# 7

# Cable Force Adjustment and Construction Control

Danjian Han
*South China University of Technology*

Quansheng Yan
*South China University of Technology*

## 7.1 Introduction

Due to their aesthetic appeal and economic advantages, many cable-stayed bridges have been built over the world in the last half century. With the advent of high-strength materials for use in the cables and the development of digital computers for the structural analysis and the cantilever construction method, great progress has been made in cable-stayed bridges [1,2]. The Yangpu Bridge in China with a main span of 602 m, completed in 1993, is the longest cable-stayed bridge with a composite deck. The Normandy Bridge in France, completed in 1994, with main span of 856 m is now the second-longest-span cable-stayed bridge. The Tatara Bridge in Japan, with a main span of 890 m, was opened to traffic in 1999. More cable-stayed bridges with larger spans are now in the planning.

Cable-stayed bridges are featured for their ability to have their behavior adjusted by cable stay forces [3–5]. Through the adjustment of the cable forces, the internal force distribution can be optimized to a state where the girder and the towers are compressed with little bending. Thus, the performance of material used for deck and pylons can be efficiently utilized.

During the construction of a cable-stayed bridge there are two kinds of errors encountered frequently [6,13]: one is the tension force error in the jacking cables, and the other is the geometric error in controlling the elevation of the deck. During construction the structure must be monitored and adjusted; otherwise errors may accumulate, the structural performance may be substantially influenced, or safety concerns may arise. With the widespread use of innovative construction methods, construction control systems play a more and more important role in construction of cable-stayed bridges [18,19].

There are two ways of adjustment: adjustment of the cable forces and adjustment of the girder elevations [7]. The cable-force adjustment may change both the internal forces and the configuration of the structure, while the elevation adjustment only changes the length of the cable and does not induce any change in the internal forces of the structure.

This chapter deals with two topics: cable force adjustment and construction control. The methods for determing the cable forces are discussed in Section 7.2, then a presentation of the cable force adjustment is given in Section 7.3. A simulation method for a construction process of prestressed concrete (PC) cable-stayed bridge is illustrated in Section 7.4, and a construction control system is introduced in Section 7.5.

## 7.2 Determination of Designed Cable Forces

For a cable-stayed bridge the permanent state of stress in a structure subjected to dead load is determined by the tension forces in the cable stays. The cable tension can be chosen so that bending moments in the girders and pylons are eliminated or at least reduced as much as possible. Thus the deck and pylon would be mainly under compression under the dead loads [3,10].

In the construction period the segment of deck is corbeled by cable stays and each cable placed supports approximately the weight of one segment, with the length corresponding to the longitudinal distance between the two stays. In the final state the effects of other dead loads such as wearing surface, curbs, fence, etc., as well as the traffic loads, must also be taken into account. For a PC cable-stayed bridge, the long-term effects of concrete creep and shrinkage must also be considered [4].

There are different methods of determining the cable forces and these are introduced and discussed in the following.

### 7.2.1 Simply Supported Beam Method

Assuming that each stayed cable supports approximately the weight of one segment, corresponding to the longitudinal distance between two stays, the cable forces can be estimated conveniently [3,4]. It is necessary to take into account the application of other loads (wearing surface, curbs, fences, etc.). Also, the cable is placed in such a way that the new girder element is positioned correctly, with a view to having the required profile when construction is finished.

Due to its simplicity and easy hand calculation, the method of the simply supported beam is usually used by designers in the tender and preliminary design stage to estimate the cable forces and the area of the stays. For a cable-stayed bridge with an asymmetric arrangement of the main span and side span or for the case that there are anchorage parts at its end, the cable forces calculated by this method may not be evenly distributed. Large bending moments may occur somewhere along the deck and/or the pylons which may be unfavorable.

### 7.2.2 Method of Continuous Beam on Rigid Supports

By assuming that under the dead load the main girder behaves like a continuous beam and the inclined stay cables provide rigid supports for the girder, the vertical component of the forces in stay cables are equal to the support reactions calculated on this basis [4,10]. The tension in the anchorage cables make it possible to design the pylons in such a way that they are not subjected to large bending moments when the dead loads are applied.

This method is widely used in the design of cable-stayed bridges. Under the cable forces calculated by this method, the moments in the deck are small and evenly distributed. This is especially favorable for PC cable-stayed bridges because the redistribution of internal force due to the effects of concrete creep could be reduced.

### 7.2.3 Optimization Method

In the optimization method of determining the stresses of the stay cables under permanent loads, the criteria (objective functions) are chosen so the material used in girders and pylons is minimized [8,11]. When the internal forces, mainly the bending moments, are evenly distributed and small, the quantity of material reaches a minimum value. Also the stresses in the structure and the deflections of the deck are limited to prescribed tolerances.

In a cable-stayed bridge, the shear deformations in the girder and pylons are neglected, the strain energy can be represented by

$$U = \frac{1}{2}\int_0^L \frac{M^2}{2\ EI}dx + \frac{1}{2}\int_0^L \frac{N^2}{2\ EA}dx \tag{7.1}$$

where $EI$ is the bending stiffness of girder and pylons and $EA$ is the axial stiffness.

It can be given in a discrete form when the structure is simulated by a finite-element model as

$$U = \sum_{i=1}^{N} \frac{L_i}{4\ E_i}\left(\frac{M_{il}^2 + M_{ir}^2}{l_i} + \frac{N_{il}^2 + N_{ir}^2}{A_i}\right) \tag{7.2}$$

where $N$ is the total number of the girder and pylon elements, $L_i$ is the length of the $i$th element, $E$ is the modulus of elasticity, and $I_i$ and $A_i$ are the moment of inertia and the sections area, respectively. $M_{ir}$, $M_{il}$, $N_{ir}$, and $N_{il}$ are the moments and the normal forces in the left and right end section of the $i$th element, respectively.

Under the application of dead loads and cable forces the bending moments and normal forces of the deck and pylon are given by

$$\{M\} = \{M_D\} + \{M_P\} = \{M_D\} + [S_M] * \{P_0\} \tag{7.3a}$$

$$\{N\} = \{N_D\} + \{N_P\} = \{N_D\} + [S_N] * \{P_0\} \tag{7.3b}$$

where $\{M_D\}$ and $\{M_P\}$ are the bending moment vectors induced by dead loads and the cable forces, respectively; $[S_M]$ is the moment influence matrix; and $[S_N]$ is the normal force influence matrix, the component $S_{ij}$ of influence matrix represents changes of the moment or the normal force in the $i$th element induced by the $j$th unit cable force. $\{N_D\}$ and $\{N_P\}$ are the normal force vectors induced by dead loads and cable forces, respectively. $\{P_0\}$ is the vector of cable forces.

The corresponding displacements in deck and pylon are given as

$$\{F\} = \{F_D\} + \{F_P\} = \{F_D\} + [S_F] * \{P_0\} \tag{7.4}$$

where $\{F\}$ is the displacement vector, $\{S_F\}$ is the displacement influence matrix, and $\{F_D\}$ and $\{F_P\}$ are the displacement vectors induced by dead loads and by cable forces, respectively.

Substitute Eqs. (7.3a) and (7.3b) into Eq. (7.2), and replace the variables by

$$\{\overline{M}\} = [A]\{M\}, \{\overline{N}\} = [B]\{N\} \tag{7.5}$$

in which $[A]$ and $[B]$ are diagonal matrices:

$$[A] = Diag\left[\sqrt{L_1 / 4E_1 I_1}, \sqrt{L_2 / 4E_2 I_2}, \ldots, \sqrt{L_n / 4E_n I_n}\right]$$

$$[B] = Diag\left[\sqrt{L_1/4E_1A_1}, \sqrt{L_2/4E_2A_2}, \ldots, \sqrt{L_n/4E_nA_n}\right]$$

Then the strain energy of the cable-stayed bridge can be represented in matrix form as

$$U = \{P_0\}^T[\bar{S}]^T[\bar{S}]\{P_0\} + 2\{\bar{P}_D\}^T[\bar{S}]\{P_0\} + \{\bar{P}_D\}^T\{\bar{P}_D\} \tag{7.6}$$

in which $[\bar{S}] = (\bar{S}_M, \bar{S}_N)^T = [A, B](S_M, S_N)^T$, and $\{\bar{P}_D\} = \{M_D, N_D\}^T$.

