Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1647

MECHANICAL AND LOW-CYCLE FATIGUE BEHAVIOR OF STAINLESS REINFORCING STEEL FOR EARTHQUAKE ENGINEERING APPLICATIONS

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ABSTRACT

Use of stainless reinforcing steel in reinforced concrete structures is a promising solution to the corrosion issues. However, for stainless reinforcing steel to be used in seismic applications, several mechanical properties need to be investigated. These include specified and actual yield strengths, tensile strengths, uniform elongations and low-cycle fatigue behavior. Three types of stainless reinforcing steel (Talley S24100, Talley 316LN and Talley 2205) were tested and the results are reported in this paper. They were compared with the properties of A706 carbon reinforcing steel, which is typical for seismic applications, and MMFX II, which is a high strength, corrosion resistant reinforcing steel. Low-cycle fatigue tests of the reinforcing steel coupons were conducted under strain control with constant amplitude to obtain strain life models of the steels. Test results show that the stainless reinforcing steels have slightly lower moduli of elasticity, higher uniform elongations before necking, and better low-cycle fatigue performance than A706 and MMFX II. Among the three types of stainless reinforcing steel tested, Talley S24100 possesses the highest uniform elongation before necking, and the best low-cycle fatigue performance.

Keywords: Stainless reinforcing steel; low-cycle fatigue.

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Introduction

Corrosion of structural steel and concrete reinforcing bars has contributed to the premature failure of highway bridge decks, columns and superstructures and thus shortened the service lives of bridges. Two important causes for corrosion of reinforcing steel are chloride attack due to deicing salts and seawater and carbonation of concrete due to carbonic acid from carbon dioxide. While chloride-induced corrosion is generally more pernicious and expensive to repair, carbonation-induced corrosion of reinforcement may affect a far wider range of reinforced concrete structures. Stainless reinforcing steel is a promising solution for addressing these issues because of its superior corrosion resistance compared to carbon steel and surface treated steel such as epoxy coated reinforcement, galvanized reinforcement, and stainless clad reinforcement (Smith 2007). Despite its higher initial cost, the use of stainless reinforcing steel in bridges and highways has been growing over the past 20 years. The expected lower life cycle cost associated with a corrosion resistant structure is undoubtedly the reason (Schnell and Bergmann 2007).

According to current design provisions for buildings (Section 21 of ACI 318-08 2008) and bridges (Section 5 of ASSHTO 2007), primary reinforcing steel bars located at the plastic hinge regions of earthquake-resistant reinforced concrete structures are expected to undergo large inelastic strain reversals under strong ground shaking. This can lead to low-cycle fatigue failure of the reinforcement. Low-cycle fatigue is defined as a fatigue life of less than 10^5 cycles (Stephens et al. 2001) and typically results from inelastic strain reversals. This paper presents results of the low-cycle fatigue tests of four types of stainless reinforcing steel, as well as A706 carbon steel and MMFX II as a baseline for comparison. Other mechanical properties associated with seismic design are also presented including yield strengths, uniform elongations before necking, actual and specified yield strengths, and ratios of tensile to yield strengths.

