SPLICE LENGTH OF DEFORMED STEEL REINFORCING BARS TO PRESTRESSED STRANDS WITHIN THE TRANSFER ZONE

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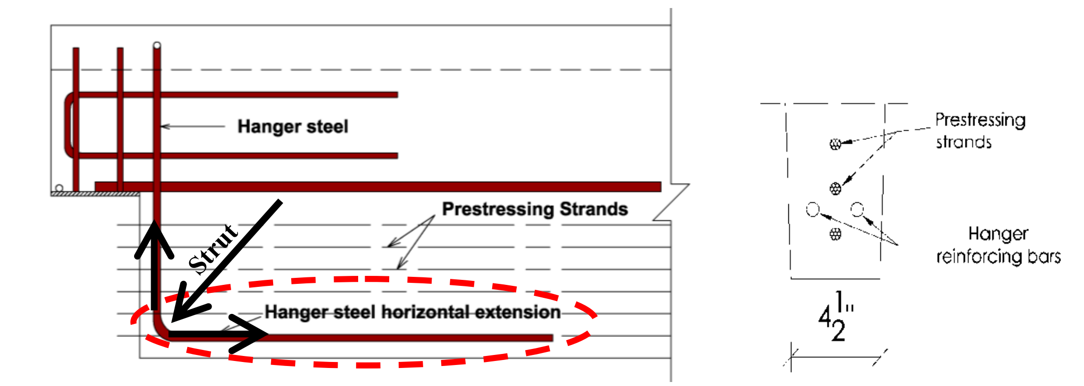
ABSTRACT

This paper presents the findings of a research program conducted to study the behavior of the splice between deformed steel reinforcing bars and prestressing strands within the strand transfer zone. Such a splice can be critical to the end-region performance of dapped-end, thin-stemmed precast concrete members. Within the dapped-end zone, this splice is required to transfer the force in the horizontal extension of the hanger reinforcement to the adjacent prestressing strands within the transfer zone at the end of the beam. The study included an experimental program to determine the splice length required to develop the yield strength of the steel reinforcing bars. Specially-designed splice specimens were tested to failure with each specimen consisting of steel reinforcing bars lap-spliced to fully tensioned prestressing strands inside a concrete prism. The paper presents details of the test specimens, instrumentation and test setup used, and results of the experimental program. The main variable studied in the program was the size of the deformed reinforcing bars. Results of the experimental program indicated that failure could develop due to yield of the reinforcement, loss of strand bond, or longitudinal splitting resulting in loss of strand and reinforcing bar bond. Design recommendations are proposed for splice lengths between reinforcing steel bars and pretentioned strands.

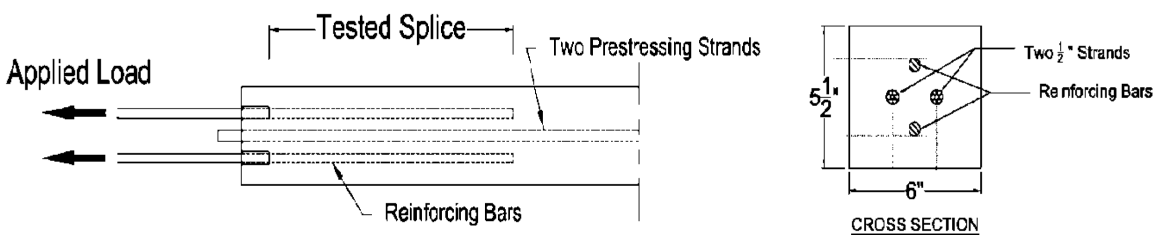
Keywords: Splice length, Transfer zone, Dapped end, Hanger reinforcement.

INTRODUCTION

Splices between deformed steel reinforcing bars and pretensioned strands are typically used in precast prestressed concrete members. For dapped end single and double tee prestressed members, the current design procedure[1] recommends anchorage of the hanger deformed bar reinforcement by bending the bars horizontally to overlap with the prestressing strands along the bottom of the thin web as shown in Figure 1(a). Such a splice has been shown to have significant effect on the performance of the end region of dapped-end thin-stemmed precast concrete members[2]. Within the dapped-end region, this splice is required to transfer the force from the horizontal extension of the hanger reinforcement to the adjacent prestressing strands within the transfer zone of the prestressing steel at the end of the beam. Transfer of the horizontal force is required to equilibrate the horizontal component of the diagonal strut at the end of the beam as shown in Figure 1(a).



(a)



(b)

Fig.1: Elevation and cross section of (a) typical splice of the hanger reinforcement to the prestressed strands in a dapped end beam (b) lap splice specimen

The splice between the hanger horizontal reinforcement (tail) and the pretensioning strand is unlike a conventional splice. In a conventional splice, tensile forces are transferred between the spliced bars as tensile cracks develop. As the hanger reinforcement tail is stressed, the reinforcing bar tensile force decompresses the concrete stem, without significantly increasing the stress in the pretensioning strand. After the tensile force overcomes the precompression, transverse cracks develop. These cracks disrupt the bond between the pretensioning strand and surrounding concrete, resulting in strand slip and loss of pretensioning force. As tension in the deformed reinforcing bars increases to failure, transverse cracks develop further into the section, causing strand slip and increasing bond stress, which leads to splitting, complete loss of bond, and failure.

