Evaluate of Flexural Behavior of the Prestressed Concrete Girder Using Carbon Fiber Reinforced Plastics via Finite Element Method

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***Abstract*—A flexural experiment was conducted on the tested prestressed concrete girder using carbon fiber reinforced plastics (CFRP) tendons, which has the full scale of an actual one and was placed next to the main girders of Shinmiya Bridge in the corrosive environment nearly 30 years. In this study, the flexural behavior of this tested girder was investigated by the finite element method. A three-dimensional analysis model was built in LS-DYNA and analyzed by an explicit finite element program. The load-bearing capacity, load-deflection curve, and the crack pattern were evaluated in comparing with experimental results. The comparison result showed that there was a consistency between results obtained from the simulation and that obtained from the experiment of the tested girder in 2017. Based on this model, the decrease of pre-stressing force in the tendons, the reduction of the compression concrete strength were studied to evaluate the change in the behavior of the structure.**

***Index Terms*— CFRP, flexural behavior, numerical analysis, prestressed concrete girder**

I. Introduction

Shinmiya Bridge was known as the first bridge using Carbon Fiber Reinforced Plastics (CFRP) tendons in the main girders of the prestressed concrete bridge against salt damage in Japan and in the world. This bridge was built in 1988 in Ishikawa, Japan where suffer remarkably by seawater and flying salinity. Its length and effective width were 6.1 m, 7.0 m, respectively. The 26 beams were made of the same size including 24 main girders for the bridge and 2 test girders. These test girders were placed next to the main girders on two sides to confirm long-term quality performance and their names were mountainside girder and seaside girder (shown in Fig. 2). After 6 years (in 1994), the seaside girder was removed to the laboratory and a series experiment was conducted on this tested girder. The project continued to test with the mountainside girder in 2017–30 years after construction time. The load-bearing capacity of the girder in these times has been evaluated and recorded. The durability and serviceability of the girder reinforced by CFRP tendons in the corrosive environment have been confirmed [1][2]. The results and conclusions of these studies agree with previous studies that CFRP is suitable for replacing the conventional steel as the method against salt damage in bridge constructions.

Figure 1. Shinmiya Bridge in December 2017

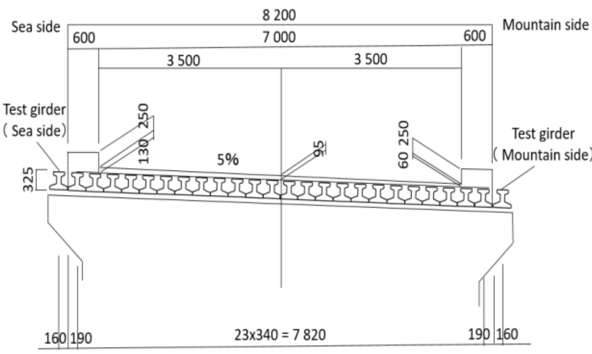

Figure 2. Cross-section of Shinmiya Bridge (unit: mm)

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In the research of P. Potyrala (2011) showed that 355 bridge structures in the world were applied fiber reinforced plastic (FRP) as the main material until 2011 [3]. Studies on using CFRP for bridge construction are invested from experiments to analyses, simulation and application. CFRP was divided into several shapes, selected for different parts of the bridge, and made from the small specimen to the full-scale specimen [4]–[9]. Recent years, to deeply understand the structural behavior and the phenomena observed, three-dimensional models were built and studied by the researchers via commercial finite element analysis software which has been become more popular in the field of construction [10]–[14]. This method not only provides technical benefits but also saves costs and time in the study, especial for the full-scale structure.

In this study, the aim is to use the finite element method to evaluate the behavior of the prestressed concrete girder using CFRP tendons subjected to four-point bending after 30 years in the corrosive environment. LS-DYNA commercial software was selected because it has many advantages for nonlinear analysis of structure. The result of the numerical simulation was confirmed by the comparison with the experimental results of the mountainside girder of Shinmiya Bridge in 2017. After that, a parametric study was conducted to consider the effect of the level of pre-stressing force in the tendons and the reduction in the compression strength of concrete to the load-bearing capacity of the girder.