Experiments

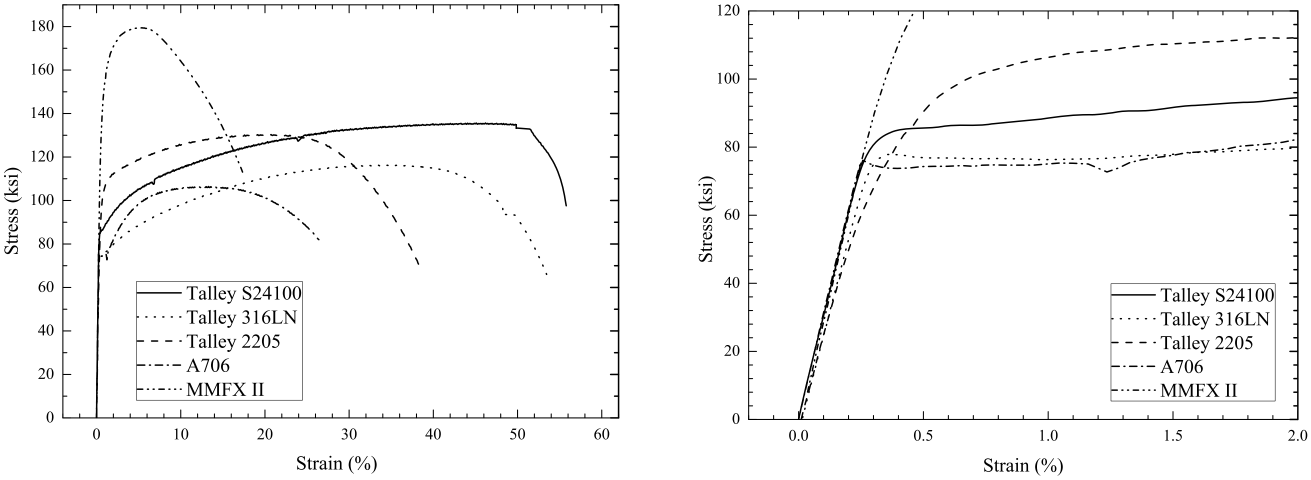
Talley S24100, Talley 316LN and Talley 2205, designated as S24100, S31653, S31803 in ASTM A955 (ASTM 2004), respectively, were the three types of stainless reinforcing steels investigated. A706 reinforcing steel, typically used for seismic design, and MMFX II (MMFX Technologies Corp. 2008), a high strength and corrosion resistant reinforcing steel recently introduced on the market, were also tested for comparison purposes. All test specimens belonged to the same heat for each individual type of reinforcing steel. Monotonic tensile tests were carried out first to determine the basic mechanical characteristics of the reinforcing steels investigated. Fatigue loading tests with constant strain amplitude were conducted to investigate the low-cycle fatigue behavior of the reinforcing steels. The overall cyclic response of the reinforcing steel is not greatly affected by the deformations in the reinforcing steel bars, provided buckling is precluded (Restrepo-Posada et al. 1994). Specimens for monotonic tensile and fatigue tests were designed according to ASTM E8 and ASTM E606 (ASTM 2004), respectively. As suggested by ASTM E606, buckling of the steel specimens was prevented. Detailed specimen design and loading protocol can be found in the former paper (Zhou et al. 2008). The strain ratio, R , is defined as

$$R = \varepsilon_{\min} / \varepsilon_{\max} \tag{1}$$

where $\varepsilon_{\min}$ and $\varepsilon_{\max}$ are the largest compressive and tensile strains respectively, with a sign convention of tension-positive. Fatigue tests with $R = -1$ were used for experimental data regression, and tests with other values of R were also carried out in order to investigate the mean strain effect. Failure of the fatigue specimen was defined as the point at which the maximum stress decreased by more than 50 % according to ASTM E606 (ASTM 2004). Referred to previous researchers, a strain rate of 0.005/sec was used in this low-cycle fatigue test (Mander et al. 1994). Low cycle fatigue tests in previous studies (Mander et al. 1994 and Brown et al. 2004) were carried out on unaltered specimens with original cross section and deformations, and the lateral support spacing for the specimens was six bar diameters. The specimens were tested up to strain amplitudes of 3% to 4%. Thus, the effects of buckling were incorporated into the test results. However, in the present study, buckling was prevented following the ASTM standard E606 (ASTM 2004).

Monotonic Tensile Test Results

Fig. 1(a) presents five individual stress-strain curves from the monotonic tensile tests for the reinforcing steels, and Fig. 1(b) shows a close-up view of yield plateau region of Fig. 1(a). The major characteristic stress-strain control parameters for each type of steel are listed in Table 1. In this table, the actual yield strengths determined by the 0.2% offset method per ASTM E8 (ASTM 2004) and the 0.35 percent strain method per Section 3.5.3 of ACI 318 (2008) were denoted as σ_{y1} and σ_{y2} , respectively.