Mattock and Abdie[3] investigated the behavior of this type of splice by testing prestressed concrete prisms with two reinforcing bars lap spliced to one single ½ inch diameter strand. The experimental program examined the effect of the reinforcing bars size and the splice length of the reinforcing bars to the strand. Test results indicated that the ultimate capacity of the splice increases by increasing the lapped length of the bars. Their results also showed that the required splice length to develop the yield strength of the deformed steel bars is considerably greater than the standard development length required by ACI 318-14[4]. They introduced an expression to calculate the lap length required to develop the yield strength of #No. 5 and smaller diameter reinforcing bars when lap spliced to a single ½inch diameter strand.

Forsyth[5] tested eight lap splice specimens with a configuration similar to those tested by Mattock and Abdie[3]. The size of the reinforcing bars was kept constant as #No. 4 bars and the size of the strands was varied to determine the required length to develop the yield strength of the deformed reinforcing bars. The three different failure modes observed during the tests were: loss of strand bond, reinforcing bar pull out and bar rupture. Specimens with short lap lengths exhibited reinforcing bar pullout failures while specimens with longer splices achieved higher ultimate capacity and yielding of the reinforcing bars. Forsyth concluded that a lap length of 1.7 times the development length of the steel bar specified by ACI318-14 is sufficient to cause yielding of a #No. 4 bar in a bar-to-strand splice typical of those found in the bottom of dapped end members.

This paper presents an experimental program undertaken to determine the lap splice length required to develop the yield strength of deformed reinforcing bars spliced to prestressing strands. A series of pullout tests were conducted on prestressed concrete prisms as shown in Figure 1(b). The specimen was designed to simulate possible configurations of the splice between the horizontal extension of the hanger reinforcement and the adjacent prestressing strands in the end region of a dapped-end thin-stemmed double tee beam.

The lap splice testing program described in this paper was carried out in the first phase of a two-phase research program that included testing of full-scale dapped end beams with a wide variety of reinforcement details.

TEST SPECIMENS

Eight specimens were fabricated and tested to investigate the force transfer mechanism of reinforcing bars lap spliced to prestressing strands within the transfer zone. The concrete section dimensions, reinforcing bar sizes and lap lengths were selected to mimic typical conditions of a splice within the end region of typical dapped end beam.

Details of the eight lap splice specimens are shown in Figure 2. Specimens, 1, 2, 3 and 4, consisted of 2 #No. 4 deformed steel reinforcement bars lap-spliced to two fully-tensioned

½inch diameter strands within a concrete prism. Specimens, 5 and 6, consisted of two #No. 6 deformed steel reinforcement bars lap-spliced to two ½ inch diameter strands in a similar configuration. Specimens 7 and 8, consisted of one #No. 8 bar lap spliced to two ½ inch diameter strands. The first six specimens were designed to replicate the case where the hanger bars are located on either side of the strand in a dapped end beam while the last two specimens, 7 and 8, replicate the condition of a single hanger bar inserted between two columns of strands. The specimens were fabricated with the deformed steel bars protruding from one end of the prism. A steel tube section was cast integrally with the specimen just outside the test zone, and was used to provide reaction when tension was applied to the specimen as shown in the top and bottom views of Figure 2.

