

# Shear and Flexural Behavior of Concrete Members Reinforced with MMFX Steel

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## ABSTRACT:

Corrosion of reinforcing steel is typically one of the main problems causing deterioration of concrete structures. The Microcomposite Multistructural Formable (MMFX) steel, which is a new commercially available steel, has proven to have high corrosion resistance in comparison with conventional steel without the use of coating materials. This characteristic was achieved by propriety alteration of the steel composition and microstructure. In addition, the MMFX steel has a higher strength than the conventional grade 60 steel which is attributed to the control of the MMFX steel's microstructure morphology. Therefore, replacing the conventional steel with the new MMFX steel is expected to be economically beneficial due to the use of lower reinforcement ratio, in addition to the advantage of increasing the service life of the structure. A brief discussion of the fundamental characteristics of MMFX steel as a flexural reinforcement of concrete beams and slabs is presented.

This paper focuses on the use of MMFX steel for mat foundations typically used for high-rise structures. Mat foundations are normally not reinforced for shear and are usually heavily reinforced at locations of the columns, therefore reduction of the steel ratio, by using the MMFX steel to replace conventional reinforcement, will help reduce reinforcement congestion, construction time and improve concrete placement. Also, the use of MMFX steel for this type of application provides a high resistance to corrosion due to severe environmental exposure in comparison to the use of conventional grade 60 steel.

Two deep beams with identical cross-section and shear span to depth ratio of 2.45 were reinforced using MMFX steel and conventional grade 60 steel and tested to failure using the same loading configuration. The area of the longitudinal MMFX steel used in the beams was 40 percent less than the area of grade 60 steel to utilize the high tensile strength of the MMFX steel. Test results indicate that the replacement of the conventional grade 60 steel by MMFX steel with 40 percent less area of steel in such beams results in a similar behavior and load carrying capacity.

## 1 INTRODUCTION

Corrosion of reinforcement is a leading cause of deterioration of concrete structures and necessitates expensive rehabilitation, repair and replacement. To address this issue, MMFX Technologies Corporation has developed a new type of reinforcement called Micro-Composite Multi-Structural Formable reinforcing steel (MMFX). MMFX is a high strength, highly corrosion resistant steel which is promising for use in civil engineering applications. Because it is a relatively new technology, the effective use of this type of reinforcement as flexural and shear reinforcement for concrete members is still under development by many researchers.

This paper examines the use of MMFX steel as flexural and shear reinforcement for concrete members. The strength of concrete sections reinforced with MMFX is presented using a simple cracked section analysis. The paper also focuses on the shear behavior of mat foundations reinforced with MMFX steel utilizing 40 percent less reinforcement ratio in comparison to conventional grade 60 steel to utilize the high strength of MMFX steel.

## 2 BACKGROUND

MMFX Technologies Corporation is currently producing Micro-Composite Multi-Structural Formable reinforcing steel (MMFX), which is highly corrosion resistant compared to conventional steel. Corrosion of conventional steel is an electrochemical process that occurs at the microstructural level. The microstructure of conventional steels consists of bands of ferrite and iron-carbide. These bands form a microgalvanic cell within the steel in which ferrite is the anode and iron-carbide acts as the cathode. Electrons from the ferrite travel to the iron-carbide and react to form corrosion byproducts including rust (MMFX Technologies Corporation, 2002). This process is illustrated in Figure 1 and the associated chemical equations are presented in the same figure.

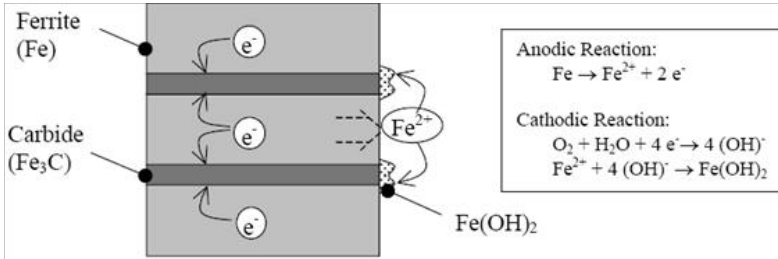


Figure 1: Schematic of a Microgalvanic Cell in Steel. (MMFX Technologies Corporation, 2002)

