Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 51 (1986)

Artikel: Quality control in the erection of cable-stayed bridges

Autor: Yamamoto, Takao / Kitahara, Toshio

DOI: https://doi.org/10.5169/seals-39586

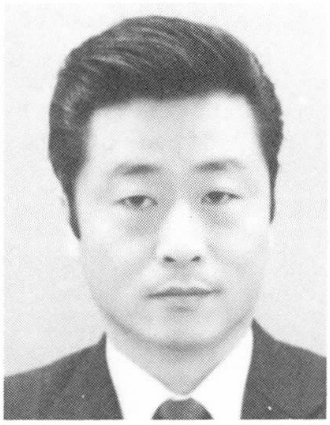
Quality Control in the Erection of Cable-Stayed Bridges

Contrôle de la qualité au cours de la construction des ponts haubannés

Qualitäts-Kontrolle beim Bau von Schrägseilbrücken

Takao YAMAMOTO
Civil Engineer
Sumitomo Heavy Ind., Ltd.
Yokosuka, Japan

Toshio KITAHARA
Civil Engineer
Sumitomo Heavy Ind., Ltd.
Yokosuka, Japan



Takao Yamamoto, born in 1947, received his M.E. degree from Kyoto Univ., 1974 and Eng. degree from Stanford Univ., 1978. He has been involved in bridge engineering works from research to erection at Sumitomo Heavy Ind., Ltd. and is a qualified professional engineer.

Toshio Kitahara, born in 1942, received his M.E. degree from Nihon Univ., 1968. He was engaged in the study of wind engineering at the Univ. of Tokyo in 1970 & 1971 and is a senior engineer for technical problems in bridge engineering at Sumitomo Heavy Ind., Ltd.

SUMMARY
The quality control aspects in the erection of cable-stayed bridges are generally discussed with the presentation in terms of error analysis. This approach is definitely effective if combined with the use of computer controlled measuring instruments. In this paper, however, it is shown that error simulation itself may present rather decisive data, taking the example of the Adhamiyah Bridge constructed in Baghdad, in 1984.

RÉSUMÉ
Le contrôle de qualité lors de la construction des ponts haubannés est généralement basé sur l'analyse d'erreurs. Cette approche par simulation est très efficace, plus spécialement lorsqu'elle est combinée avec l'utilisation d'instruments de mesure commandés par ordinateur. Cette étude, basée sur le pont d'Adhamiyah construit en 1984 à Baghdad, montre que l'approche par simulation peut aboutir à des résultats concluants.

ZUSAMMENFASSUNG
Die Gesichtspunkte der Qualitäts-Kontrolle beim Bau von Schrägseilbrücken werden umfassend auf der Grundlage von Methoden der Fehler-Analyse dargestellt. Kombiniert mit computergesteuerten Messinstrumenten ergibt sich so ein sehr wirksamer Weg der Qualitäts-Kontrolle am Bau. Am Beispiel der 1984 in Bagdad erstellten Adhamiyah-Brücke wird jedoch gezeigt, dass die Simulation von Fehlern und das Verfolgen der Auswirkungen allein schon wesentliche Hinweise für eine zielgerichtete Qualitäts-Kontrolle geben können.

1. INTRODUCTION

Cable-stayed bridges are generally required to take rather consistent erection control because of their highly statically indeterminate structural system.
In other words, as for ordinary type of bridges fabrication errors arising from cutting, welding and assembling are considered to be the main factors for the overall quality control and certain guarantee is given to their completion quality as far as appropriate closure procedure is applied.
As for suspension bridges, hunger tensions are assumed to be uniform over the span just like a distribution of dead load. And the fabrication and erection errors of main cables to be regarded as dominant factors for overall erection quality can be adjusted by hunger length. Therefore, it may be concluded that the fabrication quality can be more or less reflected to the completion stage.
On the other hand, in the case of cable-stayed bridges more unknowns are introduced due to the fact that the cables to be connected between the girder and the tower directly are not installed at the time of shop assembly. Also, theoretical evaluation on the overall non-linear behavior, the effective width etc., becomes more complicated due to the installation of cables.
In this report, error analysis approach to predict influential region due to the errors occurring at each stage is attempted referring to some notable technical features. And practical examples are shown regarding the construction of the first cable-stayed bridge in the Middle East.

