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# COMPUTER AIDED DESIGN AND QUALITY CONTROL SYSTEM FOR CABLE-STAYED BRIDGES

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## SUMMARY

This is a report on features and application examples of the latest version of a computer aided design system for long-span cable-stayed bridges, which has been proven under extensive actual uses and believed to be one of the most advanced systems of its kind. Moreover, in this paper, an application example of the version to the quality control system during construction will be described, along with high technology systems.

## INTRODUCTION

Computer aided design ( CAD ) systems for long-span cable-stayed bridges should have the capability of processing efficiently under design conditions and non-linear problems typical with this type of bridges, as well as the enormous amount of input and output data. The systems have been undergoing considerable changes due to these requirements and the advance in analytical theories, numerical calculation techniques, computers and drawing devices. On the other hand, quality control systems during construction have been influenced by the rapid progress in the so-called high technology field.

This paper is a report on a system developed by the authors. First, the authors will describe, with a flowchart, the outline and the features of various sub-programs which compose this system and have pre- and post-processing routines improved by utilizing drawing devices. Following this will be a special mention of various analytical theories and techniques that have been incorporated into this system, such as non-linear static analysis of the effect of cable sag, non-linear seismic response analysis by piecewise linearization using the approximated chordal stiffness and linearized aerodynamic analysis considering the system damping.

Moreover, an actual design example performed by the use of the latest version will be described in order to verify its high efficiency. Also, an application example of the version to the quality control system in a construction yard will be described in order to verify the effectiveness of results obtained by using high technology systems, such as data communications equipments and automatic measurement devices.

## OUTLINE AND FEATURES OF THE SYSTEM

This computer aided design system [ 1 ] has been believed to be one of the most advanced systems of its kind, and performs the processing shown in Fig.1. The system consists of two programs : "PLANE" for analyses of plane frames and "SPACE" for space frames. Moreover, these programs include pre- and post-processing routines improved by utilizing drawing devices.

Various sub-programs in Fig.1 have the following outline and features. Where sub-programs named 'STATIC ANALYSIS' and 'DYNAMIC ANALYSIS' can perform several kinds of analyses not only for the completed stage, but also for each stage of construction.

### Sub-programs - 'STRUCTURAL DATA' and 'INITIAL CONDITION'

In this system, structural data for plane frames are processed at first. The re-numbering function enables users to take any node or member numbers in the case of a beam model or a truss model as a main girder. Also, by practical use of patterns and rules governing structural characteristics of cable-stayed bridges, automatic data processing of various kinds for any given nodes or members is made possible with a great reduction of time and labor.

Next, non-stressed shapes of a main girder and towers, and non-stressed lengths of cables can be automatically determined from their required stressed conditions with such data as girder elevation, tower inclination and cable tension involving the prestress at the completed stage [ 2 ]. As a result of determining these initial conditions, diagrams of skeleton and camber are drawn. Furthermore, data of co-ordinates and lengths at the non-stressed conditions are automatically passed to "PLANE" and " SPACE" along with structural data at the completed stage.

### Sub-program - 'INFLUENCE-LINE ANALYSIS'

With "PLANE", the influence-line analysis for section forces, reaction forces and displacements at each point can be performed. Diagrams of calculated influence -lines involving much information are drawn, and then vertical distances, positive and negative areas of influence-lines are multiplied by the live load values. Particul-

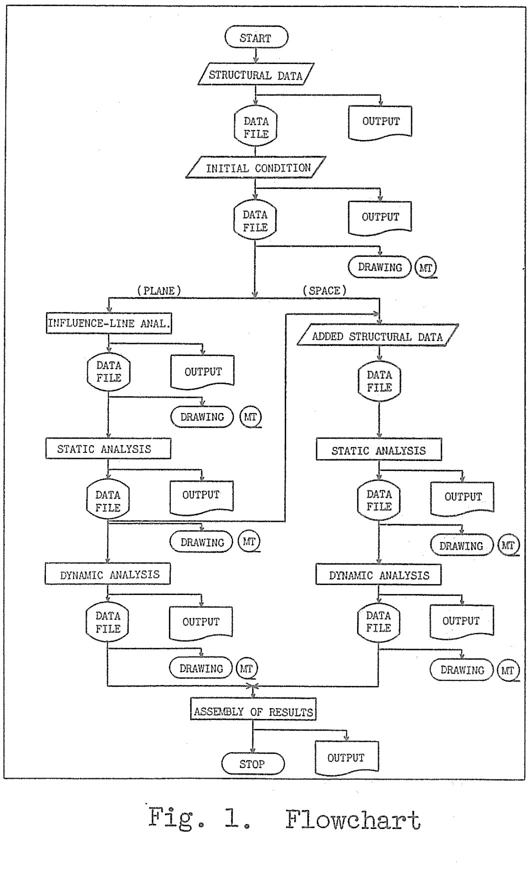


Fig. 1. Flowchart

arly for railway loads, the live loads are treated as uniform loads with specified lengths to automatically obtain the position of loading. As the result, the maximum and minimum values of forces and displacements are able to be evaluated at aimed points.

## Sub-programs - 'STATIC ANALYSIS' and 'ADDED STRUCT. DATA'

With "PLANE", non-linear static analyses for various types of loading can be performed by using the generalized technique on the basis of the finite element method and the finite displacement theory. For solving non-linear equations expressed in terms of band matrices, the mixed method employing the incremental method and the iteration method is applied. Then necessary data obtained are automatically passed to "SPACE".

On the other hand, with "SPACE", by addition of characteristic data for space frames to the data received from "PLANE", a NASTRAN data file [3] is compiled with the minimum of time and labor. Consequently, linearized static analyses can be performed through NASTRAN by using either fish-bone models or truss models as main girders.

Furthermore, with "PLANE" and "SPACE", by directly changing the values of non-stressed length, co-ordinate, section rigidity, load and temperature, analyses for errors due to various factors can be performed easily. Also, drawings can be derived for the results of all of static analyses.

## Sub-program - 'DYNAMIC ANALYSIS'

With "PLANE", time series response analyses for seismic excitation of plane frame models with geometrical nonlinearity can be performed by the direct integration method.

On the other hand, with "SPACE", eigen-value analyses of linearized equations of motion for space frame models can be performed, and natural frequencies and vibration modes are calculated. In addition, these are then applied to seismic response analyses by using the earthquake response spectra, and to their time series analyses by the mode superposition method.

Furthermore, with"SPACE", by using unsteady aerodynamic forces estimated in results of wind-tunnel tests, time series analyses can be performed for the response due to aeolian oscillations. Similarly, drawings can also be derived for the results of all of dynamic analyses.

## Sub-program - 'ASSEMBLY OF RESULTS'

Lastly, all results mentioned above,namely displacements, section forces and dynamic responses, etc., are assembled and edited to produce many kinds of tables in the form of calculation sheets for design of each cable-stayed bridge. Particularly, in this system, by recognizing patterns of apace-framed truss in the case of analyses using beam or fish-bone models as main girders, section forces for each member of truss can be evaluated automatically as required.

## SPECIAL MENTION OF ANALYTICAL THEORIES AND TECHNIQUES

Into this system, various analytical theories and techniques are incorporated for static and dynamic analyses. These theories and techniques contain the following distinctive ones proposed and established by the authors' group.

