to highly dense matter. Figure 3 shows examples of density distribution plots for the same amount of material and various boundary conditions. It shows that, for a given quantity of material various efficient structural shapes are obtained depending on the boundary conditions.

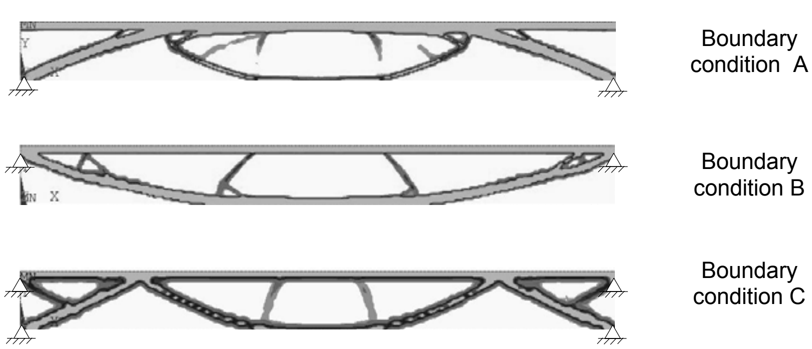


Figure 3 Optimised shapes for various boundary conditions, with $V = 0.27V_0$ and $L/h = 10$

Figure 4 shows the relationship between the decrease in volume and the decrease in stiffness of the system A of figure 2, with a slenderness L/h = 10. Change in stiffness is expressed here as a ratio of vertical displacement of the initial system, w_0, to the displacement of the optimised system, w. It is evident that the volume and the global structural stiffness are not proportional. In the initial part of the curve, a decrease in volume of material causes almost no change in stiffness, because material with a very small contribution to the stiffness is removed. After a certain level of volume reduction, the volume decreases by diminution of the thickness of the members, while the shape remains the same. The decrease in stiffness is then much faster. It must be pointed out that in this example the initial volume contains a portion which is not subjected to optimisation (in this case the deck of the bridge, which is necessary as a driving surface, has a constant density over its thickness). The point for w_0/w = 0 in figure 4 corresponds to the case in which all matter except for the deck has been removed ($V = 0.10\ V_0$). Similar curves have been obtained for other boundary conditions (fig. 2) and for slenderness values L/h varying between 10 and 30.

The curves plotted in the figure 5 show the global structural stiffness as a function of the slenderness and the boundary conditions. An important difference in stiffness is observed between the various shapes resulting from the optimisation. The under-spanned structure obtained for boundary conditions B is much more flexible than the combination of an arch and an under-spanned central span that results from boundary conditions A and C.

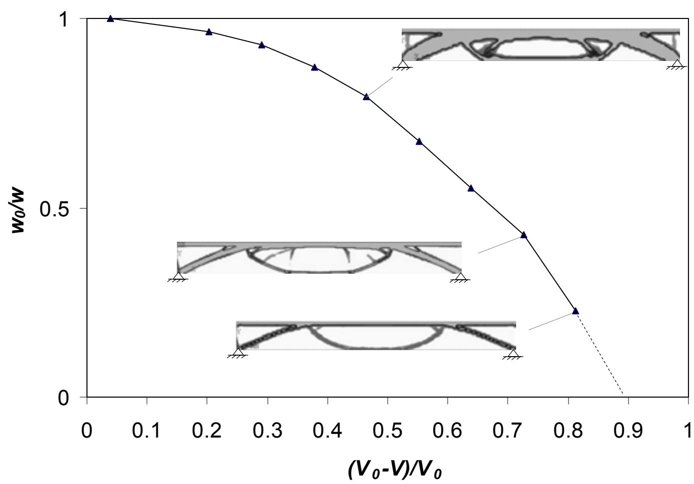


Figure 4 Change in structural stiffness (w_0/w) in function of the volume reduction for the boundary conditions A of figure 2 and L/h = 10 with the corresponding optimised shapes

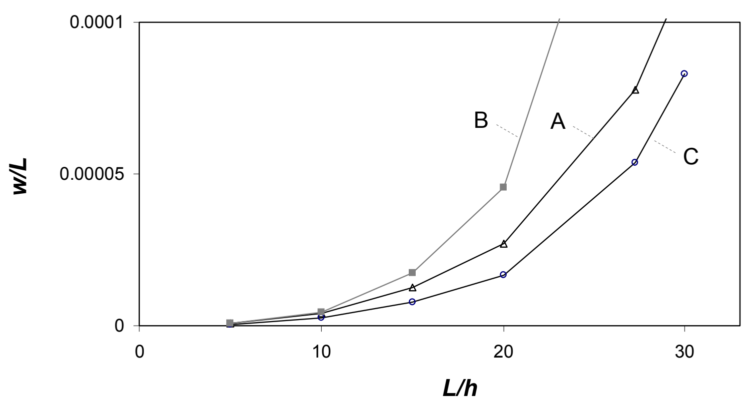
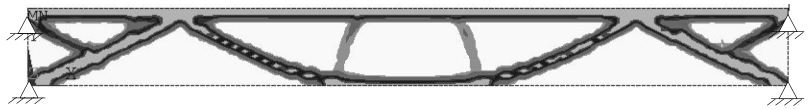