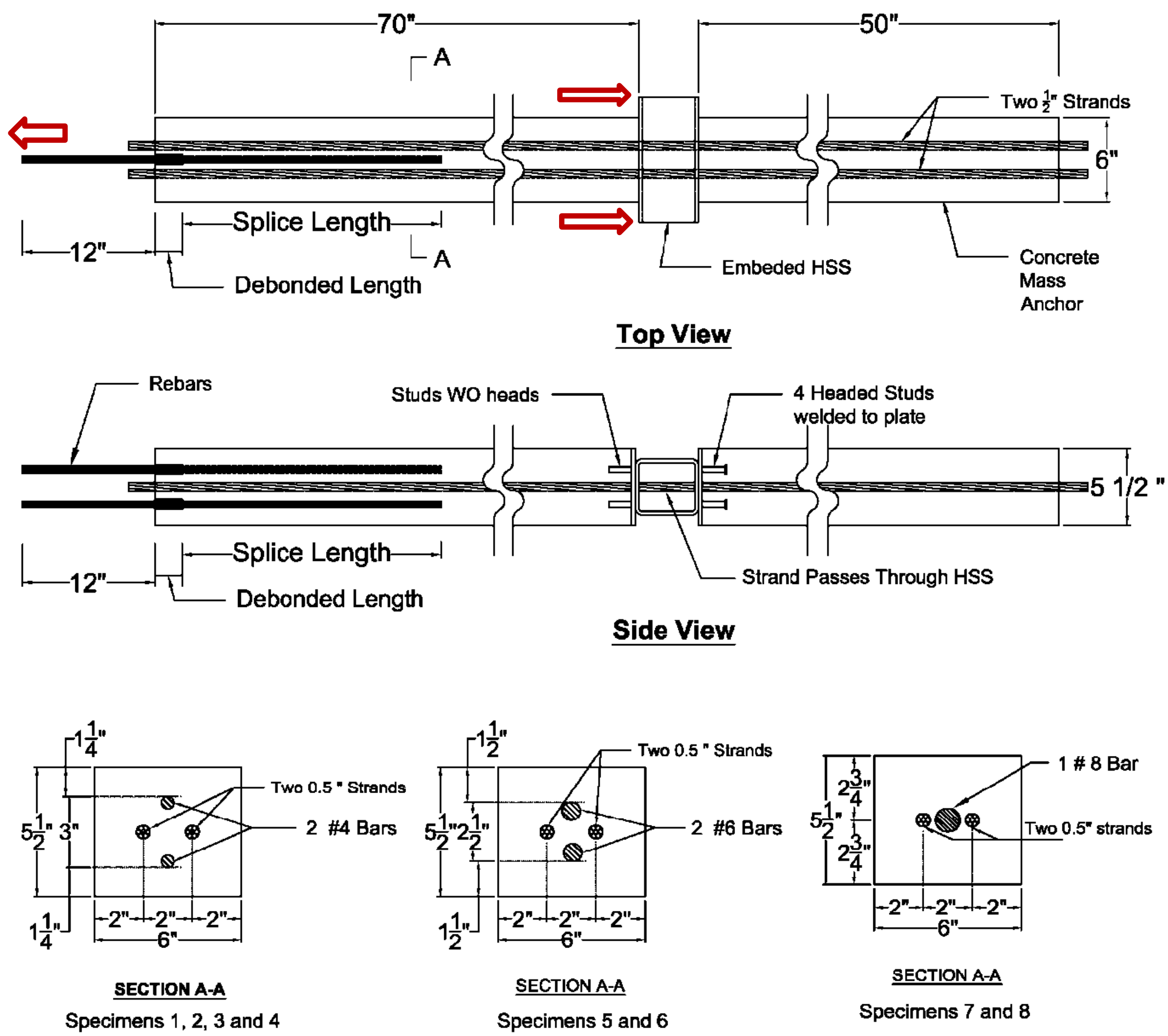


Fig. 2: Details of lap splice specimens

The test matrix of the testing program is given in Table 1. The program included different splice lengths of the deformed steel to determine the lap-length required to develop the yield strength of #No. 4, #No. 6 and #No. 8 deformed steel bars spliced to two ½ inch seven wire strands within the transfer zone. The splice lengths used for the deformed steel bars varied from 0.8 to 3.3 times the standard bar development length specified by ACI 318-14. The reinforcing bars were de-bonded for the first 2 inches from the face of each specimen to model the clear cover from the front face of a dapped end beam to the hanger reinforcement bars. The bars were debonded for the first 10 inches in specimen 4 to simulate a dapped end reinforcement detail utilizing inclined hanger reinforcement bars. De-bonding was achieved by using a plastic tube to prevent bonding of the bar to the concrete at the end of the specimen. The steel used for all specimens was Grade 60 deformed reinforcing bar. Specimens were designed for a nominal compressive strength of 6000 psi with 3500 psi specified strength at release. Steel bars diameter, debonded length at the end of the specimen, ratio of the splice length to the strand transfer length as well as ratio of the splice length to the bar development length are given in Table 1.

Table 1: Testing matrix for lap splice specimens

Spec. # No.	Bar size	De-bonded length (in)	Splice length (l) (in)	Splice length to transfer length[1] ratio	Concrete cover to bar diameter ratio[2], c_b/d_b	Development length of the reinforcing bars[3], l_d (in)	Splice length to development length ratio
1	2 #No.4	2	12	0.5	2.5	12	1.0
2			20	0.8	2.5		1.6
3			40	1.6	2.5		3.3
4		10	12	0.5	2.5		1.0
5	2 #No.6	2	24	1	1.2	30	0.8
6			54	2.2	1.2		1.8
7	1 #No.8		28	1.1	2.5	24	1.2
8			56	2.2	2.5		2.3

[1]Transfer length assumed to be 25 in. or 50 times the strand diameter

[2]Confinement term used in Eq. 25.4.2.33 a. of ACI 318-14, where c_b is the distance from the surface of the concrete to the center of the deformed steel bar or 1/2 of the center to center deformed steel bars spacing, and d_b is the bar diameter.

[3]Development length of the bars, l_d was calculated using Eq. 25.4.2.3 a in ACI 318-14 using the measured material properties for steel and concrete.

FABRICATION OF SPECIMENS

The test specimens were fabricated in a precast plant. The wooden forms for the lap splice specimens were built and arranged in one line between two fixed abutments, as shown in Figure 3. Two ½ inch diameter strands were pulled between the two fixed abutments and tensioned to a force of 28.9 kips, which corresponds to 70 percent of the ultimate strength of the prestressing strands. The reinforcing bars were positioned between the prestressing strands at the front faces of the specimens. The bars were kept in place by tying them firmly to the prestressing strands using steel wires. All eight specimens were cast simultaneously from the same batch of concrete. The strands were torch cut to simulate the sudden shock of the prestress force on the live end, which is a typical de-tensioning procedure in casting the prestressed concrete dapped end thin web prestressed concrete members.

(a) (b)

Fig. 3: Fabrication of lap splice specimens (a) pulling strands in wooden forms (b) after casting of concrete

TEST SETUP AND INSTRUMENTATION

The test setup for all specimens is illustrated in Figure 4. It was configured such that load could be applied to the protruding reinforcing bars or bar without interfering with the lapped splice region of the specimen. Load was applied by pulling the projecting deformed steel bars and reacting against the steel tube blocked at 70 inches (in.) from the pulling end of the test specimen. This arrangement placed the portion of the specimen between the tips of the steel bars and the steel tube in tension. The remaining 50 in. of the specimen beyond the square steel tube was in compression due to prestressing, serving to anchor the prestressing strands at the far end. Tensioning of the reinforcing bars or bar was achieved by welding a steel plate to the ends of the protruding bars. The tension load was applied to the plate using two high-strength steel threaded rods. The two threaded rods were loaded by a single large diameter threaded bar through a small spreader beam. The test specimens were supported on plastic rollers along its entire length to allow movement of the specimen and to minimize friction with the testing framework. A spherical bearing surface was used at the connection between the large threaded bar and the small spreader beam to ensure equal distribution of the applied tension force to the two threaded rods.