2. BASIC APPROACH IN QUALITY CONTROL

2.1 Clarification of Error Factors

At each construction stage different type of errors will occur at different time by different amounts. Therefore, it is almost impossible to clarify all the error factors so precisely. However, conceivable error factors can be summarized in such a characteristic diagram as shown in Fig.1. Among those errors, some outstanding errors may be indicated in consideration of structural characteristics, erection conditions and other empirical factors. In cases, simulation approach can be an effective method to represent their influences quantitatively.

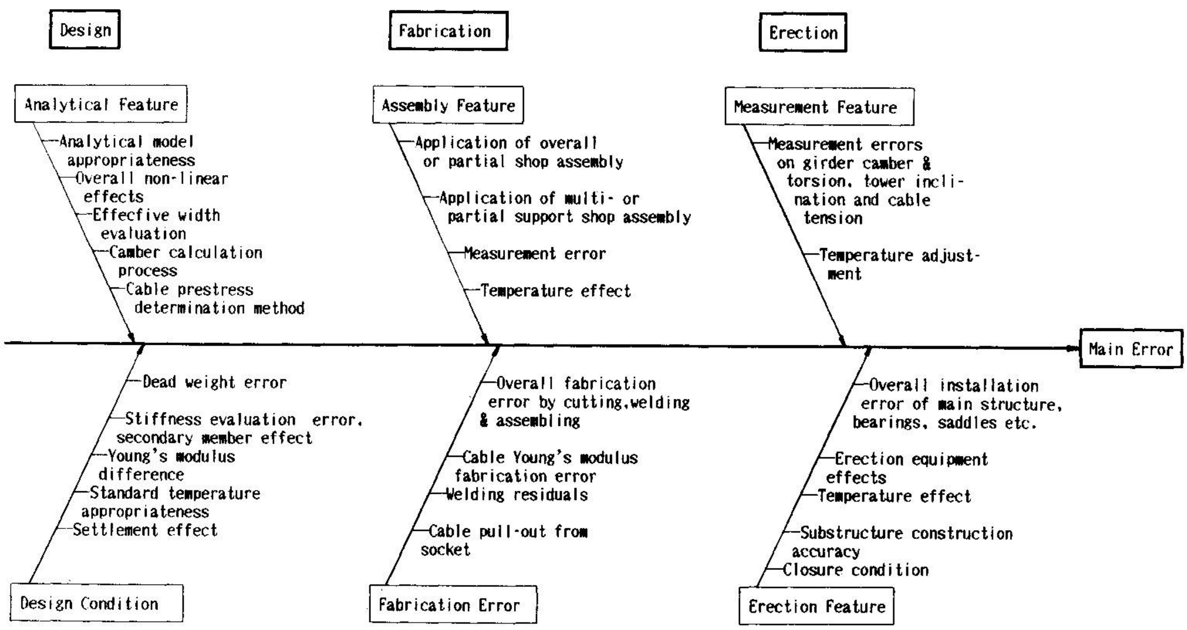


Fig.1 Characteristic diagram for main error factors

2.2 Basic Control Idea on Error Analysis

Those outstanding factors selected in that diagram are stochastically applied in the error analysis on the basis of propagation of errors as described below.

$$E_i = \sqrt{\sum_{j=1}^{m} (\Delta F_{ij})^2}$$

where E_i : total influenced value at point i of the bridge

ΔF_{ij} : influenced value at point i by the error factor j

m : number of error factors

On the other hand, the main objective of quality control is to restrain the deviation of cable tension and profile from calculated values within certain allowable range. And in case of exceeding such range, adjustments are carried out ordinarily to cable length using shim plates or such similar devices either for overall profile or for cable tension.
Hence, it is conceivable to establish some certain bases for erection quality control using the error analysis approach. From this point of view the possible flow chart for that is presented in Fig.2.

