BOND STRESS-SLIP RELATIONSHIP FOR STEEL STRAND EMBEDDED IN SELF-CONSOLIDATING CONCRETE

Andrew M. Pozolo, EI, University of Illinois at Urbana-Champaign, Urbana, IL
Bassem Andrawes, Ph.D., University of Illinois at Urbana-Champaign, Urbana, IL

ABSTRACT

While self-consolidating concrete (SCC) is comparable to conventional concrete (CC) in terms of strength, the comparability of SCC's bond to steel is less well-defined. A keen understanding of SCC's bond strength and its impact on transfer length is essential for widespread SCC use in precast/prestressed applications. This paper focuses on utilizing experimental pullout test data to derive bond stress-slip relationships for 0.5-inch diameter steel strand in SCC and CC and use them to evaluate analytically the end-slip of prestressing strands. First, fifty-six pullout tests are conducted on seven-wire strands embedded in SCC and CC blocks. Pullout results are used to develop a finite element model comprising spring elements to account for bond-slip behavior. The stress-slip relationships obtained from the pullout tests and analyses show minor differences between the bond behavior of SCC and CC. The relationships are then integrated in a finite element model of a prestressed hollow box girder. The end-slip of the girder's prestressing strands is predicted analytically for both SCC and CC at three compressive strengths. Minimal difference is observed between the strands' end-slip in SCC and CC.

Keywords: Self-Consolidating Concrete, Bond Stress-Slip, End-Slip, Pullout

1. INTRODUCTION

In the early 1980's, the declining number of skilled workers in Japan's construction industry prompted concerns over the quality of the country's concrete infrastructure[1]. To improve concrete durability without the need for skilled labor, researchers developed a high performance concrete which would compact into formwork via its own weight. Today, self-consolidating concrete (SCC) has emerged as a viable alternative to conventional concrete (CC) in structural applications across the globe; however, inconclusive research on SCC behavior in prestressed members has thus far limited the technology's impact on the United States' prestressed concrete industry.

A keen understanding of SCC's bond strength and its impact on transfer length is essential to safely incorporate SCC in modern design. To foster this understanding, several American universities and State Departments of Transportation (DOTs) have recently sponsored projects analyzing bond characteristics of prestressing strands in SCC girders, comparing experimental data to provisions currently stipulated by the American Concrete Institute (ACI) and the American Association of State Highway Transportation Officials (AASHTO)[2-3]. A comprehensive summary of these studies may be found in a synthesis review executed in 2009 by Andrawes, Shin, & Pozolo[4]. As evidenced in the review, the studies' collective results were inconclusive primarily due to variations in mix constituents, specimen types, and test procedures throughout the projects. These parameters provided no constant with which to compare dissimilar results or predict bond adequacy of SCC mixes not tested in the studies. Furthermore, the large-scale nature of the studies did not encourage iterative testing to eliminate inherent experimental uncertainties. Thus, separate tests are necessary to assess bond behavior in prestressed members cast with alternative SCC mixes.

To augment previous research and explore the application of SCC in its own bridges, the Illinois DOT (IDOT) has sponsored a study comprising, in part, the aforesaid synthesis review and the contents of this paper. The article at hand focuses on utilizing experimental data to derive bond stress-slip relationships for steel strand in IDOT-approved SCC and CC. The relationships are then integrated in finite element analyses to predict the average end-slip of strands in a prestressed hollow box girder common to Illinois bridge construction. Ongoing analysis omitted from this paper seeks to refine the stress-slip relationships and correlate analytical end-slip vales to transfer lengths, outlining a method to predict transfer lengths in prestressed SCC members when large-scale testing is impractical. Subsequent research will confirm the accuracy of analytical predictions, investigate development length through full-scale flexural testing, and recommend IDOT either modify or adopt for SCC the current ACI and AASHTO provisions for prestressed CC members.

2. PULLOUT EXPERIMENTS

Fifty-six pullout tests were performed on seven-wire 0.5-inch diameter low-relaxation strands embedded in SCC and CC blocks. Concrete compressive strengths and the strands' force-slip responses were recorded at curing ages of 1, 3, 7, and 28 days.

2.1. SPECIMEN DESCRIPTION

Four large pullout blocks and thirty-two 6 inch x 12 inch cylinder specimens were cast simultaneously. Each pullout specimen was 24 inches x 24 inches x 66 inches and contained fourteen 0.5-inch diameter, 270-ksi tensile strength strands embedded 18 inches into the concrete. All block dimensions including strand spacing, longitudinal reinforcement, and clear cover are shown in Figure 1. Half of the specimens used SCC and the other half used CC. Standard slump flow, J-ring, L-box, and visual stability index tests were conducted on the fresh SCC. The results are compared to common industry standards in Table 1, showing moderate passing ability, moderate filling ability, and little segregation of the mix[5]. Batch constituents for the SCC and CC are given in Table 2. Both mixes used Type III Portland cement, a coarse aggregate with maximum 0.5-inch nominal diameter, and a natural sand fine aggregate. Use of a high-range water reducer (HRWR) and an air-entraining agent ensured proper workability for each mix. No viscosity modifying admixture was used in the SCC because its HRWR was promoted as a single component SCC admixture.

