



Saskatoon, Saskatchewan, Canada
June 2-5, 2004 / 2-5 juin 2004

PROPOSED MODIFICATION TO THE ACI 318-02 CODE EQUATION ON BOND STRENGTH FOR MMFX STEEL

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ABSTRACT: This paper summarizes an investigation undertaken to study the bond characteristics of Micro-composite Multi-structural Formable reinforcing steel rebars, commercially known as MMFX, with concrete. The objective of the investigation is to examine the applicability of the current equation of the ACI 318-02 Code on bond to predict the bond capacity of the MMFX steel rebars. The experimental program consisted of testing eight beam-splice specimens reinforced with MMFX steel rebars. The bond behaviour of the MMFX steel rebars was found to be similar to that of conventional Grade 420 MPa (60 ksi) steel up to the proportional limit of 550 MPa (80 ksi). The bond strength of the MMFX significantly changes as the tensile stresses developed in the rebar exceed the proportional limit. Therefore, test results indicated that the current ACI 318-02 Code equation on bond is adequate and resulted in conservative prediction at low stress levels. However, at high stress levels, the prediction is unconservative due to the nonlinear behaviour of MMFX stress-strain curve. This paper proposes a modification to the ACI 318-02 Code equation, using same format, to predict the bond forces beyond the proportional limit for MMFX steel rebars.

1. INTRODUCTION

The new Micro-composite Multi-structural Formable Steel, commercially known by MMFX steel rebar, is claimed by its innovators to have a significantly high corrosion resistance, compared to conventional steel, and superior mechanical properties (MMFX Steel 2002). The company claims that the average chloride threshold, in lbs of chloride ions per cubic yard of concrete, for the MMFX steel rebars is 8.8 times that of the conventional carbon steel and the time to corrosion initiation for MMFX steel rebars is 69 years compared to 22 years for the carbon steel. MMFX possess higher yield strength than conventional carbon steel which could allow designers to specify less rebar quantities for a specific structure and therefore simplifies/reduces field installation costs (MMFX Steel 2002). For the MMFX Microcomposite steel rebars to be acceptable to the concrete community, a number of design and detailing characteristics must be determined as well as their fundamental mechanical characteristics, including the bond characteristics as reinforcing rebars for concrete structures.

Bond characteristics of deformed reinforcing Grade 420 MPa (60 ksi) steel rebars and concrete has been thoroughly investigated by many researchers. Their experimental results contributed to the ACI Committee 408 database on "Bond and Development of Straight Reinforcing Bars in Tension" and were used in formulating the current equation in the ACI 318-02 Code to predict the bond force as well the proposed equation in the current draft of the ACI Committee 408.

2. OBJECTIVES

The main objective of this research study is to determine, experimentally, the bond characteristics of straight deformed MMFX steel rebars as flexural reinforcement for normal strength concrete members. Results of the experimental program are used to assess the applicability of the current ACI 318-02 code equation to predict the bond strength of the MMFX steel rebars with concrete. Another objective of the research is to propose an equation or modify existing equation to predict the bond of MMFX up to and beyond the proportional limit.

3. EXPERIMENTAL PROGRAM

An experimental program was conducted to examine the bond characteristics and the development length of the MMFX rebars as flexural reinforcement for concrete beams using large-scale beam-splice specimens reinforced with MMFX steel rebars of various sizes. The parameters considered were the bar size and splice length at the maximum constant moment region.

3.1. Mechanical Properties of MMFX

Uniaxial tension tests were conducted to determine the stress-strain characteristics of MMFX steel rebars (ASTM E8-01 and ASTM A370-97a). The behaviour during testing was monitored using 50 mm (2 in) gage length axial mechanical extensometers and strain gages installed at mid-length of the rebars. For comparison purposes, tension tests have been conducted on No.19 (#6) conventional Grade 420 MPa (60 ksi) steel rebars with nominal diameter of 19.1 mm (0.75 in) as shown in Figure 1. More details can be found in El-Hacha and Rizkalla (2002-a and b). The Young's Modulus of Elasticity, E , for the MMFX steel determined as the slope of the linear elastic portion of the stress-strain curve was equal to 200×10^3 MPa (29×10^6 psi) which is the same value obtained for the Grade 420 MPa (60 ksi) reinforcing steel. As shown in Figure 1, the MMFX steel does not have a definite yield point and does not exhibit a yielding plateau. For this reason, the 0.2% offset method (ASTM E111-97) was used to define the yield strength, f_y . The 0.2% offset yield strength was found equal to 827 MPa (120 ksi) for No.19 (#6) and No.25 (#8) rebars. The strain corresponding to the 0.2% offset yield strength of MMFX was determined as 0.6%. The maximum tensile strength of MMFX, f_u , is 1227 MPa (178 ksi) for No.19 (#6) and No.25 (#8) and the corresponding strain is 6%. The behaviour of MMFX steel is non-linear beyond yielding up to the maximum tensile strength achieved, after which necking occurred reflected by reduction of the corresponding engineering stress and failure occurred at strain of 20% for No.19 (#6), and 24% for No.25 (#8) steel rebars.