II. OUTLINE OF EXPERIMENT

A. Detail of Test Specimen

The tested girder, namely the mountainside girder, was fabricated in 1988 and put next to the main girders of Shinmiya Bridge in the same environment. After existing in the actual corrosive environment nearly 30 years, the tested girder was removed to the laboratory and subjected to a series of experiment to evaluate the durability and serviceability of the prestressed concrete girder using CFRP tendons including the bending test [2].

The tested girder with I-shaped cross-section has length, height, and width of the upper flange, width of the lower flange of 6060 mm, 325 mm, 200 mm, and 320 mm respectively. The girder was reinforced with eight CFRPs with Ø12.5 mm and seven strands, in which six CFRPs was used for the tensile zone and two CFRPs located in the compression zone. The space between CFRPs in upper flange was 80 mm while this number was 50 mm of five CFRPs in the lower flange. The number three of CFRPs in the tensile zone was located at the center of the lower flange and at a height of 90 mm from the bottom of the girder (seen in Fig. 3). Epoxy coated rebar of D6 was set up for stirrups and the compressive strength of concrete in 1988 was 59.8 N/mm^2.

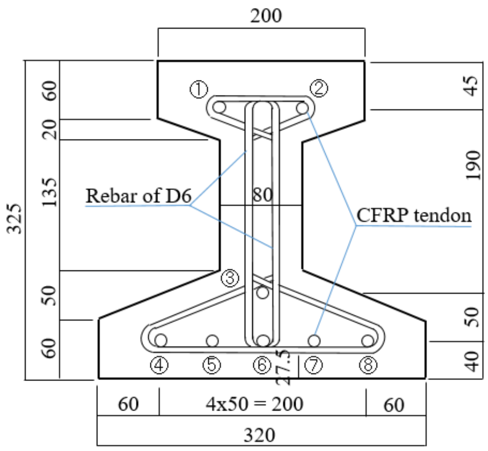

Figure 3. Cross-section of Shinmiya Bridge (unit: mm)

B. Set-up of Experiment

The mountainside girder was placed on two steel support systems and the flexural load was applied to the girder through a load-spreader. The design of the loading distributed at the two points spaced at 1000 mm in the middle of the span. Load cell, displacement meter and strain gauges were used to record the force, displacement and strain during the time of the experiment. The set-up of the experiment for the girder was shown in Fig. 4.

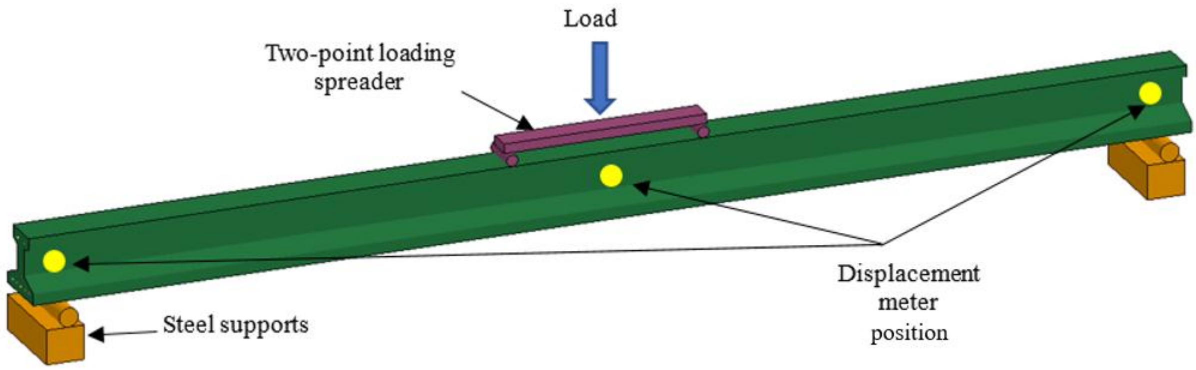

Figure 4. Setup of the experiment for Shinmiya bridge girder

C. Loading Procedure

The loading procedure was divided into three loading and unloading cycles to separate the elastic and inelastic stages under the load-displacement curve. The load was applied on the girder including 35.4 kN, 82.8 kN (the crack initiation load) and 157 kN (the ultimate load).