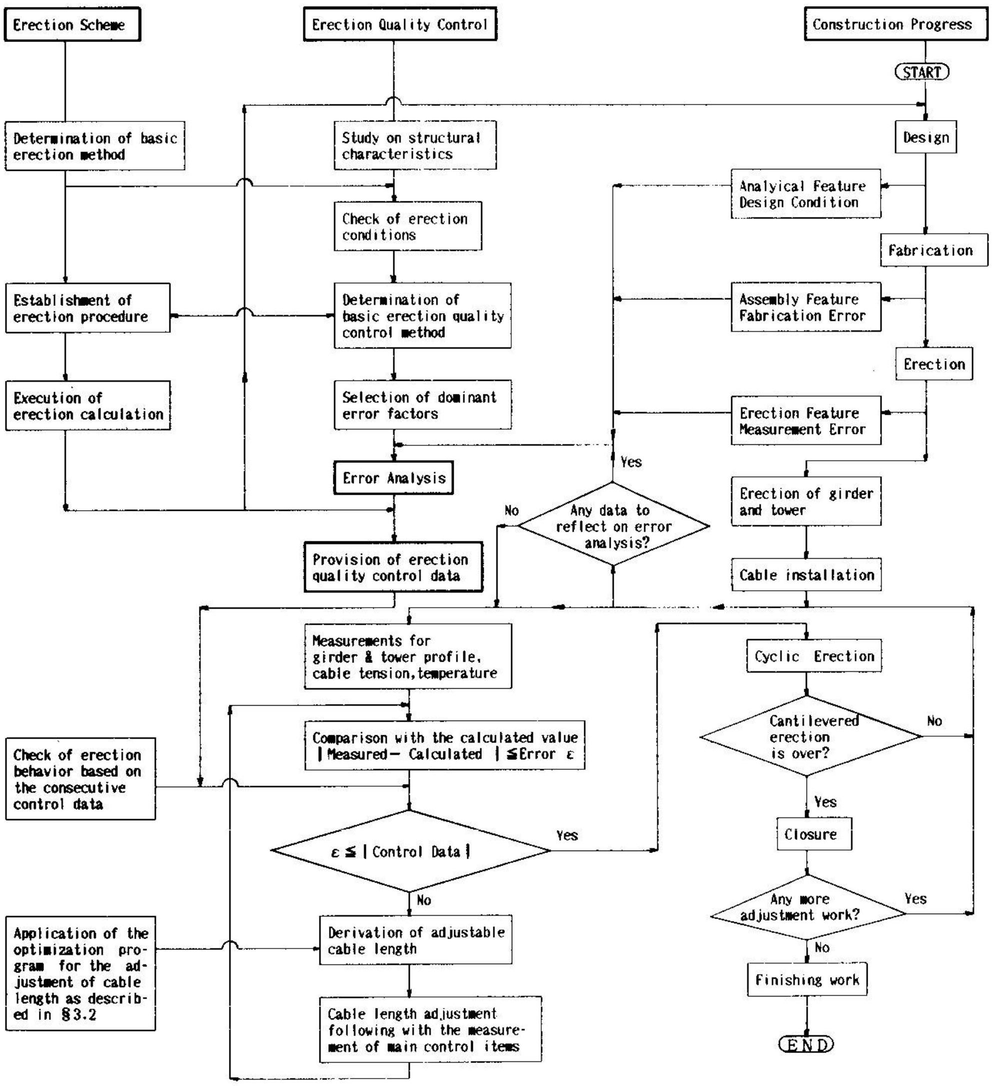


Fig.2 Flow chart for erection quality control of cable-stayed bridges

3. TECHNICAL FEATURES IN APPLICATION

3.1 Non-linear Behavior of Cables

For the non-linear effect of cables the well-known Ernst's equation has been practically applied. But the theoretical discrepancy in that equation was also indicated in its strict sense of application [1]. On the other hand, with the development of analytical approach such non-linear behavior was analyzed on the catenary configuration basis and combined into overall structural analysis [2, 3]. Owing to this, from erection to completion stage consistent erection calculation is to be proceeded once unstressed length is defined. Using this program which is also useful for the error analysis, comparison was made as shown in Fig.3 and Table 1 with the calculation results by the Ernst's equation for the erection of the Adhamiyah Bridge.
From these data it is pointed out that the difference between two approaches attains to 10~20% at the time of cable installation and even at the closure of steel box girder.

