완도대교의 최적 케이블장력 및 제작 Camber 산정에 관한 연구

A Study on Optimal Cable Prestressing and Fabrication Camber of Wando Bridge

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Abstract

Cable-stayed bridge is a bridge that consists of one or more pylons, with cables supporting the deck. Cable-stayed bridges have come into wide use recently because of their economy, stability, and excellent appearance. It is possible to achieve a uniform moment distribution in the stiffening girders mainly by prestressing the cables, which leads to a more economical design in material and weight than other types of bridges. However, to achieve a more uniform moment distribution is vague objective, so it cannot be easily defined as the optimization problem. In other words, the minimization of cost or weight as the objective is not directly related to the optimization of cable prestressing. Therefore, it has been considered as one of the most important, difficult and also interesting topics among many researchers and bridge engineers to determine the optimal tensioning strategy how to apply prestressing forces of the cables of cable-stayed bridge.

A number of approaches (Wang *et al.* 1993, Negrão and Simões 1997, Agrawal 1997, Janjic *et al.* 2003) to determine the optimal cable tensions have been proposed in the literature. Among these approaches the unit load method (Janjic *et al.* 2003) is considered in this paper because it can take into account the actual construction process while other approaches are based on the configuration of the final structure only. In this paper, "2-step approach" based on the unit load method is proposed to find the optimal tensioning strategy especially for the atypical asymmetric bridge under construction, which has continuous deck supported by one pylon and stay cables. Some numerical results will be given to show the validity of the new approach suggested in this paper.

1. Introduction

Although the idea of supporting a beam with inclined tension members has its origin in Egyptian sailing boats where stay ropes were used to support cross beams (Leonhardt and Zellner 1991), the first modern cable-stayed bridge was the Strömsund Bridge in Sweden opened to traffic in 1956, which could be regarded as the start of an impressive development of the cable-stayed system (Gimsing 1999).

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The systematic calculation of cable forces performed in the construction of the Strömsund Bridge opened a new era for cable-stayed bridges. Recent record of the span length progressed rapidly, passing from 465 to almost 900 m; it is now expected that 1200 m will be reached soon. Cable-stayed bridges have also developed in directions other than very long spans: flexible decks, extradosed cables and multispan cable-stayed bridges which will certainly receive a wider development for large projects (Virlogeux 1999). The state-of-the-art in modern cable-stated bridges can be found in the reference paper (Ito 1996).

The main components of cable-stayed bridges, i.e. the pylon, the deck, and the cable stays, govern the distribution of member forces more significantly as the length of a bridge becomes longer. The longer bridge is, the more cables are required; and it makes the cable-stayed bridges with multiple stays highly redundant and very difficult to be analyzed with good accuracy. In spite of the difficulties involved in the analysis of a bridge, a long span cable-stayed bridge has attracted many bridge engineers to take it in their project thanks to the slenderness of the modern bridge girders, which made it imperative for the bending moments to remain within tight limits throughout the construction process. It is crucial to achieve a desired optimal bending moment distribution in the final stage of the structure, the main applied loads of which are self weight, prestressing forces of cables, and the second dead loads are weights of barriers, parapets, pavements and etc. The determination of the moment distribution for the final stage is an important step in the design procedure because it is one of the main check-lists to be reviewed in the tender design. Lots of papers can be found in the literature on this issue, i.e. how to determine the optimal bending moment distribution in the final stage (Negrão and Simões 1997, Simões and Negrão 2000, Wang *et al.* 1993, Behin and Murray 1992, Lazar *et al.* 1972, Trotisky 1998, Gimsing 1997, Agrawal 1997, Chen *et al.* 2000). It is noted here that most of these researches have been focused on the typical symmetric cable-stayed bridges.

It is the main concern of this paper to present a new method that can be easily applicable to atypical asymmetric cable-stayed bridges. Reviews on the optimization problems in cable-stayed bridges are given in section 2. In section 3 the new approach, especially valid for asymmetric type of cable-stayed bridges, to attain optimal cable prestressing forces is proposed with minor modification of the unit load method. Numerical example is given in section 4 to show the validity of the new approach presented in section 3. In the following section, conclusions are drawn based on the numerical study performed in this paper.

2. Review of Optimization Problems in Cable-stayed Bridges

A number of approaches found in the literature to achieve appropriate initial cable forces can be classified into two main categories as follows: (1) the methods based on the configuration of the final structure, e.g. ZDM(Zero Displacement Method), OM(Optimization Method) and FQM(Force eQuilibrium Method); (2) the method based on the actual construction process.