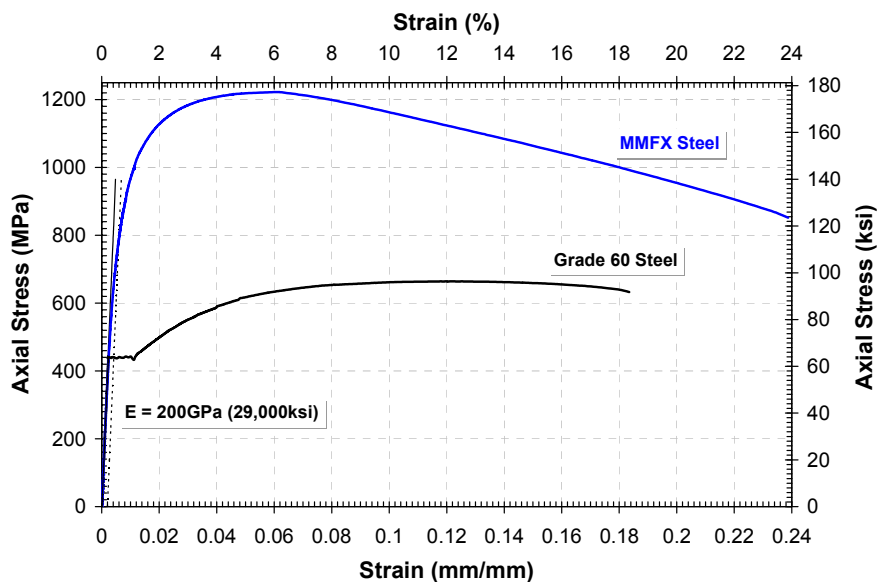


Figure 1. Stress-Strain Curves of MMFX and Grade 60 Steel Rebars

3.2. Beam-Splice Specimens

A total of eight large-scale concrete beams reinforced with MMFX steel rebars spliced at the midspan were tested. Four specimens were each reinforced with 2No.19 (2#6) MMFX steel rebars and the other four with 1No.25 (1#8) MMFX steel rebar. The beam-splice specimens were divided into four groups as shown in Table 1. The spliced lengths varied from one specimen to another and ranged from 305 mm to 1830 mm (1.0 ft to 6.0 ft) as shown in Table 1. To minimize the effect of the applied loads on the spliced length, the distance between the end of the splice length and the center of the applied load was always more than 305 mm (1.0 ft). For the specimens reinforced with No.25 (#8) MMFX steel rebars, double-legged closed stirrups were evenly distributed along the splice length to provide the required level of confinement around the spliced rebars. To prevent possible premature shear failure, shear reinforcement was provided using No.10 (#3) Grade 60 double-legged closed stirrups spaced at 127 mm (5 in) along the shear span for all tested beam specimens. Compression reinforcement was provided by 2No.13 (2#4) Grade 420 MPa (60 ksi) steel rebars as top reinforcement. The variation in the beam's dimensions was selected to achieve different stress levels in the MMFX steel rebar length at failure. The bottom and side concrete covers and the transverse spacing between the spliced rebars were kept constant for all the beams reinforced with 2No.19 (2#6) MMFX steel rebars. The selected splice lengths were $1.8d_b$, $3d_b$, and $6d_b$ where d_b is the rebar diameter. For beams reinforced with 1No.25 (1#8) MMFX steel rebar, the bottom and side concrete covers were also kept constant at values of $1.375d_b$ and $5d_b$, respectively. The average concrete compressive strength determined using three 102 mm \times 204 mm (4 in \times 8 in) cylinders according to ASTM C39-01 at age of 28 days was 41.8 MPa (6071 psi). The concrete compressive strengths as measured on the day of testing are given in Table 2.

