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Estimation of Construction Accuracy of Steel Bridges

Evaluation du degré de précision dans l'exécution de ponts métalliques

Abschätzung der Ausführungs-Genauigkeit von Stahlbrücken

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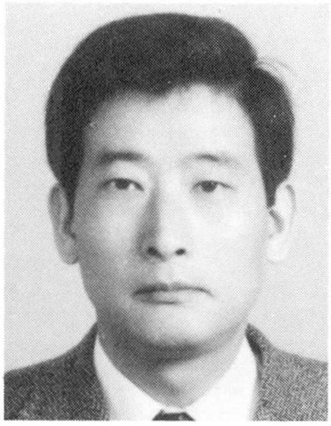

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SUMMARY

A methodology to estimate construction accuracy is presented by treating initial imperfections as random variables. A stochastic finite element method and optimization technique are applied. A numerical example on a cable stayed bridge provides some discussion about the method to improve construction accuracy.

RÉSUMÉ

Une méthode d'évaluation du degré de précision d'une construction consiste à considérer les imperfections initiales comme des variables aléatoires. On applique alors la méthode stochastique des éléments finis et la technique d'optimalisation. Une méthode permettant d'améliorer le degré de précision de la construction est illustrée à l'aide de l'exemple numérique d'un pont à haubans.

ZUSAMMENFASSUNG

Die vorgeschlagene Methode zur Abschätzung von Ausführungs-Genauigkeit besteht darin, anfänglich vorhandene Unvollkommenheiten als Zufallsvariablen zu betrachten. Auf diese stochastischen Grössen werden sodann die Methode der Finiten Elemente und die Optimierungstechnik angewendet. Eine Schrägseilbrücke dient als Zahlenbeispiel und gestattet die Auseinandersetzung mit dem Problem der Festlegung der anzustrebenden Ausführungs-Genauigkeiten.

1. INTRODUCTION

Because of the presence of various kinds of initial imperfections introduced during the construction processes of bridges, the geometrical shape and stress distribution do not always conform to those intended by designers when completed. Such construction errors deviated from design values represent the important quality characteristics of the bridge. For the purpose of quality assurance, the constructor should make much effort to achieve good construction accuracy by taking effective quality control activities.

This paper presents a methodology to estimate stochastically the effects of initial imperfections upon the construction accuracy of bridges, and based on this, some discussions about the procedures to improve construction accuracy, especially the operation of cable length adjustment in the erection of cable stayed bridges.

The factors of initial imperfections which causes construction error are discussed first. The variation of dead load and stiffness parameters from design values, and also dimensional imperfections of each member are taken into account for initial imperfections. Secondary, analytical approach is described. The stochastic finite element method [1] is applied to analyze the effects of initial imperfections upon the construction accuracy, and the optimization technique [2] is used for the cable length adjustment. By a numerical example, some useful and important informations concerning the quality control of cable stayed bridges are presented.

2. INITIAL IMPERFECTIONS AND CONSTRUCTION ACCURACY

2.1 Initial Imperfections

Even though there will possibly be a variety of initial imperfections which may lead to the construction error, the representative ones of them are considered to be the following items as shown in Fig. 1

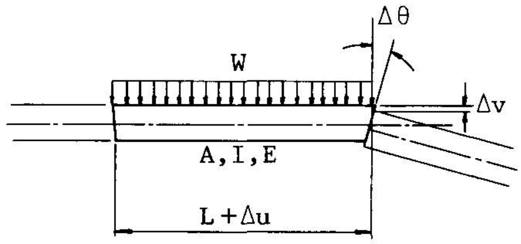

Fig.1 Initial Imperfections

The first one is uncertainty of self weight (W) and stiffness parameters such as sectional area (A), moment of inertia (I) and Young's modulus (E) of each member. They are decided deterministically in design, but actually random variables whose precise values are not known. The dimensional variation in thickness, width and height of each component may be the factors to the variation of the design constants. The variation of wire radius will be related to the cable stiffness together with the variation of Young's modulus. Furthermore, the modeling error will probably become an important factor. Dead load, which will be fluctuating spacially, is usually simplified to uniform load. Load tests on actual bridges frequently certify the contribution of secondary elements, for instance non-composite concrete deck slab, lateral bracing, etc., to the bridge rigidity even if they are assumed, as the design phylosophy, not to act to the global behavior.

