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## **Statical Model Tests of Suspension Bridge under Construction**

Essais statiques sur modèle d'un pont suspendu en construction

Statische Modellversuche einer im Bau befindlichen Hängebrücke

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## **SUMMARY**

This paper presents the results of the statical test with a large three dimensional model, which simulates a suspension bridge with 3-span continuous truss stiffened girder having no hanger in the side spans. The purpose of this test is to observe the statical characteristics of the bridge model, and confirm the validity of the erection method and effect of wind bracing method, which is presented here. The accuracy of the analytical method is also certified.

## **RÉSUMÉ**

L'exposé traite des résultats obtenus à partir d'essais statiques menés avec un grand modèle tridimensionnel qui simule un pont suspendu avec poutre de rigidité continue sur trois travées et ne possédant aucune suspension dans les travées latérales. L'objet de ces essais est d'analyser les caractéristiques statiques de ce modèle de pont. La validité de la méthode de montage et les effets de la méthode de contreventement, qui font l'objet du présent exposé, sont entièrement confirmés. La précision de la méthode analytique est également prouvée.

## **ZUSAMMENFASSUNG**

Dieser Aufsatz legt die Ergebnisse eines statischen Versuches an einem grossen dreidimensionalen Modell vor, das eine Hängebrücke mit einem über drei Felder durchlaufenden, fachwerkartigen Versteifungsträger ohne Hänger in den Seitenfeldern simuliert. Zweck dieser Untersuchungen ist, die statischen Kennwerte des Brückenmodells festzustellen. Zudem wurden die Eignung des vorgesehenen Montageverfahrens und die Wirksamkeit des gewählten Windverbandssystems überprüft. Die Genauigkeit des analytischen Verfahrens wird ebenfalls bestätigt.



## 1. INTRODUCTION

Recently a number of long span suspension bridges such as the Honshu-Shikoku bridges and others are either under construction or being planned to be constructed in Japan.

In planning and constructing such bridges, special considerations must be given to the extremely severe climatic and other conditions, including typhoons and earthquakes, to which the bridges are exposed from time to time.

The experiment explained in this paper aims:-

- To observe static characteristics of deflection and stress in a long span suspension bridge under construction.
- To confirm the validity of the erection method proposed in this paper, thereby certifying the accuracy of analytical calculation method developed by the authors [1] [2]. In the experiment, a large three dimensional model is used, which simulates "a 3-span suspension bridge with a continuous truss stiffened girder, that has no hanger in the side spans", (Fig. 1).

The experiment is required by the reasons that there are only a few experimental reports on the behaviours of the suspension bridge with rigidly connected stiffening girder, during erection [3], and these testing models are too small for the detailed and reliable measurements and observations of those behaviours, in case of the erection method proposed in this paper.

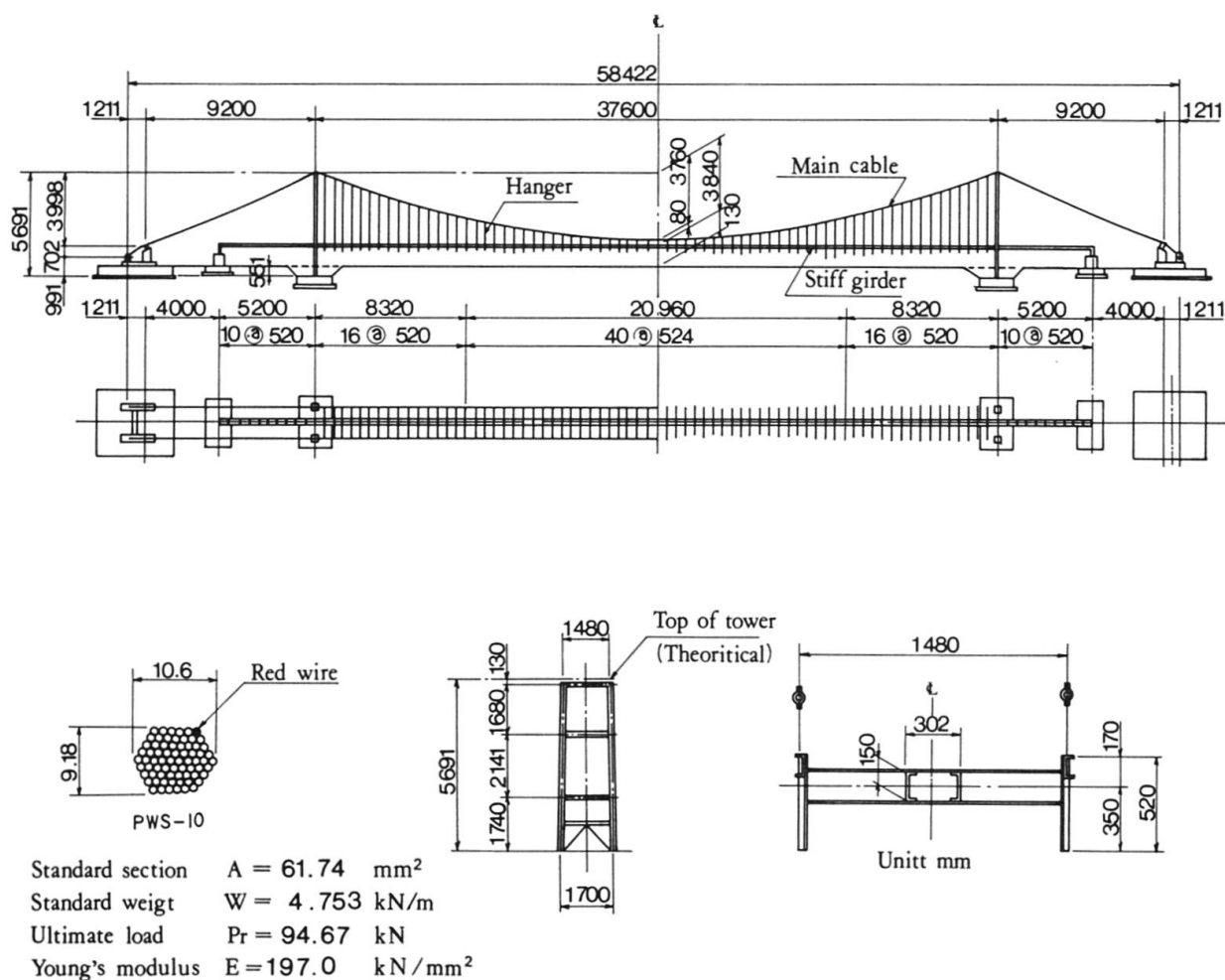


Fig. 1. General view of model

The proposed erection method is as follows:

