Performance of Double-T Prestressed Concrete Beams Strengthened with Steel Reinforced Polymer

by P. Casadei, A. Nanni, T. Alkhrdaji, and J. Thomas

Synopsis: In the fall of 2002, a two story parking garage in Bloomington, Indiana, built with precast prestrestressed concrete (PC) double-T beams, was decommissioned due to a need for increased parking-space. This led to the opportunity of investigating the flexural performance of the PC double-T beams, upgraded in the positive moment region with steel reinforced polymer (SRP) composite materials, representing the first case study where this material has been applied in the field. SRP makes use of high-strength steel cords embedded in an epoxy resin. This paper reports on the test results to failure of three beams: a control specimen, a beam strengthened with one ply of SRP and a third beam strengthened with two plies of SRP anchored at both ends with SRP U-wraps. Results showed that SRP can significantly improve both flexural capacity and enhance pseudo-ductility.

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INTRODUCTION

The use of advanced composite materials in the construction industry is nowadays a mainstream technology[1], supported by design guidelines such as the ACI 440.2R-02 (ACI 440)[2] in the United States, the Fib-Bulletin 14 (2001)[3] in Europe and the recently published TR55 (2004)[4] in the United Kingdom. Fiber reinforced polymer (FRP) composite materials, even though very attractive, may be hindered by lack of ductility[5] and fire resistance[6]. Both issues are currently under study by the research community, in order to provide on one hand, better knowledge in terms of overall structural performance and, on the other, remedies such as coatings that could prolong fire resistance.

A new family of composite materials based on unidirectional high strength twisted steel wires (about 7 times stronger than typical common reinforcing bars) of fine diameter (*0.20~0.35 mm* (*0.0079~0.0138 in*) see Figure 1), that can be impregnated with thermo-set (referred to as steel reinforced polymer, SRP) or cementitious (referred to as steel reinforced grout, SRG) resin systems is presented in this work (Hardwire 2002)[7]. SRP/G has the potential to address the two shortcomings mentioned for FRP, indeed: a) steel cords have some inherent ductility; and b) impregnation with cementitious paste may overcome the problems of fire endurance and lowering down the application cost considerably.

The steel cords used in SRP are identical to those used for making the reinforcement of automotive tires, and manufactured to obtain the shape of the fabric tape prior to impregnation (Hardwire, 2002). The twisting of the wires allows some mechanical interlock between the cords and the matrix, and may also induce an overall ductile behavior upon stretching. The cords are also coated with either brass or zinc making the material potentially free of any corrosion and suitable for different kind of environmental exposure. Characterization work, including durability as well as bond related issues, is currently in progress as necessary for implementation in future design guidelines. Recent test results[8] showed that the material does not experience a substantial yielding, but rather a similar behavior to the one experienced by high-strength steel used in prestressed concrete (PC) construction, with a slight non-linear range prior to rupture of the cords (see Figure 2).

The opportunity for experimenting this new material in the field, became available in the winter of 2003 when the City of Bloomington, Indiana, decommissioned an existing parking garage near the downtown area, built with double-T PC beams. The concrete repair contractor, Structural Preservation Systems, Hanover, MD, strengthened in flexure the bottom stem of several double-T beams with epoxy-based SRP. This paper reports on the experimental results of tests to failure conducted on three beams: a control specimen, a beam strengthened with one ply of SRP and a third beam strengthened with two plies of SRP anchored at both ends with U-wraps.

EXPERIMENTAL PROGRAM

Building Characteristics

The parking garage used for the tests was a two story structure constructed in the 1980s (see Figure 3*a* and *b*). It consisted of a reinforced concrete (RC) frame, cast in place columns and precast reversed-T PC beams, supporting double-T PC beams, of span length varying from *4.66 m (15.3 ft)* to *13.41 m (44 ft)*.

Since no maintenance or construction records were available for the materials and the layout of the prestressing tendons, a field investigation was carried out. Based on the survey, it was determined that the double-T PC beams were of type *8DT32* (see Figure 3*c*) according to the Prestressed Concrete Institute (1999)[9] specifications with concrete topping of *76 mm (3in)*, and with an arrangement of the tendons different from current specifications. For the span of *4.66 m (15.3 ft)*, two straight 7-wire strands were found in each stem, each with a diameter of *12.7 mm (0.5 in)*, corresponding to an area of *112 mm²* *(0.174 in²)*, the first at *248 mm (9.75 in)* from the bottom of the stem and the second spaced *305 mm (1 ft)* from the first one. No mild reinforcement was found at any location. Welded pockets, connecting two adjacent beams, were positioned every *910 mm (3ft)* at a depth of *76 mm (3 in)* from top surface. Concrete properties were evaluated using three cores taken from three different beams at the location of the stem and an avarage concrete cylinder strength of $f_c'=34$ N/mm2 ($f_c'=5000$ psi) was found and its modulus of elasticity was determined according to ACI 318-02 Section 8.5.1[10] provisions.

