Bending Strength of RC Beam Reinforced with Carbon Fiber Sheet by Using FEM Modeling

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1. Introduction

The Carbon Fiber Sheet (CFS) bonding method can be used to repair and strengthen the RC beams. The CFS is very light and has a long service life. A lot of tests for RC members reinforced with CFS have been done at Industrial Technology of Nihon University for over 5 years. For understanding more about the RC members with CFS, it would be great help by using Finite Element Method (FEM) that has been widely used in academic area. In the academic area, the FEM helps professors and students to understand more about experiments because the FEM shows numerical results for the inner part of the specimens. Therefore, authors had used the FEM to model a simple support reinforced concrete (RC) beam with CFS and compared with the test results. The program was called DIANA 8.1.2 [1] had been used.

2. Test Materials, Specimen Sizes, Test Method and CFS Bonding Procedures [2 and 8]

A. Experimental Material

The test specimens were produced by using ordinary Portland cement, coarse aggregates with a maximum size of 20mm, and D16 steel re-bars of the SD 295A class. The physical properties of concrete and steel re-bars are listed in Table1. High-strength continuous carbon fiber sheets (CFS) with a unit weight of 202g/m^2, a tensile strength of 4,420N/mm^2, a thickness of 0.111mm, and a width of 300mm were used as the reinforcing material to be placed on the bottom of RC beam specimen. The physical properties of CFS are listed in Table 2. Epoxy resin was used to bond CFS to the specimens

B. Experimental Dimension

Figure 1 illustrates the RC specimens that were produced for the test. Following shows more detail of RC beam specimen.

a) RC beam (2800mm×300mm×210mm)

The RC beam specimens had a span of 2000mm, a width of 300mm and a depth of 210mm. The three steel re-bars were placed on the tension side in such a manner that the effective depth was 172mm. The two steel re-bars were placed on the compression side.

C. Test Method (Bending Test)

Figure 2 shows the bending test using a static load that was performed by the wheels (diameter 350mm and width 250mm) stopped in the center of the span, the point where the maximum bending stress occurs. The load was increased from 0.0kN with 10.0kN increments until 50kN and changed the increments to 5kN until the test specimen broke. The deflection and the strain of the concrete and reinforcements were measured for each loading.

D. CFS Bonding Procedures

First, the bottom surface of RC beams was ground smoothly. Then, epoxy primer and connection epoxy were applied to the bottom surfaces of RC beam specimens. A single layer of CFS was then placed on the bottom of test specimen in the same direction as the primary steel re-bars (longitudinal direction). The details are expressed in Figure 3.

3. Specimen Model and Material Properties and Analysis Procedure for FEM

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Table 1 Properties of concrete and steel re-bars

Compressive strength of concrete (N/mm^2)	Steel Re-Bar (SD295A/D16)		
	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Young's modulus (kN/mm^2)
38.5	368	568	196

Table 2 Physical properties for CFS

Unit weight (g/m^2)	Tensile strength (N/mm^2)	Young's modulus (kN/mm^2)
202	4420	243

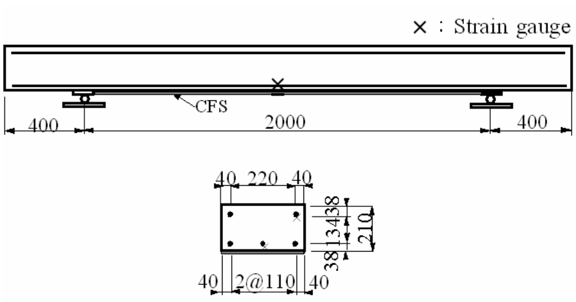


Figure 1 Specimen size and arrangement of steel re-bars

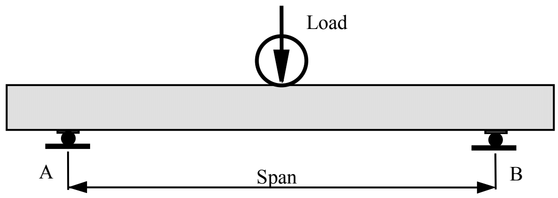


Figure 2 Bending test (Static-load)

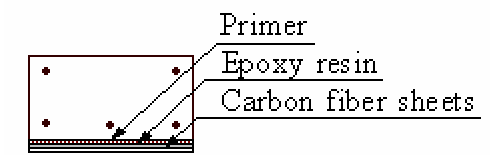
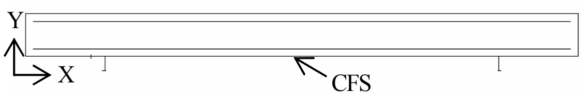
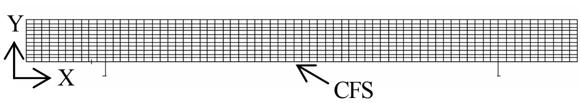


Figure 3 Bonding method of CFS



(A) Model for RC beam with CFS



(B) Mesh for RC beam with CFS

Figure 4 Model and Mesh for RC beam

A. Specimen Model for FEM

Model was two-dimensional simple support beam model and created by DIANA [1]. Steel Re-bars were included in the modeling, as well. For the mesh type, an eight-node quadrilateral isoparametric plane strain element was used for concrete and CFS. Fig. 4 shows the model and mesh.