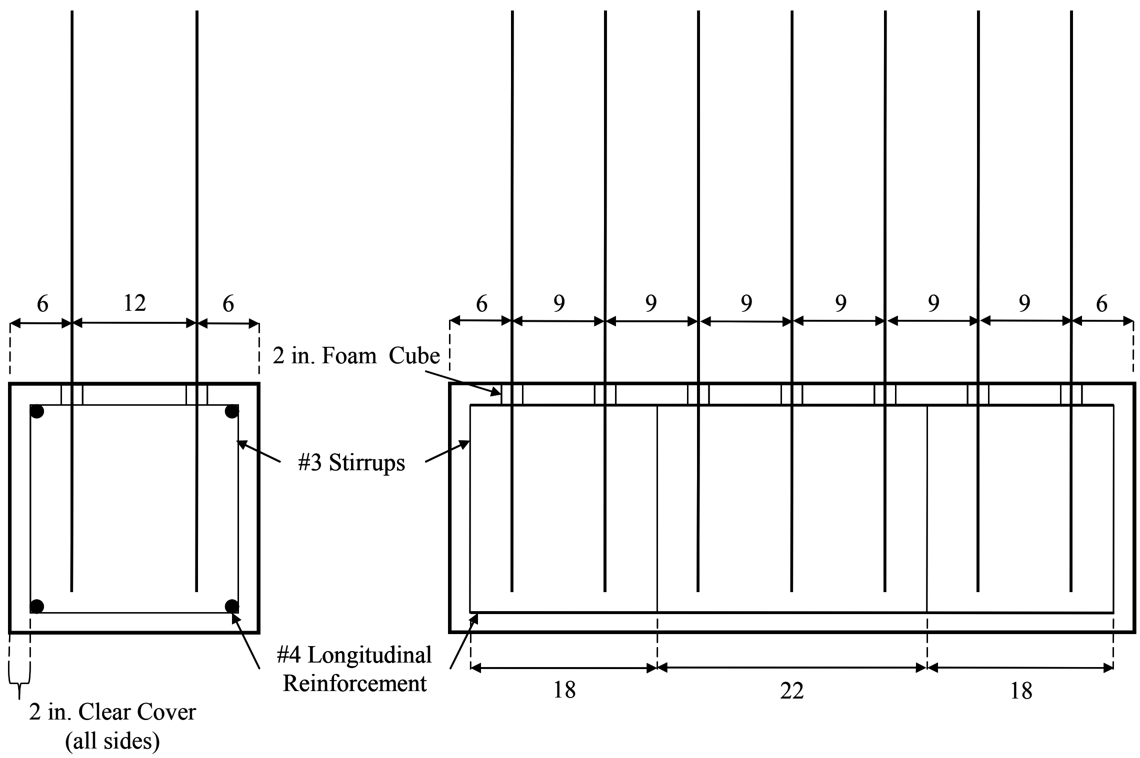


Figure 1. Dimensions (in.), strand placement, and reinforcement of pullout blocks in study.

Table 1. Results of Experimental SCC Mix Tests and Typical Test Values

Mix Properties	Units	SCC, Exp.	SCC, Typ.
Slump Flow	in.	22	22-30
J-Ring Value	in.	2	<2
L-Box Value	%	75	>75
VSI	-	0-1	<2

Table 2. Batch Constituents for CC and SCC Mixes

Mix Constituents	Units	CC	SCC
Cement (Type III)	lbs	670	662
Coarse Aggregate (CM13)	lbs	1849	1607
Fine Aggregate (FA02)	lbs	1180	1441
Air-Entraining Agent	oz	33	14
High Range Water Reducer	oz	45	81
Water	gal	26.6	22
W/C Ratio	-	0.33	0.28
Coarse / Fine Aggregate Ratio	-	1.6	1.1
Fine / Total Aggregate Ratio	-	0.39	0.47

2.2. TEST PROCEDURE

The servo-controlled assembly in Figure 2 was utilized to apply load to strands in the pullout tests. The assembly comprised one hydraulic cylinder with a retractable piston, one steel adapter piece, one 100-kip load cell, two protective steel plates, and one prestressing chuck. A linear variable differential transducer (LVDT) attached to the cylinder monitored displacement of an aluminum plate secured to the top of the piston. Strands were loaded at a constant displacement-controlled rate of 0.4 in/min, resulting in rates below the maximum 20 kip/min as set forth by Logan[6]. Load was applied continuously until strands were completely pulled out or fractured. Fourteen pullout tests and eight uniaxial compression tests were conducted each day; half were on SCC specimens and half were on CC specimens.

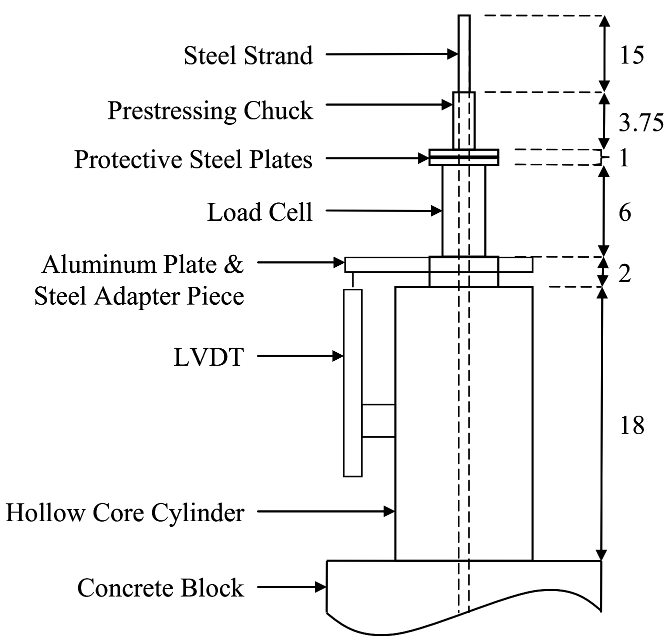


Figure 2. Components of pullout test assembly (dimensions in inches).