The strands properties were assumed to be conventional *1861 MPa (270 ksi)* strength. Table 1 summarizes construction material properties.

Specimens and Installation of Steel Reinforced Polymer

A total of three double-T PC beams were tested (see Figure 4*a* and *b*): beam DT-C is the control beam, beam DT-1 represents the beam strengthened with one ply of SRP and DT-2U the one strengthened with 2 plies of SRP anchored with SRP U-wraps. Figure 4*c* illustrates the strengthening geometry details for beam DT-1 and DT-2U.

The epoxy resin for both strengthened beams was SikaDur Resin 330[11]. The choice of the resin was based on constructability so that it could be rolled onto the surface for overhead applications, while having enough consistency, even before curing, to be able to hold the weight of the steel tape during cure.

Table 2 reports the resin properties supplied by the manufacturer and verified by testing according to ASTM standards by Huang et al. 2004[8]. Figure 5*a* shows the mixing of the resin prior to installation.

The tape was medium density consisting of *6.3 cords per cm (12 WPI)*, with material properties defined in Table 3. The typical stress-strain diagram for an impregnated medium density tape, tested following the ASTM D 3039[12] recommendations, is reported in Figure 2 (properties based on steel net area).

SRP was installed following the recommendations of ACI 440[2] provisions for FRP materials. The sequence of installation steps is reported in Figure 5. The bottom stem of the double-T beams was first abrasive-blasted to ensure proper bond of the SRP system. With the surface roughened and cleaned, the first layer of epoxy was directly applied (see Figure 5*b*), without primer coating. The steel tape was cut to length of *4.57 m (15 ft)* and width of *102 mm (4 in)*, covering the bottom of the stem length and width entirely. A rib-roller was then utilized to press onto the tape to ensure epoxy impregnation and encapsulation of each cord and allow excess resin to squeeze out. The excess resin was spread with a putty-knife to create an even surface (see Figure 5*c*) and a synthetic scrim was applied to avoid any dripping of the resin (see Figure 5*d*). For the two ply application, once the first ply was in place and the excess resin leveled, the second ply was installed, following an identical procedure. This time the ply started *152 mm (6 in)* away from the terminations of the first ply, making it *4.27 m (14 ft)* long. To provide a mechanical ancorage for the two longitudinal plies, an SRP U-wrap *914 mm (3 ft)* wide was installed at both ends of the stems (see Figure 5*e*). Due to the stiffness of the steel tape, pre-forming is done with a standard sheet metal bender before installation. For this reason, the U-wrap was obtained by overlapping two L-shaped wraps. A final coat of epoxy resin was then applied on top of the U-wrap as final layer to impregnate the tape (see Figure 5*f*).

Test Setup and Instrumentation

The experimental setup is shown in Figure 6*a* and Figure 6*b*. The beams were tested under simply supported conditions and subject to a single concentrated load spread over both stems at mid-span, that is, 3-point bending at mid-span (see Figure 6*c*).

All three tests were conducted using a close-loop load configuration, where no external reaction is required. The load was applied in cycles by one hydraulic jack of *890 kN (200 kip)* capacity connected to a hand-pump. The load was transferred to the PC beam in two points through one spreader steel beam (see Figure 6*b*). The reverse-T PC-Ledger beams, on which the double-T beam rests, supplied the reaction. As the hydraulic jack extended, it pulled on the high-strength steel bars, which lifted the reaction bailey-truss below. The reaction truss was built with three bailey-truss frames *6.09 m (20 ft)* long assembled as per manufacturer's specifications (Mabey Bridge and Shore, Baltimore, MD) [13], and properly designed to carry the test load (see Figure 6*a*). Plywood was placed at each contact point to protect the concrete. The load was measured using a *890 kN (200 kip)* load cell placed on top of the jack (see Figure 6*c*). The preparation work consisted of drilling one hole of small diameter (*~50 mm (2 in)*) necessary for passing the high-strength steel bar through the flange of the double-T PC beam and isolating each test specimen from the adjacent beams originally joined by the welded-pockets.