## Effect of cable sag

By replacing a sagging cable member with linking axial members, the effect of sag is taken into consideration fairly well. The approach, however, requires the calculation of a tangential stiffness matrix with a great band width in general. Therefore, the greatest difficulties in the method are to occupy a great part of the storage area of a computer and to spend long operating time.

As an alternative and representative method, Ernst [4] proposed a modified elastic modulus of a sagging cable by taking into account material as well as geometric elongation. However, judging from the assumption used in the theory, the method holds in limited cases, for example, frames with small nonlinearity and cables with a fairly low sag ratio. Therefore, particularly in order to perform more reliable and reasonable analyses for each stage of construction by the cantilever erection method, a more exact method should be used instead of the modified modulus.

For the purpose of introduction into non-linear analyses by the mixed method, the authors' group formulated and proposed non-linear cable equations and tangential stiffness matrices for sagging cables [5], [6]. Also, it was found that, by using the proposed formulae, non-linear static analyses of long-span cable-stayed bridges had sufficient accuracy in practice even for each stage of construction through some numerical examples.

## Improvement on non-linear dynamic analysis

An analytical solution of non-linear equations of motion is apparently introduced by a pure iteration method. The method, however, requires a great number of iterations and a lengthy operating time at every time step in a numerical integration. For this reason, the demand for reduction of an operating time has drawn attention of many investigators.

As a representative study, by piecewise linearization using tangential stiffness matrices, Fleming [7] carried out in-plane seismic response analyses of cable-stayed bridges with geometrical nonlinearity. The piecewise linearization is one of the powerful method for time series response analyses by the direct intagration method. But, in the method, the degree of accuracy of the linearized stiffness, approximated at each incremental time step, is the most closely related to rational reduction of an operating time. Therefore, in order to perform more efficient analyses, a more accurate approximated stiffness should be used instead of a tangential stiffness.

The authors' group formulated a chordal stiffness matrix, and proposed the direct integration method by piecewise linearization using approximated chordal stiffness matrices [8], [9]. Similarly, it was found that the accuracy of the approximated chordal stiffness enabled to prevent excess accumulation of nemerical errors due to linearization, by employing a time-increment smaller than a value needed not to produce immoderate truncation errors due to interpolation of inertia forces.

## Consideration to the system damping

The system damping effect which would prevent bending and torsional oscillations of cable-stayed bridges and secure hereby their dynamic safety, was first pointed out by Leonhardt [10]. However, judging from the results of full-scale measurements of several bridges built in Japan, the effect cannot be considered as characteristics common to all of the cable-stayed bridges. Namely, it seems that governing causes and real responses are not completely clarified yet, and the development of analytical study is indispensable as well as further actual bridge tests. Because the effects on wind-induced responses, principally observed at a few actual bridge tests and during the construction, are difficult to be directly examined by full-model wind-tunnel tests. Consequently, there are many problems remaining unsolved, and the application to a design has not been generally carried out yet.

In these circumstances, the authors' group defined that the function of staying cables as a damped absorber ( tuned mass damper in a wide sense ) and the beating phenomena ( from another angle, a main girder and particular cables exchange their oscillation energy ) were governing causes of the system damping, when the so-called internal resonance in terms of bending or torsional oscillations of a main girder and of transverse local oscillations of cables occurred remarkably. Also, the authors' group proposed an analytical technique of time series response using unsteady aerodynamic forces given by a sectional-model wind-tunnel test for aeolian oscillations, taking into consideration the internal resonance [11], [12]. Already, the validity of the definition and the analytical technique had been confirmed by an actual bridge test and a design example with multi-cable system respectively.

## APPLICATION TO ACTUAL DESIGN EXAMPLE

The latest version of this system has been proven under extensive actual uses. Therefore, in order to verify its high efficiency, a part of results of application to an actual design example [13].

Their results are the following diagrams, by a drawing device, and tables, by a line printer, in the form of calculation sheets for design in Japan. Where Fig.2 is a diagram of skeleton and camber drawn with the sub-programs 'STRUCT. DATA' and 'INITIAL CONDIT.'. Fig.3 shows diagrams with the sub-program 'INFUL. -LINE ANAL.'. Next, figures from Fig.4 to Fig.6 show diagrams with the sub-program 'STATIC ANAL.'. Also, figures from Fig.7 to Fig.10 show diagrams with the sub-program 'DYNAMIC ANAL.'. Furthermore, tables from Table 1 to Table 4 are the ones printed with the sub-program 'ASSEMBLY OF RESULTS'.

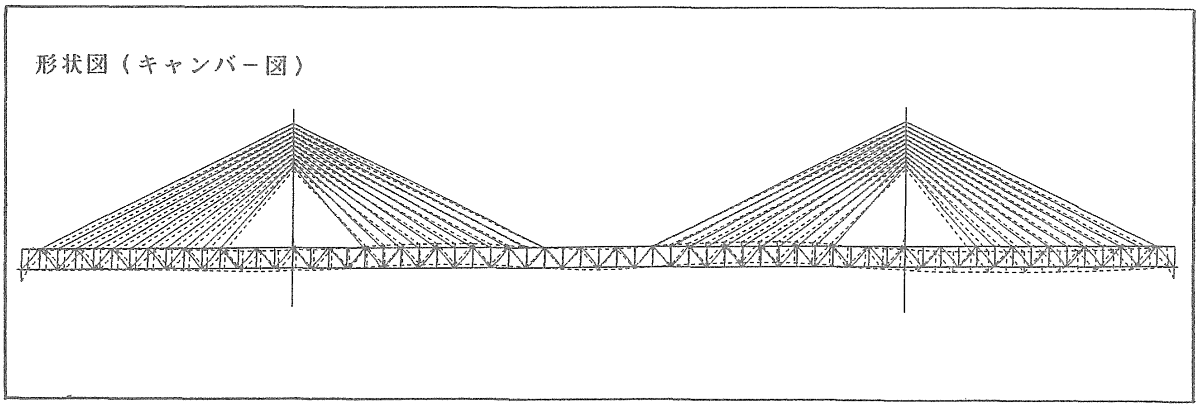
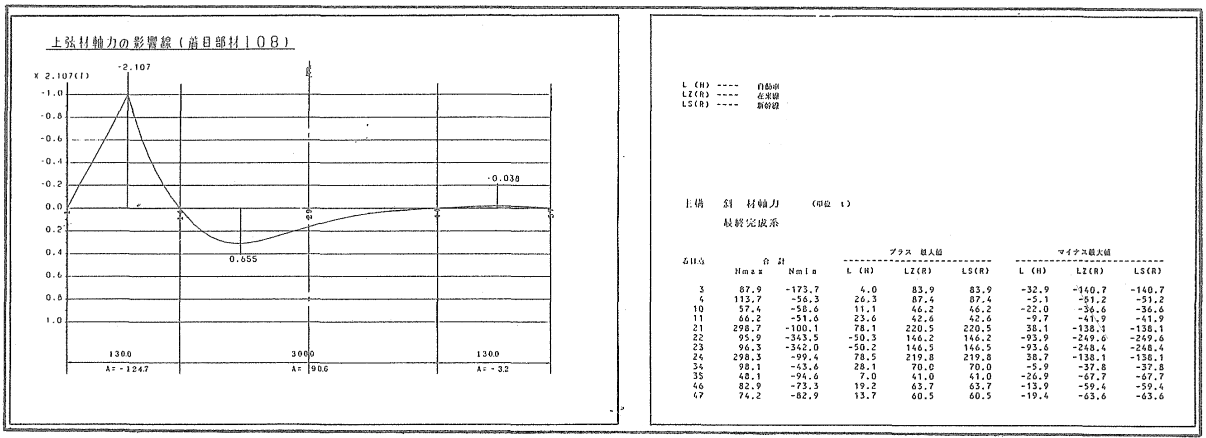


