PERFORMANCE OF LAP SPLICES IN CONCRETE MASONRY SHEAR WALLS UNDER IN-PLANE LOADING

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SUMMARY

This research investigated the performance of reinforcement lap splices in concrete masonry shear walls incorporating common reinforcing details and loaded in in-plane flexure until failure. Results from the lap splice tests of this study indicate satisfactory performance of reinforcement splices with lap lengths of 48 bar diameters, provided the bars are centered in the masonry cells and are in masonry walls incorporating horizontal reinforcement. Bars offset in the cells, resulting in reduced cover, performed relatively poorly, even when provided with lap lengths of 60 bar diameters.

INTRODUCTION

Splices of reinforcing bars are required for the construction of most masonry structures. While splicing alternatives exist, such as proprietary mechanical devices, lap splices are the most widely-used and cost-effective method. The current lap splice provisions in the 2005 Masonry Standards Joint Committee (MSJC) *Building Code Requirements for Masonry Structures* are largely based on research performed in the late 1990's. Since their introduction, the provisions have been scrutinized and debated, in part because they can produce very large and impractical lap lengths when certain variables are encountered. The current provisions are well supported by laboratory tests of lap splices. Most of the tests upon which the provisions are based, however, involved loading the lap splices in direct tension, and the test panels typically did not contain any reinforcement transverse to the lapped bars. While this loading scheme provides a clear indication of lap performance, it does not represent typical loading of lap splices in real structures. Additionally, recent research National Concrete Masonry Association (2005) has shown improvements in lap splice behavior resulting from confinement to the lap splice from horizontal reinforcement.

The primary objective of this research is to evaluate the behavior of reinforcement lap splices in concrete masonry shear walls loaded under in-plane lateral loading. More realistic loading

conditions, specifically tensioning of the reinforcement through flexural action and in masonry walls with transverse reinforcement, are used to evaluate the performance of lap splices. Variables investigated in this study include length of lap, size of bar, concentrated versus distributed reinforcement, and reduced cover resulting from bars offset in the cells.

BACKGROUND

In general, failure of splices in reinforced masonry structures subjected to a tensile loading can take four possible modes (Thompson, 1997). The first failure mode is bond failure, which occurs when internal radial cracks propagate until either the masonry splits or the reinforcement is released with fragmentation of the grout. The second failure mode is course separation, which occurs when masonry is subjected to tension, thus splitting the courses at the weak mortar bond and greatly altering the distribution of bond stresses along the length of the reinforcing bar. The third failure mode is longitudinal splitting of the masonry assemblage, which results from a combination of radial stresses and the "riding-up" of one lapped bar on another. The final failure mode is reinforcement yielding.

In the current 2005 MSJC Code, there is a single equation for determining the minimum required lap splice length, presented here as Equation (1). This equation was derived to fit a broad set of test data of lap splices loaded in direct tension. The intent of the MSJC provisions is to achieve 125% of nominal yield strength in the lapped bars, with a prescriptive minimum lap length of 305 mm (12 inches) to prevent bond failure and pullout.

$$l_s = \frac{1.5 d_b^2 f_y \gamma}{K\sqrt{f'_m}} \quad (\text{mm, MPa}) \qquad l_s = \frac{0.13 d_b^2 f_y \gamma}{K\sqrt{f'_m}} \quad (\text{in., psi}) \qquad (1)$$

In the above equations, K shall not exceed the least of the masonry cover, clear spacing between adjacent reinforcement, and 5 times d_b. The bar size factor, γ, is equal to 1.0, 1.3, and 1.5 for small (M#10, M#13, and M#16), intermediate (M#19, M#22), and large (M#25 and larger) bar sizes, respectively.

In previous editions of the MSJC Code, separate lap splice equations existed for Allowable Stress Design (ASD) and Strength Design (SD) provisions. Equation (2) is the ASD design equation used by the MSJC Code between 1988 and 2005. This equation also appeared in other building codes for a number of decades preceding the 1988 MSJC Code, and is therefore widely known in the masonry design community.

$$l_s = 0.29 d_b F_s \quad (\text{mm, MPa}) \qquad l_s = 0.002 d_b F_s \quad (\text{in., psi}) \qquad (2)$$

F_s is the maximum allowable stress in the reinforcement. For Grade 60 reinforcement, F_s = 24,000 ksi, and thus, l_s, is equal to 48 bar diameters.

