# POST-TENSION STRENGTHENING VIA CARBON FIBER SHEET FOR EXISTING STEEL BRIDGE GIRDER

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**ABSTRACT**

In Japan, 20 tons track load had been adopted for bridge design codes since 1956, and it was upgraded to 25 tons in 1993. Although newly constructed bridges have been designed based on this code, most of the old bridges are still remaining under poor load capacity and are supporting heavy traffic until they would be strengthened. As well known, post-tension strengthening method has mainly been used for concrete bridges. However, this method becomes useful to strengthen existing steel bridges because additional load can be applied to meet the upgraded codes.

In the present study, carbon fibre reinforced composites (CFRP) was tried as post-tension strengthening materials. Here CFRP was placed at the bottom of bridge girders to reduce tensile stress. Though expensive, the lightweight characteristic of carbon fibre was considered to bring a big benefit without increasing the weight.

The post-tension load was introduced into bridge girders by newly developed devices to pull and install Carbon Fibre sheet on the bottom of bridge girders. Then epoxy resin was impregnated into CF sheet. Finite element analysis has also been carried out to find out the design policy of this post-tension strengthening. With increasing the post-tension load, onset of delamination was expected. The analysis was mainly focused on how to prevent possible delamination at the end of CFRP.

One of the smart and cheap ways to avoid onset of delamination between CFRP and steel plate is to suppress opening defection at the end of bonded CFRP by attaching the holding plates. The experimental results are also presented. It is important to develop devices to introduce post-tension load in the bridge girder. Newly developed devices are also shown in this report.

## 1. INTRODUCTION

In addition to the increase in dead load caused by the attachment of overlay or sound insulating wall, the live load also increases with increasing the traffic volume or large-size cars in Japan. Especially, most of the old bridges are confronted with the problems on a lack of the load carrying capacity owing to the revision of the transport regulation, where the upper limit of a truckload was changed from 20 to 25 tons in 1993.

The post-tension strengthening method using outer cables or steel plates is often adapted to the reinforcement of concrete bridges because the dead load plays an important role in such kinds of structures. However, the live load plays a more important role in steel bridges, where the reduction of fatigue damage is required as well. In other words, the development of novel strengthening method effective against the dead load and live load is a pressing task.

Recently, the strengthening method using CFRPs has been used for the reinforcement of such steel bridges [1], where the CFRP plates are attached to the lower flanges of the girders. This kind of method is effective to increase the load bearing capacity against the dead load and live load because the allowable strain of CFRPs is much higher than that of common steels. However, the strengthening method using CFRPs is still on the way of development. Especially, the debonding of adhesive layer is one of the biggest problems for the long-term use. Some researchers have, therefore, tried to characterize the onset and growth of the debonding using of the fracture mechanics [2].

In this study, the fracture behaviour of adhesive interface between the CFRP and steel girder has been investigated on the basis of numerical and experimental results.