Fig. 2. Diagram of skeleton and camber



L (H) ---- 自動車
LZ(R) ---- 在来線
LS(R) ---- 新幹線

上構　斜　材軸力　(単位 t)
最終完成系

| 着目点 | 合 計 |  | プラス 最大値 |  |  | マイナス最大値 |  |  |
|---|---|---|---|---|---|---|---|---|
|  | Nmax | Nmin | L (H) | LZ(R) | LS(R) | L (H) | LZ(R) | LS(R) |
| 3 | 87.9 | -173.7 | 4.0 | 83.9 | 83.9 | -32.9 | -140.7 | -140.7 |
| 4 | 113.7 | -56.3 | 26.3 | 87.4 | 87.4 | -5.1 | -51.2 | -51.2 |
| 10 | 57.4 | -58.6 | 11.1 | 46.2 | 46.2 | -22.0 | -36.6 | -36.6 |
| 11 | 66.2 | -51.6 | 23.6 | 42.6 | 42.6 | -9.7 | -41.9 | -41.9 |
| 21 | 298.7 | -100.1 | 78.1 | 220.5 | 220.5 | 38.1 | -138.1 | -138.1 |
| 22 | 95.9 | -343.5 | -50.3 | 146.2 | 146.2 | -93.9 | -249.6 | -249.6 |
| 23 | 96.3 | -342.0 | -50.2 | 146.5 | 146.5 | -93.6 | -248.4 | -248.4 |
| 24 | 298.3 | -99.4 | 78.5 | 219.8 | 219.8 | 38.7 | -138.1 | -138.1 |
| 34 | 98.1 | -43.6 | 28.1 | 70.0 | 70.0 | -5.9 | -37.8 | -37.8 |
| 35 | 48.1 | -94.6 | 7.0 | 41.0 | 41.0 | -26.9 | -67.7 | -67.7 |
| 46 | 82.9 | -73.3 | 19.2 | 63.7 | 63.7 | -13.9 | -59.4 | -59.4 |
| 47 | 74.2 | -82.9 | 13.7 | 60.5 | 60.5 | -19.4 | -63.6 | -63.6 |

Fig. 3. Diagrams of influence line, and maximum and minimum values

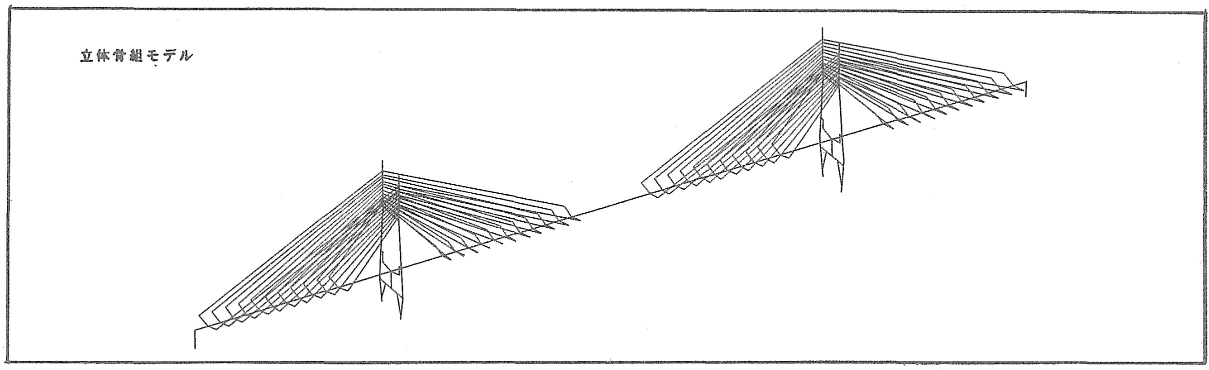


Fig. 4. Diagram of skeleton of space frame model ( fish-bone model )