III. Finite Element Model

A. Overview of Analysis

The commercial software LS-DYNA was employed to investigate the structural behavior in order to deeply understand the final behavior of the girder. Normally, the quasi-static problem was solved by the implicit finite element method. However, it is sometimes difficult to converge on the model of nonlinear and progressive damage failure [13]. Therefore, the explicit finite element method was chosen in this study. The model was simulated as closely as the experiment with five main part namely the roller supports, concrete beam, tendons, stirrups and the load plates as shown in Fig. 5.

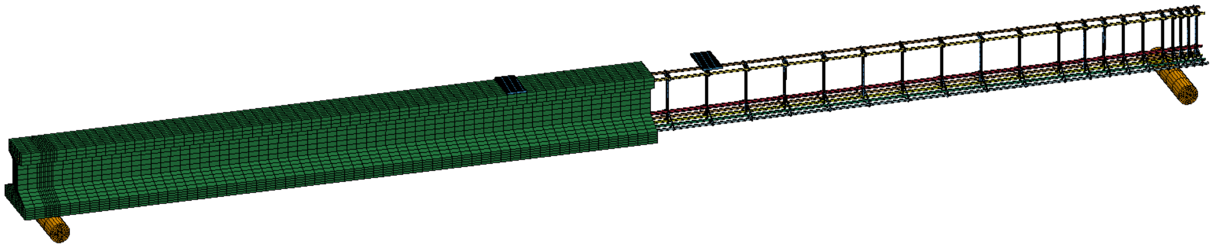

Figure 5. Three-dimensional analysis model for experiment girder

B. Method for Prestressed in Tendon

Pre-stress can apply to the structure by many methods in LS-DYNA. In this study, applying a thermal gradient was employed for the tendons obtained the pre-stress. The decrease in the temperature in tendons causes shrinkage and tensile stress in tendons. The material property of tendons with the variation of temperature was defined by using the material card *MAT_ELASTIC_PLASTIC_THERMAL (MAT 004) [15]. Following this card, the *LOAD_THERMAL_LOAD_CURVE card [15] was used for defining the relationship between time and temperature, two curves needed to add for this option. The dynamic relaxation phase was carried out by *DYNAMIC RELAXATION card [15] that required the first curve. This curve was a sudden decrease in temperature from an initial temperature to a determined temperature and then the temperature kept constant. The second curve was used for an explicit phase; it was a constant temperature with time variable. The change in the temperature can be calculated from the following equation [16][17]:

$$\Delta T = \frac{f}{\alpha E_c A_c} + \frac{f}{\alpha E_t A_t} \tag{1}$$

Here, ΔT is the temperature change; E_c, E_t are respectively Young's modulus of concrete and tendons; A_c, A_t are respectively sectional area of concrete and tendons; α is the thermal expansion coefficient of the tendons. In this study, a temperature gradient of 1866.2°C was input for CFRP tendons to obtain the pre-stress.

