# Repair Works on a Composite Girder Cable-Stayed Bridge damaged by Ship Collision (Binh Bridge in Vietnam)

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## Abstract

The Binh Bridge, a 3-span cable-stayed bridge with composite girders and a center span of 260m, was opened to traffic in 2005. In 2010, 3 ships swept upstream by a typhoon collided with the bridge, resulting in serious damage to the main girder and several cables. Repair and rehabilitation works on the bridge were awarded to IHI Infrastructure Asia Co., Ltd.

The complexity of repairing a composite girder cable-stayed bridge required the utilization of innovative methods in the analysis, planning and execution of the repair works. The repair works included, cutting of the damaged steel girders and on-site welding of new plates and stay cable replacement utilizing the adjacent stay cables in temporary hanger system that reduced erection loads during repair works.

## Introduction

Binh Bridge, located in Haiphong City, Vietnam, is a 3-span cable-stayed bridge with composite girders and a center span of 260m that was completed in 2005. Figure 1 shows a complete view of the Binh Bridge at completion. In July 17th 2010, three cargo ships that had been moored for repair at a shipyard near the Port of Haiphong were carried approximately 600 m upstream by typhoon No. 1 and collided with the composite girder of the Binh Bridge. Fig. 2 shows a general view of one of the ship's bridge stuck onto the composite edge girder after collision.

**Figure 1  Binh Bridge at Completion**

**Figure 2 Ship Collision of Main Girder**

In response to a request from the Binh Bridge Management Company, IHI Corporate Research & Development, IHI Infrastructure Systems Co., Ltd. (IIS) and IHI Infrastructure Asia Co., Ltd. (IIA) working together as the IHI Group, initiated investigations and evaluations of the degree of damage immediately after the accident. A damage report was submitted together with a proposal of the repair method. The works were classified as part of the ODA (Official Development Assistance) emergency assistance program and in March 2012, IHI Group was given awarded the repair works of the bridge.

The Binh Bridge is designed as a cable-stayed bridge with a composite girder of 2 steel edge girders and a concrete deck slab, making 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 in an analytical model. By conducting these analyses particularly carefully, the repair of the girder and replacement of the stay cable were performed without incident.

This may have been the first attempt in the world to repair 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.

## Damage Outline

The main areas of damage were; lower-flange of the main girder (22.5m), two stay cables, the guard railing and a navigation sign board in downstream side. (Figure 3)

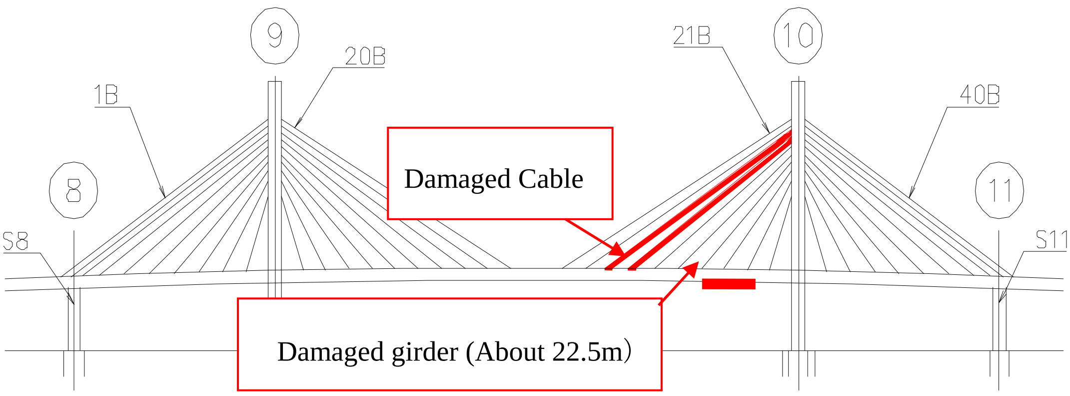


**Figure 3 Damage locations on bridge**

The main girder lower-flange was deformed in the out-of-plane direction with the vertical stiffeners exhibiting complete buckling. Figure 4, 5 show the damaged edge girder. However, the floor beams and concrete deck slabs were undamaged and sound.