- 1) Erection of blocks of the truss stiffened girder is carried out by connecting them together successively from the tower side to span center, balancing the forces and deflections of center span and the side span blocks, for stability against wind turbulence.
- 2) Hinges for erection are provided in the truss stiffened girder of the center span, for reduction of hanger stresses.
- 3) Erection blocks are composed of a complete truss stiffened girder block, for shortening of construction time and manhours.
- 4) The truss stiffened girder for the side span is erected by first assembling the blocks from the tower side towards the span center, untill it overhangs to the temporary support near the abutment. It is then set down on the support shoe at the abutment by jacking. This method reduces the cost of construction.
- 5) Setting of the last block in the middle of the center span is carried out by the surcharge method for reduction of cost.
- 6) All erection members are brought to the site by sea, and blocks of the center span are hoisted into position by the lifting crane and assembled by the block erection method.

The following matters are investigated in the experiment.

- 1) Measurement of deflections and forces under construction as well as in the complete bridge state, and comparing them with the calculated values.
- 2) For the erection method.
  - a) Relations between deformation of stiffening girder and tension force of the hanger by the pull in loading.
  - b) Observation of clearance of stiffening girder at the hinge point for erection.
  - c) Observation of surcharge method of last block setting in the middle of center span.
  - d) Relations between deformation of stiffening girder and force of jack-up loading at the site temporary support in the side span.
- 3) Observation of deflection of stiffening girder and cable by lateral loading equivalent to wind load.
- 4) Observation of effects of wind bracing proposed in this paper.

## 2. THEORITICAL FORMULA FOR ANALYTICAL METHOD

Fundamental formula for the axial forced member shown in Fig. 2 based on the finite displacement theory is as follows [2].

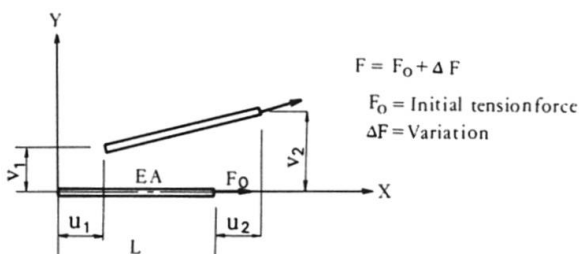


Fig. 2. Axial forced member

Strain:

$$\epsilon_x = \left[ \left( 1 + \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2 \right]^{1/2} - 1$$

$$\approx \frac{\partial u}{\partial x} + \frac{1}{2} \left( \frac{\partial v}{\partial x} \right)^2$$

here,

$$\frac{\partial u}{\partial x} = \frac{u_2 - u_1}{L} = \frac{DU}{L}$$

$$\frac{\partial v}{\partial x} = \frac{v_2 - v_1}{L} = \frac{DV}{L}$$



Strain energy:

$$U_x = \frac{1}{2} EA \int_0^L \epsilon x^2 \cdot dx$$

$$= \frac{EA}{L} \left[ \frac{1}{2} (U_2 - U_1)^2 + \frac{1}{2} \frac{(u_2 - u_1)(v_2 - v_1)^2}{L} + \frac{1}{8} \frac{(v_2 - v_1)^2}{L^2} \right]$$

Axial forces:

$$f_{x1} = \frac{\partial U_x}{\partial u_1} = \frac{EA}{L} \left[ (u_2 - u_1) + \frac{(-v_1 + v_2)}{2L} (v_1 - v_2) \right]$$

$$f_{y1} = \frac{\partial U_x}{\partial v_1} = \frac{EA}{L} \left[ \frac{N}{EA} (v_1 - v_2) + \frac{(-v_1 + v_2)^2}{2L^2} (v_1 - v_1) \right]$$

$$f_{y2} = \frac{\partial U_x}{\partial u_2} = -f_{x1}, \quad f_{y2} = \frac{\partial U_x}{\partial v_2} = -f_{y1}$$

$$\text{here, } N = \frac{EA}{L} (-u_1 + u_2) + Fo$$

Indication by Matrix:

$$F = KU$$

$$K = K_0 + K_1 + K_2$$

$$K_0 = \frac{EA}{L} \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad K_1 = \frac{EA}{L} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \alpha & 0 & -\alpha \\ 0 & 0 & 0 & 0 \\ 0 & -\alpha & 0 & \alpha \end{bmatrix}$$

$$K_2 = \frac{EA}{L} \begin{bmatrix} 0 & \beta & 0 & -\beta \\ 0 & \gamma & 0 & -\gamma \\ 0 & -\beta & 0 & \beta \\ 0 & -\gamma & 0 & \gamma \end{bmatrix}$$

$$\text{here, } \alpha = \frac{Fo}{EA} + \frac{DU}{L}, \quad \beta = \frac{DV}{2L}, \quad \gamma = \frac{DV^2}{2L^2}$$

### 3. EXPERIMENT

#### 3.1 Model

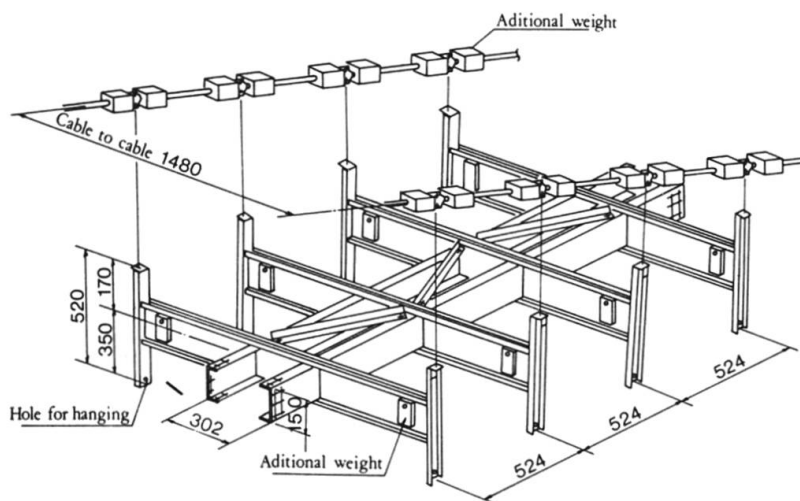
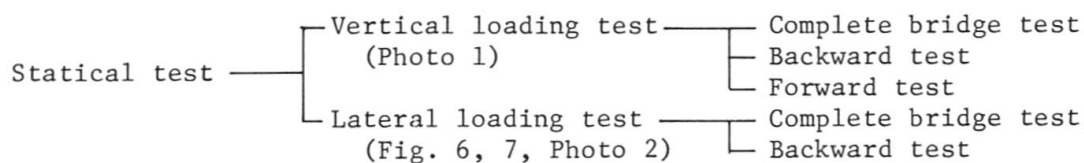