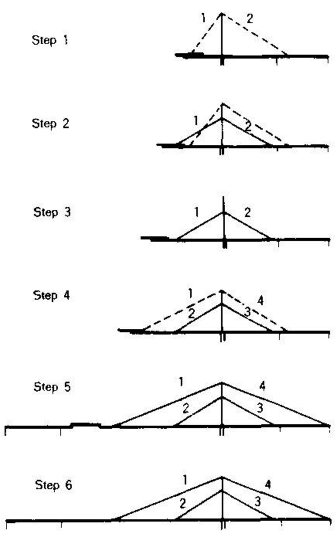


Fig.3 Erection Sequence

Erection Steps	Cable No.	f/ℓ	Cable Section Area (m²)	Average Cable Tension (KN)	σ (KN/m²)	Eeq×10 (Ernst)	Eeq/Ec
1	1 2	1/318 1/217	0.01467	5935 3855	404564 262662	1.598 1.558	0.999 0.974
2	1 2	1/142 1/139	0.0967	10290 10546	106468 109058	1.276 1.296	0.799 0.810
3	1 2	1/275 1/270	0.0967	20052 20503	207403 212033	1.547 1.550	0.967 0.969
4	1 2 3 4	1/302 1/292 1/272 1/321	0.01467 0.0967 0.0967 0.01467	5690 19914 20532 6092	388103 205971 212298 415395	1.579 1.546 1.551 1.589	0.987 0.966 0.969 0.994
5	1 2 3 4	1/160 1/216 1/215 1/157	0.0394 0.0967 0.0967 0.0394	9094 15755 16275 9153	230839 162964 168330 232261	1.455 1.494 1.504 1.459	0.909 0.934 0.940 0.912
6	1 2 3 4	1/123 1/215 1/209 1/123	0.0394 0.0967 0.0967 0.0394	7004 15677 15873 7220	177649 162130 164092 183182	1.313 1.492 1.477 1.337	0.821 0.933 0.934 0.836

Table 1 Comparison of cable non-linearity

3.2 Profile and Cable Tension Adjustment

In the progress of erection work it is inevitable to provide some adjustments to overall profile or cable tension. Under the condition that the main adjustment is for overall profile, the following equations are applied.

Overall Profile ; $\{\Delta L\} = [A]^{-1} \{\Delta X \pm \alpha\}$

Cable Tension ; $\{\Delta L\} = [B]^{-1} \{\Delta T + \kappa T \pm \beta\}$

Where $\{\Delta L\}$, $\{\Delta X\}$: cable length to be adjusted and profile error
$\{T\}$, $\{\Delta T\}$: calculated cable tension and its error
$[A]$, $[B]$: influence matrices upon profile and cable tension by unit length adjustment
α, β, κ : allowable error residuals and weight coefficient
$\{\ \}$, $[\ ]$: column vector and matrix

In the above equations both $\{\Delta L\}$ do not coincide each other generally, which attributes to the minimization problem of $\sum_{i=1}^{n} (\Delta L_i)^2$ (n: cable numbers).

3.3 Design Considerations

With the development of digital computer, new analytical method for cable-stayed bridges have been developed and have become more accurate as indicated in § 3.1. In the application stage, however, there arises a wide range of design problems as tabulated in Table 2. These items are to be respectively studied according to its structural characteristics, erection features etc., referring to § 2.

