

Huang, P.C, J.J Myers and A. Nanni, "Dapped-End Strengthening in Precast Prestressed Concrete Double Tee Beams with FRP Composites," Proc., 3<sup>rd</sup> Inter. Conf. on Advanced Composite Materials in Bridges and Structures, Ottawa, Canada, J. Humar and A.G. Razaqpur, Editors, 15-18 Aug. 2000, pp. 545-552.

## **DAPPED-END STRENGTHENING OF PRECAST PRESTRESSED CONCRETE DOUBLE TEE BEAMS WITH FRP COMPOSITES**

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### **ABSTRACT**

The research program focused on precast prestressed concrete double tee members strengthened using FRP composites. Two different strengthening schemes were used and compared to attain a better understanding of the dapped-end behavior and the novel upgrading method of concrete reinforcement with externally bonded FRP composites. A 0°/90° wrapping technique was used. In order to attain fiber rupture rather than peeling, an end-anchor was added. It was demonstrated that the number of plies (stiffness) of FRP reinforcement and the application of an end anchor increased the ultimate capacity of the member. Ultimate failure by fiber rupture was achieved for the specimen that was strengthened.

## INTRODUCTION

In recent decades, precast prestressed concrete (PC) structures have become more and more prevalent in the construction industries. A precast concrete structure is composed of individual prefabricated members with different types of connections. The design of dapped-end connections is complex in a precast PC structure. The unusual shape of the dapped-end beam develops a severe stress concentration at the reentrant corner. Therefore, if suitable reinforcement is not provided close to the reentrant corner, a diagonal tension crack may propagate rapidly and failure may occur with little or no warning.

The use of FRP for reinforcement for concrete members has emerged as one of the most exciting and promising technologies in materials and structural engineering [1]. FRP composites consist of high strength fibers embedded in a polymeric resin. The fibers are the main load-carrying element and have a wide range of strengths and stiffnesses with a linear stress-strain relationship up to failure. Strengthening with externally bonded FRP reinforcement has been shown to be applicable to many types of concrete structures including the dapped-end studied herein.

The main objective of this study is to develop a method for strengthening the dapped-end using FRP materials thereby simplifying the manufacturing process or the repair of double tees. The variable under investigation was the design of the reinforcement for the dapped-end. Secondary objectives were:

- To investigate the contribution of FRP laminates to the strength capacity of the dapped-end.
- To investigate the possibility of replacing part of the mild steel reinforcement with FRP laminates.
- To develop new expressions to evaluate the strength of the dapped-end when FRP composites are used.

## EXPERIMENTAL PROGRAM

### Strengthening Strategies

Researches on the dapped-end design had verified the five potential failure modes (see Figure 1) proposed by PCI [2]. These failure modes are caused respectively by flexure and axial tension in the extended end, direct shear, diagonal tension at the reentrant corner, diagonal tension in the extended end, and diagonal tension in the undapped portion. Each of these potential failure modes should be investigated separately. Strengthening of the dapped-end using FRP laminates was based on the principles outlined in PCI provisions with modifications as necessary. Several parameters were modified due to the design need. The most common method of shear strengthening with FRP sheets is to wrap the sides and bottom of the section. This method referred to as a "U-wrap". The 0° wrap has fibers oriented along the longitudinal axis of the specimen; the 90° wrap has fibers oriented perpendicular to the longitudinal axis of the specimen. Figure 2 illustrates the FRP strengthening concepts in comparison with the traditional approaches.