MMFX steel is designed to eliminate the mechanisms that cause corrosion. Its microstructure consists of alternating bands of austenite and martensite. Consequently, MMFX steel is practically carbide free and microgalvanic cell formation is minimized (MMFX Technologies Corporation, 2002). MMFX exhibits greater corrosion resistance than ASTM A615 steel reinforcement as demonstrated by the results of “Accelerated Chloride Threshold” testing conducted on both materials (Zia, 2003). Furthermore, MMFX steel exhibits an ultimate tensile strength approximately 2.5 times that of conventional Grade 60 steel making it well suited for use in civil engineering applications.

MMFX Corporation proposes the following equation to represent the stress-strain behavior of MMFX steel (Vijay et. al., 2002; Zia, 2004).

$$f_{MMFX} = 165(1 - e^{-185\varepsilon_{MMFX}}) \quad (\text{ksi}) \quad (1a)$$

$$f_{MMFX} = 1137(1 - e^{-185\varepsilon_{MMFX}}) \quad (\text{MPa}) \quad (1b)$$

where  $f_{MMFX}$  and  $\varepsilon_{MMFX}$  are the stress and the strain in the MMFX reinforcing bars, respectively. Using the 0.2% offset method, the yield strain of MMFX reinforcement using equation 1 is 0.006. Equation 1 above closely represents the actual tensile stress-strain curve of MMFX

steel as can be seen in Figure 2. This equation also corresponds well with experimental stress-strain curves of several sizes of MMFX bars reported by NCSU (El-Hacha *et al.*, 2002).

Several limitations have been proposed to represent the tensile stress strain behavior of MMFX steel. The Concrete Innovations Appraisal Service (CIAS) has verified that MMFX steel can conservatively be represented by an elasto-plastic stress strain curve with a modulus of elasticity of 138,000 MPa and yield strength of 690 MPa as proposed by MMFX Corporation (Zia, 2004). The American Concrete Institute (ACI) in clause 9.4 of ACI 318-02 limits the yield strength of concrete reinforcement to 550 MPa (ACI committee 318, 2002). However, to accurately represent the behavior of concrete beams reinforced for flexure with MMFX steel, the design of these members should be based on the expression presented in equation 1 (Dawood *et al.*, 2004).

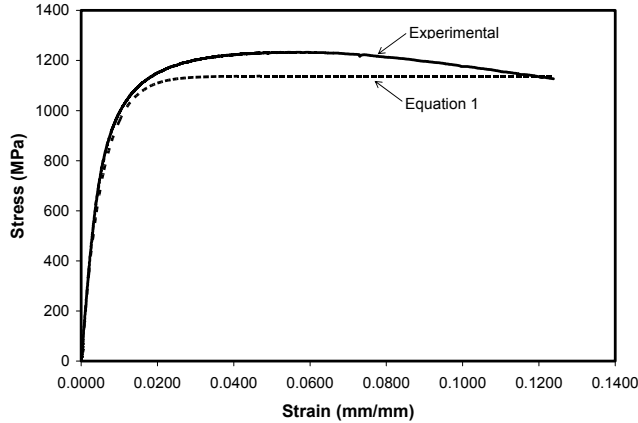


Figure 2: Comparison of proposed MMFX material models

This paper presents a methodology for the design of singly reinforced concrete beams reinforced for flexure using MMFX steel. The stress-strain relationship of the MMFX reinforcement is modeled using equation 1.

This paper also presents the shear behavior of one beam reinforced with MMFX steel and another beam reinforced with grade 60 steel tested under the same load configuration. The area of the longitudinal MMFX steel used was 40 percent less than the area of grade 60 steel, to utilize the higher strength of the MMFX steel.

