PERFORMANCE OF REINFORCEMENT LAP SPLICES

IN CONCRETE MASONRY

By

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Abstract

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This research investigated the performance of reinforcement lap splices in concrete masonry panels. Reinforcement lap splices in twelve concrete masonry panels were constructed and subjected to direct tension loading. The effects of reduced masonry cover, reinforcement distribution in the cells, and positioning of the transverse reinforcement inside or outside the spliced region were investigated.

Results from the tests of the lap splices indicate that transverse reinforcement restrains tension cracking in the masonry and improves splice performance. The current Masonry Standards Joint Committee (MSJC) provisions are conservative in predicting the strength of the splices. The MSJC provisions including a modification factor recently proposed based on research at the National Concrete Masonry Association provided a reasonable prediction of lap splice performance when the transverse reinforcement is placed inside the spliced region. Accuracy of the prediction was reduced when the transverse reinforcement was placed outside the spliced region.

The distribution of the spliced reinforcement has a significant effect on performance. For the same amount of reinforcement, the splices performed better when distributed in adjacent masonry cells rather than being concentrated in one cell.

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CHAPTER 1

INTRODUCTION AND OBJECTIVES

1.1 Introduction

Lap splices are widely used in masonry structures because of limited lengths of rebar combined with relative ease of construction and cost when compared to other splicing methods. Extensive research performed in the late 1990's led to the current lap splice provisions in the 2008 Masonry Standards Joint Committee (MSJC) *Building Code Requirements for Masonry Structures.* Although these provisions include many factors that influence the splice performance, such as the bar size, masonry strength and cover, there has been considerable discussion about the validity of the provisions since they produce very large and impractical lap lengths for large bar sizes and reduced cover.

Recent research at the National Concrete Masonry Association (NCMA 2004, 2005, 2007, 2009) has shown that the transverse reinforcement provides some degree of confinement and improves the splice performance. This research resulted in a proposed modification factor to be applied to the current MSJC equation to account for the beneficial effects of the transverse reinforcement. Although many reinforcement configurations were investigated in the NCMA studies, the transverse reinforcement was always placed inside the spliced region. Construction of masonry strucutres would be improved if it was possible to locate the transverse reinforcement outside of the spliced region and still obtain similar improvements in splice performance.

1.2 Study Objectives

This research had four objectives:

1. Investigate the validity of the recently proposed NCMA modification factor accounting for the positive effects of transverse reinforcement;
2. Investigate the influence on splice performance of the positioning of the transverse reinforcement inside or outside of the spliced region;
3. Investigate the effects of reinforcement distributed in adjacent masonry cells rather than being concentrated in one cell; and
4. Investigate the accuracy of the current MSJC provisions compared to the historic $48d_b$ equation.

In this study, lap splices were constructed in twelve concrete masonry panels and were subjected to direct tension loading. Variables investigated included size of bar, concentrated versus distributed reinforcement, length of splice, positioning of the transverse reinforcement and reduced cover resulting from bars offset in the cells.

CHAPTER 2

BACKGROUND AND PREVIOUS RESEARCH

2.1 Background

In editions of the Masonry Standards Joint Committee (MSJC) *Building Code Requirements for Masonry Structures* prior to 2005, separate lap splice provisions existed for Allowable Stress Design (ASD) and Strength Design (SD). Equation 2.1a given below is the ASD design equation that appeared in the MSJC between 1988 and 2005. Equation 2.1b is the equivalent equation using SI units.

$$l_d = 0.002 d_b F_s \qquad \text{(Equation 2.1a)}$$

$$l_d = 0.29 d_b F_s \qquad \text{(Equation 2.1b)}$$

where:

l_d = required lap splice length of reinforcement, in. (mm);

d_b = diameter of reinforcement, in. (mm); and

F_s = maximum allowable stress, psi (MPa).

The length of a lap splice was required to not be less than 12 in. (305 mm) to prevent bond failure and pullout.

For Grade 60 reinforcement, F_s = 24,000 psi (170 MPa), and Equation 2.1 simplifies to l_d = 48 d_b. This simple equation appeared in many building codes for a number of decades and is therefore widely known in the masonry design community. Although it is very simple, this equation does not take account of several important parameters, such as reduced masonry cover, the strength of masonry assemblage, or the effects of transverse reinforcement - all of which have been shown to influence lap splice performance.

Many research studies of lap splice performance were conducted in the 1990's and 2000's, including those of Soric and Tulin from the University of Colorado at Boulder (Soric, 1987); The US Army Corps of Engineers in association with Atkinson-Noland & Associates (Hammons, 1994); Thompson from Washington State University (Thompson, 1998); the Council for Masonry Research (CMR, 1998); Mjelde from Washington State University (Mjelde, 2008); and the National Concrete Masonry Association (NCMA, 2004, 2005, 2007, 2009). A large range of specimen variables was investigated in these studies, including bar sizes from No. 4 (M#13) to No. 11 (M#36); 8 in. (203 mm) and 12 in. (305 mm) concrete masonry panels; 4 in. (102 mm) and 6 in. (153 mm) clay masonry panels; masonry compressive strengths ranging from 1,700 psi (12 MPa) to 6,400 psi (44 MPa); various positions of lap within the panels; and various lap lengths.

The results of these research studies showed an amplified potential for longitudinal splitting of the masonry as the cover of masonry decreases or as the diameter of longitudinal reinforcement increases. In the 2005 MSJC, a new equation appeared based on a best fit to the test data from these studies. The required splice length was chosen to provide 1.25 times the specified yield strength of the reinforcement, on average. This MSJC equation is given below as Equation 2.2a. Equation 2.2b is the equivalent equation using SI units.

$$l_d = \frac{0.13 {d_b}^2 f_y \gamma}{K\sqrt{f'_m}} \qquad \text{(Equation 2.2a)}$$

$$l_d = \frac{1.5 {d_b}^2 f_y \gamma}{K\sqrt{f'_m}} \qquad \text{(Equation 2.2b)}$$

where:

l_d = required lap splice length of reinforcement, in. (mm);

d_b = diameter of reinforcement, in. (mm);

f_y = specified yield stress of the reinforcement, psi (MPa);

γ = 1.0 for No. 3 (M#10) through No. 5 (M#16) reinforcing bars;

1.3 for No. 6 (M#19) through No. 7 (M#22) reinforcing bars;

1.5 for No. 8 (M#25) through No. 11 (M#36) reinforcing bars;

K = lesser of [masonry cover, clear spacing of reinforcement, $5d_b$], in. (mm); and

f'_m = strength of masonry assemblage, psi (Mpa).

The length of a lap splice is required to not be less than 12 in. (305 mm) to prevent bond failure and pullout.

The transition to this new equation resulted in a substantial increase in required lap splice lengths, particularly for larger diameter bars or small cover distances. For some combinations of bar diameter and cover distance, the required length of lap increased more than two times compared to the $48d_b$ of the simplified equation, causing construction problems. Moreover, no unexplainable lap splice failures were observed when using the historical lap splice lengths, which pointed to some other mechanism perhaps increasing the capacity of the lap splices in actual masonry structures.

In the 2009 edition of the International Building Code (IBC), separate lap splice provisions exist for Allowable Stress Design (ASD) and Strength Design (SD). Equation 2.3a given below is the ASD design equation presented in the 2009 IBC. Equation 2.3b is the equivalent equation using SI units. There is a prescriptive minimum length of 12 in. (305 mm) or 40 bar diameters, whichever is less.

$l_d = 0.002 d_b f_s$ (Equation 2.3a)

$l_d = 0.29 d_b F_s$ (Equation 2.3b)

where:

l_d = required lap splice length of reinforcement, in. (mm);

d_b = diameter of reinforcement, in. (mm); and

f_s = computed stress in reinforcement due to design loads, psi (MPa).

In regions of moment where the design tensile stresses in the reinforcement are greater than 80 percent of the allowable steel tension stress, F_s, the lap length of splices shall be increased not less than 50 percent of the minimum required length.

The SD equation is the same as the current MSJC equation presented earlier (Equation 2.2), except with a prescriptive maximum of 72 bars diameters.