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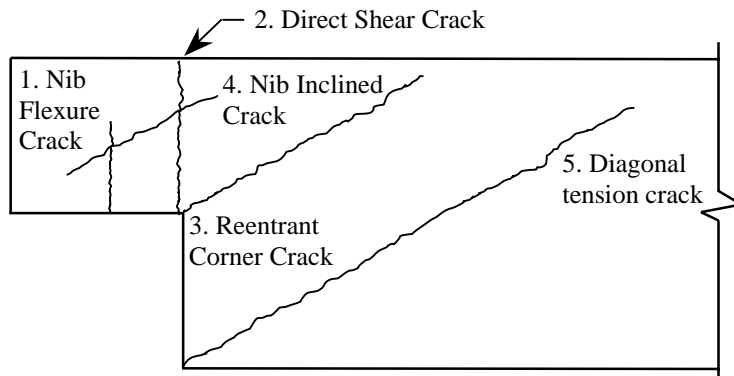


Figure 1: Five Failure Modes Proposed by PCI

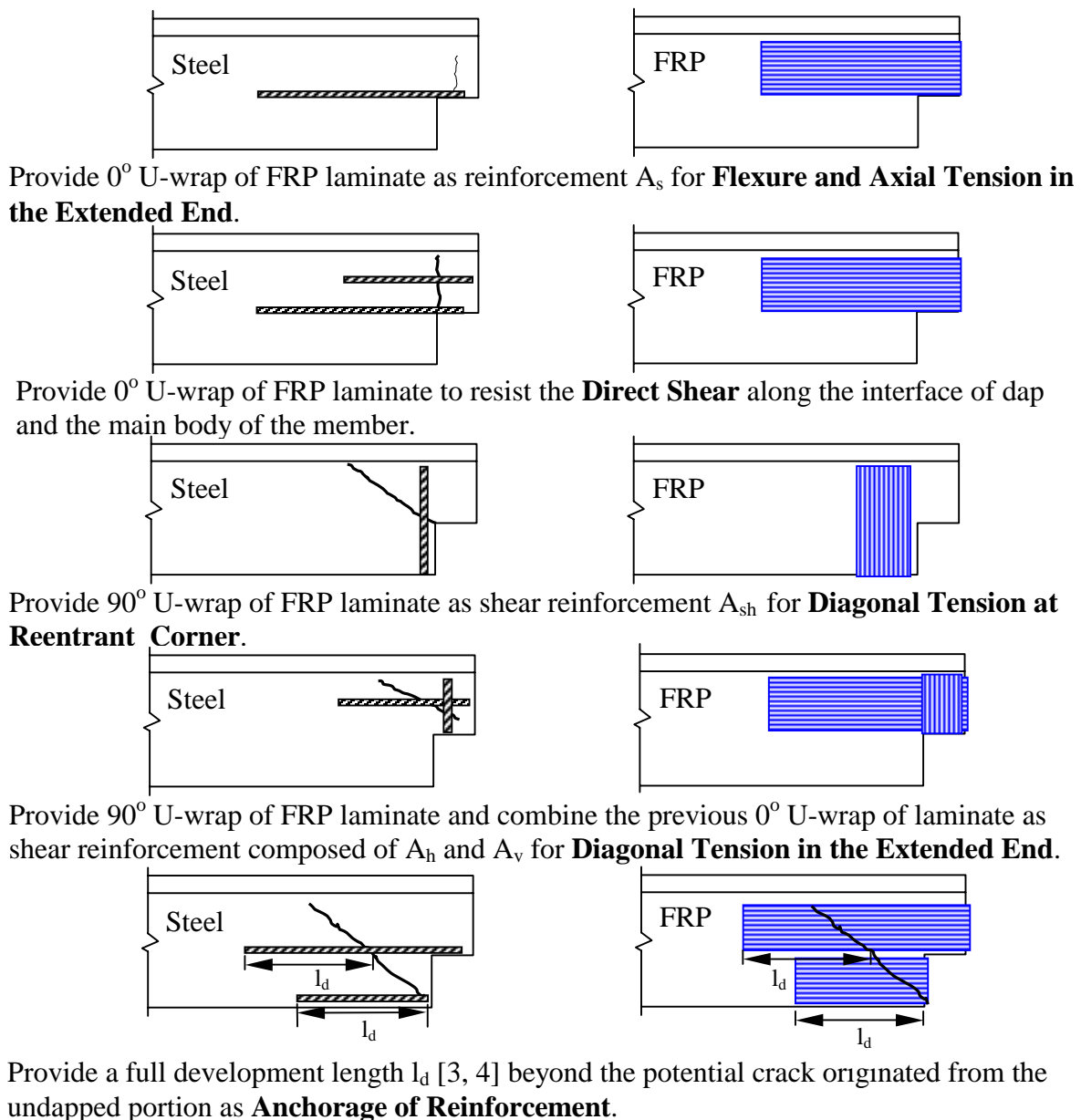


Figure 2: FRP Strengthening Strategies

### Test Specimens

In this experimental program, three PC concrete double tee beams having a nominal concrete strength of 6,000 psi were used. One dapped-end in each beam was constructed with the proper mild steel reinforcement, the other dapped-end did not contain any mild steel reinforcement. These dapped-ends were strengthened using externally bonded CFRP sheets with and without end anchors. The layouts of steel, one-ply, and two-ply FRP reinforcement are shown in Figure 3, 4, and 5. Figure 6 illustrates the example of the loading configuration and instrumentation of the two-ply FRP reinforced specimen.