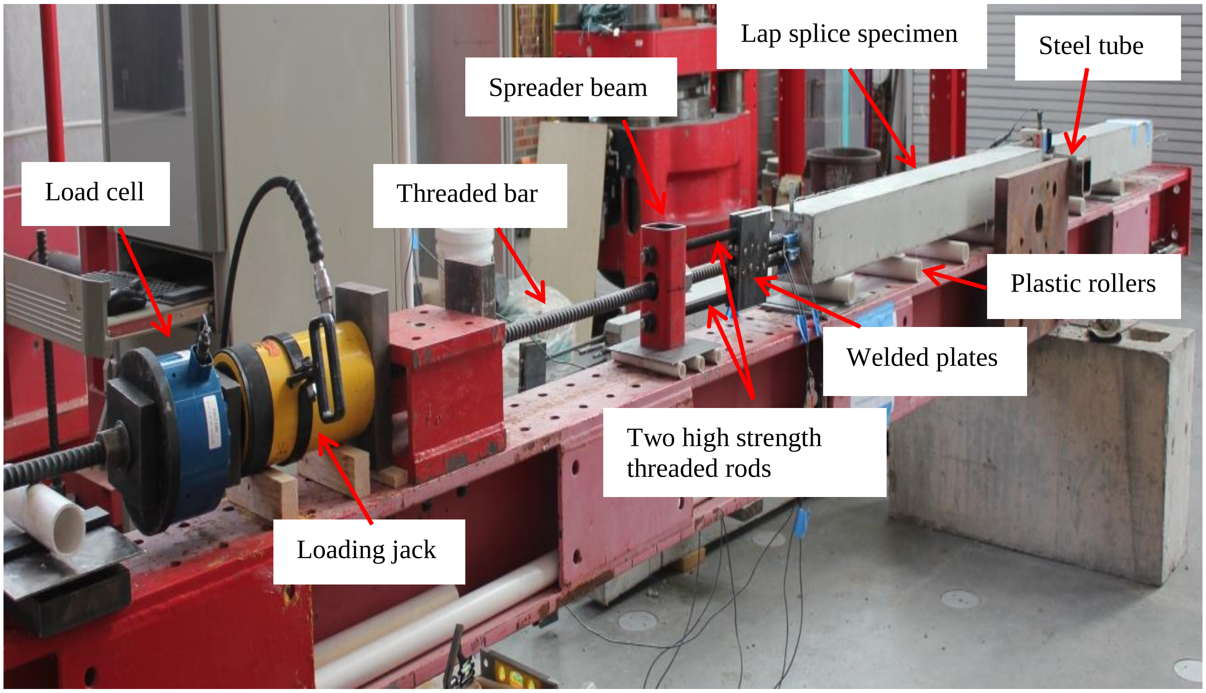


Fig. 4: Typical lap splice test setup

Each specimen was instrumented with a load-cell and electronic linear potentiometers to measure displacement of the strand and reinforcing bar relative to the specimen front face. Typical instrumentation used for the lap splice specimen is shown in Figure 5. Six linear potentiometers were installed at the front face of the specimen. Two linear potentiometers were installed on each reinforcing bar and one potentiometer on each strand. For specimens 7and 8, with the single #No. 8 bar, four linear potentiometers were installed at the front face of the specimen; two potentiometers on the reinforcing bar and one potentiometer on each strand.

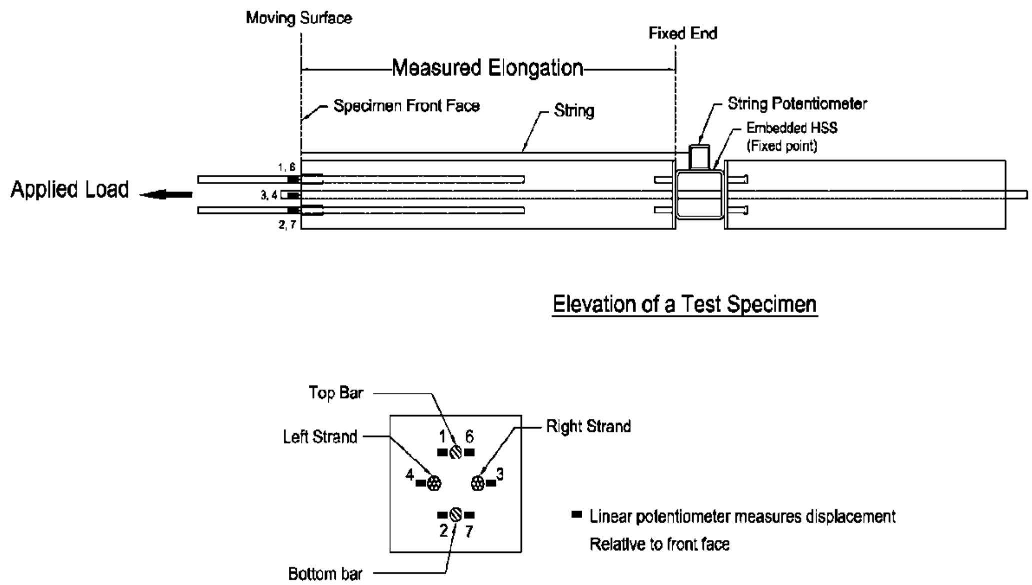


Fig. 5: Instrumentation of lap splice specimen

TEST RESULTS

The measured concrete strengths at the time of release, 3 days after casting, and at the time of testing, 28 days after casting, were 4800 and 7000 psi, respectively. The measured steel material properties for the #No. 4, #No. 6 and #No. 8 bars are summarized in Table 2.