Now, we want to minimize the strain energy of structure, i.e., to let

$$\partial U/\partial P_0 = 0 \tag{7.7}$$

under the following constraint conditions:

1. The stress range in girders and pylons must satisfy

$$\{\sigma\}_L \le \{\sigma\} \le \{\sigma\}_U \tag{7.8}$$

in which $\{\sigma\}$ is the maximum stress value vector. And $\{\sigma\}_L, \{\sigma\}_U$ are vectors of the lower and upper bounds.

2. The stresses in stay cables are limited so that the stays can work normally.

$$\{\sigma\}_{LC} \le \left\{\frac{P_{0C}}{A_C}\right\} \le \{\sigma\}_{UC} \tag{7.9}$$

in which $A_C$ is the area of a stay, $P_{0C}$ is the cable force and $\{\sigma\}_{LC}, \{\sigma\}_{UC}$ represent the lower and upper bounds, respectively.

3. The displacements in the deck and pylon satisfy

$$\{|D_i|\} \le \{\Delta\} \tag{7.10}$$

in which the left hand side of Eq. (7.10) is the absolute value of maximum displacement vector and the right-hand side is the allowable displacement vector.

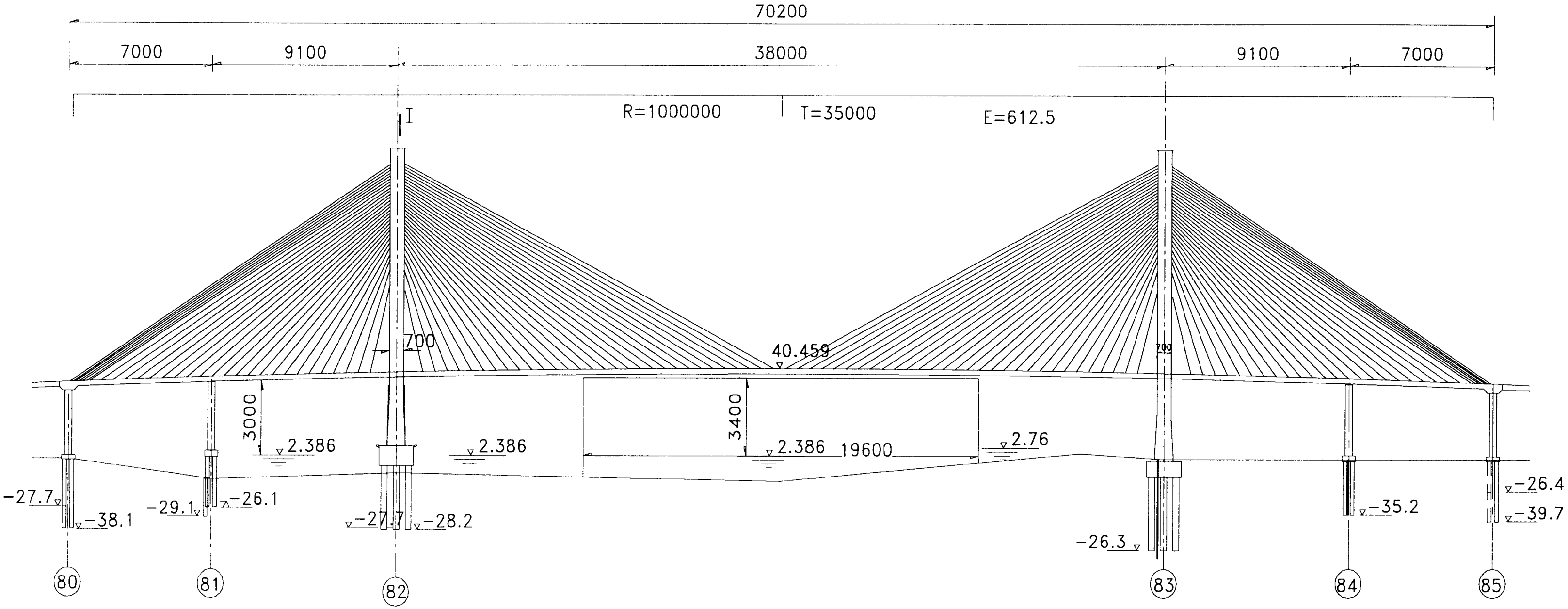
Eqs. (7.6) and (7.7) in conjunction with the conditions (7.8) through (7.10) is a standard quadric programming problem with constraint conditions. It can be solved by standard mathematical methods.

Since the cable forces under dead loads determined by the optimization method are equivalent to the cable force under which the redistribution effect in the structure due to concrete creep is minimized [8], the optimization method is used more widely in the design of PC cable-stayed bridges.

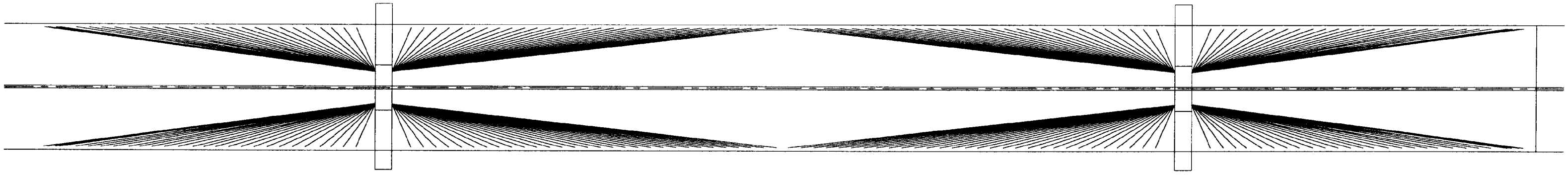
### 7.2.4 Example

For a PC cable-stayed bridge as shown in Figures 7.1 and 7.2, the forces of cable stays under permanent loads (not taking into account the creep and shrinkage) can be determined by the above methods. The results obtained are shown in Figures 7.3 and 7.4. In these figures SB represents the "Simply Supported Beam Method," CB the "Continuous Beam on Rigid Support Method," OPT the "Optimization Method," M the middle span, and S the side span numbering from the pylon location.

As can be seen, because the two ends of the cable-stayed bridge have anchored parts the cable forces located in these two regions obtained by the method of simply supported beam (SB) and by the method of continuous beam on rigid supports (CB) are not evenly distributed. The cable forces in the region near the pylon are very different with the three methods. In the other regions there is no prominent difference among the cable forces obtained by SB, CB, and OPT.



Elevation



Plane

FIGURE 7.1 General view of a PC cable-stayed bridge.

