Pullout Strength of Prestressing Strand in Spun Concrete

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Background

Centrifugally cast concrete, often referred to as spun concrete, is a technology that is used in the manufacture of prestressed concrete products such as poles and pipes. Centrifugal casting provides significant benefits. Concrete is spun against the interior surface of steel molds by centrifugal action to form a dense, hard concrete wall. The fresh concrete is subjected to high centrifugal forces (as high as 60 Gs), which compact the material against the interior of the steel mold and expel excess water from the mixture. It is perceived that the bond of steel in spun concrete is significantly improved due to this method of concrete consolidation. While information is widely available on the bond of traditionally cast concrete to prestressing steel, very little information is available on bond of steel in spun concrete. This study is an effort to compare the bond strength of steel in spun and conventionally cast concrete.

Literature Review

Studies have been conducted researching the bond stress between steel and concrete (Kankam), the comparison of bond strength in coated and uncoated strand (Cousins, Badeaux, and Moustafa), the comparison of bond strength between normal and high strength concrete (Harajli), and the bond behavior of plain round bars confined in concrete (Wu, Zhang, Zheng, Hu, and Li). However, there are not any studies comparing the bond strength of statically cast concrete to spun concrete. Studies regarding the topics listed above are discussed and summarized in this section.

The purpose of Kankam's study was to formulate a unique bond stress-steel stress-slip relationship based on two commonly used hypotheses, the first stating bond stress is a linear function of slip (Nilson 1971; Mirza and Houde 1979) and the second regarding the relationship of bond stress to steel stress (Glanville 1913)[1]. To establish a bond stress relationship, Kankam tested plain round bars and ribbed bars confined in concrete. From the study, he found that the bond stress distribution did not conform to a pattern for the plain round bars, but the maximum point occurred at the loaded end and the minimum point was at the central anchored point[1]. Testing of the ribbed bars had different results. An increase in the load resulted in an increase of the bond stress[1]. Furthermore, the results showed that the rate of slip was higher for the plain round bars compared to the ribbed bars. Kankam attributed the variation in slip to the different surface patterns of the bars and the relative resistance developed against the movement of the bar[1].

The purpose of Cousins, Badeaux, and Moustafa's study was to establish a test method in order to determine the bond stress of steel strand and concrete. In this study, they investigated the bond stress of coated and uncoated prestressing strand. According to the authors, a simple pull out test reproduces the adhesion and mechanical interlock, but not the Hoyer effect or associated frictional forces[2]. In order to evaluate bond stress, a test method was developed that replicated the effects of not only adhesion and mechanical interlock but also the Hoyer effect and frictional forces. For the test, a specimen with a cross section of 8 inches x 8 inches and a length of 12 inches was used. Dial gages were used to measure the slip of the steel strand. From the results, it was determined that the bond stress at initial strand slip was greater for coated strand compared to uncoated strand[2]. However, it was concluded that further testing was needed because the bond stress was nearly equal for the 3/8 inch diameter coated and uncoated strand[2].

Harajli addressed the effect of the compressive strength of concrete on bond strength and in the study, he compared the bond strength of normal-strength and high-strength concrete. From the results, it was determined that the bond stress distribution at failure is nonuniform along the bar development length for both normal-strength and high-strength concrete, with the nonuniform distribution being more profound for the high-strength[3]. Furthermore, it was found that the bond strength at bond failure was lower for the high-strength concrete in comparison to the normal-strength concrete[3]. From the test results and data, Harajli established a relationship between bond strength and compressive strength of concrete. For short development lengths, high-strength concrete has a higher bond strength than normal-strength concrete[3]. At 15 to 20 times the bar diameter, the bond strength for both types of concrete are approximately equal; however, as the development length increases, the bond strength of the normal-strength concrete is higher than the high-strength concrete[3]. In this study, it was observed that bond strength is nonuniform across the length of the steel bar and is more prominent in the high-strength concrete. Harajli attributed this factor to the concentration of bond forces in a section of the bar at the loaded end due to larger development lengths of the steel bars[3.]