All beams were simply supported loaded in four-point bending. The load was applied using an MTS actuator operated under displacement-control mode at a constant loading rate of 1.07 mm/min (0.042 in/min). The constant moment region span was 1829 mm (6 ft) and 2438 mm (8 ft) for the 4879 mm (16 ft) and 6096 mm (20 ft) long specimens, respectively, as shown in Figure 2. The beams were instrumented to measure the deflection at midspan using LVDT. Two electrical resistance strain gages were installed on the MMFX steel rebars, one on each side of the splice length within the constant moment zone to measure the strain in the rebar. Concrete strain at the top surface of the beam specimens was also measured using PI gages. Test set-up and instrumentation of the beam-splice specimens is shown in Figure 2.

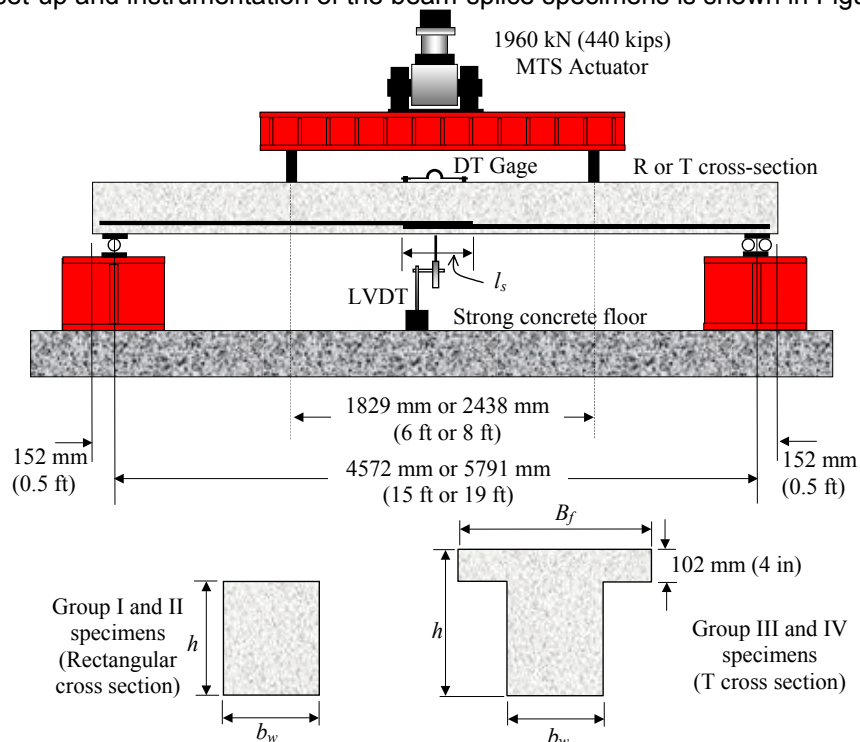


Figure 2. Test Set-Up of the Beam-Splice Specimens

Table 1. Test Matrix of Experimental Program 2: Beam-Splice Specimens

Group #	Specimen ID*	l_s mm	Concrete dimensions **					Cover and spacing			Stirrups details along splice length			
			L mm	b_w mm	B_f mm	h mm	d mm	C_{so} mm	C_{si} mm	C_b mm	N	S mm	d_{st} mm	f_{yt} MPa
I	B-6-12	305	4877	305	—	311	264	60.3	54.0	38	0	—	—	—
II	B-6-24	610	4877	311	—	362	314	54.0	70.0	38	0	—	—	—
III	B-6-36	914	4877	305	613	464	419	54.)	60.3	35	0	—	—	—
IV	B-6-60	1524	6096	305	1219	457	413	57.2	57.2	35	0	—	—	—
I	B-8-12	305	4877	305	—	305	254	123.8	—	38	1	305	9.53	420
II	B-8-24	610	4877	305	—	356	305	123.8	—	38	2	305	9.53	420
III	B-8-48	1220	4877	311	616	470	422	114.3	—	35	5	245	9.53	420
IV	B-8-72	1830	6096	305	1219	470	410	120.7	—	35	7	260.4	9.53	420

* The first letter of the beam designation “B” stands for Beam; the middle number identifies the rebar size No.19 (#6) and No.25 (#8); while the last number represents the spliced length of the rebar in inches

** The dimensions of the specimens were measured after casting

Table 2. Summary of Predicted and Experimental Test Results of Experimental Program 2: Beam-Splice Specimens