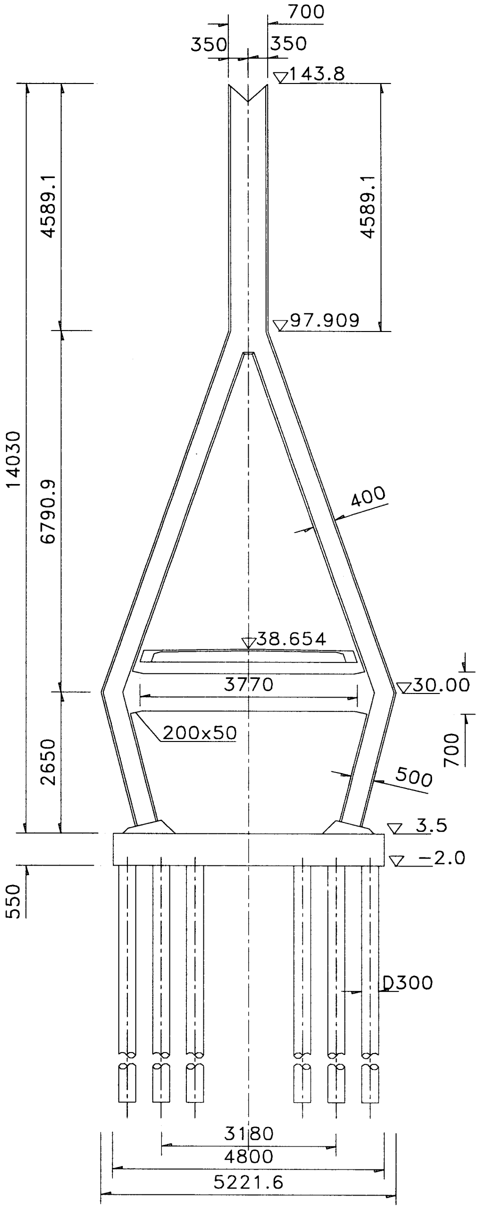


**FIGURE 7.2** Side view of tower.

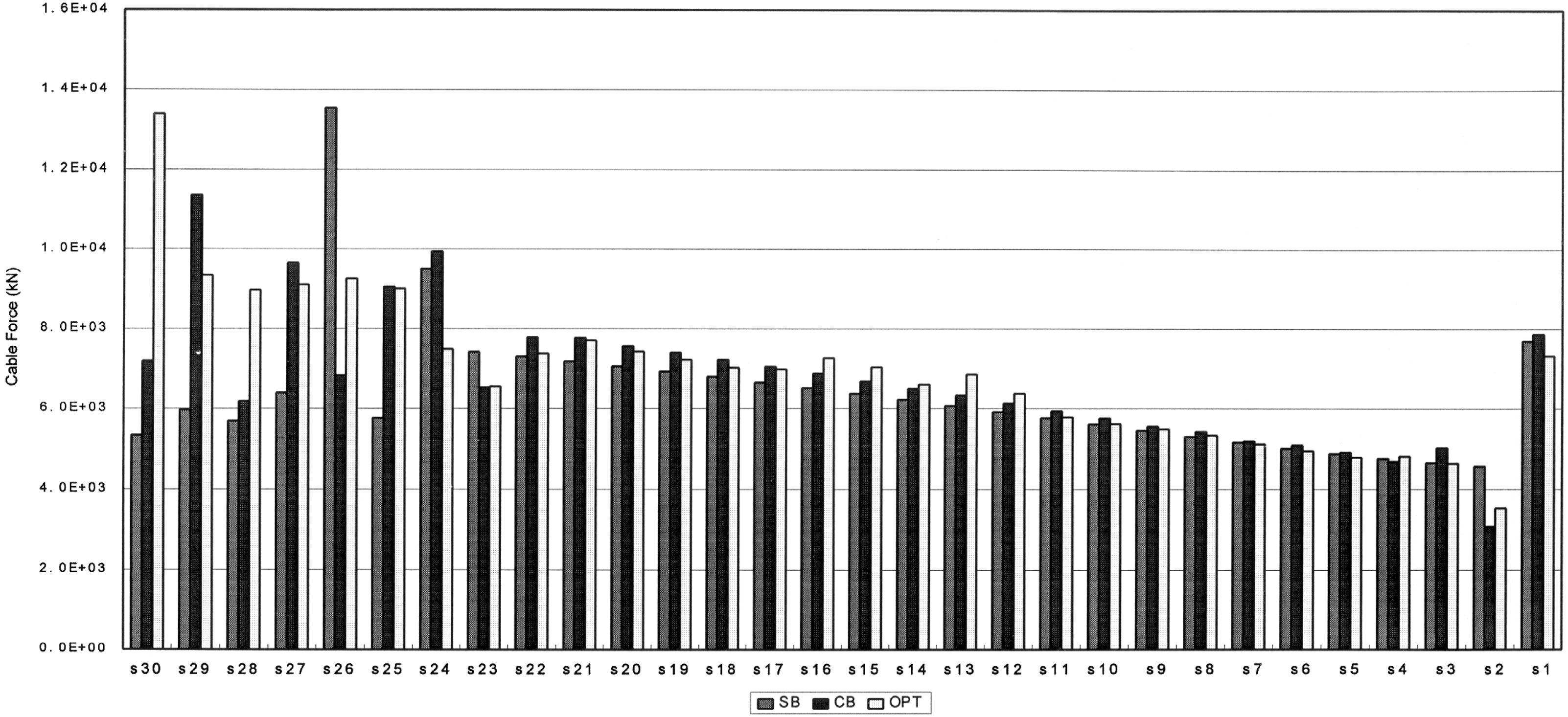


**FIGURE 7.3** Comparison of the cable forces (kN) (side span).

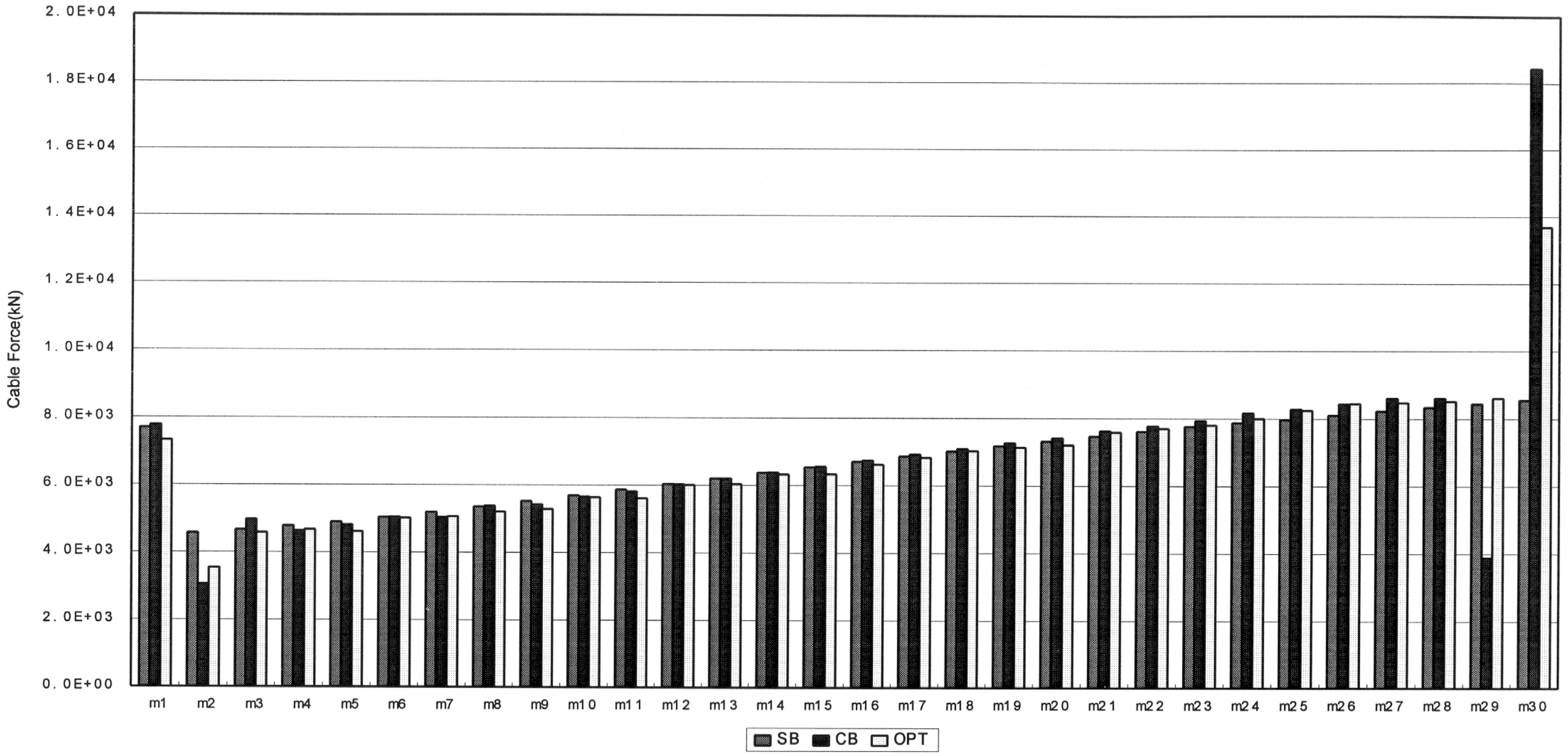


FIGURE 7.4 Comparison of the cable force (middle span).

Generally speaking, the differences of cable forces under dead loads obtained by the above methods are not so significant. The method of simply supported beam is the most convenient and the easiest to use. The method of continuous beam on rigid supports is suitable to use in the design of PC cable-stayed bridges. The optimization method is based on a rigorous mathematical model. In practical engineering applications the choice of the above methods is very much dependent on the design stage and designer preference.

## 7.3 Adjustment of the Cable Forces

### 7.3.1 General

During the construction or service stage, many factors may induce errors in the cable forces and elevation of the girder, such as the operational errors in tensioning stays or the errors of elevation in laying forms [14,16,17]. Further, the discrepancies of parameter values between design and reality such as the modules of elasticity, the mass density of concrete, the weight of girder segments may give rise to disagreements between the real structural response and the theoretical prediction [13]. If the structure is not adjusted to reduce the errors during construction, they may accumulate and the structure may deviate away from the intended design aim. Moreover, if the errors are greater than the allowable limits, they may give rise to the unfavorable effects to the structure. Through cable force adjustment, the construction errors can be eliminated or reduced to an allowable tolerance. In the service stage, because of concrete creep effects, cable force may need to be adjusted; thus, an optimal structural state can be reached or recovered.