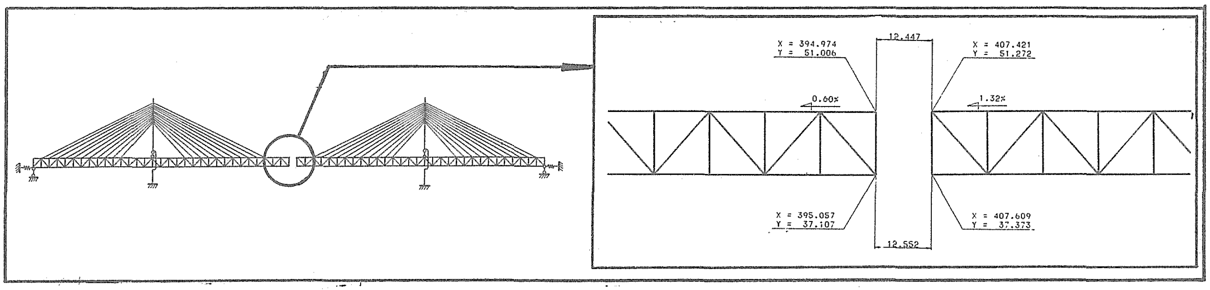


Fig. 5. Diagram of deformation of cantilever girder at closing step

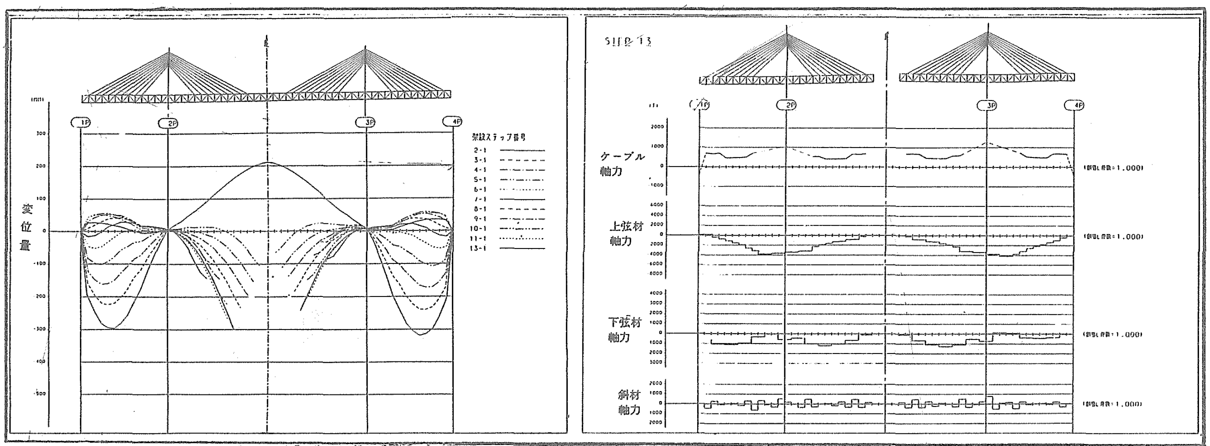
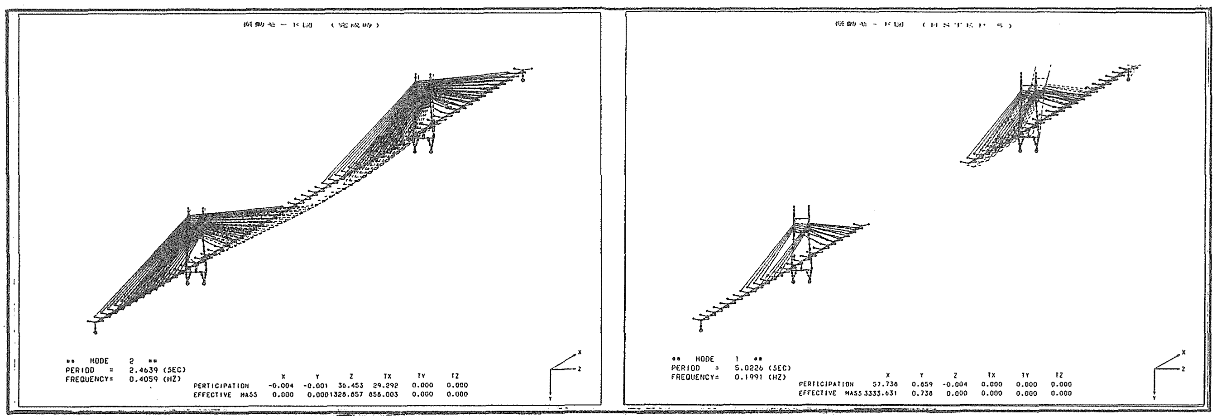


Fig. 6. Diagrams of displacements, and forces for construction stage



```
**   MODE      2   **
PERIOD   =    2.4639 (SEC)
FREQUENCY=    0.4059 (HZ)
                                    X        Y        Z        TX       TY       TZ
                 PERTICIPATION    -0.004   -0.001   36.453   29.292   0.000    0.000
                 EFFECTIVE  MASS   0.000    0.0001326.857  858.003   0.000    0.000
```

```
**   MODE      1   **
PERIOD   =    5.0226 (SEC)
FREQUENCY=    0.1991 (HZ)
                                    X        Y        Z        TX       TY       TZ
                 PERTICIPATION    57.736    0.659   -0.004    0.000    0.000    0.000
                 EFFECTIVE  MASS 3333.631   0.738    0.000    0.000    0.000    0.000
```