While the previous ASD equation is simple to apply, it does not recognize several parameters found to influence lap splice performance, including masonry strength and reinforcement cover. In addition, results from numerous laboratory tests indicated the ASD design equation was unconservative for certain lap splice configurations, particularly for larger bar sizes.

Accordingly, the 2005 edition of the MSJC Code adopted unified lap splice provisions for both ASD and SD, largely based on the original SD provisions.

EXPERIMENTAL PROGRAM

Nine concrete masonry cantilever shear walls incorporating flexural reinforcement lap splices at the bases of the walls were subjected to in-plane cyclic loading. The wall specimens were constructed on heavily-reinforced concrete footings that anchored the specimens to the floor, thus providing rigid support at the wall bases. The walls were constructed of fully grouted concrete masonry in running bond. All walls had dimensions of 121 cm x 19.4 cm x 263 cm (47.6 in. x 7.63 in. x 104 in.). The height of load application for each wall was 213 cm (84 in.), and thus the wall aspect ratio was 1.76. The testing matrix is presented in Table 1.

The test specimens were designed such that side cover met or exceeded code defined (MSJC) end cover requirements for all vertical reinforcement bars. The compressive strength of the masonry was determined from tests of masonry prisms to be 23,600 kPa (3420 psi). The specified yield strength of the reinforcing steel was 414 MPa (60 ksi), with a measured yield strength of 449 MPa (65 ksi). Horizontal reinforcement in the walls was provided so as to exceed the required shear strength as predicted by moment-curvature analysis. Horizontal bars with hooks on each end were placed in every other course, beginning with the first and ending with the last. The horizontal reinforcement consisted of M#13 (No. 4) bars unless otherwise specified in Table 1.

A hydraulic actuator applied in-plane lateral loading to the walls through two steel channels bolted to the walls. Figure 1 shows a photograph of a wall during testing. The shear walls were tested under displacement control. Displacement amplitudes were based on multiples of the theoretical displacement to cause first yielding of the extreme tensile reinforcement bar in each wall. The loading pattern consisted of three cycles at a given displacement level, which was progressively increased until failure of the wall, defined as a 20% drop in applied load.

Figure 1. Test Setup

Table 1. Test Specimen Details

					2005 MSJC		Previous ASD	
Wall	Bar Size	Lap Length, cm. (in.)	Comment	Side Cover, cm. (in.)	Required Lap Length, cm. (in.)	% of Required Lap Length Provided	Required Lap Length, cm. (in.)	% of Required Lap Length Provided
1	M#25 (No. 8)	122 (48)	48 db splice, concentrated reinforcement	8.4 (3.3)	155 (61)	79%	122 (48)	100%
2	M#25 (No. 8)	91 (36)	36 db splice, concentrated reinforcement	8.4 (3.3)	155 (61)	59%	122 (48)	75%
3	M#25 (No. 8)	91 (36)	36 db splice, concentrated reinforcement, horizontal reinforcement is 2 No.3's @ 40.6 cm (16 in.) o.c.	8.4 (3.3)	155 (61)	59%	122 (48)	75%
4	M#25 (No. 8)	152 (60)	60 db splice, concentrated reinforcement	8.4 (3.3)	155 (61)	99%	122 (48)	125%
5	M#19 (No. 6)	91 (36)	48 db splice, distributed reinforcement, one bar each in first and second cells, each side	8.6 (3.4)	74 (29)	125%	91 (36)	100%
6	M#19 (No. 6)	69 (27)	36 db splice, distributed reinforcement, one bar each in first and second cells, each side	8.6 (3.4)	74 (29)	94%	91 (36)	75%
7	M#19 (No. 6)	91 (36)	48 db splice, concentrated reinforcement, offset bars	5.1 (2.0)	125 (49)	74%	91 (36)	100%
8	M#19 (No. 6)	69 (27)	36 db splice, concentrated reinforcement, offset bars	5.1 (2.0)	125 (49)	55%	91 (36)	75%
9	M#19 (No. 6)	114 (45)	60 db splice, concentrated reinforcement, offset bars	5.1 (2.0)	125 (49)	92%	91 (36)	125%

TEST RESULTS

For seven of the nine walls tested, the ultimate failure mechanism was identical on both the north and south sides of the walls. For the two walls that exhibited multiple ultimate failure mechanisms, there is strong correlation between the peak applied lateral applied loads for the north and south sides. For these reasons, the data from the north and south sides of each wall are presented as a single average value in this report. For brevity, typical failure pictures and load-displacement hysteresis curves are provided; detailed test results will be given in Mjelde (2008).