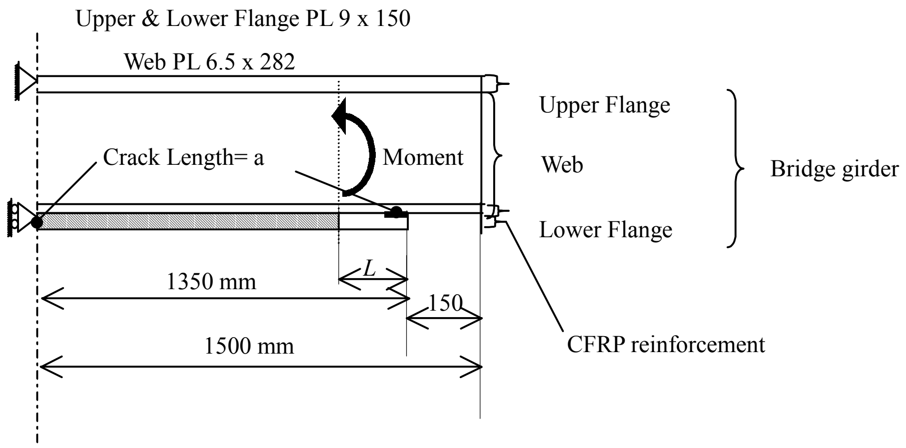
## 2. NUMERICAL ANALYSIS

Two-dimensional elastic analysis considering the large deformation was carried out using a FEM (Finite Element Method) code, MSC.Marc 2001. The CFRP was modelled with orthotropic homogeneous elements though it is not homogeneous in a strict sense. Figure 1 shows the FEM model, where the interfacial debonding was modelled as an artificial slit. The steel girder was considered as an isotropic homogeneous elastic body with Young's modulus $E$ = 210 GPa and Poisson's ratio $\nu$ = 0.3. The CFRP was considered as an orthotropic homogeneous elastic body in the analysis.

The mechanical properties of the CFRP are shown in Table 1. The width and thickness of the CF sheets was 100 mm and 0.165 mm/layer, respectively. The thickness and fibre volume fraction of CFRP was 1.115 mm/layer and 14.8 %, respectively. Bending moment of 20 kNm was applied to the steel girder as shown in Fig. 1. Energy release rate, $G_I$, for mode I, $G_{II}$, for mode II and $G_{total}$ (= $G_I + G_{II}$) was calculated by the crack closure method [3] to discuss the onset of debonding between the CFRP and steel girder.

"**Table1.** Mechanical properties of CFRP."

| Properties | Fibre | Matrix | Composite($V_f$=14.8 %) | Remarks |
|---|---|---|---|---|
| Young's modules $E_1$ (GPa) | 640 | 3.3 | 98 | |
| $E_2$ (GPa) | 10 | - | 3.9 | |
| Poisson's ratio • | 0.28 | 0.39 | 0.37 | $\nu_{31}$=0.0 |
| Shear modules $G$ (GPa) | 24 | 1.2 | 1.5 | |
| Thermal expansion (•m/mK) | -1.1 | 57 | 0.27 | |



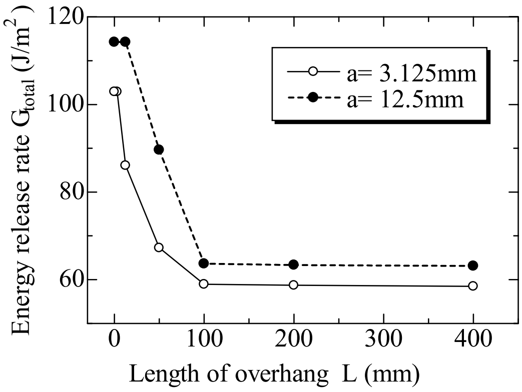

"**Fig. 1**□Schematic view of FEM-model and boundary condition to apply pure bending."

a) Effect of overhangs length of CFRP

In general, the purpose of strengthening using CFRP is to reduce the applied bending moment of the middle part of the girder, which is larger than that of the end part. However, the length to be reinforced is usually longer than the part required to be strengthened to reduce the stress concentration at the end of reinforcement even in the case of strengthening works using steel plates. It would be rational to set overhangs of CFRP outside the strengthened part, where the tensile prestress is introduced, to avoid the debonding.

Figure 2 shows the results of the finite element analyses demonstrating the effect of overhang length on the energy release rate, where the girder was reinforced by 3 layers of the CFRP. The abscissa represents the length of overhang, which is the distance between the end of CFRP and the acting point of bending moment. The ordinate represents the energy release rate calculated by the crack closure method.