2.3. EXPERIMENTAL RESULTS

Figure 3 presents the force-slip response of seven strands embedded in the SCC block tested three days after concrete placement. Typical of all results regardless of concrete age or type, the figure shows each response characterized by an initial linear region and an ensuing nonlinear region. Linear behavior occurred while strands remained fully bonded to concrete and steel deformed elastically. Nonlinear behavior began at the point of first slip as localized bond failure significantly reduced pullout resistance. Progressive bond failure gradually diminished pullout resistance until strands reached their peak pullout capacities, after which resistance decayed until ultimate bond failure occurred.

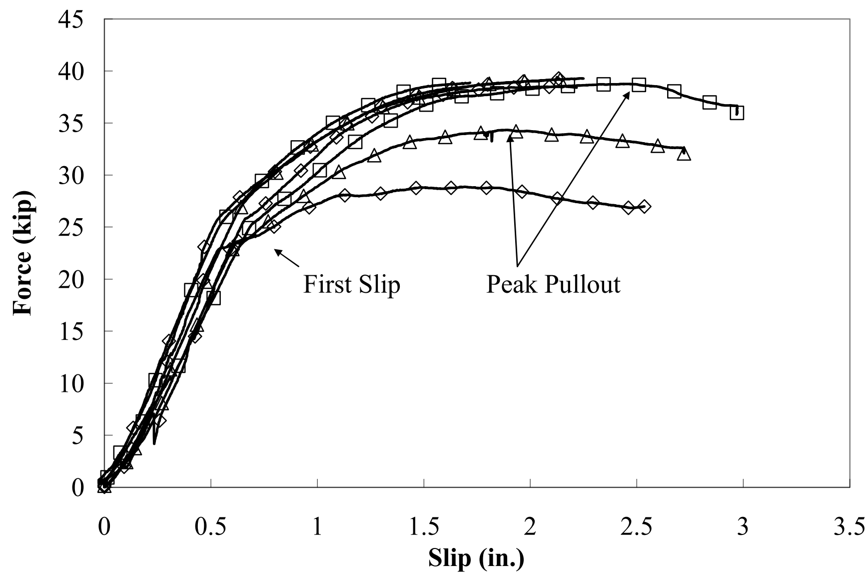


Figure 3. Force-slip response of strands in SCC 3 days after concrete placement.

Normalization techniques should be considered when comparing bond performance in different concretes. Several studies on bond performance have shown a correlation between bond strength and $\sqrt{f'_c}$, where f'_c is the concrete compressive strength[7-8]. ACI provisions, moreover, state that development lengths of reinforcing bars are inversely proportional to $\sqrt{f'_c}$, implying a linear relationship between bond strength and $\sqrt{f'_c}$. Thus, this article presents both absolute and normalized experimental results, assuming a linear relationship between bond strength and $\sqrt{f'_c}$.

The compressive strengths of SCC and CC at each testing age are shown in Figure 4. Both concretes achieved adequate strength for initial pullout tests and strengthened over time, reaching 5000 psi after 28 days. To better assess the bond behavior of SCC and CC, the effect of normalization on first slip and peak pullout loads is highlighted between Figures 5 and 6. Figure 5 shows the average absolute first slip and peak pullout loads at all ages with an assumed error range of two standard deviations to account for non-homogeneity within the concrete blocks. Pullout loads increased over time, ranging in SCC from 36-38 kips and in CC from 30-36 kips. Figure 6 shows first slip and peak pullout loads normalized using

$\sqrt{f'_c}$. Normalized first slip loads differed between SCC and CC by an average of 10% for all tests. Only the 1-day tests showed first slip loads higher in SCC than in CC. Normalized pullout loads differed between SCC and CC by as much as 25% at 1 day and as little as 1% at 3 days. Only the 7-day tests produced lower normalized pullout loads in SCC than in CC, an anomaly explained by the high compressive strength recorded for SCC at that age. If outlier data were removed from these results, SCC strength at 7 days would be 4315 psi instead of 5255 psi, shifting the corresponding normalized loads in line with data from the other three days.

Strands in both SCC and CC attained higher peak pullout loads as concrete aged, which matched the behavior of the concrete strength over time, albeit at a significantly lower rate (see Figures 4-6). No correlation was observed between concrete compressive strengths and first slip loads. Pullout responses were independent of strand location in the blocks to mitigate the effect of concrete non-homogeneity. Sufficient bond was observed between the strands and SCC based on comparison to strands in CC and comparable results from analogous research.

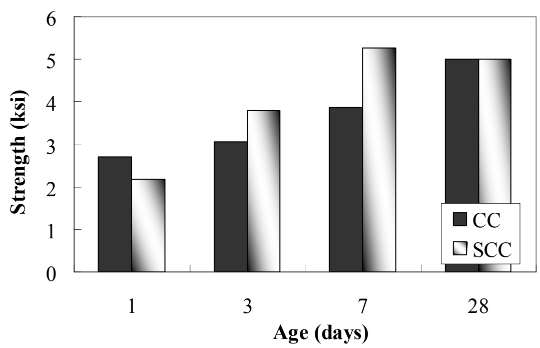
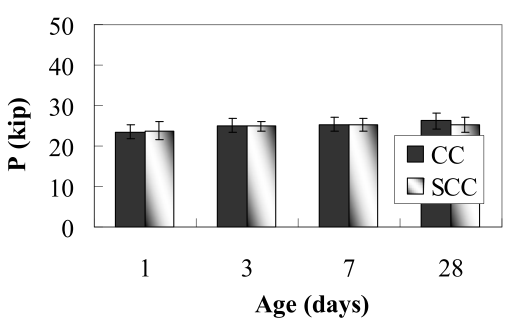
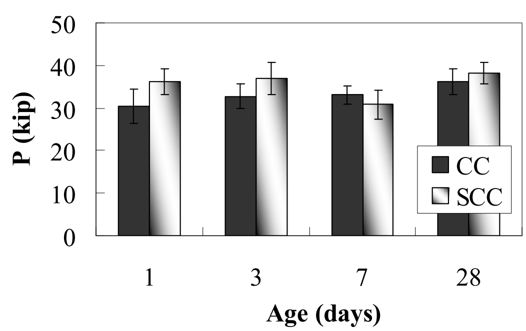