### 3 FLEXURAL BEHAVIOR

A cracked section analysis was conducted to study the behavior of concrete beams reinforced with MMFX steel. For a given section, concrete strength and reinforcing ratio, the nominal flexural resistance of the concrete section can be determined using equilibrium and compatibility relationships. The nominal flexural moment resistance,  $M_n$ , in terms of the reinforcement ratio,  $\rho$  is given in equation 2.

$$\frac{M_n}{bd^2} = \rho f_{MMFX} \left(1 - 0.5 \frac{\beta_1 c}{d}\right) \quad (2)$$

In equation 2,  $f_{MMFX}$  is the stress in the MMFX, which can be calculated using equation 1 for the strain which satisfies equilibrium and compatibility of the section. The term  $\beta_1$  is a stress block factor which is a function of the concrete strength (ACI committee 318, 2002).

For a given concrete strength,  $f_c'$ , of 45 MPa the nominal flexural resistance is shown in Figure 3 for different reinforcement ratios. The same relationship for conventional Grade 60 steel reinforcement is presented in the same figure for comparison purposes. Experimental results of MMFX reinforced beams tested by the University of North Florida (UNF) and Florida DOT are also shown in the same figure (Malhas, 2002; Ansley, 2003).

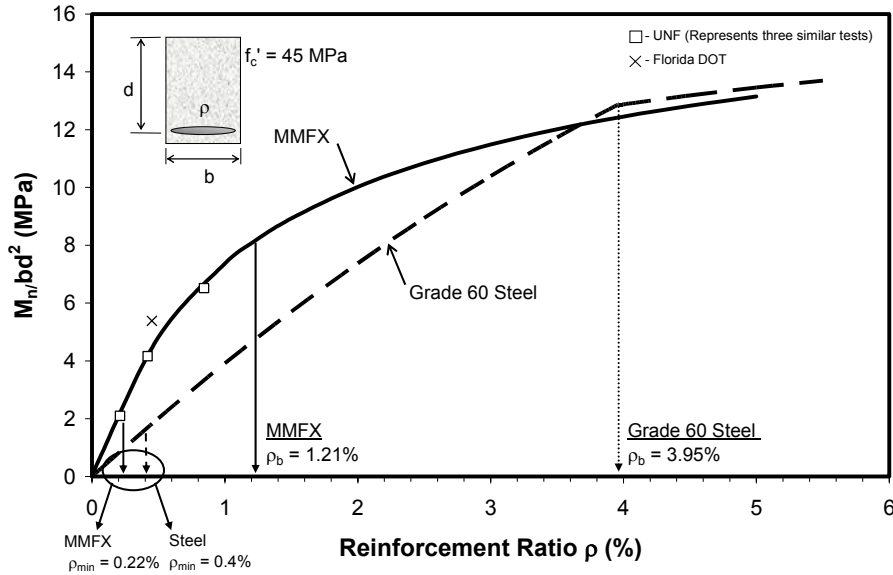


Figure 3: Nominal moment capacity of MMFX reinforced concrete beams

From Figure 3 it can be seen that equation 2 accurately predicts the nominal moment capacity of several MMFX reinforced concrete beams which were tested by other researchers. It is also evident that, for a reinforcement ratio less than 3.5 percent, sections reinforced with MMFX steel exhibit a higher nominal moment capacity than sections reinforced with conventional steel using the same reinforcement ratio. This is due to the high strength characteristics of MMFX steel. The use of MMFX reinforcing steel provides a balanced reinforcement ratio of 1.2 percent which is much lower than the balanced reinforcement ratio of 4.0 percent provided using conventional steel reinforcements. Sections reinforced with a reinforcement ratio greater than the balanced reinforcement ratio typically exhibit a brittle failure governed by crushing of the concrete prior to yielding of the reinforcement. Therefore a closer investigation of the ductility of sections reinforced with MMFX steel should be conducted for each design case.

#### 4 SHEAR BEHAVIOR

The main objective of this part of the paper is to study the shear behavior of a concrete beam reinforced with MMFX steel with an area of steel 40 percent less than the area of grade 60 steel used to reinforce a similar beam with the same cross-section. Both beams were not reinforced with any stirrups and were tested under the same load configuration.