Typical Wall Failure – Longitudinal Splitting of Masonry Assemblage

All walls exhibited similar ultimate failure characteristics. Of the eighteen wall splices tested (two per wall), sixteen exhibited lap failures concurrent with a significant decrease in load and some degree of longitudinal splitting of the masonry assemblage. Typically, hairline radial cracks developed slowly over a number of cycles on the masonry faceshell nearest the internal lapped bars. Depending on the lap detailing, these hairline radial cracks would grow to between 7 and 21 centimeters (3 and 8 inches) before the point of peak load resistance and corresponding lap failure. When a lap splice failed, the longitudinal splitting was often sudden and dramatic, creating an “unzipping” effect as the crack developed from the tip of any existing radial crack to the top of the lap. A significant drop in load was observed every time a

lap failed from this "unzipping" effect of longitudinal splitting of the masonry assemblage. A picture of Wall 1 displaying longitudinal splitting of the masonry assemblage is given in Figure 2. The load-displacement hysteresis curves for Wall 1 are given in Figure 3.

Figure 2. Longitudinal Splitting of the Masonry Assemblage in Wall 1

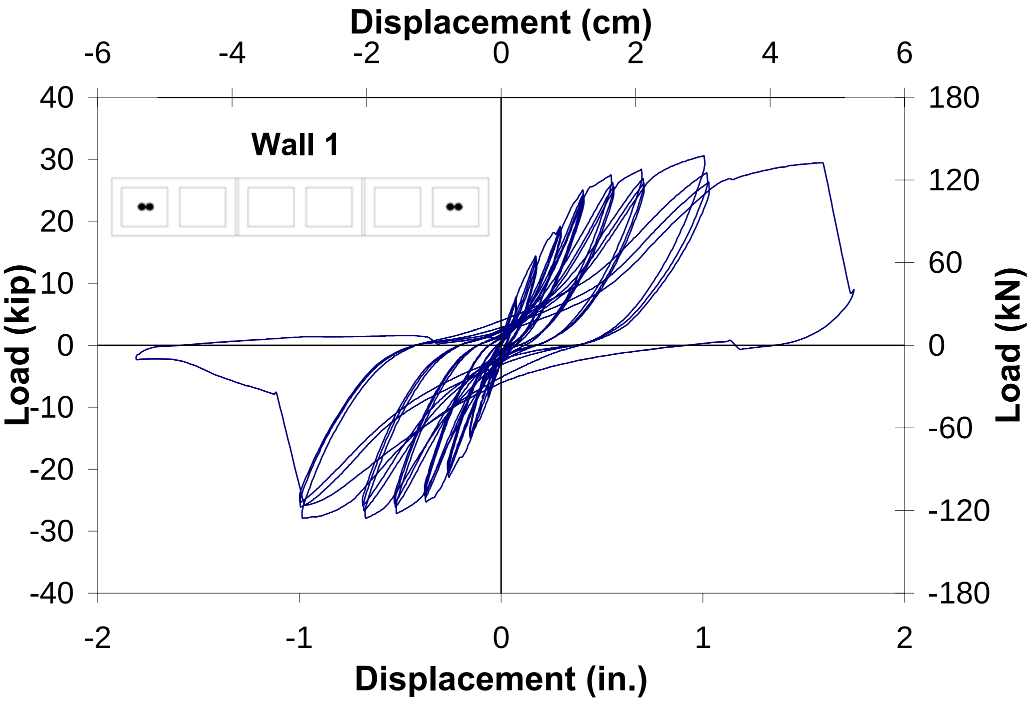

Figure 3. Load-Displacement Hysteresis Curves; Wall 1

Walls 1, 2, 3, and 4 were constructed using a single M#25 (No. 8) bar in each of the outer cells. A graph of the backbone of the load-displacement hysteresis curves for Walls 1 through 4 is given in Figure 4. The two walls with $36d_b$ lap lengths exhibited almost no ductility. Increased lap lengths resulted in significant improvements with respect to displacement ductility and ultimate load resistance.