Figure 4. Average compressive strengths.



(a) First Slip Loads



(b) Peak Pullout Loads

Figure 5. Average absolute first slip (a) and peak pullout (b) loads with standard deviation.

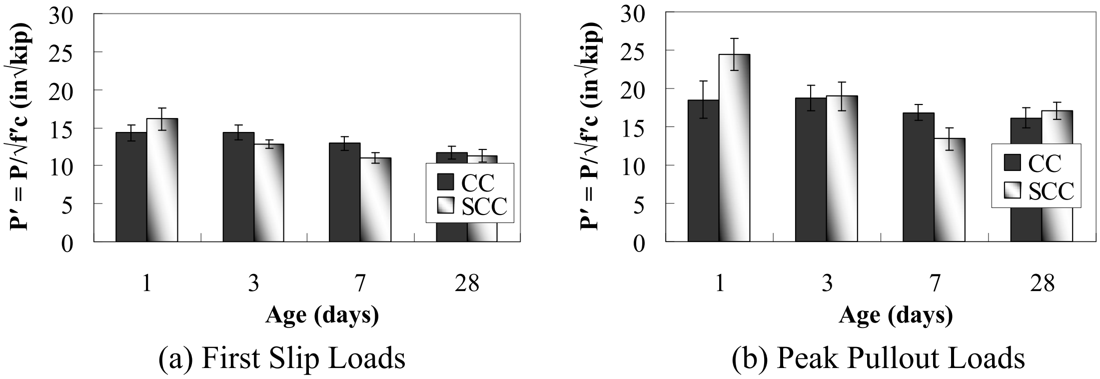


Figure 6. Average normalized first slip (a) and peak pullout (b) loads with standard deviation.

3. FINITE ELEMENT ANALYSIS

Results from the pullout tests were used in conjunction with finite element analysis to derive bond stress-slip relationships for steel strand embedded in SCC and CC.

3.1. FE MODEL DESCRIPTION

The finite element program ANSYS was employed to examine a representative portion of a pullout block. Preliminary analysis showed a 10 inch x 10 inch x 24 inch concrete prism comprising 1-inch long cube elements surrounding one steel strand could accurately capture the pullout response observed in the experiments. The prism was modeled with a single 0.5-inch diameter steel strand embedded 18 inches along its center axis. The strand extended to a point located 24 inches above the concrete surface, where a displacement was applied in ramped increments of 0.1 inches to simulate load transfer via the prestressing chuck. Applied nodal constraints allowed the strand to move only along the line of pullout action and restricted the concrete prism from movement at the pullout surface. Three springs were affixed between each pair of coincident concrete and steel nodes to model the bond-slip mechanism at the concrete-strand interface.

Concrete was modeled using SOLID65 brick elements capable of cracking under tension, crushing under compression, and plastic deformation[9]. The elements had three translational degrees of freedom at each of their eight nodes. Concrete material properties were defined according to the Willam and Warnke failure model[10]. The shear transfer coefficients for open and closed cracks were set to 0.3 and 0.99, respectively, to avert divergence of the FE solution. The uniaxial cracking stress was taken as the modulus of rupture, and the uniaxial crushing capability was disabled.

The concrete's stress-strain behavior was entered as a multi-linear curve with an initial slope equal to the concrete's elastic modulus. The curve adopted for this study was obtained for SCC and CC at 1, 3, 7, and 28 days according to the Todeschini stress-strain model[11]. The concrete prism comprised 2,400 SOLID65 elements defined by 3,025 nodes.

Steel strand was modeled as LINK8 spar elements which resisted uniaxial tension-compression forces and did not consider bending. The elements had three translational degrees of freedom at each of their two nodes and were restricted to 1-inch length to ensure nodes of steel elements coincided with nodes of concrete elements. Steel was assigned a multi-linear isotropic stress-strain curve for 270-ksi strand, a 0.153 inches^2 cross-sectional area, and zero initial strain. The steel strand comprised 42 LINK8 elements defined by 43 nodes.

To model bond-slip behavior at the concrete-strand interface, three COMBIN39 spring elements connected each of the 19 pairs of coincident concrete and steel nodes. Two springs at each pair were relatively rigid and acted only to prevent coincident nodes from slipping relative to each other in the horizontal plane. The third spring acted only in the direction of pullout and was characterized by nonlinear force-deflection inputs derived from experimental data. In total, the model encompassed 3068 nodes and 2,499 elements.

3.2. BOND-SLIP MODEL

Bond between concrete and steel has been well-represented by spring elements in previous FE analyses[12]. In this study, bond-slip was defined by the nonlinear stiffness parameters of the COMBIN39 spring elements. Data from the experimental pullout tests was used to derive the springs' force-deflection inputs for SCC and CC at 1, 3, 7, and 28 days. After verifying that the FE model adequately represented pullout behavior, the force-deflection properties were correlated to bond stress-slip relationships for strand embedded in SCC and CC.

