ANALYSIS OF CONCRETE BRIDGE GIRDERS STRENGTHENED WITH CFRP LAMINATES UNDER SERVICE AND EXTREME LOADING CONDITIONS

SUMMARY

Externally bonded carbon fiber reinforced polymer (CFRP) laminates are a feasible and economical alternative to traditional methods for strengthening and stiffening deficient reinforced concrete and prestressed concrete girders as shown in Fig. (1). Although extensive research has already been undertaken to investigate the behavior of CFRP strengthened bridge girders, the majority of work conducted to date has been experimental in nature. Furthermore, while some studies have proposed design models and methodologies to identify the necessary number of laminates to achieve a target strength or stiffness, many important design issues still remain unresolved, particularly issues related to delamination and degradation under reversed cyclic loading typical of seismic excitations.

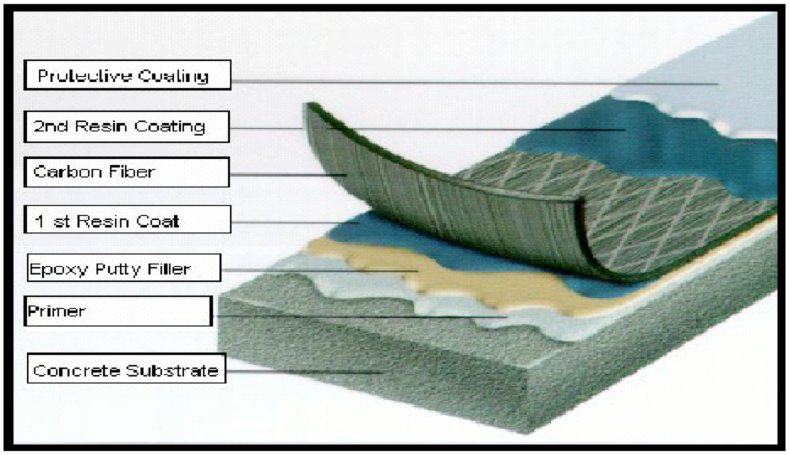

Figure 1 External Bonding with CFRP Laminates

BACKGROUND

A research study was initiated to develop a nonlinear numerical software for analysis of concrete girders strengthened with CFRP laminates. The model is based on the well-established displacement formulation and considers bond-slip effects. The inelastic behavior of the element is based on section discretization into fibers. Nonlinear material laws were assigned to the concrete, steel and CFRP fibers as shown in Fig. (2). The modified Kent and Park model was used to model the concrete behavior, the Menegotto-Pinto model was used to model the reinforcing steel behavior, while the CFRP was assumed to be elastic up to failure. In addition, a continuous interface element was developed to model the interfacial bond between the CFRP laminate and concrete. The bond constitutive law followed the Eligehausen model.

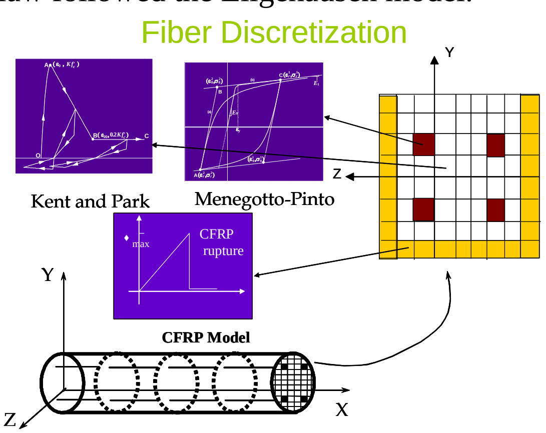

Figure 2 Modeling of CFRP-Strengthened RC Girders

OBJECTIVE

The objective of the work is to develop and validate an analytical software for nonlinear analysis of CFRP-strengthened RC girders. The model could be used by designers to evaluate the stress in the CFRP sheets under different loading conditions, the necessary number of layers to achieve a certain level of strength; and to detect the failure mode and whether it's due to bond delamination, rupture, or concrete crushing.

ANALYTICAL RESULTS

A series of numerical studies have been conducted in order of validating the accuracy of the newly developed model. A discussion of the numerical results for two test specimens is presented next.

Shahawy Specimens

The first series of specimens were tested at the laboratory under four point bending by Shahawy and Beitelman (1999). The beam layout is shown in Fig. (3).

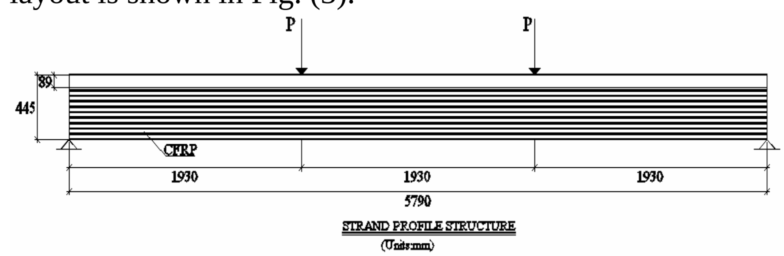

Figure 3 Shahawy Beam Layout

Figure (4) shows the beam section dimension and Table (1) shows the cross section properties. The beam was strengthened with CFRP laminates with varying amounts and with different configurations. The details of the CFRP-strengthened specimens are given in Table (2), and the CFRP properties are given in Table (3).

