

# Report on Rehabilitation Project of the “Binh Bridge” in Vietnam

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“Binh Bridge,” located in Hai Phong City, Vietnam, is a cable-stayed bridge with composite girders that was completed in 2005. In July 2010, parts of the main girder and several stay cables of the bridge suffered serious damage after three ships washed away by typhoon No. 1 collided with it. Rehabilitation works on the bridge were awarded to IIA in March 2012 following a collaborative emergency investigation within the IHI Group (IHI, IIS, IIA). This is the first time IHI undertook cable replacement works and the complex stress distributions in the composite girder necessitated extensive planning. This report describes the rehabilitation works carried out on the bridge, in particular the main girder repair and stay cable replacement.

## 1. Introduction

The “Binh Bridge,”<sup>(1)</sup> located in Hai Phong City, Vietnam, is a 3-span cable-stayed bridge with composite girders and a center span of 260 m that was completed in 2005. **Figure 1** shows a complete view of the “Binh Bridge.” On July 17, 2010, three cargo ships swept upstream by a typhoon collided with the bridge resulting in serious damage to the main girder and several cables. The cargo ships had been moored for repair at a shipyard near the Port of Hai Phong. They were carried approximately 600 m upstream by typhoon No. 1 that hit Vietnam that day, and collided with the “Binh Bridge.” **Figure 2** shows a general view of one of the ships’ bridges stuck on the composite edge girder after collision, and **Fig. 3** shows some of the damage to the bridge.

In response to the request from the bridge management company, the IHI Group companies IHI Corporate Research & Development, IHI Infrastructure Systems Co., Ltd. (IIS), and IHI INFRASTRUCTURE ASIA CO., LTD. (IIA) worked together to investigate and evaluate the degree of damage immediately after the accident. A damage report



**Fig. 1** “Binh Bridge” upon completion



**Fig. 2** General view after ship collision



**Fig. 3** Close-up photograph of damaged part

was submitted with a proposal on a repair method. This work was classified as part of the ODA (Official Development Assistance) emergency assistance program and in March 2012, IHI Group was awarded the repair work for the bridge.

The bridge was designed as a cable-stayed bridge with a composite girder made up of 2 steel edge girders and a concrete deck slab, which causes the stress conditions in the main girder to be influenced by the bridge’s construction

steps. Accordingly, to evaluate the stress levels in the damaged sections, it was necessary to faithfully simulate the construction stages using an analytical model. By conducting these analyses particularly carefully, the repair of the girder and replacement of the stay cable were able to be performed without incident.

This may have been the first attempt in the world to replace the main girder of a composite-girder cable-stayed bridge. In addition, replacing the cables of a cable-stayed bridge was a first experience for IHI, and only a small number of cases have been reported in the world. It is for these reasons that we are reporting on this valuable experience.

## 2. Outline of damage

The main areas of damage were the bottom flange and web (approximately 22.5 m) on the downstream side, two stay cables, guard railing, and a navigation sign board. **Figure 4** shows the locations of damage.

The cargo ships had been unloaded so the parts that were higher than the decks collided with the bridge girder. It is presumed that since the concrete deck slab, crossbeams, and cable anchorages were not severely damaged, the collision did not result in a severe accident, such as bridge collapse.

The lower portion from half of the height of the main girder web was deformed in out-of-plane direction, and the bottom flange was also deformed in out-of-plane directions.

On the inner side of the girder, some of the stiffeners were completely buckled, and some of them were deformed into S-shaped forms. However, the floor beams and concrete deck slab were undamaged and sound. **Figure 5** shows the damage on the outer side of the main girder, and **Fig. 6**



Fig. 6 Steel girder damage (inner side)

shows damage on the inner side of the main girder.

The polyethylene covers (PE covers) of two stay cables were peeled off, completely exposing the wire strands which had partial damage to the galvanizing cover. White rust of the zinc coating was also observed. Judging from the state of the damage, it was obvious that salty water had gotten into the stay cable and thus the stay cable would require replacement. **Figure 7** shows the damage to one of the stay cables.

## 3. Evaluation of degree of damage

### 3.1 Traffic control

After the accident, we restricted traffic until safety was confirmed. Only one of the four lanes was open to traffic (upstream side). This lane was opened as a two-way lane for use by two-wheeled vehicles.

Subsequently, we conducted analysis on the assumption that the lower half of the cross section of the main girder was damaged. It was thus confirmed that the main girder would have a slight margin of stress, so we eased the traffic control to allow passenger cars with a mass of 20 kN or less to pass through one lane and the sidewalk on the upstream side.