Wang *et al.* (1993) suggested ZDM in which the tensioning forces are calculated based on the desired geometrical profiles of a bridge assuming that the girder is a continuous beam strongly supported at cable anchorages. OM determines the tensioning forces by minimizing the objective function designed carefully by relating it to structural efficiency or economy (Negrão and Simões 1997, Simões and Negrão 2000). FQM utilizes the idea of force equilibrium to find the optimized cable tensioning forces. The interaction among tower, cables and deck is taken into account, and the unknown cable forces are obtained through an iteration process. Though these methods can give the desired tensioning forces within their own criteria, there remains a disadvantage that the appropriate precamber should be carefully introduced to define the final geometry of a bridge before the tensioning procedure is defined (Behin and Murray 1992, Chen *et al.* 2000). It is noted that these solutions are only applicable to the final structures and do not take into account of the constructional procedures of a bridge. Hence, the resulting values from these methods may be impractical in some cases.

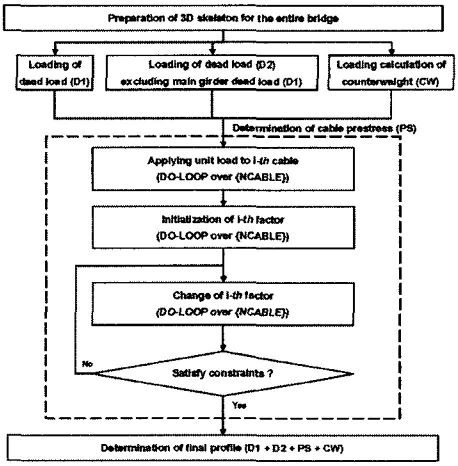

Figure 1. ULM(Unit Load Method)

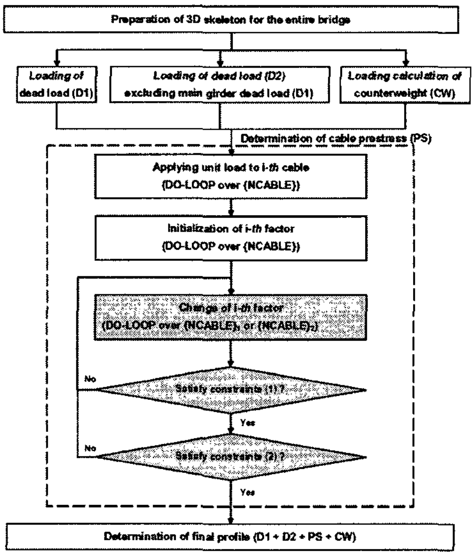

Figure 2. Two-step approach (this study)

To overcome the drawbacks of the aforementioned three methods, i.e. ZDM, OM, and FQM, that are based on the final configuration of the structure, ULM(Unit Load Method) has been suggested by Janjic *et al.* (2003). ULM determines the adequate factors which should be multiplied to the applied unit loads based on a certain desired criteria such as moments and deflections. This method allows the definition of a desired-moment distribution in the final structure under dead load.

The main advantage of ULM is that it can provide tensioning strategy during the individual construction stages taking into account time-dependent effects, such as creep and shrinkage or relaxation of prestressing tendons, and geometrically nonlinear behavior. The tensioning strategy obtained by ULM will give the same distribution in the final structure under dead load. Figure 1 shows the main procedure to determine the optimized prestressing forces using ULM suggested by Janjic *et al.* (2003), where {NCABLE} is a cable set whose i-*th* prestressing force is obtained by multiplying the final i-*th* factor by the corresponding i-*th* unit load.

3. New Approach: Two-step Method

ULM described in section 2 is taken as a fundamental method considering its easy extensibility and applicability to real construction engineering problems involved in the Wando Bridge, which will be introduced in the following section. As a first step of this study, ULM was applied without any modification. It was found that ULM has room for further improvement from the fact that it does not produce well-distributed cable forces and girder moments (see Figure 6 and Figure 7). This unsatisfactory results obtained by ULM results from the atypical characteristics of the Wando Bridge, e.g. the proximity effect between cable 15 and 16 (see Figure 5), the big difference of the length between main and side span, the continuous girder over the whole length of the bridge, and so forth. From authors' point of view, the results can be improved if additional constraints other than displacement criteria, which meet the case of atypical cable-stayed bridges, are introduced. Therefore, an additional iteration loop is added to ULM as shown in Figure 2 for the purpose of introducing the upper and/or the lower bounds for the cable force(s) of special interest. In Figure 2, the cable set $\{\text{NCABLE}\}_k$ and the corresponding constraints (k) are used during k-th DO-LOOP. For the clear explanation, detailed treatment of constraints will be addressed in the following section using numerical example.