B. Material Properties for FEM

For the cracking, the Smeared-cracking modeling [3 and 5] would be used that deals macroscopically with cracks and reinforcing bars by expressing the average stress and average strain relationships in an element. The Von Mises [1 and 6] plasticity that is a circular cylinder in the principal stress space would be used for the concrete and the steel re-bars.

(1) Concrete

$$\sigma_{tk} = 0.28\sigma_{ck}^{2/3} \tag{1}$$

where:

σ_{tk}: Tension strength (N/mm^2),

σ_{ck}: Compression strength (N/mm^2).

$$\sigma'_c = -\frac{\frac{E_{ci}}{E_{cl}}\frac{\varepsilon'_c}{\varepsilon_{cl}} - \left(\frac{\varepsilon'_c}{\varepsilon_{cl}}\right)^2}{1+\left(\frac{E_{ci}}{E_{cl}}-2\right)\frac{\varepsilon'_c}{\varepsilon_{cl}}}\sigma_{ck} \tag{2}$$

where:

$$E_{ci} = E_{co}\left(\frac{\sigma_{ck}}{\sigma_{com}}\right)^{1/3}$$

E_{ci}: the tangent modulus

E_{co}: 2.15×10^4 (N/mm^2);

σ_{co}: 10 (N/mm^2);

σ'_c: Stress for compression (N/mm^2);

ε'_c: Strain for compression;

ε_{cl}: -0.0022;

E_{cl}: $\sigma'_c/0.0022$= secant modulus from the origin to the peak compressive stress;

$$\varepsilon_u^{cr} = \frac{\sigma_{sy}}{E_s} \tag{3}$$

where:

ε^{cr}_u: ultimate strain,

σ_{sy}: Steel re-bar's yield (N/mm^2),

E_s: Steel re-bar's young's modules (kN/mm^2).

The compression strength was found in uniaxial compression test. After knowing the compression strength, using the formulas from the Standard Specifications for Concrete Structures [4] to calculated tension strength (Equation 1), young's modules, and yield strength, is the 1/3 of compression strength [4 and 5]. For the concrete stress and strain relationship (Equation 2), adopted the equation from CEB-FIP [8]. Linear tension softening was chosen for concrete. DIANA has suggested using the steel re-bar's yield strength (Equation 3) for the ultimate strain in the linear tension softening. For considering the tension stiffening and tension softening together, the average of steel re-bar's yield strength (ultimate strain) would be consider, therefore, divided Equation 3 by half as the ultimate strain for the tension softening curve. The shear retention factor [1, 5 and 6] was full shear retention because there was no dowel effect for the static bending test [5]. Fig. 5 shows the concrete stress-strain relationship for the specimens in the modeling.

(2) Steel Re-Bars

Steel re-bar's property that used in modeling was bi-linear. In the smeared-cracking modeling, the average stress-strain should be used, and the re-bar was embedded in concrete. After the steel re-bar yield strength, the slop of 0.01E would be use. Equation 5 is calculation before the steel re-bar yield strength and Fig. 6 shows the properties of steel re-bar.

$$\sigma_S = E_S \varepsilon_S \qquad (5)$$

Where,

σ_s and ε_s are the average stress and strain of mild steel re-bar, respectively; σ_{sy} and ε_{sy} are re-bar's yield stress and yield strain, respectively; E_s is the modulus of elasticity for steel re-bar.

