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CONCRETE COVER DELAMINATION IN RC BEAMS STRENGTHENED WITH FRP SHEETS

Gustavo Tumialan, Paolo Serra, Antonio Nanni and Abdeldjelil Belarbi

Synopsis:

In addition to the conventional modes of failure observed in RC beams, some new ones can be observed in members strengthened by means of externally bonded reinforcement. Concrete cover delamination is a mode of failure caused by shear transfer and local regions of tension stress fields. A series of tests were carried out in order to study the concrete cover delamination failure, wherein the variables were length of beam span, bonded, number of plies, and U-jacketing. Two mechanisms within the concrete cover delamination failure were observed. One starting at the cutoff point of the FRP, which is originated by a high concentration of normal (out-of-plane) and shear stresses. A second one starting from a flexural crack between the outermost crack and the maximum bending moment zone. The latter mode of failure is caused by normal and shear stresses at the level of the steel reinforcement. From the point of view of design, it is important to recognize this premature type of failure, and determine algorithms for its prediction.

INTRODUCTION

The failure of a RC member strengthened in flexure can be caused by the crushing of concrete, rupture of the FRP laminate, peeling-off, or concrete cover delamination. In the first two modes of failure, the ultimate strength of the structural member can be easily predicted by following conventional RC flexural theory. However, whenever the mode of failure is peeling-off or concrete cover delamination, the strengthened member is not able to reach its ultimate strength; hence, the prediction of these kinds of failures is not an easy task. These failures are sudden, brittle, and without warning.

It has been observed that the horizontal shear crack found in cover delamination occurs at depth of longitudinal steel reinforcement. This mode of failure is different from the so-called peeling-off failure, where delamination is at the interface concrete-FRP.

Concrete cover delamination failure is caused by shear and local regions of tension (out-of-plane) stresses at the level of the steel reinforcement. The magnitude of these stresses is influenced by geometrical parameters such as thickness of the external reinforcement and adhesive, distance from the support to the end of the FRP reinforcement, and stiffness of various components.

As part of this research, RC beams strengthened with CFRP sheets were tested. Variables such as the number of plies of CFRP, bonded area, length of the span, and contribution of U-jacketing (wrapping) were studied. The tests made it possible to distinguish two mechanisms within the cover delamination failure.

EXPERIMENTAL PROGRAM

A total of 16 RC beams with a rectangular cross section of 6 by 12 in. (150 by 300 mm) and length 14 ft (4.26 m) were built for this experimental program, the effective depth of the section was 10 in. (250 mm). The stirrups were spaced 5 in. (125 mm) for Series A and B, and 10 in. (250 mm) for Series C. The longitudinal steel reinforcement consisted of four #5 (15.6 mm) bars, whereas the transversal steel reinforcement was made of #3 (9.4 mm) bars. Both longitudinal and transversal reinforcement had average yield stress of 62 ksi (427.5 MPa), average ultimate was 102 ksi (703.3 MPa), and the average Modulus of Young was 30100 ksi (207.5 GPa).

All the specimens were constructed at a precast plant using conventional fabrication, curing, and transportation techniques. Dry sand blasting was performed by the contractor using industrial grade equipment in order to remove the fine particles and paste and leaving the coarse aggregate exposed.

Unidirectional carbon fiber sheets were used. For the fibers, according to the manufacturer's information, the tensile strength was 493 ksi (3.4 GPa), the modulus of elasticity was 33400 ksi (203.3 GPa), and the design thickness was 0.0065 in (0.165 mm). In tension, the CFRP sheets have a linear elastic behavior up to failure. The mechanical properties of the epoxy resin or adhesive were 290 ksi (2.0 GPa) for the modulus of elasticity and 0.36 for the Poisson's ratio (1).