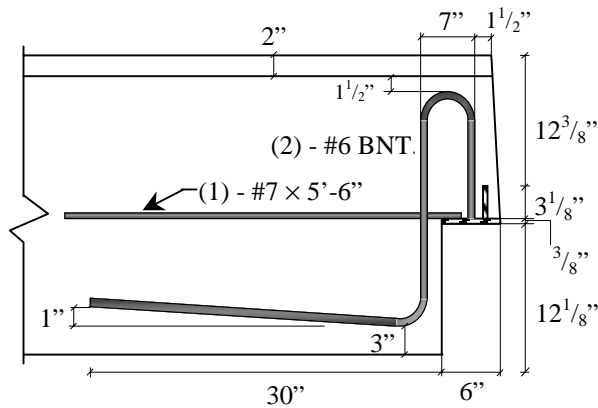


Figure 3: Layout of Steel Reinforcement

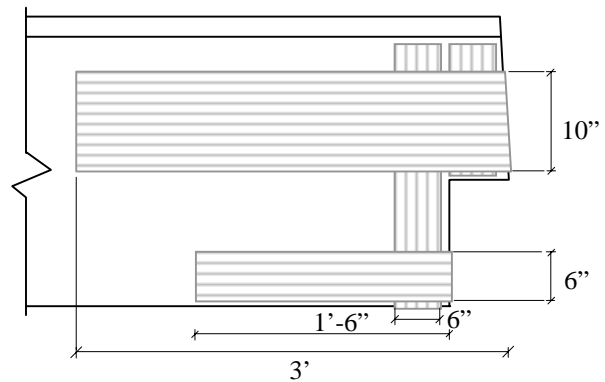


Figure 4: Layout of One-ply Reinforcement

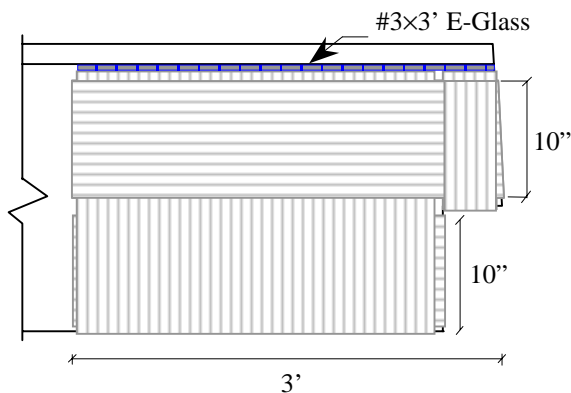


Figure 5: Layout of Two-ply FRP Reinforcement

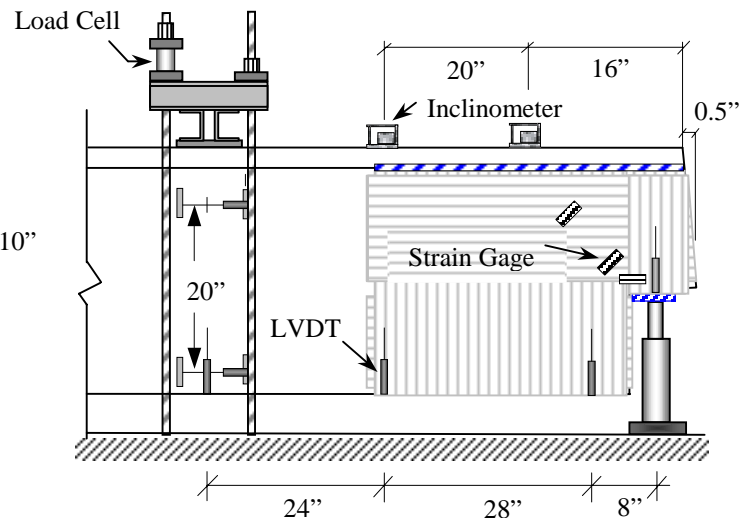


Figure 6: Example of Instrumentation

### End Anchor System

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An anchor system called U-anchor has been proposed and developed at University of Missouri–Rolla to improve the performance of surface mounted reinforcement for concrete/masonry made of fiber reinforced polymer (FRP) composites [5]. The U-anchor

prevents debonding of the reinforcement in applications where bond and/or development length of FRP is critical. The U-anchor is compatible with any external FRP strengthening system and may avoid high stress concentration and durability concerns comparing to traditional mechanical anchors made of steel plates and bolts. The anchor involves bending the end of FRP sheet into a preformed groove in the concrete flange at the corner, partially filling the cavity with epoxy paste, placing an FRP rod, and complete the filling of the cavity.

### **Test Procedure**

The test began with installing the instrumentation and loading equipment. Once the instruments were connected to the data acquisition system and the hydraulic cylinders were connected to the pump, a preliminary load cycle was ran. The preliminary load cycle applied a relatively small load (less than 5 kips) to insure that the equipment was functioning properly. After this preparatory work was completed, the load test commenced. The load test involved applying several load cycles. Each load cycle consisted of loading the structure in steps. A minimum of four approximately equal load steps were used to load the structure