An electronic data acquisition system recorded data from four linear variable differential transducers (LVDTs) and two electrical strain-gages applied to the SRP in beams DT-1 and DT-2U. Two LVDTs were placed at mid-span, and the remaining two LVDTs, were placed under the reverse-T ledger beams to verify potential support settlements. Strain gages were installed at mid-span on the bottom flange of the two strengthened double-T beams, directly onto the SRP material.

RESULTS AND DISCUSSION

All beams failed in flexure and had a similar behavior up to the cracking load. Beam DT-C failed due to fracture of the lowest tendon. In beam DT-1, since the SRP ply was not mechanically anchored, failure was dictated by peel off of the ply from each stem almost simultanuously. Beam DT-2U, strengthened with two anchored plies per stem, failed due to rupture of the lower tendon. Table 4 reports the test results.

In beam DT-C flexural cracks were concentrated in the mid-span region where the point load was applied (see Figure 7*a*). As soon as cracking occurred, since no mild reinforcement was present and tendons were placed far away from the bottom of the stem, cracks developed throughout the entire stem and deck (see Figure 7*b*). In beams DT-1 and DT-2U a similar behavior occurred with the difference that the presence of the SRP allowed the formation of additional flexural cracks. In beam DT-1 the SRP laminate started debonding at mid-span initiated by the widening of mid-span cracks (see Figure 7*c*) and then progressed towards the supports (see Figure 7*d*). Complete detachment of the laminate occurred at one end of the beam with part of the concrete substrate attached to the laminate, denoting a good interface bond between the concrete and the SRP (see Figure 8*a* and *b*). In beam DT-2, SRP could not completely peel off due to the presence of U-wraps. Delamination propagated from mid-span towards the supports similarly to Beam DT-1, until rupture of the lower tendon occurred (see Figure 7*e*) and immediately followed by SRP rupture exactly at the location where the SRP U-wrap started (see Figure 7*f*). No shear cracks were noted on any of the three beams.

Figure 9 shows the Load-vs-mid-pan Deflection curves for all three beams. The capacities of beams DT-1 and DT-2U increased approximately 12% and 26% with respect to the control specimen DT-C.

Figure 10 report the Load-vs-Mid-Span Strain responses for beams DT-1 and DT-2U. Two distinct phases, pre- and post-cracking, characterize the behavior of each specimen. Up to cracking there was practically no strain in the SRP. Past the cracking load, the presence of the SRP significantly affected performance.

Beam DT-C cracked at a considerably lower load (250.8 kN (56.4 kip)), with respect to the other two strengthened specimens. The occurrence of the first crack, at mid-span only, corresponds to the load drop in the Load-vs-Displacement plot. Upon unloading, the beam remained almost perfectly elastic, recovering almost all deflection. At the third loading cycle the lower strand suddenly fractured at a load of 344.3 kN (77.4 kip). For beams DT-1 and DT-2U the cracking load increased of approximately 23% and 17% with respect to DT-C. The lower cracking load for DT-2U may be explained by the fact that the beam had been previously repaired by means of epoxy injection.

Beam DT-1 reached the peak load of 387 kN (87 kip) and held it constant with increasing deflection, while SRP progressively delaminated from mid-span towards the support. The strain profile reported in Figure 10 shows how the SRP was not engaged until cracking occurred and as soon as the first crack opened at mid-span, the SRP bridged the crack and strain suddenly increased to approximately 5500 με (strain-gauge was placed at mid span where the first crack occurred). The maximum strain recorded in the steel tape (12300 με), prior to complete peel-off, shows how the material was well bonded to the concrete substrate. The ductility reported in the load-deflection curve, is the result of the slow peeling propagation rather than to the yielding of the reinforcing steel tape itself. Figure 2 shows in fact an almost elastic behavior till rupture of the SRP laminate.

Past the cracking load (see Figure 10), beam DT-2U behaved almost linearly, although with a lower stiffness, until it reached the load of 400 kN (90 kip) then, stiffness decreased significantly till the peak load was reached. When the load of 434 kN (97.6 kip) was reached, the lower tendon ruptured and a sudden drop in the load-deflection curve was recorded. The strain in the SRP material at time which the tendon ruptured was 6400 με. At this stage, once the lower tendon ruptured, the SRP laminate was completely debonded except for the region where anhoring was provided by the U-wraps. The test was continued untill suddenly the SRP laminate ruptured at 388 kN (87.2 kip). The strain recorded in the SRP laminate at failure was 12000 με, similarly the values attained in beam DT-1.