Notable Items	Practical Applications	Remarks
1. Evaluation on non-linear behavior of cables	Ernst's modified Young's modulus	10 ~ 20 % of errors are introduced at erection stages.
	Non-linear analysis based on the flexibility approach	Effective for erection stages and long spans bridges.
2. Derivation of cable prestress	1. Derived as additional initial tension by equalizing the bending moment distribution of girder at the completed stage. 2. Derived from balancing of cable horizontal forces at the completed stage 3. Derived from the zero bending moment condition at the closure. 4. Derived from the overall stress check for the whole structure from erection to completion.	The concept of cable prestress is based on the linear analysis and is not applicable for the said non-linear analysis where consistent calculation is possible from erection to completion as cable unstressed length is defined for the completion stage.
3. Evaluation on effective width	Overall width is effective.	Ordinarily, overall width is applied for camber calculation and effective width for stress check.
	Derived from the equivalent span length based on the continuous girder assumption where zero bending moment points are regarded as supports.	At each erection stage and loading case, detailed check calculation is required.
	In the above case cable anchorage points are regarded as supports.	ditto
	Other application such as by shear lag analysis.	Usually applied for bending moments, and for axial forces overall width is applied. Above check is also required.
4. Calculation procedure for fabrication camber	1. By eliminating each load in the opposite way to the erection sequence. 2. By superposition according to the erection sequence. Results are confirmed to be within allowable range by repetitive calculation from derived camber to final profile.	For composite girder, the influence of weight and stiffness of formwork is to be checked.
5. Closure procedure	No closure deformation and stress had better be realized.	In the case of remaining, such influences are to be checked including camber calculation.

Table 2 Design considerations

4. QUALITY CONTROL IN THE ADHAMIYAH BRIDGE CONSTRUCTION

4.1 Structural Aspects

The Adhamiyah Bridge now renamed as the 14th Ramadan Bridge is taken as a practical example. This 4 span continuous composite box girder bridge as shown in Fig.4, has many innovative structural features such as tensile connection system at tower block joints and at brackets cantilevering out by 10.5m from the spine box, prestressed link bearing with rotational capability, diagonal bracing system between the outer girder and the spine box, etc. Especially, the longitudinally hinged connection system at the tower base was considered to have a significant influence on the erection quality control. Also, 750mm jacking down at one pier between the stages of concrete placement affected the fabrication camber calculation along with the evaluation on composite effect of the girder during the erection stages.

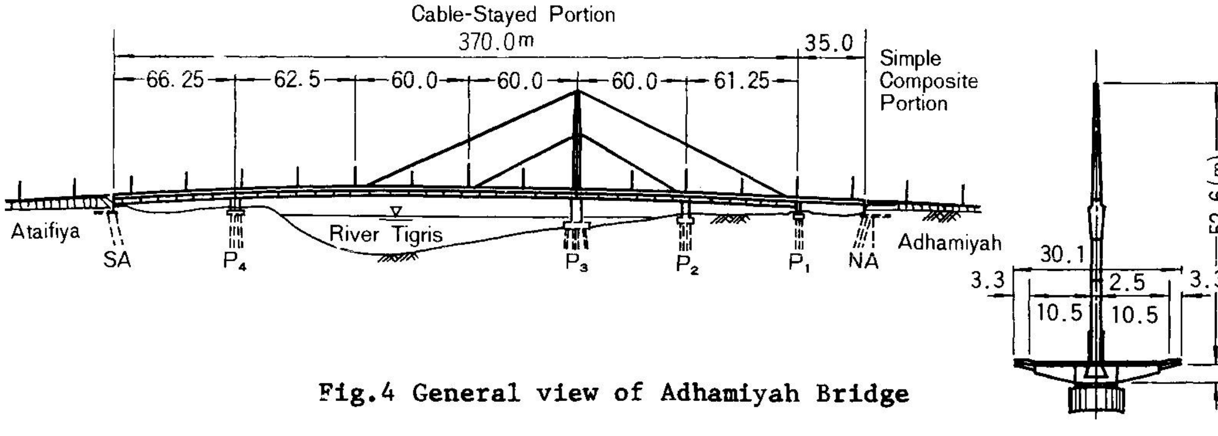


Fig.4 General view of Adhamiyah Bridge

4.2 Erection Features

In the erection sequence as partially shown in Fig.3, following erection methods were applied. Between P1 and P3 the push-out method using the erection girder and between P4 and SA the staging method were adopted respectively. Between P3 and P4 the maximum 162.5m cantilevered erection method was applied as shown in Photo.1. In any method it is noted that the trial assembly was carried out at site with three consecutive boxes to check their fabrication camber. Then, subsequently each one box was separated and advanced to erection front for final setting. Thus, the cantilevering was carried out cyclically using temporary and permanent cables.