2.2 Previous Research

The National Concrete Masonry Association conducted a number of studies to investigate the effects of reinforcement placed transverse to the lapped bars (NCMA 2004, 2005, 2007, 2009). This research showed that transverse reinforcement can be effective at providing some degree of confinement and results in significantly improved performance and greater capacity of the splice. The research consisted of four phases. All specimens were tested in direct tension to determine the strength and performance of the splices.

For the first series of tests (NCMA, 2004), five sets of three identical concrete masonry panels were constructed using nominal 8 in. (203 mm) concrete masonry units. The longitudinal reinforcement in the panels consisted of two sets of No. 8 (M#25) longitudinal bars placed in the center of the cells and incorporating a splice length of 48 in. (1,219 mm), and the transverse reinforcement consisted of No. 4 (M#13) transverse bars placed transversally to the splices in five different configurations: no reinforcement and one or two bars positioned every course or top and bottom course only. All fifteen specimens were solidly grouted. Test results showed that transverse reinforcement was effective at providing some degree of confinement and improving the capacity of the splice. The difference in capacity between the least and the most reinforced panels (no reinforcement and two No. 4 (M#13) transverse bars placed in every course) was 50% for similarly configured lap splices. However this amount of reinforcement is uncommon, and three additional series of tests were conducted in order to investigate more precisely the effects of various types of transverse reinforcement on the splice performance.

In a second series of tests at NCMA (2005), nine sets of three identical concrete masonry panels were constructed using nominal 8 in. (203 mm) concrete masonry units. The longitudinal reinforcement consisted of two sets of No. 6 (M#19) longitudinal bars placed in the center of the cells and incorporating a splice length of 36 in. (914 mm), and the transverse reinforcement consisted of bar reinforcement placed in bond beams, bed joint reinforcement, or confinement hoops. All specimens were solidly grouted. The results showed that the presence of bond beam reinforcement or bed joint reinforcement noticeably increased the capacity of the splice, but it appeared that the presence of confinement hoops was slightly detrimental to the performance of the splices.

In a third series of tests at NCMA (2007), twenty-eight sets of three identical concrete masonry panels were constructed using nominal 8 in. (203 mm) concrete masonry units. The longitudinal reinforcement consisted of two sets of No. 8 (M#25) longitudinal bars placed in the center of the cells and incorporated splice lengths of 48 in. (914 mm), 40 in. (914 mm), 32 in. (914 mm) and 24 in. (914 mm),), and the transverse reinforcement consisted of No. 4 (M#13), No. 6 (M#19) and No. 7 (M#25) bars placed in bond beams positioned at the top and bottom of each splice, No. 3 (M#10) deformed confinement hoops placed in each course, bar positioners placed in each course, or structural fibers added in the grout. All specimens were solidly grouted. Four sets of panels were constructed using nominal 12 in. (305 mm) concrete masonry units to investigate the effects of positioning the transverse reinforcement relatively to the splice. The longitudinal reinforcement consisted of two sets of No. 8 (M#25) longitudinal bars placed at 3.8125 in. (96.8 mm) from the outside of the wall (same cover as bars placed in the center of 8 in. (203 mm) cells). All specimens were solidly grouted.

Test results showed that the addition of transverse reinforcement increased the tensile strength of the lap splice but that confinement hoops and bar positioners had little effect on the splice strength. The addition of structural fiber to the grout caused little increase in splice strength; however it reduced the amount of cracking on the post fracture surface of the masonry panels.

In the fourth series of tests at NCMA (2009), fourteen sets of three identical concrete masonry panels were constructed using nominal 8 in. (203 mm) concrete masonry units. The longitudinal reinforcement consisted of two sets of No. 8 (M#25) longitudinal bars placed in the center of the cells or offset with a cover of 2 in. (51 mm) and incorporating splice lengths of 48 in. (1219 mm) or 36 in. (914 mm), and the transverse reinforcement consisted of one No. 4 (M#13) of No. 5 (M#15) placed in the top and bottom courses. For the panels including offset longitudinal reinforcement, the transverse reinforcement was placed on either side of the splice (toward the center of the cell or toward the 2 in. (51 mm) cover). All specimens were solidly grouted. Test results showed that the transverse reinforcement in the offset panels was more effective in providing some degree of confinement when placed toward the 2 in. (51 mm) clear cover side of the splice. Still, all reinforced specimens had increased capacity compared to the centered bars and specimens without transverse reinforcement.

After conducting the four phases of research, the NCMA proposed a modification factor to be applied to the lap splice design equations, including several limitations. The proposed factor is given below as Equation 2.4a. Equation 2.4b is the equivalent equation using SI units.

$$l_d = \left(\frac{0.13{d_b}^2 f_y \gamma}{K\sqrt{f'_m}}\right)\varepsilon \quad ; \quad \varepsilon = 1 - \frac{2.3A_{str}}{{d_b}^{2.5}} \qquad \text{(Equation 2.4a)}$$

$$l_d = \left(\frac{1.5{d_b}^2 f_y \gamma}{K\sqrt{f'_m}}\right)\varepsilon \quad ; \quad \varepsilon = 1 - \frac{11.6A_{str}}{{d_b}^{2.5}} \qquad \text{(Equation 2.4b)}$$

where:

l_d = requires lap splice length of reinforcement, in. (mm);

d_b = diameter of longitudinal reinforcement, in. (mm);

f_y = specified yield stress of the reinforcement, psi (MPa);

γ = 1.0 for No. 3 (M#10) through No. 5 (M#16) reinforcing bars;
1.3 for No. 6 (M#19) through No. 7 (M#22) reinforcing bars;
1.5 for No. 8 (M#25) through No. 11 (M#36) reinforcing bars;

K = lesser of [masonry cover, clear spacing of reinforcement, $5d_b$], in. (mm);

f'_m = strength of masonry assemblage, psi (Mpa); and

A_{st} = area of transverse reinforcement, limited to 0.35 in^2 (23 mm^2).

The minimum lap splice length for confined splices was specified as 36 d_b. Additionally, the transverse reinforcement shall be placed within 8 in. (200 mm) of the ends of the lap splice and shall be offset no more than 1.5 in. (38 mm) from the lap splice. Further, the transverse reinforcement shall be placed on the near cover side of the lap for offset splices except when code-required cover distance cannot be maintained.

In 2008, Mjelde conducted research at Washington State University. Among other conclusions in his study, he found that there was no significant difference between testing lap splices in in-plane flexure walls or direct tension panels provided with the same reinforcement characteristics.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Specimen Details

Twelve wall panels were constructed using 8 in. (203 mm) nominal width concrete masonry units laid in running bond. All panels were solidly grouted. The lap spliced longitudinal reinforcement consisted of No. 6 (M#19) and No. 8 (M#25) bars and was positioned in three different configurations: centered, offset, and staggered offset, as shown in Figure 3.1.