The cutoff points of the CFRP sheets were located at the beginning of the pin and roller supports. Three different series of beams were tested. In series A, the beam span was 7 ft (2.13 m). Beam A0 was used as control beam. The width of externally bonded reinforcement to the bottom of the beam was 6 in. (150 mm) for beams A1 to A5. The purpose of the different number of plies was to observe its incidence in the cover delamination failure. The number of plies employed in each beam is described in Table 1. The width of the CFRP laminate in beams A6, A7 and A8 was 3 in. (75 mm). Beam A7 was strengthened with two plies of CFRP; whereas, beam A8 had six plies. The purpose of these configurations was to observe and compare their behavior to beams A1 and A3, strengthened with the same amount of CFRP but in different bonded area.

Beam A4 and A5 were partially and totally wrapped (U-jacketing) at 90^0, respectively. The length to be wrapped in beam A4 was determined after the test of beam A3, which showed a horizontal crack running approximately 2 ft (0.60 m) from the cutoff point of the sheets. The purpose of testing a partially wrapped beam was to improve the capacity of beam A4 by delaying the cover delamination failure. In the beam A5, the purpose was to compare the partial and total wrapping.

Series B consisted of four beams, their testing span was 13 ft (3.96 m). Beam B1 was strengthened with one ply of CFRP, 6 in. (150 mm) width. In beams B2 and B3 the width was 3 in. (75 mm) with one a two plies, respectively. The sought objective in this series was to compare the behavior of beams similarly strengthened but with different bonded lenghts.

Three beams were tested in series C. The beam span was 7 ft (2.13 m), similarly to series A. The only difference compared to that series is the stirrups spacing, which was 10 in. (250 mm). The purpose of this series was to observe if the stirrups spacing had any influence in the final failure.

Table 1 summarizes the different strengthening schemes used in the experimental program.

All beams were tested as simply supported beams under one symmetrical load with a total span of either 7 ft (2.13 m) or 13 ft (3.96 m). The load was applied in cycles of loading and unloading. One cycle before cracking of the concrete and two cycles before yielding of the steel reinforcement were done. The total number of cycles depended on the maximum expected load. By applying the load by cycles, the stability of the system can be checked.

MECHANISMS OF FAILURE

Two mechanisms of failure were observed within the concrete cover delamination failure. For simplicity, they are to be called Failure Mode I and Failure Mode II. Failure Mode I refers to failure starting at the cutoff of the sheets; whereas, Failure Mode II refers to failure starting at an intermediate crack and developing towards the beam midspan.

Mechanism of Failure Mode I

This mode of failure may occur when the laminate is relatively thick (i.e. when more than one ply of FRP is attached to the concrete surface). The curtailment of the laminate adjacent to a support originates a high concentration of normal and shear stresses at the cutoff point of the sheet. Previous research (2) for RC beams strengthened with FRP plates has shown that the magnitude of these stresses depends on the geometry of the reinforcement, the engineering properties of the adhesive, and tensile and shear strength of the concrete. In the case of RC beams strengthened with FRP sheets, the geometry refers to the number of plies (thickness of the FRP sheets) as well as the distance from the support to the edge of the sheets. The stress distributions for normal and shear stresses needed to ensure the equilibrium of an isolated element from a beam at the level of the steel reinforcement, as well as the existing forces, are described in a previous investigation (3).

The stress distributions on the horizontal plane are those obtained from a previous analytical model (4). When the principal stress associated to the peak of the normal (out-of-plane) and shear stresses exceeds the modulus of rupture of concrete, the failure will occur. They were derived by assuming fully composite action between concrete and the external reinforcement and uncracked section. The failure caused by Failure Mode I starts at the ends of the sheets (see Figure 1) and is induced by the high concentrations of stresses at that point. The development of the horizontal crack depends on flexural cracks, shear cracks and bond stresses along the steel reinforcement. Previous studies relative to bonded steel plates (5) have shown two kinds of failures. One failure was caused by the peeling-off of the plate, leaving the concrete cover intact, and another failure was caused by concrete cover delamination, which leaves the steel reinforcement exposed. RC beams strengthened with FRP sheets which fail by peeling-off beginning from the cutoff point have not been reported; whereas concrete cover delamination, as shown in Figure 1, is common.