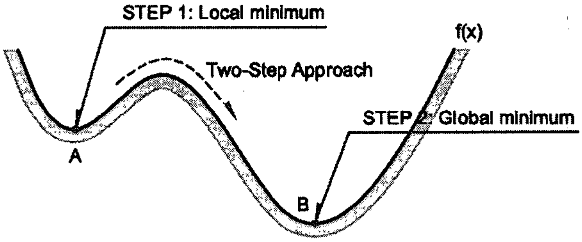

Figure 3. Concept of two-step approach

The concept of the two-step approach is shown in Figure 3 where point A is the nearest local minimum from global minimum (point B) and f(x) is a strain energy function or a cost function of the system. Two-step approach, in which constraints are imposed both on the nodal displacements and on the cable forces simultaneously over DO-LOOPs, plays a role to overpass the hill from point

A to point B. It is noted here that the two-step approach is not necessary if point A and point B are identical as in the case of typical cable-stayed bridges with symmetric cable arrangements.

4. Numerical Example

The Wando Bridge now under construction is located between the Wando island and the Haenam district which are located in the southern part of Korean peninsula. The height of pylon is 75 m, the width of girder is 30.4 m, and the total length of the bridge is 500m with main span length 200 m as shown in Figure 4. This asymmetric cable-stayed bridge is taken as an example to show how the new approach presented in this study works in determining the optimum prestressing forces of cables.

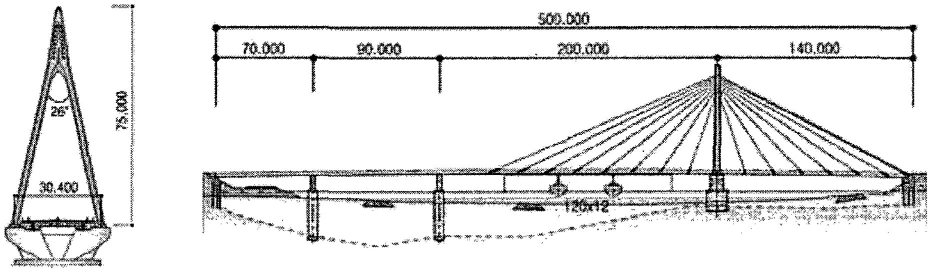

Figure 4. General arrangement of Wando Bridge (unit : m)

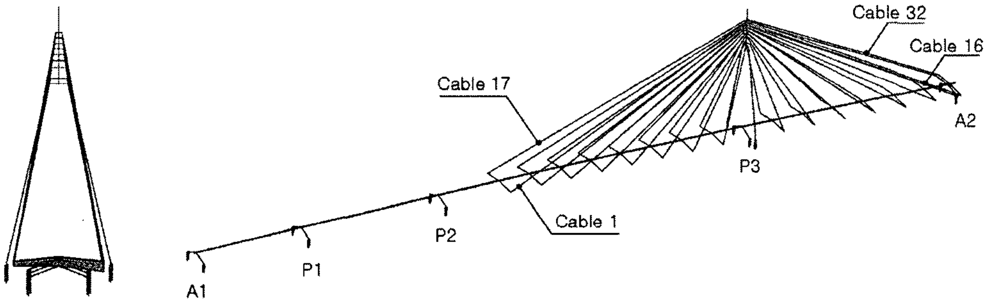

Figure 5. Modeling of the Wando Bridge

A conventional three-dimensional skeleton model was prepared for the analysis of the overall structure as shown in Figure 5. It is a fishbone model in which each girder is a single road and virtual members are extended to cable anchor points. The numbering of the cables is also illustrated in Figure 5.

From Figure 6 to Figure 10 show the results obtained by Method-I and Method-II, where Method-I and Method-II indicate the conventional ULM (see Figure 1) and the newly proposed "two-step approach" (see Figure 2), respectively.

The cable forces obtained by Method-I and Method-II are shown in Figure 6, where all the forces are in the acceptable range from 100 tonf to 450 tonf. The Method-II has "two-steps" as discussed in section 3. At the first step, it is required to select some cables of special interest which have excessive forces or show sudden changes in forces, e.g. cable 2, 16, 18, and 32, obtained by Method-I. At the second step, the additional constraints, in this case the upper bound (400 tonf) of cable forces, are artificially imposed to remove the unfavorable cable forces. In other words, the status of Method-I (point A of Figure 3) can be changed into that of Method-II (point B of Figure 3) simply by introducing the second step. No sudden changes in the cable forces are found in the results from Method-II while some excessive changes are found from Method-I. This implies the fact that the cross sectional areas of the adjacent cables vary widely and thus the efficiency of the bridge system may become lower, or the cost of the cables become higher.