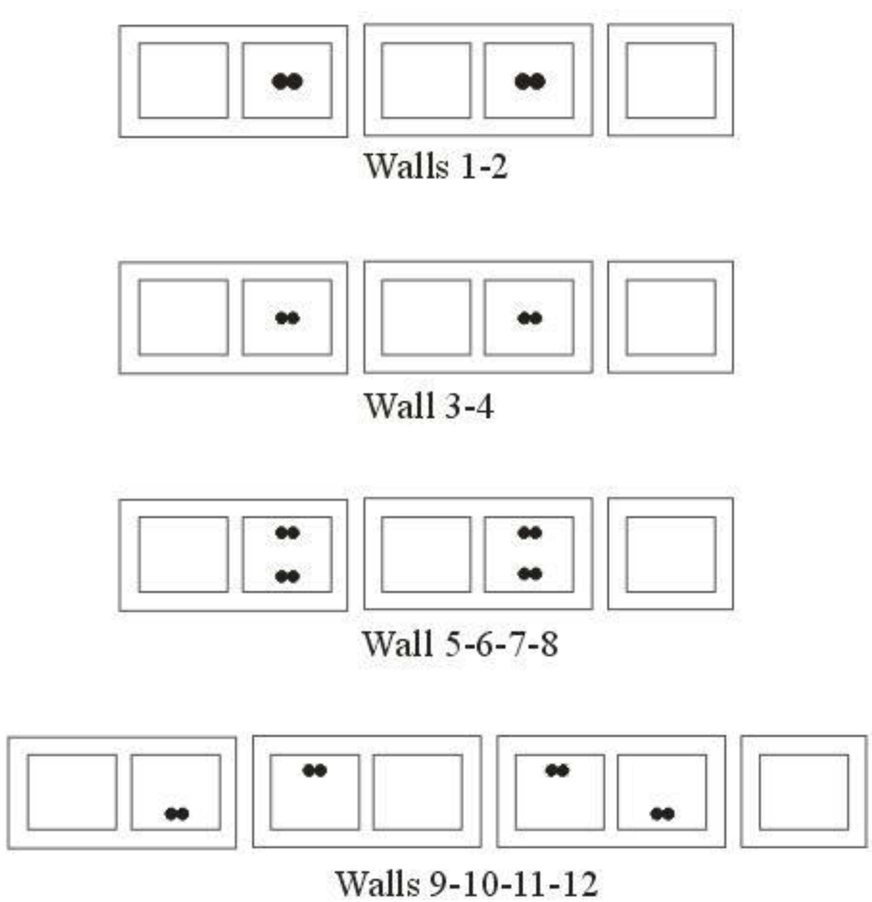

Figure 3.1. Longitudinal Reinforcement Configurations

Each panel included two sets of spliced bars to reduce eccentric moments created when loading the spliced bars in tension. For each splice, one bar protruded from the top and the other from the bottom of the panel. Each bar was loaded in direct tension to determine the strength of the splice. Loading jacks were connected in parallel to the same hydraulic system in order to equalize the forces applied to each of the splices. A drawing of the test setup is given in Figure 3.2.

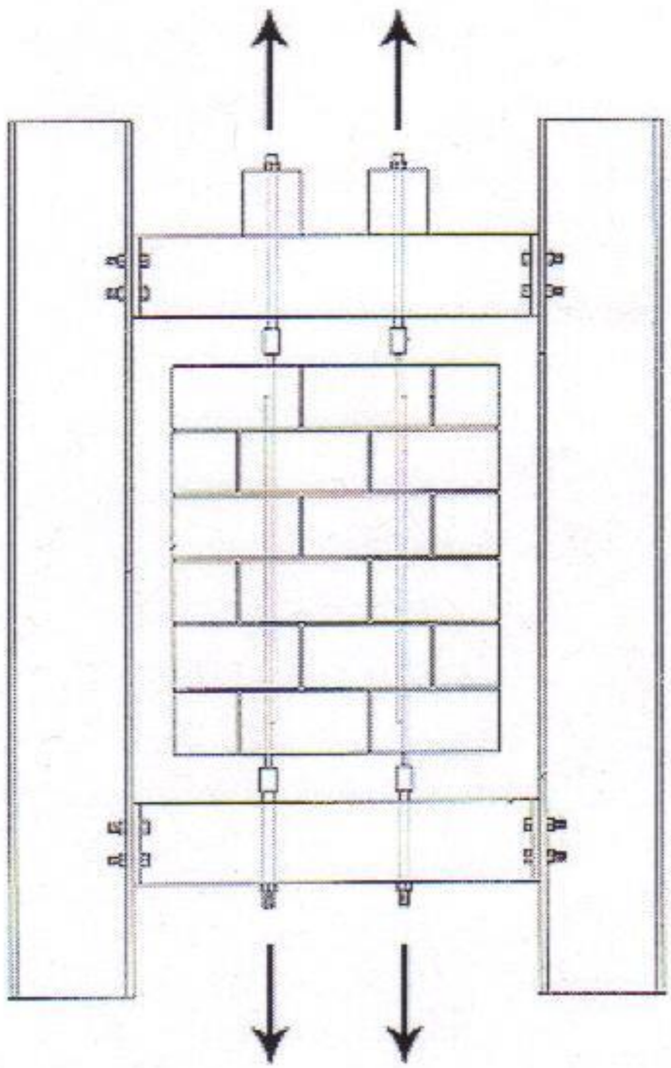

Figure 3.2. Testing Setup

Various splice lengths were used in the panels, as given in Table 3.1. Lap values are listed with respect to five measurements: absolute length, ratio to bar diameter, ratio to the simplified equation (Equation 2.1), ratio to the MSJC equation (Equation 2.2), and ratio to the MSJC equation including the modification factor (Equation 2.4).

All panels contained transverse reinforcement consisting of two No. 4 (M#13) bars placed either inside or outside the spliced region, as listed in Table 3.1. The transverse reinforcement incorporated standard 90 degree hooks at the ends for anchorage.

Table 3.1. Provided Lap Lengths

	Bar Size	Trans. Reinf.	Lap Length (in.) (1)	Lap Length (d_b)	Ratio of MSJC	Ratio of Simplified	Ratio Proposed
1	No. 8 (M#25)	Outside	36	36	0.50	0.75	0.93
2	No. 8 (M#25)	Outside	48	48	0.67	1.00	1.24
3	No. 6 (M#19)	Outside	27	36	0.78	0.75	1.00
4	No. 6 (M#19)	Outside	36	48	1.03	1.00	1.33
5	No. 6 (M#19)	Inside	36	48	0.61	1.00	1.33
6	No. 6 (M#19)	Inside	27	36	0.46	0.75	1.00
7	No. 6 (M#19)	Outside	27	36	0.46	0.75	1.00
8	No. 6 (M#19)	Outside	36	48	0.61	1.00	1.33
9	No. 6 (M#19)	Inside	36	48	0.61	1.00	1.33
10	No. 6 (M#19)	Inside	27	36	0.46	0.75	1.00
11	No. 6 (M#19)	Outside	27	36	0.46	0.75	1.00
12	No. 6 (M#19)	Outside	36	48	0.61	1.00	1.33

(1) 1 in=25.4 mm

The largest lap lengths (i.e., 48 in. (1219 mm) for the No. 8 bars and 36 in. (914 mm) for the No. 6 bars) were selected on the basis of the historical equation of a $48d_b$ lap length. The smaller lap lengths (i.e., 36 in. (914 mm) for the No. 8 bars and 27 in. (686 mm) for the No. 6 bars) were chosen to examine the potential beneficial effects of lateral reinforcement on splice performance.

The height of each wall panel was adjusted to accommodate the transverse reinforcement in the top and bottom course and depended on the lap length and whether the transverse reinforcement was placed inside or outside the spliced region. Figure 3.3 shows front views of panel 5 and panel 8, both incorporating a lap length of 36 in. (914 mm) but with different placement of the transverse reinforcement.