Mechanism of Failure Mode II

This failure is caused by cover delamination starting from one of the intermediate flexural cracks between the outermost crack and the maximum bending moment zone. The horizontal crack is originated by splitting of concrete at the steel reinforcement level, and mainly, by normal and shear stresses at that level which are needed to ensure equilibrium. Figure 2 illustrates the cracking progression of this failure.

Initially flexural cracks for a certain level of external load are observed. With further increases in external loads, the reduced area of bulk concrete at the level of the steel reinforcement pulls away from the rest of the beam after the horizontal crack appears starting at point F.

An element between two flexural cracks is isolated. The distributions corresponding to shear, normal, and bond stresses, as well as the existing forces in the FRP sheets, are described in Reference 3. Although more research is needed to obtain the exact distribution and magnitude of the normal and shear stresses that originate cover delamination; some assumptions can be made. For instance, the profile of the normal stress distribution may be similar to that found in the analytical models previously studied. Since there are no shear forces, due to the cracked section, acting on the vertical faces of the isolated element, the shear stresses at the edges of the isolated element must be zero. The failure occurs when the principal stress at the edge is larger than the modulus of rupture of concrete.

EXPERIMENTAL RESULTS

Series A: In the control beam A0, the final failure was typical of those observed in under reinforced RC flexural members, which is characterized by plastification of steel rebars followed by concrete crushing in the compression zone. Until the failure of the beam A3 the response of beam A4 is the same. It is after this point, failure of beam A3, where the contribution of the U-jacketing is appreciated. The employment of the U-jacketing delayed the cover delamination failure. A premature failure was observed in beam A5, possibly caused by cover delamination. In a similar way to beam A4, this beam wrapped in its entire length followed the theoretical flexural behavior more closely. Although, the final load at failure was increased, the ultimate deflection is less than in the case of the non-strengthened beam. Even though, beam A1 had twice amount of external reinforcement, A6 and A1 showed close values for the experimental values of load at failure. The premature characteristic of the concrete cover delamination failure caused that A1 did not develop its full capacity. On the other hand, beam A6, which failed due to CFRP rupture, behaved closely to what was expected.
From the results obtained in beams A7 and A8, it is concluded that beams strengthened with the same amount of CFRP on different bonded areas had similar behavior.

All the strengthened beams showed important increases in flexural stiffness and ultimate capacity as compared to the control beam A0. In order to quantify the flexural stiffness of the beams, average values of the slope of the load deflection curves after the concrete cracks and before the steel yields were taken. The flexural stiffness for a simply supported beam with a concentrated load, applied at the midspan can be computed as $EI = \frac{L^3}{48} \cdot K$, where L is the length of the span and K is the slope of the Load vs. Deflection Curve. As shown in Table 2, the tests results showed that the stiffness of beam A1 increased 13%, the stiffness of beam A2 increased, roughly, 15%; while the beam A3 displayed a 28% increase. In the beams A4 and A5, the stiffness is roughly the same as that found in beam A3 because the contribution of the U-Jacketing is observed once beam A3 reached the final failure. As expected, after steel yielding, the flexural stiffness increased when the number of plies of CFRP was increased. The test results indicated that by employing externally bonded sheets, important increases in flexural stiffness and ultimate capacity are achieved. However, these increases were afforded at the sake of some ductility losses.

Considering ductility (μ) is defined as the deflection at the ultimate state of failure (δu) divided by the deflection at the yielding of steel (δy). It can be observed from Table 2 that the control beam A0 had a ductility of 4.3. On the other hand, the ductility in the strengthened beams decreased, gradually, when the number of plies was increased (See Table 2 and Figure 3). However, owing to the employment of the U-jacketing the ductility increased in Beams A4 and A5, as shown in Figure 4, because the cover delamination failure was delayed.

