CABLE STRETCHING FORCE OPTIMIZATION IN CABLE-STAYED BRIDGES

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ABSTRACT

Cable stretching optimization problems may basically be of two types: *a)* finding the installation forces of the cables, so as that feasible minimum cost design and the dead load geometry condition are met; *b)* finding the adjustment forces which correct errors in deflections under control while resulting in minimum stress increase in further erection stages and final structure. In the first type one intends to simultaneously optimize cable prestressing, sizing and shape design variables so as to get minimum structural cost. In the latter it is assumed that a structure is under construction. Therefore, design variable set consists only of cable prestressing changes. This paper discusses some of the main issues of such problems and the approaches undertaken by the authors to handle them. Illustrative examples of both types are briefly presented.

KEYWORDS

Cable-stayed bridges, Stretching forces, Multicriteria Optimization

INTRODUCTION

Some authors [1],[2] investigated the cost optimization of cable-stayed bridges using sizing and shape design variables. The problem of optimizing either the global or corrective stretching forces set was dealt with in [3],[4]. However, the obvious issue of combining sizing/shape with prestressing design variables, which provides suitable and realistic optimal solutions, has not yet been attempted. On the other hand, most studies concerning the optimization of cable forces rely on the use of an influence coefficient matrix which assumes the validity of the linear model and whose determination is a lenghty and expensive process, namely when a multi-cable system is considered. Besides, analysis and optimization tools used in such problems are often independent software tools, requiring the development of specific interfaces for pre- and post-processing in order to organize data in the proper format required for each module. Besides ensuring interfacing among modules, these must also provide for automatic data updating, because the current design is continuously changing throughout the optimization process. Therefore, no matters how powerful the optimization algorithm is, the effectiveness of the whole process may result seriously affected unless such interfacing tools are available.

CIAO PROGRAMME

These considerations were on the basis of the development of a F.E. based integrated analysis and optimization software package, suited to the predimensioning of cable-stayed bridges. The programme was named CIAO, standing for "Cable-stayed bridges Integrated Analysis and Optimization". Aware of the misconfort of the typical civil engineering professional towards Mathematical Programming techniques, the authors adopted an user-friendly philosophy in code implementation. Some interactive resources are also provided so as the solution process may be monitored by those interested.

A brief description of the programme features concerning this specific study shall be made in the following sections. For a more detailed description readers are committed to references [5]-[7].

Design variable library

A great variety of parameters related to the cross-sectional description of structural elements, overall geometry and cable and deck prestressing may be considered in selecting a trial design for a cable-stayed bridge. Thus, it is desirable that a wide choice of potential design variable types is available. For this purpose, the concept of *design variable library* was used. When structural cost optimization is intended, the best solutions result from mixing sizing, shape and prestressing parameters. Therefore, all the three kinds of design variables were included in the library. Figures 1-2 represent the currently available types. One must notice that only shape design variables are structure dependant and therefore other structural systems may be handled by the programme, on the condition that only sizing optimization is considered.

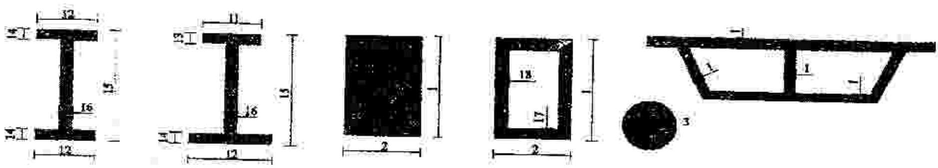

Fig. 1 - Sizing design variable types

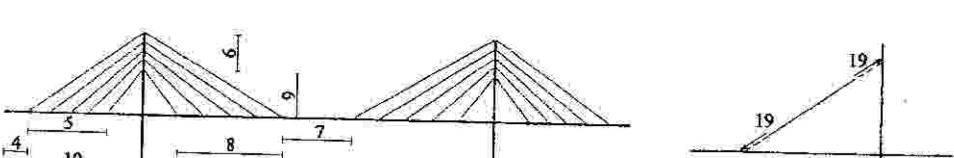

Fig. 2 - Shape and cable stretching design variable types

The variable linking with the finite element mesh is provided through a *dependancy matrix*, which is a constant integer array in which the position of the *i-j* coefficient defines the link between element number *i* and design variable *j*, whose type is defined, from the library set, by the coefficient value, 0 standing for no direct linking.

Sensitivity analysis

Cable-stayed bridge structural optimization problems may easily involve as much as 100 design variables. On the other hand, depending on the level of discretization of cross-sectional dimensions, critical design conditions may take place all over the structure. This issue makes difficult the use of a constraint deletion strategy based on potentially critical regions, namely when multiple static and dynamic loading cases must be considered, which is the case if a reliable optimal solution is sought. Therefore, hundreds or even thousands of stress and displacement (for the problem of geometry control) constraints must be accounted for.
The analytic discrete direct method was selected for sensitivity analysis, given the availability of the F.E. source code.