### 7.3.2 Influence Matrix of the Cable Forces

Assuming that a unit amount of cable force is adjusted in one cable stay, the deformations and internal forces of the structure can be calculated by finite-element model. The vectors of change in deformations and internal forces are defined as influence vectors. In this way, the influence matrices can be formed for all the stay cables.

### 7.3.3 Linear Programming Method [7]

Assume that there are $n$ cable stays whose cable forces are going to be adjusted, the adjustments are $T_i$ ($i = 1,2,\ldots,n$), these values form a vector of cable force adjustment $\{T\}$ as

$$\{T\} = \{T_1, T_2, \ldots, T_n\}^T \tag{7.11}$$

Denote internal force influence vector $\{P_l\}$ as

$$\{P_l\} = (P_{l1}, P_{l2}, \ldots, P_{\mathrm{ln}})^T \qquad (l = 1,2,\ldots,m) \tag{7.12}$$

in which $m$ is the number of sections of interest and $P_{lj}$ is the internal force increment due to a unit tension of the $j$th cable. Denote displacement influence vector $\{D_i\}$ as

$$\{D_i\} = (D_{i1}, D_{i2}, \ldots, D_{in})^T \qquad (i = 1,2,\ldots,k) \tag{7.13}$$

in which $k$ is the number of sections of interest and $D_{ij}$ is the displacement increment at section $i$ due to a unit tension of the $j$th cable. Thus, the influence matrices of internal forces and displacements are given by

$$\{P\} = (P_1, P_2, \ldots, P_m)^T \tag{7.14a}$$

$$\{D\} = (D_1, D_2, \ldots, D_k)^T \tag{7.14b}$$

respectively. Under application of the cable force adjustment $\{T\}$ (see Eq. (7.11)), the increment of the internal forces and displacements can be given by

$$\{\Delta P\}=\{P\}^T\{T\} \tag{7.15a}$$

$$\{\Delta D\}=\{D\}^T\{T\} \tag{7.15b}$$

respectively.

Denote deflection error vector $\{H\}$ as

$$\{H\}=\left(h_1,h_2,......,h_m\right)^T \tag{7.16}$$

Denote vector of internal force $\{N\}$ as

$$\{N\}=\left(N_1,N_2,......,N_m\right)^T \tag{7.17}$$

After cable force adjustments, the absolute values of the deflection errors are expressed by

$$\left|\lambda_k\right|=\left|\sum_{i=1}^{n}D_{ik}T_i-h_k\right| \tag{7.18}$$

and the absolute values of internal force errors are expressed by

$$\left|q_l\right|=\left|\sum_{i=1}^{n}P_{il}T_i-N_l\right| \tag{7.19}$$

The objective function for cable force adjustments may be defined as the errors of girder elevation, i.e.,

$$\min\left|\lambda_k\right| \tag{7.20}$$

and the constraint conditions may include limitations of the internal force errors, the upper and lower bounds of the cable forces, and the maximum stresses in girders and pylons. Then the optimum values of cable force adjustment can be determined by a linear programming model.

The value of cable adjustment $\{T\}$ could be positive for increasing or negative for decreasing of the cable forces. Introduce two auxiliary variables $T_{1i},T_{2i}$ as

$$T_i=T_{1i}-T_{2i} \qquad T_{1i}\geq 0\,,\ T_{2i}\geq 0 \tag{7.21}$$

Substitute Eq. (7.18) into (7.20), then a linear program model is established by

$$\min\text{: }\lambda_k \tag{7.22}$$

subject to

$$\sum_{i=1}^{n}p_{li}(T_{1i}-T_{2i})\geq N_l-\xi\overline{p}_l\ \ (l=1,2,\ldots m) \tag{7.23a}$$

$$\sum_{i=1}^{n}p_{li}(T_{1i}-T_{2i})\leq N_l+\xi\overline{p}_l\ \ (l=1,2,\ldots m) \tag{7.23b}$$

$$\sum_{i=1}^{n} D_{ji}(T_{1i} - T_{2i}) \geq h_j - d_j \ (j = 1,2,\ldots k) \tag{7.23c}$$

$$\sum_{i=1}^{n} D_{ji}(T_{1i} - T_{2i}) \geq h_j - d_j \ (j = 1,2,\ldots k) \tag{7.23d}$$

$$T_{1i} - T_{2i} \leq \eta \overline{T}_i \,, \quad T_{1i} - T_{2i} \geq -\eta \overline{T}_i \,(I = 1,2,\ldots,n) \tag{7.23e}$$

in which $\overline{p}_l$ is the design value of internal force at section $l$, $\xi$ is the allowable tolerance in percentage of the internal force, $\overline{T}_i$ is the design value of the cable force, and $\eta$ is the allowable tolerance in percentage of the cable forces.

Equations (7.22) and (7.23) form a standard linear programming problem that can be solved by mathematical software.

### 7.3.4 Order of Cable Adjustment

The adjustment values can be determined by the above method; however, the adjustments must be applied at the same time to all cables, and a great number of jacks and workers are needed [7]. In performing the adjustment, it is preferred that the cable stays are tensioned one by one.

When adjusting the cable force individually, the influence of the other cable forces must be considered. And since any cable must be adjusted only one time, the adjustment values can be calculated through the influence matrix of cable force.

$$\left\{\overline{T}\right\} = [S]\{T\} \tag{7.24}$$

where $\left\{\overline{T}\right\} = \left\{\overline{T}_1, \overline{T}_2, \ldots \overline{T}_n\right\}$ is the vector of actual adjustment value of cable tension. $[S]$ is the influence matrix of cable tension, whose component $S_{ij}$ represents tension change of the $j$th cable when the $i$th cable changes a unit amount of force.

## 7.4 Simulation of Construction Process

### 7.4.1 Introduction

Segmental construction techniques have been widely used in construction of cable-stayed bridges. In this technique, the pylon(s) is built first; then the girder segments are erected one by one and supported by the inclined cables hung from the pylon(s). It is evident that the profile of the main girder and the final tension forces in the cables are strongly related to the erection method and the construction scheme. It is therefore important that the designer should be aware of the construction process and the necessity to look into the structural performance at every stage of construction [9,12].

In any case, structural safety is the most important issue since the stresses in the girder and pylon(s) are related to the cable tensions. Thus the cable forces are of great concern. Further, during construction, the geometric profile of the girder is also very important. It is clear that if the profile of the girder were not smooth or, finally, the cantilever ends could not meet together, then the construction might experience some trouble. The profile of the girder or the elevation of the bridge segments is mainly controlled by the cable lengths. Therefore, the cable length must be appropriately set at the erection of each segment. It also should be noted that in the construction process, the internal forces of the structure and the elevation of the girder could vary because usually the bridge segments are built by a few components at a time and the erection equipment is placed at different positions during construction and because some errors such as the weight of the segment and the tension force of the cable, etc., may occur. Thus, monitoring and adjustment are absolutely needed.

To reach the design aim, an effective and efficient simulation of the construction process step by step is very necessary. The objectives of the simulation analysis are [4,12]:

1. To determine the forces required in cable stays at each construction stage;
2. To set the elevation of the girder segment;
3. To find the consequent deformation of the structure at each construction stage;
4. To check the stresses in the girder and pylon sections.

The simulation methods are introduced and discussed in detail in the following sections. In the next section, the technique of forward analysis is presented to simulate the assemblage process. Creep effects can be considered; however, the design aim may not be successfully achieved by such simulation because it is not so easy to determine the appropriate lengths of the cable stays which make the final elevation to achieve the design profile automatically. Another technique presented is the backward disassemblage analysis, which starts with the final aim of the structural state and disassembles segment by segment in a reverse way. The disadvantage of this method is that the creep effects may not be able to be defined. However, values obtained from the assemblage process may be used in this analysis. These two methods may be alternatively applied until convergence is reached.

It is noted that the simulation is only limited to that of the erection of the superstructure.

### 7.4.2 Forward Assemblage Analysis

Following the known erection procedure, a simulation analysis can be carried out by the finite-element method. This is the so-called forward assemblage analysis. It has been used to simulate the erection process for PC bridges built by the free cantilever method.