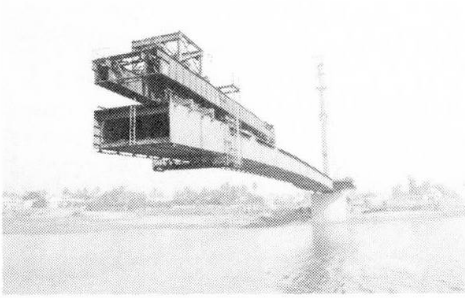


Photo.1 Cantilevered erection

4.3 Outline of Applied Erection Control

Considering the structural characteristics and the erection features as mentioned above, it is pointed out that the profile of the tower designed as an axial member is to be checked to restrain the excessive bending moment due to the unbalanced cable horizontal forces especially at the time of cable installation. Then, referring to this point the erection calculation was executed in details with determining the cable unstressed length to be balanced horizontally.
One example is given for the installation of inner main cables. The erection views before and after the transfer of temporary cable tension to the inner main cables are given in Photos.2 and 3 respectively. In Fig.5 the installation results are presented in terms of cable tension and pulling and slackening lengths. Throughout the erection, the detailed erection calculation was provided in similar way for all other stages. Additionally, as for the measurement, typical equipments such as theodolites, levels and jacks with electrically controlled pump were applied. Also, in order to avoid temperature effect the erection of the spine box was carried out early in the morning. For cables, installation was made according to their marked length and not to tension. Measurements were surely executed before dawn.

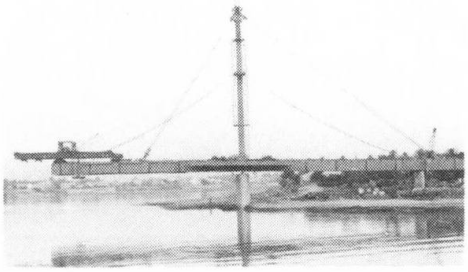


Photo.2 View before the transfer of cable tension

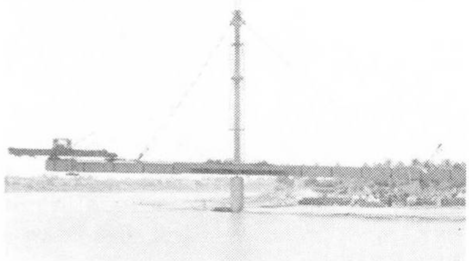


Photo.3 View after the transfer

Thus, on the basis of the above erection procedure and erection calculation the error analysis was applied for important erection steps.

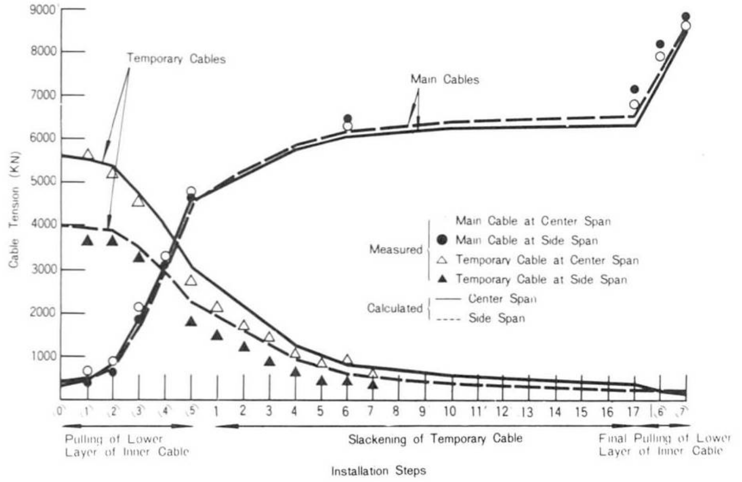


Fig.5 Results for the cable tension transfer

4.4 Practical Example of Error Analysis

Some design and erection features regarding the quality control of this bridge have been presented in the discussion so far. Other notable features were as follows.