followed by at least two steps to unload the structure. Each load step was maintained for at least one minute. During this time the deflection of the beams was monitored for stability. Once the deflection began to increase with a constant load, the system has past the elastic threshold and the test was halted. The peak load for each successive cycle was gradually increased to approach the maximum test load. Two cycles using the maximum test load were applied to verify repeatability of the measurements. The actual load cycles may vary slightly depending on the performance of the system as monitored during the test.

## **TEST RESULT**

The three test specimens strengthened with FRP failed in shear at the reentrant corner. In all cases, the first crack appeared at the reentrant corner. This was either detected by visual observation of the concrete surface for steel reinforced specimens or by the reading of 45° strain gages mounted at the reentrant corner of the FRP reinforced specimens. A summary of the test results is presented in Table 1. A detailed description of the shear contribution for each component is presented by Huang, P. C. [6].

Figure 7 shows the load-net deflection diagram of the one-ply CFRP reinforced specimens and the companion control specimen. These curves illustrate the consistent relationship between applied load and deflection. The control specimen, steel reinforced specimen 1S-8, failed in shear-flexure at an ultimate load of 45.68 kips per stem rather than shear failure at the reentrant corner. FRP reinforced specimens, 1F-8 and 2F-8, failed in shear at reentrant corner at ultimate loads of 35.12 kips and 44.92 kips respectively. Both failures of FRP reinforced specimens were caused by the peeling of laminates at the reentrant corner. Specimen 1F-8 failed at a load 10 kips lower than that of specimen 2F-8.