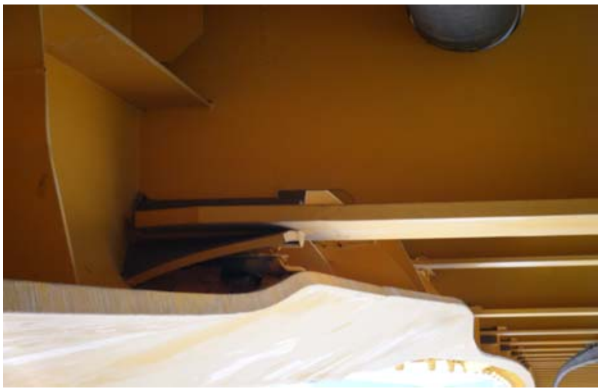

**Figure 4 Damaged Edge Girder (Inner side)**

**Figure 5 Damaged Edge Girder (Outer side)**

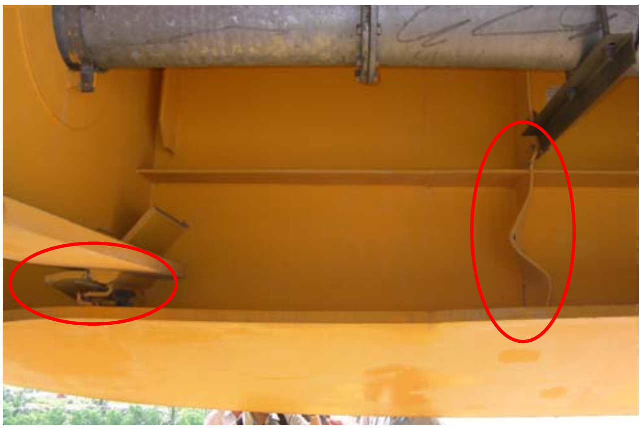

**Figure 6 Buckled Stiffeners**

**Figure 7 Cable Damage**

The polyethylene cover(PE cover) of the two stay cables was peeled off completely exposing the wire strands which had partial damage to the galvanizing cover. Figure 7 shows the damaged cable. “White rust” of the zinc coating was also observed. From the damage condition, it was obvious that salty water had gone into the stay cable and thus the stay cable would require replacement.

## Traffic Control

After the accident, we restricted traffic until safety was confirmed. Only one of the lanes out of the four lanes was open to traffic (upstream side). This lane was opened as a two-ways 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, passenger cars were restricted crossing the bridge all day 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 temporarily operated ferry or another bridge located 5 km upstream during the period of this traffic control.

## 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. Webs had cracks in places near cable anchorages and were shifted by a distance nearly equal to the plate thickness (20 mm) in an out-of-plate 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 6 shows the buckled 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 $5t$ ($\varepsilon = 10\%$) 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[2] of steel materials from the viewpoint of ensuring the toughness of steel plates. Figure 8 shows the surface curvature of bent plate being measured.

$\varepsilon = t/(2R)$ ………………………… (1)

$t$: Plate thickness

$R$: Surface curvature

**Figure 8 Surface curvature of bent plate**

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, we 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 and 1050 mm from the bottom of the main girder, which is slightly higher than half of the girder height. Figure 9 shows the portion that would be replaced in the main girder.

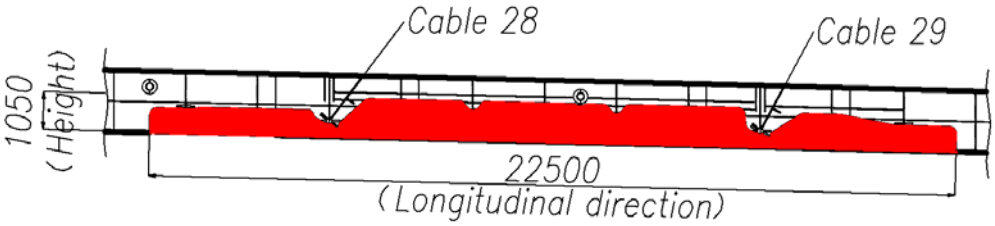


**Figure 9 Replaced main girder range**

## 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 their fatigue strength varies depending on 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 cover, scratches on cable wires, damage to galvanized paint on the wires, and development of white rust were observed. These types of damage pose severe problems for cables.