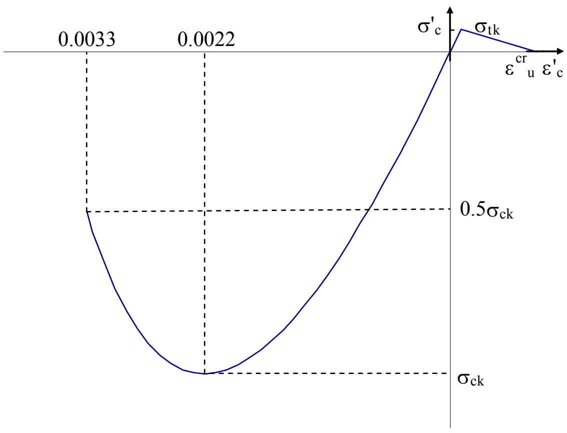


Fig. 5 Concrete's Stress and Strain Relationship

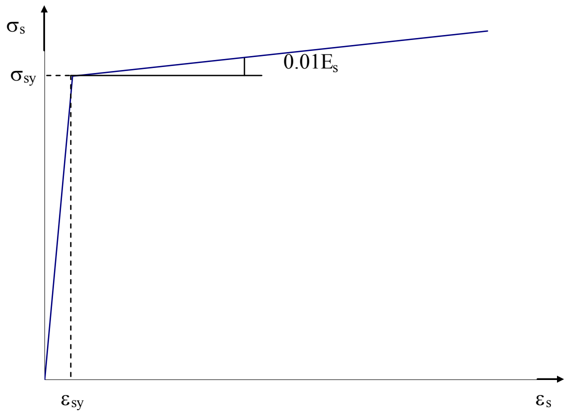


Figure 6 Steel Re-bar's Stress and Strain relationship

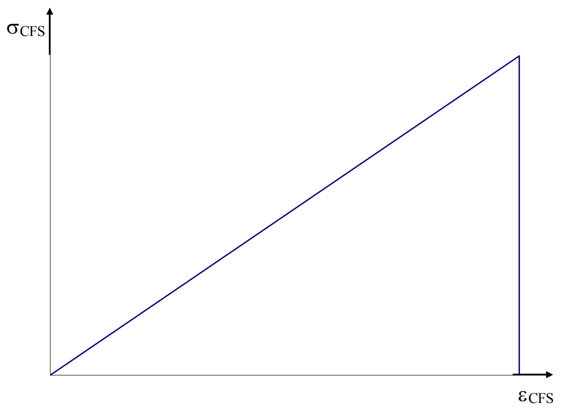


Figure 7 CFS Stress and Strain relationship

(3) CFS

For modeling of CFS, assuming the CFS was a part of concrete material, and the interface between CFS and concrete would not be considered in here. It was because when the specimens failed, the CFS had not been tearing away from each other. Also, CFS did not peeling away from concrete because of the epoxy. Observing from the test, the reason for the CFS peeling away from the RC beams was cracks of RC beams. Once the cracks started to happen, small pieces of concrete would be failed off from the bottom of RC beams that did not reinforced with CFS. It was the same as CFS reinforced RC beams because when the cracks started to be happen the concrete was failed off at the bottom with the bonded CFS [9]. Therefore, the authors made the assumption that the high strength CFS

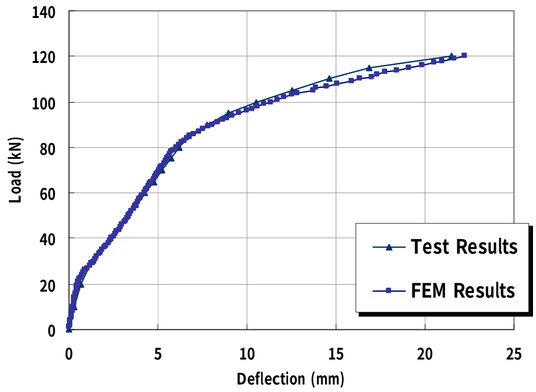


Figure 7 Loads and Deflection Relationship

material was part of RC beam at the bottom surface. Fig. 7 shows the relationship for CFS's stress and strain.

C. Analysis Procedure

The load steps were used for the non-linear analysis calculation, and the increment for the step was 1kN. For the iterative procedure, Quasi-Newton [1], uses the information of previous solution vectors and out-of–balance force vectors during the increment to achieve a better approximation, would be used with force norm for convergence criteria. Twenty interactions would be used for each load steps, and convergence tolerance would be 0.001.

4. Comparing the Test Results with the Modeling

Deflection will be comparing for the test results and modeling results that show in Fig. 7 for RC beam reinforced with the CFS

(1) Test Results

Under the static-load, the load carrying capacity of RC beam with CFS was 120.0kN. The steel re-bars' yield strength was around 85.0kN. The initial crack would be happen between 10.0kN to 20.0kN.

(2) Modeling Results

The calculation was set to be stop at 120.0kN where the maximum average value for the test specimens. However, by looking at the center top point of the model, when the load was 106.0kN, the concrete compression strain (ε_{ck}) was 0.0022. The calculation keep going because the steel re-bar and the CFS were not reached to their maximum stage. The yield strength for the steel re-bar was around 78.0kN. The first initial cracks would happen around 11.0kN.

5. Conclusion

(1) For modeling to get more close results as the test results, the input parameters would be critical and needed to try out for each different parameter.

(2) From the FEM, the top center point of the model reached to the concrete compression strength was around 106.0kN.

(3) RC beam with CFS modeling, there still have a lot of studies from the modeling since the assumption for the CFS as part of RC beam. The different kind of methods could be trying out in the feature studies.

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