TORSIONAL STRENGTHENING OF SPANDREL BEAMS WITH COMPOSITE LAMINATES

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Abstract

The present paper describes the experimental and analytical findings of a project focused on the structural strengthening of reinforced concrete (RC) spandrel beams using carbon fiber reinforced polymer (CFRP) composite laminates, and subjected to pure torsion. Current torsional strengthening and repair methods are time and resource intensive, and quite often very intrusive. The proposed method however, uses composite laminates to increase the torsional capacity of concrete beams.

Six identical spandrel beams were built and tested. Two of the beams were considered as baseline specimens, the remaining four were strengthened using three different composite laminates. In order to eliminate the flexural and shear forces on the beam, a close to pure twisting force was applied at the end of the beam specimen. In traditional cast-in-place construction the slab adjacent to the spandrel beam does not allow a complete wrap around the beam. To simulate this, the CFRP laminate was provided only on three sides of the beam, and special anchors were used to allow a continuous torsional shear flow around the specimens. The experiments showed that this method increased the torsional strength of the spandrel beams up to 113%. Excessive concrete cracking followed by composite delamination caused the specimen failure. An equation was also developed which, for most of the specimens, accurately predicted the composite contribution. This analytical procedure was based on the existing information on the torsional resistance provided by closed stirrups, and on the equations developed to design the composite shear retrofit of RC beams.

Introduction

Spandrel beams located at the perimeter of buildings carry loads from slabs, joists and beams from one side of the member only. This loading mechanism generates torsional forces that are transferred from the spandrel beams to the columns. Many existing reinforced concrete (RC) beams have been found to be deficient in torsional shear capacity and in need of strengthening. In current practice, torsional strengthening of concrete members is achieved by one of the following methods: by increasing the member cross-sectional area combined with adding of transverse reinforcement; by using surface bonded steel plates and pressure grouting the gap between plate and concrete element; or by applying an axial load to the member by post-tensioning. Although these methods will continue to be used in many more instances, carbon fiber reinforced polymer (CFRP) composites provide another option for strengthening. The present study verifies their effectiveness in increasing the torsional capacity of RC spandrel beams using FRP composites.

Even though the present project is unique in addressing torsional strengthening using FRP materials, there is ample information on the torsional behavior of RC members. A recent study by Koutchoukali and Belarbi (2001) addresses the torsional capacity of high-strength reinforced concrete beams. A new expression for minimum torsional reinforcement was developed based on the assumption that a 20% reserve of strength after cracking is necessary to avoid brittle failure.

Y. L. Mo et al. (2000) focused on the torsional behavior of prestressed box bridge girders with corrugated steel webs. Four reduced–scale specimens were subjected to reverse cycling torsion and the results compared with a truss model theory for pre-stressed concrete members which was developed by Belarby and Hsu (1991) and by Vecchio and Collins (1993). The analytical results on the torque-twist curves were similar to the experimental results.

A study conducted by Cochi et al. (1996) on the inelastic analysis of RC beams subjected to combined torsion, biaxial bending, and axial loads was based on an extension of the diagonal compression field theory. It was presumed that when concrete cracks are formed by torsion, the RC member becomes a hollow section with varying wall thickness, and may be discretized into a system of wall elements. A study was performed by Di Franco et al. (1995) on the role of spandrel beams on the response of slab-beam-column connections. Full-scale exterior beam-column-slab sub-assemblages were tested under reversed cyclic loading to investigate the role of the spandrel beam in the overall response.

Objectives and Scope

In order to investigate the torsional behavior of FRP strengthened RC spandrel beams, six identical beams were designed, built and tested. The results from the two, unretrofitted baseline specimens were compared with the four composite retrofitted samples, addressing the following factors: the amount, combination, and fiber orientation of the carbon FRP laminates, and the effects of composite anchors. An analytical procedure was developed to predict the increase in torsional strength provided by the composite laminates for a greater number of combinations of factors.

The spandrel beam specimens were manufactured following the current design guidelines outlined in the ACI 318-99 (1999) code. Each specimen was mounted in the loading frame in such a way that a fixed end and a torsional pinned end were simulated. A pure torque applied at a 1219 mm distance from the pinned end generated a torsional stress on the beam. The pinned end condition eliminated bending moment and shear forces from the beam. In order to create a torsional deficiency, the specimens were built with insufficient transverse torsional reinforcement. The specimens were tested with a gradually increased half-cycle load (load in one direction only), with each load step applied three times.