From the point of view of design and following the philosophy of ACI 318-95, sections with significant loss of ductility must be compensated with a higher strength reserve, which is accomplished by applying a strength reduction factor of 0.70 to brittle sections instead of 0.90 for ductile sections.

Regarding to the ultimate capacity, the beams A4 and A5 displayed increases over the beam A3 of 15% and 23%, respectively. In addition, loads associated to cracking and yielding are, also, increased with the number of plies. During the tests, it was observed that the employment of CFRP sheets delayed the presence of the first visible cracks, and also, the distance between flexural cracks decreased when the number of plies of CFRP increased. In addition, there is evidence from previous works that the crack widths are reduced (6).

Series B: The purpose of this series, the results of which are shown in Figure 5, was to compare the behavior of strengthened beams with different testing span, 13 ft (3.96 m) to those of series A with span of 7 ft (2.13 m). From comparing beam B3 to beam A7. (Figure 6). It can be observed that up to yielding of the steel reinforcement the specimens behaved in similar way, without any influence of the length span. It is after this point, that other phenomena take place (i.e. absorption of energy) which cause the final failure.

Series C: Since the area of bulk concrete between stirrups was larger in these beams, the purpose of these series was to observe if there was any influence of the stirrups spacing in the concrete cover delamination failure. After observing the results of beams with stirrups at 10 in. (250 mm), it can be concluded that there was no significant influence in the mode of failure.

Table 1 summarizes the predicted (Mu), experimental (Mn) values for flexural capacities as well as the final mode of failures obtained in each test performed in this investigation. An analytical model based on the compatibility of deformations and equilibrium of forces was used to predict the behavior of RC beams externally bonded with CFRP sheets.

CONCLUSIONS

The following conclusions are drawn from the experimental program carried out in this investigation:

- Strengthening of RC beams with externally bonded CFRP sheets is effective and leads to increases in flexural strengthening between 30% to 60%.

- Premature failure in beams strengthened with CFRP sheets was observed, which was caused by concrete cover delamination. Two modes of failure within this failure were observed which were called Failure Mode I and Failure Mode II in this investigation.
- Beams strengthened with the same amount of CFRP in different bonded areas had similar behavior.
- The stirrups spacing did not have a remarkable influence in the concrete cover delamination failure.

ACKNOWLEDGMENTS

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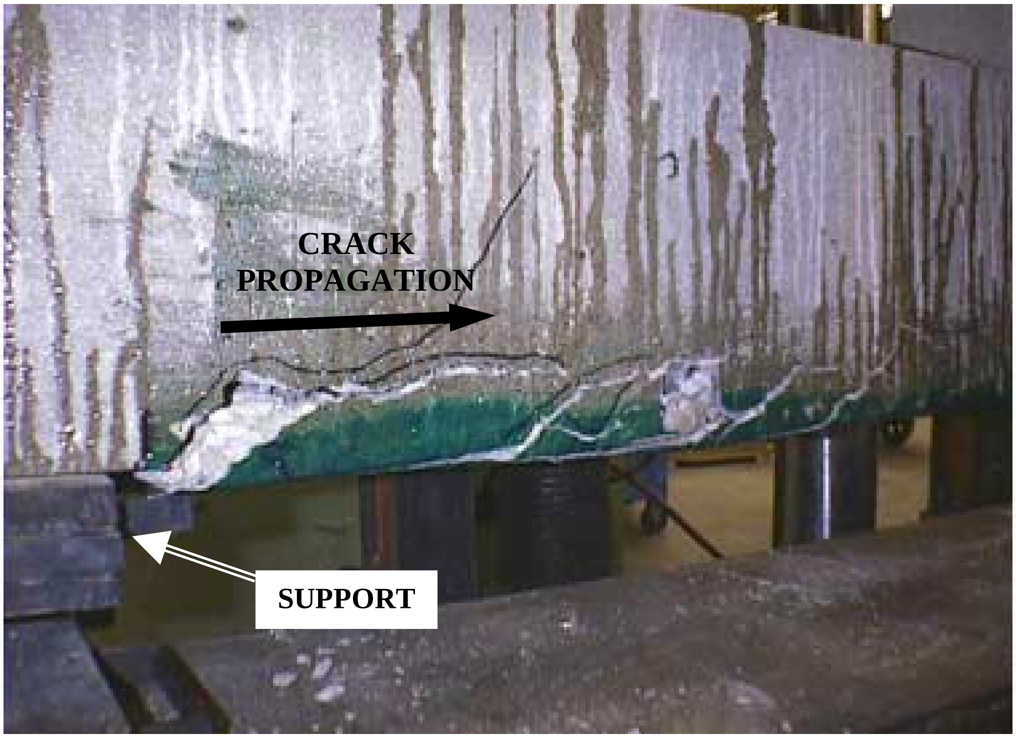

