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Advanced Cable Stayed Bridge Construction Process Analysis with ANSYS

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Abstract: *This paper demonstrates how sophisticated computational techniques can help to understand better the behaviour of cable-stayed bridges and what kind of tools are available for bridge engineers to handle even the most extreme situations. Since one of the key elements in the success of this structural system lies in its construction method, the main focus of this paper is on the simulation of the free-cantilever construction process and the determination of cable forces during the phases of the erection in order to achieve the desired shape and internal force distribution in the final state of the structure. The paper, using ANSYS/CivilFEM, a software package developed for advanced civil engineering analyses, presents different numerical techniques (based on both linear and non-linear analysis) to determine the final state of the bridge and the backward process analysis to conduct a step-by-step analysis of the construction.Finite Element Analysis can provide engineers with an overwhelming amount of data therefore the efficient presentation of results (post processing) is of outmost importance especially for such complex systems as cable-stayed bridges.The paper also demonstrates how the flexibility of ANSYS/CivilFEM allows the users to find a sensible way to access all the necessary data and produce both texts based and graphical outputs. A typical example of a cable-stayed bridge is analyzed by the methods described in the paper and the results are presented using post processing techniques.Cable stayed bridges have good stability, optimum use of structural materials, aesthetic, relatively low design and maintenance costs, and efficient structural characteristics. Therefore, this type of bridges are becoming more and more popular and are usually preferred for long span crossings compared to suspension bridges. A cable stayed bridge consists of one or more towers with cables supporting the bridge deck.In terms of cable arrangements, the most common type of cable stayed bridges are fan, harp, and semi fan bridges. Because of their large size and nonlinear structural behaviour, the analysis of these types of bridges is more complicated than conventional bridges. In these bridges, the cables are the main source of nonlinearity. Obtaining the optimum distribution of post-tensioning cable forces is an important task and plays a major role in optimizing the design of cable stayed bridges. An optimum design of a cable-stayed bridge with minimum cost while achieving strength and serviceability requirements is a challenging task.In this thesis, an advanced and comprehensive numerical model is used to obtain the post-tensioning forces and the optimum design of the three types of cable-stayed bridge. The numerical method is based on finite element, B-spline curves, and real coded genetic algorithm. The optimization accounts for all the variables that define the geometry and cross-section of the bridge. Comparison between the three types, in terms of post-tensioning forces and cost, is carried out in this thesis.*

Keywords: *Dynamic Mechanic Analysis, Stability Isolated Base, Non Linear Response Cable, Pre-Stressing Load.*

I. Introduction

Civil FEM is a customization of the finite element analysis software ANSYS, which has the aim to approach the Civil Engineering World with the general purpose tools of ANSYS. The structure of Civil FEM is made up of a main program, called Civil FEM Intro, onto which several specific modules of Civil Engineering applications can be added: Bridges, Prestressed Concrete and

Geotechnics.

The first of these modules has utilities for modeling and analyze virtually any bridge types:

- Metallic bridges.
- Prestressed concrete bridges.
- Mixed or composite bridges.

With different types of supports:

- Simple supports.
- Suspension bridges.
- Cable-Stayed bridges.
- Arch bridges.

The history of cable stayed bridges dates back to 1595, found in a book by the Venetian inventor (Bernard et al., 1988). Many suspension and cable-stayed bridges have been designed and developed since 1595 such as the Albert bridge and the Brooklyn bridge (Wilson and Gravelle, 1991), (Bernard et al., 1988). Cable-stayed bridges have been later constructed all over the world. The Swedish Stromsund bridge, designed in 1955, is known as the first modern cable-stayed bridge (Wilson and Gravelle, 1991).

The total length of the bridge is 332 m, and its main span length is 182 m. It was opened in 1956, and it was the largest cable-stayed bridge of the world at that time. This bridge was constructed by Franz Dischinger, from Germany, who was a pioneer in construction of cable-stayed bridges (Tori et al., 1968). The designers realized that cable stayed style requires less material for cables and deck and can be erected much easier than suspension bridges (Bernard et al., 1988), (Tori et al., 1968), (Wilson and Gravelle, 1991), (Simoes and Negrao, 1994), (Ren and Peng, 2005), and (Nieto et al., 2009).