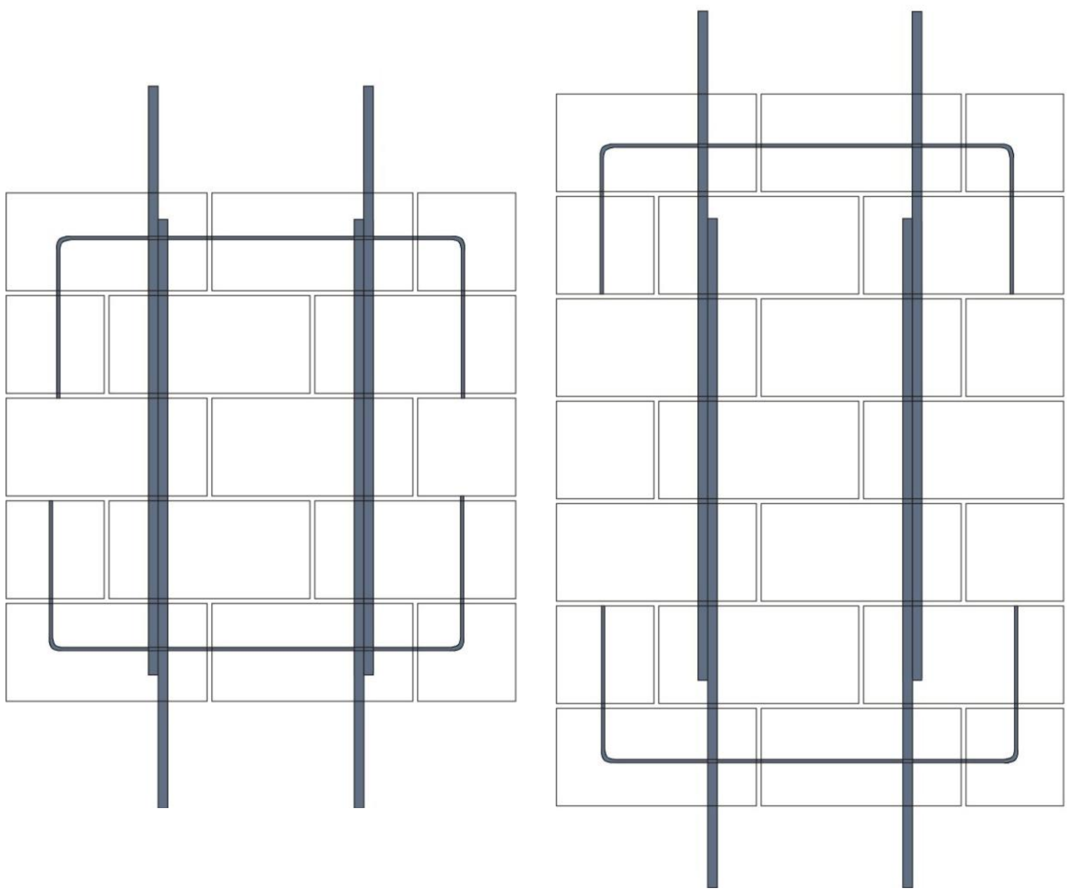

Figure 3.3. Panel 5 – Inside and Panel 8 - Outside

3.2 Materials and Material Properties

All twelve wall panels were constructed out of 8 in. (203 mm) nominal width concrete masonry units laid in running bond. Both full and half blocks, nominally 8 x 8 x 16 in. (203 x 203 x 406 mm) and 8 x 8 x 8 in. (203 x 203 x 203 mm) were used. The actual dimensions of the units were 7.625 x 7.625 x 15.625 in. (194 x 194 x 397 mm) and 7.625 x 7.625 x 7.625 (194 x 194 x 194 mm). The webs of the concrete masonry units were knocked out when needed to accommodate the transverse reinforcement. Results from compressive tests of the concrete masonry unit are given in Table 3.2.

Table 3.2. Concrete Masonry Units Test Results

Specimen	Compressive strength
1	2,728 psi (18.8 MPa)
2	2,710 psi (18.7 MPa)
3	2,413 psi (16.6 MPa)
4	2,679 psi (18.5 MPa)
Average	**2,633 psi (18.2 MPa)**

Type S masonry cement mortar was mixed onsite and used to construct all panels and prisms. Five test cylinders of the mortar (conforming to ASTM C780), 2 in. (51 mm) diameter by 4 in. (102 mm) height were made during construction and set aside for later compression testing. The results of mortar testing are summarized in Table 3.3.

Table 3.3. Mortar Test Results

Specimen	Compressive strength
1	3,048 psi (21.0 MPa)
2	2,494 psi (17.2 MPa)
3	1,924 psi (13.3 MPa)
4	1,937 psi (13.4 MPa)
5	2,844 psi (19.6 MPa)
Average	**2,450 psi (16.9 MPa)**

A coarse aggregate grout containing 6.5 sacks of Portland cement was obtained from a local ready-mix supplier and was used in the panels. Three grout prisms conforming to ASTM C1019 were made during construction, set aside and then capped for later compression testing. The results of the grout testing are summarized in Table 3.4.

Table 3.4. Grout Test Results	
Specimen	Compressive strength
1	4,980 psi (34.3 MPa)
2	4,388 psi (30.3 MPa)
3	5,179 psi (35.7 MPa)
Average	**4,849 psi (33.4 MPa)**

At the same time as the panels were constructed, three grouted masonry prisms were constructed, set aside and then capped for later compression testing in accordance with ASTM C1314. The results of masonry prism testing are summarized in Table 3.5.

Table 3.5. Masonry Prisms Test Results	
Specimen	Compressive strength
1	2,510 psi (17.3 MPa)
2	2,753 psi (19.0 MPa)
3	2,585 psi (17.8 MPa)
Average	**2,616 psi (18.0 MPa)**

The longitudinal reinforcement consisted of No. 6 (M#19) and No. 8 (M#25) bars, and the transverse reinforcement consisted of No. 4 (M#13) bars. All bars used in this study were specified as Grade 60 (410 MPa). Tension tests were performed on short bar sections to determine actual yield strengths. The results of the bar testing are summarized in Table 3.6.

Table 3.6. Reinforcing Bar Tests	
Bar size	Average yield strength
No .4 (M# 13)	**66.8 ksi** (460.2 MPa)
No .6 (M# 19)	**63.7 ksi** (439.3 MPa)
No. 8 (M# 25)	**62.3 ksi** (429.4 MPa)

3.3 Construction of Test Specimens

The panels were constructed on wooden platforms which incorporated circular holes to ensure precise positioning of the longitudinal reinforcement (Figure 3.4). No initial leveling bed of mortar was used. The wall panels where the longitudinal reinforcement was in the "centered" and "offset" configurations were two and a half blocks long (walls No. 1 to No. 8), and the "staggered offset" panels were three and a half blocks long (walls No. 9 to No. 12), to ensure a consistency in the cover in the transverse direction and in the placement of the transverse reinforcement. All panels were constructed such that the longitudinal reinforcing bars protruded 8 in. (203 mm) from the masonry to allow mechanical coupling to the bars for direct tension testing.

Professional masons constructed all twelve panels in running bond with face shell and web mortar bedding. As each wall was constructed, the transverse reinforcement was placed and tied in position using small-gage tie wire. On the first day of construction, the mortar and blocks for all twelve specimens were placed and the lapped bars, tied together using small-gage wire, were dropped into the cells and through the wood form (Figure 3.5). On the second day of construction, all twelve specimens were fully grouted. The grout was placed in the panels in a single lift and mechanically consolidated and reconsolidated using a vibrator (Figure 3.6). A wood board which incorporated circular holes was then placed on top of the panel to ensure a proper positioning of the bars (Figure 3.7). The panels were cured under ambient conditions in the laboratory.

Figure 3.4. Start of Construction

Figure 3.5. Panel Ready for Grouting

Figure 3.6. Grouting and Vibrating

Figure 3.7. Panels Curing

3.4 Testing Procedures

The testing setup consisted of a steel frame constructed of four members bolted together to form a rectangular perimeter around the test panel, mechanical couplers, two hydraulic jacks and a hydraulic control. The frame was placed transversely on the laboratory floor and each panel was lowered into the testing frame onto two smooth steel bars acting as rollers to allow panel movement during testing.

The mechanical couplers were high-strength commercial couplers specified to develop 150% of the yield strength of the bars. They were placed onto each piece of the protruding reinforcement and tightened. On the other end of the coupler, extension rods were connected and extended through the steel frame. They were anchored to one side of the testing frame and were connected to the loading jacks on the other side of the frame.

Figure 3.8 shows a panel in the “centered” configuration and placed in the loading frame used to apply direct tension in the reinforcing bars.

Figure 3.8. Testing Setup (Panel No.4)

Once the specimen was securely positioned in the frame, the hydraulic pump was activated and loading of the specimen began. Fluid pressure was increased manually, and the loads were monitored with a pressure gage on the hydraulic pump.

The specimen was loaded until failure occurred, defined by longitudinal splitting of the masonry, pullout of the reinforcement, or failure of the couplers or the extension rods. In this last case, when the failure was not caused by the panel itself, the element that failed was reinforced or replaced and the panel was loaded again until failure.