Concerning finite-element modeling, the structure may be treated as a plane frame or a space frame [4]. A plane frame model may be good enough for construction simulation because transverse loads, such as wind, can generally be ignored. In a plane frame model, the pylon(s) and the girder are modeled by some beam elements, while the stays are modeled as two-node bar elements with Ernst modules [3,4] by which the effects of cable sag can be taken into account. The structural configuration is changed stage by stage. Typically, in one assemblage stage, a girder segment treated as one or several beam elements is connected to the existing structure, while its weight is treated as a load to apply to the element. Also, the cable force is applied. Then an analysis is performed and the structure is changed to a new configuration.

In finite-element modeling, several factors such as the construction loads (weight of equipment and traveling carriage) and effects of concrete creep and shrinkage, must be considered in detail.

Traveling carriages are specially designed for construction of a particular bridge project. Generally there are two kinds of carriages. One is cantilever type (Figure 7.5a). The traveling carriages are mounted near the ends of girders, like a cantilever to support the next girder segment. In this case, the weight of the carriage can be treated as an external load applied to the end of the girder.

With the development of multiple cable systems, the girder with lower height becomes more flexible. The girder itself is not able to carry the cantilever weights of the carriage and the segment. Then an innovative erection technique was proposed [1]. And another type of carriage is developed. This new idea is to use permanent stays to support the form traveler (Figure 7.5b) so that the concrete can be poured *in situ* [1,9]. This method enjoys considerable success at present because of the undeniable economic advantages. Its effectiveness has been demonstrated by bridge practice. For the erecting method using the later type of carriage, the carriage works as a part of the whole structure when the segmental girder is poured *in situ*. Thus, the form traveler must be included in the finite-element model to simulate construction. A typical flowchart of forward assemblage analysis is shown in Figure 7.6.

With the forward assemblage analysis, the construction data can be worked out. And the actual permanent state of cable-stayed bridges can be reached. Further, if the erection scheme were modified during the construction period or in the case that significant construction error occurred, then the structural parameters or the temporary erection loads would be different from the values used in the design. It is possible to predict the cable forces and the sequential deformations at each stage by utilizing the forward assemblage analysis.

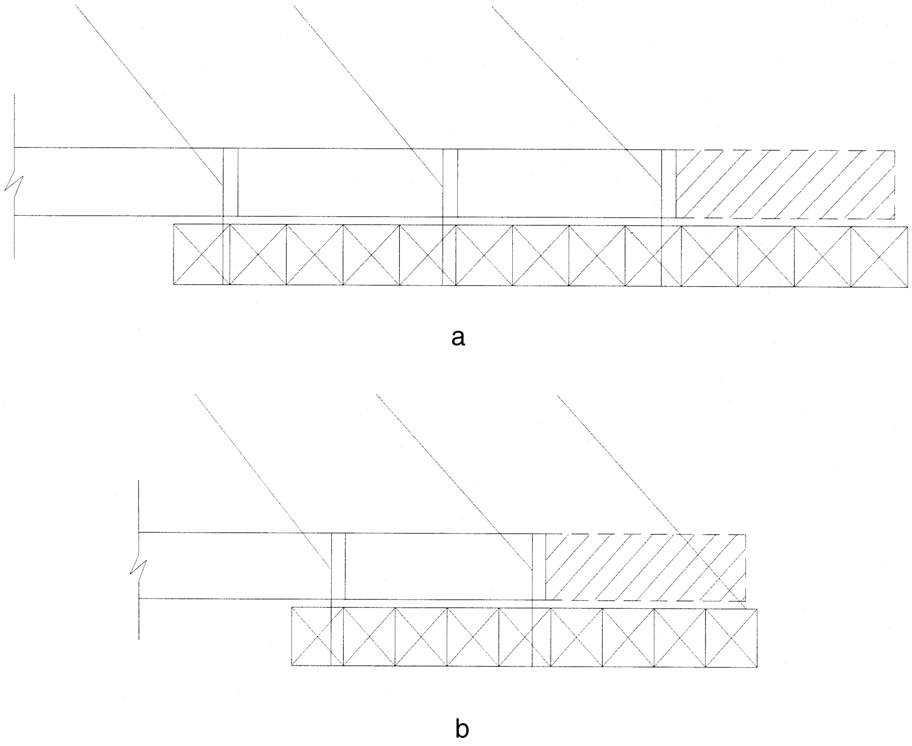


**FIGURE 7.5** (a) Cantilever carriage; (b) cable-supported cantilever carriage.

### 7.4.3 Backward Disassemblage Analysis

Following a reverse way to simulate the disassemblage process stage by stage, a backward analysis can be carried out also by finite-element method [11,12]. Not only the elevations of deck but also the length of cable stays and the initial tension of stays can be worked out by this method. And the completed state of structure at each stage can be evaluated.

The backward disassemblage analysis starts with a very ideal structural state in which it is assumed that all the creep and shrinkage deformation of concrete be completed, i.e., a state 5 years or 1500 days after the completion of the bridge construction. The structural deformations and internal forces at each stage are considered ideal reference states for construction of the bridge [11]. The backward analysis procedure for a PC cable-stayed bridge may be illustrated as follows:

Step 1. Compute the permanent state of the structure.
Step 2. Remove the effects of the creep and shrinkage of concrete of 1500 days or 5 years.
Step 3. Remove the second part of the dead loads, i.e., the weights of wearing surfacing, curbs and fence, etc.
Step 4. Apply the traveler and other temporary loads and supports.
Step 5. Remove the center segment, to analyze the semistructure separately.
Step 6. Move the form traveler backward.
Step 7. Remove the weight of the concrete of a pair of segments.
Step 8. Remove the cable stay.
Step 9. Remove the corresponding elements.

Repeat the Steps 6 to 9 until all the girder segments are disassembled. A flowchart for backward disassemblage analysis is shown in Figure 7.7.