Two beams with shear span to depth ratio ( $a/d$ ) of 2.45 were tested up to failure under three point loading configuration. The 40 percent reduction in the cross-sectional area of the MMFX steel is based on the specified 690 MPa yield strength of the MMFX steel. Details of the dimensions and reinforcement of the beams are shown in Figure 4.

Both beams were cast using one batch of concrete. Sufficient number of concrete cylinders was cast for each beam to evaluate the concrete compressive strength at the time of testing. The cylinders were cured under room temperature and stored next to the beams. The average concrete compressive strength ( $f'_c$ ) for both beams at the day of testing (32 and 34 days after casting) was 32 MPa.

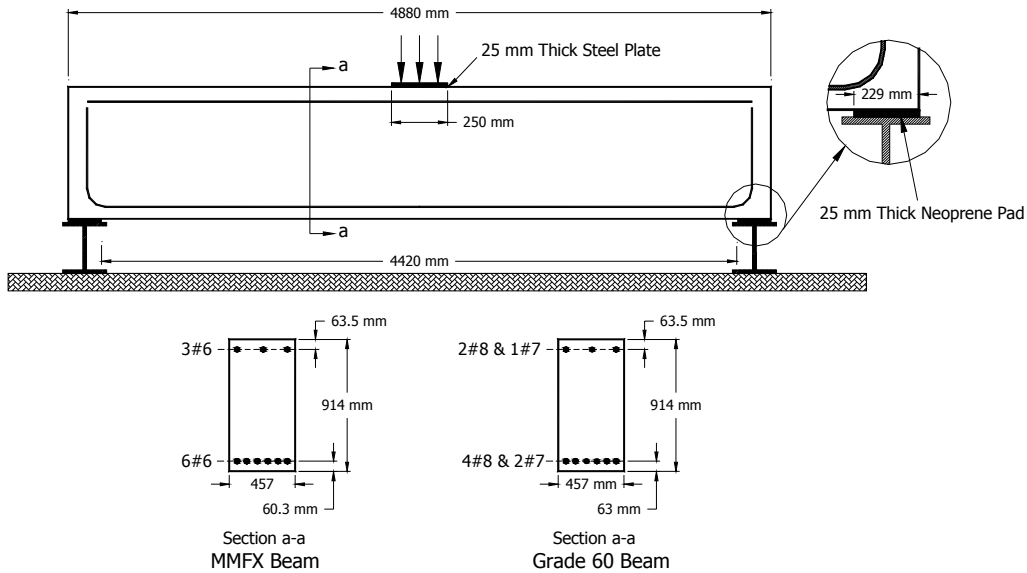


Figure 4: Test beams reinforcement details.

#### 4.1 Test Results and Shear Behavior

The beam reinforced with grade 60 steel was tested 32 days after casting, while the beam reinforced with MMFX steel was tested 34 days after casting. Both beams were tested using a clear span of 4420 mm under three point loading configurations. Both beams exhibited flexure-shear failure where flexural cracks initiated first, followed by inclined flexure-shear cracks. The inclined cracks propagated towards the compression zone and eventually caused failure of the beam when splitting of the concrete near the anchorage of the longitudinal reinforcement occurred at the lower end of the major diagonal crack. Both beams after failure are shown in Figure 5.