Table 2: Measured properties for the steel bars

Bar size	Elastic Modulus (ksi)	Yield Strength (ksi)	Ultimate Strength (ksi)
4	24094	66	95
6	24401	63	94
8	23696	61	92

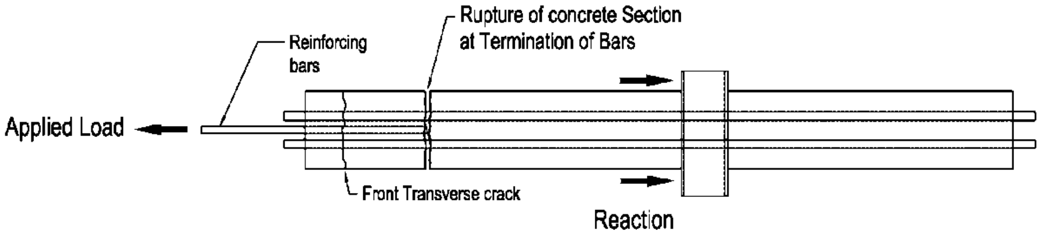
After curing for 28 days, tension bond tests were performed on all of the specimens. Load was applied at a slow rate to failure with time allowed between loading levels for marking cracks and making observations. The measured failure loads and the observed failure modes are given in Table 3. The measured strand slip and the ratio of the measured peak load to the yield load of the deformed reinforcing bars are also listed in Table 3. Specimen behavior under loads and the three observed failure modes are discussed in detail in the following sections.

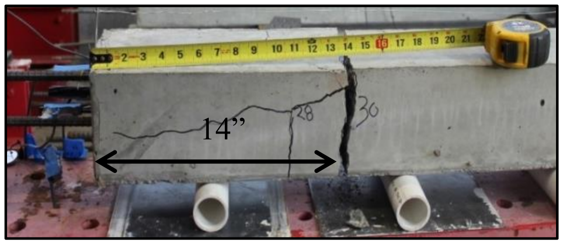
Table 3: Lap-Splice Pullout Test Results

Spec. #No.	Splice length / development length of the reinforcing bars l / l_d	Failure load (kips)	Maximum stress in Reinforcing bars at failure (ksi)	Average strand slip just before failure (in)	Load at which longitudinal splitting cracks initiated (kips)	Failure load / yield load*	Failure mode
1	1.0	30.5	76.2	0.004	--	1.16	SB
2	1.6	35.3	88.4	0.042	--	1.35	SB
3	3.3	28.9	72.3	0.003	28.9	1.10	SP/RB
4	1.0	36.8	92.1	0.006	36.5	1.40	SP/SB
5	0.8	44.9	51.0	0.050	42	0.81	SP/SB
6	1.8	47.0	53.4	0.240	42.3	0.84	SP/SB
7	1.2	43.4	54.9	0.084	41	0.90	SP/SB
8	2.3	59.6	75.4	0.066	50	1.23	SP/SB

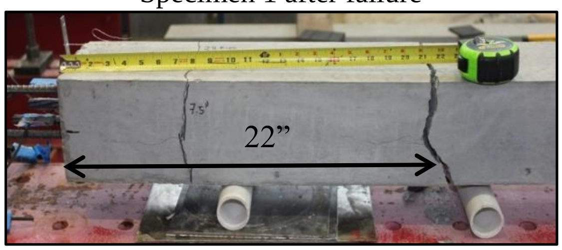
SB: Strand bond failure
SP/RB: Splitting and reinforcing bar bond failure
SP/SB: Splitting and strand bond failure
*Yield load calculated based on the measured yield strengths in Table 2

1. Strand bond failure: This failure mode was observed for specimens with the short splice lengths of 12 inches (1.0 bar development length) and 20 inches (1.6 bar development length) in specimens 1 and 2 respectively. Strand bond failure was evident by rupture of concrete section at the embedded end of the deformed reinforcing steel bars. The behavior typically started by formation of a transverse crack between the front face of the specimen and the end of the embedded reinforcing bar at an early stage of the loading. At ultimate, failure occurred due to sudden formation of transverse crack at the end of the deformed reinforcement. Failure of the two specimens is shown in Figure 6. This failure mode was due to the short splice length and termination of the reinforcing bars within the transfer zone of the prestressing strand, that is, in the zone where the effective prestressing force was not fully developed. The concrete section ruptured at the bars termination when the tension force was sufficient to overcome the prestressing effect and the tensile strength of the concrete. After failure, further loading caused sliding of the part of the prism containing the deformed steel bar along the length of the strands which indicated total loss of bond between strands and the concrete prism.





Specimen 1 after failure



Specimen 2 after failure

Fig. 6: Strand bond failure

The measured displacement of the reinforcing bars (R1 and R2) and prestressing strands (S1 and S2) with respect to the specimen front face for specimen 2 is shown in Figure 7. Test results indicated yielding of the reinforcing bars prior to failure. Results of specimens 1 and 2 indicated that it was possible to develop the yield strength of the #No. 4 reinforcing bars with a splice length equal to the development length of the bar. The results of these two specimens also indicated that the splice strength increase with increasing the splice length.