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This was attributed to the insufficient saturant used in the CFRP laminates during impregnation. This result indicates that the peeling of laminate due to poor installation is of great concern. Figure 8 illustrates the load-net deflection diagram of one two-ply CFRP

reinforced specimen (3F-5) and its control specimen (3S-5). Although the loading span was shortened to 5-ft, specimen 3S-5 still failed in shear-flexure at an ultimate load of 57.4 kips per stem. For the FRP reinforced specimen 3F-5, using the U-anchor, the shear failure at reentrant corner was due to fiber rupture rather than peeling of the laminate as in previous tests. With two plies of CFRP reinforcement and anchor, the shear capacity improved to be 54.1 kips per stem at ultimate.

Table 1: Summary of Test Results

Code	Reinforcement	Loading Span (ft)	Theoretical				Experimental		
			V <sub>s</sub> (kip)	V <sub>f</sub> (kip)	V <sub>c</sub> (kip)	V <sub>n</sub> (kip)	V <sub>cr</sub> (kip)	V <sub>n</sub> (kip)	Failure Mode
1F-8	1 Ply CFRP	8	---	12.61	8.93	21.54	27.50	35.12	Peeling of Laminate
1S-8	Steel	8	52.80	---	14.60	67.40	28.22	45.68	Shear-Flexure
2F-8	1 Ply CFRP	8	---	12.61	8.93	21.54	28.00	44.92	Peeling of Laminate
3F-5	2 Plies CFRP	5	---	29.71	8.93	38.64	29.40	54.10	Fiber Rupture
3S-5	Steel	5	52.80	---	14.60	67.40	29.10	57.40	Shear-Flexure

Note: 1) V<sub>s</sub> = shear resisted by the vertical component of steel reinforcement A<sub>sh</sub>

V<sub>f</sub> = shear resisted by the vertical component of FRP reinforcement A<sub>sh</sub>

V<sub>c</sub> = shear resisted by the concrete

V<sub>cr</sub> = shear at first crack at the reentrant corner

V<sub>n</sub> = ultimate shear at failure at reentrant corner

2) No vertical component of prestress along each stem of tested specimens, therefore

V<sub>p</sub> = 0.

3) Theoretical V<sub>c</sub> is calculated using ACI Eq. (11-4) in Section 11.3 for member subject to axial compression