Secondary, there will be some dimensional imperfections such as member length error (Δu), misalignment (Δv) and inclination ($\Delta\theta$) at the joint connecting to the adjacent member block. They are introduced during the fabrication and erection process. The dimensions of each member are usually inspected during the shop assembling, and their tolerances are specified in the code. The member length error of ±2 or ±3 mm is allowed depending on it's length for the highway bridge in Japan [3]. The joint inclination will be caused by warping of the member, mis-perpendicularity at the member end surface as well as the angular displacement due to welding or bolting of the joint during the member assembling process.

Due to the complexity of sources and the difficulty of measurement, the statistical data available to estimate the error in the imperfections described above will not be sufficient except that accumulated from the inspection results of member dimensions.

2.2 Construction Accuracy

According to the final inspection results on actually constructed bridges, some error in geometry are observed, and also some degree of deviation in stress distribution from the original design one will probably be induced.

In case of cable system, the cable tension is usually measured because of the importance to adjust to the design value. An example of the histogram of the cable tension error for a few cable stayed bridges [4, 5] constructed in Japan is shown in Fig.2.

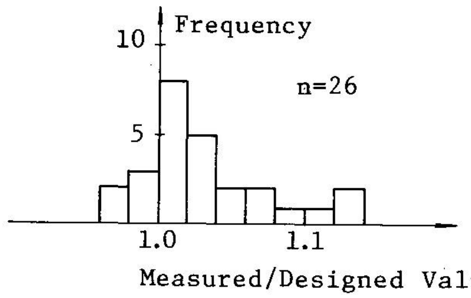

Fig.2 Histogram of Cable Tension Error

3. ANALYSIS TO ESTIMATE CONSTRUCTION ACCURCY

3.1 Construction Accuracy by Member Assembling

The bridge system will be considered to be the assembly of many members as shown in Fig.1. This member can be represented as the equivalent beam element whose stiffness matrix and end forces are functions of randomly varying initial imperfections.

If load vector, stiffness matrix and displacement of the system are expressed in terms of design values P_D, K_D and X_D, mean error terms P, K, X and the fluctuating component ΔP, ΔK and ΔK, respectively, linear elastic equations of actual and designed systems are represented by the following equations.

$$P_D + P + \Delta P = (K_D + K + \Delta K) \cdot (X_D + X + \Delta X) \qquad (1)$$

$$P_D = K_D \cdot X_D \qquad (2)$$

Subtracting Eq.(2) from Eq.(1), and then separating it into the mean error term and fluctuating component, the following expressions of geometrical error are obtained.

$$X = \bar{K}^{-1} (P - K \cdot X_D) \qquad (3)$$

$$X = \bar{K}^{-1} (\Delta P - \Delta K \cdot \bar{X}) \qquad (4)$$

in which $\bar{K} = K_D + K$ and $\bar{X} = X_D + X$ are mean stiffness and displacement, respectively, and the product $\Delta K \cdot \Delta X$ is neglected as is expected to be small. Eq.(3) can be solved by the ordinary deterministic approach.

The load vector of Eq.(4) expressed as

$$Q = \Delta P - \Delta K \cdot \bar{X} \qquad (5)$$

is caused by the variation of various initial imperfections r. The first order approximation of Eq.(5) can be obtained by taking partial derivative of Q with respect to each ramdom variable r_i. That is

$$Q = \frac{\partial Q}{\partial r} \cdot \Delta r \qquad (6)$$

$\partial Q/\partial r_i$ is a load vector due to unit imperfection of r_i, and in case of dimensional imperfections, it is represented as nodal forces equivalent to those enforcing the member to have unit deformation.

The convariance matrix C_{xx} of ΔX can be obtained from Eq.(4) and (6) as follows

$$C_{xx} = \Delta X \cdot \Delta X^T = H \cdot C_{rr} \cdot H^T \tag{7}$$

where

$$H = \bar{K}^{-1} \frac{\partial Q}{\partial r} \tag{8}$$

is the influence matrix due to r, suffix T means the matrix transpose.

Eq.(7) shows the relationship between the covariance C_{rr} of the initial imperfections r and that of responce (geometrical error) X caused by r. The diagonal elements of C_{xx} represent the variances and the off diagonal elements give information regarding the degree of correlations among responces of various parts of structure.