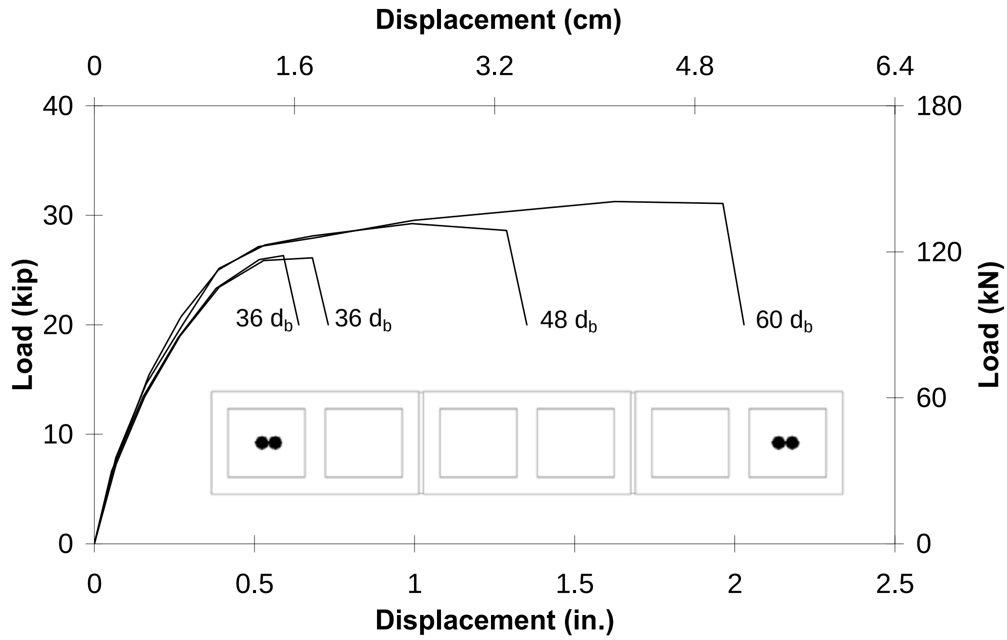

Figure 4. Backbone Curves; Walls 1-4

Walls 5 and 6 were constructed using M#19 (No. 6) bars in the first and second cells on each side. A graph of the backbone of the load-displacement hysteresis curves for Walls 5 and 6 is given in Figure 5. An increase in lap length from $36d_b$ to $48d_b$ resulted in moderate improvements with respect to displacement ductility and ultimate load resistance.