Wu, Zhang, Zheng, Hu, and Li conducted a study regarding the bond behavior of plain round bars in concrete. In the study, three types of bars and three concrete mixes were used during testing. From the results, the authors concluded that each curve consisted of three parts: ascending, descending, and residual[4]. As the slip increases, the bond stress first increases up to the ultimate strength, then decreases gradually, and finally reaches a stable residual bond strength[4]. Furthermore, it was established that the bond resistance of the plain round bars is proportional to the normal stress applied at the interface between the bar and concrete; consequently, an increase in compressive stress increases the bond strength while an increase in tensile stress decreases the bond strength[4]. Based on the results from the study, the authors were able to establish a bond stress-slip relationship which was supported by the test results from this study. The experimental results demonstrate that an increase in tensile stress results in a peak bond stress at a larger value of slip and the application of compressive stress results in a peak bond stress reached at a smaller value of slip[4].

Research Objective

The purpose of the study is to compare the bond strength of prestressing steel strand in spun and traditionally cast concrete using pullout tests. The testing will provide relative bond strength values to shed light on the degree of improvement in bond strength resulting from the concrete spinning process. In the study, spun and cast concrete specimens were tested using a universal testing machine to determine the rate of slip at load increments until each specimen failed. From the recorded data, bond strengths were determined and compared.

Experimental Program

<subhead 1>

Specimen Dimensions

Figure 1 shows the dimensions of the specimens used for pullout testing. Fifty six specimens, 28 static and 28 spun were manufactured. The requested length was 12 inches, with eight inches of steel strand bonded and two inches of steel strand unbonded at both the live and dead ends. The requested length of strand was a minimum of 34 inches, with 12 inches inside of the specimen and at least 20 inches exposed.

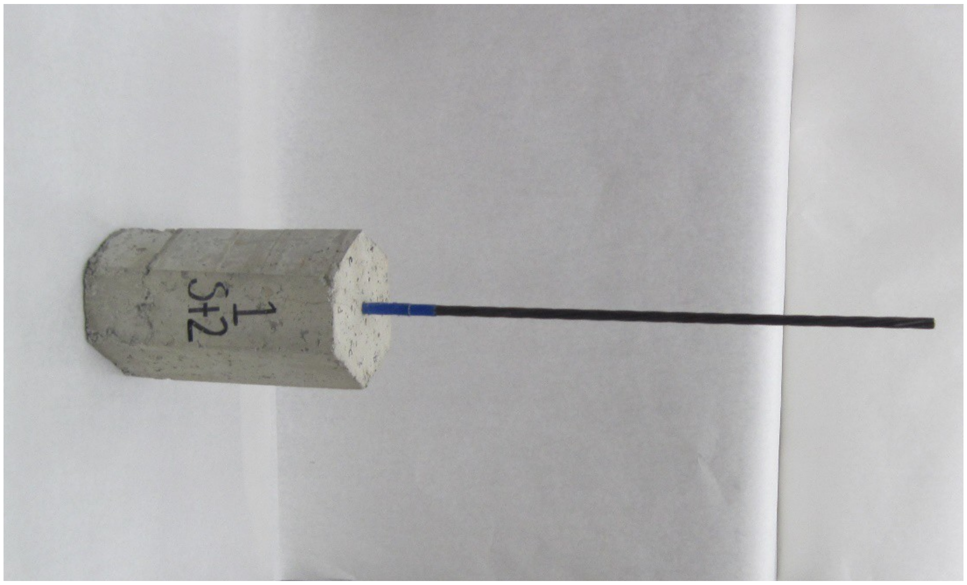

Fig. 1 Specimen with dimensions

A similar specimen size was used by Cousins, Badeaux, and Moustafa in their study. The specimens had a cross section of eight inches by eight inches and a length of twelve inches, which was the optimal size to avoid splitting failure and resist radial tension stresses[2]. Before testing, measurements for each specimen were recorded and the average values are summarized in the table below.

Table 1 Average Measurements of Specimens

	Static	Spun
Length of Concrete (in)	12.00	11.89
Length of Strand (in)	23.29	26.33
Weight (lbs)	42.11	46.51
Cross Sectional Area (in^2)	37.98	41.34
Length of Sleeve (in)	1.99	2.01

<subhead 2>

Manufacturing of Specimens

Fifty six specimens, 28 static and 28 spun were manufactured. The spun specimens were cast in custom built wooden forms, shown in Figure 2.

Fig. 2 Wooden form

The steel strand was constrained in the forms with ties prior to placement in the cylindrical mold. With the wooden form placed inside of the mold, 550 pounds of concrete was poured. After pouring, the specimens were spun for 15 minutes before removal. The mold used for the spinning process is shown in Figure 3.