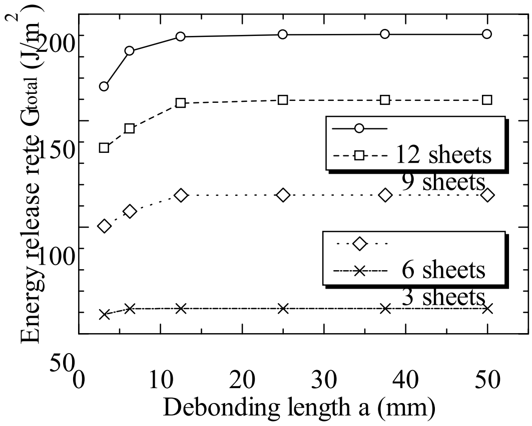
As shown in the figure, the energy release rate, $G_{total}$, decreases with increasing the length of overhang, $L$, for $L < 100$ mm, which is independent of the initial crack length, $a$. This result suggests that the overhang is effective to prevent the debonding of CFRP. However, the actual loading conditions, where the bending moment varies gradually over the span of the girder for example, are different from the boundary condition assumed in the present analyses, which should be considered in the actual design.




"**Fig. 2.** Effect of the overhang length on the energy release rate at the adhesive interface."

b) Effect of crack propagation

Figure 3 shows the analytical results on the effect of the crack length, *a* on the energy release rate, $G_{total}$, where the number of CF sheet varied from 3 to 12. The abscissa represents the length of debonding. The ordinate represents the energy release rate. This result indicates that the crack propagates unstably without arrested after the onset of crack growth under the present boundary conditions.

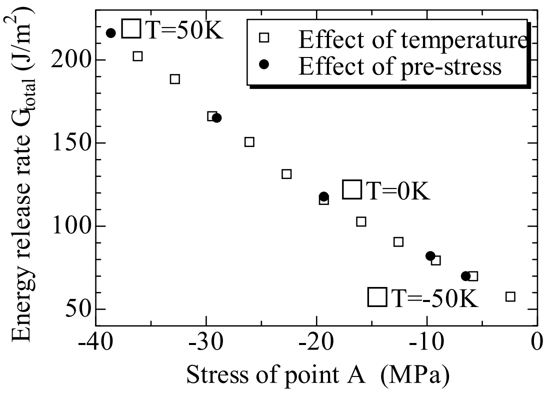



"**Fig. 3.** Effect of the crack length on the energy release rate at the adhesive interface."

c) Effect of temperature and prestress

The difference of thermal expansion coefficient between the CFRP and steel induces the thermal stress at the adhesive interface. In Japan, steel bridges are designed to endure the temperature from -10 to +50 C for through bridges and steel deck bridges in usual districts, from -10 to +40 C for other bridges in usual districts and -20 to +40 C in cold districts, respectively. Figure 4 shows the energy release rate induced by thermal stress, which is essentially the same as that induced by the prestress. As shown in the figure, the energy release rate, $G_{total}$, reaches 100 J/m$^2$, which is approximately equal to the fracture toughness of the adhesive interface, for $\Delta T$ = 50 K.

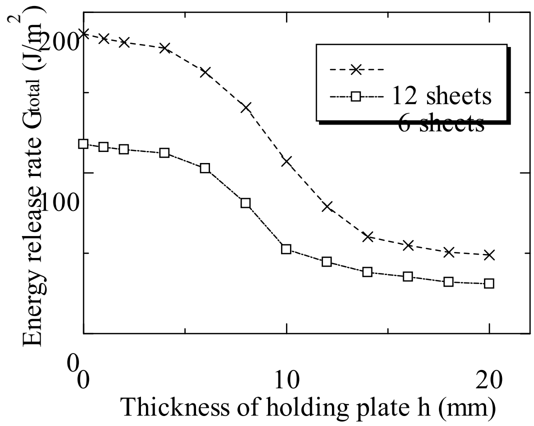
This result suggests that the debonding can be caused by the thermal stress under the actual service condition and the effect of post-tensioning can be lost by the thermal stress. The above discussion is based on the assumption that CFRP is an orthotropic but homogeneous material. However, CFRP is actually an inhomogeneous material consisting of carbon fibres and epoxy resin. Hence, the above results would have to be verified through experimental studies in the further investigations because the inhomogeneity might affect the local stress field in the vicinity of the crack tip.