## Influence of Scratches of wire

Scratches deep enough to catch a fingernail were observed on parts of the surfaces of element 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 axially along the surfaces of the element wires.

Since the scratches on the surfaces of the element wires were small, it was presumed that the static strength of the wires had not been degraded. The fatigue strength of the wires, however, varies depending on the shape of the scratches, and even a scratch as long as 100 μm may cause strength degradation. Accordingly, the fatigue strength of damaged element wires should be regarded as degraded. However, it was presumed that only the element wires on the outermost layer of the steel wire bundles were scratched and that the element 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.

**Influence of Corrosion of wires**

White rust developed on the surfaces of element 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 element 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 $g/m^2$) of galvanized steel wires immersed in seawater will likely 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 element 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.

**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.

**Repair and rehabilitation works**

After long detailed investigation by the Employer, IHI was awarded this repair and rehabilitation works on the Binh Bridge in March 2012. These works included all of the repair and rehabilitation works (Edge Girder, Stay Cable, Railing, concrete deck slab and so on).

**Repair of Girder**

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 reinforcement 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 for supporting 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.

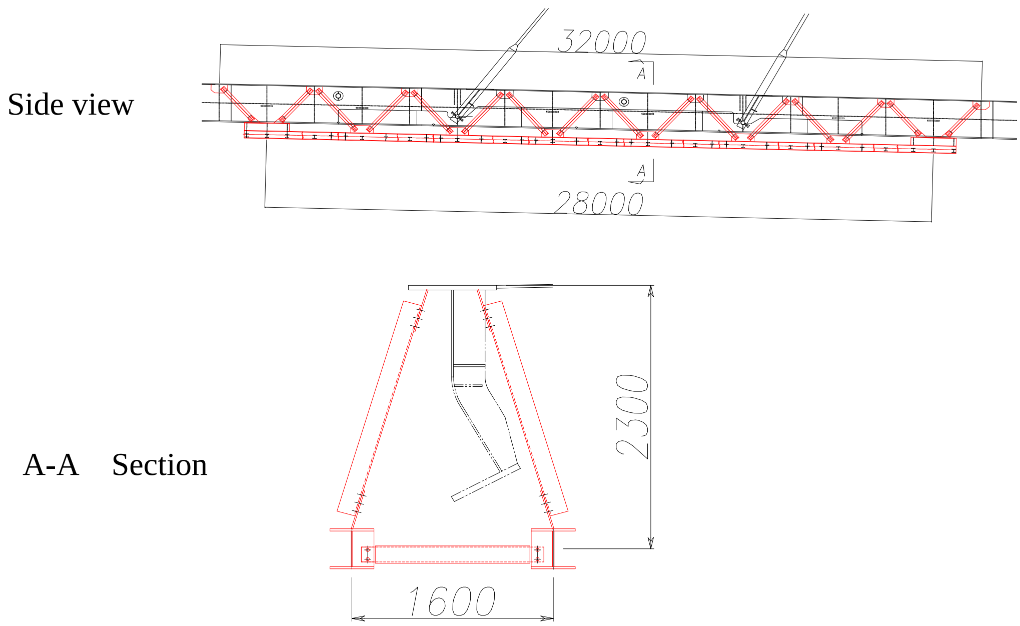


**Figure 10 Temporary Bypass Truss (Drawing)**

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 for supporting 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 1000 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). Figure 10 illustrates the structure of the truss.

**Figure 11 Temporary Bypass Truss**

## Repair of main girder

In the process of installing scaffolds and the temporary bypass 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 temporary bypass truss in order to allow members to be transferred horizontally.

**Figure 12 Cutting of the damaged parts**

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 a horizontal stiffener near the portion that would become the free end of the web in order to reinforce the portion.

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 temporary bypass truss and measured the stresses and strains at each construction stage to confirm safety. We also measured the elevation of the main girder at each major construction stage to confirm that no abnormal values were observed.

Cutting girder and groove making were performed on site. Dismantled girder was cut to approximately 2m pieces for easier handling when transferring the pieces from under bridge to over the deck slab easily.