Specimen Preparation and Test Setup

Six identical reinforced concrete spandrel beams were built. The beams were 2438 mm long with an L–shaped cross-section. The (102 mm x 203 mm) flange represented a section of the floor slab at the perimeter of a R/C diaphragm. The specimens were reinforced with 6 - 16 mm and 2 - 13 mm diameter longitudinal bars located around the perimeter of the beam. Stirrups of 13 mm diameter were spaced 152 mm on center throughout the beam length. Additional 13 mm hooks were placed in the beam flange, and represented the negative reinforcement from the connecting slab. The compressive strength of the concrete was 55 MPa, and the yield strength of the reinforcing steel was 414 MPa in all specimens.

Out of the six specimens, two were not retrofitted with CFRP and served as baseline specimens. Four were retrofitted with a carbon fiber reinforced polymer (CFRP) composite laminate along the length of the beam and around the cross section, excluding the lateral face of the 102 mm flange. In order to simulate the presence of a slab in that location, the FRP was discontinued in this area.

In order to ensure good bonding of the composite materials to the reinforced concrete, the samples were cleaned by a 21 MPa water pressure and allowed to dry prior to composite application.

This procedure removed loose particles and contaminations from the specimen surface. Furthermore, just before composite application, the beams were wire brushed and vacuumed. The specimens were then primed, and a thin layer of adhesive was applied to the entire bond area, creating a smooth surface and a good bond between the concrete specimen and the CFRP laminates. Meanwhile, the unidirectional carbon fabric was saturated with a two-component laminating epoxy. The saturated fabric was then placed on the surface of the beam, and with the use of a plastic tool, the air bubbles and the excess resin were removed.

Specimen TB2 was strengthened with a [0/90] laminate, where the 90°-lamina was placed perpendicular to the longitudinal axis of the RC spandrel beam. No anchors were used for this specimen. The 0°-lamina was applied to delay diagonal cracking, and functioned similarly to the longitudinal torsional bars. The 90^{o}-lamina provided additional torsional strength to the specimen, and performed similarly to the stirrups in an RC spandrel beam.

Specimen TB3 was strengthened with a [±45] laminate and utilized a special laminate anchoring system. A 51 mm x 51 mm x 5 mm steel angle was used as the inside support for 6 mm diameter stainless steel anchor bolts along the longitudinal axis at the beam at 305 mm on center. A 51 mm x 5 mm steel plate was placed at the bottom of the beam, and connected to the angle by the bolts which passed through the beam (see Figure 1). This arrangement provided a good anchoring for the laminate, and delayed a composite delamination initiated by tensile forces present in the inside corner of the spandrel beam. For simplicity, steel angles and plates were used in this project. However, in a real retrofit project stainless steel shapes would be used to prevent steel corrosion.