An idealized bond stress-slip relationship was developed for each set of seven pullout tests by calculating the average load and slip at four critical points, as shown in Figure 8 for 3-day SCC. The averages corresponded to the points of first slip, peak pullout, ultimate failure, and midpoint between first slip and slip at peak pullout. The load at each point was correlated to bond stress by assuming the entire embedded strand uniformly resisted pullout load. Slip was calibrated using constitutive properties to eliminate the effect of strand elongation: $u_{elong} = PL/AE$, where P is the pullout load, L is the distance between the concrete surface and the point at which slip is measured, A is the strand's cross-sectional area, and E is the strand's modulus of elasticity. The same calibration method was used in the eleven instances when strands failed by rupture, despite the strands' inelastic behavior. Rupture failure was not consistent with concrete age or type.

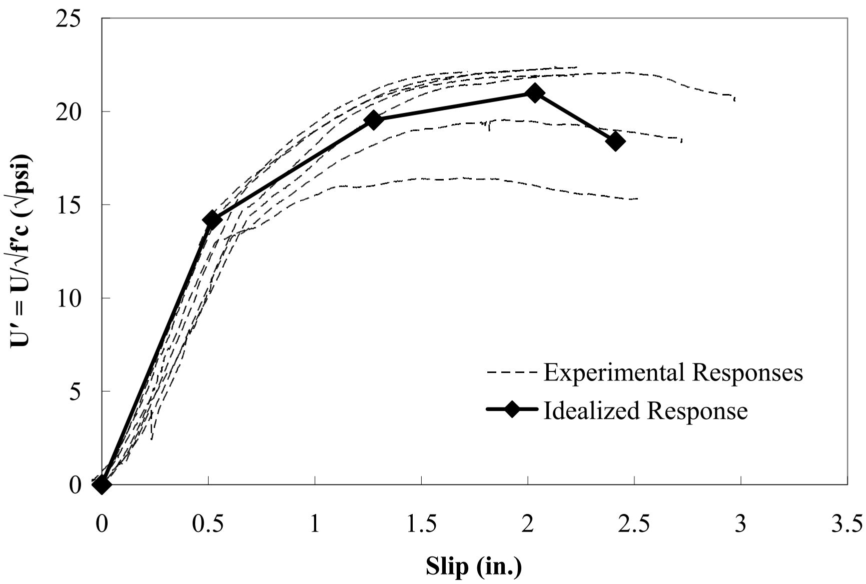
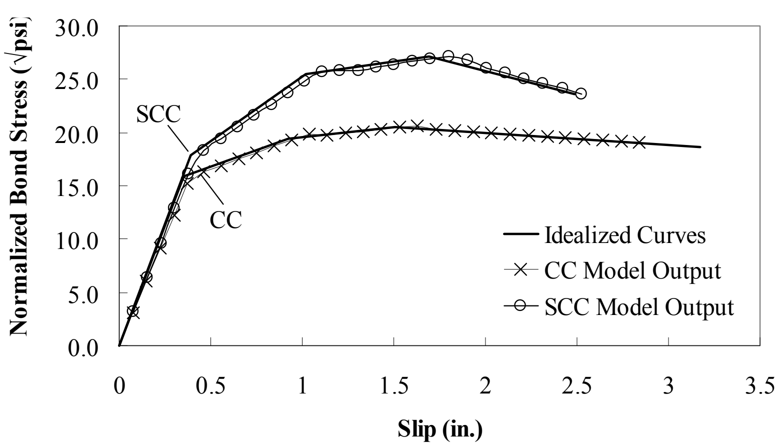
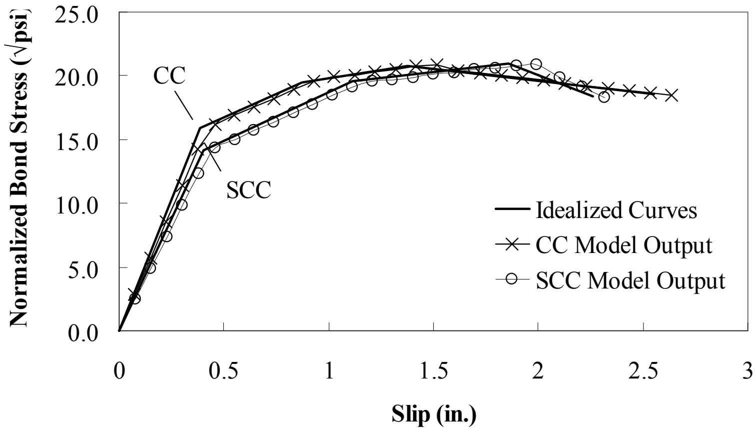


Figure 7. Idealized and experimental bond stress-slip for strands in 3-day SCC.