Fig. 3. Model of stiffening girder

The model of suspension bridge used in the experiment is shown in Fig. 1, and a stiffening girder composed of steel channel beams simulates the truss stiffened girder as shown in Fig. 3. The center span of the prototype is 940 m long. Scale of length is 1/25, and weight is 1/6, 36. Conditions of similarity are obtained by Buckingham's  $\Pi$  theorem. Main cable is composed of a parallel wire strand (PWS-70, 70 piano wires with 1.06 mm dia.), and hanger is made of the same single piano wire.

### 3.2 Experiment

The flow of experiment work is as follows:



The test process of experiment is shown in Fig. 4, The items and points of measurement are described in Fig. 5.

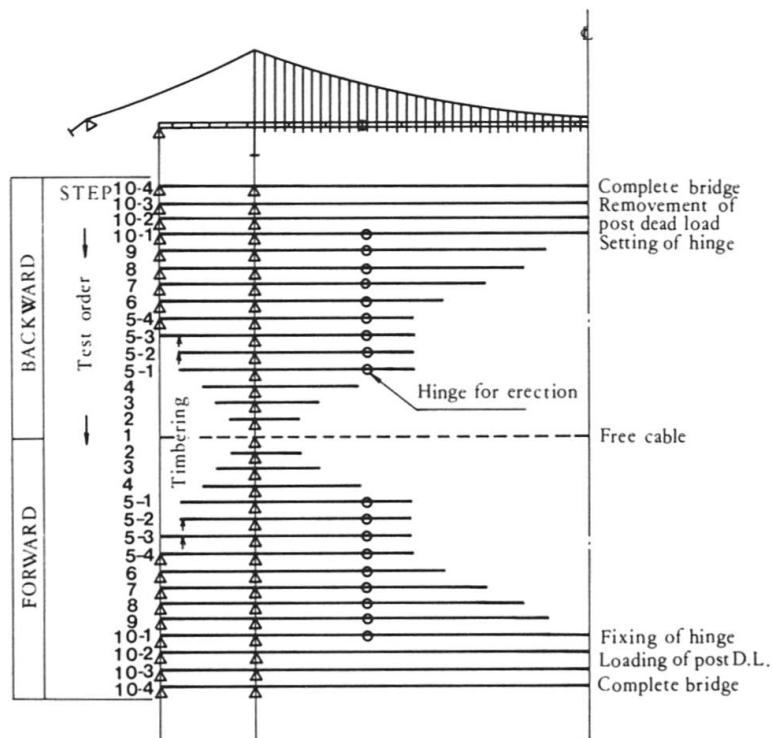


Fig. 4. Procedure of experiment

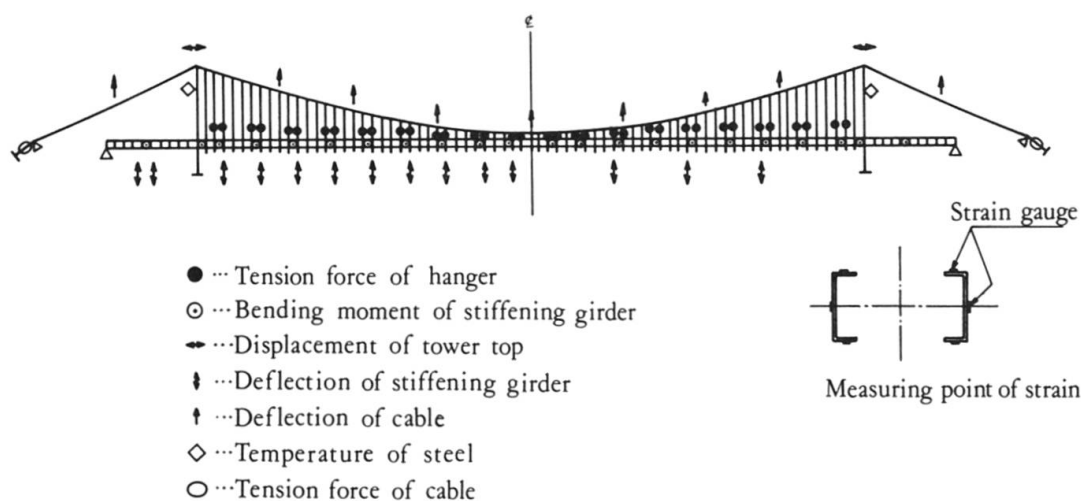


Fig. 5. Items of measurement

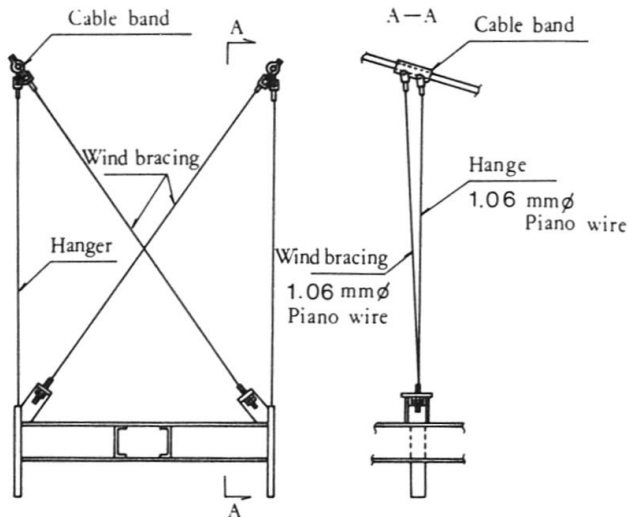


Fig. 6. Wind bracing

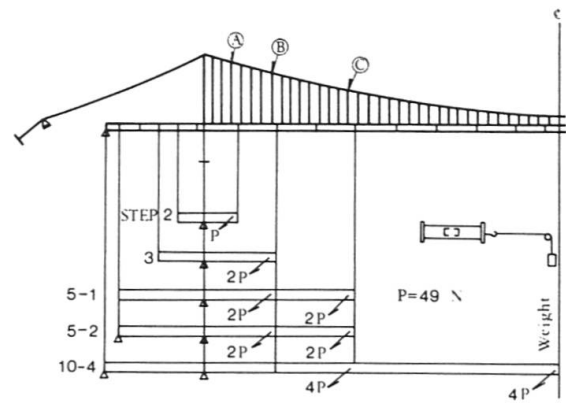


Fig. 7. Procedure of lateral loading test

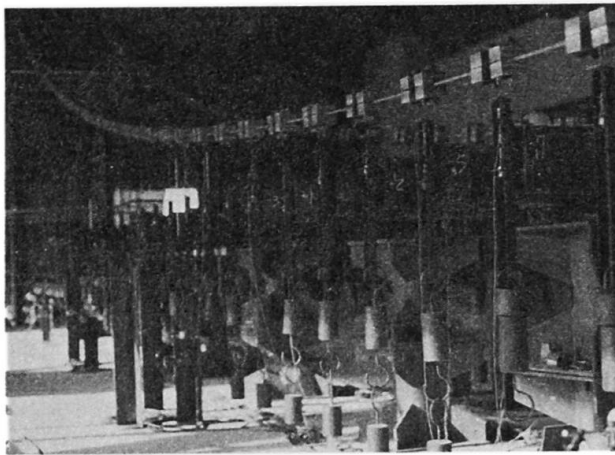


Photo 1 Vertical loading test



Photo 2 Lateral loading test

In this experiment, "backward" means process from the complete bridge state to the free cable state, and "forward" means from the free cable to the complete bridge state as shown in Fig. 4. The backward and forward tests are repeated twice each, and practically no difference was noted between them. The backward test result is adopted in this paper.