Figure 1. Concrete Cover Delamination – Failure Mode I (Beam A3)

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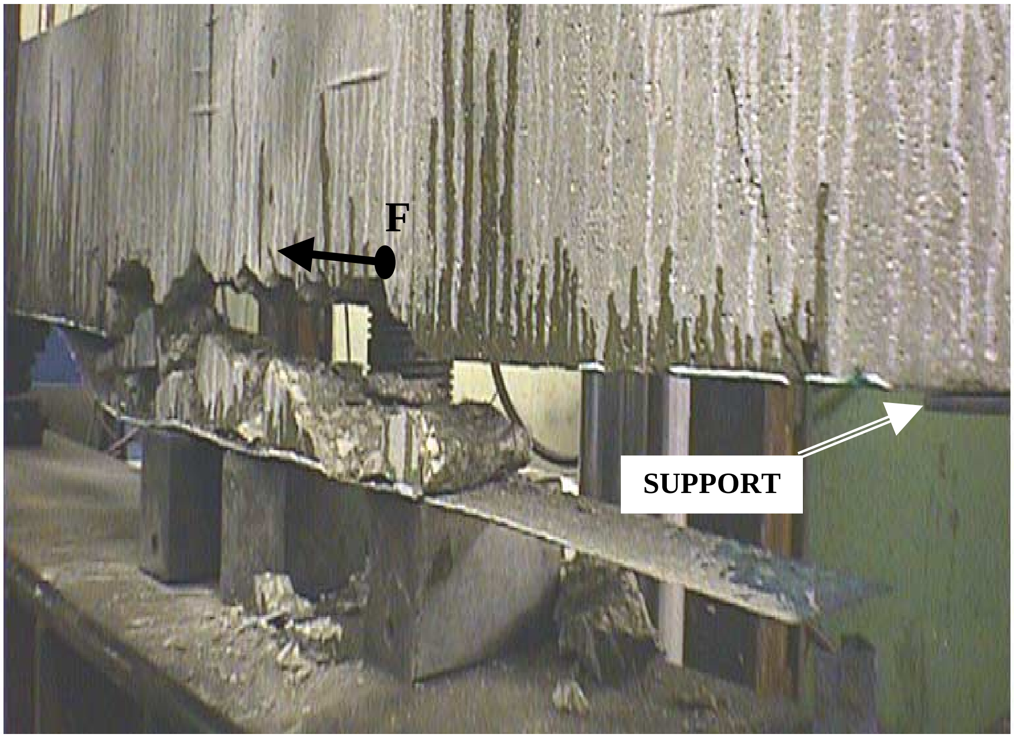

Figure 2. Concrete Cover Delamination – Failure Mode II (Beam A2)