In several instances, the couplers connecting the bars protruding from the panels to the loading rods slipped on the bars (Figure 3.9.) and resulted in damage to the couplers, especially when connected to the No.8 (M#25) bars (Specimens No.1 and No.2). New couplers were installed and the bars reloaded until failure was achieved in the specimen.

Figure 3.9. Damage in Coupler

CHAPTER 4

TEST RESULTS AND DISCUSSION

4.1 Cracking Patterns and Failure Modes

Cracking patterns and failure modes in the test specimens varied as a function of the longitudinal reinforcement distribution and the positioning of the transverse reinforcement relative to the splice. Two general patterns of cracking were observed:

- Panel tension cracking – cracking along bed joints perpendicular to the longitudinal reinforcement, indicating that the spliced bars reached large strain levels. Typically, this type of cracking appeared towards the end of the loading process and widened as the load increased (see Figure 4.1).

Figure 4.1. Tension Cracking

- Panel longitudinal splitting – splitting of the masonry parallel to the spliced bars. Typically, this type of cracking appeared at the ends of the panel towards the end of the loading process (see Figure 4.2), and the cracks extended suddenly on the side of the panel at failure (see Figure 4.3).

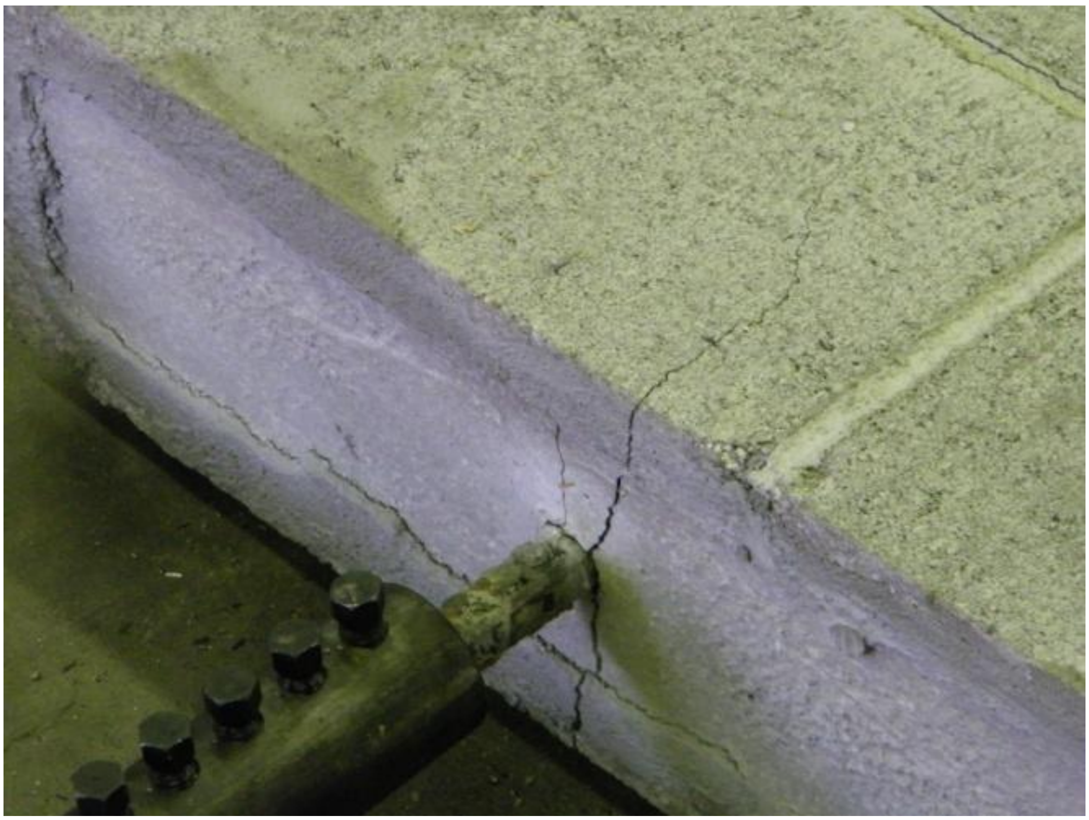

Figure 4.2. Initial Longitudinal Cracking

Figure 4.3. Longitudinal Cracking at Failure

Cracking patterns in the failed specimens can be categorized as a function of the longitudinal reinforcement configuration:

- For the "centered" reinforcement configuration, the panels reinforced with a 36 d_b splice length showed significant splitting of the masonry, while the panels reinforced with a 48 d_b splice length presented mainly transverse cracking. Typical cracking patterns are shown in Figure 4.4 for 36 d_b and Figure 4.5 for 48 d_b.

Figure 4.4. Typical Failure, Centered 36 d_b

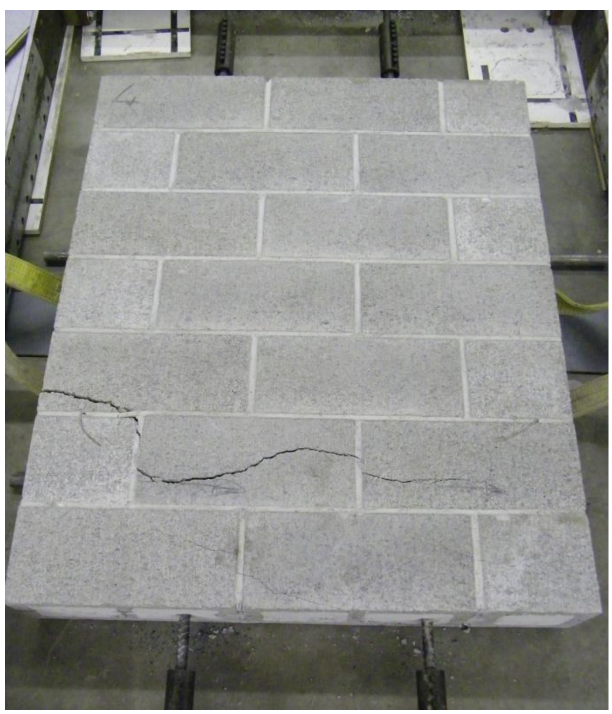

Figure 4.5. Typical Failure, Centered 48 db

- For the “offset” reinforcement configuration, the panels showed very significant damage in the masonry, regardless of the splice length or the transverse reinforcement position, perhaps caused by the reduced cover combined with a large amount of reinforcement concentrated in one cell. However, while the global failure of the specimens incorporating transverse reinforcement placed inside the splice was a classic splitting of the masonry (see Figure 4.3), the specimens where the transverse reinforcement was placed outside the splice showed extensive transverse cracking in the middle of the panel along with the cracks parallel to the splice (see Figure 4.6).