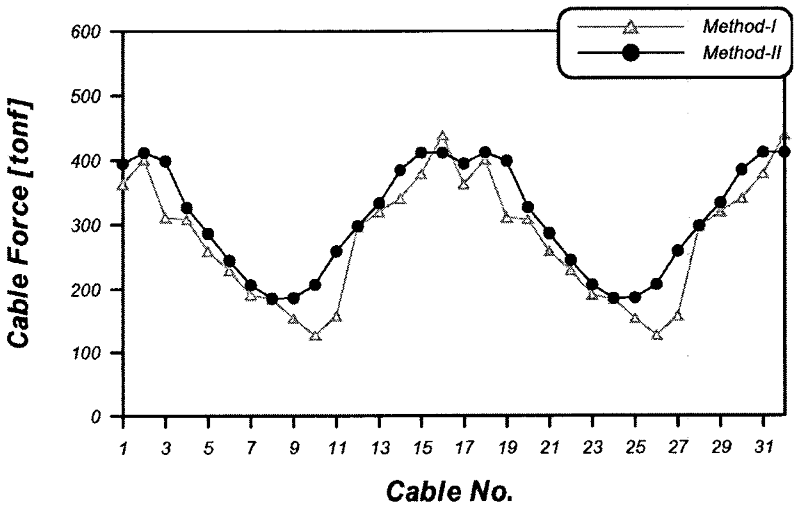

Figure 6. Cable forces

It is interesting that there are significant differences of two methods in the bending moment distribution as shown in Figure 7 over the range from 200 m to 500 m, which is supported by stay cables. It is noted that there exist no differences in the range from 0 m to 200 m, which also can be found in the shear forces, axial forces and displacements as shown in Figure 8~Figure 10. The differences of member forces, i.e. bending moments, shear forces, and axial forces, in the range from 200 m to 500 m affect the displacements significantly as shown in Figure 10. Considering the prefabrication camber, which is obtained by reversing the displacements of the main girder, it may not be acceptable to the manufacturer to have this fluctuations in main girder especially in the cable supported ranges. If the prefabrication camber is minimized as shown in this study using Method-II, it will be relatively easy for field engineers to control the geometrical configuration of the main girder during construction.

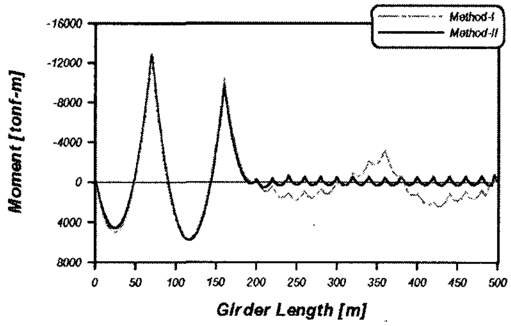

Figure 7. Bending moment diagram

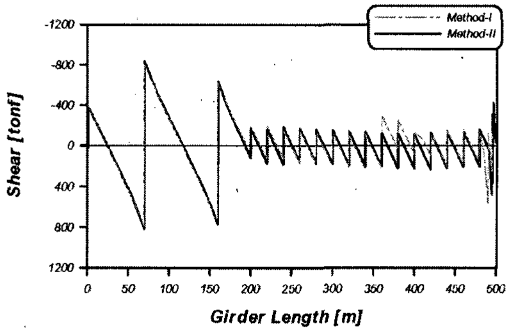

Figure 8. Shear force diagram

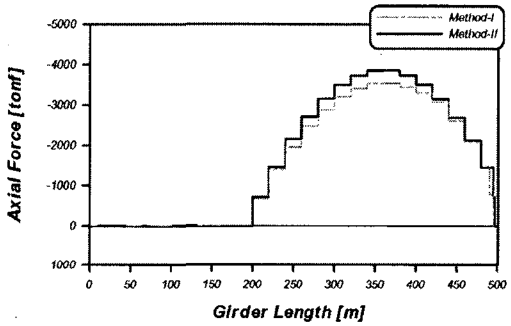

Figure 9. Axial force diagram

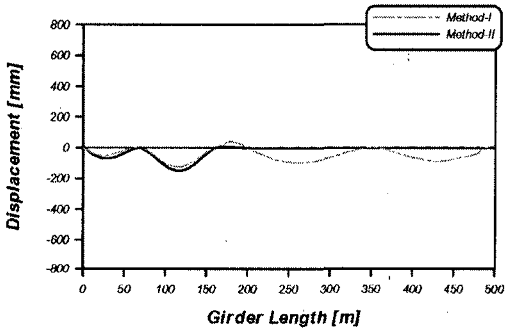

Figure 10. Displacement

5. Conclusions

Utilizing an idea of the unit load method, a new method named “two-step approach” is presented for the determination of an optimum scheme for the initial cable forces of an atypical asymmetric cable-stayed bridge. In the proposed method, new constraints for the cable force(s) of special interest are introduced in addition to the conventional displacement constraints of the unit load method. Numerical tests performed in this study show the efficiency and validity of the proposed method. Particularly, “two-step approach” proved its effectiveness in optimizing further the bending moment distribution as well as the cable forces of the Wando Bridge. It is also expected that the prefabrication camber calculated in this study by using the proposed method will contribute to the successful construction of the Wando Bridge with high quality.

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