"**Fig. 4.** Effect of temperature and prestress on the energy release rate at the adhesive interface."

d) Effect of holding plate

It is indicated that the debonding of CFRP can be suppressed by constraining the end of the CFRP (1). Here the effect of small holding plates is examined by finite element analyses, where the thickness of the holding plate was varied from 1 to 20 mm for $L$ = 0 mm and $a$ = 25 mm. The holding plate, which was fixed at the end of the CFRP, was modelled as a spring.




"**Fig. 5.** Effect of thickness of steel holding plate for suppressing crack opening defection of CFRP on energy release rate, $G_{total}$."

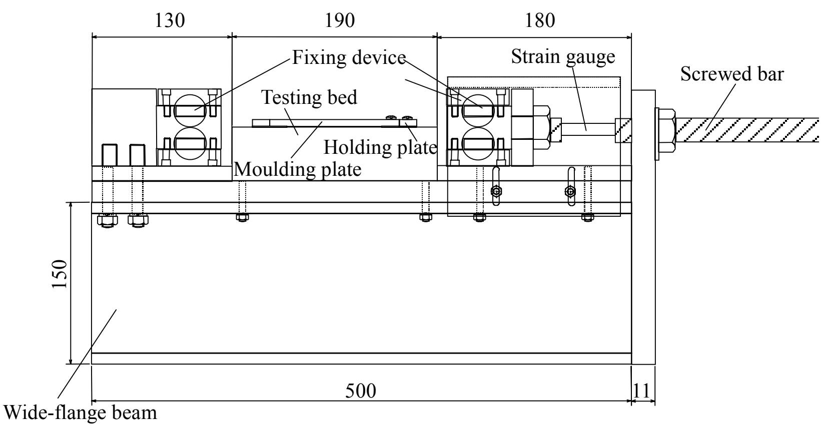
Figure 5 shows the effect of holding plate on the energy release rate and is plotted the numerical results for the CFRPs of 6 and 12 layers, respectively. In both cases, the energy release rate, $G_{total}$, decreases with increasing the thickness of the holding plate. These results indicate that the energy release rate, $G_{total}$, can be reduced to 1/3 by using a holding plate of proper thickness.

## 3. VERIFICATION OF THE EFFECT OF HOLDING PLATE

The effectiveness of the holding plate was investigated on the basis of experimental results using a miniature specimen. As shown in Fig. 6, CF sheets are bonded to the fixing devices; one is settled to the base and another is mechanically pulled by a screwed bar. The experimental procedures are itemized as follows:

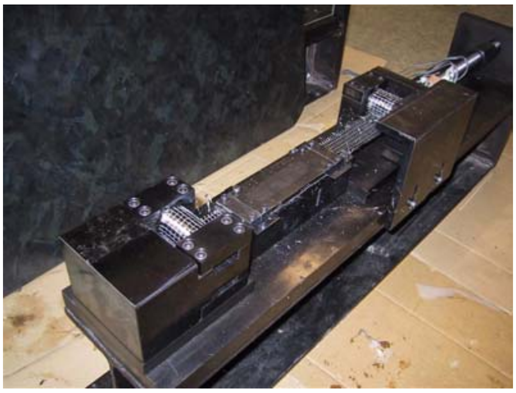
1) To apply the designated tensile force to the CF sheet
2) To impregnate epoxy resin into the CF sheets and to set the holding plate and moulding plate
3) To check the debonding of CFRP after removing the moulding plate and reducing the tensile force gradually by loosening the screw
4) To check the debonding again after removing the holding plate

A layer of CF sheet of high strength type was used in the experiment. The width and thickness of the CF sheet was 30 mm and 0.165 mm, respectively. The clearance between the CF sheet and steel plate was controlled to be 0.5 mm using a clearance gauge. Consequently, the thickness and fibre volume fraction of the CFRP were accurately 0.5 mm and 33 %, respectively. Two types of specimens were tested; one had a smooth machined surface and another had a rough ground surface on the testing bed. The tensile force, which was varied from 4 to 10 kN, was measured with strain gauges attached to the screwed bar.