Stress errors of each member are also evaluated as the same form of Eq.(7). In this case, the influence matrix H can be calculated by using the corresponding displacement and stress matrix as well as the end forces of each element.

3.2 The Effects of Cable Length Adjustment

In the erection of cable systems such as cable stayed bridges and Nielsen type bridges, cable adjustment is usually taken to improve construction accuracy by varying the cable length using shim plates, screws, etc. It is usually impossible to adjust everthing perfectly, and therefore the items to be controlled for the purpose of adjustment, such as geometry of bridges and/or cable tension, will be decided.

Separating the construction errors in vector Y and Z which are the purpose of adjustment or not of this operation, respectively, then the construction accuracy Y_1 and Z_1 after adjustment are expressed as the following equations.

$$Y_1 = Y + A \cdot s \tag{9}$$

$$Z_1 = Z + B \cdot s \tag{10}$$

in which, A and B are influence matrix due to unit cable length adjustment. Construction accuracy Y and Z before adjustment are random variables whose stochastic nature is evaluated by means of the method described in 3.1.

The vector s representing the change in cable length are assumed that they are so determined [2] as to minimize the sum of squares of the components of Y_1. That is, the objective function is expressed as

$$\Omega = Y_1^T \cdot \rho \cdot Y_1 \tag{11}$$

in which ρ is the diagonal matrix whose diagonal elements represent the weight coefficients of construction accuracy to be improved. From the simultaneous equations of $\partial\Omega/\partial s_j = 0$ for each cable j, the vector s is obtained as follows.

$$s = -(A^T \cdot \rho \cdot A)^{-1} \cdot A^T \cdot \rho \cdot Y \tag{12}$$

By substituting Eq.(12), Eq.(9) and Eq.(10) are written as

$$Y_1 = Y - A \cdot (A^T \cdot \rho \cdot A)^{-1} \cdot A^T \cdot \rho \cdot Y = Y - A_1 Y \tag{13}$$

$$Z_1 = Z - B \cdot (A^T \cdot \rho \cdot A)^{-1} \cdot A^T \cdot \rho \cdot Y = Z - B_1 Y \tag{14}$$

Eq.(13) and Eq.(14) show that the construction accuracy after the operation of cable length adjustment can be expressed as the linear equations of that before adjustment. Therefore, their stochastic nature can be evaluated by using that of Y and Z.

It is obvious that the mean of Y_1 and Z_1 are obtained by using that of Y and Z in these equations. Covariance matrix of Y_1 and Z_1 are also expressed as the following equations.

$$\begin{cases} C_{Y_1Y_1} = C_{YY} + A_1 \cdot C_{YY} \cdot A_1^T - (A_1 + A_1^T) \cdot C_{YY} \\ C_{Z_1Z_1} = C_{ZZ} + B_1 \cdot C_{YY} \cdot B_1^T - B_1 \cdot C_{YZ} - B_1^T \cdot C_{YZ}^T \\ C_{Y_1Z_1} = C_{YZ} + A_1 \cdot C_{YY} \cdot B_1^T - A_1 \cdot C_{YZ} - B_1^T \cdot C_{YY} \end{cases} \qquad (15)$$

From Eq.(15), the variance and correlation coefficient of various construction errors are obtained.

4. NUMERICAL EXAMPLE

4.1 Model Description

The cable stayed bridge as shown in Fig. 3 is considered as a numerical example. The design value, mean and standard deviation of the main parameters are indicated in Tab.1. Some dimensional imperfections as shown in Tab.2 are also assumed. The total number of initial imperfections in the bridge system is 134, and they are assumed to be statistically independent to each other, even if there will possibly be some degree of correlations between them. Under the above condition, the construction accuracy and that improved by the operation of cable adjustment are calculated by means of the method described in 3.

	Design Value	Mean	Standard Deviation
Dead Load	W_D = 18.0 t/m	$1.02W_D$	$0.03W_D$
Girder Stiffness	I_D = 1.8 m^4	$1.05I_D$	$0.05I_D$
Cable Stiffness	A_D = 0.06 m^2 ~ 0.03 m^2	$1.02A_D$	$0.01A_D$

Tab.1 Design Values and Their Imperfections

It should be pointed out that in the design of this type of bridge, the cable tensions are usually so determined as to reduce the bending moment at every sections of girder and tower. The bending moment diagram and cable tensions intended by designers of this bridge model are assumed as that shown in Fig.3. This design condition is related to the analysis as can be seen in Eq.(3) and Eq.(4).