After exact measurement of the remaining girder piece, the new girder member was fabricated the factory of IHI Infrastructure Asia.

**Figure 13 Fabrication of new parts**

**Figure 14 Installation of new parts at site**

**<u>Replacement of damaged Stay Cable</u>**

The cable adjacent and above the damaged cable was used as a Temporary Hanger System. This system reduced the sag of the cable being removed and the one being installed, resulting in efficient installation works. This replacement work's procedure is shown in the following figure.

The installation step details are as follows

1) Install the scaffolding around cable anchorage of pylon side and girder side.

2) Center-hole Jack and tension rod are installed on the anchorage of girder side.

3) Winch for lifting up or down device is installed.

4) Pulleys to be able to move on the cable are installed on the Stay Cable adjacent and above the damaged cable. Temporary hanger System is hanged from pulleys.

5) Band of Temporary Hanger System is fixed to replacement cable to support the self-weight of replacement cable with tensioning by Temporary Hanger System.

6) At the anchorage of girder side, the tension of existing stay cable is un-load by Center-Hole jack.

7) Remove the socket from the anchorage of girder side.

8) Remove the socket form the anchorage of pylon side.

9) Replacement cable with pulleys is lifting down by Winch.

In case of installation of new stay cable, opposite works of abovementioned procedure is performed.