Our repair work started in May 2012, and in order to use heavy machines such as construction cranes, the passage of passenger cars was restricted all day everyday during this period to constrain the traffic of heavy objects other than construction machines and materials for the repair work. Automobiles crossing the river were asked to use a

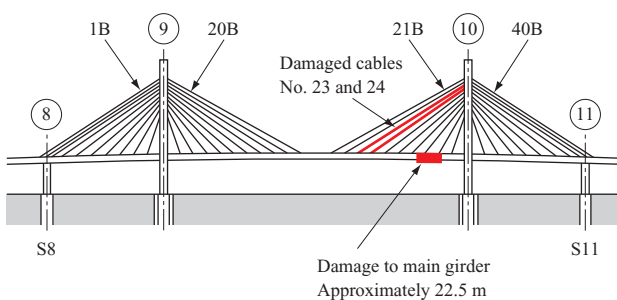


Fig. 4 Locations of damage



Fig. 5 Steel girder damage (outer side)



Fig. 7 Stay cable damage

temporarily operated ferry or another bridge located 5 km upstream during the period of this traffic control.

### 3.2 Evaluation of damage to girder

The main girder was significantly bent on the bottom flange side by the collision and had residual plastic deformation. A web was pulled by the bottom flange until it developed out-of-plane deformation. The web had cracks in places near cable anchorages and was shifted by a distance nearly equal to the plate thickness (20 mm) in an out-of-plane direction. Stiffeners on the inner side of the main girder were pushed upward by the bottom flange until they were buckled, and it was impossible to replace the stiffeners. **Figure 8** shows a cracked web, and **Fig. 9** shows the buckling of stiffeners.

We conducted evaluation in terms of the strain of the plates with the aid of Expression (1) below. In the evaluation, we used cold bending radius  $5t$  ( $\epsilon = 10\%$ ) that is stated in the Specifications for highway bridges as a guide, in order to achieve Charpy absorbed energy higher than or equal to the required performance<sup>(2)</sup> of steel materials from the viewpoint of ensuring the toughness of steel plates. **Figure 10** shows the surface curvature of a bent plate being measured.

$$\epsilon = t/(2R) \dots \dots \dots (1)$$

$t$  : Plate thickness

$R$  : Surface curvature

The simple strain evaluation by this method revealed that most portions had a strain of 3% (corresponding to a load of  $15t$ ) or lower. The strains were at levels that would not cause problems. However, our client determined to replace portions with cracks and those with apparent residual deformation anyway. The bridge portion that would be replaced is approximately 22.5 m long in the longitudinal direction



Fig. 8 Crack in web plate



Fig. 9 Buckling of stiffeners

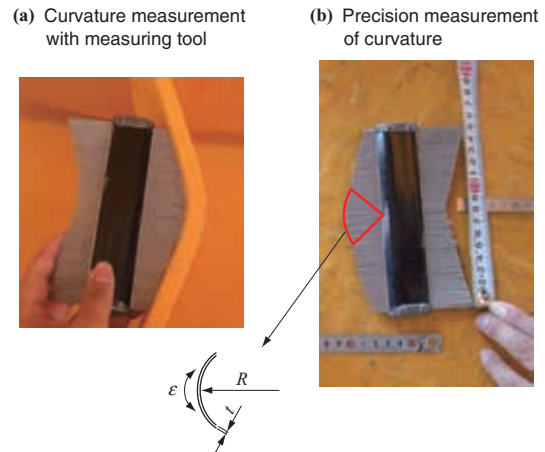


Fig. 10 Measurement of radius of bent plate

and 1 100 mm from the bottom of the main girder, which is slightly higher than half of the girder height. **Figure 11** shows the portion that would be replaced in the main girder.

### 3.3 Evaluation of damage to cables

Since the wires of the damaged cables were not broken, we judged that their tensile strength was not degraded. The durability of a cable is affected by scratches and corrosion on the surface of its wires. This is because the fatigue strength of the wires varies depending on the presence and degree of scratches and corrosion. For cable-stayed bridges, the durability of their cables means the durability of the bridges. Accordingly, measures to repair damage to cables need to be taken as quickly as possible.

In this investigation, damage to PE covers, scratches on cable wires, damage to galvanization on the wires, and development of white rust were observed. These types of damage pose severe problems for cables.

#### 3.3.1 Influence of scratches

Scratches deep enough to catch a fingernail were observed on parts of the surfaces of wires that were exposed to the atmosphere with PE covers removed. The scratches were formed in the axial direction, making it easy to see that a steel material slid along the surfaces of the wires.