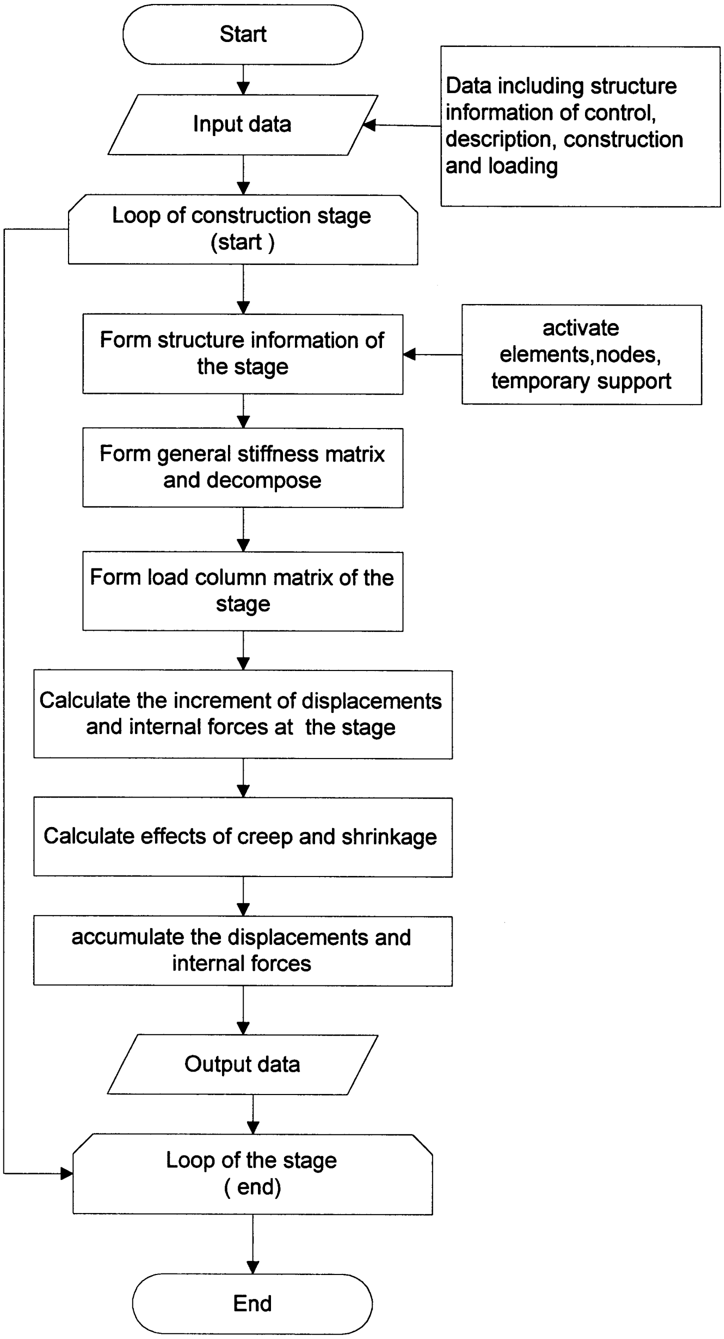


**FIGURE 7.6** Flowchart of forward assemblage analysis.

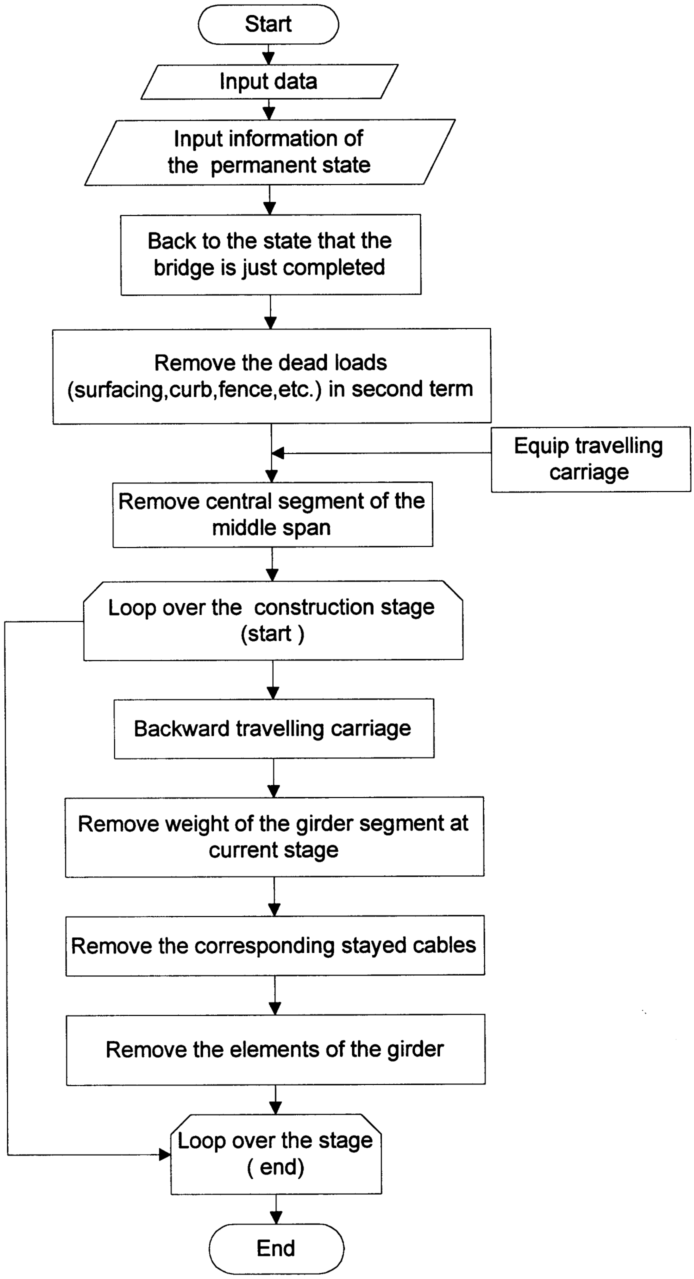


**FIGURE 7.7** Flowchart of backward disassemblage analysis.

As mentioned above, for the erecting method using conventional form traveler cast-in-place or precast concrete segments, the crane or the form traveler may be modeled as external loads. Thus the carriage moving is equivalent to a change of the loading position. However, for an erection method utilizing cable-supported traveling carriage the cable stays first work as supports of the carriage and later, after curing is finished, the cable stays are connected with the girder permanently. In backward disassemblage analysis, the form traveler moving must be related to a change of the structural system.

The backward analysis procedure can establish the necessary data for the erection at each stage such as the elevations of deck, the cable forces, the deformations of structure, and the stresses at critical sections of deck and pylon.

One of the disadvantages of backward analysis is that creep effects are not able to be estimated; therefore, forward and backward simulations should be used alternately to determine the initial tension and the length of stay cables.

## 7.5 Construction Control

### 7.5.1 Objectives and Control Means

Obviously, the objective of construction control is to build a bridge that achieves the design aim with acceptable error. During the construction of a cable-stayed bridge, some discrepancies may occur between the actual state and the state of design expectation [14,15]. The discrepancies may arise from elevation error in laying forms, errors in stressing cable stays by jacks, errors of the first part of the dead load, i.e., the self-weights of the girder segments, and the second part of the dead load, i.e., the self-weights of the surfacing, curbs and fencing, etc. On the other hand, a system error may occur in measuring the deflection of the girder and the pylons. It is impossible to eliminate all the errors. Actually, there are two basic requirements for the completed structure [12]: (1) the geometric profile matches the designed shape well and (2) the internal forces are within the designed envelope values; specifically, the bending moments of the girder and the pylons are small and evenly distributed.

Since the internal forces of the girder and the pylons are closely related to the cable forces, the basic method of construction control is to adjust the girder elevation and the cable forces. If the error of the girder elevation deviated from the design value is small, such error can be reduced or eliminated by adjusting the elevation of the segment without inducing an angle between two adjacent deck segments. In this way we only change the geometric position of the girder without changing the internal force state of the structure. When the errors are not small, it is necessary to adjust the cable forces. In this case, both the geometric position change and the changes of internal forces occur in the structure.

Nevertheless, cable force adjustment are not preferable because they may take a lot of time and money. The general exercise at each stage is to find out the correct length of the cables and set the elevation of the segment appropriately. Cable tensioning is performed for the new stays only. Generally, a comprehensive adjustment of all the cables is only applied before connecting the two cantilever ends [21]. In case a group of cables needs to be adjusted, careful planning for the adjustment based on a detailed analysis is absolutely necessary.

### 7.5.2 Construction Control System

To guarantee structural safety and to reach the design aim, a monitoring and controlling system is important [13,15,19]. A typical construction controlling system consists of four subsystems: measuring subsystem, error and sensitivity analysis subsystem, control/prediction subsystem, and new design value calculation subsystem. An example of a construction control system for a PC cable-stayed bridge [18,20] is shown in Figure 7.8.

1. Measuring subsystem — The measuring items mainly include the elevation/deflection of the girder, the cable forces, the horizontal displacement of the pylon(s), the stresses of sections in the girder and the pylon(s), the modulus of elasticity and mass density of concrete, the creep and shrinkage of concrete, and the temperature/temperature gradient in the structure.