Group #	Specimen ID	l_s mm	f'_c MPa	f_s MPa		P kN	M kN.m	
				Test	Prediction using			
					ACI 318-02 Code Equation			
I	B-6-12	305	40.0	430.8	281.1	77.0	58.4	
II	B-6-24	610	39.4	605.1	558.2	135.7	100.0	
III	B-6-36	914	44.0	792.7	824.7	824.7	246.8	180.0
IV	B-6-60	1524	39.4	830.6	1301.4	1301.4	201.5	189.5
I	B-8-12	305	40.0	337.8	197.3	49.8	34.0	
II	B-8-24	610	39.4	504.6	396.6	88.1	71.3	
III	B-8-48	1220	47.4	806.5	857.4	857.4	229.1	166.8
IV	B-8-72	1830	41.0	954.7	1180.6	1180.6	206.8	194.0

3.3. Experimental Results

3.3.1 Failure Mode

The failure mode of all beam-splice specimens was splitting bond failure. This was associated with formation of an extensive crack pattern along the splice length. All beams reinforced with 2No.19 (2#6) MMFX steel rebars exhibited an excessive increase in the width of the main flexural cracks, formed at the ends of the splice length, accompanied with bond failure as a result of the rebar slippage as shown in Figure 3. For the beams reinforced with 1No.25 (1#8) MMFX steel rebar with the short splice length (B-8-12 and B-8-24) showed excessive widening of the main flexural cracks at time of failure. However, for the beams with longer splice length no significant increase in the crack width was observed at failure as shown in Figure 4 for beam B-8-48. Similar behaviour was observed in beam B-8-72. The tensile stresses developed in the MMFX steel rebars just before failure calculated are given in Table 2.

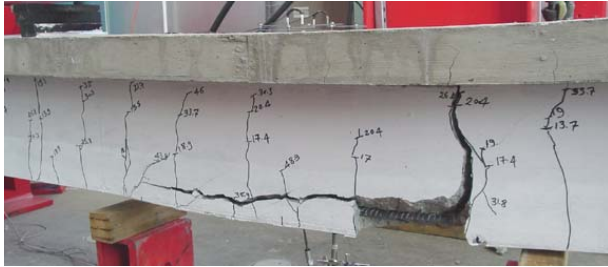


Figure 3. Failure of Beam-Splice Specimen B-6-36

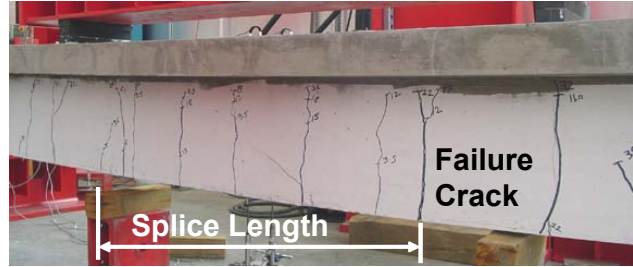


Figure 4. Failure of Beam-Splice Specimen B-8-48

3.3.2 Evaluation of Bond Strength and Splice Length

The bond capacity of the No.19 (#6) and No.25 (#8) MMFX rebars was evaluated using the current ACI 318-02 code equation and compared with the experimental results as shown in Figure 5 and Figure 6, respectively. The results were also compared with other available equations in the literature as can be found in El-Hacha et al. (2003). Test results indicated that the current ACI 318-02 equation provided conservative prediction of the bond capacity of No.19 (#6) and No.25 (#8) MMFX steel rebars at stress levels up to the proportional strength of 579 MPa (84 ksi) and 607 MPa (88 ksi), respectively. At higher stress levels, the prediction turned rapidly towards the unconservative side. Therefore, there is a need to modify the current ACI 318-02 equation. The stress limitation imposed by the ACI 318-02 code for the maximum allowed design yielding strength of 550 MPa (80 ksi) has been selected as an upper boundary. Therefore, modification of the equation has been proposed beyond the stress level of 550 MPa (80 ksi).

3.3.2.1 Unconfined Rebar

The current ACI 318-02 code equation, for rebars not confined with transverse reinforcement ($T_b = T_c$ and $T_s = 0$), as is the case for beams B6-12, B6-24, B6-36 and B6-60, the bond force, T_b , is given by:

$$[1] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c}{f_c'^{1/2}} = \frac{5}{18} l_d \pi (c'_{\min} + 0.5d_b) \quad (\text{SI Units})$$

$$[1a] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c}{f_c'^{1/2}} = \frac{10}{3} l_d \pi (c'_{\min} + 0.5d_b) \quad (\text{Imperial Units})$$