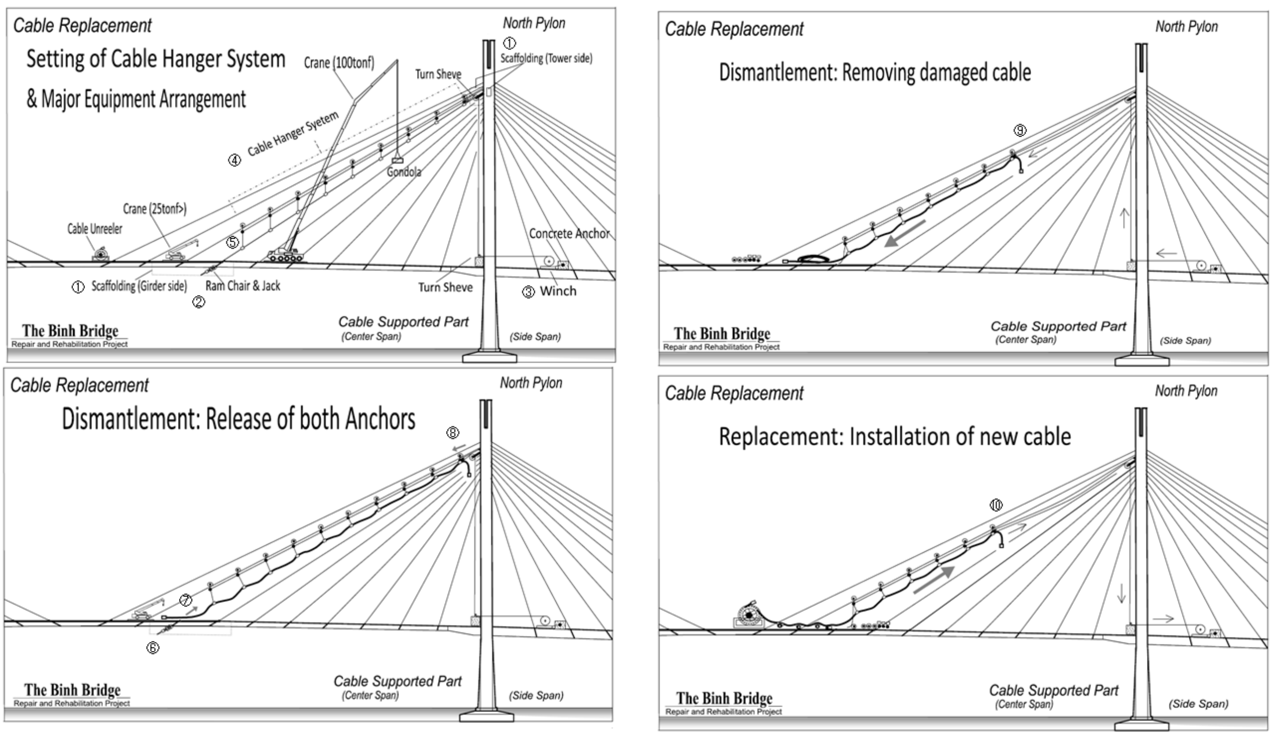


**Figure 15 Dismantle and Installation of Stay Cable**

**Figure 16 Installation of new stay cable**

## Design and analysis

We designed an analytic model by incorporating the Temporary Bypass truss into a three-dimensional frame model of 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 25 illustrates the three-dimensional frame model.

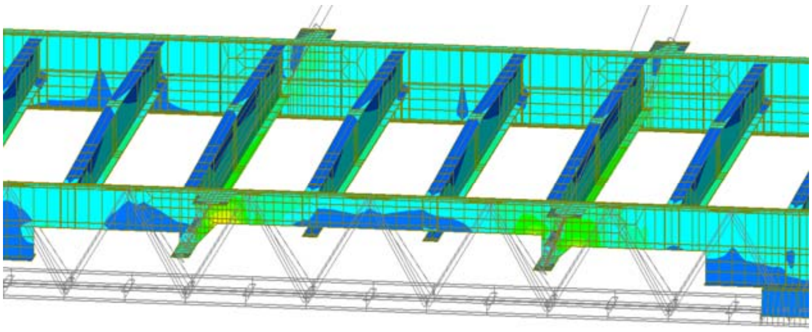

**Figure 17 FEM Model for checking local stress**

The local influence of factors such as the shape of the cut 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 Temporary Bypass truss and applied the section forces 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.

## Stress Monitoring

To confirm the validity of the analysis result and the safety of construction, we also monitored stress by using strain gauges attached to the upper and lower flanges and the Temporary Bypass truss. The monitoring was performed at the following four stages with respect to stress values observed