Since the scratches on the surfaces of the wires were small, it was presumed that the static strength of the wires had not been degraded. Fatigue strength, on the other hand, varies depending on the shape of the scratches, and a scratch with a length of even 100  $\mu\text{m}$  may cause strength degradation. Accordingly, the fatigue strength of damaged wires should be regarded as degraded. However, it was

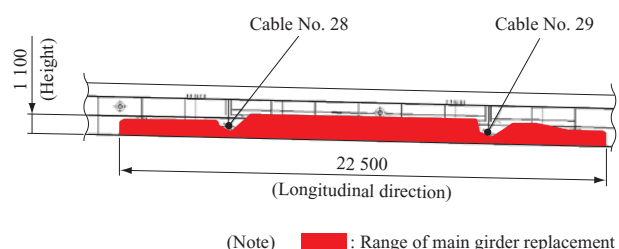


Fig. 11 Range of main girder replacement (unit:mm)



presumed that only the wires on the outermost layer of the steel wire bundles were scratched and that the wires in the inner layers were sound. Therefore, we concluded that cable fatigue evaluation with the influence of corrosion ignored should be performed on the premise that loads acting on the cable will be supported only by inner-layer element wires.

### 3.3.2 Influence of corrosion

White rust developed on the surfaces of wires that were exposed to the atmosphere as their PE covers had been stripped away. This fact suggests that after the PE covers had been stripped away, the surfaces of the wires were exposed to rainwater. Accordingly, it is presumed that rainwater permeated the steel wire bundles and accumulated in the bottoms of the cables.

The zinc layers (minimum: 300 g/m<sup>2</sup>) of galvanized steel wires immersed in seawater will corrode until they completely disappear in as little as one year. In addition, after the zinc has been lost, the corrosion of steel wires will progress which degrades the fatigue strength.

The “Binh Bridge” is located near an estuary that is exposed to sea breezes. Accordingly, the rainwater collecting in cables presumably contains salt. Therefore, there was the possibility that in the rainwater-holding portions of the third (No. 23) and fourth (No. 24) cables from the top, zinc on the surfaces of wires would be lost in as little as one year and that the cable fatigue strength would start to degrade.

It was difficult to accurately evaluate the durability of the damaged cables, so it was impossible to guarantee their quality for the future. Therefore, we determined to replace the damaged cables with new cables.

### 3.3.3 Cable socket portions

In three cable socket portions of other cables, abrasion that seems to have been made due to contact with a steel material was found. In the main bodies of some of these sockets, indentations were found in the corner portions at their ends, but no abnormalities were found at the anchorages, which are the most important parts. Some of the anchor caps were partially deformed and had damaged bolts.

No cracks were found in the painting at the member boundary portions between cable sockets and shim plates and between shim plates and washers. This indicates that the cable sockets did not rotate or move in the accident.

Therefore, we judged that the three anchors that had scratches on their cable sockets would function soundly such that cable replacement would not be required.

## 4. Repair of girder

### 4.1 Policy on reinforcement

Before partially replacing the damaged portion of the main girder, we first examined section forces by analysis with consideration given to continuous composition performed at the construction stage of the bridge and thereby investigated the stresses exerted in the present state of damage. Since the bridge consists of a composite girder, the stress check was performed by adding the stresses exerted before the composition and those exerted after the

composition. This process allowed us to estimate the stress condition before the accident. However, it was difficult to estimate the stiffness degradation of the portion damaged by the accident and to examine stress redistribution due to the stiffness degradation. Consequently, we were not able to accurately ascertain the stress condition after the accident.

Therefore, as our reinforcement policy, we determined to provide additional reinforcements ensuring sectional performance higher than or equal to the section stiffness of the main girder in a sound state, so that when the main girder was undergoing partial cutting, the section force of the cut portion and fluctuating loads would be supported. We decided to cut and replace the damaged portion under these conditions.

In addition, we designed reinforcements that support the section force according to the following policy. We assumed that after the accident, the bottom flange and web of the damaged girder were also supporting stresses occurring in a sound state. We also assumed that stresses released by cutting the damaged portion on the above assumption would be redistributed to the reinforcements and the remaining portion of the girder. Based on these assumptions, we designed the required section of the reinforcements.

### 4.2 Reinforcement structure

In order to partially cut the main girder and remove the cut portion to replace it with a new member, it was necessary to first attach reinforcements to support the section force. A large crane was not able to be placed immediately above the damaged portion, so we were only able to place a hydraulic crane with a lifting capacity of 1 000 kN. Moreover, in order to perform the repair work, we needed to pass the boom of the crane through the space between existing stay cables. It would be impossible to transfer very large members through the space. Since we could only use limited equipment to reinforce the bridge and with limited space, we determined to perform the reinforcement work by using a truss structure (Temporary Bypass truss (TB truss)). **Figure 12** illustrates the structure of the truss.