Equations (1 and 1a) can be rewritten in terms of l_d as follows:

$$[2] \quad \frac{l_d}{d_b} = \frac{9}{10} \frac{f_y}{\sqrt{f_c'}} \frac{1}{\left(\frac{C'_{\min} + 0.5d_b}{d_b} \right)} \quad (\text{SI Units})$$

[2a]
$$\frac{l_d}{d_b} = \frac{3}{40} \frac{f_y}{\sqrt{f'_c}} \frac{1}{\left(\frac{c'_{\min} + 0.5d_b}{d_b} \right)}$$
 (Imperial Units)

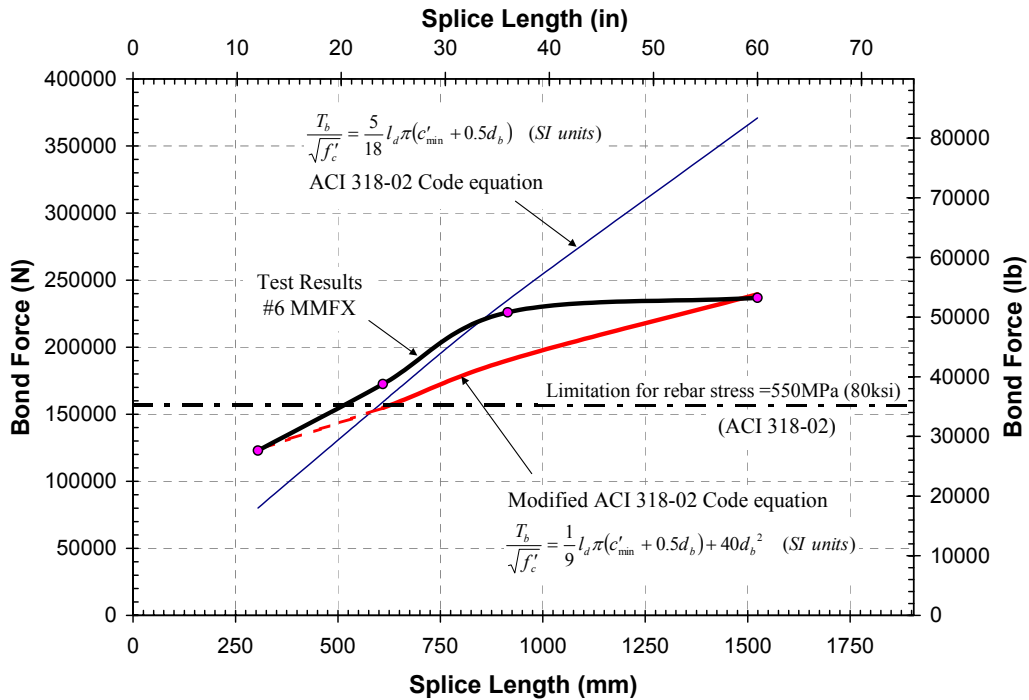


Figure 5. Bond Force vs. Splice Length for Beams Reinforced with No.19 (#6) MMFX Steel Rebars