Figure 5 Global structural stiffness in function of slenderness, for boundary conditions A, B and C; $V = 0.43V_0$

Analogies can be found between the obtained topologically optimal shapes and actual concrete structures. This is clearly exemplified in figure 6 which shows a striking resemblance between the results of the optimisation and a recently built structure.



a) Optimal density distribution plot

b) Villa Bedretto Bridge, Switzerland (Muttoni 2002)

Figure 6 Recognition of form: transition from numerical simulation to a structural system

4 Potential of predefined structural shapes

Further optimisations require the introduction of additional constrains related to the material behaviour, design requirements, constructability or economy. To that end, it is helpful to start from predefined shapes that represent various structural systems applicable to bridge design. This broadens the scope of the optimisations compared to the previous purely topological optimisation.

The potential of various known structural shapes has already been investigated by several researchers. In the work presented in (Samyn 2004, Muttoni 2004), structural performance is analytically expressed in terms of volume and displacement indicators, W and Δ, where $W = \sigma \cdot V / F \cdot L$ and $\Delta = \delta \cdot E / \sigma \cdot L$. Thus, the volume and displacement in these cases are functions of the slenderness ratio only (fig. 7). This approach enables a clear comparison of the efficiency of various structural shapes. The main hypotheses used in these studies are: homogeneity of materials with an elastic behavior, in-plane loading and no second-order effect.

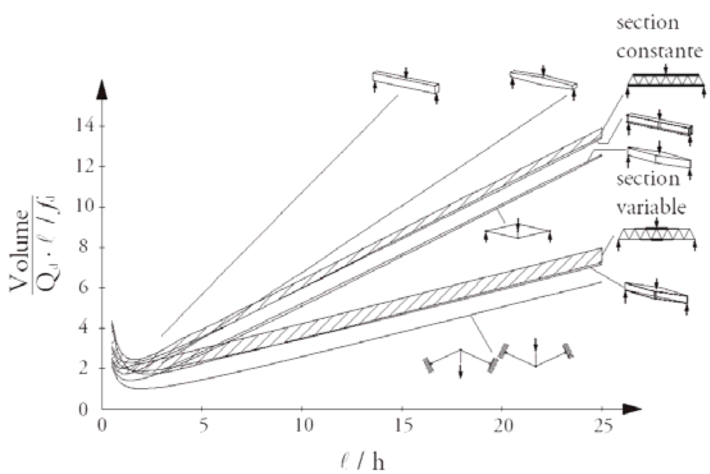


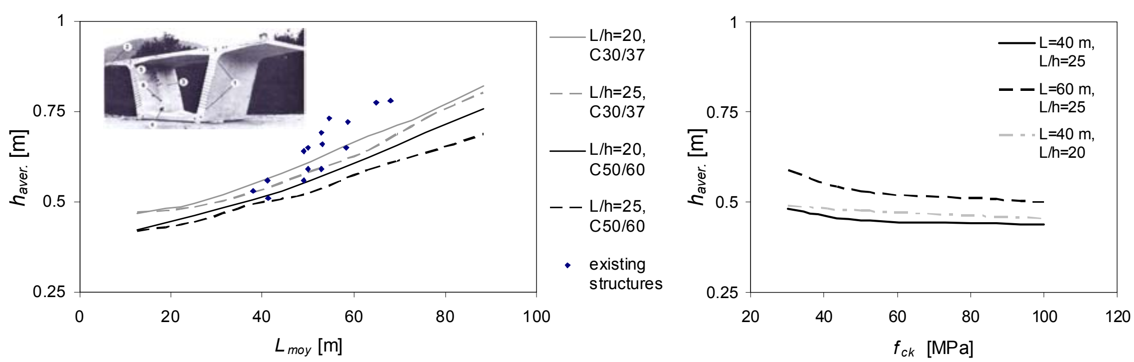
Figure 7 Efficiency of various structural girders: material quantity in function of their slenderness (Muttoni 2004)

5 Behaviour of reinforced and prestressed concrete bridges

To extend the approach of investigation of predefined shapes to concrete bridges, the development of numerical models was required. These models include not only constrains related to statics and geometry but also related to the design of concrete structures. This constrains are formulated as ultimate limit state, serviceability limit state and constructive requirements.
Because the research deals in particular with statically indeterminate systems, to adequately model the response of these structures, it is necessary to take into account the non-linear behaviour of the material. The interest is to observe the influence of particular materials behaviour, such is the one of UHPFC, on the structural response at the ultimate limit states. The implementation of non-linear material behaviour is under way; the results of the parametric study shown below do not yet include these effects.