Fig. 3 Wooden form in cylindrical mold

After the spinning process, the specimens were allowed to cure for 28 days. After the curing process, the form was taken apart to remove the seven individual specimens, illustrated in Figure 4.

Fig. 4 Spun concrete specimens

Static specimens were cast in the same wooden forms as the spun specimens. The only difference in the manufacturing process was the static specimens were not spun. The forms designed and built for casting the static specimens are illustrated in Figure 5.

Fig. 5 Static cast specimens

<subhead 3>

Test Setup

The 60 kip Tinius Olsen machine was used to test the spun and static specimens. The test setup is shown in Figure 6. The specimen was placed on steel plates on the top crosshead. The dial gage was secured to the frame of the testing machine and the probe carefully positioned on the center wire of the steel strand (Figure 7). Placement of the dial gage was important to ensure that the slip readings were representative of the movement of the strand. The steel strand extends from the specimen through the top and bottom crossheads. A reusable chuck was placed on the end of the steel strand for loading. A steel plate was placed between the bottom crosshead and the chuck as well.

Fig. 6 Test setup

Fig. 7 Placement of dial gage on center wire of strand

Results and Discussion

Each specimen was loaded at a rate of 3,000 pounds per minute with the 60 kip Tinius Olsen Testing Machine. Slip of the strand was recorded at load increments of 200 pounds from 0 to

10,000 pounds and at load increments of 500 pounds from 10,000 pounds to failure. Additional readings were recorded as the specimen approached failure to ensure the accuracy of the slip vs. load plot. The data collected was used to plot slip vs. load for each specimen. Graphs for both spun and cast specimens are shown in Figures 8 and 9.

Fig. 8 Slip vs. Load of Spun Specimens

Fig. 9 Slip vs. Load of Static Cast Specimens

During the tests, it was observed that the specimens followed the same pattern during the loading process. For the spun specimens, small increases in slip were observed during initial loading up to a load between 10,000 and 15,000 pounds. From this point, slip increased at a steady rate as the load increased to failure. For the static specimens, small increases in slip were observed during initial loading up to a load between 10,000 and 15,000 pounds. From this point, slip increased at a steady rate as the load increased to failure. As Figure 8 illustrates, the slip vs. load plots are consistent for the 28 spun specimens. A majority of the specimens had a final slip between 0.4 inch and 0.8 inch. In addition, most of the specimens failed at a maximum load greater than 35,000 pounds. As shown in Figure 9, the slip vs. load plots are consistent for the static cast specimens. Most of the specimens had a final slip greater than 0.8 inch. The maximum load was between 20,000 pounds and 30,000 pounds for all of the static specimens.

At the end of each test, the maximum load, final slip, and mode of failure were recorded for each specimen. Failure resulted in the steel strand breaking, the concrete cracking, the load decreasing rapidly, or reaching the maximum capacity of the dial gage. To compare the rate of slip between the spun and cast specimens, the load at a slip of 0.1, 0.2, and 0.3 inch was determined. The values for each of the 28 spun and 28 cast specimens were averaged and the results are in Tables 2 and 3 as well as Figure 10.

Table 2 Summary of Pullout Tests for Spun Specimens

Load at 0.1 in	Load at 0.2 in	Load at 0.3 in	Maximum Load	Final Slip (in)

Slip (lbs)	Slip (lbs)	Slip (lbs)	(lbs)	
16,509	24,253	30,070	38,246	0.5029

Table 3 Summary of Pullout Tests for Static Cast Specimens

Load at 0.1 in Slip (lbs)	Load at 0.2 in Slip (lbs)	Load at 0.3 in Slip (lbs)	Maximum Load (lbs)	Final Slip (in)
15,388	20,479	24,017	30,493	0.8948

Fig. 10 Average Load at Defined Slip Increments

In Tables 2 and 3, the load at slip increments of 0.1, 0.2, and 0.3 inch is provided for both the spun and static specimens. Based on the data, the spun specimens had higher loads and therefore, better performance during testing. The average loads at the slip increment of 0.1, 0.2, and 0.3 inch as well as the maximum load are depicted in Figure 10. At 0.1 inch, there is only a 1,000 pound difference in the load; however, for the other increments, there is at least a 4,000 pound difference in the loads. Finally, the average maximum load and average final slip were compared. The spun and static specimens had an average maximum load of 38,246 and 30,493 pounds, respectively. The average final slip was 0.5029 inch for the spun specimens and 0.8948 inch for the cast specimens. The spun specimens were able to resist higher loads compared to the static specimens and furthermore, the spun specimens had a lower value of slip. Additionally, the data supports that the spun specimens had less slip compared to the cast specimens due to a higher bond strength between the steel strand and concrete.