Fig. 7. Results of eigen-value analyses

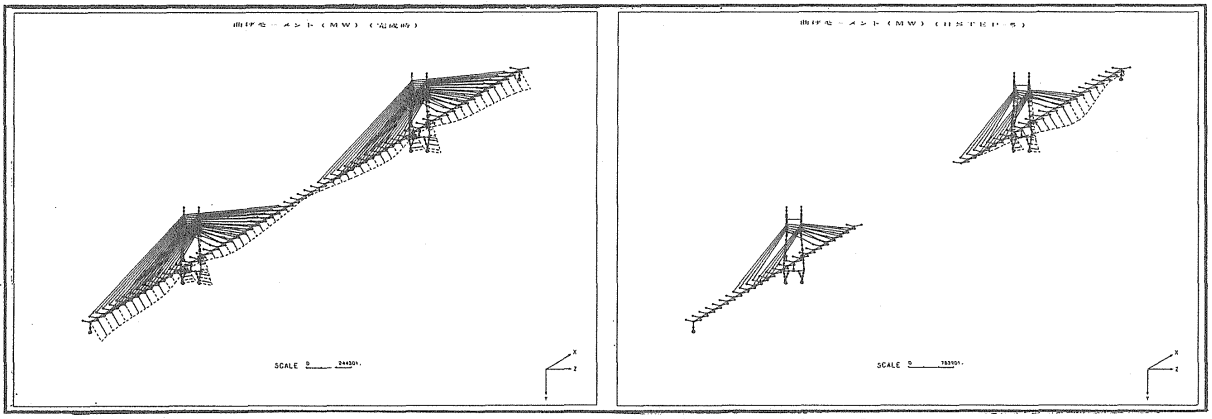


Fig. 8. Results of seismic analyses using earthquake response spectra

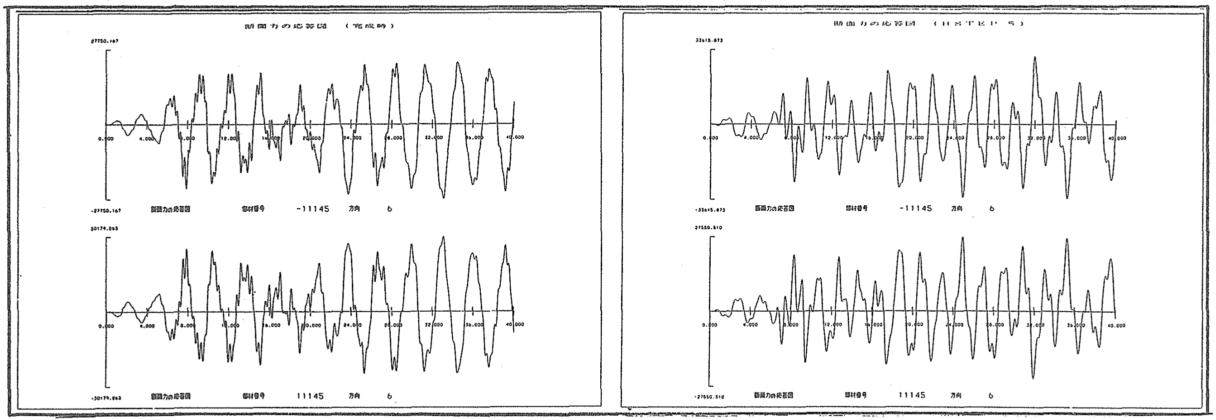


Fig. 9. Results of time series response analyses for seismic excitation

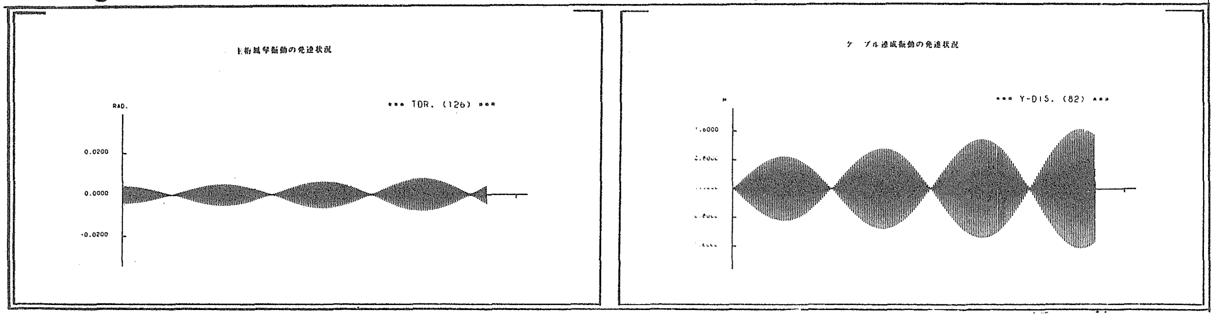


Fig.10. Result of system damping analysis for aeolian oscillation

Table 1. Section forces for every construction stage

上弦材　軸　力

| | 121 | 122 | 123 | 124 | 125 | 126 | 127 |
|---|---|---|---|---|---|---|---|
| (+) 最大値 | 584.2 | 121.9 | 598.9 | 121.0 | 595.3 | 120.7 | 598.4 |
| (-) 最大値 | -2935.8 | -2630.8 | -2266.4 | -2085.4 | -1701.6 | -1442.7 | -865.5 |
| STEP 4-3 | 514.6 | 95.2 | 592.3 | -.5 | --- | --- | --- |
| STEP 5-S-1 | 442.8 | 72.7 | 592.1 | -.6 | --- | --- | --- |
| STEP 5-S-2 | 388.6 | 57.7 | 591.4 | -.6 | --- | --- | --- |
| STEP 5-C-1 | -6.3 | -252.5 | 219.5 | -.6 | --- | --- | --- |
| STEP 5-C-2 | -331.6 | -496.7 | -77.4 | -.7 | --- | --- | --- |
| STEP 5-3 | 312.7 | 116.9 | 598.9* | 121.0 | 122.7 | --- | --- |
| STEP 6-S-1 | 229.4 | 81.4 | 575.1 | 121.0* | 122.9 | --- | --- |
| STEP 6-S-2 | 164.1 | 53.3 | 556.0 | 120.8 | 122.9 | --- | --- |
| STEP 6-C-1 | -210.9 | -291.3 | 161.0 | -139.4 | 117.5 | --- | --- |
| STEP 6-C-2 | -524.7 | -570.9 | -162.7 | -336.9 | 112.5 | --- | --- |
| STEP 6-3 | 53.3 | 60.1 | 523.7 | 56.0 | 595.3* | -.4 | --- |
| STEP 7-S-1 | -81.8 | -13.7 | 459.9 | 36.2 | 595.2 | -.5 | --- |
| STEP 7-S-2 | -177.6 | -66.3 | 414.1 | 21.8 | 594.6 | -.6 | --- |
| STEP 7-C-1 | -693.1 | -586.9 | -167.3 | -435.7 | 46.9 | -.7 | --- |
| STEP 7-C-2 | -1076.7 | -968.3 | -595.9 | -760.7 | -347.8 | -.7 | --- |
| STEP 7-3 | -625.3 | -422.5 | -9.2 | -193.2 | -284.1 | 120.7* | 122.5 |
| STEP 8-S-1 | -753.7 | -508.4 | -92.5 | -234.5 | | | |
| STEP 8-S-2 | -847.8 | -571.3 | -153.4 | -264.7 | | | |
| STEP 8-C-1 | -1217.9 | -980.9 | -599.9 | -677.1 | | | |
| STEP 8-C-2 | -1504.8 | -1295.0 | -944.9 | -986.9 | | | |
| STEP 8-3 | -1156.2 | -825.1 | -445.1 | -422.3 | | | |
| STEP 9-S-1 | -1286.6 | -923.8 | -544.7 | -482.2 | | | |
| STEP 9-S-2 | -1382.3 | -996.4 | -618.1 | -526.5 | | | |
| STEP 9-C-1 | -1683.5 | -1356.4 | -1003.0 | -923.6 | | | |
| STEP 9-C-2 | -1920.8 | -1639.6 | -1308.3 | -1232.7 | | | |
| STEP 9-3 | -1657.3 | -1237.1 | -883.7 | -708.7 | | | |
| STEP 10-S-1 | -1785.3 | -1344.0 | -994.0 | -784.4 | | | |
| STEP 10-S-2 | -1879.0 | -1422.3 | -1074.8 | -839.8 | | | |
| STEP 10-C-1 | -2126.5 | -1739.7 | -1408.4 | -1216.6 | | | |
| STEP 10-C-2 | -2317.8 | -1987.8 | -1671.5 | -1510.8 | | | |
| STEP 10-3 | -2142.1 | -1668.1 | -1337.6 | -1055.4 | | | |
| STEP 11-S-1 | -2269.2 | -1781.2 | -1455.2 | -1143.6 | | | |
| STEP 11-S-2 | -2355.9 | -1859.8 | -1537.2 | -1205.7 | | | |
| STEP 11-C-1 | -2541.8 | -2114.3 | -1800.3 | -1527.0 | | | |
| STEP 11-C-2 | -2684.6 | -2316.5 | -2011.4 | -1785.0 | | | |
| STEP 11-3 | -2573.1 | -2060.8 | -1747.4 | -1387.5 | | | |
| STEP 12 | -2499.5 | -1818.5 | -1499.5 | -974.4 | | | |
| STEP 13-1-1 | -2607.9 | -2161.6 | -1862.4 | -1550.0 | | | |
| STEP 13-1-2 | -2628.4 | -2164.0 | -1860.0 | -1545.7 | | | |
| STEP 14 | -2771.7 | -2382.5 | -2051.6 | -1791.0 | | | |
| STEP 15 | -2771.7 | -2382.1 | -2051.2 | -1790.3 | | | |
| STEP 16 | -2935.8* | -2630.8* | -2266.4* | -2085.4* | | | |