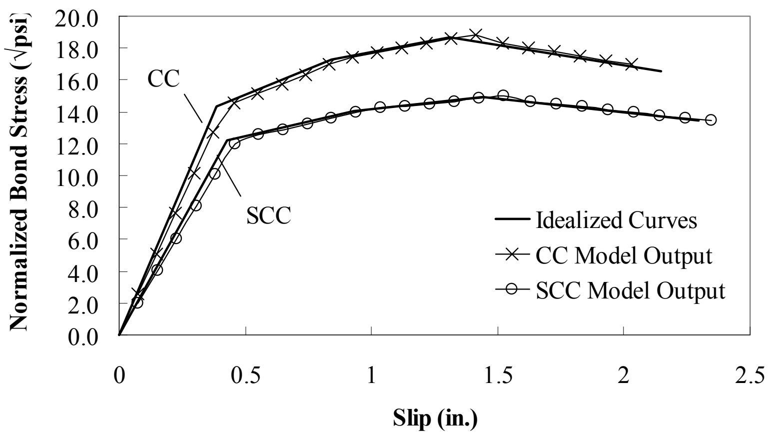
Figure 9 compares the idealized bond stress-slip relationships to those output from the FE model. As the figure shows, the peak normalized bond stress of SCC was nearly 30% greater than that of CC 1 day after concrete placement. After 7 days, however, the converse held true; the peak normalized bond stress of CC was approximately 30% greater than that of SCC. It should again be noted that SCC strength at 7 days was most likely overestimated, thereby underestimating the corresponding bond stress-slip relationship. If outlier data were removed, the initial stress-slip for 7-day SCC would have more closely paralleled that of 7-day CC, as it did at all other ages. The differences between the concretes' peak bond stresses at 3 and 28 days were negligible. In all cases, the FE model output correlated well with experimental data.



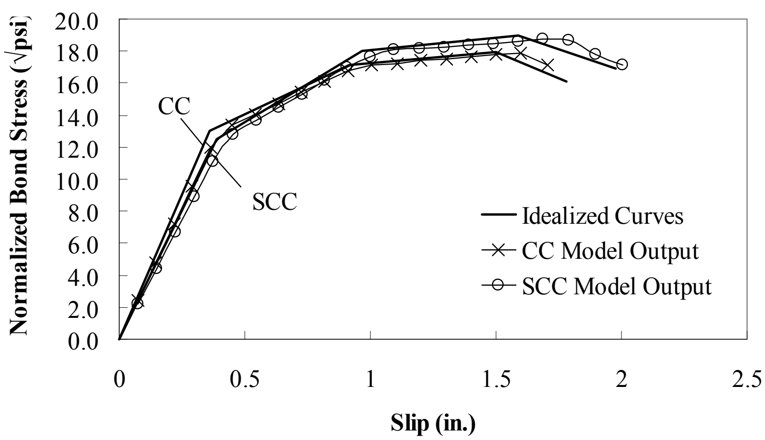
(a) Normalized bond stress-slip at 1 day.



(b) Normalized bond stress-slip at 3 days.



(c) Normalized bond stress-slip at 7 days.



(d) Normalized bond stress-slip at 28 days.

Figure 8. Ideal vs. analytical bond stress-slip relationships for SCC and CC at (a) 1 day, (b) 3 days, (c) 7 days, and (d) 28 days after concrete placement, normalized by $\sqrt{f'_c}$.

4. END-SLIP ESTIMATION

The normalized bond stress-slip relationships for SCC and CC at 28 days were used to estimate the end-slip of strands within a prestressed hollow box girder common to Illinois bridge construction. A finite element girder model was created to perform analysis using the same element types, modeling techniques, and bond stress-slip parameters utilized in the FE pullout model. Analysis considered three concrete compressive strengths.

4.1. BOX GIRDER FE MODEL

A finite element model was assembled for the simply supported hollow box girder shown in Figure 9. The girder was 27 feet long and was reinforced with twenty-six 0.5-inch, 270-ksi prestressing strands. To reduce the computational effort required in analysis the girder was modeled along one axis of symmetry, as shown in Figure 10. All points along the axis of symmetry were restrained to prevent out-of-plane deformation.

SOLID65 elements were again used to model concrete, the material properties for which were derived for three cases as per Section 3.1, assuming compressive strengths of 4 ksi, 6 ksi, and 8 ksi. LINK8 elements modeled the steel strands, which retained the same material properties as before but now included an initial strain of 0.004286 in/in to impart a prestress of 120 ksi. Most concrete and steel elements were 6 inches long, though elements at both ends were refined to more accurately capture stresses within transfer zones. The model contained 26,532 SOLID65 elements defined by 30,753 nodes and 858 LINK8 elements defined by 871 nodes.

As in the pullout model, three COMBIN39 elements were affixed between each pair of coincident concrete and steel nodes to represent bond-slip along the beam's longitudinal axis. This method assumed that camber was small enough to neglect the vertical component of prestressing force after beam deformation. The 28-day normalized experimental stress-slip relationships for SCC and CC were used to calculate the force-deflection parameters for longitudinally-oriented COMBIN39 elements in each of the three cases. Force-deflection inputs were modified according to element tributary area. The model contained 2,613 COMBIN39 elements. In total, the model encompassed 30,003 elements defined by 31,624 nodes.