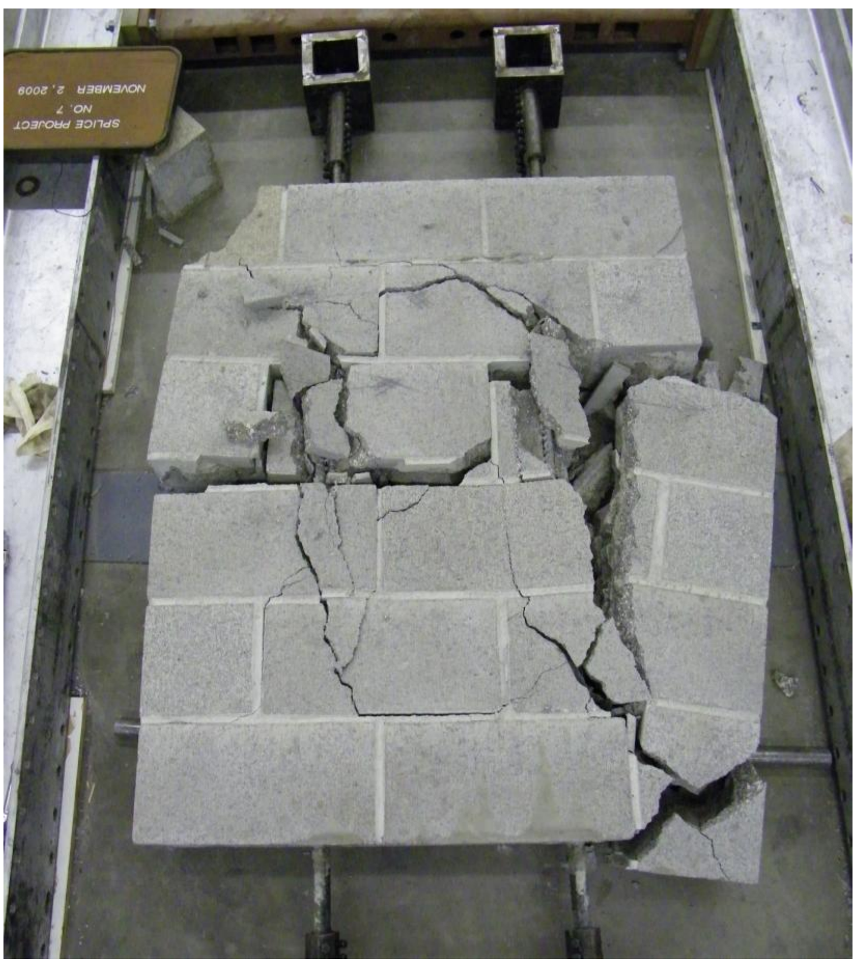

Figure 4.6. Typical Failure, Offset Outside

- For the “staggered offset” reinforcement configuration, the panels showed significant splitting of the masonry, although it was generally less dramatic than for the “offset” configuration (see Figure 4.7). The distribution of the area of longitudinal reinforcement in two cells, resulting in a lower percentage of reinforcement in a cell, seems to preserve the integrity of the masonry. The positioning of the transverse reinforcement inside or outside the splice did not have a significant effect on the cracking pattern at failure.

Figure 4.7. Typical Failure, Staggered Offset

All specimens in this study developed yielding in the bars prior to failure in the panels. Final failure modes were categorized as follows:

- Longitudinal splitting – extensive and sudden cracking of the masonry resulting in the release of the lap spliced reinforcement.
- Bar pullout (bond failure) – slippage of longitudinal reinforcement with moderate longitudinal cracking.
- Extreme yielding causing significant wall damage

Table 4.1 summarizes the failure mode observed for each panel.

Table 4.1. Splice Failure Modes

	Bar Size	Trans. Reinf.	Lap Length (in.) [1]	Failure Mode Observed
1	No. 8 (M#25)	Outside	36	Longitudinal Splitting
2	No. 8 (M#25)	Outside	48	Extreme Yielding
3	No. 6 (M#19)	Outside	27	Longitudinal Splitting
4	No. 6 (M#19)	Outside	36	Bar Pullout
5	No. 6 (M#19)	Inside	36	Longitudinal Splitting
6	No. 6 (M#19)	Inside	27	Longitudinal Splitting
7	No. 6 (M#19)	Outside	27	Longitudinal Splitting
8	No. 6 (M#19)	Outside	36	Longitudinal Splitting
9	No. 6 (M#19)	Inside	36	Longitudinal Splitting
10	No. 6 (M#19)	Inside	27	Longitudinal Splitting
11	No. 6 (M#19)	Outside	27	Longitudinal Splitting
12	No. 6 (M#19)	Outside	36	Extreme Yielding

[1] 1 in=25.4 mm

4.2 Reinforcement Stresses at Failure

The load at failure for each specimen was recorded. Table 4.2 lists the characteristics of each panel, the stress in the spliced bars at failure, and the ratio of measured bar stress to the specified yield stress.

Table 4.2. Ratio of Developed Stress to Specified Yield Stress

	Bar Size	Trans. Reinf.	Lap Length (in.) [1]	Lap Length (db)	Ratio of MSJC	Ratio of Simplified	Ratio of Proposed	Stress (ksi) [2]	Ratio to Specified Yield
1	No. 8 (M#25)	Outside	36	36	0.50	0.75	0.93	72.2	1.20
2	No. 8 (M#25)	Outside	48	48	0.67	1.00	1.24	79.0	1.32
3	No. 6 (M#19)	Outside	27	36	0.78	0.75	1.00	84.6	1.41
4	No. 6 (M#19)	Outside	36	48	1.03	1.00	1.33	95.5	1.59
5	No. 6 (M#19)	Inside	36	48	0.61	1.00	1.33	77.7	1.30
6	No. 6 (M#19)	Inside	27	36	0.46	0.75	1.00	75.7	1.26
7	No. 6 (M#19)	Outside	27	36	0.46	0.75	1.00	66.8	1.11
8	No. 6 (M#19)	Outside	36	48	0.61	1.00	1.33	78.4	1.31
9	No. 6 (M#19)	Inside	36	48	0.61	1.00	1.33	98.9	1.65
10	No. 6 (M#19)	Inside	27	36	0.46	0.75	1.00	85.9	1.43
11	No. 6 (M#19)	Outside	27	36	0.46	0.75	1.00	79.1	1.24
12	No. 6 (M#19)	Outside	36	48	0.61	1.00	1.33	83.9	1.32

(1) 1 in=25.4 mm (2) 1 ksi=6.895 MPa

4.3 Discussion of test results

In addition to the results obtained for the specimens tested in this study, results from recent NCMA investigations (2005 and 2007) were also included in the graphs and labeled as *NCMA No. 8 centered (inside)* and *NCMA No. 6 centered (inside)*.

The *NCMA No. 8 centered (inside)* were four sets of panels tested a part of NCMA research Phase III (2007) and incorporated similar characteristics as panels 1 and 2 of this study (fully grouted 5-cells wide panels, reinforced with two No. 8 (M#25) longitudinal bars centered in the cells and one No. 4 (M# 13) transverse bar top and bottom course only, tested in direct tension) except for the positioning of the transverse reinforcement (placed inside the splice in the NCMA research and outside in this study). Each of the four sets incorporated a different lap length (48 in., 40 in., 32in. and 24 in. respectively 1219 mm, 1016 mm, 813 mm and 610 mm).

The *NCMA No 6 centered (inside)* was one set of three identical panels tested as part of NCMA research Phase II (2005) and incorporated similar characteristics as panels 3 and 4 of this study (fully grouted 5-cells wide panels, reinforced with two No. 6 (M#25) longitudinal bars centered in the cells and one No. 4 (M# 13) transverse bar top and bottom course only, tested in direct tension) except for the positioning of the transverse reinforcement (placed inside the splice in the NCMA research and outside in this study). The panels incorporated 36 in. long lap splices.

Comparisons with Simplified Equation

A plot of the lap splice length as a ratio with the simplified equation (Equation 2.1) for 48 d_b lap splice lengths versus the ratio of developed stress to specified yield stress is presented in Figure 4.8. An ideal fit is when a stress ratio of 1.25 is achieved at a lap splice ratio of 1.0.