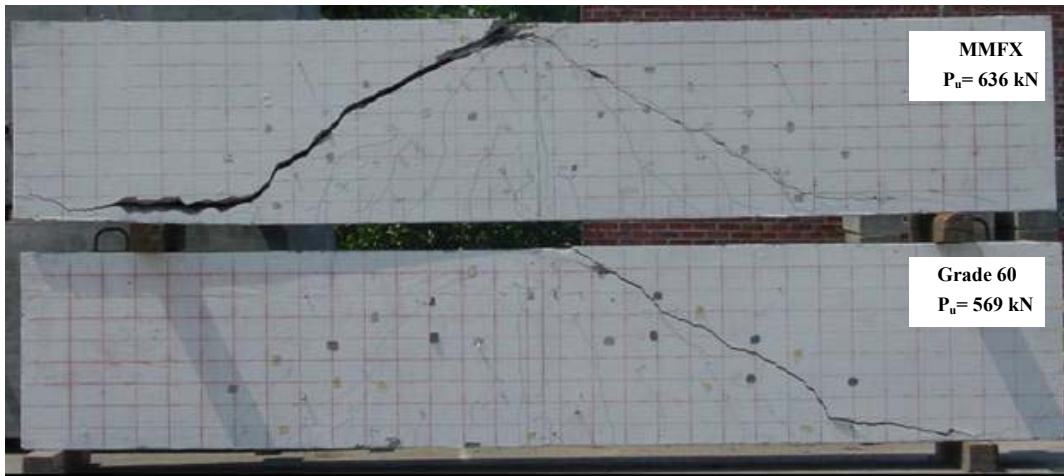


Figure 5: Two beams, reinforced with MMFX and grade 60 steel after failure.

##### 4.1.1 Load-Deflection Response

The first flexural cracks for the beam reinforced with grade 60 steel were observed at a load level of 320 kN, followed by inclined flexure-shear cracks. A major diagonal crack initiated at a load level of 440 kN, which is equivalent to a nominal shear stress of  $1.20\sqrt{f'_c}$ . A second major diagonal crack, which eventually caused the beam failure, initiated on the other side of the beam

at a load level of 467 kN. The beam failed suddenly at a load level of 569 kN, which is equivalent to a nominal shear stress of  $1.56\sqrt{f'_c}$ , and at mid-span deflection of 6.9 mm, as shown in Figure 6.

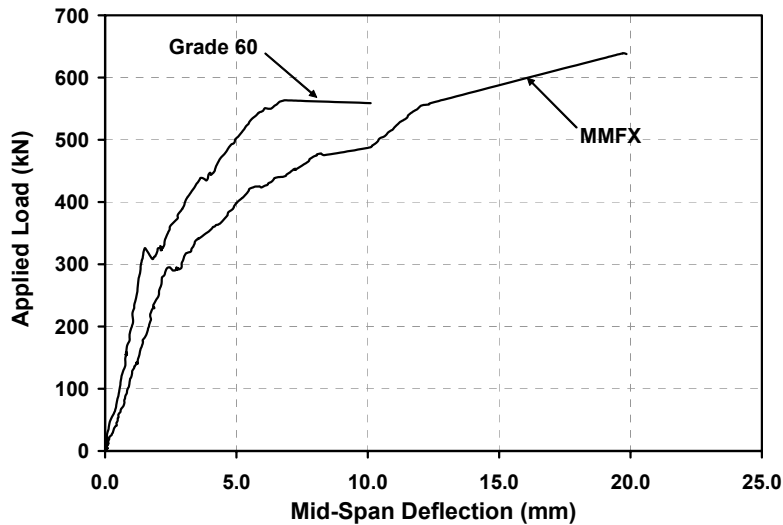
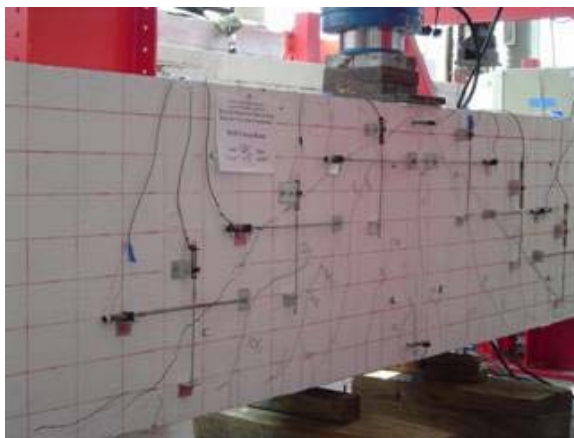