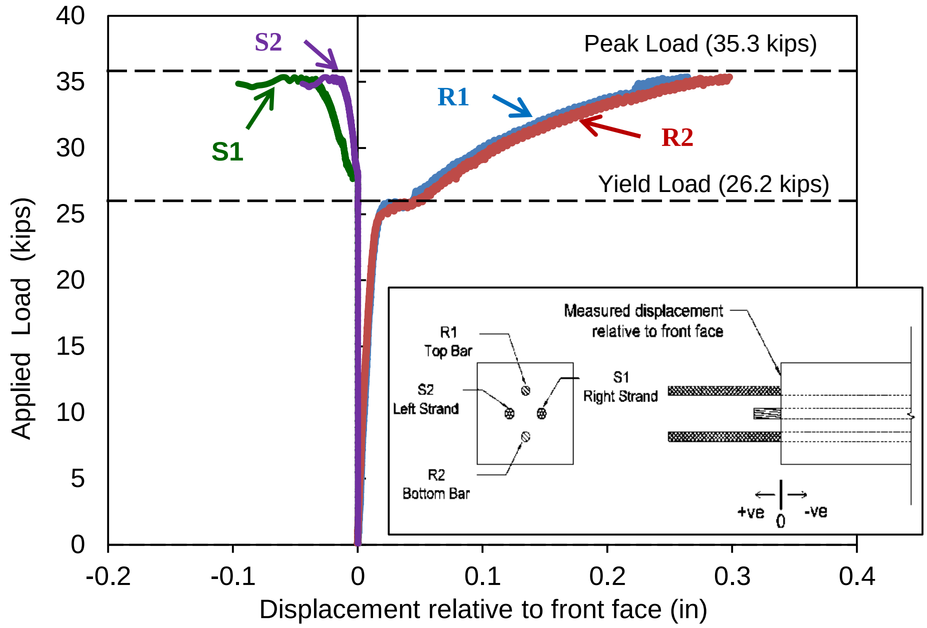
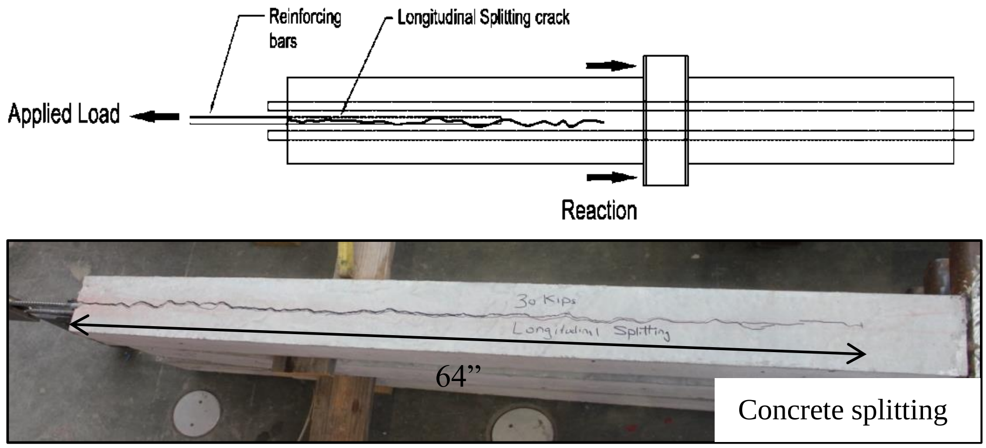
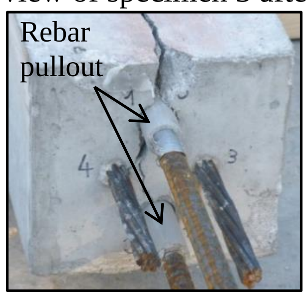


Fig. 7: Measured displacement for reinforcing bars and strands, specimen 2 (2 #No. 4 bars)

2. Splitting and reinforcing bar bond failure: This failure mode was observed for specimen 3 with the long splice length of 40 inches, which is 3.3 times the bar development length. Failure was due to splitting of the concrete and failure of the bond between the deformed steel reinforcing bars and the concrete prism as shown in Figure 8(a). Prior to failure, a longitudinal splitting crack formed along the plane containing the two reinforcing bars. The crack originated at the front face of the specimen, as shown in Figure 8(b) and progressed rapidly along the length of the prism. The longitudinal splitting crack resulted from high circumferential tensile stresses induced from bearing of the bar lugs on the concrete along the bonded length of the bar.