#### 4. RESULTS OF EXPERIMENT

##### 4.1 Vertical loading test

###### 1) Complete bridge state

Before the test in the construction state, vertical loading test in the complete bridge state is carried out to confirm the validity of the analytical calculation method as mentioned previously.

The results are shown in Fig. 8, 9.

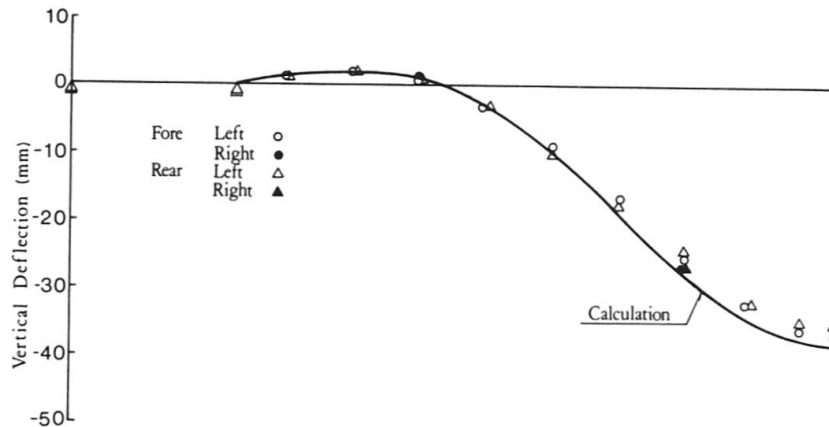


Fig. 8 Vertical deflections of stiffening girder (Sym., complete bridge)

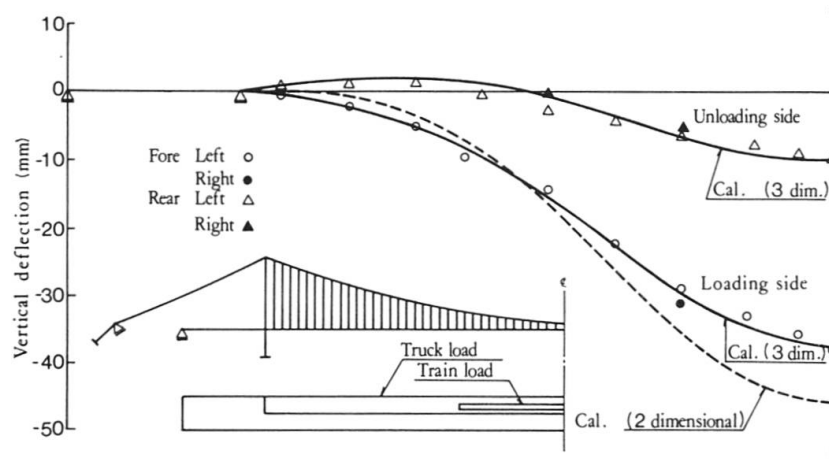


Fig. 9. Vertical deflections of stiffening girder (Ansym., complete bridge)

In a symmetrical loading case, the mean value of the measured vertical deflection of stiffening girder is 35.9 mm at the middle of the center span, while the analytically calculated value is 38.8 mm. Consequently, the difference between the measured and calculated values is 7.5 %. In an eccentrical loading case, the deflection on the loading side is 38.1 mm and that on the unloading side is 10.1 mm. Calculated values of the three dimensional analytical method are 37.1 mm and 9.8 mm respectively, which means that the differences are 2.7 % and 3.1 % respectively.