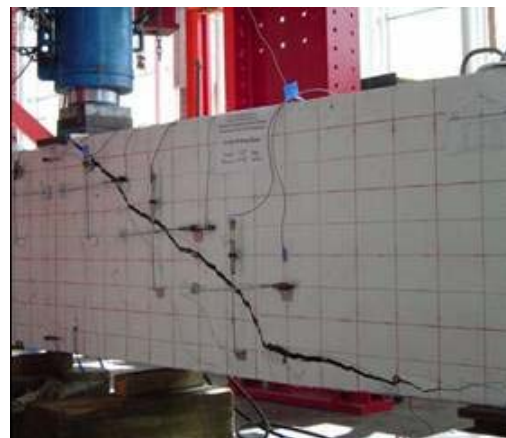
Figure 6: Load-deflection response for both beams.

The first flexural cracks for the beam reinforced with MMFX steel were observed at a load level of 289 kN, followed by inclined flexure-shear cracks. A major diagonal crack initiated at a load level of 449 kN, which is equivalent to a nominal shear stress of  $1.22\sqrt{f'_c}$ . A second major diagonal crack, which eventually caused the failure of the beam, initiated on the other side of the beam at a load level of 534 kN. The load-deflection response of the beam is shown in Figure 6; the beam failed at a load level of 636 kN, which is equivalent to a nominal shear stress of  $1.73\sqrt{f'_c}$ , and mid-span deflection of 19.8 mm. In Figure 6, the measured load-deflection indicates that the beam reinforced with MMFX steel has less stiffness than the beam reinforced with grade 60 steel due to the use of less area of steel, which reduces the transformed moment of inertia of the section.

Figure 7 shows the behavior of the beam reinforced with MMFX steel at loading level equivalent to the failure load of the beam reinforced with grade 60 steel. Test results indicate that the number of cracks in the beam reinforced with MMFX steel is more than the number of cracks in the beam reinforced with grade 60 steel at different load levels. This behavior suggests better bond characteristics of the MMFX steel in comparison to grade 60 steel.



(a) Beam reinforced with MMFX steel



(b) Beam reinforced with grade 60 steel

Figure 7: Beams reinforced with MMFX and grade 60 steel at  $P = 569$  kN.

#### 4.1.2 Analysis of the Test Results

Diagonal cracks in deep beams are typically controlled by shear rather than bending where a compression zone exists at the tip of the diagonal crack. Typical shear transfer mechanism is shown in Figure 8 where 'c' is the depth of the compression zone,  $V_c$  is the shear force in the concrete compression zone;  $V_a$  and  $H_a$  are the vertical and horizontal components of the aggregate interlock shear force, respectively; and  $V_d$  is the force due to the dowel action of the longitudinal reinforcement. In the following analysis, the aggregate interlock force is very small at failure due to the large crack width developed near failure.

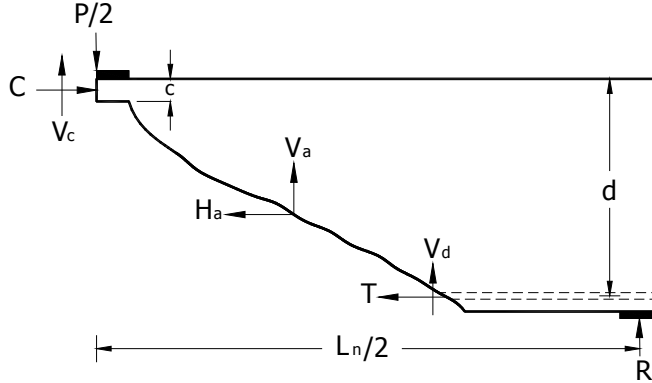


Figure 8: Free-body-diagram of a beam with diagonal crack at failure.

Based on equilibrium of the external moment due to the applied force,  $P_u$ , and the internal moment due to the compression force in the concrete 'C' and the tension force in the reinforcement 'T', the depth of the rectangular stress block 'a' can be determined using the following equation.

$$0.85f'_c ab(d - a/2) = \frac{P_u L_n}{4} \quad (3)$$

In Equation 3, ' $f'_c$ ' is the concrete compression strength measured at the time of testing, and 'b' is the width of the cross-section of the beam. Using equilibrium of forces in the horizontal direction, the stresses and strains in the longitudinal reinforcement at the location of the diagonal crack are given in Table 1. The results presented in the table indicate that the stresses in the MMFX and grade 60 reinforcements were within their elastic limits.