### 4.3 Procedure for repair of main girder

#### 4.3.1 Installation of scaffolds and TB truss

In the process of installing scaffolds and a TB truss, the main girder was first marked with girder cutting lines and reference lines. We arranged rails consisting of channel steels with rollers on the scaffolds and the TB truss in order to allow members to be transferred horizontally. **Figure 13** shows the arrangement of the scaffolds and the TB truss.

#### 4.3.2 Installation of horizontal stiffeners

By cutting a web of the damaged portion, the remaining side of the web would form a free end, and stress would be released. There was a possibility that the released stress might be redistributed near the free end causing the web to develop local buckling. Accordingly, before cutting the damaged member, we added horizontal stiffeners near the portion that would become the free end of the web in order to reinforce the portion. **Figure 14** illustrates the cross section containing the additional horizontal stiffener.

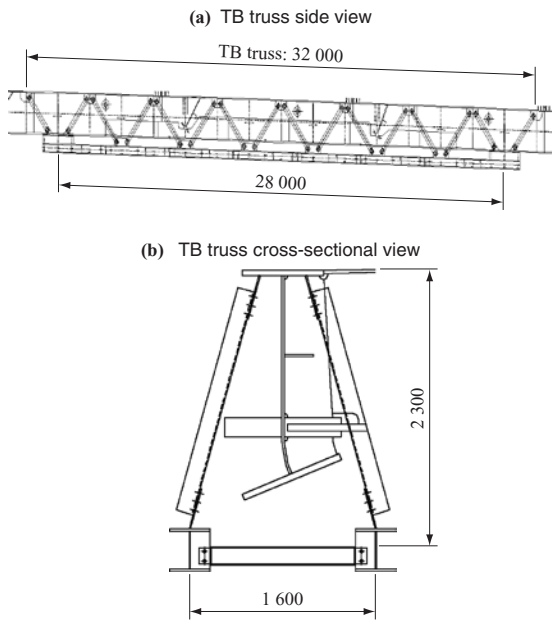


Fig. 12 Sketch of Temporary Bypass truss (unit:mm)

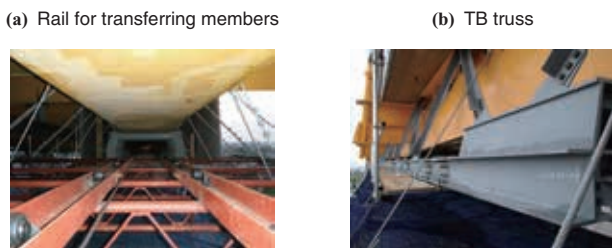


Fig. 13 Installation of temporary bypass truss

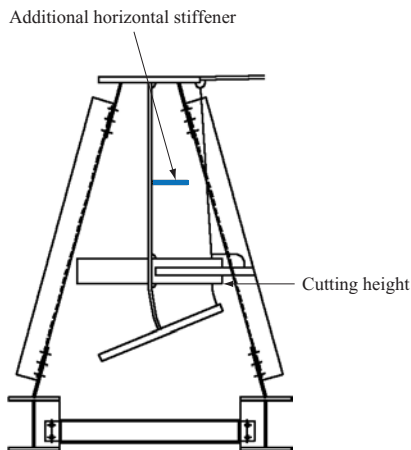


Fig. 14 Cross sectional view of additional horizontal stiffener

#### 4.3.3 Stress monitoring

In order to compare the actual stresses with those calculated for design, we attached a uniaxial strain gauges to the upper and bottom flanges of the main girder and the TB truss and measured the stresses and strains at each construction stage to confirm safety. **Figure 15** shows the strain being measured. We also measured the elevation of the main girder at each major construction stage to confirm that no abnormal values were observed.



Fig. 15 Measurement of strain

#### 4.3.4 Girder cutting and edge preparation

We cut the damaged portion of the girder by gas cutting and prepared the edges. **Figure 16** shows the main girder being cut, and **Fig. 17** shows edge preparation.

#### 4.3.5 Fabrication and installation of main girder member

We accurately measured the shape of the cut portion and used the data to fabricate a new main girder member for replacement. We fabricated the member at a Vietnam factory of an IHI Group company (IIA, approximately 30 minutes away from the site), transferred the member to the site, and performed welding after edge preparation. **Figure 18** shows fabrication of the main girder member in the factory, and **Fig. 19** shows welding for installation of the main girder member.