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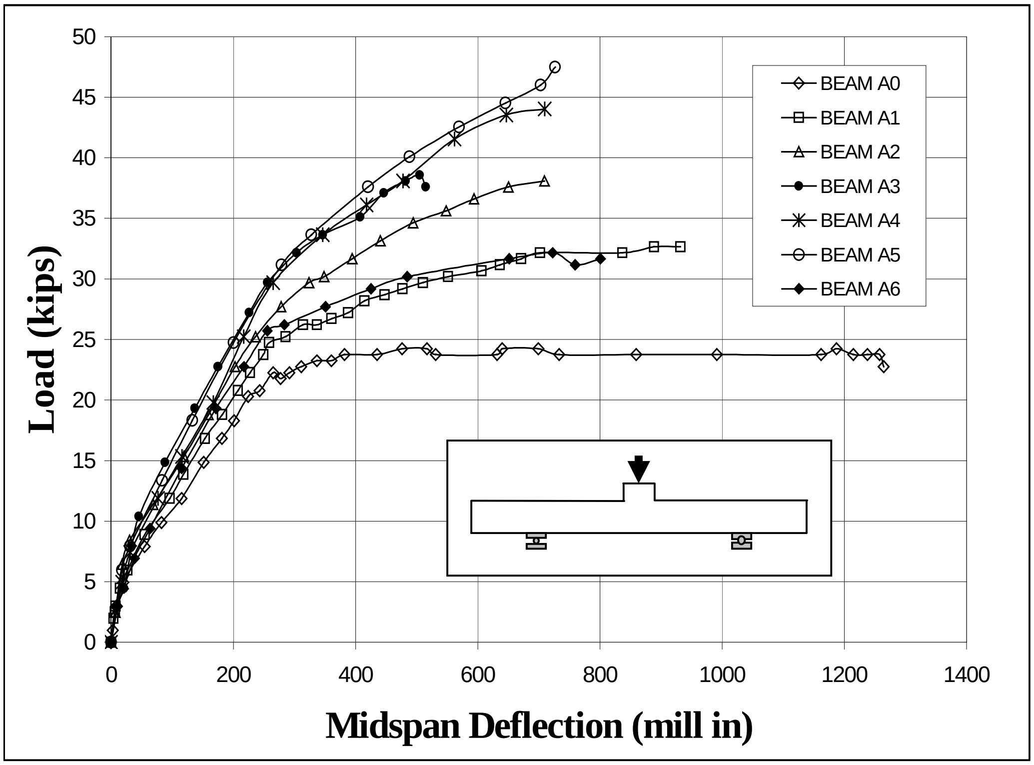

Figure 3. Experimental Load vs. Deflection Curves – Series A

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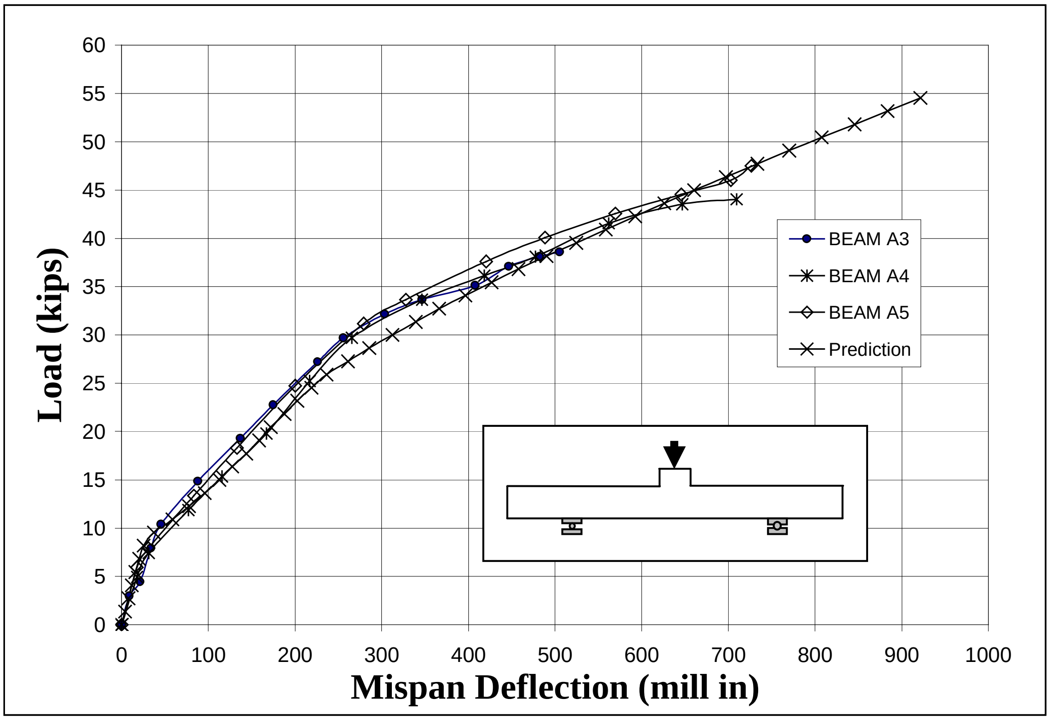