		Standard Deviation
Cable Length		3 mm
Block Length		1.5 mm
Joint Indication	Girder	1/5,000 rad.
	Tower	1/10,000 rad.

Tab.2 Dimensional Imperfections

4.2 Estimated Construction Accuracy

The ranges of construction accuracy in the ($\mu \pm 2\sigma$) level are represented by the region between two solid lines in Fig.4, where μ and σ are mean and standard deviation of construction errors. The probability that the construction

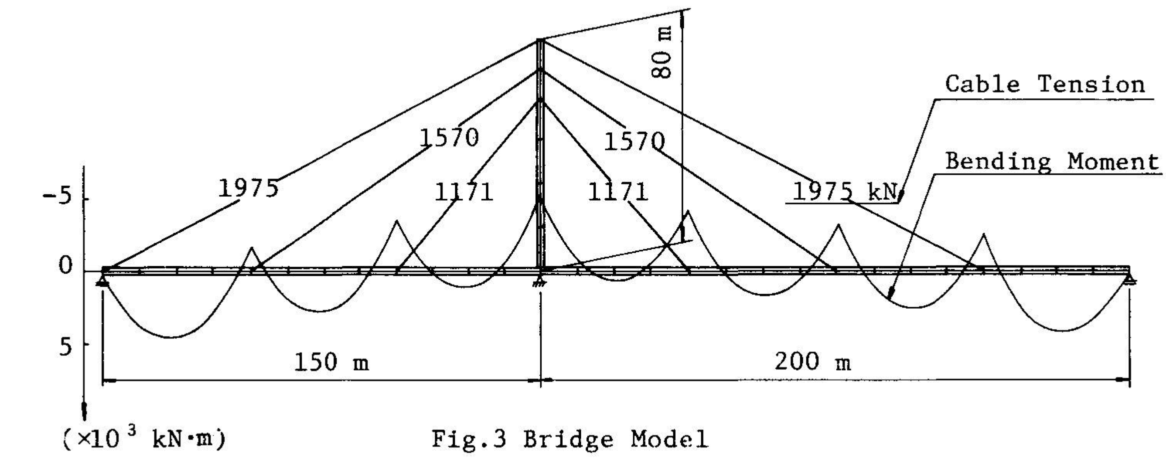

Fig.3 Bridge Model

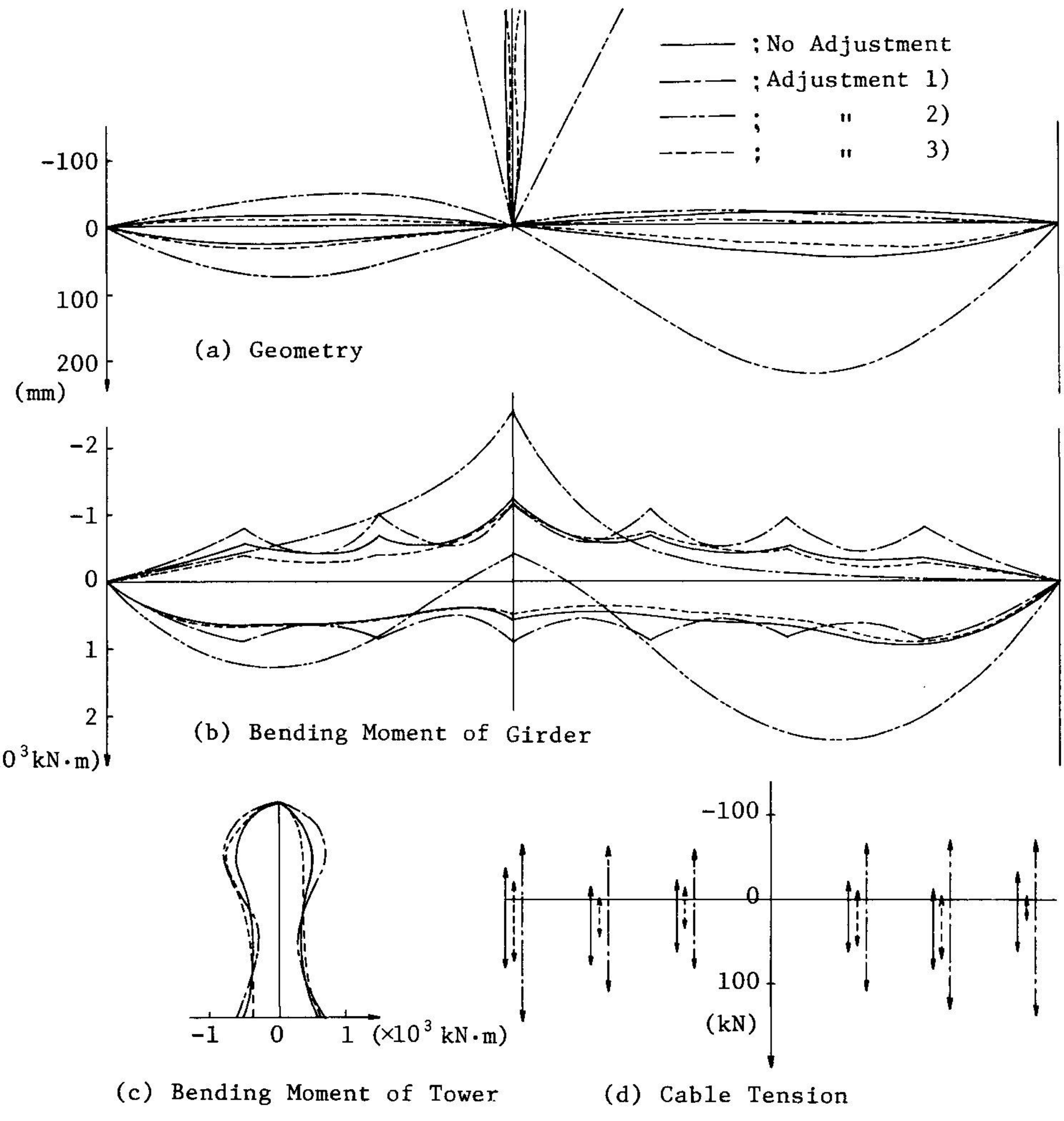

Fig.4 Estimated Construction Error ($\mu \pm 2\sigma$ level)

accuracy falls into these ranges is 95%, as they are considered to be Gaussian distribution by the central limit theorem.

The mean of geometrical error is mostly caused by dead load discrepancy from design value. The effects of mean error in both dead load and girder stiffness superimpose to the bending moment of girder.

Fig.5 shows the standard deviation of geometrical and bending moment error of girder. The effects of sensitive imperfections affecting to the construction accuracy is also plotted together with the total effects of all imperfections. The geometrical error is dominately affected by the randomness of dead load. On the other hand, the bending moment of girder is notably sensitive to joint inclinations, particularly to that of neighbouring joints.

Correlations between each imperfections has essential meaning to the bridge quality. If the correlation coefficients equal to -0.5 are considered for the inclinations between adjacent joints, construction error of girder is drastically reduced as shown in Fig. 5. The fact of this suggests the importance to decrease effectively the construction error during each construction process by using the informations in preceeding processes.