### 5. Replacement of cables

#### 5.1 Constraints

Only a small number of cases of cable replacement for a cable-stayed bridge have been reported in the world. It



Fig. 16 Cutting of main girder



Fig. 17 Grooved weld edge



Fig. 18 Fabrication at IIA



Newly installed members

Fig. 19 View of girder after replacement and welding

was also a first experience for IHI Group. At the early stages of the project, it seemed that cable removal would be possible by following in reverse order the normal procedure for cable installation. Specifically, a tension rod to pull the cable would be attached to the cable socket on the girder side, firstly the tensile force of the cable would then be reduced by using a center hole jack, and after that the tensile force of the cable would be gradually reduced while cable sag is removed by using a large crane placed on the girder. Reducing the tensile force of the cable until horizontal force is eliminated would allow the socket cable on the tower side to also be removed. The cable could then be removed.

Figure 20 shows the arrangement of equipment that was to be used for cable removal by following the cable installation procedure in reverse as planned at the early stages of the project.

However, this method would require a large crane for removing sag and a crane for removing the cable socket on the girder side to be placed on the girder. A winch would also be required for towing the cable horizontally. In addition, although the sag-removing crane could serve as a substitute, another crane would also be required for bringing the cable down after the socket on the tower side had been removed.

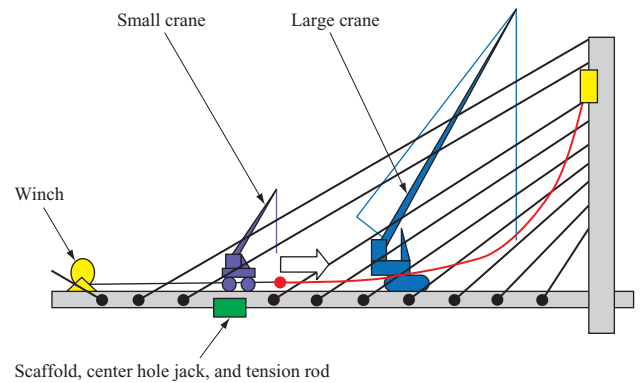


Fig. 20 Unorthodox cable installation procedure

In addition, since the third and fourth cables from the top needed to be replaced in this construction, sound cables would still be in place above the cables to be replaced. Accordingly, for sag removal and removal of the socket on the tower side, the upper cables would interfere with crane operation, so that construction would be impossible.

Moreover, removing a cable would reduce the load bearing capacity of the girder, and accordingly, the mass of the construction equipment and materials that would be placed on the girder also needed to be limited.

## 5.2 Procedure for cable replacement

In this construction, we devised the following cable replacement method so that the replacement could be achieved by using a small crane and a winch with consideration given to the above-mentioned constraints. This method effectively used two upper cables as a sag-removal cable and a guide cable.

Figure 21 shows the procedure for cable removal using this method, and Fig. 22 shows removal of an actual cable.

## 6. Design and analysis

### 6.1 Design policy

Although the deformed bottom flange and web were thought to be supporting a fair portion of the load, in the stress check of the damaged girder, to be on the safe side we assumed the bottom half of the girder to be missing.

As described in Section 4.2, we designed a TB truss member in order to stiffen the main girder and support section force during the repair work. The TB truss was designed on the assumption that the stress that had been acting on the damaged lower-half portion of the main girder in its sound state would be redistributed in the remaining sound cross section and the TB truss. In addition, in order to suppress main girder deformation due to fluctuating loads, we designed the TB truss so as to ensure at least as much stiffness as the section stiffness of the main girder in its sound state.

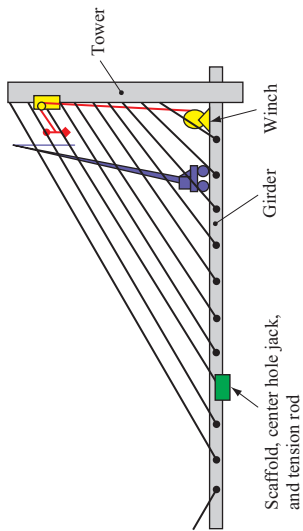
For the replacement of cables, we performed analysis of when one cable is removed at a time to check the safety of the bridge.

### 6.2 Analytic model

We designed an analytic model by incorporating a TB truss member into a three-dimensional frame model of

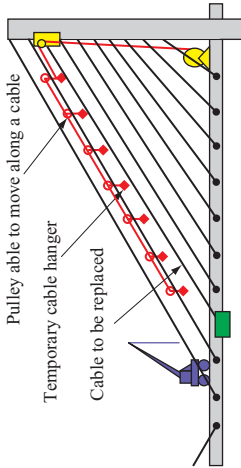
Step 1

1. Scaffolds are installed on the girder side and the tower side.
2. A center hole jack and a tension rod are attached to the cable anchorage on the girder side.
3. A winch for hoisting and lowering is set up.