FIGURE 4. LOAD VS. DEFLECTION CURVES - EFFECT OF U-JACKETING

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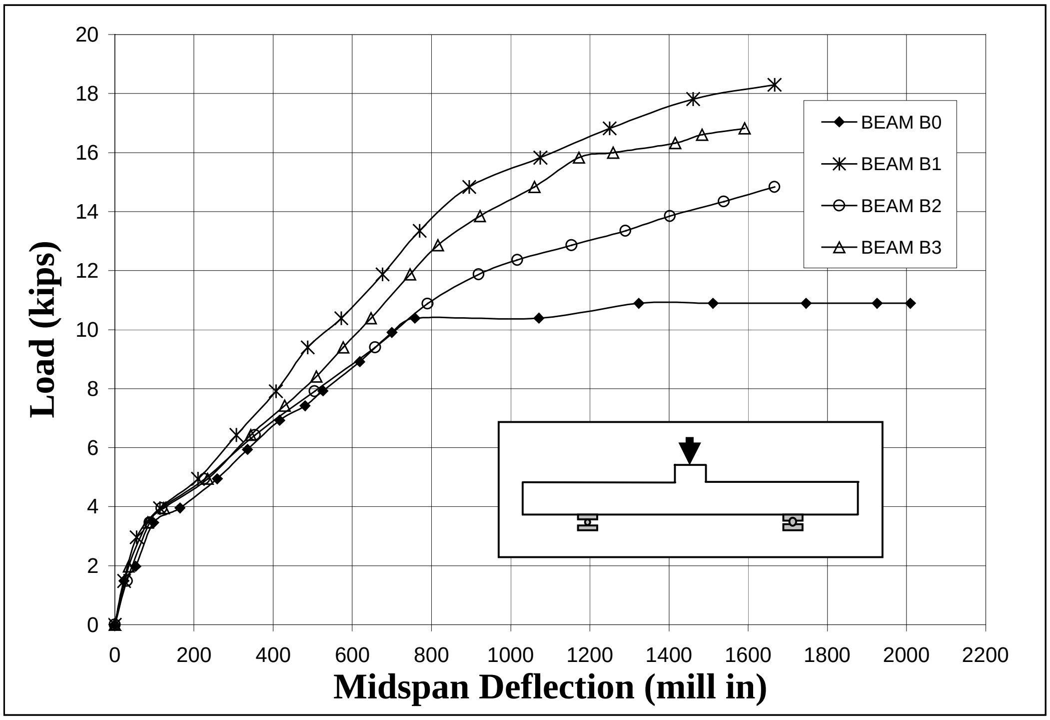