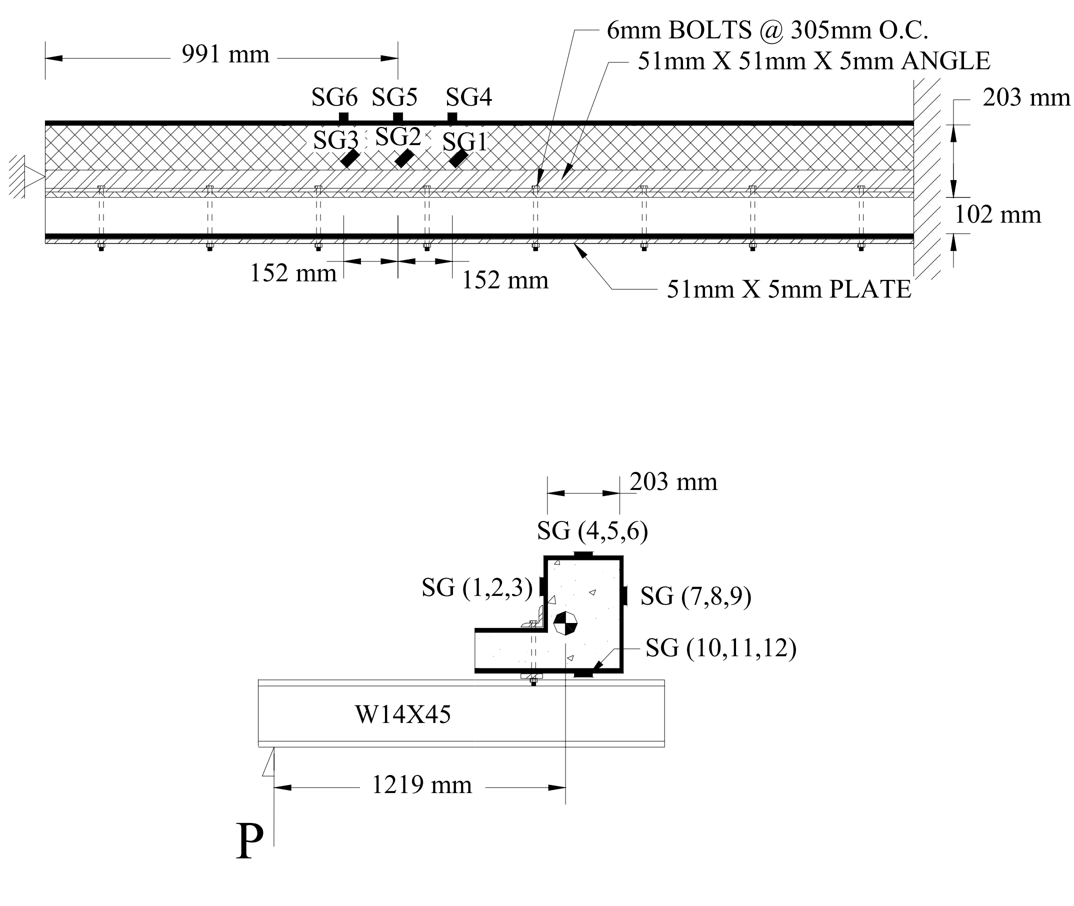

Figure 1. FRP Strengthened Specimen Detail

Specimen TB4 was strengthened in a way similar to specimen TB2, but TB4 used the anchoring system described for TB3. Specimen TB5 was strengthened only by one sheet of composite lamina placed perpendicular to the beam longitudinal axis (i.e. [90] lamina), and anchored similarly to specimens TB3 and TB4.

Test Setup and Instrumentation

Several instruments were used to monitor the behavior of the RC beams. These instruments recorded the strain in the rebars and in the composite, the specimen displacement at three different locations of the cross section, and the hydraulic pressure acting on the beam. The rotation of the specimen was calculated based on the readings from displacement transducers. In addition, to provide backup data, a load cell recorded the force during the test. Figure 1 shows the position of the strain gages on the FRP laminate and a cross section of specimen TB3.

The beams were subjected to a half-cyclic loading at predetermined increments. This loading consisted of a pushing force, followed by a passive unloading governed only by the weight of the steel beam connected to the piston, and by the resistance of the concrete beam. The only exception to this loading pattern was for specimen TB1, for which the force was monotonically applied in one direction until failure and then reversed in the other direction. This was done to monitor the specimen behavior for a pushover analysis.

EXPERIMENTAL RESULTS

Baseline Specimens

Specimen TB1 reached a maximum torque of 20.3 kN-m and a maximum rotation of 0.125 radians (or 7.2^0). As mentioned before, this was the only specimen in the experimental project that was subjected only to an increasing pushing force until failure. At the end of the monotonic load, the load was reversed, and a 6.8 kN-m torque was reached. Failure was determined at the point where the specimen lost its capacity to carry more load in that loading direction. At 20.3 kN-m the strain in the steel reinforcement reached 0.24%, clearly indicating a plastic behavior.

Specimen TB6 reached a maximum torque of 24.4 kN-m at an angle of 0.059 radians, or 3.4^0. Again, failure was determined as the point where the torque could not be sustained by the sample, and was caused by forming extensive cracks at 45^0 along the longitudinal length of the beam (see Figure 2). One of the strain gages on a stirrup recorded a maximum strain of 0.28%, therefore, the torsional reinforcement yielded.

The two baseline specimens supported an average maximum torque of 22.3 kN-m, and an average maximum rotation of 0.092 radians at an average maximum rebar strain of 0.26%.

Retrofitted Specimens

The testing procedure for the CFRP retrofitted beams was identical to the baseline test for specimen TB6 (specimen TB1 included a load reversal). In addition to the instruments on the steel reinforcement, strain gages were also attached to the FRP laminate around the perimeter of the cross section and were oriented in the fiber direction of the outside lamina.

Figure 2. Baseline Specimen (TB6) Failure Mode

Specimen TB2 with the [0/90] composite laminate (no anchors) reached a maximum torque of 32.5 kN-m with a rotation of 0.16 radians. Failure occurred close to the fixed end of the sample due to an extensive torsional crack, which was followed by composite delamination (see Figure 3). The peak composite tensile strain was 0.15%, well bellow the composite ultimate strain of 1.30%. It is important to note that the stress values in the CFRP were negligible up to the load level corresponding to the formation of the first cracks for the baseline specimens. This result proves that the retrofit material begins working only after sufficient cracking occurred in the member.