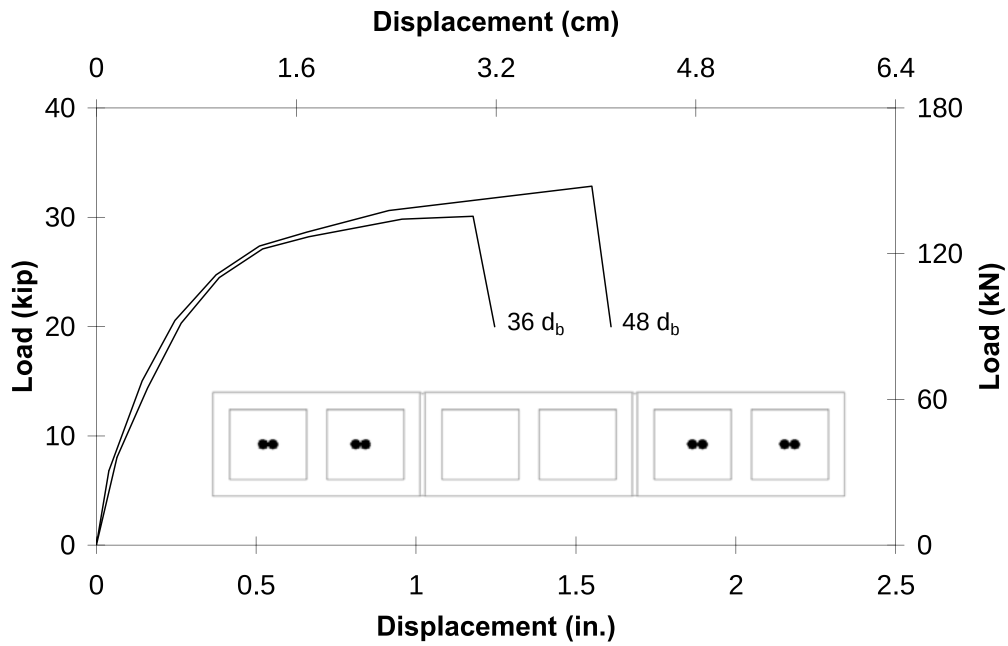

Figure 5. Backbone Curves; Walls 5-6

Walls 7, 8, and 9 were constructed using two M#19 (No. 6) bars offset in the outer cells. The MSJC-prescribed minimum cover of 5 centimeters (2 inches) was used as the side cover in all walls of this type. A graph of the backbone of the load-displacement hysteresis curves for Walls 7 through 9 is given in Figure 6. The wall with $36d_b$ lap length exhibited almost no ductility. Increases in lap length resulted in only moderate improvements with respect to displacement ductility and ultimate load resistance.

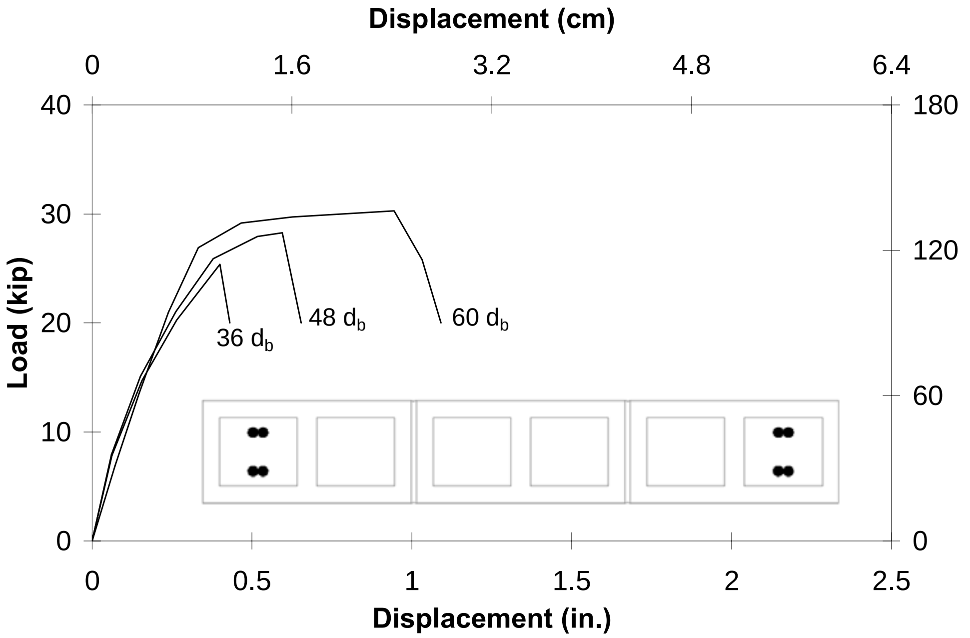

Figure 6. Backbone Curves; Walls 7-9

Reinforcement Stresses at Failure

Of the twenty-eight strain gages installed on the lapped longitudinal reinforcing bars, only seven survived and were functioning at the point of peak load. Moment-curvature analysis was performed on applicable wall cross-sections using actual material properties. The product of an applied load during physical testing and the height of load application can be related to a specific moment from the moment-curvature analysis. Using this relationship as the bridge between physical testing and computer modeling, the seven valid strain data from testing were used to compare measured strains with values from the moment-curvature analysis (theoretical). The average difference between the theoretical and measured strain values was 2%, indicating good agreement between the moment-curvature analysis and the test data.

Table 2 provides a summary of the peak stresses in the lapped bars for the 9 walls of this study, expressed as a ratio of the stress to the specified yield strength of the reinforcement.