C. Material Modeling

1) Concrete

Concrete was modeled by using solid eight-node element. The mesh size was considered the number of elements and the sensitivity analysis of mesh. In LS-DYNA software, there are various types of material for modeling concrete model, such as MAT_PSEUDO_TENSOR (MAT 016), MAT_CONCRETE_DAMAGE (MAT 072), MAT_CONCRETE_DAMAGE_REL3 (MAT 072R3), MAT_WINFRITH_CONCRETE (MAT 084/085) and MAT_CONTINUOUS_SURFACE_CAP_MODEL (MAT 159) [15], each of these types has both of advantage and disadvantage. In this study, *MAT 72R3 was employed for the simulation of concrete. The Karagozian & Case concrete model is a plasticity, it has three independent strength surfaces including the maximum strength surface, yield strength surface and residual strength surface [15]. The input data is simple relatively for users because almost parameter can be generated automatically based on the unconfined compressive strength of concrete [18][19]. Moreover, this model obtained the accurate results for analyzing the behavior of concrete in the prestressed concrete structure in the older studies [13][17]. Young's modulus and unconfined compressive strength of concrete were collected from the results of the compressive test, which was carried out for specimens collected from the tested girder after the bending test. The parameters used in LS-DYNA to define concrete model shown in Table I.

When the tensile stress in the concrete element reached the value that larger than the maximum initial tensile stress, the concrete element fails and removes from the model. *MAT_ADD_EROSION card [15] was used in this study to define the maximum initial tensile stress at failure.

2) Stirrup and CFRP tendons

The stirrups selected Hughes-Liu with 2x2 Gauss cross-section for beam elements and *MAT_PIECEWISE_LINEAR_PLASTICITY (MAT 003) [15] for material. As while the tendons chose Hughes-Liu with 2x2 Gauss cross-section for beam elements with **MAT_ELASTIC_PLASTIC_THERMAL (MAT 004) for material. *MAT 004 was used to define the temperature dependent material property for tendons and linked the keyword *LOAD_THERMAL_LOAD_CURVE to define the variation of temperature versus time. The parameters were input for stirrups and CFRP tendons as shown in Table I

TABLE I. MATERIAL PROPERTIES OF NUMERICAL MODEL

Part	Material model card	Input parameter	Value	Unit
Concrete	*MAT 72R3	Mass density	2.30E-09	ton/mm^3
		Unconfined strength	7.51E+01	N/mm^2
		Young's modulus	3.72E+04	N/mm^2
Tendon	*MAT 004	Mass density	1.99E-09	ton/mm^3
		Young's modulus	1.33E+05	N/mm^2
		Poisson's ratio	0.3	
		Yield stress	2063	N/mm^2
		Plastic hardening modulus	1000	N/mm^2
		Thermal expansion coefficient	2.00E-06	
Stirrups	*MAT 003	Mass density	7.83E-09	ton/mm^3
		Young's modulus	2.07E+05	N/mm^2
		Poisson's ratio	0.3	
		Yield stress	395	N/mm^2
		Tangent modulus	2000	N/mm^2
Support	*MAT 001	Mass density	7.83E-09	ton/mm^3
		Young's modulus	2.07E+05	N/mm^2
		Poisson's ratio	0.3	
Plate	*MAT 020	Mass density	7.83E-09	ton/mm^3
		Young's modulus	2.07E+05	N/mm^2
		Poisson's ratio	0.3	

3) Supports and plates

Solid element and *MAT_ELASTIC (MAT 001) [15] were employed for the support. This material model has the simple isotropic elastic behavior and can be used for any element type in LS-DYNA. The load plate used the shell element and *MAT_RIGID (MAT 020) card [15] was selected in numerical simulation. Table I shows the input values used to define these material models.

4) Contact and boundary conditions

The bonding between the concrete, steel, and CFRP tendons was assumed a fully bonded. Because of the geometry characteristic, the node of concrete has not overlapped the node of reinforcement. Therefore, the card *CONSTRAINED_BEAM_IN_SOLID [15] was selected to couple beam element to solid elements. The interface for the contact between the roller supports and concrete, as well the load plates and concrete were defined by contact card*AUTOMATIC_SURFACE_TO_SURFACE [15]. The compression load was transferred from the slave surface to the master surface. All directions of the roller supports were constrained moving and rotating. The analysis was carried out by applying incremental displacement via keyword *BOUNDARY_MOTION_RIGID [15].