(a) (b)

Figure 1. Stress-strain results for monotonic tensile tests
(a) complete view; (b) close-up view for yield plateau region.

Table 1: Monotonic tensile test results

Steel Name	E **(ksi)**	**Specified** σ_y **(ksi)**	**Actual** σ_{y1} **(ksi)**	**Actual** σ_{y2} **(ksi)**	**Actual** σ_u **(ksi)**	$\dfrac{\sigma_u}{\sigma_{y2}}$	**Uniform Elongation (%)**
Talley S24100	29,848	75	84.2	83.5	136.3	1.63	47.7
Talley 316LN	28,981	75	77.1	77.8	116.3	1.50	34.1
Talley 2205	27,705	75	94.1	97.0	130.5	1.35	20.0
A706	30,244	60	73.7	72.6	106.0	1.46	13.2
MMFX II	31,533	100	137.9	100.7	179.4	1.78	5.3

σ_{y1} is determined by 0.2% offset method according to ASTM E 8 (ASTM 2004).

σ_{y2} is defined as the stress corresponding to a strain of 0.35 percent (ACI 318 2008).

Uniform elongation: Strain at the maximum force sustained by the test piece just prior to necking or fracture, or both according to ASTM E 8 (ASTM 2004).

Based on the test results shown above, compared to A706, the modulus of elasticity (E) is slightly smaller for the three types of stainless reinforcing steel, and higher for MMFX II. In fact, the value of E of Talley S24100 is quite similar to that of the A706. These differences regarding the moduli of elasticity are known and correspond relatively well to the recommendations given in Note 8 of ASTM A370 (ASTM 2004).

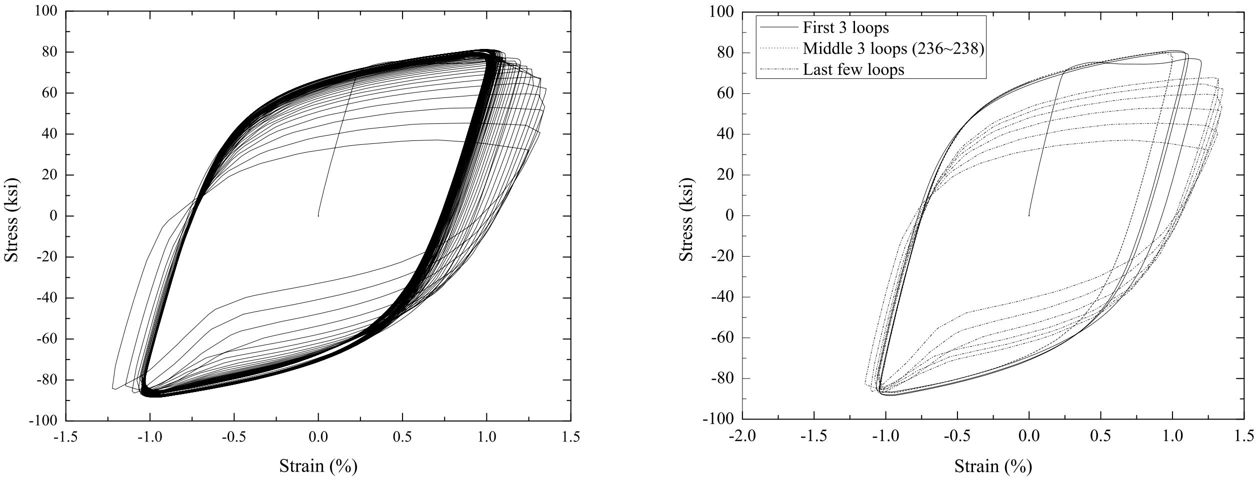
The stress-strain curves of Talley 316LN and A706 shows a clear yield plateau while those for Talley S24100, Talley 2205 and MMFX II did not show a distinct yield plateau. Comparing the data of σ_{y1} and σ_{y2} in Table 1, one could conclude that the yield strengths for the stainless reinforcing steels and A706, determined by the 0.2% offset method are similar to those defined by the stress corresponding to a strain of 0.35 percent. Among the six types of reinforcing steels tested, MMFX II has the highest yielding stress, $\sigma_{y2} = 100.7\ \text{ksi}$. Reinforcing steel of such a high yield strength has been accepted by the ACI 318 (2008) chapter 3.5.3 to be used as confinement reinforcement to improve the constructability (Post 2007). Note that the use of reinforcing steel bars of a higher yield strength tends to result in greater crack widths and deflections of structural elements under service loads. Partly due to this reason, current building (ACI 318 2008) and bridge codes (AASHTO 2007) generally do not allow the use of design yield strengths greater than 80 ksi and 75 ksi, respectively. If σ_{y2} is chosen to be the actual yield strength value for the sake of conservation, all types of reinforcing steels investigated, except Talley 2205, satisfy the requirement by Section 21.1.5.2 of ACI 318 (2008) that the actual yield strength does not exceed the specified yield strength by more than 18 ksi.