(1) 7 cases of fabrication camber calculation were carried out for composite effect of the girder, overall non-linear effects, effective width evaluation, influence of formworks of concrete, erection sequence, etc. including 750mm jacking down at P4. Then, one reasonable solution was adopted from the various cases of results.

(2) The distance between cable anchorages in the girder and the tower was measured at the shop assembly. These results were reflected on the final cable unstressed length.

(3) The standard Young's modulus for locked coil rope was applied for the erection calculation. The difference from the fabricated one was confirmed to be within ± 2 % and was reflected upon the error analysis.

(4) The pulling-out of strand from socket was confirmed by the tensile test under 50 % of the breaking load prior to the fabrication. Then, 5mm pulling-out was adopted and reflected upon the final cable unstressed length.

Taking those quality features into account, the error analysis was proceeded according to § 2.1 and 2.2. Some examples are presented in Figs. 6 ~ 9. In these cases cable unstressed length was regarded as the representative error factor. Namely, those errors with 1/10000 of fabrication accuracy, ±10mm of installation and measurement errors, 5mm of pull-out of strand and others were totaled as ±30mm for the outer main cable and ±20mm for the inner main cables. The results by the error analysis and by the erection calculation and the measurement are given in Figs.6 and 7 respectively for the stage where the installation of the outer main cable was completed. Similarly, in Figs.8 and 9 the results are shown for the stage where the erection of the spine box girder