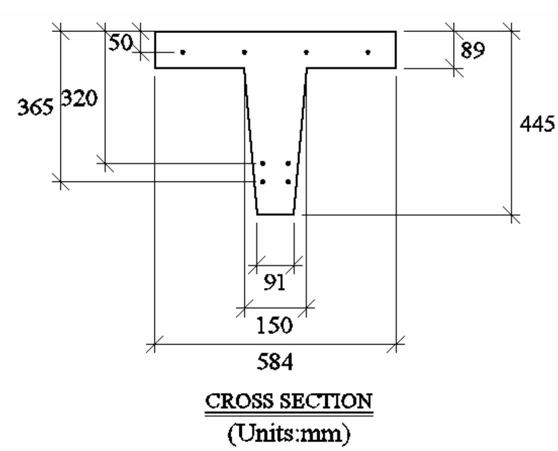

Figure 4 Cross Section Dimension

A	95380	mm^2
A_s	1135	mm^2
A_s'	284	mm^2
S_b	$4.9*10^6$	mm^3
S_t	$10.8*10^6$	mm^3
I	$1.5*10^9$	mm^4
f_y	441	Mpa
E_s	203	Gpa

Table 1 Cross Section Properties

The beam was analyzed under monotonically increasing load. The Bending Moment-Midspan Deflection curve is shown in Fig. (5) for all specimens. A comparison between the experimental and analytically - evaluated moment capacity is given in Table 4. The results confirmed the accuracy of the new model in describing the inelastic behavior of the test specimens.

Specimen	Mn(KN-m)	Reinforcement description	f_c (Mpa)
C-OL5	189.8	Control specimen, no carbon	35.9
P-2	190.6	Two layers on bottom of stem	37.2
W-1	211.4	One layers on full stem	35.9
W-2	259.9	Two layers on full stem	35.1
W-3	282.5	Three layers on full stem	35.1
W-4	305.1	Four layers on full stem	35.1

Table 2 Details of CFRP-strengthened specimens

Property	Value	Unite
Tensile strength	3.65	Gpa
Tensile modulus	231	Gpa
Filament diameter	7	µm
Filament/yarn	12,000	
Ultimate elongation	1.4	%

Table 3 CFRP Properties

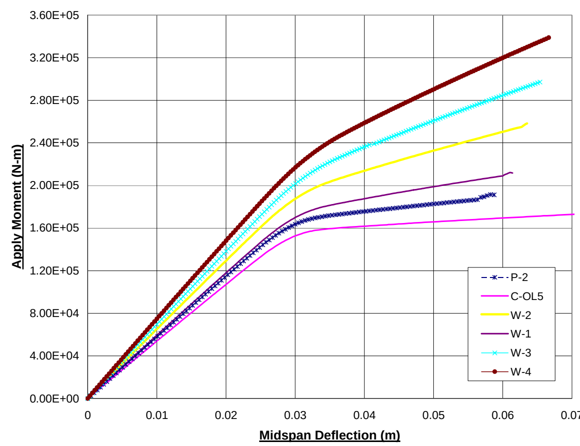

Figure 5 Load-Deformation Behavior of Shahawy Beams

Specimen	Mn (KN-m)	Mn By FEA (KN-m)
C-OL5	189.8	180.4
P-2	190.6	191
W-1	211.4	212
W-2	259.9	258
W-3	282.5	297
W-4	305.1	339

Table 4 Comparison between Experimental and Numerical Results

The new model was also used to predict the interfacial bond behavior. The distribution of bond stresses along the bema length for specimen P2 is shown in Fig. (6). From Fig. (6), it is clear the maximum bond stress occurred near the point of application of load.

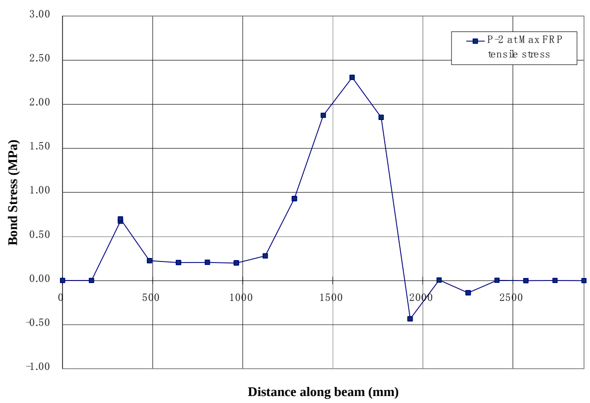

Figure 6 Interfacial Bond Distribution

Zarnic Specimens

A second set of specimens tested by Zarnic et al. were used in the analytical study. The beam layout is shown in Fig. (7). The cross section dimension and details are shown in Fig. (8) and Table (5) respectively.