The mode of failure was examined to establish patterns for the spun and cast specimens. Each specimen failed in one of four ways: the strand breaking, the concrete cracking, the load dropping rapidly, or reaching the maximum slip. 270 ksi seven wire steel strand with a maximum load capacity of 41,000 pounds was embedded in the 56 specimens. The compressive strength of the concrete was determined by testing a total of 12 standard 4 x 8 inch concrete cylinders, four before testing began, four during testing, and four after testing ended. The average compressive strength of the concrete was 11,460 psi before testing, 11,629 psi during testing, and 12,074 psi after testing. A summary of the compressive strength test results is given in Table 4.

Table 4 Compression Test Results

	Before Testing (10/28/2016)	During Testing (11/10/2016)	After Testing (11/17/2016)
	Compressive Strength (psi)		
Cylinder 1	11,047	11,688	11,911
Cylinder 2	11,682	11,451	12,353
Cylinder 3	11,903	11,767	11,770
Cylinder 4	11,209	11,611	12,261
Average	11,460	11,629	12,074

Each specimen was tested until failure occurred and the mode of failure was recorded. Failure included the steel strand breaking, the concrete cracking, the load decreasing, and reaching the maximum capacity of the dial gage. The mode of failure for each specimen identified patterns in the static cast and spun specimens and the results are summarized in Table 5.

Table 5 Mode of Failure for Static Cast and Spun Specimens

	Static Cast	Spun
Strand Broke	0	6
Concrete Cracked	1	21
Load Dropped	25	0
Reached Max Slip	2	1

The most common mode of failure for the spun specimens was splitting and cracking. A total of 21 specimens failed due to the concrete cracking. Cracking occurred at a load between 32,150 pounds and 40,500 pounds. During these tests, the load continued to increase to the maximum load and the load did not drop. The cracking occurred across the live end of the specimen and the cracks extended up the sides of the specimen to the dead end. Figures 11 and 12 are representative of the spun specimens that failed due to the concrete cracking.

Fig. 11 Specimen 7Sp2 failure due to cracking

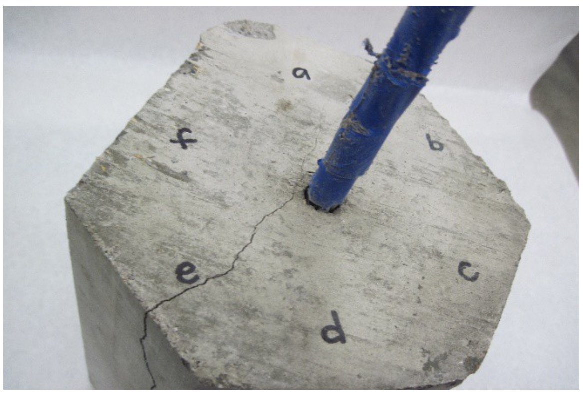

Fig. 12 Specimen 7Sp2 cracking on live end

Six of the specimens failed because the strand broke during loading. Breaking of the strand would occur at a load between 36,800 and 41,250 pounds. Since the seven wire steel strand has a maximum capacity of 41,000 pounds, it was expected for failure to occur at a load in this range. In addition, the steel strand of these specimens was partially rusted, resulting in failure at smaller loads. During these tests, the load continued to increase to the maximum load and the load did not drop. In addition, there was no indication of cracking in the concrete. The strand of these six specimens broke before achieving the ultimate pullout load and would have a higher maximum load if the strand had remained in intact. Therefore, the average pullout load is considered conservative and a lower bound value. Figure 13 is representative of the spun specimens that failed due to the breaking of the strand. Due to the load exceeding the ultimate capacity of the strand, it would break, resulting in the unraveling of the strand and pieces of the wire separating from the strand.

Fig. 13 Specimen 4Sp2 failure due to strand breaking

None of the specimens failed due to the load dropping and one specimen failed because the maximum slip was reached. When the maximum capacity of the dial gage was reached, the testing was stopped.

Four of the spun specimens exhibited crushing at the live end during testing. Of the four specimens, two specimens failed due to the strand breaking and the other two specimens failed due to cracking. Figure 14 is representative of the specimens with signs of crushing after testing.