IV. COMPARISONS BETWEEN THE NUMERICAL ANALYSIS AND EXPERIMENTAL RESULTS

The comparison between numerical and experimental results was done to evaluate the accuracy of the finite element method. Load-bearing capacity, the curve of applied load versus middle span deflection, and crack pattern were the objects in this evaluation.

The finite element model predicted the load-bearing capacity and middle span deflection at failure of the tested prestressed concrete girder were 158 kN and 91 mm, respectively. In fact, these numbers in the results of the experiment were 157 kN of the ultimate load and 84 mm of the displacement in the central of the span.

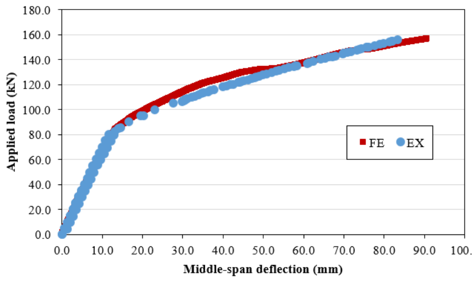

Figure 6. Relationships between applied load and middle-span deflection.

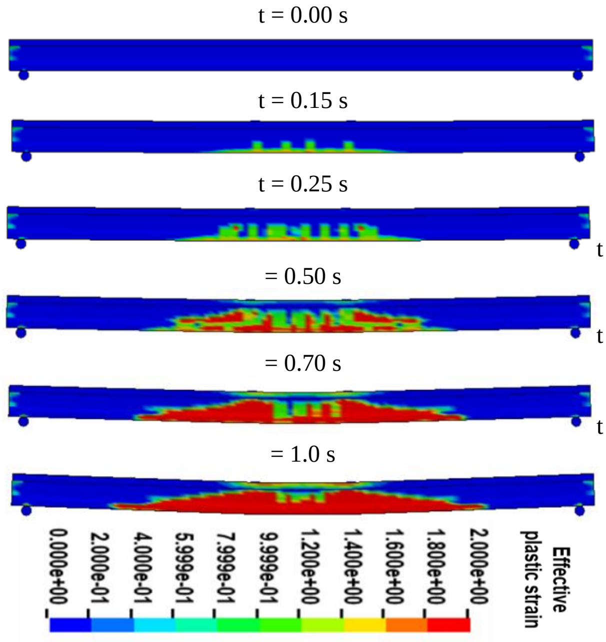

Figure 7. Deformation and strain situation in several stages of simulation.

Fig. 6 shows the relationship between applied load and middle-span deflection obtained from the experiment and simulation. The trend of the analytical curve was similar to the experimental curve from the beginner to the failure. The slope of the applied load-deflection curve, which was the transfer between the elastics stage and plastic stage, was modelled well. However, both of the ultimate load and middle-span deflection predicted from the numerical analysis slightly higher than these values in the experiment.

Deformation and strain situation in several stages of the simulation were shown in Fig. 7. Firstly, the cracks appeared in the middle of the span in the tensile zone. Then, these cracks expanded and developed to the compressive zone. In the same time, the shear cracks also occurred in the tested girder when the applied load was increased. Finally, the failure model of the tested girder was crushing of concrete in the compressive zone.

It can be concluded that there was a good agreement between numerical analysis and experiment results for the behavior of the prestressed concrete girder using CFRP tendons.

V. Parametric Study

A. *Effect of the Pre-stressing Force in Tendons.*

This section studied the effect of pre-stressing force in tendons to the change of the behavior of the tested girder. The pre-stressing loss varied from 10% to 30%.

In Fig. 8, the relationship between the load and deflection in the mid-span using with the initial pre-stress is showed in the red curve. The yellow curve and green curve are those relationships when the pre-stress losses 10% and 30%, respectively. According to Fig. 8, there is no significant change in the trend as well the shape of the relationship curves. The deflections in the mid-span obtained from three studied cases are quite similar. However, the inclination angle in the plastic stage has the lower trend and the load-bearing capacity of the girder decreases significantly when the pre-stress in the tendons was reduced. This difference in load-bearing capacity is small, which is just around 4% when pre-stressing loss was 10%. Whereas, this change quickly climbed to 12.2% when pre-stressing loss was 30%.