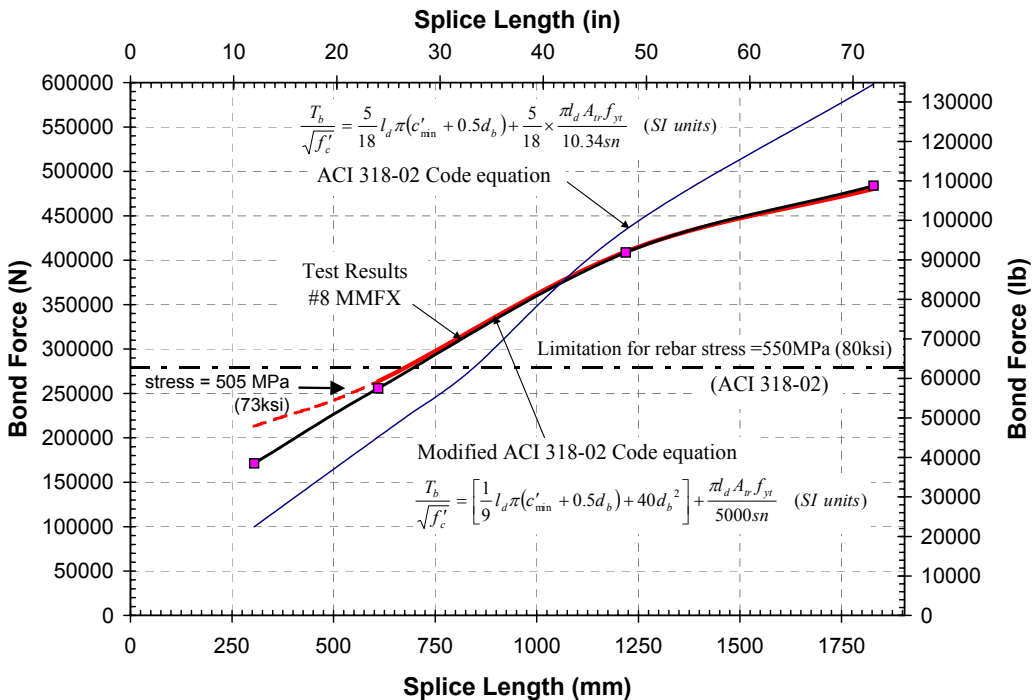


Figure 6. Bond Force vs. Splice Length for Beams Reinforced with No.25 (#8) MMFX Steel Rebars

Based on the tested results, the above equation was modified by changing the numerical constants and addition of a term function of d_b^2 . The proposed modification of the ACI 318-02 equation for MMFX beyond stress level of 550 MPa (80 ksi) is:

$$[3] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c}{f_c'^{1/2}} = \frac{1}{9} l_d \pi (c'_{\min} + 0.5d_b) + 40d_b^2 \quad (\text{SI Units})$$

$$[3a] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c}{f_c'^{1/2}} = \frac{13}{10} l_d \pi (c'_{\min} + 0.5d_b) + 500d_b^2 \quad (\text{Imperial Units})$$

Equations (3 and 3a) can be rewritten in terms of l_d as follows

$$[4] \quad \frac{l_d}{d_b} = \frac{\frac{f_y}{\sqrt{f_c'}} - 51}{\frac{4}{9} \left(\frac{c'_{\min} + 0.5d_b}{d_b} \right)} \quad (\text{SI Units})$$

$$[4a] \quad \frac{l_d}{d_b} = \frac{\frac{f_y}{\sqrt{f_c'}} - 637}{\frac{52}{10} \left(\frac{c'_{\min} + 0.5d_b}{d_b} \right)} \quad (\text{Imperial Units})$$

Using the above modified equation to predict the bond capacity of No.19 (#6) MMFX steel rebars for stress levels higher than 550 MPa (80 ksi) the maximum test/predict ratio was about 1.19 as can be seen in Figure 5.

3.3.2.2 Confined Rebar

The current ACI 318-02 code equation, for rebars confined with transverse reinforcement ($T_b = T_c + T_s$), in terms of bond force T_b , as is the case for beams B8-12, B8-24, B8-48 and B8-72 is given by:

$$[5] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c + T_s}{f_c'^{1/2}} = \frac{5}{18} l_d \pi (c'_{\min} + 0.5d_b) + \frac{5}{18} \frac{\pi l_d A_{tr} f_{yt}}{10.34sn} \quad (\text{SI Units})$$

$$[5a] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c + T_s}{f_c'^{1/2}} = \frac{10}{3} l_d \pi (c'_{\min} + 0.5d_b) + \frac{10}{3} \frac{\pi l_d A_{tr} f_{yt}}{1500sn} \quad (\text{Imperial Units})$$

Equations (5 and 5a) can be rewritten in terms of l_d as follows:

$$[6] \quad \frac{l_d}{d_b} = \frac{9}{10} \frac{f_y}{\sqrt{f_c'}} \frac{1}{\left(\frac{c'_{\min} + 0.5d_b + k_{tr}}{d_b} \right)} \quad \text{and} \quad k_{tr} = \frac{A_{tr} f_{yt}}{10.34sn} \quad (\text{SI Units})$$

$$[6a] \quad \frac{l_d}{d_b} = \frac{3}{40} \frac{f_y}{\sqrt{f_c'}} \frac{1}{\left(\frac{c'_{\min} + 0.5d_b + k_{tr}}{d_b} \right)} \quad \text{and} \quad k_{tr} = \frac{A_{tr} f_{yt}}{1500sn} \quad (\text{Imperial Units})$$