Specimen TB3 with the [±45] anchored composite laminate reached a maximum torque of 43.4 kN-m at an angle of 0.11 radians (see Figure 4). The failure mode was very similar to the specimen TB2. The peak tensile strain in the FRP was 0.31% (this is a relative value, measured from the peak to the "at rest" value). It is important to note how quickly the CFRP was engaged as the test progressed. This quick involvement was due to the ±45° orientation of the laminate, which matched the direction of the principal stresses with respect to the beam longitudinal axis.

Specimen TB4 with the [0/90] anchored composite laminate reached a maximum torque of 35.3 kN-m at an angle of 0.14 radians. And finally, specimen TB5 with a [90] anchored composite lamina reached a maximum torque of 33.9 kN-m at a rotational angle of 0.12 radians. After hairline cracks developed in the beam, a general composite delamination occurred, followed by extensive concrete cracking.

Summary of Experimental Results

As it can be seen, the composite strengthened beams reached significantly higher torsional resistance. As expected, the [±45] laminate was the most effective, followed by the [0/90] laminates with anchors, and finally, the [90] laminate had the least effect on the results. By using anchors, the torsional resistance of the beams was increased by 13% (TB2 vs. TB4), and less damage to the specimen was observed. The contribution of the 0° lamina on TB2 and TB4 was significant in keeping the width of the cracks small, and provided a higher stiffness to the spandrel beam specimen.