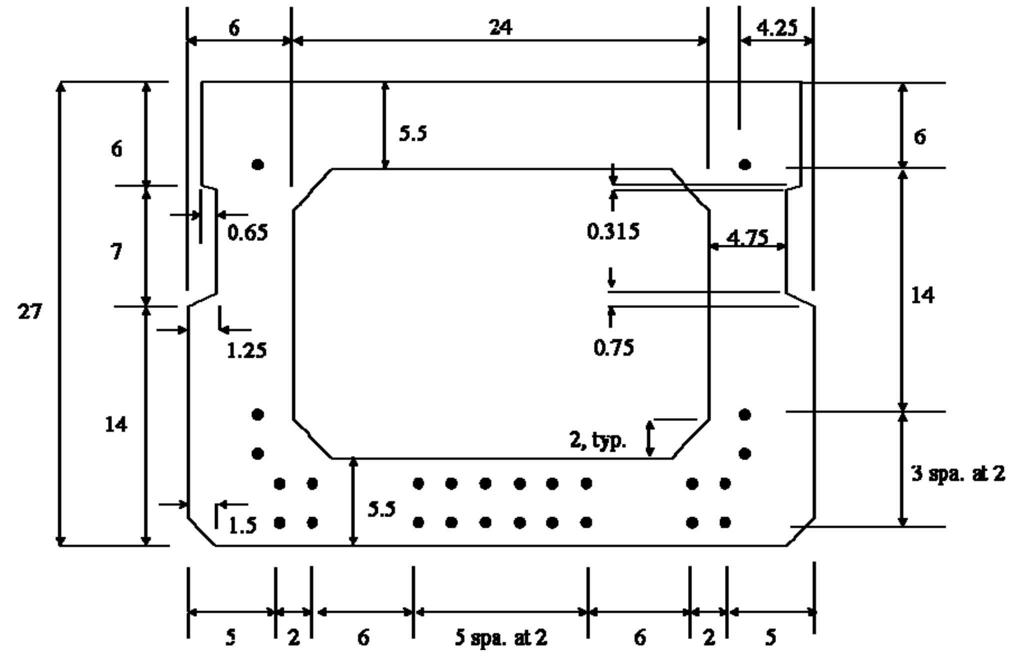


Figure 9. Geometry and strand locations for hollow box girder (dimensions in inches).

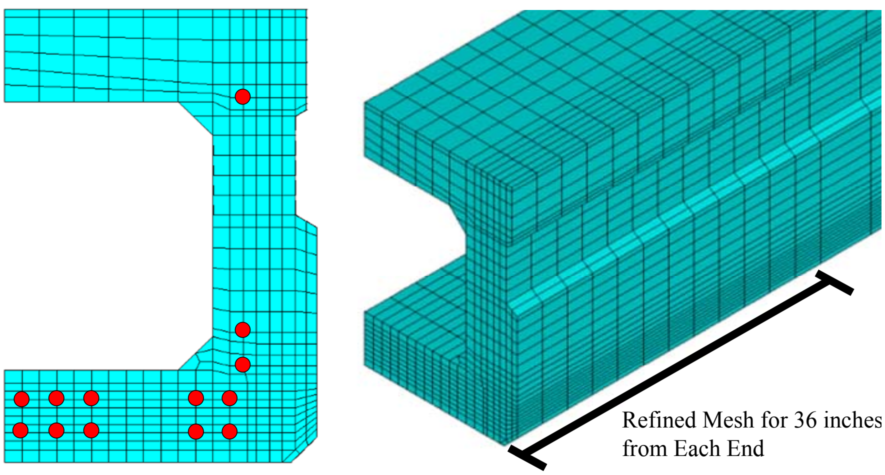


Figure 10. FE girder model discretization with strands shown as circles.

4.2. END-SLIP RESULTS

The analytical end-slip for each case was taken as the average of the end-slip values obtained for all strands within the girder. Shown in Figure 11, the end-slip values for strands in 4 ksi, 6 ksi, and 8 ksi concrete were for SCC 0.141 inches, 0.128 inches, and 0.119 inches, respectively, and for CC 0.133 inches, 0.121 inches, and 0.113 inches, respectively. The slight differences between the analytical slip values are compatible with the variances observed in the experimental stress-slip relationships. End-slip in SCC was at maximum 6% larger than end-slip in CC.

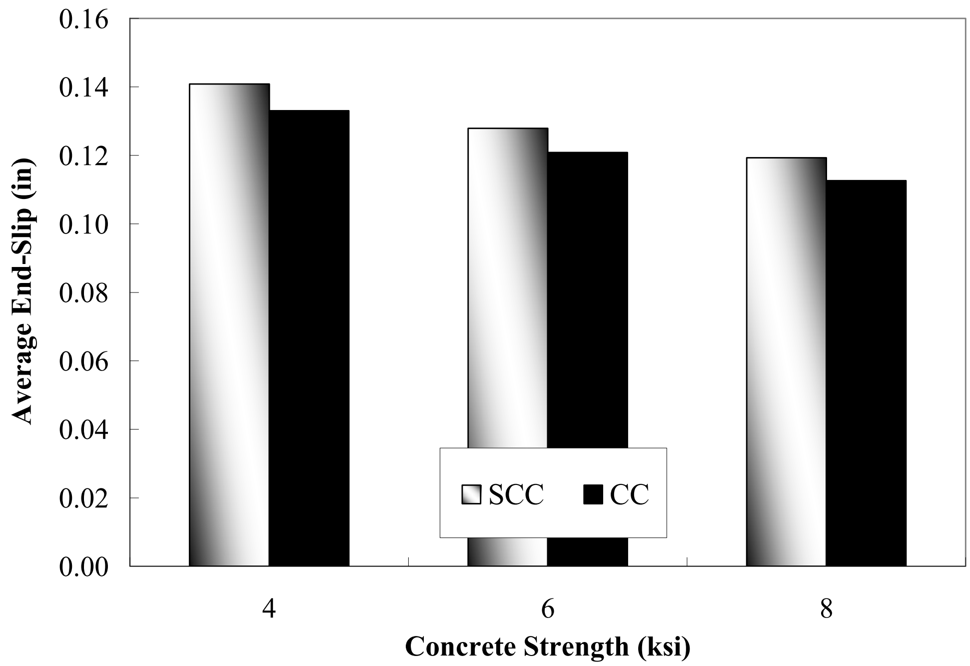


Figure 11. End-slip values for SCC and CC using three compressive strengths.