CONCLUSIONS

The following conclusions may be drawn from this experimental program:

- SRP composite materials have shown to be effective in increasing the flexural capacity of the double-T PC beams.

- End anchors in the form of SRP U-wraps have shown to be effective by preventing a complete detachment, once debonding has occurred throughout the concrete-SRP interface.

- SRP is similar to FRP in terms of ease of installation, although self weight should not be ignored when selecting the resin system in overhead applications.

- A good bond between the steel tape and the concrete substrate was achieved using epoxy resin.

FUTURE WORK

Since the completion of this test campaign, a bridge in Missouri has been strengthened with SRP materials as part of a joint MODOT – University of Missouri-Rolla (UMR) initiative[14] and studies[15] at UMR are underway to characterize the material and to properly calibrate the design factors.

ACKNOWLEDGMENTS

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Table 1 - Properties of Construction Materials

Material	Cylinder Compressive Strength, MPa (psi)	Yield Strength MPa (ksi)	Rupture Strength MPa (ksi)	Elastic modulus[2] MPa (ksi)	7 wire Tendon Cross Section, Ap mm² (in²)
Concrete [1]	34.4 (5,000)	-	-	27,600 (4,000)	-
Steel	-	1585 (230)	1862 (270)	200,000 (29,000)	112 (0.174)

[1] Average of 3 specimens [76.2 mm×152.4 mm (3 in×6 in) cylinders].

[2] $E_c = 4700\sqrt{f_c'}$ ACI 318-02 Section 8.5.1

Table 2 - Mechanical Properties of Epoxy Resin

Matrix	Tensile Strength, MPa (psi)	Ultimate Rupture Strain ε_{fu}^* (%)	Tensile Modulus of Elasticity, MPa (ksi)
SikaDur 330[1]	30 (4350)	1.5	3800 (551)

[1] Values provided by the manufacturer (Sika, 2002)

Table 3 - Material Properties of Steel Tape[8]

Cord Coating	Cord Area per 12 Wires, mm² (in²)	Cords per cm (in)	Nominal Thickness[1], t_{SRP} mm (in)	Tensile Strength f_{fu_SRP}, MPa (ksi)	Ultimate Rupture Strain ε_{fu_SRP} (mm/mm)	Tensile Modulus of Elasticity, GPa (ksi)
Brass	0.396 (0.000615)	3.7 (9.5)	0.148 (0.0058)	3070 (447)	0.0167	184 (26700)

[2] The nominal thickness has been computed assuming the area of each cord and counting the number of cords in each ply, reported in *cords per cm*

Table 4 – Beam Test Results

Beam	Failure load kN (kip)	Load Capacity Increase	SRP Strain at Failure ε_{SRP}	Failure Mode
DT-C	344 (77.4)	1	-	Rupture of Lower Tendon
DT-1	387 (87)	1.12	0.0123	SRP Delamination
DT-2U	434 (97.6)	1.26	0.0064	Rupture of Lower Tendon

a) **Front view of Tape with Cords Held Together by a Polyester Scrim**   *b)* **Back view of Tape with detail of Polyester Scrim**