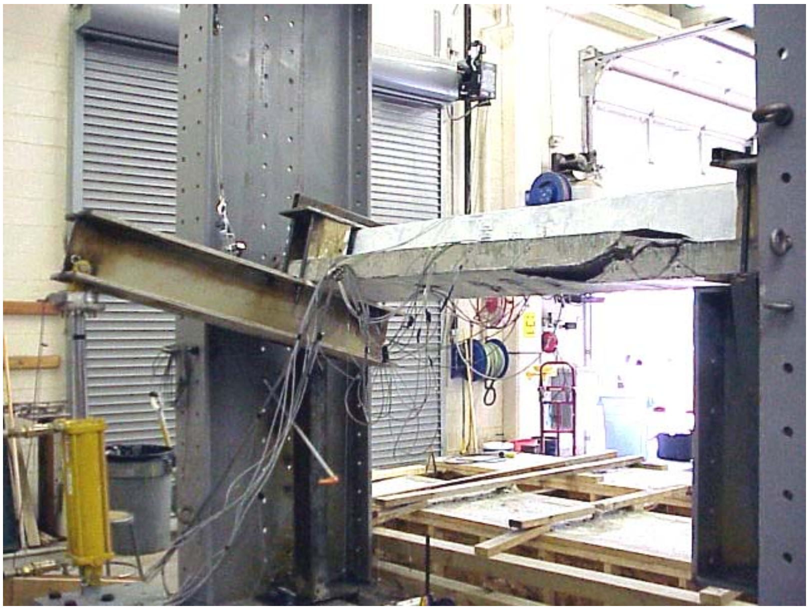

Figure 3. Strengthened Specimen (TB2) Failure Mode

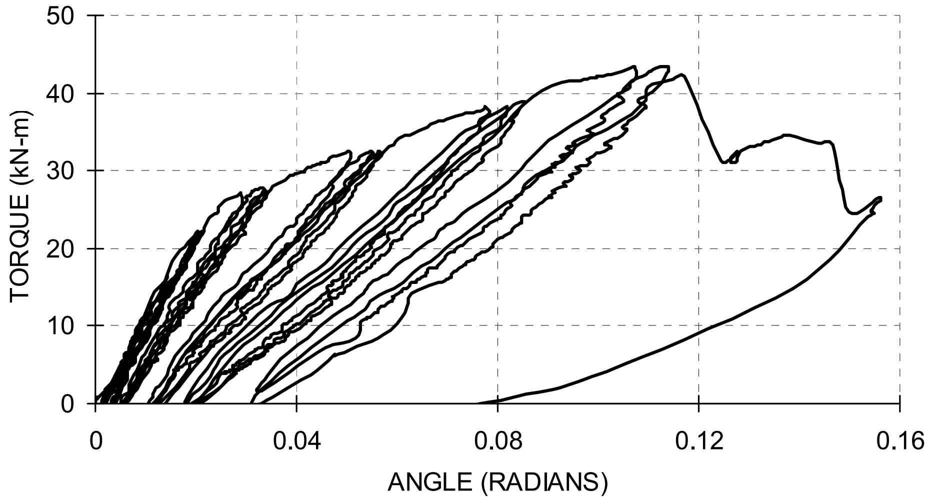

Figure 4. Specimen TB3 – Torque vs. Angle of Rotation

Analytical Results

In this paper it was assumed that the composite laminates around the perimeter of the beam behave similarly to the closed stirrups, where the stainless steel anchors provided the closing leg on the fourth side. By combining the equation used to design the steel torsional reinforcement (from ACI 318-99) with the formula currently used to estimate the shear capacity of FRP jackets applied to concrete members (ACI 440, 2001), Equation (1) was developed to obtain the torsional contribution from the CFRP laminate.

$$T_f = \frac{2A_o A_f f_{fe}}{s}(\cos\alpha + \sin\alpha) \tag{1}$$

where $T_f =$ torsional strength provided by CFRP laminate (kN-m); $A_o =$ gross area enclosed by shear flow path (m^2); $A_f = nw_f t_f$ area of composite laminate (m^2); $n =$ number of composite plies; $w_f =$ width of the composite laminate (m); $t_f =$ thickness of one composite ply (m); $A_o =$ area enclosed by CFRP transverse torsional reinforcement (m^2); $f_{fe} = \varepsilon_{fe}E_f$ effective composite stress (kPa); $\varepsilon_{fe} =$ effective composite strain (m/m) (the absolute value was used); $E_f =$ composite modulus of elasticity (kPa); $\alpha =$ angle between fiber orientation and beam longitudinal axis (degrees); $s =$ spacing of composite laminates along the beam longitudinal axis (m).

Using the following CFRP material properties: $t_f = 0.00058$ m/layer, $E_f = 103{,}862{,}000$ kPa, $\varepsilon_{fe} = 0.15\%$, and the specimen dimensions, the torsional resistance provided by the composite laminates for specimen TB2 (with a [0/90] anchored laminate) can be calculated as follows:

$$T_f = \frac{2(0.203 \times 0.305)(1 \times 1.0 \times 0.00058)(0.0015 \times 103{,}862{,}000)}{1.000}(\cos 90 + \sin 90) = 11.2\ \text{kN-m} \tag{2}$$

This value compares well with the experimental result of 12.2 kN-m (obtained by comparing the results from specimen TB1 and TB2). Table 1 compares the analytical and the experimental results for both series. In general, except for specimen TB5, the experimental data closely match the analytical results.

Table 1. Comparison of Analytical and Experimental Results

Specimen (1)	**Composite Laminate (2)**	**CFRP Strain Level (%) (3)**	**Maximum Torque (kN-m) (4)**	**CFRP Contribution (kN-m)**	
				Experimental (5)	**Analytical (6)**
TB1	BASELINE	-	20.3	-	-
TB2	[0/90]	0.15	32.5	12.2	11.3
TB3	[±45][a]	0.31	43.4	23.1	31.7
TB4	[0/90][a]	0.17	35.3	14.9	12.7
TB5	[90][a]	0.21	33.9	9.5	14.9
TB6	BASELINE	-	24.4	-	-

[a]Anchors

Conclusions

From the analytical and experimental studies presented here, the following conclusions can be made:

- The torsional strength of the retrofitted beams exceeded that of the baseline specimens by up to 113%. Although more experimental and analytical work is required in this area, these results proved that composites will increase the torsional strength of RC spandrel beams, even at relatively low FRP strain levels.
- The addition of anchors increased the composite contribution to the beam torsional resistance by an additional 27%. This increase was due to the shear flow in the anchors, which delayed the composite delamination. It is not exactly clear, however, why did the laminates without the anchor system increased the torsional capacity to the level observed. Further studies are required to fully understand and to quantify this behavior.
- The 0° ply had a positive influence on the specimen overall behavior. Similar to the longitudinal torsional reinforcement in traditional RC beams, this ply influenced the crack propagation in the specimen, as well as improving overall stiffness.
- As expected, the anchored [±45] laminate was the most efficient retrofit of the spandrel beams. Although not always practical, the orientation of these laminates allowed the composite material to be stressed in the fiber direction.
- The analytical results were close to the experimental results. The developed equation combined the formulas for torsional steel reinforcement and the procedure used to estimate the shear strength provided by FRP laminates applied to concrete members.

Acknowledgement

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