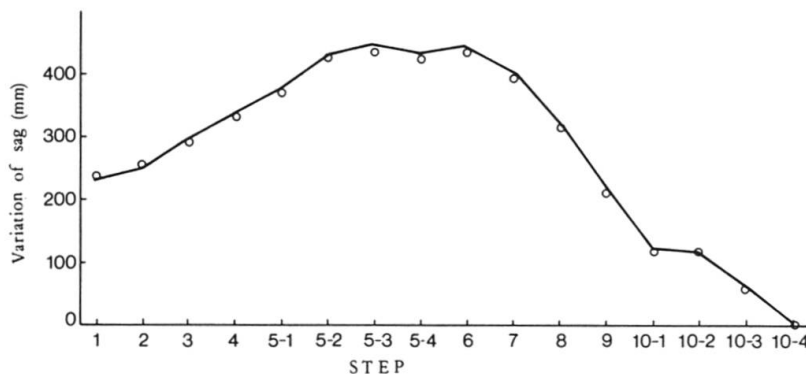
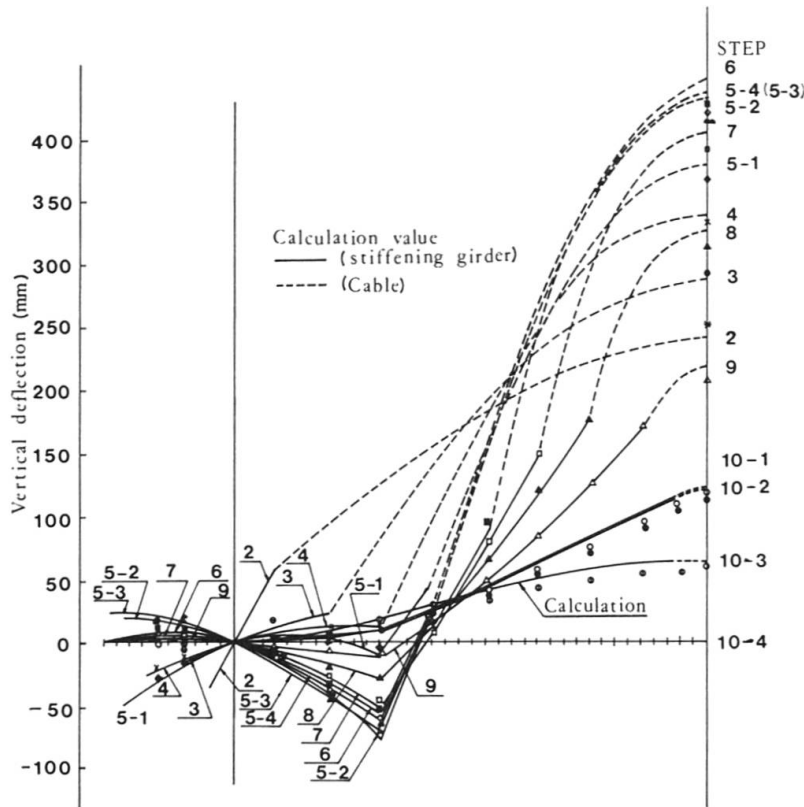


Fig. 10. Variations of sag in center span

## 2) Under construction state

Maximum variation of sag in the center span is 447 mm on STEP-6 as shown in Fig. 10, while the calculated value is 425 mm, showing a difference of 5 % between the measured and calculated values. On STEP-1, the measured value is 237 mm, while the calculated value is





235 mm, showing a difference of 1 %.

Deflections of the stiffening girder are shown in Fig. 11. Max. deflection at the tip of the erecting girder in the centerspan is 177 mm on STEP-8, and 59.5 mm on STEP-5-2 at the erection hinge, while the calculated values are 187.2 mm and 63.1 respectively, with a difference of 5 ~ 6 %.

Bending moments of the girder are shown in Fig. 12, 13. It is recognized that the maximum stress arises on the support of girder on the tower side on STEP-5-1. This stress is almost equal to the allowable limit of stress, and consequently, also the maximum overhanging state of stiffening girder in side span during construction.

Fig. 11. Vertical defections of stiffening girder

tal displacement at the top of the tower on every step also coincide with the analytical calculated values as shown in Fig. 14, 15.

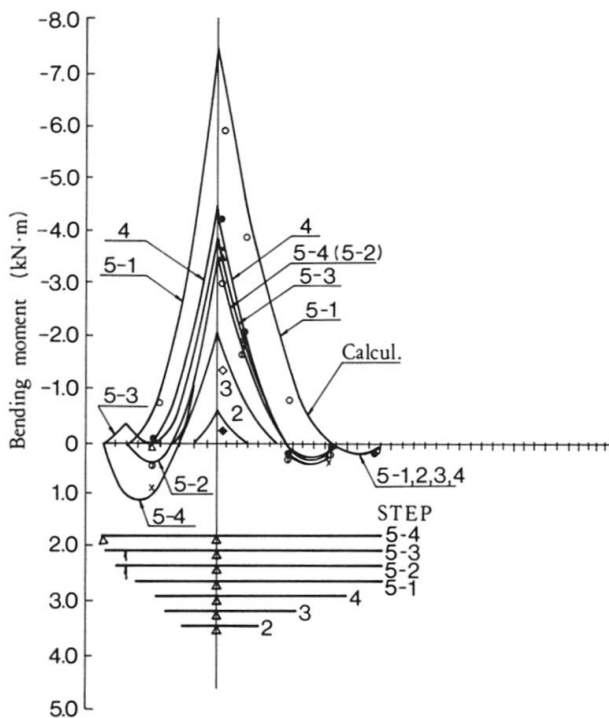


Fig. 12.

Bending moment of stiffening girder (1)

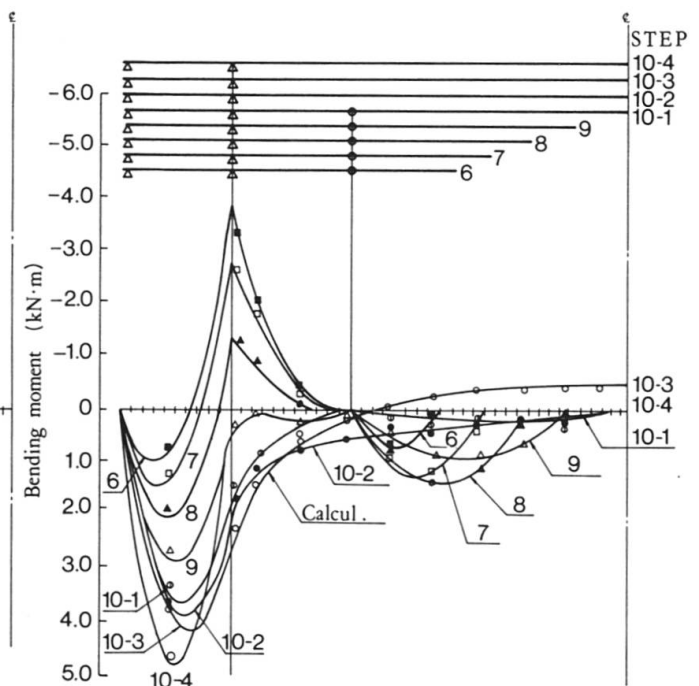


Fig. 13.