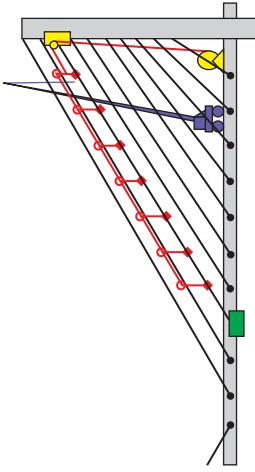
Step 2

- Pulleys able to move along a cable are set on the cable immediately above the cable to be replaced, and temporary cable hangers are suspended from them.



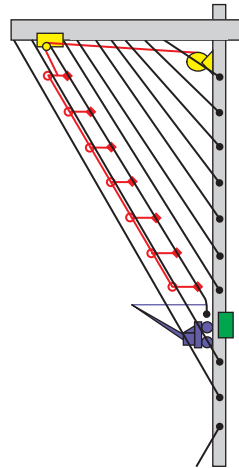
Step 3

- The temporary cable hangers are fixed with bands to the cable to be replaced, and tension is applied to the hangers to make them support the weight of the cable.



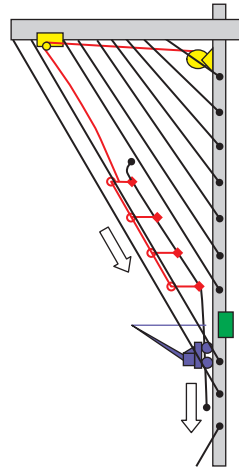
Step 4

1. Tension force on the girder-side socket is released with the center hole jack.
2. The girder-side socket is removed.



Step 5

1. The tower-side socket is removed.
2. By controlling the winch, the pulleys are removed one by one, and the cable to be replaced is lowered little by little.



Step 6

- A new cable is installed by following the above procedure in reverse order.

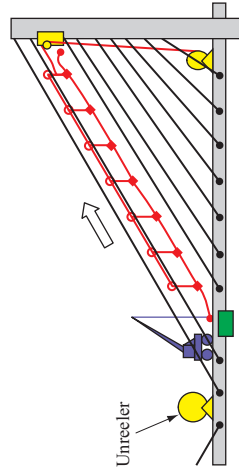


Fig. 21 Stay cable replacement procedure





Fig. 22 Removal of stay cable

the entire cable-stayed bridge. We used it to conduct a sequential analysis for examining fluctuating loads in each construction step to sum the section forces and evaluated the total section force. **Figure 23** illustrates the three-dimensional frame model.

The local influence of factors such as the shape of the cut-away portion of the girder, and the structural influence of factors such as the effective width of the slab, cannot be accurately taken into consideration by performing only a stress check based on section forces obtained by the frame analysis. Accordingly, for the replacement portion of the girder, we also designed a Finite Element Method (FEM) model with consideration given to cable anchorages and the TB truss and applied the section force obtained from the above frame model to the FEM model to evaluate local stress intensity. In this process of using the FEM model, we also simulated the sequential steps to confirm safety. **Figure 24** illustrates the FEM model.

## 7. Stress monitoring

To confirm the safety of construction, we monitored stress by using strain gauges attached to the top and bottom flanges of the main girder and the TB truss. The monitoring was performed during the following four steps:

Step 1 : Installation of the TB truss

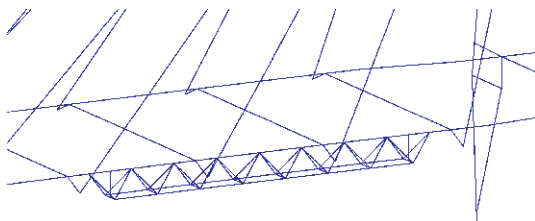


Fig. 23 Three dimensional frame model

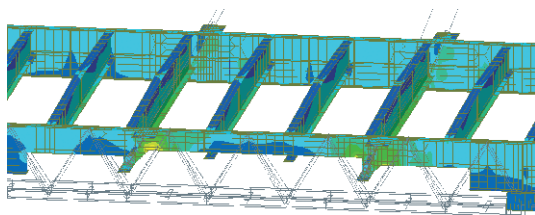


Fig. 24 FEM Model for checking local stress

- Step 2 : Work for cutting off the damaged girder portion
- Step 3 : Work for attaching the new girder by welding
- Step 4 : Work for removing the TB truss

**Figure 25** outlines forces exerted on the bottom flange and the bottom chords of the TB truss during the repair work. **Figure 26** shows monitoring results at monitoring points 1 and 2. The vertical axis denotes the magnitude of acting forces, and the horizontal axis denotes the steps