This is mainly due to advances in design and construction method and the availability of high strength steel cables. The Theodor Heuss bridge was the second true cable-stayed bridge and was erected in 1957 across the Rhine river at Dusseldrof. It had a main span of 260 m and side spans of 108 m which was larger than the Stromsund.

It has a harp cable arrangement with parallel stays and a pylon composed of two free-standing posts fixed to the deck. The reason for choosing the harp style was aesthetics appearance. The Severins Bridge in Köln designed in 1961 was the first fan shape cable stayed bridge, which has a A-shape pylon.

In this bridge, the cross section of the deck was similar to the one used in Theodor Heuss bridge (Bernard et al., 1988). The Flehe bridge was the first semi-fan type which was erected in 1979 in Dusseldrof, Germany over the Rhine river. The remarkable feature of this bridge was the reinforced concrete tower, which has the shape of an inverted Y (Bernard et al., 1988). In what follows, the main types of long span bridges are reviewed.

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II. Study Area

2.1 Analysis Algorithm

The purpose of the analysis is to study the stresses the cables must have during the construction phases, to achieve at the end of the construction and for a specified load state, a certain deformed shape of the deck (usually null movements). To obtain this, the following process calculates the structure at its final stage, obtaining this way the final stresses in the cables and, step by step, removes the cables and deck elements in the opposite order to the building procedure (backward analysis).

Apart from movements, forces and moments in towers and deck, at each step the forces in the cables are also obtained. The prestressing load in each cable is equal to the force in the cable in the last calculation step before the cable is "killed", i.e. removed from the model. The calculation steps can be described as follows:

1. Cable forces are calculated for the final state of the bridge (all the cable elements are alive):

- The deformations of the deck due to the self weight of the structure and additional dead load is calculated using linear analysis.
- Every cable is prestressed by unit change in the length (-1 m) one by one (the other cables are assumed to be stress free) and the deformations of the deck are calculated for each case using linear analysis.
- A system of linear equations is assembled: $K \cdot f = u$. The response of the structure – the "stiffness of the structure" - to the unit cable shortening are the elements of the coefficient matrix (K). The deformations (UY of the deck and UX of the tower top) are the elements of the vector on the right-hand side (u).
- The system of linear equations is solved and f is determined. The elements of the f vector are the actual cable shortening required to achieve the desired shape of the structure.

The f vector is applied as cable shortening and the structure is solved again.

2. Nonlinear construction process analysis: backward analysis ('demolishing' the bridge step by step)

- Remove additional dead load.

- Remove the last section of the deck.
- Loop over the rest of the structure:
- remove one cable (kill cable element).
- remove one segment of the deck (kill deck element).

2.2 Process Automation

To make this task easier, Civil FEM's Bridge Module has programmed Wizards which will generate the model of the structure from its geometrical characteristics and materials, and will create the different load steps and solve the analysis procedure described in the previous section and shown in Fig.2.1 & Fig. 2.2