Bending moment of stiffening girder (2)

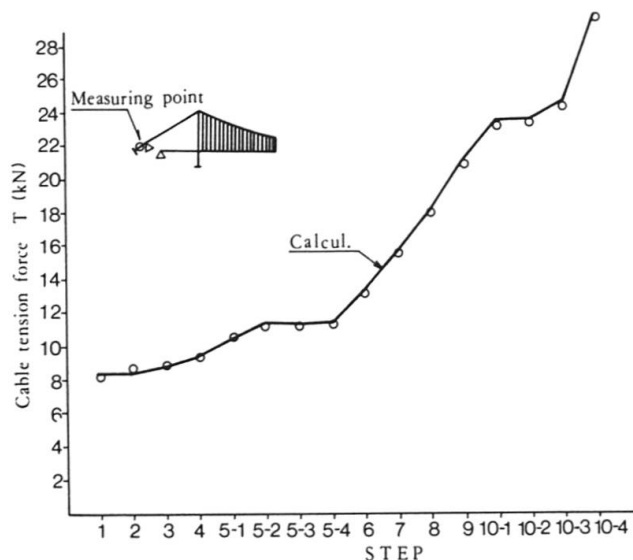


Fig. 14. Cable tension forces

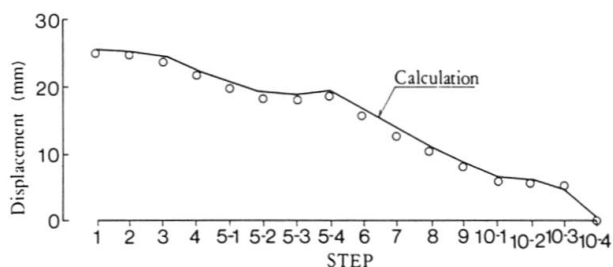


Fig. 15. Displacements of tower top

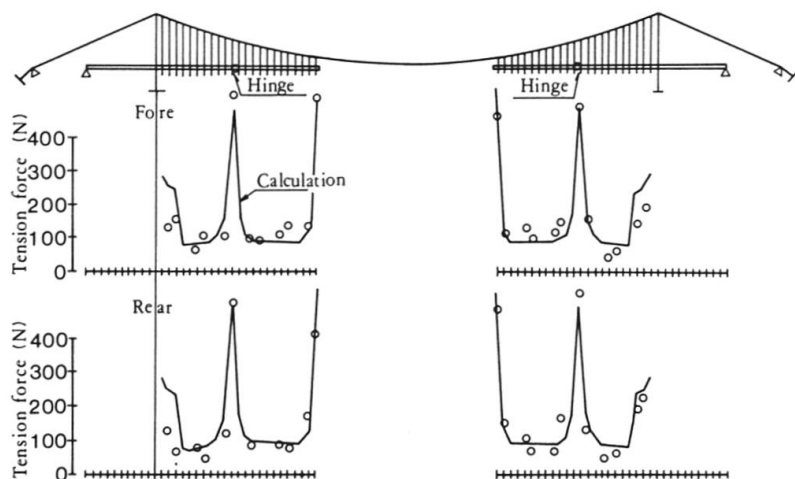


Fig. 16. Tension force of hanger STEP-7

Tension forces of the hanger represent the characteristics as shown in Fig. 16.

In view of the nearness of analytical results mentioned above to the experimental results, the analytical method presented here may well be considered so certified.

### 3) Investigations of the erection method.

- a) Relations between deformation of stiffening girder and tension force of hanger by the pull-in loading method. Fig. 17 shows the main points of process for pull-in loading method, and it is made clear that the relation between the force applied and deformation is non-linear as shown in Fig. 18. The analytical method represents a nonliNear behavior with tolerable accuracy. For example,  $\Delta P = 411.6$  N/bridge is needed in case of  $\Delta Y = 16$  mm

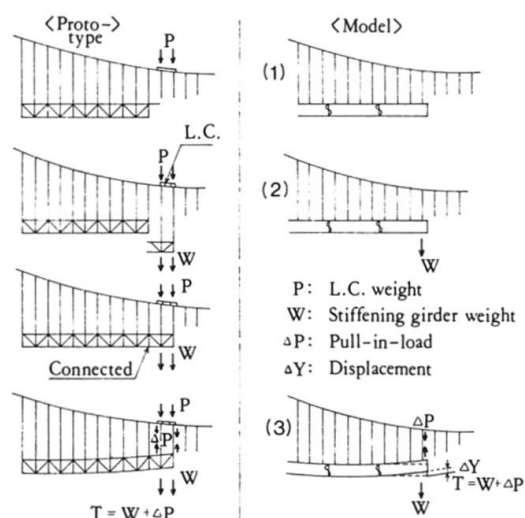
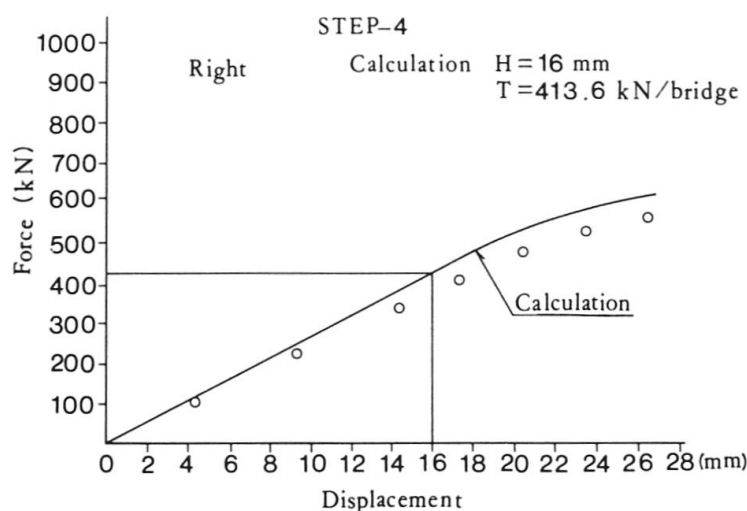


Fig. 17. Procedure of pull-in loading



for model, where  $\Delta P$  means 4,124 kN/bridge and  $\Delta Y$  means 400 mm for the prototype.