Step 1: Installation of Temporary Bypass Truss

Step 2: Cutting of the damaged Girder

Step 3: Welding of the new girder

Step 4: Dismantling the Temporary Bypass Truss

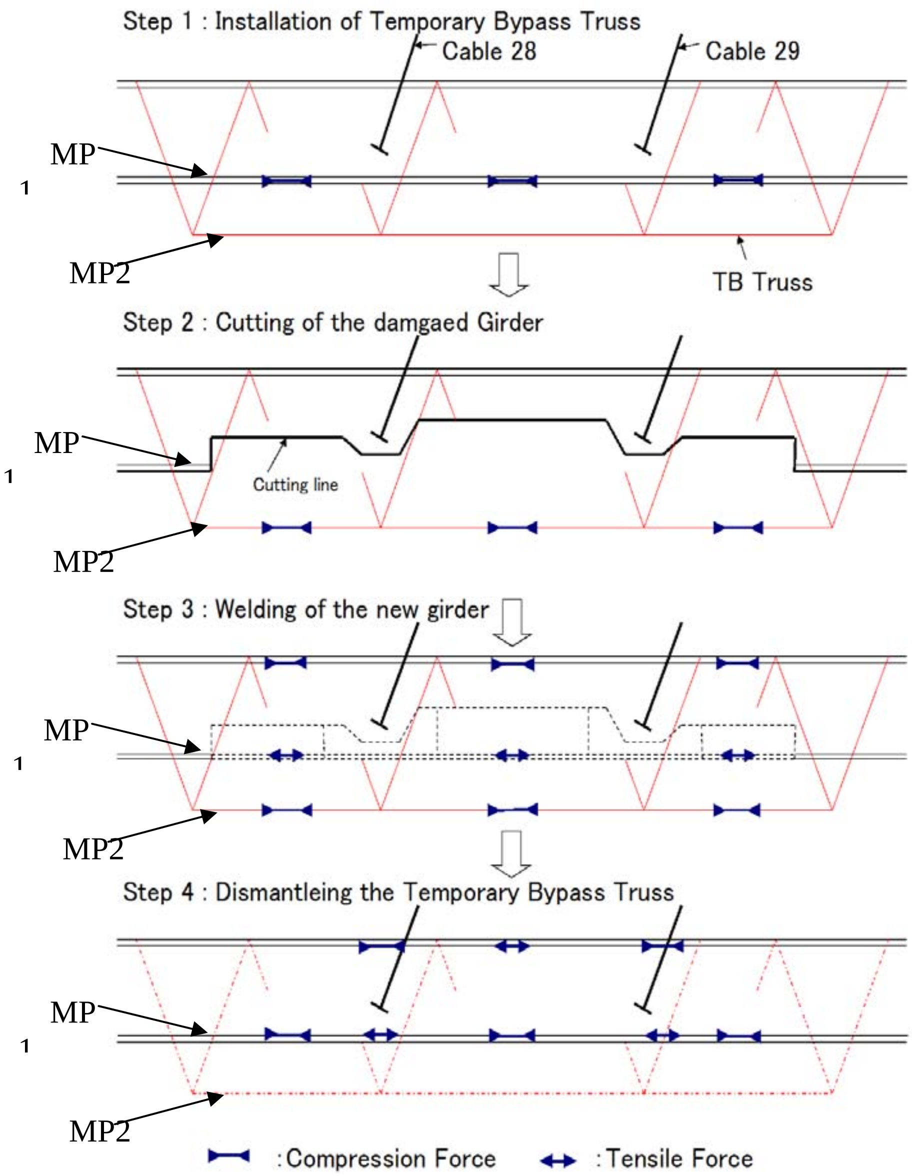


**Figure 18 Stress monitoring for each construction step**

In the figure 18, load flow transferring to lower flange and Temporary Bypass Truss during repair is shown. In the figure 19, the result of monitoring measuring point (MP)1 and 2 is shown by graph. For the vertical axis of this graph acting force is shown and for the horizontal axis construction step is shown. Regarding vertical bar of this graph, the changing force of lower flange and Temporary Bypass Truss per each construction step is shown. And Regarding polyline of this graph the sum total of that is shown.

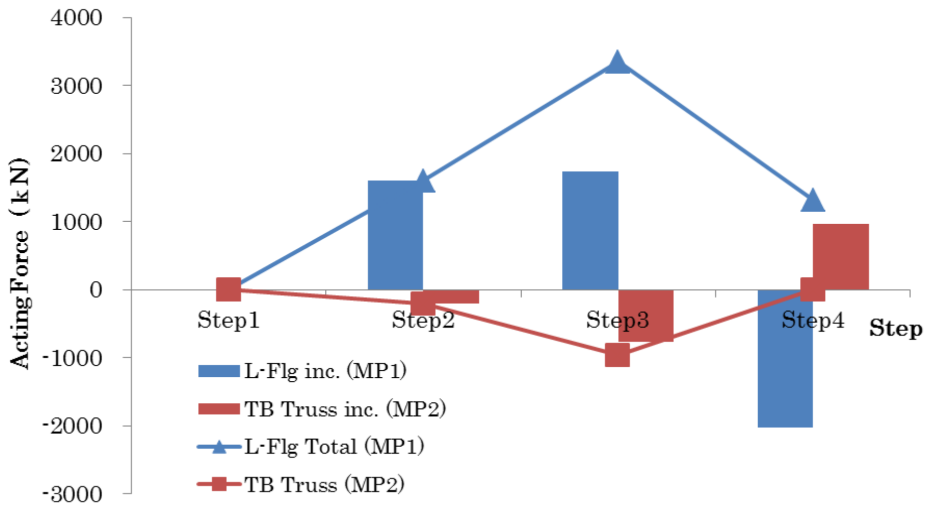


**Figure 19 Force changes during construction**

When cutting the lower flange deformed in the out-plain direction, the residual stress is released and the behavior which be back to non-deformed condition was confirmed. In the measuring result of monitoring, stress difference between edge girder of upstream side and that of downstream side due to out-plain deformation of edge girder was confirmed.

In the measuring result, the average value between the stress on edge girder of upstream side and that of downstream side is plotted to remove the influence of out-plain deformation.