5.1 Optimisation of a cross section

A large number of contemporary prestressed concrete road bridges are built as continuous box girders. This successful classical solution is taken as a reference system for the approach presented here. Figure 8a shows the average concrete depth over the bridge surface, $h_{aver.}$, needed for various slenderness, *L/h*, and material strengths. The results are plotted against the values corresponding to existing structures, obtained from (Menn 1982). A good correlation between the simulated values and the statistical data is observed. Figure 8b shows the influence of an increase in concrete strength on this system. As expected, this structural system is rather insensitive to compressive strength of concrete, in particular for smaller spans and for structures with a limited slenderness. For characteristic concrete strengths higher than 60 MPa, almost no effect is observed. This behaviour is mostly due to the fact that a large part of the concrete cross section is constituted by the bridge deck and the webs. The web dimensions are mostly governed by constructive constrains related to cables and concrete placement. This suggests that the use of external prestressing can be a possible solution for a better exploitation of this system (Benouaich et al. 2000).



a) Influence of the span on the amount of concrete, compared to existing structures

b) Influence of the concrete strength on the amount of concrete

Figure 8 Parametric simulation of structural response

A promising improvement of this concept is seen in application of UHPFC, whose characteristics enable to avoid passive reinforcement, allowing an important decrease in dimensions. The new concept of a ribbed upper slab, with an equivalent depth of less than 0.14 m, is currently under investigation. This system provides a significant decrease in weight in comparison to application of ordinary and high strength concrete, while keeping a sufficient stiffness and allowing an easy construction by prefabricated elements. To support this design, a testing programme is currently under way at the Structural Concrete Laboratory at the EPFL. This experimental research should provide knowledge on particular structural responses and failure modes, leading to safe design approach enabling a better application of this material's advanced properties.

6 Conclusions

A review of existing structures and their development allowed identifying a strong tendency towards structures with a small weight to stiffness and strength ratio. The design of bridges relies significantly on experience and feedback from existing structures, and innovations take typically a long time to be included in usual design approaches.
A systematic application of topological optimisation enabled identifying the shapes with a maximum structural stiffness for a given amount of materials. Systems combining an arch or a frame with an underspanned element have been found to be very efficient.
Starting with efficient predefined structural shapes, additional constrains such as realistic material behaviour, constructability or economy need to be directly or indirectly introduced. Following this approach and introducing constrains related to the design of prestressed concrete bridges, the influence of the slenderness, material strength and other factors on the required amount of materials is derived. For the case of a typical continuous box girder bridge with internal prestressing, the results match closely those obtained in a survey of this type of bridges in Switzerland. A promising improvement of this system is seen in application of UHPFC, with the concept of ribbed upper slab.

7 Acknowledgments

The author thanks the Swiss Federal Roads Authority (FEDRO) which provided the necessary financial support for this investigation.
The topological optimization was performed using the ANSYS program from ANSYS Inc.

References

Bendsoe, M. P., 1995, Optimisation of Structural Topology, Shape, and Material, Springer-Verlag Berlin Heidelberg, Berlin, Germany.

Sigmund, O., 2001, A 99 Line topology optimisation code written in Matlab, Structural and Multidisciplinary Optimisation 21, pp. 120-127.

Samyn, P., 2004, Etude de la morphologie des structures, Académie Royale de Belgique, Belgique.

Muttoni,A., 2004, L'art des Structures, Presses polytechniques et universitaires romandes, Lausanne, Switzerland.

Muttoni, A., 2002, Two bridges with composite prestressed tension chords, Structural concrete in Switzerland, SIA, Zurich, Switzerland, pp. 72-75.

Menn C., 1982, Comparison of costs and material quantities for some highway bridges in Switzerland, Prestressed Concrete of Switzerland, Techniche Forschungs-und Beratungsstelle der Schweizerischen Zementindustie, Wildegg, Switzerland, pp. 41-48.

Benouaich, D., Badoux, M., Burdet, O., 2000, Précontrainte extérieure des ponts, Ecole Polytechnique Fédérale de Lausanne, Lausanne, VSS, Zurich, Switzerland.

Park, H., Chuang, E., Ulm, F.-J., 2003, Model-Based Optimisation of Ultra High Performance Concrete Highway Bridge Girders, Massachusetts Institute of Technology, Cambridge, USA.

Simon, A., Hajar, Z., 2002, Realisation of two road bridges with Ultra-High-Performance Fiber-Reinforced Concrete, Proceedings of 6th Int. Symposium of utilization of High Strength / High Performance Concrete, Leipzig, pp. 753-768.