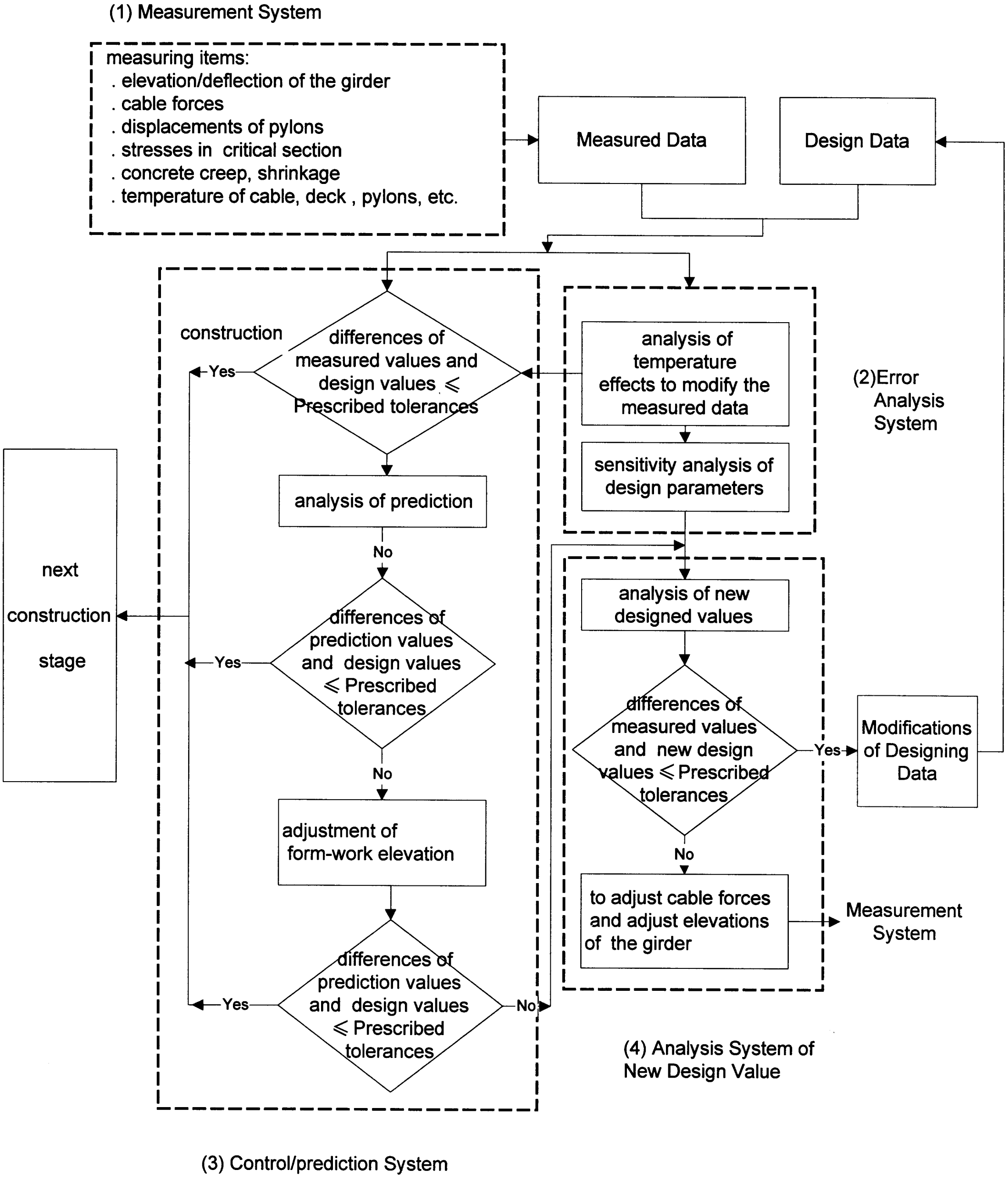


**FIGURE 7.8** A typical construction control system for a PC cable-stayed bridge.

2. Error and sensitivity analysis subsystem — In this subsystem, the temperature effects are first determined and removed. Then the sensitivity of structural parameter such as the elasticity modulus of concrete, self-weight, stiffness of the girder segment or pylon, etc., are analyzed. Through the analysis, the causes of errors can be found so that the corresponding adjustment steps are utilized.
3. Control/prediction subsystem — Compare the measuring values with those of the design expectation; if the differences are lower than the prescribed limits, then go to the next stage. And the elevation is determined appropriately. Otherwise, it is necessary to find out the reasons, then to eliminate or reduce those errors through proper measures. The magnitude of cable tension adjustment can be determined by a linear programming model.

4. New design value calculation subsystem — Since the structural parameters for the completed part have deviated from the designed values, the design expectation must be updated with the changed state of the structure. And the sequential construction follows new design values so that the final state of structure can be achieved optimally.

## 7.6 An Engineering Example

The general view of a PC cable-stayed bridge is shown in Figure 7.1. The cable-stayed portion of the bridge has a total length of 702 m. The main span between towers is 380 m and the side anchor span is 161 m. The side anchor spans consist of two spans of 90 and 71 m with an auxiliary pier. The main girder is composed with two edge girders and a deck plate. The edge girders are laterally stiffened by a T-shaped PC girder with 6-m spacing. The edge girder is a solid section whose height is 2.2 m and width varies from 2.6 m at intersection of girder and pylon to 2.0 m at middle span. The deck plate is 28 cm thick. The width of the deck is 37.80 m out-to-out with eight traffic lanes. Spatial 244 stay cables are arranged in a semifan configuration. The pylon is shaped like a diamond with an extension mast (see Figure 7.1). All the cable stays are anchored in the mast part of the pylon. The stay cables are attached to the edge girders at 6 m spacing.

At the side anchor span an auxiliary pier is arranged to increase the stiffness of the bridge. And an anchorage segment of deck is set up to balance the lifting forces from anchorage cables.

### 7.6.1 Construction Process

The bridge deck structure is erected by the balance cantilevering method utilizing cable-supported form travelers. The construction process is briefly described as follows.

- Build the towers.
- Cast in place the first segment on timbering support.
- Erect the No. 1 cable and stress to its final length.
- Hoist the traveling carriages and positioning.
- Erect the girder segments one by one on the two sides of the pylons.
- Connect the cantilever ends of the side span with the anchorage parts.
- Continue to erect the girder segments in the center span.
- Connect the cantilever ends of the center span.
- Remove traveling carriages and temporary supports.
- Connect the girder with the auxiliary piers.
- Cast pavement and set up fence, etc.

A typical erection stage of one segment is described as follows:

- Move the traveling carriage forward and set up the form at proper levels.
- Erect and partially stress the stay cables attached to the traveler.
- Place reinforcement, post-tensioning bars and couple the stressed bars with those of the previously completed deck segment.
- Cast in place the deck concrete.
- Stress the stay cables to adjust the girder segments to proper levels.
- Cure deck panel and stress the longitudinal and lateral bars and strands.
- Loosen the connection between the stay cable and traveling carriage.
- Stress cable stays to the required value.

The above erection steps are repeated until the bridge is closed at the middle span.

**TABLE 7.1** Predicted Initial Cable Forces (kN)

| No. | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| NCS | 7380 | 3733 | 4928 | 5130 | 5157 | 5373 | 5560 | 5774 | 5969 | 6125 |
| CS | 7745 | 3854 | 5101 | 5331 | 5348 | 5549 | 5694 | 5873 | 6050 | 6185 |
| No. | S11 | S12 | S13 | S14 | S15 | S16 | S17 | S18 | S19 | S20 |
| NCS | 6320 | 6870 | 7193 | 7283 | 7326 | 7519 | 7317 | 7478 | 7766 | 8035 |
| CS | 6367 | 6908 | 7209 | 7331 | 7467 | 7639 | 7429 | 7580 | 7856 | 8114 |
| No. | S21 | S22 | S23 | S24 | S25 | S26 | S27 | S28 | S29 | S30 |
| NCS | 8366 | 8169 | 7693 | 8207 | 9579 | 9649 | 9278 | 9197 | 9401 | 12820 |
| CS | 8442 | 8246 | 7796 | 8354 | 9778 | 9791 | 9509 | 9296 | 9602 | 12930 |
| No. | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | M10 |
| NCS | 7334 | 3662 | 4782 | 4970 | 5035 | 5426 | 5479 | 5628 | 5778 | 6108 |
| CS | 7097 | 3433 | 4591 | 4877 | 5006 | 5477 | 5567 | 5736 | 5904 | 6231 |
| No. | M11 | M12 | M13 | M14 | M15 | M16 | M17 | M18 | M19 | M20 |
| NCS | 6139 | 6572 | 6627 | 6918 | 6973 | 7353 | 7540 | 7742 | 7882 | 7978 |
| CS | 6263 | 6706 | 6756 | 7031 | 7088 | 7422 | 7624 | 7813 | 7942 | 8060 |
| No. | M21 | M22 | M23 | M24 | M25 | M26 | M27 | M28 | M29 | M30 |
| NCS | 8384 | 8479 | 8617 | 8833 | 9175 | 9359 | 9394 | 9480 | 9641 | 13440 |
| CS | 8452 | 8561 | 8694 | 8931 | 9212 | 9413 | 9459 | 9570 | 9716 | 13570 |

No.: Cable number; M: middle span; S: side span; CS: with the effects of creep and shrinkage of concrete; NCS: without the effects of creep and shrinkage of concrete.

## 7.6.2 Construction Simulation

The above construction procedure can be simulated stage by stage as illustrated in Section 7.4.2. Since creep and shrinkage occur and the second part of the dead weight will be loaded on the bridge girder after completion of the structure, a downward displacement is induced. Therefore, as the erection is just finished the elevation of the girder profile should be set higher than that of the design profile and the pylons should be leaning toward the side spans. In this example, the maximum value which is set higher than the designed profile in the middle of the bridge is about 35.0 cm, while the displacement of pylon top leaning to anchorage span is about 9.0 cm. The initial cable forces are listed in Table 7.1 to show the effects of creep. As can be seen, considering the long-term effects of concrete creep, the initial cable forces are a little greater than those without including the time-dependent effects.