c) **Steel Cord with Wires Wrapped by One Wire**
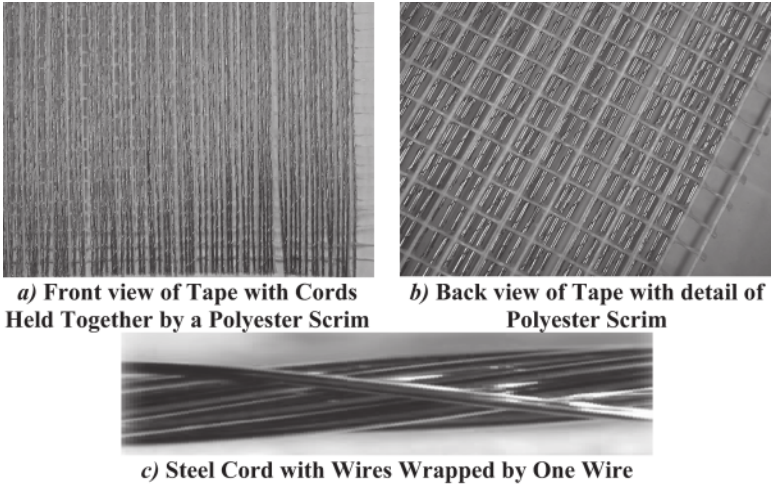
Figure 1 – Example of 12X Steel Cord and Medium Density Tape
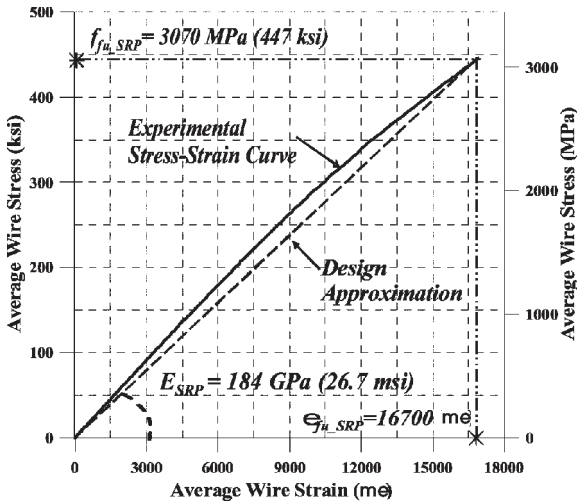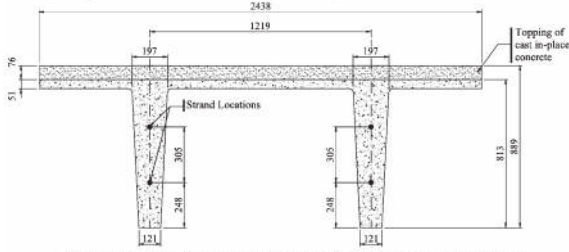

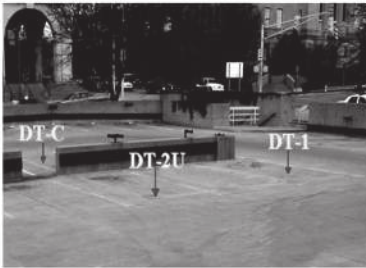Figure 2 – SRP Laminate Stress vs Strain Behavior

a) Top View of the Deck   b) Bottom View of the Deck

c) Cross Sextion Geometry Details (*SI units 1 mm = 0.039 in*)
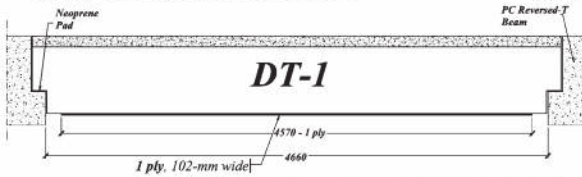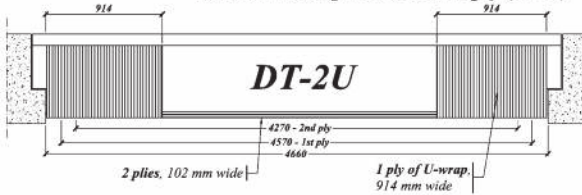
Figure 3 – Bloomington Parking Garage

a) Saw-Cut Marks on Top of Deck   b) Plan View
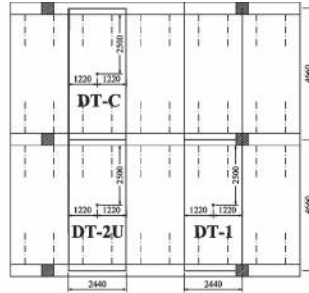
c) Beam Strengthened with 1 ply (DT-1)

d) Beam Strengthened with 2 plies + U-wrap (DT-2U)
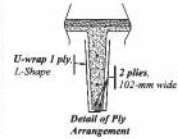
Figure 4 – Test Beams (*SI units 1 mm = 0.039 in.*)

a) Mixing of the Epoxy Resin b) Application of Longitudinal Ply

c) Squeezing Out the Resin Excess d) Application of Scrim on Longitudinal Ply

e) Application of U-Wraps f) Application of Epoxy on U-Wrap

Figure 5 – SRP Installation Procedure

a) Bottom View

b) Top View
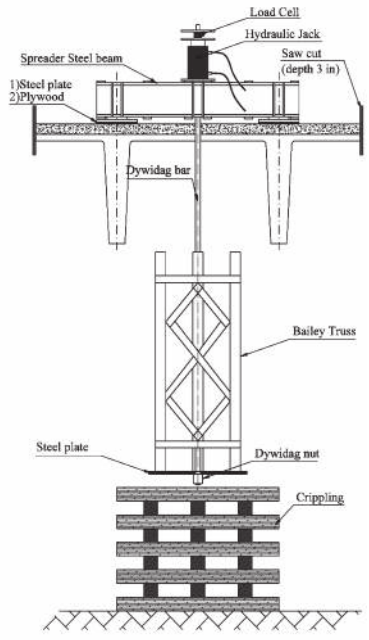
c) Cross Section at Mid-Span