Table 2. Section forces due to each loading combination

記号の説明

TRZ ; 在来線荷重の合計

TRK ; ＫＳ－１６荷重の合計

DV ; 死荷重（鉛直解析）

DTRQ ; 死荷重（ねじり解析）

T ; 温度変化の影響

SD ; 支点移動の影響

E ; 製作及び架設誤差の影響

LHV ; 自動車荷重（鉛直解析）

LHQ ; 自動車荷重（ねじり解析）

LRVZ ; 列車（在来線）荷重（鉛直解析）

LRQZ ; 列車（在来線）荷重（ねじり解析）

LRVK ; 列車（ＫＳ－１６）荷重（鉛直解析）

LRQK ; 列車（ＫＳ－１６）荷重（ねじり解析）

主構　上弦材

荷重組合せ D+L+T+SD+E

一次完成時　Ｎｍａｘ　（単位　Ｔｏｎ）

| 着目部材 | 合計 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TRZ | TRK | : | DV | DTRQ | T | SD | E | LHV | LHQ | LRVZ | LRQZ | LRVK | LRQK |
| 3002 | -1269 | -1796 | : | -2353 | 27 | -155 | 96 | -15 | 261 | 3 | 528 | -1 | 0 | 0 |
| 3004 | -1469 | -2526 | : | -3621 | 28 | -315 | 192 | -30 | 524 | 6 | 1059 | -2 | 0 | 0 |
| 3006 | -602 | -2187 | : | -3805 | 15 | -474 | 287 | -45 | 786 | 11 | 1590 | -5 | 0 | 0 |
| 3008 | 1406 | -722 | : | -2883 | -13 | -633 | 383 | -60 | 1049 | 23 | 2120 | -8 | 0 | 0 |
| 3010 | 4710 | 2334 | : | -810 | -65 | -792 | 479 | -75 | 1388 | 52 | 2651 | -18 | 284 | -9 |
| 3012 | 2970 | 1267 | : | -633 | -25 | -558 | 339 | -53 | 902 | 23 | 1695 | -8 | 0 | 0 |
| 3014 | 1879 | 821 | : | -384 | -7 | -364 | 221 | -35 | 570 | 8 | 1055 | -3 | 0 | 0 |
| 3016 | 1311 | 599 | : | -157 | -1 | -213 | 129 | -21 | 387 | 5 | 710 | -2 | 0 | 0 |
| 3019 | 1181 | 570 | : | 9 | -16 | -104 | 63 | -11 | 349 | 18 | 604 | -7 | 0 | 0 |
| 3022 | 1243 | 583 | : | 131 | 1 | 29 | 19 | 2 | 397 | 4 | 661 | -1 | 0 | 0 |
| 3025 | 1380 | 679 | : | 129 | -10 | 69 | 44 | 6 | 408 | 13 | 696 | -5 | 0 | 0 |
| 3028 | 1457 | 742 | : | 132 | 3 | 119 | 75 | 11 | 399 | 3 | 716 | -1 | 0 | 0 |
| 3031 | 1468 | 762 | : | 132 | -6 | 134 | 84 | 12 | 382 | 12 | 702 | -4 | 0 | 0 |
| 3034 | 1366 | 733 | : | 129 | 3 | 152 | 96 | 14 | 336 | 3 | 634 | -1 | 0 | 0 |
| 3037 | 1302 | 716 | : | 123 | -3 | 156 | 98 | 14 | 310 | 12 | 581 | -5 | 0 | 0 |

Table 3. Maximum and minimum section forces

タイトル　説明

CASE-1　D+L+T+SD+E/1.00

CASE-2　D+W+T+SD+E/1.50

CASE-3　D+W(L)+L(W)+T/1.35

CASE-4　D+EQ+L(EQ)+T+SD+E/1.50

断面力集計　（単位　Ｔｏｎ）

主構　上弦材

| 着目部材 | | 設計断面力 | | 一次完成時 | | | | 最終完成時 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | CASE-1 | CASE-2 | CASE-3 | CASE-4 | CASE-1 | CASE-2 | CASE-3 | CASE-4 |
| 3002 | N-MAX | -1139 | : | -1269 | -1207 | -1155 | -1264 | -1247 | -1213 | -1139 | -1262 |
| | N-MIN | -3827 | : | -3704 | -1861 | -2497 | -2017 | -3827 | -1863 | -2588 | -2043 |
| 3004 | N-MAX | -1235 | : | -1469 | -1321 | -1349 | -1791 | | | | |
| | N-MIN | -5767 | : | -5745 | -3368 | -3961 | -3131 | | | | |
| 3006 | N-MAX | -202 | : | -602 | -663 | -698 | -1579 | | | | |
| | N-MIN | -6287 | : | -6287 | -4202 | -4387 | -3366 | | | | |
| 3008 | N-MAX | 2189 | : | 1406 | 712 | 816 | -556 | | | | |
| | N-MIN | -5911 | : | -5911 | -4277 | -4173 | -2883 | | | | |
| 3010 | N-MAX | 5986 | : | 4710 | 2676 | 3187 | 1305 | | | | |
| | N-MIN | -4461 | : | -4461 | -3407 | -3061 | -1695 | | | | |
| 3012 | N-MAX | 3712 | : | 2970 | 2526 | 2296 | 806 | | | | |
| | N-MIN | -3123 | : | -2977 | -3123 | -2327 | -1181 | | | | |
| 3014 | N-MAX | 2255 | : | 1879 | 2037 | 1619 | 531 | | | | |
| | N-MIN | -2387 | : | -1765 | -2387 | -1527 | -715 | | | | |
| 3016 | N-MAX | 1635 | : | 1311 | 1570 | 1202 | 388 | | | | |
| | N-MIN | -1685 | : | -1095 | -1685 | -1019 | -391 | | | | |
| 3019 | N-MAX | 1216 | : | 1181 | 1004 | 949 | 353 | | | | |
| | N-MIN | -1087 | : | -1014 | -945 | -799 | -239 | | | | |
| 3022 | N-MAX | 1243 | : | 1243 | 517 | 799 | 307 | | | | |
| | N-MIN | -1457 | : | -1250 | -355 | -758 | -179 | | | | |
| 3025 | N-MAX | 1380 | : | 1380 | 425 | 822 | 368 | | | | |
| | N-MIN | -1656 | : | -1473 | -283 | -849 | -265 | | | | |
| 3028 | N-MAX | 1457 | : | 1457 | 731 | 948 | 396 | | | | |
| | N-MIN | -1866 | : | -1672 | -607 | -1061 | -358 | | | | |
| 3031 | N-MAX | 1468 | : | 1468 | 965 | 1035 | 421 | | | | |
| | N-MIN | -1888 | : | -1691 | -848 | -1156 | -377 | | | | |
| 3034 | N-MAX | 1366 | : | 1366 | 1176 | 1049 | 397 | | | | |
| | N-MIN | -1809 | : | -1620 | -1071 | -1198 | -395 | | | | |
| 3037 | N-MAX | 1302 | : | 1302 | 1296 | 1057 | 396 | | | | |
| | N-MIN | -1760 | : | -1561 | -1201 | -1211 | -395 | | | | |

Table 4. Check of safety for fatigue

記号の説明

TRZ ; 在来線荷重の合計

TRK ; ＫＳ－１６荷重の合計

TRS ; 新幹線荷重の合計

主構　上弦材

疲労の照査　D+L (F)　（単位　Ｔｏｎ）

| 着目部材 | | 一次完成時 | | | | 最終完成時 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 応力範囲最大 | | TRZ | TRK | 応力範囲最大 | | TRZ | TRK | TRS |
| 3002 | N-MAX | -2132 | : | -2132 | -2326 | -2110 | : | -2146 | -2335 | -2110 |
| | N-MIN | -2769 | : | -2539 | -2769 | -2821 | : | -2562 | -2821 | -2530 |
| 3004 | N-MAX | -3204 | : | -3204 | -3593 | -3047 | : | -3118 | -3498 | -3047 |
| | N-MIN | -4171 | : | -3879 | -4171 | -4120 | : | -3778 | -4120 | -3796 |
| 3006 | N-MAX | -3208 | : | -3208 | -3790 | -2793 | : | -2879 | -3478 | -2793 |
| | N-MIN | -4300 | : | -4165 | -4300 | -4026 | : | -3854 | -4026 | -3880 |
| 3008 | N-MAX | -2042 | : | -2042 | -2870 | -1316 | : | -1378 | -2240 | -1316 |
| | N-MIN | -3353 | : | -3353 | -3135 | -2758 | : | -2709 | -2514 | -2758 |
| 3010 | N-MAX | 329 | : | 329 | -548 | 1455 | : | 1452 | 553 | 1455 |
| | N-MIN | -1445 | : | -1445 | -745 | -421 | : | -354 | 308 | -421 |
| 3012 | N-MAX | 59 | : | 59 | -608 | 740 | : | 716 | 21 | 740 |
| | N-MIN | -1005 | : | -1005 | -608 | -393 | : | -362 | 21 | -393 |
| 3014 | N-MAX | 35 | : | 35 | -377 | 393 | : | 366 | -57 | 393 |
| | N-MIN | -560 | : | -560 | -377 | -245 | : | -238 | -57 | -245 |
| 3016 | N-MAX | 125 | : | 125 | -156 | 253 | : | 229 | -59 | 253 |
| | N-MIN | -276 | : | -276 | -156 | -200 | : | -187 | -59 | -200 |
| 3019 | N-MAX | 287 | : | 287 | 25 | 264 | : | 260 | -26 | 264 |
| | N-MIN | -192 | : | -192 | 25 | -251 | : | -229 | -26 | -251 |
| 3022 | N-MAX | 400 | : | 400 | 132 | 298 | : | 272 | -1 | 298 |
| | N-MIN | -186 | : | -186 | 132 | -355 | : | -328 | -1 | -355 |
| 3025 | N-MAX | 435 | : | 435 | 139 | 340 | : | 327 | 15 | 340 |
| | N-MIN | -223 | : | -223 | 139 | -382 | : | -338 | 15 | -382 |
| 3028 | N-MAX | 420 | : | 420 | 135 | 343 | : | 312 | 21 | 343 |
| | N-MIN | -258 | : | -258 | 135 | -410 | : | -379 | 21 | -410 |
| 3031 | N-MAX | 434 | : | 434 | 138 | 355 | : | 336 | 24 | 355 |
| | N-MIN | -246 | : | -246 | 138 | -412 | : | -369 | 24 | -412 |
| 3034 | N-MAX | 391 | : | 381 | 132 | 303 | : | 275 | 20 | 303 |
| | N-MIN | -235 | : | -235 | 132 | -383 | : | -354 | 20 | -383 |
| 3037 | N-MAX | 371 | : | 371 | 126 | 295 | : | 277 | 16 | 295 |