$$V_c = 2 \left[ 1 + \frac{N_u}{2000A_g} \right] \sqrt{f'_c} b_w d$$

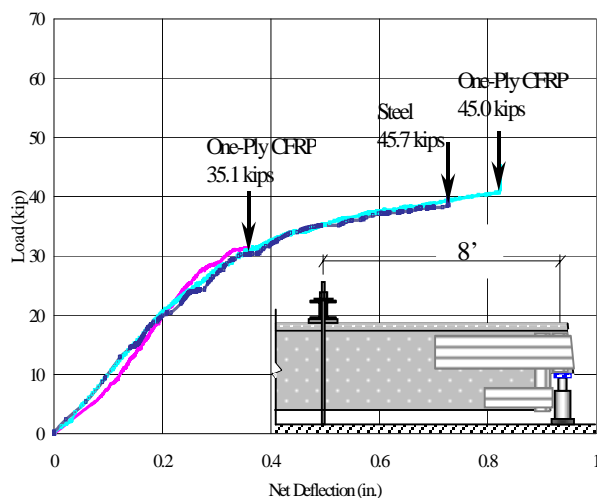


Figure 7: Load vs. Net Deflection of One-ply

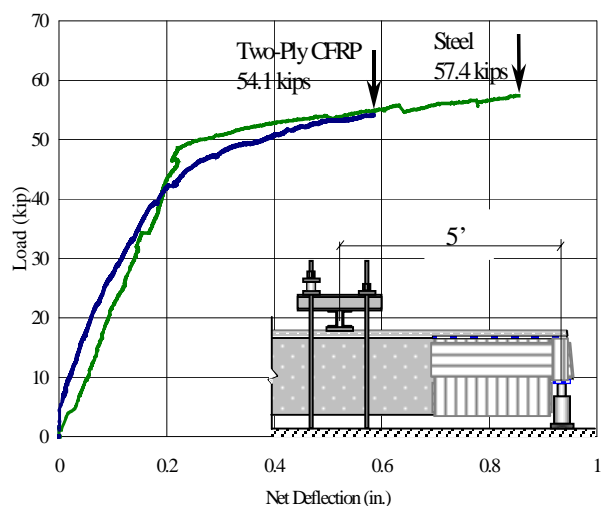


Figure 8: Load vs. Net Deflection of Two-

Figure 9 shows the strain data recorded from the strain gages at the reentrant corners of specimen 3F-5. A maximum strain in the FRP of approximately 7700  $\mu\epsilon$  was observed in gage #23. Most of the recorded strains were found to increase with load up to a certain point, beyond which they started to show an irregular behavior up to failure. Figure 10 shows the appearance of steel reinforced specimen and FRP reinforced specimen after failure.

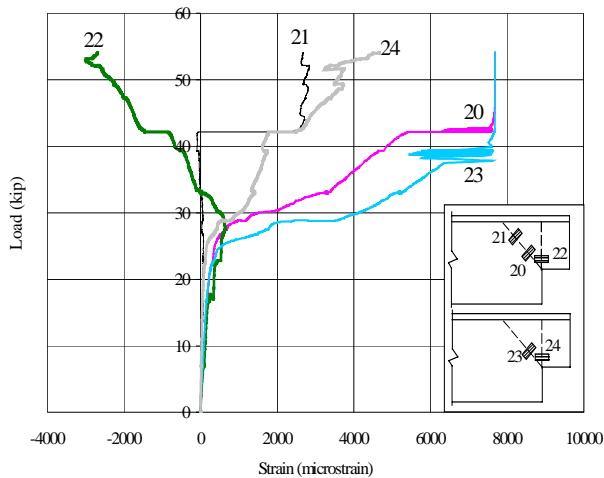


Figure 9: Load vs. Strain at the Reentrant Corner of Specimen 3F-5

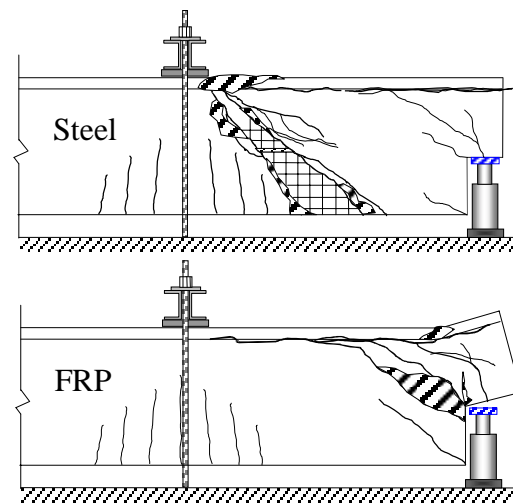


Figure 10: Appearance of Tested Specimens

## CONCLUSION

On the basis of the structural behavior of the specimens during the test and an evaluation of the test data, the following conclusions were drawn:

- Externally bonded FRP strengthening systems constitute a viable solution to retrofit/repair applications. This is due to the enhanced pseudo-ductility and strength provided by the reinforcement once the concrete has experienced cracking.
- Specimens with steel reinforcement failed in shear-flexure rather than shear at the reentrant corner. The dapped-end reinforcement designed according to the PCI Design Handbook was very conservative for the conventional members investigated.
- The application of U-anchor system to the externally bonded FRP laminates increased the ultimate capacity of a dapped-end and insured fiber rupture in lieu of peeling of the FRP sheets.

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- Strengthening of the dapped-end using externally bonded FRP laminates with the option of U-anchor may allow flexibility in the fabrication of prestressed double tee beam when ledger beam details may change.

### CONVERSION FACTORS

$$1 \text{ in.} = 25.4 \text{ mm}$$

$$1 \text{ kip} = 4.448 \text{ kN}$$

$$1 \text{ ksi} = 6.895 \text{ MPa} = 6.895 \text{ N} / \text{m}^2$$

### ACKNOWLEDGEMENT

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