Figure 5. Experimental Load vs. Deflection Curves – Series B

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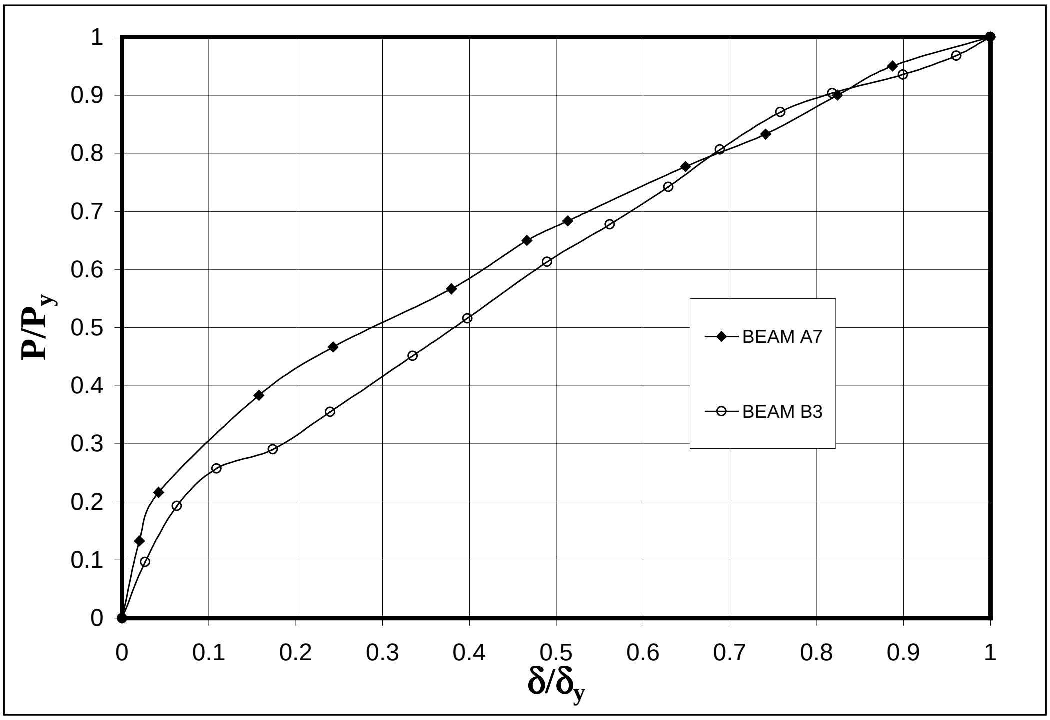

FIGURE 6. UP TO YIELDING NORMALIZED CURVE

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Table 1. Experimental Program and Tests Results Matrix

		width=6 in			width=3 in				
PLIES	0	1	2	3	1	2	6		
Span=7 ft	A0 (41.6,42.0,CC)	A1 (27.2,57.2,CD11)	A2 (66.7,77.4,CDII)	A3 (67.6,95.4,CDI)	A6 (55.4,48.0,CDII)	A7 (67.6,57.2,CD11)	A8 (77.1,95.4,CDI)	NW	SERIES A
				A4 (77.1,95.4,CDII)				PW	
				A5 (83.1,95.4,CD)				TW	
Span=13 ft	B0 (35.4,42.0,CC)	B1 (59.5,57.2,CC)			B2 (48.2,50.8,RUP)	B3 (54.7,57.2,CC)		NW	SERIES B
								PW	
								TW	
Span=7 ft	C0 (48.5,42.0,CC)	C1 (60.6,57.2,CDII)		C2 (62.3,95.4,CDI)				NW	SERIES C
								PW	
								TW	

Legend:
(Mu ft-kip, Mn ft-kip, Mode of Failure)
CC: Concrete Crushing
CDI: Concrete Cover Delamination – Failure Mode I
CDII: Concrete Cover Delamination – Failure Mode II
RUP: CFRP Rupture
NW: No wrapped
PW: Partially wrapped
TW: Totally wrapped
1ft-kip = 1.356 KN-m

Table 2. Flexural Stiffness and Ductility of Beams

BEAM	FLEXURAL STIFFNESS (kips-ft^2)	DUCTI LITY
A0	6174	4.3
A1	6946	3.4
A2	7117	2.1
A3	7889	1.9
A4	7860	2.2
A5	7902	2.6

1 kip-ft^2 = 0.413 KN-m^2

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