Table 1: Summary of the analysis of test results

Item	MMFX	Grade 60
$P_u$ (kN)	636	569
$M_u$ (kN m)	703	624
a (mm)	69	61
T (kN)	861	761
$f_s$ (MPa)	503	269
$\epsilon_s$ (mm/mm)	0.00290	0.00135

The bond between concrete and reinforcing bars is a function of concrete compressive strength, net concrete area at the level of reinforcement, and dimensions of the lugs of the reinforcing bars. Measurements of the lugs of the MMFX and grade 60 reinforcing bars used in both beams, shown in Figure 9, are given in Table 2. The measurements indicate that the lug spacing of #6 MMFX bar is less than the spacing of #7 and #8 Grade 60 bars. The height and slope of the lug of MMFX steel is close to the average of the two Grade 60 bars. The measurements suggest that the MMFX steel would provide more bond capacity than the grade 60 steel which allows the beam reinforced with MMFX steel to carry slightly more load than the beam reinforced with grade 60 steel.

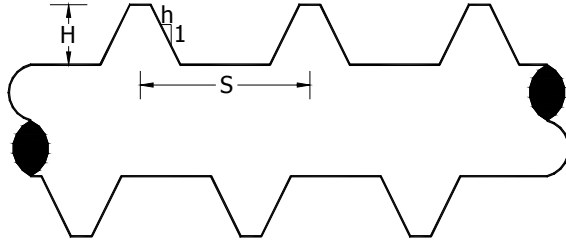
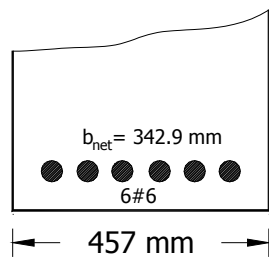


Figure 9: Typical sketch of longitudinal section of a reinforcing bar

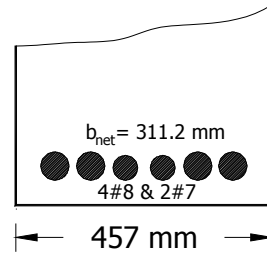
Table 2: Summary of lug measurement.

Item	MMFX	Grade 60	
	Bar # 6	Bar # 7	Bar # 8
S (mm)	12.3	13.9	15.5
H (mm)	1.04	0.81	1.27
h (mm)	54.1	73.9	53.6

The stresses in the concrete at the level of the reinforcement depend on the net area of concrete at that location. Figure 10 shows both sections at the level of the reinforcement with the net width of each section at the level of the reinforcement. The ratio of the net widths of both sections is  $343/311 = 1.102$ , which is close to the ratio of the measured shear force in the concrete at failure of both beams,  $1.73/1.56 = 1.109$ . This justifies the slight increase in the measured shear capacity of the beam reinforced with MMFX steel in comparison to the beam reinforced with grade 60 steel.



(a) Beam reinforced with MMFX steel



(b) Beam reinforced with grade 60 steel

Figure 10: Cross-sections of both beams

## 5 CONCLUSIONS

MMFX is a high strength, highly corrosion resistant reinforcing steel in comparison to grade 60 steel, and therefore, provides an excellent alternative reinforcement for several civil engineering applications, especially structural elements subjected to severe environmental conditions. Because the tensile stress-strain relationship of MMFX is unlike that of conventional Grade 60 steel, it is highly recommended to use the actual stress-strain curve of the MMFX in tension for the flexural design of concrete members.

The study presented in this paper concluded that the replacement of conventional grade 60 reinforcement in mat foundations, by using 40 percent less area of MMFX steel, resulted in a similar behavior and load carrying capacity. Reduction of the reinforcement ratio will also help reduce reinforcement congestion and concrete casting time and improve concrete placement.

## ACKNOWLEDGMENTS

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