It can be confirmed that the level of pre-stress in the tendons significantly affects the behavior of the prestressed concrete girder, especially load-bearing capacity as shown above. The pre-stressing level is an important factor that needs to consider and record in future research.

B. *Effect of the Reduction in Compression Concrete Strength*

The influential parameter in the performance of concrete is compressive strength. In this section, a reduction of 10% and 30% in compressive concrete strength was studied to consider the effect on the behavior of the structure.

According the Fig. 9, the behavior of the experimental girder in case of the study in section 4 (the red curve) was compared with the case of the reduction of 10% in compressive concrete strength (the blue curve) and the case of the reduction of 30% in compressive concrete strength (the black curve). In LS-DYNA, the input parameters of concrete are interconnected. Therefore, when the compressive strength of concrete decreases, Young's modulus of concrete will also decrease. This is a reason for the phenomena that the angle of inclination in the elastic phase is different between the three relationship curves. These inclination angles tend to be smaller when the compressive strength of concrete decreases (seen in Fig. 9). This change is the starting point of changes in later stages of the girder behavior. The load-bearing capacity of the girder declined by 1.34% and 8.87% when the compressive concrete strength reduces by 10% and 30%, respectively.

Based on the above discussion, it can be seen that the reduction in the load-bearing capacity of the prestressed concrete girder in the cases of pre-stressing loss is higher than in the case of compressive strength reduction.

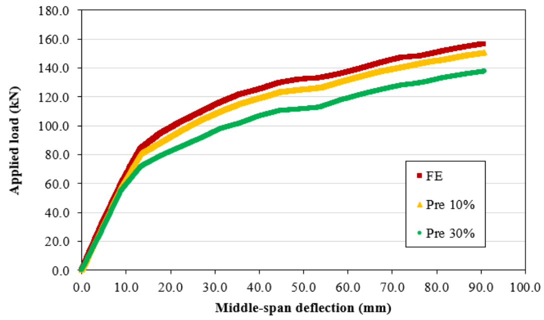

Figure 8. Relationships between applied load and middle-span deflection corresponding to the level of pre-stressing force.

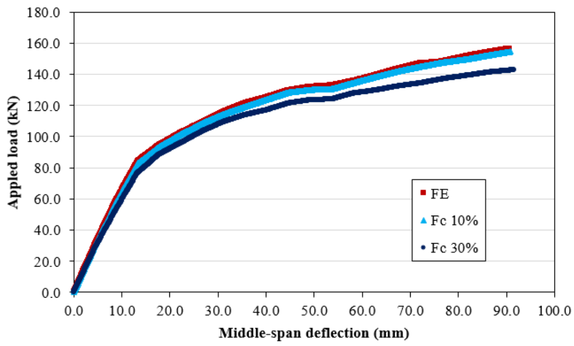

Figure 9. Relationships between applied load and middle-span deflection corresponding to the difference value of compressive strength of concrete

VI. Concluding Remarks

The following conclusions were derived from the particular results of this research:

(1) In comparing with the experimental results regarding load-bearing capacity, relationship between applied load and middle span deflection, and crack pattern, the results from the numerical analysis have a consistency with the results from the experiment. The model by finite element method can be used to understand the overview of the complex behavior and phenomena appeared in the test girder.

(2) The numerical simulation proposed a fundamental model to study the changes in the behavior of the girder using CFRP tendons when the pre-stressing force in the tendons and compressive strength of concrete reduce. It can be confirmed that the load-bearing capacity will reduce significantly when the pre-stressing loss occurs. These values are lower when the concrete strength decreases with values of 10% and 30%, respectively. These results can be used to guide for future research regarding the behavior of the girder.

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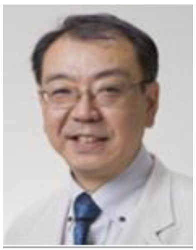

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