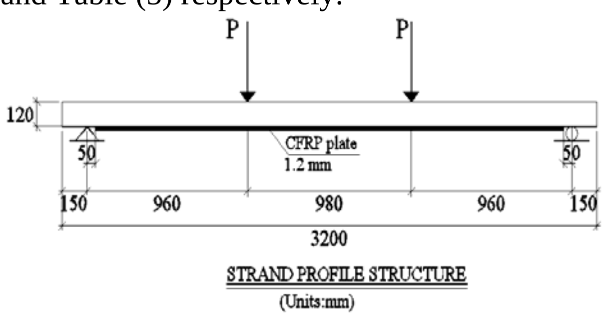

Figure 7 Zarnic Beam Layout

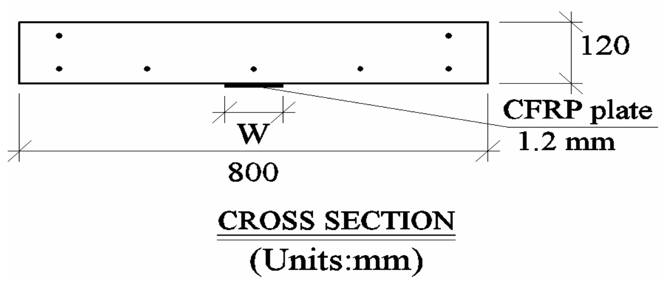

Figure 8 Cross Section Dimension

Property	Value	Units
A_s	384	mm^2
A_s'	256	mm^2
f'_c	25	MPa
f_y	460	MPa
E_s	210	GPa

Table 5 Cross Section Properties

The properties of CFRP used are given in Table (6) below.

Property	Value	Units
Tensile strength	1800	MPa
Tensile modulus	140	GPa
Thickness	1.2	mm

Table 6 CFRP Properties

The load-deformation response of Zarnic specimens for two cases with different width of CFRP sheets is shown in Fig. (9).

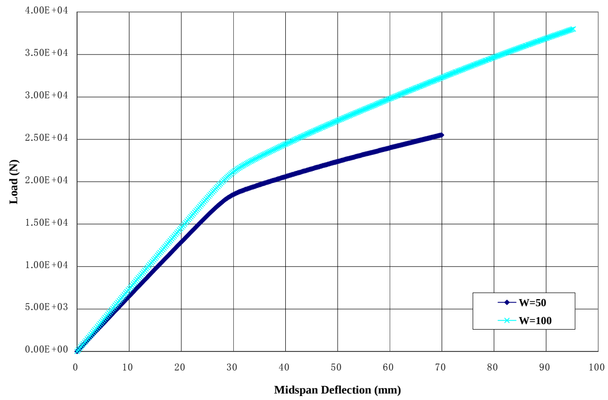

Figure 9 Load-Midspan Behavior of Zarnic Beam

The bond stress distribution along the beam length at the ultimate point is shown in Fig. (10) for both specimens.

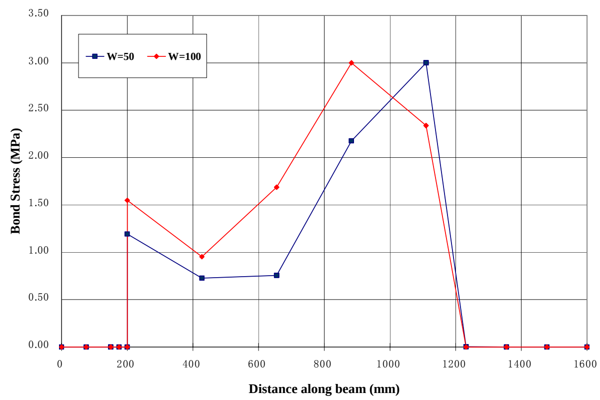

Figure 10 Bond Stress Distribution

From Figure (10), the bond stress near the point of application of the load reached the epoxy strength of 3 MPa, which suggests that debonding occurred in this region. This observation matches with the conclusions documented by Zarnic.

CONCLUSIONS

The newly developed model successfully described the inelastic behavior of CFRP-strengthened RC girders. The model was able to predict the global load-deformation response and the distribution of stress parameters along the beam length with reasonable accuracy. The model also successfully predicted the observed failure mode, and the possible delamination failure between the concrete and the CFRP sheets.

FOR FURTHER RESEARCH

Future research will aim at extending the current work to consider degradation under cyclic loading, and to accurately evaluate the design specifications proposed by ACI Committee 440. A new version of the program with user-friendly graphical interfaces will be also developed to be used by design engineers.

WANT MORE INFORMATION?

Details on this analytical work and additional data can be found in the final report.

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