To limit the probability of a pullout failure, ACI 318-02 requires that:

$$[6b] \quad \frac{c'_{\min} + 0.5d_b + k_{tr}}{d_b} \leq 2.5$$

Based on the tested results, the above equation (Eq.5) was modified by changing the numerical constants only. Therefore, the proposed modification of the ACI 318-02 equation for MMFX beyond stress level of 550 MPa (80 ksi) is:

$$[7] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c + T_s}{f_c'^{1/2}} = \left[\frac{1}{9} l_d \pi (c'_{\min} + 0.5d_b) + 40d_b^2 \right] + \frac{\pi l_d A_{tr} f_{yt}}{5000sn} \quad (\text{SI Units})$$

$$[7a] \quad \frac{T_b}{f_c'^{1/2}} = \frac{T_c + T_s}{f_c'^{1/2}} = \left[\frac{13}{10} l_d \pi (c'_{\min} + 0.5d_b) + 500d_b^2 \right] + \frac{\pi l_d A_{tr} f_{yt}}{410sn} \quad (\text{Imperial Units})$$

Equations (7 and 7a) can be rewritten in terms of l_d as follows:

$$[8] \quad \frac{l_d}{d_b} = \frac{\frac{f_y}{\sqrt{f_c'}} - 51}{\frac{4}{9} \left[\frac{c'_{\min} + 0.5d_b + k_{tr}}{d_b} \right]} \quad \text{and} \quad k_{tr} = \frac{A_{tr} f_{yt}}{556sn} \quad (\text{SI Units})$$

$$[8a] \quad \frac{l_d}{d_b} = \frac{\frac{f_y}{\sqrt{f_c'}} - 637}{\frac{52}{10} \left[\frac{c'_{\min} + 0.5d_b + k_{tr}}{d_b} \right]} \quad \text{and} \quad k_{tr} = \frac{A_{tr} f_{yt}}{533sn} \quad (\text{Imperial Units})$$

Using the above modified equation to predict the bond capacity for No.25 (#8) MMFX bars, for bar stress levels higher than 550 MPa (80 ksi), the maximum test/predict ratio did not exceed 1.0 as can be seen in Figure 6. The modified ACI 318-02 equation predicted accurately the bond force of the No.25 (#8) MMFX steel rebar confined with transverse reinforcement above stress level of 550 MPa.

Therefore, based on the limited test data, it is recommended to use of the current ACI 318-02 equation (Equation 5) to predict the splice length of MMFX steel rebars for stress levels up to 550 MPa (80 ksi) for No.19 (#6) and up to 505 MPa (73ksi) for No.25 (#8) rebars, and the modified equation (Equation 7) for stress levels between 550 MPa (80 ksi) and 831 MPa (120.5 ksi) for No.19 (#6) rebars and between 505 MPa (73 ksi) and 954 MPa (138.5 ksi) for No.25 (#8) rebars.

3.3.3 Splice Length/Rebar Diameter Ratio

The measured rebar stresses for No.19 (#6) and No25 (#8) MMFX steel rebars versus splice length to the rebar diameter are shown in Figure 7. Tests results indicated that the stress is linearly related to the splice length to the rebar diameter ratio (L_s/d_b) up to the minimum yield strength for No.19 (#6) and No25 (#8) MMFX steel rebars. The relationship suggest also that a splice length of $30d_b$ can be safely used to achieve the maximum yield strength of 550 MPa (80 ksi) limited by the current ACI 318-02 Code. As shown in Figure 7, a splice length of $45d_b$ can be used to achieve the yield strength of 758 MPa (110 ksi) for MMFX steel rebars. The linear relationships extend to a stress of 831 MPa (120.5 ksi) which corresponds to a splice length of $50d_b$. Beyond the yield strength, the relationship becomes highly non-linear and significant splice length is required to achieve higher stress levels which could be impractical to use for typical applications.