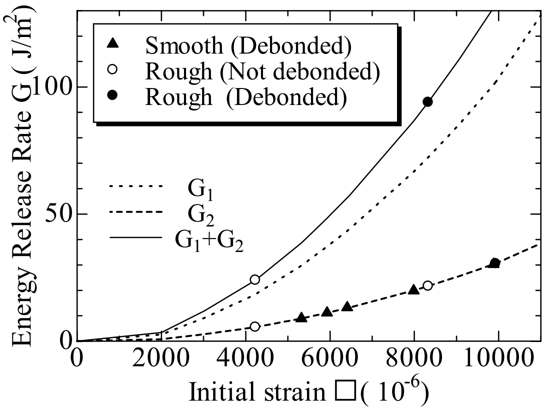



“**Fig. 6.** Schematic drawing of the debonding test apparatus.”

Figure 8 shows the results of debonding tests. The abscissa represents the tensile strain applied to the CF sheet. The ordinate represents the energy release rate at the end of adhesive interface. In the case of smooth surface specimens, CFRP was debonded from the steel plate when the screw was loosened in procedure 3. The debonding seemed to occur simultaneously all over the adhesive interface. The results of the smooth surface specimens were plotted on the solid line because the stress field was expected to be mode II under the constraint of the holding plate. Since the fracture toughness of the adhesive interface was smaller than expected in the case of the smooth surface, the effect of holding plate could not be examined. In the case of rough surface specimens, different results were obtained; CFRP was not debonded in some specimens after the procedure 4, whereas CFRP was debonded during the procedures 3 or 4 in other specimens. The results of the rough surface specimens were plotted on the dotted or broken lines. The allowable strain applied to the CF sheet is expected to be 0.4 - 0.8 % when the holding plate is not used. However, it can be raised to 0.8 - 1.0 % when the holding plate is used.



“**Fig. 7.** Delamination test apparatus.”




“**Fig. 8.** Effects of surface roughness and holding plate on the energy release rate at the adhesive interface.”

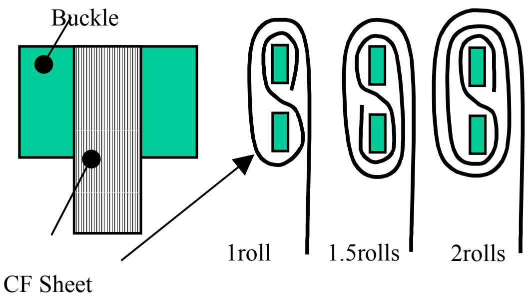
## 4. POST-TENSIONING DEVICE

In this chapter, two types of post-tensioning devices are presented. Both of the devices are tested by attaching them to the small size of I shaped beam.

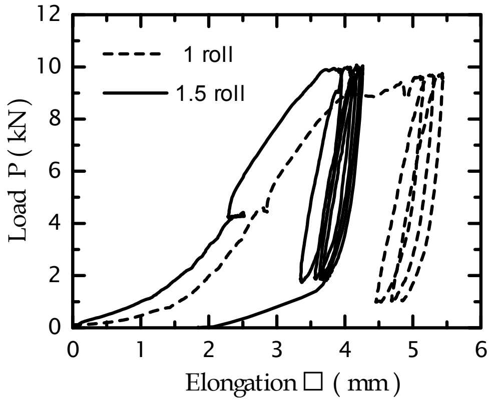
### 4.1 End Fixture

A buckle plate as an end fixture is proposed to keep the tensile force of CF sheet during the cure process of epoxy resin as shown in Figs. 9 and 10. The CF sheet can be easily adjusted in length and bonded to the structures on the construction site by using this method. As shown in Fig. 9, 3 types of the specimens were employed to study the ability of the end fixture. The width, thickness and tensile strength of the CF sheet were 300 mm, 0.165 mm and 200 GPa, respectively.