Fig. 18.  
Displacements and forces  
by pull-in-loading

- b) Clearance of the stiffening girder at the hinge point for erection. Fig. 19 shows the main points of the process by a closing method. Clearance varies with the progress of construction step as shown in Fig. 19. It is recognized that the minimum clearance occurs on STEP-10-1, and the angle of clearance  $\theta = 0.0056$  radian. Therefore, the surcharge load required is 656.6 N/bridge, which corresponds to  $\Delta P = 117.6$  kN per radian, where  $\Delta P = 6,664$  kN would be in prototype, for which the own weight of a lifting crane will be substituted in practice (see Fig. 20).

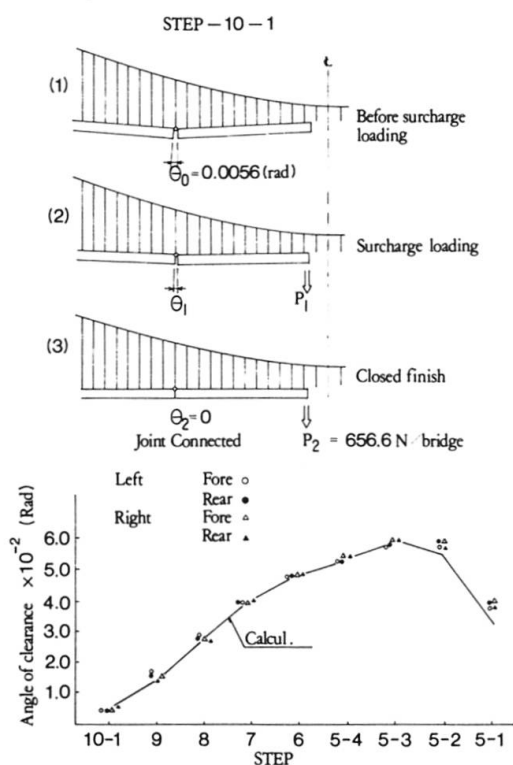


Fig. 19. Angles of clearance

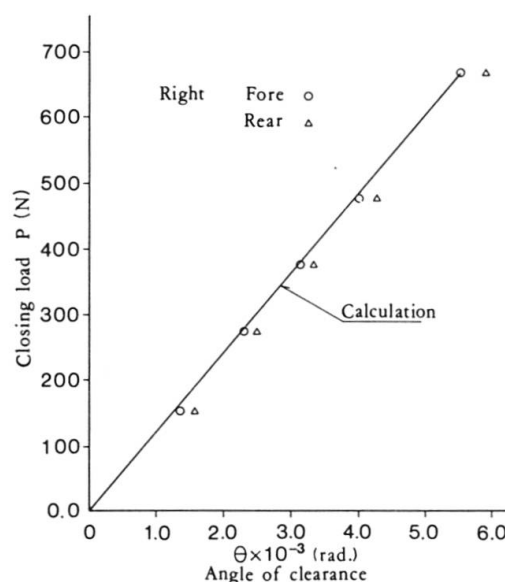


Fig. 20. Closing load of hinge

- c) Surcharge method on last block setting in the middle of the center span. In order to close the block clearance of the stiffening girder, surcharge loading will also be needed, such as lifting crane (L.C.) as shown in Fig. 21, the load of which is  $P = 705.6$  N/bridge in the model, i.e.  $P = 7,252$  kN/bridge in the Prototype. Provided that L.C. is 294 N and block weight is 980 N in the model,  $P = 705.6 - \frac{1}{2} \times 980 - 294 = -78.4$  N; which means  $P = 7,840$  kN in the prototype. Hence a little or more surcharge load may be necessary. Fig. 22 shows this relation.