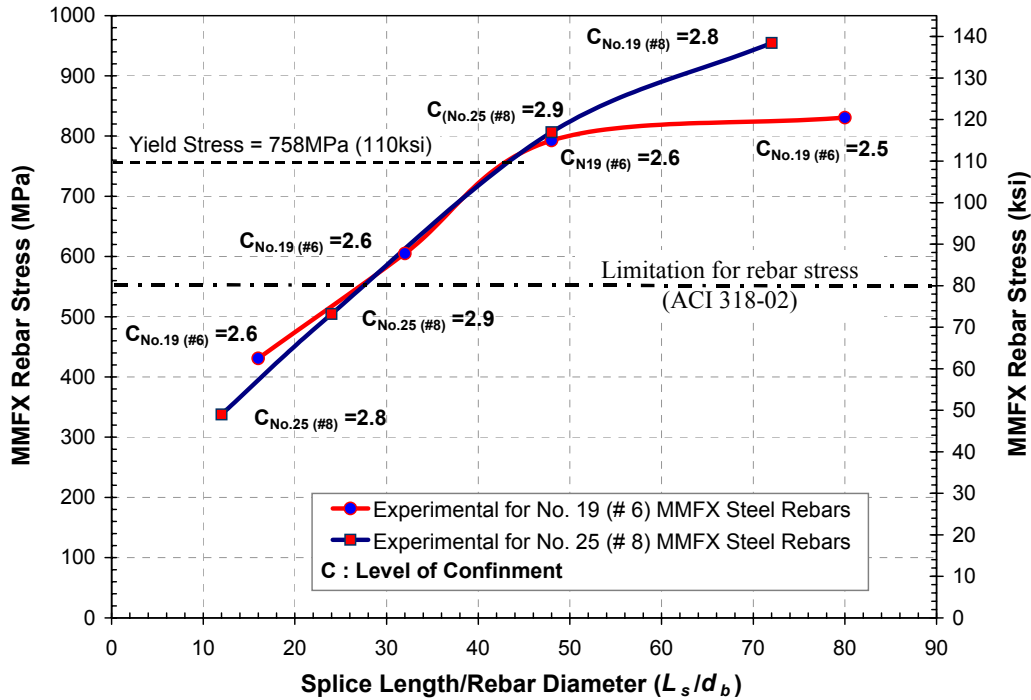


Figure 7. Steel Rebars Stress vs. Splice Length/Rebar Diameter for Beams Reinforced with No.19 (#6) and No.25 (#8) MMFX Steel Rebars

4. CONCLUSIONS

The following conclusions were made based on the limited number of tested specimens:

1. Bond behaviour of the MMFX steel rebars is similar to that of the conventional Grade 420 MPa (60 ksi) carbon steel up to stress level of 550 MPa (80 ksi). At higher stress levels, bond failure changed from the typical sudden and brittle failure, normally observed for conventional steel, to a gradual and ductile failure due to the nonlinear behaviour of the MMFX steel rebars in this range.
2. The nonlinear ductile response of the MMFX rebars at high stress levels beyond proportional limit strength, has a strong influence in reducing the bond strength of the MMFX rebars compared to Grade 420 MPa (60 ksi) steel.
3. The current ACI 318-02 Code equation for bond force, provided conservative prediction of the bond capacity for No.19 (#6) and No.25 (#8) MMFX steel rebars up to 550 MPa (80 ksi). For stress levels exceeding 550 MPa (80 ksi) and up to a stress level of 831 MPa (120.5 ksi) for No.19 (#6) and 955 MPa (138.5 ksi) for No.25 (#8) MMFX rebars, respectively, the equation was modified to provide better prediction of the bond force capacity.
4. Splice length to rebar diameter ratio is linearly related to the induced stress in the MMFX rebar up to yield strength. The relationship becomes highly nonlinear beyond a stress level of 758 MPa (110 ksi).

5. ACKNOWLEDGEMENT

The authors would like to thank the technical staff and graduate students at the Constructed Facilities Laboratory at NC State University for their help with the laboratory work. The authors are grateful to the support provided by MMFX Technologies Corporation for donating the steel materials.

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7. NOTATION

A_{tr}	area of each stirrup or tie crossing the potential plane of splitting adjacent to the reinforcement being developed or spliced
c_b	thickness of the clear bottom concrete cover
c_{si}	half the clear spacing between the spliced bars
c_{so}	thickness of the clear side concrete cover
c_{min}	minimum of concrete covers surrounding the rebar or half the clear spacing between rebars, minimum of c_{si} and (c_b or c_{so})
b_w	width of the web of a beam
B_f	width of the flange of a beam
d	effective depth of a beam
d_b	nominal diameter of the steel rebar
d_{st}	stirrups diameter
f_c	concrete compressive strength
f_s	tensile stress developed in the MMFX steel rebars just before failure as calculated using the moment curvature analysis
f_{yt}	yield strength of transverse reinforcement
h	beam height
k_{tr}	transverse reinforcement index
l_d	development length of the steel rebar
l_s	splice length of the steel rebar
L	beam length
n	number of MMFX rebar, number of spliced MMFX rebar
N	total number of stirrups along the splice length
P	applied load at failure
M	calculated bending moment at the time of failure at the splice location including the effect of self-weight of the specimen
S	average spacing of the stirrups (transverse reinforcement)
T_b	total bond force of a developed or spliced rebar = $T_c + T_s$
T_c	concrete contribution to total bond force, the bond force that would be developed without transverse reinforcement.
T_s	steel contribution to total bond force, the additional bond strength provided by the transverse steel