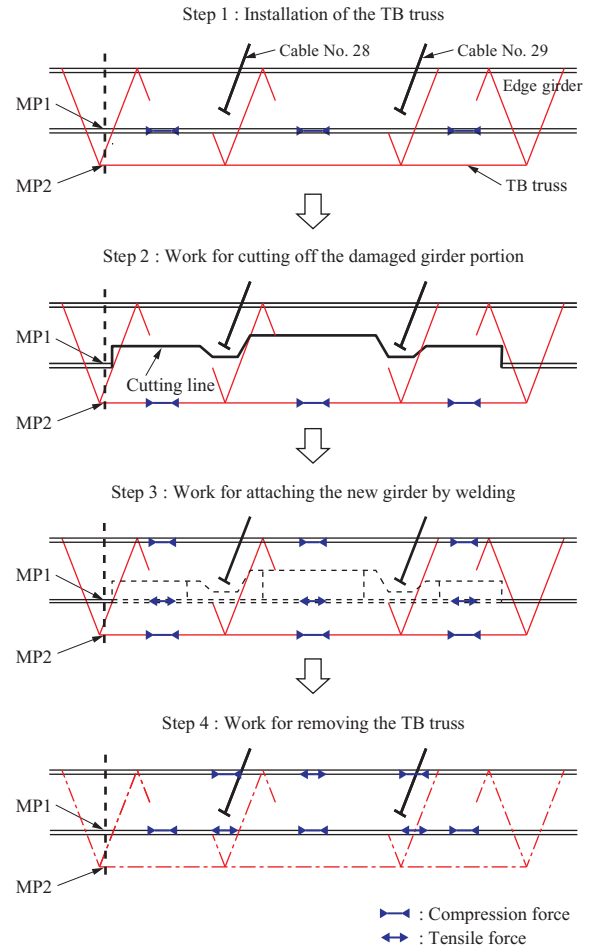


Fig. 25 Stress monitoring for each construction step

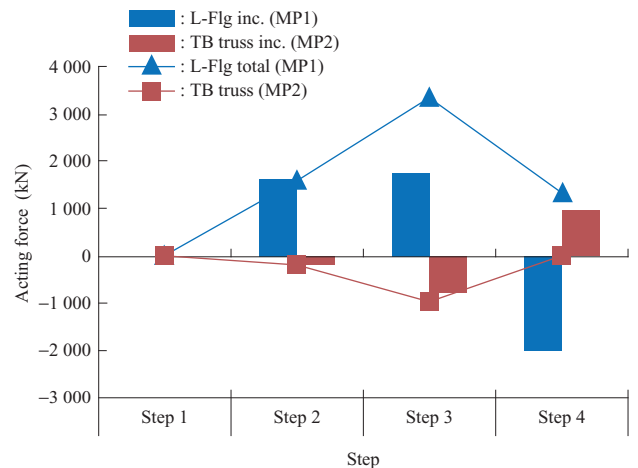


Fig. 26 Force changes during construction



of the repair work. The vertical bars show variations in forces exerted on the bottom flange and the bottom chords of the TB truss in each step, and the polygonal line graphs indicate the accumulated totals of the variations.

When the bottom flange that had been deformed in out-of-girder-plane direction was cut off, residual stress was released. Consequently, the main girder exhibited behavior that seemed to reduce its out-of-plane deformation. The stress monitoring also observed a stress difference due to out-of-plane deformation between the upstream and downstream bottom chords of the TB truss. Measured values seen in **Fig. 26** are the averages of stress values measured at the upstream and downstream bottom chords of the TB truss. These measured values were obtained by subtracting stress due to out-of-plane deformation.

No stress was applied to the bottom chords of the TB truss during installation of the TB truss (Step 1), whereas compression is presumed to be constantly exerted on the main girder. In Step 2, when the damaged portion of the main girder was cut off, the compression that had been exerted on that portion was redistributed among the deck slab and the bottom chords of the TB truss. As a result, the bottom chords of the TB truss underwent compression. In Step 3, welding shrinkage due to welding of the new girder caused the entire length of the main girder to shrink. Consequently, compression is exerted on the bottom chords of the TB truss. At the same time, tension is generated toward the weld line on the bottom flange newly attached by welding. In Step 4, when the TB truss was removed, compression that had been exerted on the bottom chords of the TB truss was released and redistributed among the main girder and the deck slab. As a result, the acting force that was finally distributed to the newly attached bottom flange became approximately 1 000 kN (equivalent to a stress intensity of approximately 22 N/mm<sup>2</sup> (cross section: 900×50 mm)) including residual stress due to welding.