Erection stages

A realistic design of a cable-stayed bridge must account for the erection stages leading to the final structure. This problem is usually handled by a backward analysis. This approach, however, is unsuitable for the purpose of structural optimization, because all the information regarding stresses, displacements and their sensitivities must be simultaneously available at the end of an analysis step and prior to calling the optimization module.
To handle this problem, the cronological sequence corresponding to the erection stages set was represented by a physical discretization. A discontinuous overall structure, made up of the complete as well as the representative intermediate structures, is generated. The resulting stiffness matrix is composed of uncoupled sub-matrices, leading to a moderate increase in solution process cost and allowing for simultaneous solution and sensitivity analysis.

Sag effect of the cables

The most significant source of nonlinear behaviour in cable-stayed bridges is the catenary effect of the stays. A number of procedures may be used to handle this problem, such as multiple-straight link, use of cable or catenary elements, etc. However, these require a pure geometrically nonlinear approach, which may be costly and cumbersome in the context of structural optimization. For that reason, the equivalent modulus or Ernst approach, allowing for the use of a pseudo-linear structural analysis, was adopted.

OPTIMIZATION FORMULATION

The methodology adopted in this paper leads to a unified approach for both optimization problems referred in the Introduction. By using the entropy-based multicriteria approach, the problem is formulated as the minimization of a scalar unconstrained convex function, with which an optimal solution (in the Pareto sense) is achieved for each starting trial design. Representing by $\underline{x}$ the design variable vector and by

$g_o(\underline{x}) = V / V_o - 1$		The cost constraint	(1)
$g_i(\underline{x}) = \sigma_i / \sigma_o - 1$	$i = 1, M_s$	The stress constraints	(2)
$g_j(\underline{x}) = \delta_j / \delta_o - 1$	$j = 1, M_k$	The kinematic constraints	(3)

the optimization problems may be posed as

$$\text{minimize} \qquad F(\underline{x}) = \frac{1}{\rho} \ln \sum_{j=s,M} e^{\rho g_j(\underline{x})} \tag{4}$$

where $M=M_s+M_k$ is the total number of behaviour constraints, σ_o is the allowable stress, δ_o is some specified tolerance for controlled total or corrective deflections and s depends on the type of optimization problem under consideration:

s=0 for cost minimization problems, in which case $\underline{x}$ will typically contain sizing/shape and prestressing design variables;

s=1 for optimization of corrective forces, in which case $\underline{x}$ will contain only prestressing design variables related to cable prestress increments (fixed sectional properties and geometry)

Two sample examples were chosen, each illustrating the adequacy of the proposed method to solve both of these optimization problems.

EXAMPLES

In Example 1, the cost optimization of a symmetric cable stayed-bridge with the geometry shown in Figure 3 is used. A three-dimensional analysis is undertaken. Four load cases are considered: live load on the whole span or either on side or central span and, additionally, dead load condition as required for deflection control. Two I-shaped plate girders in the edges of the deck support transverse beams. The pylons are made up with rectangular hollow cross sections. The cantilevering method is assumed as the erection process and the corresponding stages are included in the analysis model. Only vertical deck-to-pylon connection is provided, except for the early erection stages in which stability requires additional links. Diagonal rigid bar elements provide for the transverse deck stiffness.

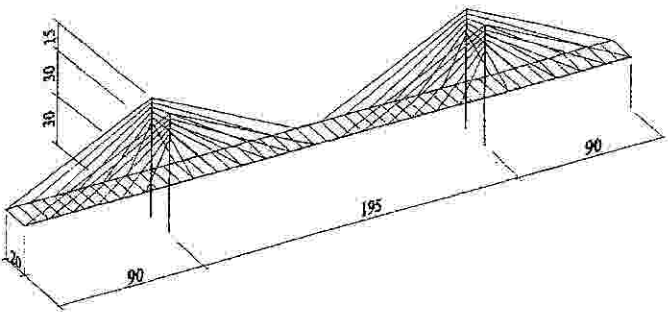

Figure 3 - Geometry of starting trial design

A total number of 55 design variables is considered. Numbers 1 through 41 are sizing design variables concerning the web and flange thicknesses and width for girders, transverse beams and pylons, as well as the cross-sectional area for the stays. Design variables 42-53 concern the fixed-end prestressing forces for the stays, while variables 54-55 are geometric type design variables, allowing for the change of height and cable end blocks positions of pylons.