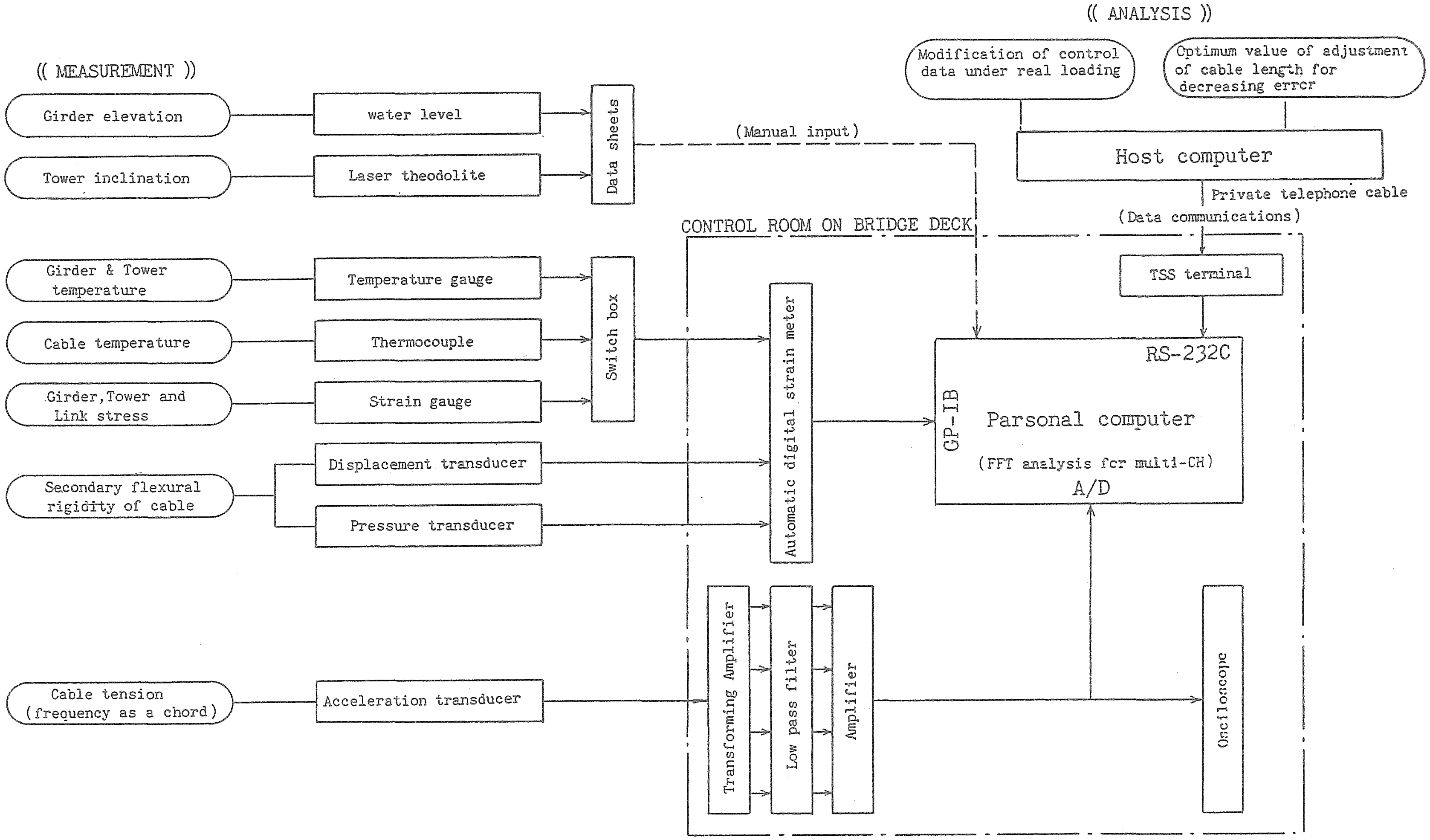


Fig. 11. Quality control system

## QUALITY CONTROL DURING CONSTRUCTION

By utilizing data communications to host computers, CAD-systems can be applied to quality control systems in construction yards. The before-mentioned latest version has been successfully applied to a control system for a long-span cable-stayed bridge by the cantilever erection method. This control system centered around a personal computer is illustrated in Fig.11, and has a faculty of the online TSS terminal in a control room placed on the bridge deck [14], [15].

Such a management system requires the speeding-up of processing most of all. Especially in this bridge, the modification of control data under real loading, the measurement of control items, the adjustment of cable lengths with shim plates and the second measurement to confirm the effects of adjustment had to be performed in one night so as not to interrupt the time schedule. Therefore, as shown in Fig.11, measurements were automatically performed by the personal computer control over the interface as far as possible. Furthermore, by adopting the so-called menu selection method on the display screen, very accurate and fast operations were made possible for most users.

For reference, Fig.12 shows the situation of the control room on the deck, as well as the host computer used in the online processing. In addition, Fig.13 shows the display screen of the personal computer, where errors in the girder elevation, tower inclination and the cable tension are displayed. Also, Fig.14 shows some drawings of results displayed on the screen by a high-speed X-Y plotter. As a result of introducing this control system during construction, the cantilever erection of the bridge with three spans was closed in very high quality, and also its construction period was reduced considerably. This bridge will be completed early next year.