This result suggests that the TB truss was functioning appropriately as it was supporting the compression exerted on the main girder.

## 8. Investigation of inside of damaged cable

After replacement of the damaged cables, we opened the cable cover of a damaged portion of cable 24B and investigated the corrosion developed on its wires. The cable

was in a pipe at the girder anchorage for the first 5.7 m from the socket and the next 7.6 m of the cable was covered by a PE tube. This PE cover of the 7.6-m long portion was damaged, and wires inside it were exposed to outside air. It was assumed that rainwater during the typhoon had intruded into the cable. The cable was covered with a provisional cover four days after the damage.

In the investigation, we cut off an approximately 1.7-m long portion from the damaged cable. This portion included the 1.5-m long portion starting from the socket cap that was filled with polybutadiene rubber. **Figure 27** shows the wires of the damaged portion.

We obtained the following results from the investigation. Some portions included in the wires of the approximately 1.2-m long portion from the socket looked as though they were brand new wires. However, even in the rubber-filled portion, the development of the white rust of zinc was observed in the upper side of the cable. Brown colored portions (a small amount of red rust) were also observed. As described in **Section 3.3.2**, it is difficult to accurately evaluate the effect of corrosion on cables. Accordingly, we decided to change the damaged cables of the bridge at an early stage from the perspective of long-term safety. Our investigation of the inside of the cable revealed that some wires developed corrosion two years after the cable cover was damaged. This fact suggests that if a covered cable is damaged, the cable needs to be repaired as soon as possible to prevent moisture from intruding into the inside.

## 9. Conclusions

This repair work is characterized by the following aspects.

- (1) The repair of the girder was performed by the temporary bypass truss method using a truss structure with a triangular cross section. This method allowed us to safely cut the damaged girder and install and weld a new girder.
- (2) The stress behavior and displacement behavior of the complex structure of the bridge were examined by performing assembly calculations faithfully simulating each construction step with the aid of both frame analysis and FEM analysis, which allowed us to safely perform and complete the repair work.
- (3) During the repair work of the girder, we performed computerized construction by conducting stress

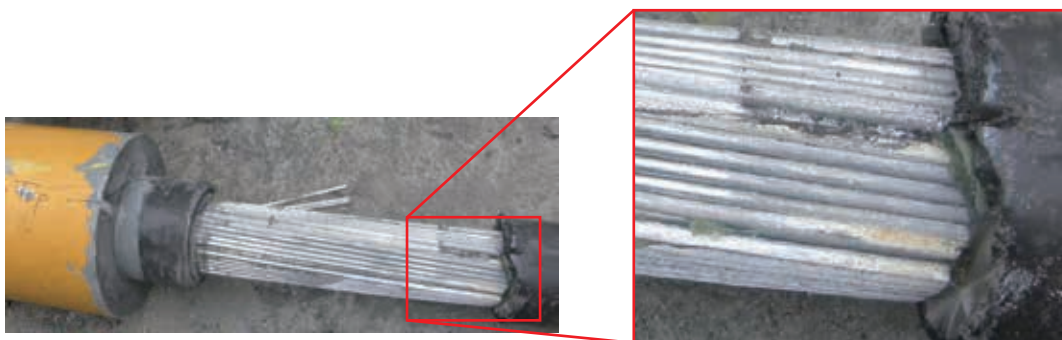


Fig. 27 Opening investigation result of damaged stay cable

monitoring for safety confirmation.

- (4) In order to replace some of the cables, we used a temporary hanger system using pulleys able to move along a cable and were thus able to replace cables in a safe and accurate manner. This method will also be able to be applied to other types of construction, such as cable replacement for aging cable-stayed bridges.
- (5) Our investigation of the inside of the cable, which was conducted two years after the cover was damaged, confirmed that the wires had corroded. So if the cover of a stay cable is damaged, it is very important to repair it so as to prevent water intrusion.

#### — Acknowledgements —

This repair work was conducted as part of the ODA emergency assistance program and was completed in cooperation with Vietnamese and Japanese government agencies, including the Vietnamese Government, the Hai Phong People's Committee, the Ministry of Economy, Trade and Industry, and the Japan International Cooperation Agency (JICA). We believe that this project has also served greatly to maintain and expand the relationship of mutual

trust of both countries.

In the process of performing the repair work, IIS and IIA cooperated with each other as members of IHI Group to generate synergistic effects under the leadership of Mr. Kurino of Chodai Co., Ltd. as the supervisor of the repair work. We were thus able to safely complete the technically difficult main girder repair and cable replacement for the composite-girder cable-stayed bridge. This project was completed with the help of all those concerned with this project and all the staff members in Vietnam. We are deeply grateful for their cooperation.

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