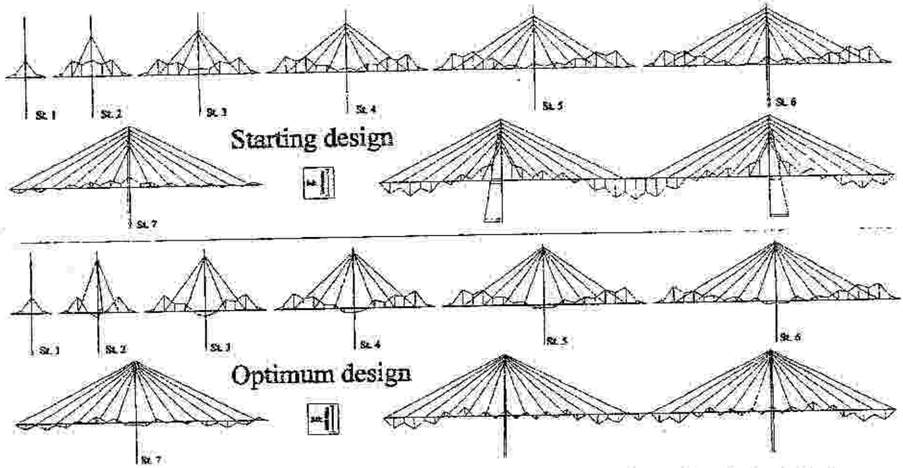

Figure 4 - Bending moments for dead-load condition in starting and optimized designs

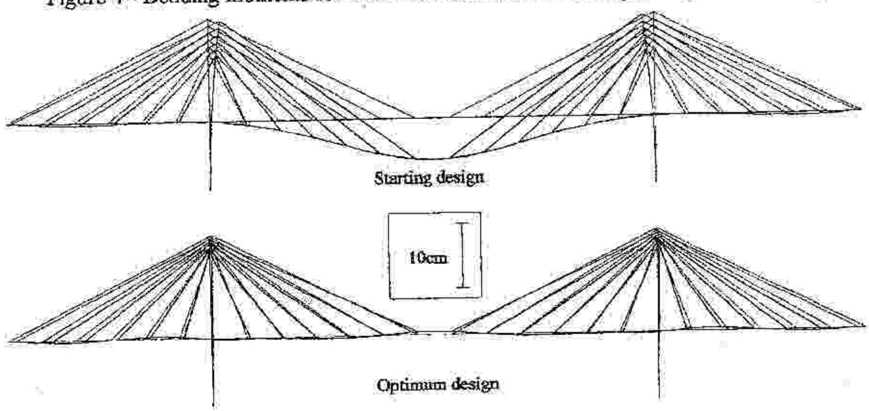

Figure 5 - Deflections in dead load condition for starting and optimized designs

Stay #	1	2	3	4	5	6	7	8	9	10	11	12
Start.	2046	2838	2496	2250	1958	1513	1513	1958	2250	2496	2838	2194
Opt.	2118	2947	2390	2149	1965	2080	1959	1847	2152	2425	2749	2416

Table 1 - Prestressing forces in starting and optimum designs of Example 1 (KN)

The overall cost reduction was about 30%, with all the structural elements being assigned the same volumic cost factor. In spite of the apparently slight changes of prestressing forces, one must

notice that the optimized structure is lighter than the starting design, which makes those forces much more effective in suspending the deck and reducing the deflections.
For example 2 one assumes that a deflection control session takes place after stage 5 is erected and the deviations from measured to expected vertical deflections, in the positions of stays end-blocks, are as shown in Table 2. Stays 1-2 and 11-12 are still to be installed, but the side cantilevers in each side of the deck extend to the position of cable 2 and 11 end blocks.

Stay #	1	2	3	4	5	6	7	8	9	10	11	12
Δ	-	+2	+3	+2	0	0	0	0	+2	+3	+4	-

Table 2 - Deviations from expected deflected shape of stage 5 ($\Delta = \delta_{measured} - \delta_{expected}$) (cm)

A new optimization problem is undertaken to find the adjustments in stays which correct these spurious displacements while resulting in minimum increase in further erection stages and final structure. Owing to the fact that the corrected solution matches the expected geometry for stage 5 of the bridge and that linear behaviour is assumed for this corrective step, no changes will result in the final deflected shape and in stresses concerning those parts still to be erected by the time of the adjustment operation. Thus, only displacements of stage 5 itself and stresses in elements shared by stages 5,6,7 and final structure are to be used as goals. Also, only 8 design variables are used, concerning the prestressing forces in stays 3 through 10. The initial and final forces in these cables and in stage 5 are shown in Table 3. The corrective additional stretching forces can be found now by either using the influence pattern of the cable forces or, if the operation is controlled by measuring the cable elongation, by simply computing the additional shim thickness from the increase of the fixed-end prestressing forces and the tangent modulus of each concerned stay.

Stay #	1	2	3	4	5	6	7	8	9	10	11	12
Bef.	-	-	2390	1529	1103	1024	1143	943	1563	2425	-	-
After	-	-	2416	1513	1053	1086	1259	844	1548	2462	-	-

Table 3 - Forces in stays and stage 5 before and after corrective stretching (KN)

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