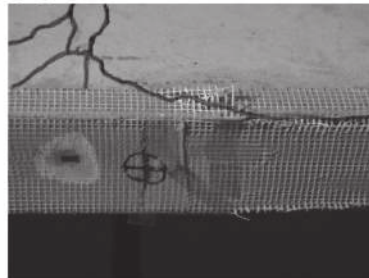Figure 6 – Test Set Up

a) Initial Crack Propagation

b) Crack Propagation Through the Deck
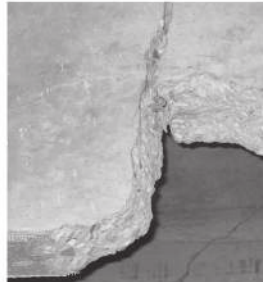
Beam DT-C

c) Crack Propagation Prior to Complete Peeling

d) Debonding Propagation from Mid-Span

Beam DT-1

e) SRP Rupture

f) Rupture of the Lower Tendon

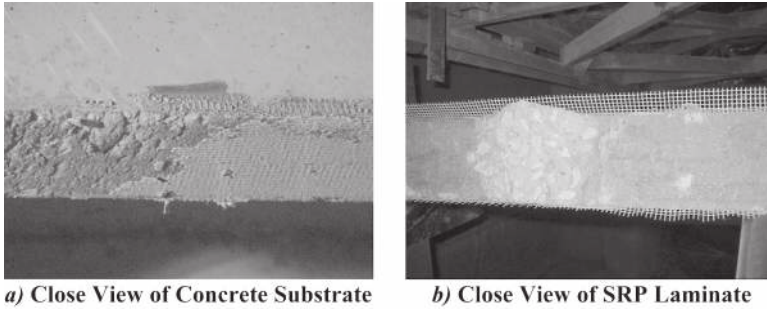Beam DT-2U

Figure 7 – Failure Mechanisms in the Three Beams

a) Close View of Concrete Substrate   b) Close View of SRP Laminate

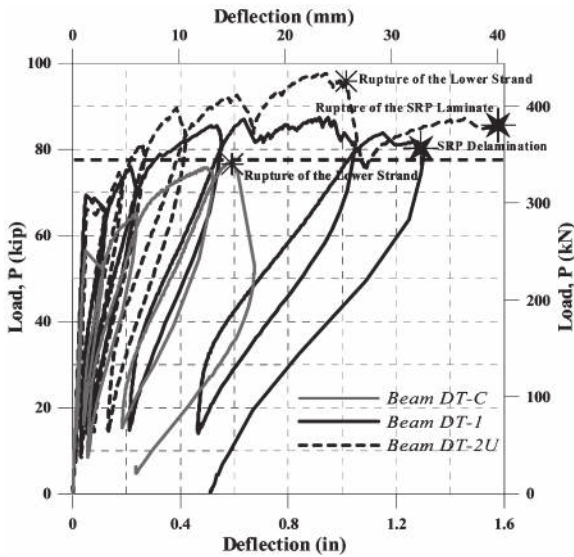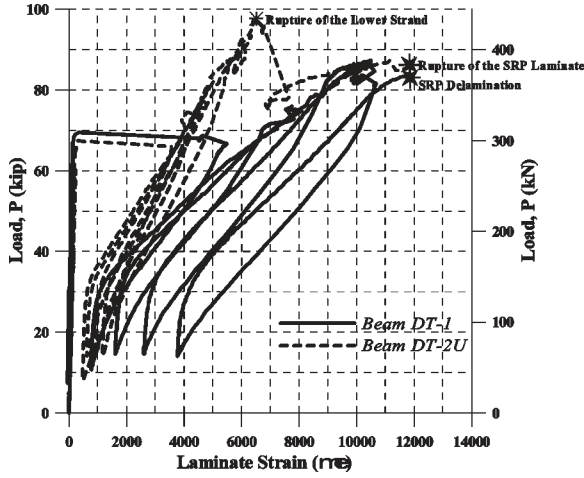Figure 8 – Concrete and SRP Laminate Condition After Debonding Has Occurred

Figure 9 – Load vs Mid-Span Deflection

Figure 10 – Load vs Mid-Span Strain