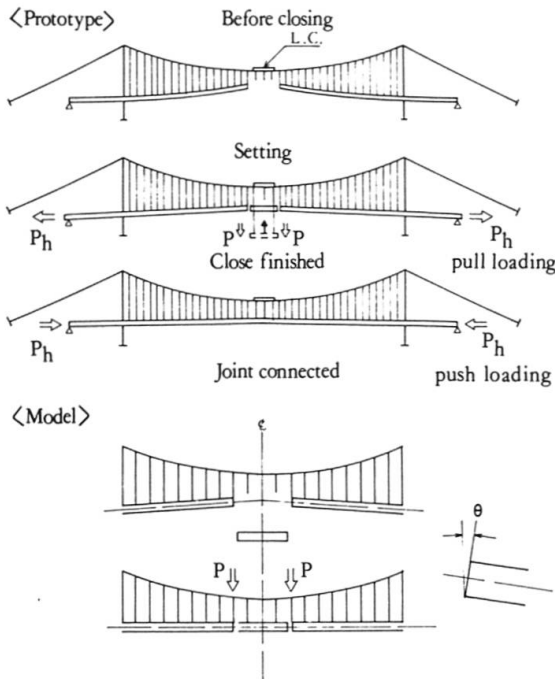


Fig. 21. Setting of final block

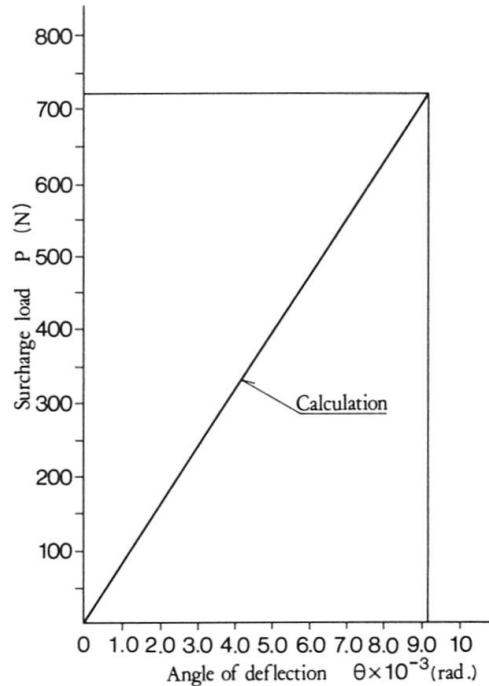
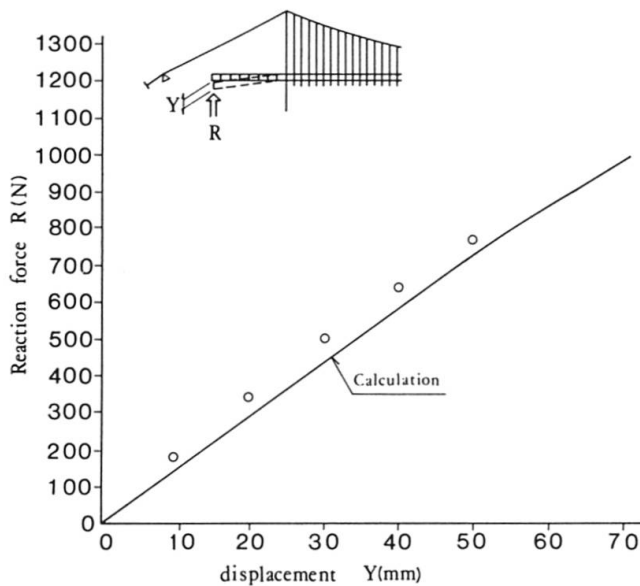


Fig. 22. Surcharge load for closing last block



d) Relation between deformation and reaction of the stiffening girder by jack-up loading on the site temporary support in the side span.

As shown in Fig. 23, relation between  $Y$  and  $R$  is linear, therefore on STEP-5-1, where  $R/Y \approx 14.7 \text{ N/mm}$ ,  $Y = 72 \text{ mm}$  would be required, and where  $R = 14.7 \times 72 = 1,058.4 \text{ N}$  in the model, which means  $Y = 1.8 \text{ m}$ ,  $R = 10,780 \text{ kN/bridge}$  in the prototype.

Fig. 23. Displacement and reaction force by jack up loading

## 4.2 Lateral loading test

### 1) Complete bridge state

Lateral deflections of the stiffening girder and cable are 12.0 mm and 15.0 mm shown in Fig. 24, while the calculated values are 12.0 mm and 14.3 mm. Differences are 0 % and 4.5 % respectively. Thus, good coincidence is obtained in spite of imperceptible loading.

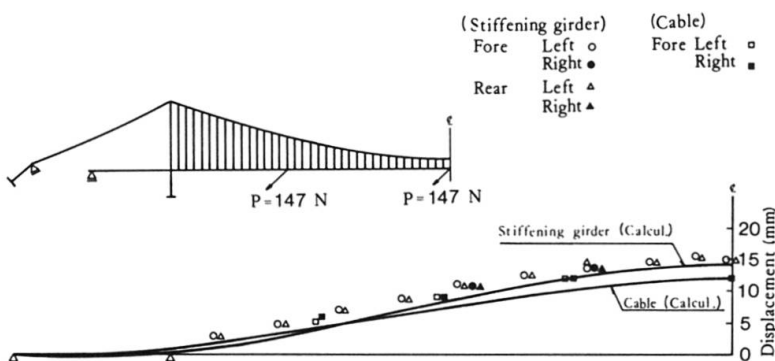


Fig. 24.

Lateral displacement (complete bridge)



## 2) Effect of wind bracing rope

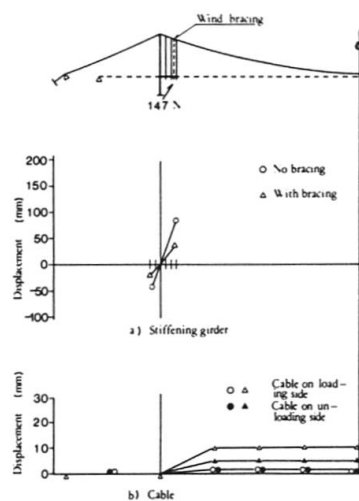


Fig. 25.  
Lateral displacement  
STEP-2

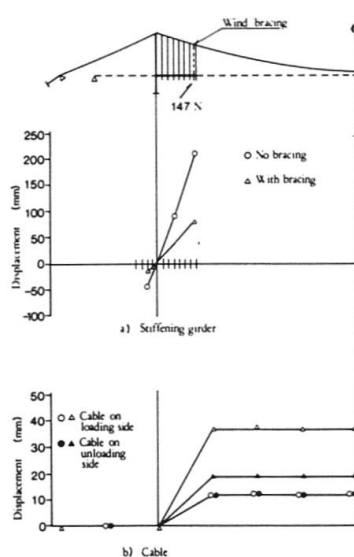


Fig. 26.  
Lateral displacement  
STEP-3

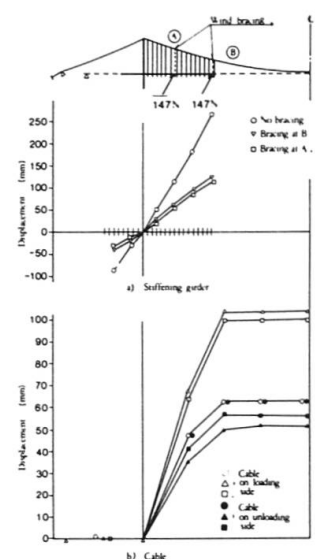


Fig. 27.  
Lateral displacement  
STEP-5-1

The deflections of the stiffening girder with wind bracing rope indicated in Fig. 6 are reduced to about 50 % of those without bracing as shown in Fig. 25 ~ 27. But, those of the cable increase to 200 % without bracing. Difference between those with bracing at A, B and with bracing at B alone is only about 5 %, indicating that it is most effective at the tip of the construction girder.

## 5. CONCLUSION

- 1) The analytical calculation method was developed for static deformations and stresses of the suspension bridge. The experimental results coincide with the theoretical results.
- 2) Erection method was presented. It is clarified that the erection method presented in this paper can be applied with high accuracy.
- 3) Wind bracing method is effective in reducing lateral deflection of the stiffening girder during construction, contributing toward preventing large lateral deflections caused by lateral wind force against the damages of the tower link and end of the stiffening girder.

## 6. ACKNOWLEDGEMENT

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