Fig. 14 Specimen 22Sp2 crushing on live end

The patterns of failure for the cast specimens were different compared to the spun specimens. A total of 25 static cast specimens failed due to the load dropping. When the load would begin decreasing, slip would begin to increase at a rapid rate because the quality of the bond had diminished. Of the 25 specimens that failed due to the load dropping, five had visible cracks or signs of crushing and the remaining 20 specimens did not have any visible cracks or signs of crushing. Figure 15 shows the visible cracks on the specimen and Figure 16 is representative of the crushing effect exhibited in the specimens that failed due to a rapidly decreasing load.

Fig. 15 Specimen 23St2 small cracks

Fig. 16 Specimen 27St2 crushing on live end

One static cast specimen failed due to the concrete cracking. Cracking occurred across the face of the live end of the specimen and the cracks extended up the sides to the dead end. When the sample split, the load was decreasing. Figures 17 and 18 exhibit the cracking from the specimen that failed from splitting.

Fig. 17 Specimen 1St2 failure due to cracking

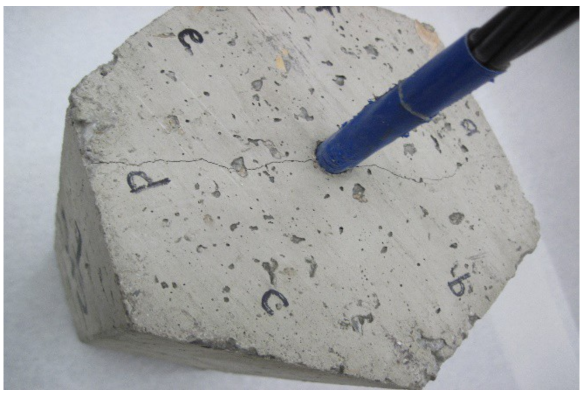

Fig. 18 Specimen 1St2 cracking on live end

The remaining two specimens reached the maximum capacity of the dial gage and testing was stopped. None of the static specimens failed because of the strand breaking.

From the results, it can be determined that the spun specimens have a higher bond strength than the static specimens. The spun specimens failed from either the concrete cracking or the strand breaking; therefore, the strength of the bond was greater than the strength of the concrete or the steel strand. The static specimens failed because the load dropped and had lower maximum loads. The decrease in the load is a result of the deterioration of the bond between the concrete and the steel strand during load.

Summary and Conclusions

Based on the results, it can be concluded that the spun specimens performed better than the static specimens in the pullout tests. The spun specimens had an average maximum load of 38,246 pounds compared to 30,493 pounds for the static specimens. The average final slip was equal to 0.5029 inch for spun specimens compared to 0.8948 inch for static specimens. Most of the spun specimens failed from cracking and a few failed from the strand breaking, indicating the bond strength is greater than the strength of the concrete or the steel strand. Most of the static specimens failed from the load dropping due to the poor bond strength and the deterioration of the bond during loading, indicating the bond strength of the static specimens is weaker than the bond strength of the spun specimens.

References

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Abstract

The purpose of this study is to determine the relative bond strength of seven wire steel strand in two types of concrete: spun and static cast. It is perceived that the spinning process used in

manufacturing of concrete poles introduces compaction forces that densifies the concrete and hence improves the steel to concrete bond. Studies have successfully been conducted determining the bond strength of steel and concrete using the pullout test method; however, there are not any studies known of that address spun cast concrete.

Pullout tests were conducted on static and spun concrete specimens with embedded seven wire 270 ksi grade steel strand. Spun specimens were made in steel molds and spun according to the process used in manufacturing of spun concrete poles. A Universal Testing Machine was used in testing. Load vs. slip data was collected and used to determine the pullout load at ultimate failure and the average bond strength. The results will be evaluated to compare the relative bond strength of spun and statically cast concrete.

Keywords

bond, prestressing strand, spun concrete, pullout strength, strand slip, concrete cracks

Figure Captions

Fig. 1 Specimen with dimensions

Fig. 2 Wooden form

Fig. 3 Wooden form in cylindrical mold

Fig. 4 Spun concrete specimens

Fig. 5 Static cast specimens

Fig. 6 Test setup

Fig. 7 Placement of dial gage on center wire of strand

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Fig. 10 Average Load at Defined Slip Increments

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