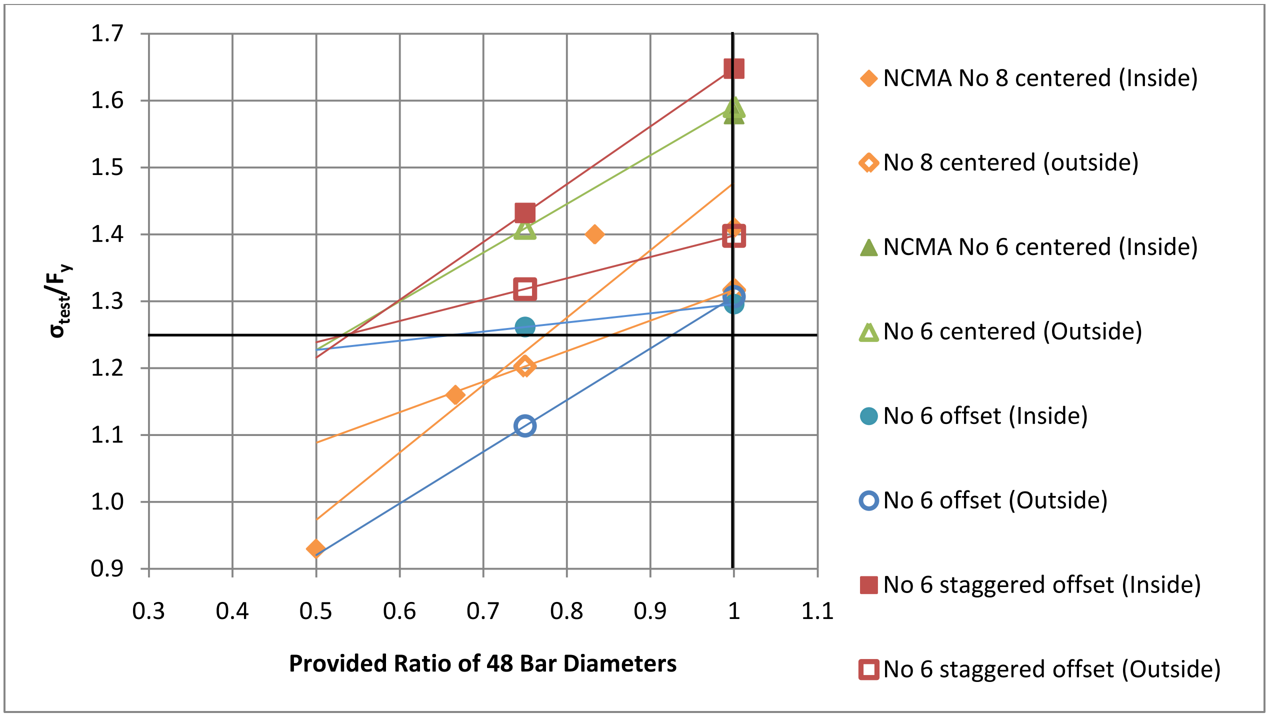

Figure 4.8. Provided Ratio of Equation 2.1 Versus σ_{test}/F_y

From this figure, several observations can be made:

- The simplified equation either provides a reasonable fit to the data or is conservative.
- For the No. 8 (M#25) bars centered in the cells, splices at 48 d_b perform better when the transverse reinforcement is placed inside the splice, and there is no notable difference with the location of the transverse reinforcement for splices at 36 d_b.
- The No. 6 (M#19) bars centered in the cells show no difference between the inside/outside placement of the transverse reinforcement.
- For the offset reinforcement configuration, the trend lines are much closer to the limit of 1.25 σ_{test}/F_y , and the positioning of the transverse reinforcement outside the splice is detrimental to the splice performance for short splice lengths but does not affect the splice strength for longer splice lengths.

- The staggered offset configuration with the reinforcement distributed in adjacent cells performs better than the offset configuration with the reinforcement concentrated in one cell. This configuration also shows a significant decrease in strength when the transverse reinforcement is placed outside the spliced region compared to when it is placed inside.

Globally, it can be concluded that lap splices of this study performed satisfactorily when compared to simplified lap splice design equation of 48 d_b, that in most cases the splices perform better when the transverse reinforcement is placed inside the spliced region, and that the distributed reinforcement configuration performs better than the concentrated configuration.

Comparisons with Current MSJC Equation

A plot of the lap splice length as a ratio to that required by the current MSJC equation (Equation 2.2) versus the ratio of developed stress to specified yield stress is presented in Figure 4.9. Again, an ideal fit is when a stress ratio of 1.25 is achieved at a lap splice ratio of 1.0.

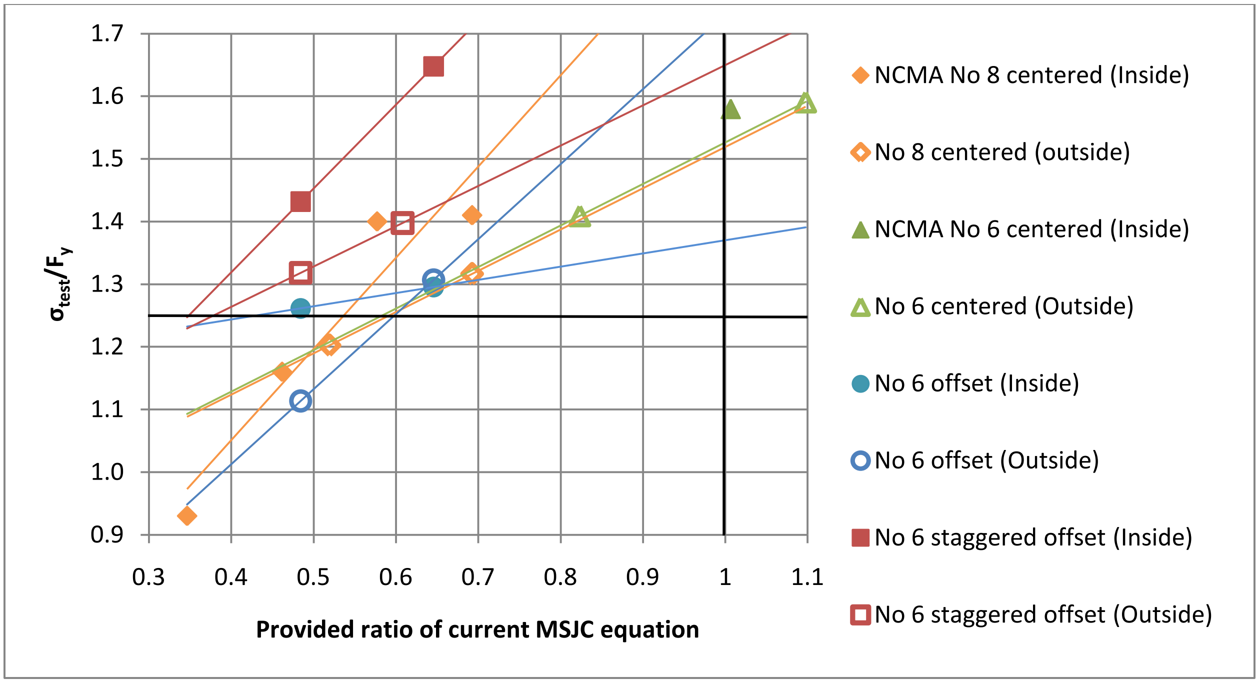

Figure 4.9. Provided Ratio of Equation 2.2 Versus σ_{test}/F_y

From this figure, several observations can be made:

- All splices are satisfactory with respect to the MSJC current equation; however, the provisions appear to be very conservative.
- For the No. 8 (M#25) bars centered in the cells, the MSJC provisions are very conservative, even when the transverse reinforcement is placed outside of the spliced region.
- The No. 6 (M#19) bars centered in the cells show no significant difference between the inside/outside placed of the transverse reinforcement. The MSJC provisions are still conservative.
- For the offset configuration, the positioning of the transverse reinforcement outside the spliced region reduces splice performance for short splice lengths but does not

affect the splice strength for longer splice lengths. Both positions produce lap performance that is conservative with respect to the MSJC current provisions.

- The staggered offset configuration with the reinforcement distributed in adjacent cells again performs better than the offset configuration with the reinforcement concentrated in one cell. Panels where the transverse reinforcement is placed inside the spliced region perform better than the panels where the transverse reinforcement is placed outside the splice.

Globally, it can be concluded that all panels perform very conservatively with respect to the current MSJC provisions, that in most cases the splices performs better when the transverse reinforcement is placed inside the splice, and that the distributed reinforcement configuration performs better than the concentrated configuration.

Comparisons with MSJC Provisions Incorporating Transverse Modification Factor

A plot of the lap splice length as a ratio to the MSJC provisions incorporating the proposed modification factor (Equation 2.4) versus the ratio of developed stress to specified yield stress is presented in Figure 4.10. Again, an ideal fit is when a stress ratio of 1.25 is achieved at a lap splice ratio of 1.0.