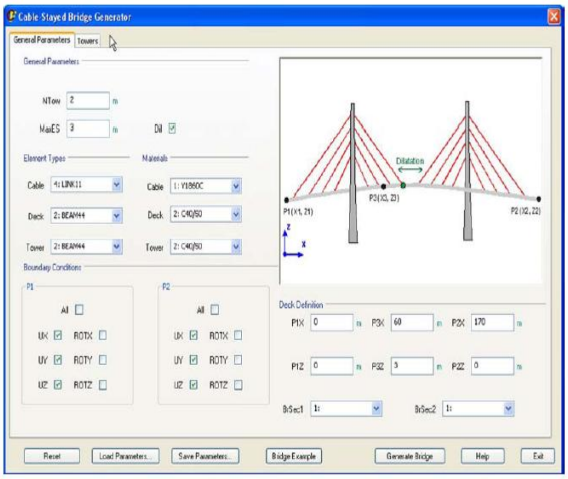

Figure 2.1 Cable-Stayed Bridge Generator 1

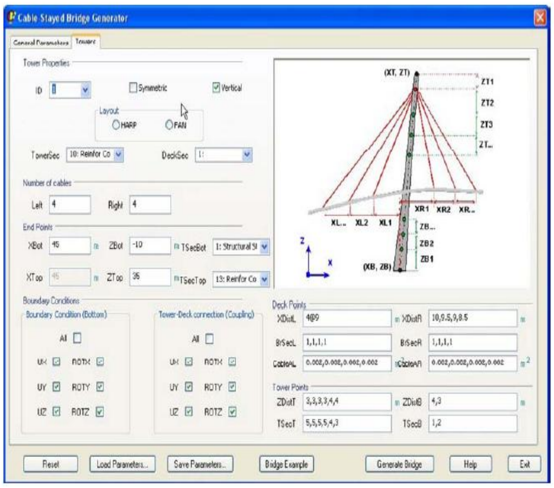

Figure 2.2 Cable-Stayed Bridge Generator 2

III. Finite Element Model

The finite element models for three main arrangement of cable-stayed bridges are the same as the ones given and are plotted in Figs for semi-fan, fan, and harp arrangements, respectively. As one can see, the three main components, i.e., pylon, girder, and the stay cables are modeled using 3D line elements.

A three-dimensional frame element is used to model the deck and the pylon, while a three-dimensional cable element is used to simulate the cables. Also, the deck is modeled using a single spine passing through its shear center. Moreover, the translational and rotational stiffness of the deck are calculated and are assigned to the frame elements of the spine.

To achieve the proper offset of the cables from the centerline of the deck, the cable anchorages and the deck spine are connected by massless, horizontal rigid links (Wilson and Gravelle, 1991). These models will be incorporated in the next sections for optimal cost design of the three cable stayed arrangements.

3.1 Real Coded Genetic Algorithm

As explained before, the optimization technique and the cost optimization problem for cable-stayed bridges contains several local minima. Therefore, Genetic Algorithms (GAs) are employed in this study to find the global optimum solution for both arrangements of cable-stayed bridges.

Note that genetic algorithms (GAs) based on the theory of biological evolution and adaptation have proved to be powerful, efficient, capable of handling large number of variables, and robust in finding global optimal solutions (Gen and Cheng, 2000).

The real coded genetic algorithm (RCGA) is a variant of genetic algorithms that are suitable for the optimization of multiple-optima objective functions defined over continuous variables (Davis, 1991). The algorithm operates on the design variables, instead of encoding them into binary strings, as in the traditional genetic algorithms.

3.2 Genetic Operators

The mutation operators employed in Algorithm 3.1 allow the RCGA to avoid local minima. These operators search for solutions in remote areas of the objective function landscape (Hassan et al., 2012). The operators used in this study are the boundary mutation, non-uniform mutation, and uniform mutation. The boundary mutation searches the boundaries of the independent variables for optima lying there. Non uniform mutation is a random search that decreases its random movements with the progress of the search.

The Uniform mutation is a random search element. The crossover operators produce new solutions from parent solutions having good objective function values. In this study, it is used to produce new bridges from pairs of low cost bridge. The crossover operators used are the arithmetic, uniform and heuristic crossovers. The first produces new solutions in the functional landscape of the parent solutions.

Details of such operators are given by Michalewics and Fogel (2004) and recently employed in Hassan et al. (2012). The above operators are applied on each population with the following values:

1) Population size = 100 solution instances
2) 4 instances undergo boundary mutation.
3) 4 instances undergo non-uniform mutation.
4) 4 instances undergo uniform mutation.
5) 2 instances undergo arithmetic crossover.
6) 2 instances undergo uniform crossover.
7) 2 instances undergo heuristic crossover.