The analytical method presented in this paper yielded strongly conservative end-slip estimates. Modifications to the method are required before analytical transfer lengths are presented and compared to design provisions. Current efforts seek to refine the experimental bond stress-slip relationships by accounting for non-uniform stress distribution and the effect of radial strand contraction during pullout[13]. The girder model must also integrate the effects of confinement and strand positioning, both of which have been shown to significantly impact transfer length[14-15]. After alterations are made, this article's analysis will be extended to predict transfer and development lengths in prestressed members for which pullout data is available.

5. CONCLUSIONS

Self-consolidating concrete has not yet proven itself as a viable alternative to conventional concrete in prestressed applications primarily due to inconclusive data regarding its bond to prestressing strands. A thorough understanding of SCC's bond strength is necessary to safely incorporate SCC in prestressed applications. Summarizing one phase of an IDOT-sponsored project, this article presented the results of fifty-six pullout tests in the form of bond stress-slip relationships for 0.5-inch seven-wire steel strand embedded in Illinois SCC and CC. When incorporated in a FE hollow box girder model, the stress-slip relationships for 28-day SCC and CC predicted the end-slip of strands in 4 ksi, 6 ksi, and 8 ksi concrete. The study afforded the following observations:

(1) Sufficient bond was observed between strands and SCC based on comparison to strands in CC. Normalized pullout loads differed between the two concrete types by as little as 1% after 3 days of curing.

(2) The stress-slip relationships obtained from pullout tests showed only minor differences between the bond behavior of SCC and CC.

(3) Finite element analysis of a pullout block model correlated well with experimental data assuming uniform bond strength along the embedded strand.

(4) The analytical end-slip values for SCC and CC at 28 days were compatible with the bond stress-slip relationships derived from experimental data. Slip values decreased as concrete strength increased and did not vary significantly between SCC and CC, with the maximum difference at 6%.

Future work for this study will consider variable bond stress along the embedded strand to refine COMBIN39 element parameters and more accurately represent bond-slip in the FE girder model. The precision of end-slip estimates and, consequently, transfer length estimates will improve. Field tests will measure transfer lengths in full-scale SCC girders, providing new data with which to compare analytical results. The final extension of this study will examine both analytically and experimentally the impact of SCC bond behavior on development lengths in prestressed members.

REFERENCES

1. Okamuru, H. and Ouchi, M., "Self-Compacting Concrete." *Journal of Advanced Concrete Technology*, V. 1, No. 1, April 2003, pp. 5-15.

2. *ACI 318-08: Building Code Requirements for Structural Concrete and Commentary.* American Concrete Institute, Farmington Hills, MI, 2008.

3. *AASHTO LRFD Bridge Design Specifications.* Third Edition, American Association of State Highway and Transportation Officials, Washington, D.C., 2004.

4. Andrawes, B., Shin, M., and Pozolo, A., "Transfer and Development Length of Prestressing Tendons in Full-Scale AASHTO Prestressed Concrete Girders using Self-Consolidating Concrete." Illinois Center for Transportation Report FHWA-ICT-09-038, Illinois Department of Transportation, Springfield, IL.

5. "Test Methods for Self-Consolidating Concrete." Technical Bulletin TB-1506C, W. R. Grace & Co.-Conn., Cambridge, MA, 2006.

6. Logan, D., "Acceptance Criteria for Bond Quality of Strand for Pretensioned Prestressed Concrete Applications." *PCI Journal*, V. 42, No. 2, 1997, pp. 52-90.

7. Chan, Y., Chen, Y., and Liu, Y., "Development of Bond Strength of Reinforcement Steel in Self-Consolidating Concrete." *ACI Structural Journal*, V. 100, No. 4, 2003.

8. Esfahani, M., Lachemi, M., and Kianoush, M., "Top-Bar Effect of Steel Bars in Self-Consolidating Concrete (SCC)." *Cement and Concrete Composites*, V. 30, No. 1, 2008, pp. 52-60.

9. *ANSYS Structural Analysis Guide*. Release 11.0, ANSYS, Incorporated, Canonsburg, PA 2007.

10. Willam, K. and Warnke, E., "Constitutive Model for the Triaxial Behaviour of Concrete." Seminar on Concrete Structures Subjected to Triaxial Stresses, International Association of Bridge and Structural Engineering Conference, Bergamo, Italy, 1974.

11. Todeschini, C., Albert, B., and Kesler, C., "Behavior of Concrete Columns Reinforced with High Strength Steels." *Journal of the American Concrete Institute*, V. 61, No. 6, 1964, pp. 701-716.

12. Padmarajaiah, S. and Ramaswamy, A., "A Finite Element Assessment of Flexural Strength of Prestressed Concrete Beams with Fiber Reinforcement." *Cement & Concrete Composites*, V. 24, No. 2, April 2002, pp. 229-241.

13. Den Uijl, J., "Bond Modelling of Prestressing Strand." *ACI Special Publications*, V. 180, 1998, pp. 145-170.

14. Stocker, M. and Sozen, M., "Investigation of Prestressed Reinforced Concrete for Highway Bridges, Part V: Bond Characteristics of Prestressing Strand." Engineering Experiment Station Bulletin 503, University of Illinois at Urbana-Champaign, Urbana, IL, 1970.

15. Peterman, R., "The Effects of As-Cast Depth and Concrete Fluidity on Strand Bond." *PCI Journal*, V. 52, No. 3, 2007, pp. 72-101.