(a) Top view of specimen 3 after failure

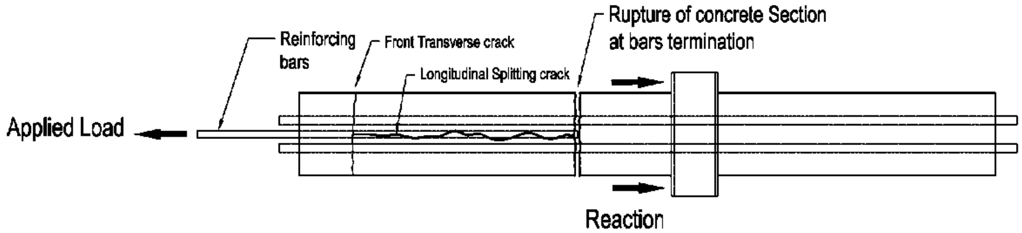


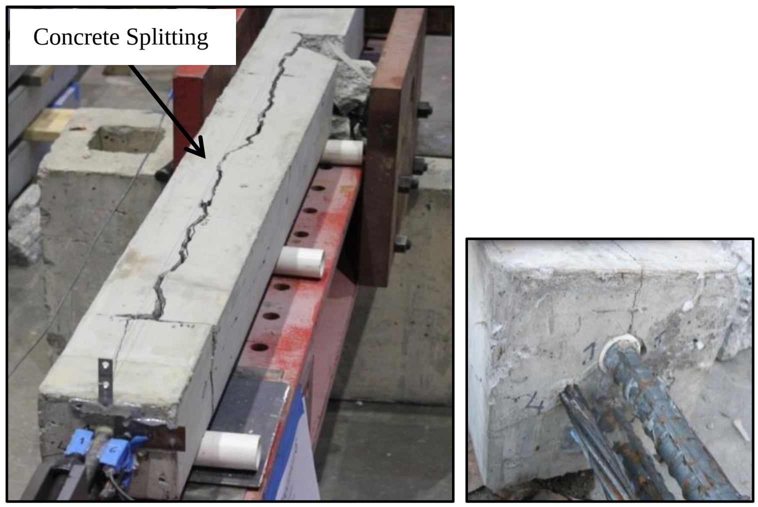
(b) Front face

Fig. 8: Longitudinal splitting and rebar bond failure

3. Splitting and strand bond failure: This failure mode was observed in all remaining specimens. Typically, while increasing the applied load, a transverse crack occurred close to the front face of the specimen at a low load level. Prior to failure, a longitudinal splitting crack initiated at the front transverse crack and extended rapidly towards the embedded end of the splice. Failure occurred, shortly after the longitudinal splitting crack appeared. Failure was by rupture of the concrete section at the section where the embedded end of the reinforcing bars terminated. This was also accompanied by slipping of the prestressing strands. Concrete splitting and strand bond failure for specimens 6 and 8 are shown in Figure 9.

Specimen 8, with a single #No. 8 reinforcing bar and a splice length of 56 inches (2.3 times bar development length) exhibited a different behavior. A series of transverse cracks formed at 7, 17, 28, 44 and 51 inches from the front face of the specimen. Longitudinal splitting cracks initiated at the transverse cracks locations and progressed along the length of the specimen as the loading was increased. Failure occurred when the concrete ruptured at the end of the reinforcing bars, and the strands slipped through the concrete prism.





Specimen 6 (2 #No. 6 bars) after failure

Specimen 8 (1 #No. 8 bar) after failure

Fig. 9: Longitudinal splitting and strand bond failure

The measured relative displacement of the reinforcing bars (R1 and R2) and prestressing strands (S1 and S2) with respect to the front face of specimen 6 is shown in Figure 10. The behavior clearly indicate that slipping of the prestressing strands increased after the formation of the longitudinal splitting crack due to loss of strand bond. The measured results, given in Table 3, indicate the load level at which the longitudinal splitting crack occurred and the maximum strand slip prior to failure. Test results indicated that failure occurred before yielding of the large diameter reinforcing bars for specimens 5, 6 and 7 due to the premature splitting cracks. The use of large diameter bars in these specimens reduces the effective confining concrete area surrounding the bars and as the reinforcement bars are loaded and the lugs engage the concrete, the radial force promotes a concrete splitting failure.

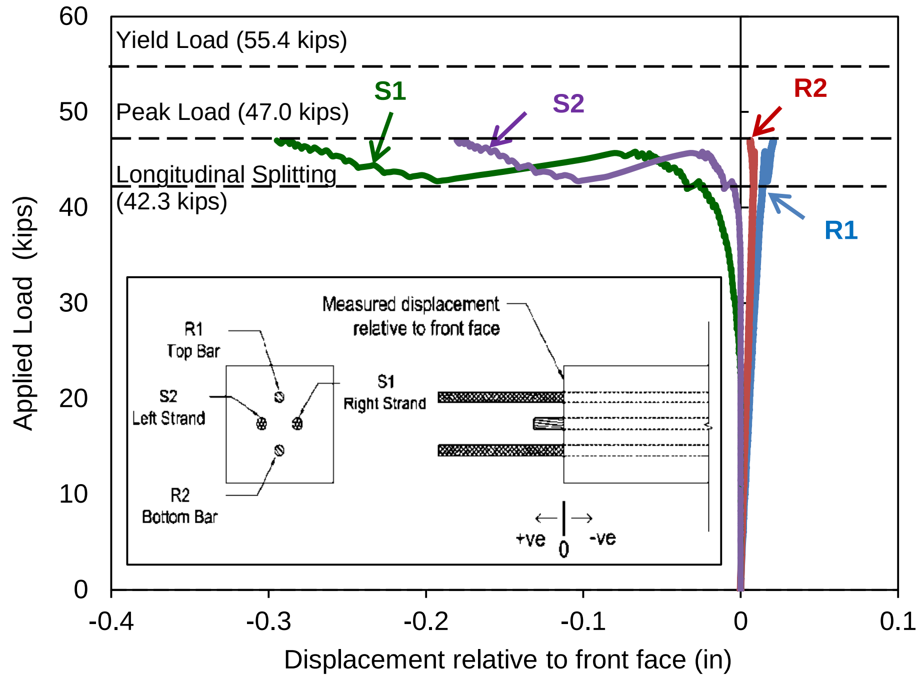


Fig. 10: Measured displacement for reinforcing bars and strands, specimen 6 (2 #No. 6 bars)

A plot of the ratio of the splice length to the bar development length versus the ratio of the measured failure load to the yield load of the deformed reinforcing steel bars for all tested specimens is shown in Figure 11(a). The figure indicates that yielding of #No. 4 bars could be developed with splice length as small as the development length of the bar. For bars with larger diameter (#No. 6 and #No. 8), the bar yielding occurred when the splice length is equal to or more than twice the bar development length. A plot of the ratio of the splice length to the strand transfer length versus the ratio of the measured failure load to the yield load of the reinforcing bars for all tested specimens is shown in Figure 11(b). The figure clearly indicates that the yield strength of the large diameter bars (#No. 6 and #No. 8) could be developed only when the splice length is at least 1.5 times the strand transfer length. It is therefore recommended to use a splice length equal to the larger of 1.5 times the strand transfer length or 2.0 times the bar development length for bars larger than #No. 4 bars. A splice length equal to the larger of the strand transfer length or the bar development length may be used for #No. 4 bars.