## 7.6.3 Construction Control System

In the construction practice of this PC cable-stayed bridge, a construction control system is employed to control the cable forces and the elevation of the girder. Before starting concrete casting the reactions of the cable-supported form traveler are measured by strain gauge equipment. Thus the weights of the four travelers used in this bridge are known.

At each stage the mass density of concrete and the elasticity modulus of concrete are tested in the laboratory *in situ*. The calculation of construction is carried out with the measured parameters. In several sections of the deck and pylon, strain gauges are embedded to measure the strains of the structure during the whole construction period, thus the stress of the structure can be monitored.

In this example the main flowchart of the construction control system for a typical erecting segment is shown in Figure 7.9.

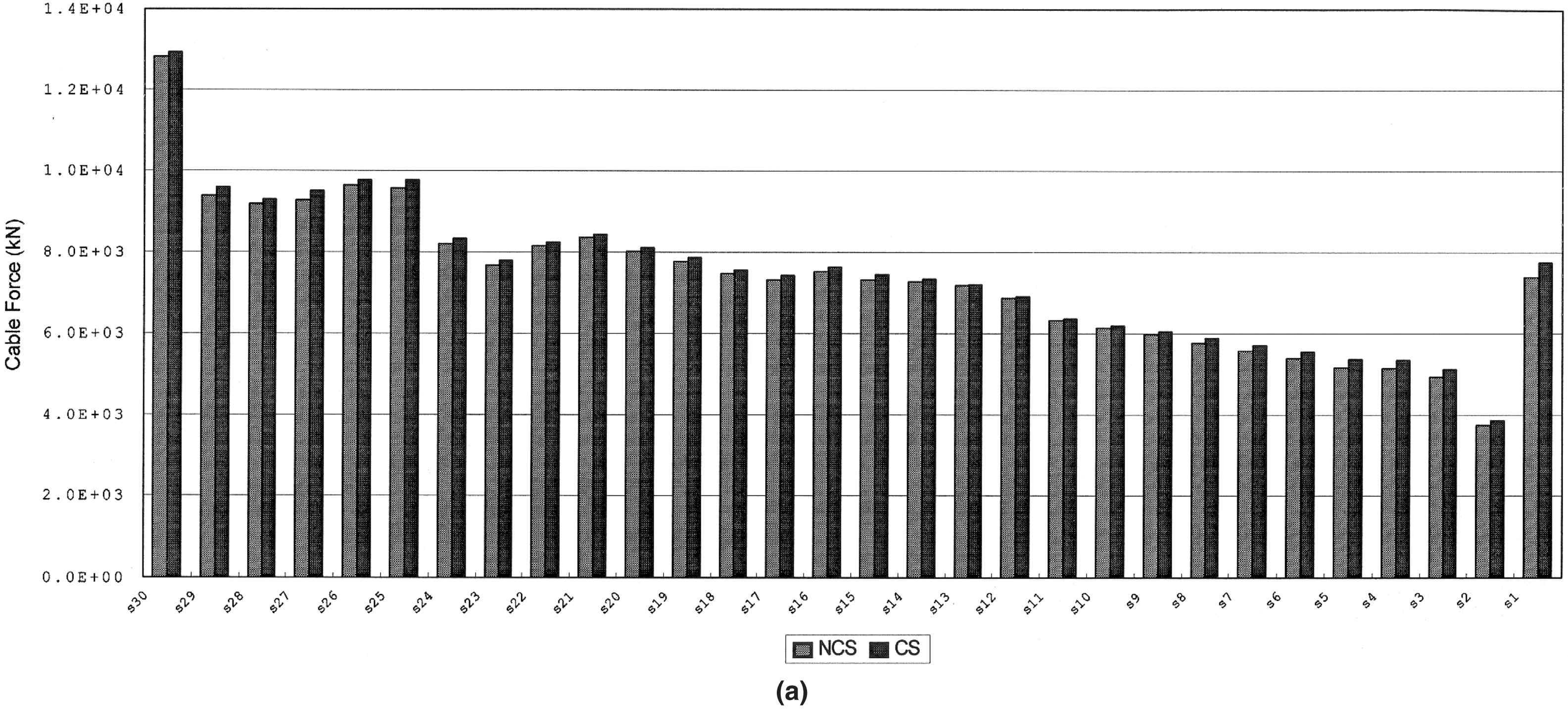
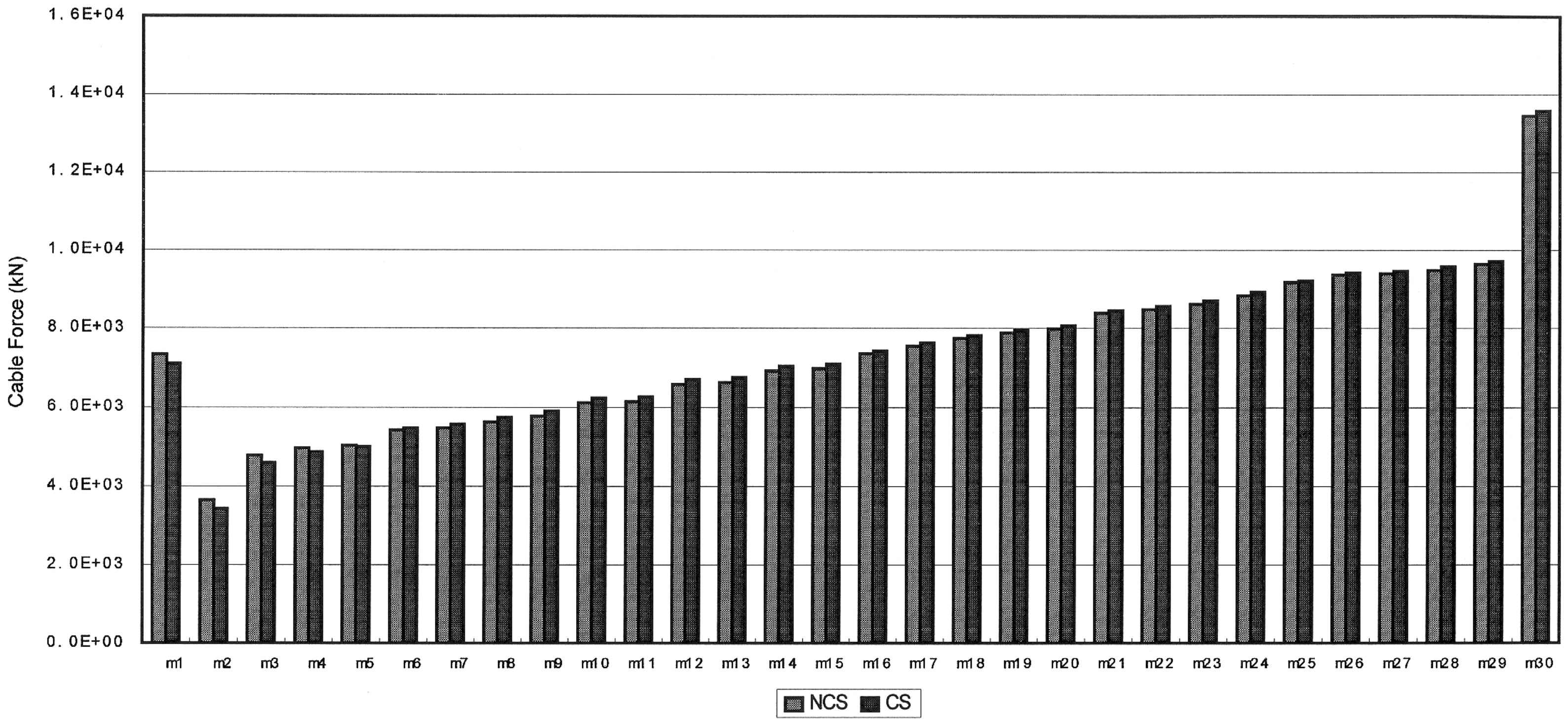


**FIGURE 7.9** (a) Initial cable forces in side span determined by simulation analysis. (b) Initial cable forces in middle span determined by simulation analysis.



**(b)**

**FIGURE 7.9** (continued)

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