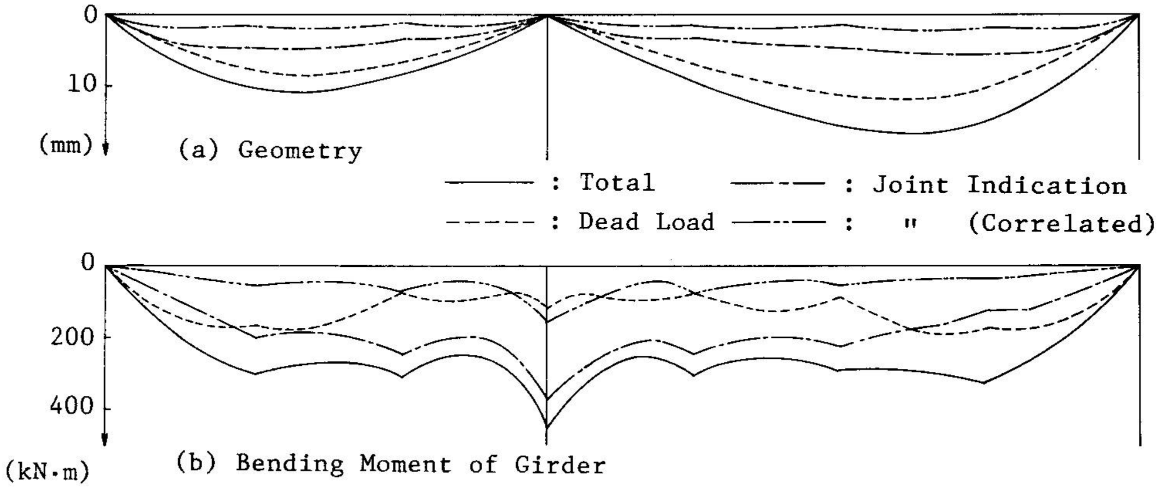

Fig.5 Standard Deviation of Construction Error

4.3 Improved Construction Accuracy by Cable Adjustment

The following three cases of cable adjustment are considered.

1) adjustment of geometry
2) adjustment of cable tension
3) adjustment of both geometry and cable tension

For the geometrical adjustment, both of deflection of girder and horizontal displacement of tower are considered to be improved. Coefficients ρ in Eq.(11) are set so that the weight of geometrical error 1 mm and the tension error 1 t becomes identical on the purpose of adjustment in case 3).

The ranges of construction accuracy after cable adjustments is shown in Fig.4. In case of geometric adjustment, both of bending moment and cable tension become deteriorated even if geometrical error will be negligible small. If cable tension is adjusted, it is obvious that the tension of all cables and the bending moment of tower conform perfectly with the designed ones. However, the error of geometry and bending moment of girder become considerably large. So as to obtain a well balanced bridge system, the simultaneous adjustment of geometry and cable tension as case c) should be made.

By calculating the improved effects of cable adjustment for each type of imperfections, it has become clear that the cable adjustment has different effects on the error due to various imperfections.

The construction error due to imperfections of cable itself (stiffness and cable length error) can perfectly be absorbed by any cases of adjustment. The same effects of adjustment are also obtained for the imperfections of block length except the error of horizontal length of girder and hight of tower.

The dominating imperfections affecting to the deteriorated geometry and overstressing of girder induced by cable adjustment (see Fig.4) is dead load imperfections. The adjustment of geometry is, therefore, appropriate for the dead load imperfections.

In case of joint inclinations and stiffness errors, the geometry will be spoiled if emphasis is put on stress improvement, and improvement of geometry leads to the contrary circumstances.

The standard deviation of stress caused by the error of bending moment is 30 to 50 kgf/cm^2, and improvement by cable adjustment cannot be expected so much. Coefficient of variation of cable tension error is about 2% before adjustment and improved to 1% or so by cable adjustment.

5. CONCLUDING REMARKS

The authors would like to conclude that the proposed method to estimate the construction accuracy of bridges is worth-while to notify quality items to be essentially controled, effective methods to improve the construction accuracy and the stress level that should be considered in design. By applying the method to a cable stayed bridge, the following knowledges are obtained.

1) The degree of correlations between imperfections has considerable influences on the bridge quality. Therefore, it is important not only to reduce the imperfections themselves, but to decrease the combined effects of them during the construction processes.

2) In case of cable adjustment, attention should be payed to improve both of geometrical error and cable tension error to lead the well-balanced system as a whole.

At the construction of complicated structure such as cable stayed bridges, it will become important to improve the bridge quality on the basis of high degree of cooperation between designers, fabricators and erectors who are concerned in each bridge project. It will be the author's pleasure that this paper contributes to such quality control activites.

REFERENCES

1. Handa K. and Anderson K., Application of Finite Element Methods in the Statistical Analysis of the Structures. Proc. of ICOSSAR '81, Trondheim, Norway, June 1981
2. Fujisawa N. and Tomo H., Computer-Aided Cable Adjustment of Stayed Bridges. Proc. of IABSE, Vancouver, Canada, November 1985
3. Japan Road Association, Standard Specifications for Highway Bridges. February 1980
4. Matsumura H. et al., Measurement and Adjustment of Cable Tension of Cable Stayed Bridges. Bridge and Foundation, Vol.13, No.8, 1979 (in Japanese)
5. Kurata O. et al., Structural Characteristics and Load Test of 2-span non-continuous Cable Stayed Bridge. Bridge and Foundation, Vol.15, No.1, 1981 (in Japanese)