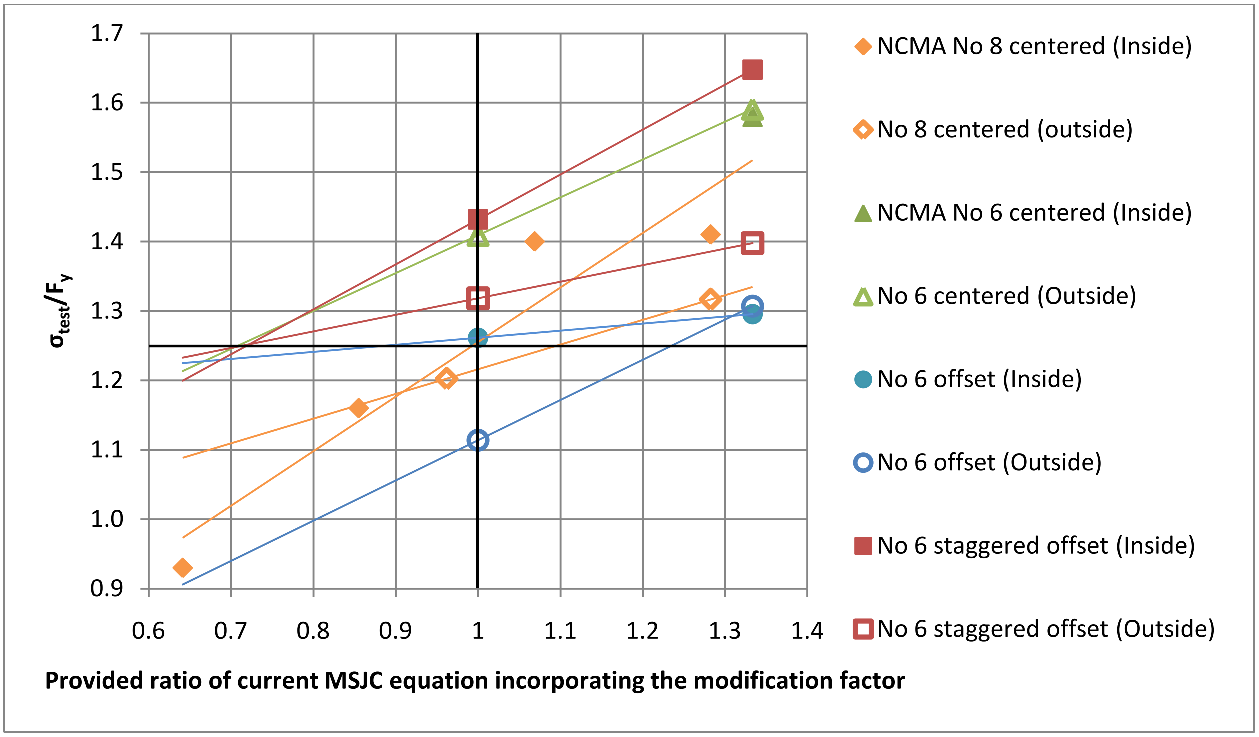

Figure 4.10. Provided Ratio of Equation 2.4. Versus σ_{test}/F_y

From this figure, several observations can be made:

- The lap splice data from this study either provides a reasonable fit to the MSJC provisions incorporating the modification factor or is slightly conservative, except for the offset configuration with the transverse reinforcement placed outside the spliced region.
- For the No. 8 (M#25) bars centered in the cells, the data fits the MSJC provisions incorporating the modification factor. Placing the transverse reinforcement outside the splice seems to be detrimental to the splice strength for large lap lengths but does not affect the splice performance for the smaller lap lengths.

- The No. 6 (M#19) bars centered in the cells show no significant difference between the inside/outside placement of the transverse reinforcement. The MSJC provisions incorporating the modification factor are slightly conservative.
- For the offset configuration, placing the transverse reinforcement outside the splice makes the provisions become slightly unconservative, while the panels where the transverse reinforcement was placed inside the splice fit the provisions.
- The staggered offset configuration with the reinforcement distributed in adjacent cells again performs better than the offset configuration with the reinforcement concentrated in one cell. However, the difference is less significant. Panels where the transverse reinforcement is placed inside the spliced region perform better than the panels where the transverse reinforcement is placed outside the splice.

Globally, it can be concluded that the MSJC provisions incorporating the modification factor fit the data or is slightly conservative, that in most cases the splices performs better when the transverse reinforcement is placed inside the splice, and that the distributed reinforcement configuration performs better than the concentrated configuration. When the three factors that can potentially decrease the strength of the splices (reduced cover, concentrated reinforcement, and transverse reinforcement placed outside the splice) are combined, it appears to cause the performance of the splices to be lower than is predicted.

Effects of Position of Transverse Teinforcement

For the “offset” and “staggered offset” reinforcement configurations, each splice length tested was reinforced with transverse reinforcement placed either inside or outside the spliced region. For the "centered" configuration, only panels incorporating outside transverse reinforcement were constructed and tested, and the results were then compared with equivalent panels tested in the NCMA research.

Table 4.3 summarizes the differences between the transverse reinforcement being placed inside or outside the spliced region for a same splice length and configuration. The table shows that panels where the transverse reinforcement is placed inside the spliced region perform an average of 7% better than the similar panel with the transverse reinforcement placed outside the splice. However these results are based on limited data; each specimen configuration was tested only once, not allowing for statistical analysis of the results.

Table 4.3. Results with Transverse Reinforcement Placed Inside and Outside

Bar Size	Configuration	Lap Length (in.)	% Difference Inside/Outside
No. 8 (M#25)	centered	48	6.4
No. 8 (M#25)	centered	36	-0.6
No. 6 (M#19)	offset	36	-0.9
No. 6 (M#19)	offset	27	11.7
No. 6 (M#19)	staggered offset	36	15.2
No. 6 (M#19)	staggered offset	27	7.9

(1) 1 in=25.4 mm

Effects of Longitudinal Reinforcement Distribution

Table 4.4 summarizes the differences between the longitudinal reinforcement concentrated in one cell or distributed in two adjacent cells for the same splice length and position of transverse reinforcement. The results given in the table show that panels where the longitudinal reinforcement is distributed in adjacent cells perform an average of 14% better than the same panel with the longitudinal reinforcement concentrated in one cell. Again, these results are based on limited data; each specimen configuration was tested only once, not allowing for statistical analysis of the results.

Table 4.4. Results with longitudinal reinf. Distributed Vs. Concentrated			
Bar Size	Trans. Reinf.	Lap Length (in.)	% Diff. Distributed/Concentrated
No. 6 (M#19)	inside	36	21.4
No. 6 (M#19)	inside	27	11.9
No. 6 (M#19)	outside	36	6.5
No. 6 (M#19)	outside	27	15.5

(1) 1 in=25.4 mm

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 Summary

This study investigated the performance of lap splices in 8 in. (203 mm) masonry panels tested in direct tension. Reinforcement lap splices in twelve panels were constructed and tested in direct tension. The effects of the following variables were investigated: length of lap, size of bar, positioning of transverse reinforcement, concentrated versus distributed reinforcement configuation, and reduced cover resulting from bars offset in the cells. Evaluations of lap splice performance in this study were based on comparisons of the test results along with results from previous research at the NCMA as well as comparisons to code requirements with and without a recently proposed modification factor to account for the potentially beneficial effect of transverse reinforcement.

5.2 Conclusions

Based on the results of this research, the following conclusions are reached:

- *2008 MSJC including the modification factor*: the equation is reasonably accurate for all configurations, except when the three factors that make the splice susceptible to early failure (reduced cover, concentrated reinforcement, and transverse reinforcement placed outside the splice) are present at the same time. Results from this study support the validity of the modification factor recently proposed through research conducted at the NCMA.

- *Positioning of the transverse reinforcement*: splice performance is reduced by 7% when the transverse reinforcement is placed outside the spliced region compared to inside the splice. Additional research is recommended to develop guidelines to more accurately quantify this reduction.
- *Effects of distribution of reinforcement*: when placed offset from center, the longitudinal reinforcement should be distributed in adjacent cells, as it significantly increases splice performance.
- *2008 MSJC provisions vs. historic equation of 48d_b*: Test results in this study are conservative when compared to the current MSJC provisions. The historic splice design equation of 48d_b is also conservative, but less so than the current MSJC provisions. It should be noted that all specimens tested in this study incorporated transverse reinforcement, which has been shown to increase the capacity of splices.

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