3.3 Post-tensioning Cable Forces

In the previous chapter, a numerical method is employed to obtain the post-tensioning cable forces for specific number of cables N, mid-span length M, and height of the pylon H. These forces are implemented in the analysis/design scheme employed in this chapter. However, in the design optimization process, the variables N, M, and H, can be assigned some random values that do not match the values considered. To overcome this issue, three-dimensional linear interpolation (N, M, and H) is conducted between the data points for the forces of post-tensioning cable forces evaluated.

3.4 Load Considerations

Dead load, wind load, and live load are considered in this thesis based on Canadian Highway Bridge Design Code (CAN/CSA-S6-06, 2006).

Dead Load

According to clause 3.6 of the CAN/CSA-S6-06 (2006), the dead load of the bridge contains the structural weight of the bridge, a thickness of 0.09 m layer of asphalt, and two concrete traffic barriers having an average thickness and height of 0.325 m and 0.85 m, respectively.

Live Load

To compute the live load acting on the bridge deck using clause 3.8.3.2 of the CAN/CSA-S6-06 (2006) the following two cases are considered:

- CL-W truck.
- CL-W truck with each axle reduced to 80% and superimposed with a uniformly distributed load (qL = 9kN=m) lane.

In short and medium span cable-stayed bridges, the main effect always results due to a single axle, group of axles, or single truck. For long span cable-stayed bridges, the critical force effect and largest deflection are due to the distributed lane loads. Hence, the live load acting on the bridge deck in this study is given as:

$$\text{Liveload} = mFnLaneqL$$

where mF is the modification factor used when more than one design lane is loaded according to clause 3.8.4.2, and Table 3.8.4.2, of CAN/CSA-S6-06 (2006), nLane, is the number of the lanes, and qL = 9kN=m is the uniformly distributed load. The nine live load configurations applied to determine the optimum cost design of three type of the cable-stayed bridge are shown in Fig.3.1 (Walther et al., 1988). The live load is calculated using the equation. It has a magnitude equal to 16.2 kN=m and 25.2 kN=m for the case of two and four lanes, respectively CAN/CSA-S6- 06 (2006).

Wind Load

Cable-stayed bridges are considered sensitive to wind load. Therefore, wind tunnel tests are required to determine the lift (CN), torsional (CM), and drag (CD) shape coefficients of the deck.

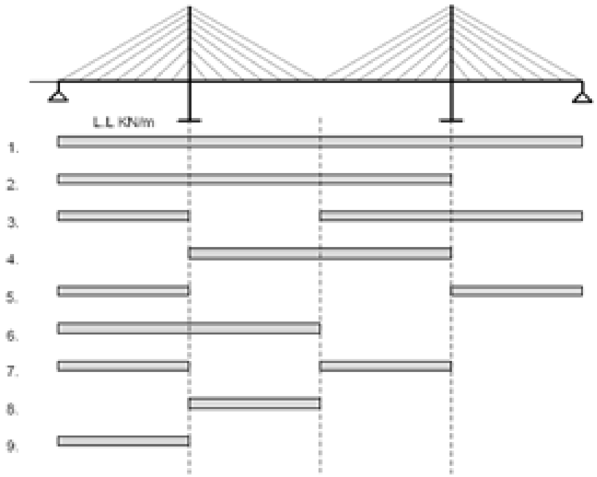

Figure 3.1: Live load cases used in the numerical model

IV. Conclusion

The algorithm described provides an accurate method to obtain the needed prestressing forces in the cables of a cable-stayed bridge, for each of the construction phases. This method allows to solve the bridge in a very short time, which provides obvious benefits compared with other optimization methods, without having to use approximations.

This accurate and rapid performance, in conjunction with the preprocessing utilities available, allows the engineer to spend more time in shape design optimization and allows to compare different solutions to obtain the best suitable one.

The postprocessing of the bridge analysis provides a quick review of the structural behavior. It also gives valuable information for the construction of the bridge by automatically exporting the prestressing forces of each cable, at each construction step.

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