The specimens were repeatedly loaded from 1 to 10 kN, which corresponds to 10 % of the tensile strength of the CF sheet, ten times with holding the maximum load for 30 seconds. Figure 11 shows the experimental results of the specimens of 1 roll and 1.5 rolls. The abscissa represents the apparent elongation of the CF sheet. The ordinate shows the load applied to the specimen. As shown in the figure, the elongation was stopped after 3 cycles for the specimen of 1.5 rolls, whereas it was not stopped for the specimen of 1 roll. This result shows that the CF sheet can be completely fixed with 1.5 rolls at the minimum case by using the buckle plates proposed by the authors. In addition, the results of creep tests indicate that the above tendency does not depend on duration of loading.




“**Fig.9.** Configuration of the buckle plate and CF sheet.” “**Fig.10.** Preparation process of the specimen.”




**“Fig.11.** Experimental results of the slip tests using the buckle plate.**”**

**4.2 Post-tension Device**

Various types of post-tension devices have been developed to introduce the tensile stress to CF sheets on the construction sites. To use CFRP instead of conventional PC bar or steel plate, new type devices are needed. 3 types of post-tension devices were proposed and tested as follows.

**a) Tension bar type post-tension device**

Figure 12 shows the appearance of tension bar type post-tension device attached to a small model girder. In this case, bending moment and compressive force can be introduced to the girder by tightening the bolts of tension bar attached to the both ends of the reinforcing area.
As the brackets are attached to the girder with high performance vises, any special machining is not necessary. In addition, as the tension bolts are used for post-tension, total tensile force can be easily increased with the increase in the number of the bolts. This type of device is convenient only in the case where small post-tension force is needed, because the prestress decreases when removing the post-tension device.

“**Fig.12.** Tension bar type post-tension device.”

“**Fig.13.** Buckle and vise type post-tension device.”

**b)** Buckle and vise type post-tension device

Figure 13 shows the appearance of buckle and vise type post-tension device used for strengthening of concrete floor of Daimotsu railway station in Japan. In this case, the CF sheet was strained with the vises attached to the floor using anchor bolts. The tensile force given to the CF sheet was 5kN.

**c)** Buckle and hydraulic jack type post-tension device

Figure 14 shows the appearance of buckle and hydraulic jack type post-tension device, where hydraulic jacks are substituted for vises of the buckle and vise type post-tension device. More than 20 kN in post-tension load can be applied to the CF sheet by this method. This type of tension device would be promising for on-the-site use in future.

"**Fig.14.** Buckle and oil-jack device."

## 5. CONCLUSIONS

The delamination between CF sheet and steel bridge girder was investigated by using FEM analysis, and conclusions are as follows.

a) About 100mm length overhang is effective to prevent the debonding of CFRP.

b) The crack propagates unstably without being arrested after the onset of crack growth under the present boundary conditions.

c) The debonding can be caused by thermal stress under the actual service condition and the effect of post-tensioning can be lost by the thermal stress.

d) The energy release rate, $G_{total}$, can be reduced to 1/3 by using a holding plate of proper thickness.

The results of experimental works are as follows.

e) The allowable strain applied to the CF sheet is expected to be 0.4 - 0.8 % when the holding plate is not used. However, it can be raised to 0.8 - 1.0 % when the holding plate is used.

f) An end fixture using a buckle plate was proposed to keep the tensile force of CF sheet during the cure process of epoxy resin.

g) 3 types of post-tensioning devices were developed and worked as expected at site.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