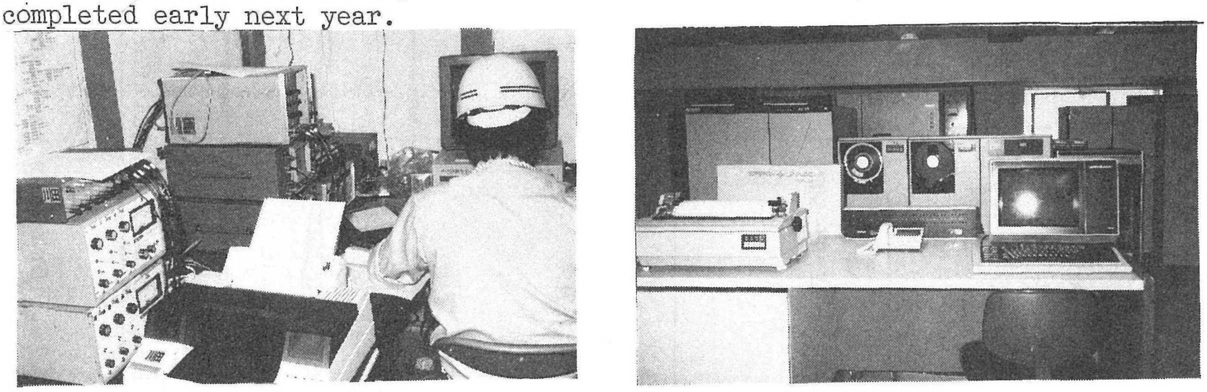


Fig. 12. Situation of control room and host computer

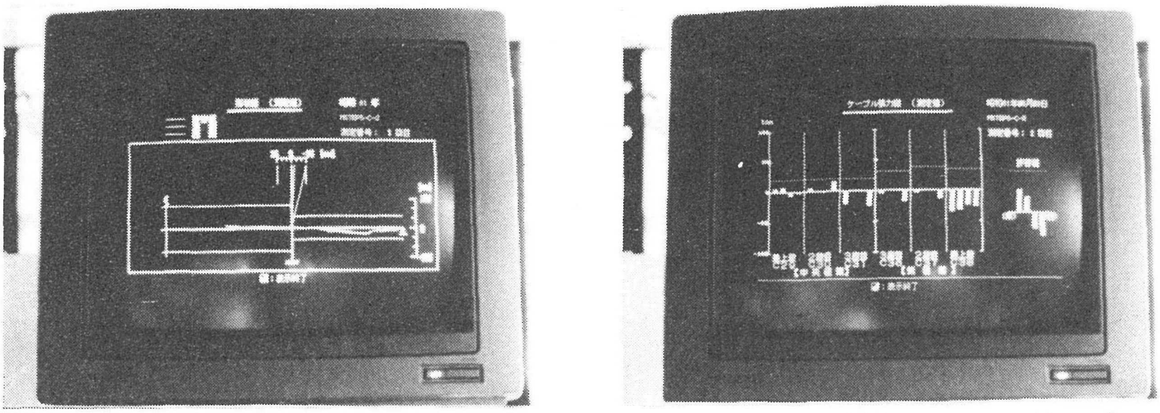


Fig. 13. Results displayed on screen ( at cantilever erection )

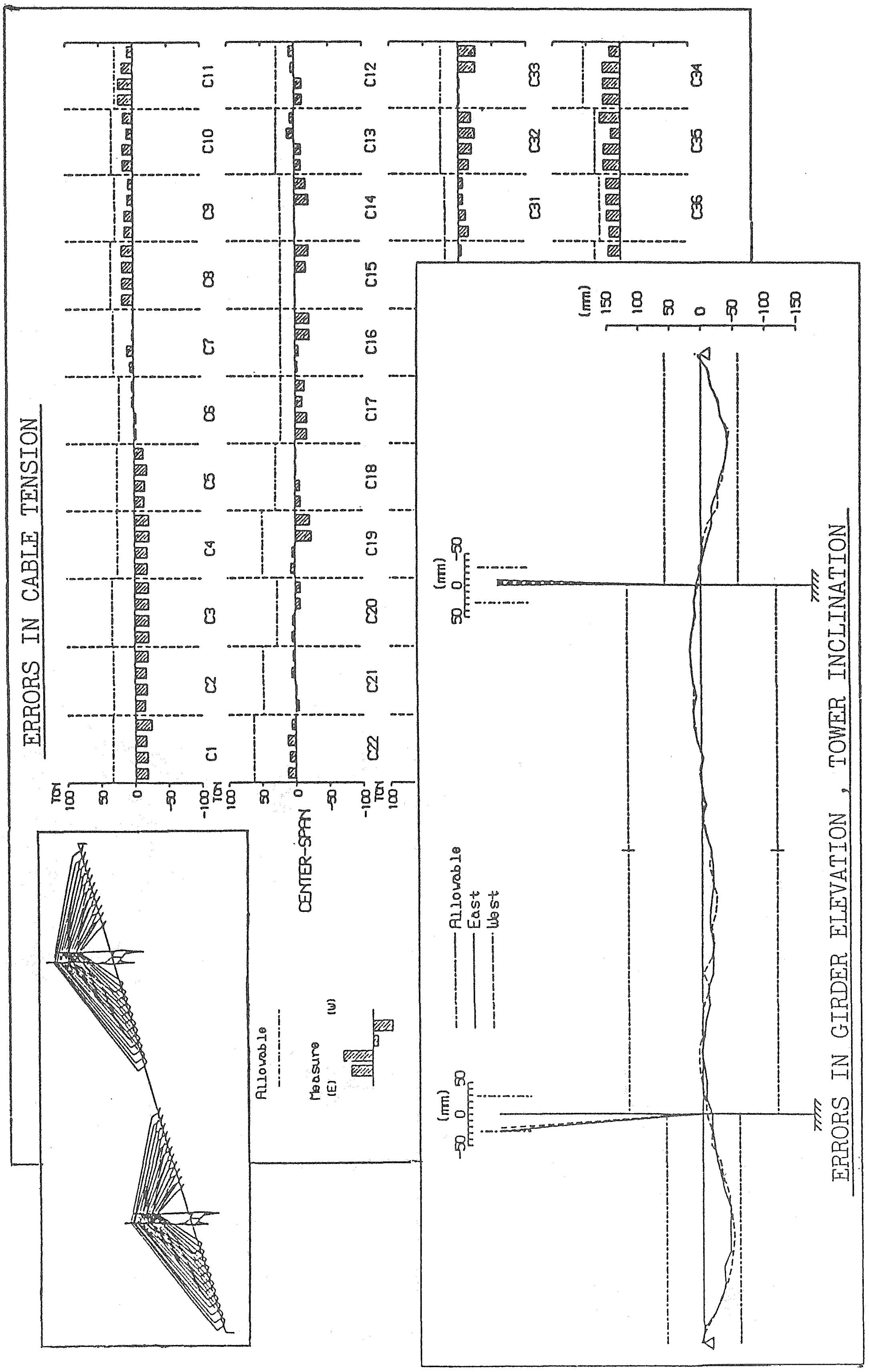


Fig. 14. Drawings by high-speed X-Y plotter ( at closing step )

## CONCLUSIONS

From the facts described above, the authors may conclude that the latest version of this computer aided design system is accurate and economical enough for practical usage. Therefore, it appears that a more efficient design of long-span cable-stayed bridges can be performed with this system.

Moreover, such a high technology system is sure to attain a much higher level in the future according to rapid progress in this field. Therefore, it seems very important that more efficient systems for the quality control during construction will be developed and introduced continually.

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