Test results indicated that the performance of the splice is affected by the size, number, and position of the bars with respect to the prestressing strands. In general, smaller diameter bars performed better than larger bars. The ratio of the concrete cover to the diameter of the bars (c_b/d_b) given in Table 1, influences the propensity for concrete splitting. ACI 318-14 indicates that splitting may be avoided if this ratio is larger than 2.5. All of the lap splice specimens had a concrete cover to bar diameter ratio of 2.5, except for specimens 5 and 6, where the cover to bar diameter ratio was 1.2. Specimens with concrete cover to bar diameter ratio of 2.5 failed at load levels, higher than the bar yield strength. Specimens with cover to bar diameter ratio less than 2.5, failed at a load level less than the yield strength of the bars regardless of the splice length. These results confirm the mechanism that large diameter bars reduce the effective confining area of concrete surrounding the bars for the same concrete cross section and promote the formation of a splitting failure. Therefore the size and location of the bars should be chosen to provide adequate concrete cover to bar diameter ratio.

The full-scale test program carried out in the second phase of this research program, which will be presented in a follow on paper, discuss the performance of a wide variety of dapped end reinforcing details with concrete cover to bar diameter ratios ranging from 1.2 to 2.4.

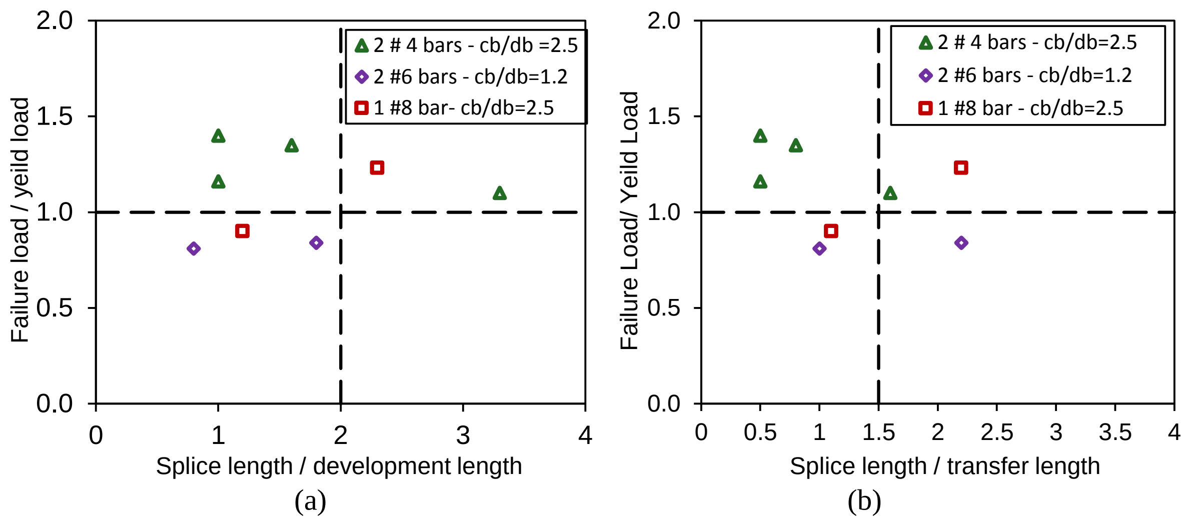


Fig. 11: (a) splice length/bar development length ratio vs. failure load/yield load ratio, (b) splice length/strand transfer length ratio vs. failure load/yield load ratio

CONCLUSIONS

Based on this study, the following conclusions and recommendations can be made:

1. Increasing the splice length increases the overall strength of the splice.
2. Failure of the splice between the deformed reinforcing bars and prestressing strands can result because of yield of the reinforcing bars, loss of strand bond, or longitudinal concrete splitting resulting from loss of strand and/or reinforcing bar bond.
3. It is recommended that the splice length should be equal to the larger of 1.5 times the transfer length of the strands or 2.0 times the development length of deformed reinforcing bars lap spliced to prestressing strands. However, a splice length equal to the larger of the bar development length or the transfer length of the strands may be sufficient for #No. 4 reinforcement bars.

4. Use of large diameter bars can lead to splitting cracks due to reduction of the effective area of concrete surrounding the bars. Where possible, it is recommended that the concrete cover to bar diameter ratio be not less than 2.5. A follow on paper on the full scale dapped tee testing program, which will be published separately, will describe the performance of a variety of dapped end details with concrete cover to bar diameter ratios ranging from 1.2 to 2.4

ACKNOWLEDGMENTS

The authors would like to thank the PCI Research and Development Council for sponsoring this research. They are also grateful for the support and guidance provided by the PCI dapped end industry advisory committee throughout all phases of this research. They are also indebted to Atlanta Structural Concrete Company for donating test specimens, materials and expertise in support of experimental program. In addition, the authors are grateful to the staff and students at the Constructed Facilities Laboratory at North Carolina State University for their help throughout the experimental program.

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