When Temporary Bypass Truss was installed on the girder, there is not stress in this Temporary Bypass Truss but compression force is acted on the edge girder (Step1). When cutting damaged edge girder, Temporary Bypass Truss is compressed due to re-distribution of compression force of cut edge girder (Step 2). When welding of newly parts of edge girder, Temporary Bypass Truss is compressed because of welding shrinkage. Also welded newly part of edge girder is tensioned (Step3). When dismantle the Temporary Bypass Truss, due to release of compression force acted on Temporary Bypass Truss, this force is distributed to edge girder and concrete deck slab (Step 4). Finally distributed acting force on the Lower Flange is approximately 1000 kN (for the stress, approximately 22 N/mm2 (Section 900mm x 60mm)) including residual stress due to welding.

From the above result, we concluded that because Temporary Bypass Truss was transferred from the compression force acted on damaged edge girder, it is very efficient for this repair work.

## Opening Investigation of damaged Stay Cable

After replacement the damaged Stay Cable, we performed the opening investigation for corrosion situation of wire of Stay Cable 24B. About 5.7m position from cable socket was into the guide pipe of Cable Anchorage and stay cable cover of about 7.6m position apart from there was damaged and wire of stay cable was exposed. Stay Cable was exposed in the rain due to typhoon and 4 days later temporary cover of Stay Cable is covered.

In our investigation, about 1.7m area from the socket including 1.5m portion cowered with polybutadiene rubber was peel. Opening investigation result is shown in Figure 20.

As a result, regarding wire from the edge of cable to 1.2m position some area is same as new product partially but the white rust could be found over the top of cable. Also in slight area the red rust could be found. As above mentioned, nevertheless it is difficult to evaluate the effect of corrosion; the replacement of damaged stay cable was decided in consideration to safety of long span. In our internal investigation, it was confirmed that wire was corroded two years later after damage Cover of Stay Cable. So if the cover of Stay Cable is damaged, the water invader should be prevented as soon as possible.

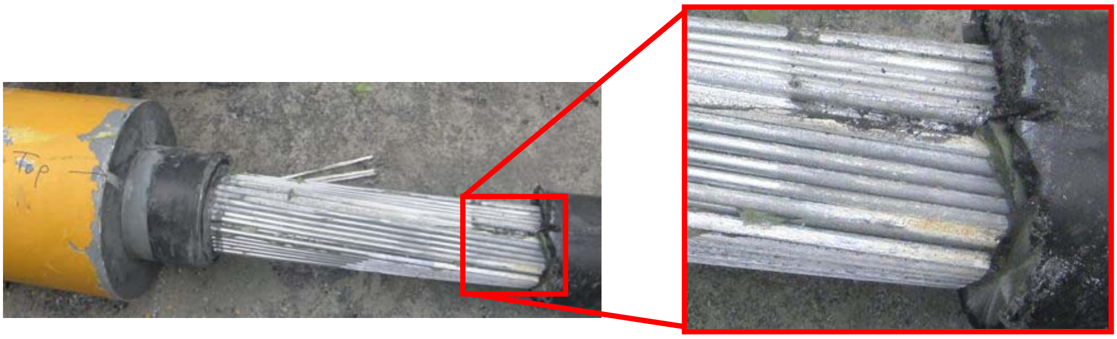

**Figure 20 Opening investigation result of damaged stay cable**

## Conclusions

Large cargo ships, which do not normally pass under the Binh Bridge, were pushed along by a typhoon until they collided with the bridge damaging the main girder and stay cables of the bridge. No one ever expected such a severe accident resulting in damage to the main girder and part of the stay cables to happen to this two-main-composite-girder cable-stayed bridge. Fortunately, however, its slabs and floor beams were sound, and consequently, the redundancy of the bridge allowed it to deliver performance far beyond expectations and not collapse.

This repair work is characterized by the following aspects.

(1) The repair of the girder was performed by the temporary bypass truss method using trusses with a triangular cross section. This method allowed us to safely complete cutting of the old girder and installation and welding of 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 complete the repair work.

(3) During the repair work of the girder, we performed computerized construction by conducting stress monitoring for safety confirmation.

(4) In order to replace some cables contained in the cable plane, 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 used for various types of construction, such as cable replacement for aging cable-stayed bridges.

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