Table 2. Ratios of Developed Stresses and Specified Yield Stresses

Wall	Bar Size	Lap Length	Stress, MPa (ksi)	$\sigma_{developed}/F_y$
1	M#25 (No. 8)	48 d_b	516.1 (74.85)	1.25
2	M#25 (No. 8)	36 d_b	470.6 (68.25)	1.14
3	M#25 (No. 8)	36 d_b	477.1 (69.20)	1.15
4	M#25 (No. 8)	60 d_b	549.9 (79.75)	1.33
5	M#19 (No. 6)	48 d_b	530.6 (76.95)	1.28
6	M#19 (No. 6)	36 d_b	493.3 (71.55)	1.19
7	M#19 (No. 6)	48 d_b	453.3 (65.75)	1.10
8	M#19 (No. 6)	36 d_b	399.6 (57.95)	0.97
9	M#19 (No. 6)	60 d_b	478.2 (69.35)	1.16

Comparisons with Required Lap Lengths

A plot of the provided lap length, expressed as a percentage of the required 2005 MSJC Code lap length, versus the ratio of developed stress to specified yield stress is given in Figure 7. Results in the figure indicate that the MSJC provisions predict the lap behavior for the wall specimens with M#19 (No. 6) bars reasonably well. However, the actual lap behavior for walls with M#25 (No. 8) bars is better than would be expected based on the MSJC requirements.

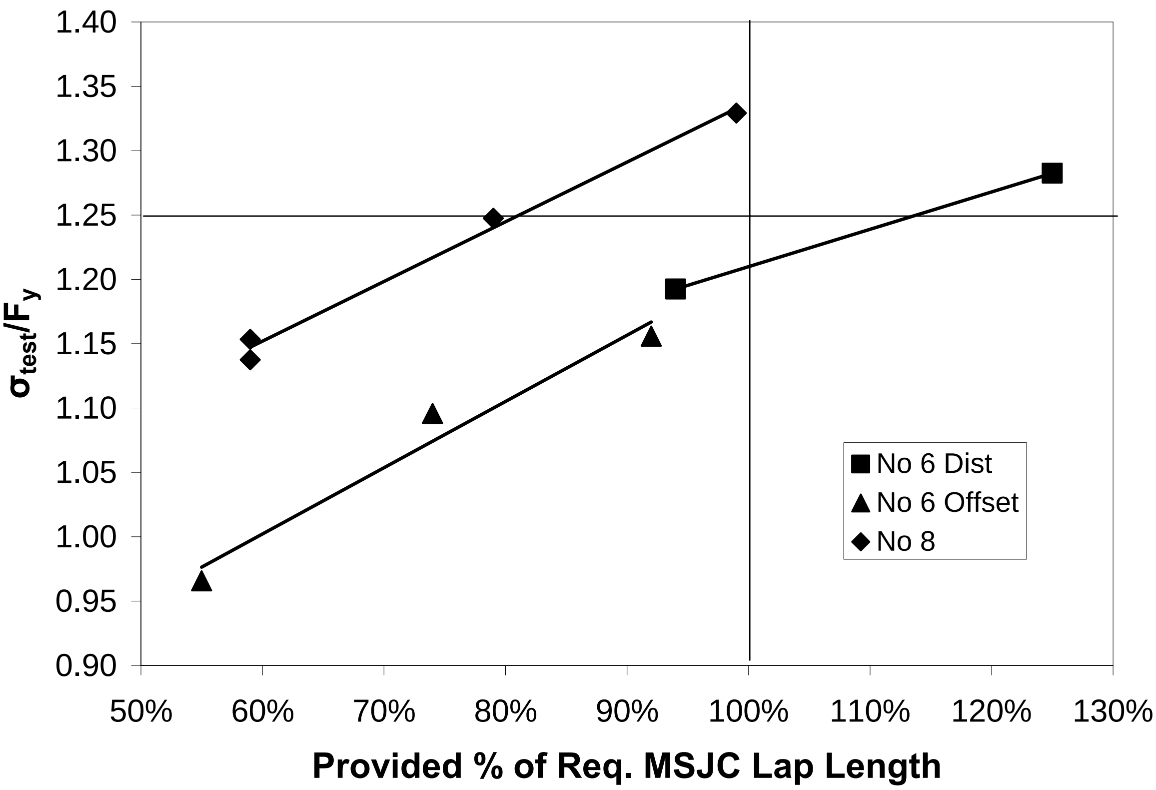

Figure 7. Provided % of Req. MSJC Lap Length versus σ_{test}/f_y

A plot of the provided lap length, expressed as a percentage of $48d_b$, versus the ratio of developed stress to specified yield stress is given in Figure 8. Results shown in this figure indicate that lap splices centered in the cells, for both the M#19 and M#25 (No. 6 and No. 8) bars, are able to achieve stress values of 1.25 times the specified yield stress for $48d_b$ lap lengths. However, lap splices off center in the cells, resulting in reduced side cover, are not able to develop this stress level, even for a $60d_b$ lap length. This later result strongly supports the need to address reinforcement cover when specifying a required lap length.