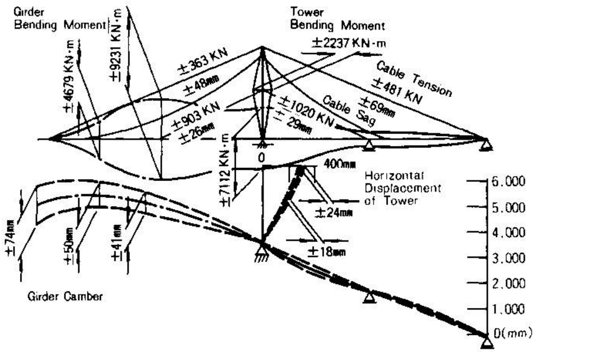


Fig.6 Influence of cable unstressed length error at the outer cable installation

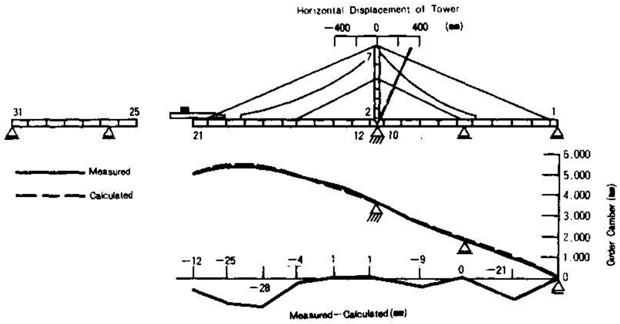


Fig.7 Error distribution between calculated and measured for the above stage

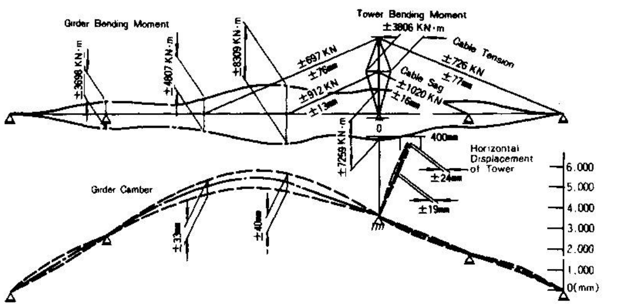


Fig.8 Influence of cable unstressed length error at the completion of spine box

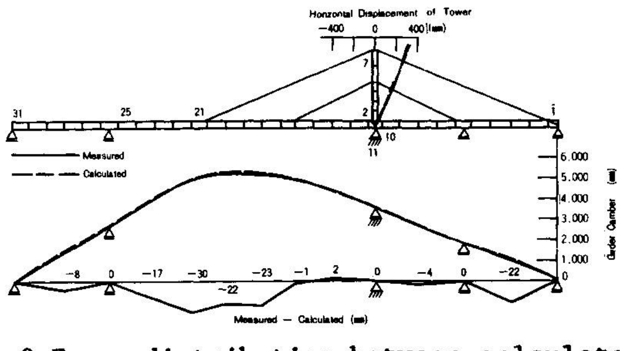


Fig.9 Error distribution between calculated and measured for the above stage

was finished.
From those results, it is known that the distribution of influential values due to the error analysis is similar to those differences between calculated and measured values. In this sense it can be stated that the error analysis itself may give certain criterion for the erection quality control.
Additionally, some other influences were checked as shown in Table 3 for the completion stage of spine box. Also, the final profile after the placement of concrete is shown in Photo.4 where the maximum difference for the girder deflection between calculated and measured values was 66mm at the outer main cable anchorage of the center span.
Considering the fact that any shim plate was never used for the adjustment throughout the erection, it is clear that the final results present very high erection accuracy.

Error		Girder					Tower		Cables			
		Def. (mm)		Bending Moment (KN·m)					Cable Tension (KN)			
Factor	Amount	Outer Cable	Inner Cable	P_4	Outer Cable	P_3	Top Disp. (mm)	B.M. (Max.) (KN·m)	Center Outer	Center Inner	Side Inner	Side Outer
Basic Value	—	147	9	−70592	26664	−22847	280	103	8495	17736	18070	8692
Girder Weight	+5%	−23	16	−5513	3561	−3522	−5	14	167	677	677	177
Girder Stiffness	+10%	−10	1	−481	795	−137	2	20	−88	39	29	−88
Cable Young's Modulus	−2%	7	6	863	1001	−912	−1	9	−98	−39	−49	−88
Temperature Overall	+25℃	0	0	−20	29	69	0	0	−10	10	10	−10
Cable / Girder	15℃ / 0℃	3	1	1972	491	29	−1	−2	20	39	39	20
Cable only	+25℃	75	72	9702	10693	11134	−18	109	−932	−569	−677	−893

Table 3 Influence of other errors

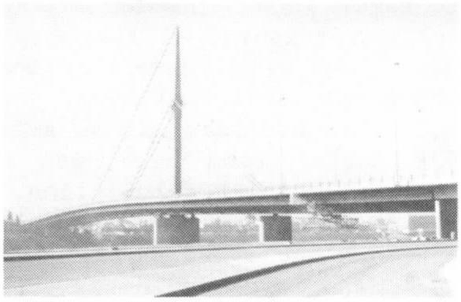


Photo.4 Completion view

5. CONCLUDING REMARKS

The outline of error analysis approach was presented for the erection control of cable-stayed bridges, taking the example of the Adhamiyah Bridge construction. In today's advanced technology, more precise measuring instruments capable of real time treatment will surely be applied in combination with the computer system at site. Considering the recent tendency of increase of multi-cable type stayed bridges, such system will be definitely utilized and contribute to the simplification of quality control works or even total erection works.
On the other hand, as described so far, it is also true that the error analysis based on simulation approach will present decisive data for the erection progress possibility.
When combined with one of those advanced systems by computer, this desk approach will provide more effective way of erection quality control just in the same way as the simulation approach has been a powerful method to the construction of suspension bridges.

REFERENCES

1. M.Ito and Y.Maeda, "Discussion of Commentary on the Tentative Recommendations for Cable-Stayed Bridge Structures", Journal of the Structural Division, ASCE, Vol.104 No.ST2, Feb,1978
2. A.H.Peyrot and A.M.Goulois, "Non-linear Analysis of Flexible Transmission Lines", Journal of the Structural Division, ASCE, Vol.104 No.ST5, May, 1978
3. T.Yamamoto and T.Kitahara,"Non-linear Analysis of Cable-Stayed Bridges under the Sag Change of Cables",Annual Convention of JSCE, 1979(in Japanese)