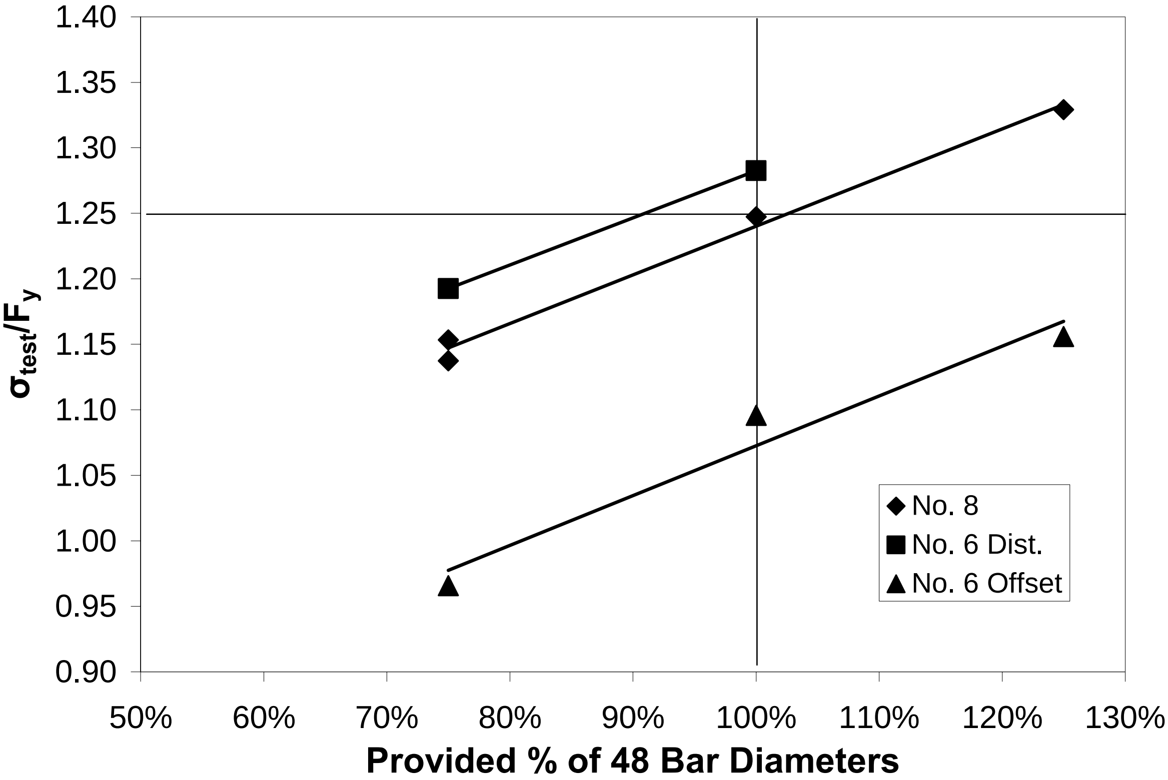

Figure 8. Provided % of 48 Bar Diameters versus σ_{test}/f_y

CONCLUSIONS

Results from the lap splice tests of this study indicate satisfactory performance of reinforcement splices with lap lengths of 48 bar diameters, provided the bars are centered in the masonry cells and are in masonry walls incorporating horizontal reinforcement. Bars offset in the cells, resulting in reduced cover, performed relatively poorly, even when provided with lap lengths of 60 bar diameters, supporting the need to address cover for lap splice design. For the parameters considered in this study, the current MSJC requirements predicted the performance of lap splices for M#19 (No. 6) bars centered and offset in the cells with reasonable accuracy; however, the provisions appear to be overly conservative for lap splices of M#25 (No. 8) bars. Further research is currently underway to test lap splices similar to those in this study but loaded in direct tension. This will enable direct comparison of results for lap splices loaded in direct tension with those loaded in flexure, thereby defining any differences resulting from the method of loading.

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