Under monotonic tensile loading, the uniform elongations before necking of the three types of stainless reinforcing steels are substantially higher than that of A706 and MMFX II. The uniform elongation of MMFX II (5.3%) is lower than that of A706 reinforcing steel (13.2%). This shows that stainless reinforcing steels are more ductile than both A706 and MMFX II. Increased ductility results in more energy dissipation prior to rupture, which is generally a desirable feature in seismic resistance design.

According to Section 21.1.5.2 of ACI 318 (2008), deformed reinforcement in members resisting earthquake-induced forces should have values of σ_u / σ_{y2} no less than 1.25 to ensure a sufficient length of the yield region to develop required inelastic rotation capacity. The reinforcing steels, Talley S24100, Talley 316LN, Talley 2205 and MMFX II all meet these requirements. Furthermore, the actual yield strength should exceed the specified yield strength no more than 18 ksi to avoid brittle shear or bond failure modes due to unexpected higher actual yield strength. If σ_{y2} is used for conservative purpose, except for Talley 2205, the other steels investigated all meet the previous requirement.

Low-Cycle Fatigue Test Results

Sample fatigue test results and representative loops (total strain vs. stress) for A706 are presented in Figs. 2(a) and 2(b). Constant strain amplitude was maintained during the stabilized cycles of the fatigue tests, but there were marginal cases with strain amplitude migration. The average values of stabilized cycles were used to calculate total strain amplitude, plastic strain amplitude and mean strain in each low-cycle fatigue test. ε_{ap} and N_f are defined as the plastic strain amplitude and the fatigue life (cycles to failure), respectively.



(a) (b)

Figure 2. Fatigue hysteresis loops for A706 at strain amplitude 1.02%
(a) complete loops; (b) loop extract.

For each type of reinforcing steel investigated, there were 10 specimens tested with mean strains of zero ($R = -1$), 5 specimens of positive mean strains ($R \neq -1$), and 3 specimens of negative mean strains ($R \neq -1$). Therefore, 18 specimens for each individual reinforcing steel, and a total of 90 coupons were tested in the low-cycle fatigue tests. Manson-Coffin relationship (Tavernelli and Coffin 1962, Manson 1962) was used for regression of the experimental data from fatigue tests with mean strains of zero ($R = -1$). The monotonic tensile test ($N_f = 0.25$) considered as the extreme data point for plastic strain amplitude larger than 2.5% in low-cycle fatigue tests was included in the regression for each type of reinforcing steel. The regression results are shown in Eqs. 2 to 6 and plotted in Fig. 3. The values of the quare of the correlation coefficient r^2 are 0.992, 0.996, 0.995, 0.964, and 0.893 for Eqs. 2, 3, 4, 5 and 6, respectively. These values suggest good correlation between the regression results and experimental data.

Talley S24100: $$\varepsilon_{ap} = 0.319\left(2N_f\right)^{-0.443} \tag{2}$$

Talley 316LN: $$\varepsilon_{ap} = 0.237\left(2N_f\right)^{-0.440} \tag{3}$$

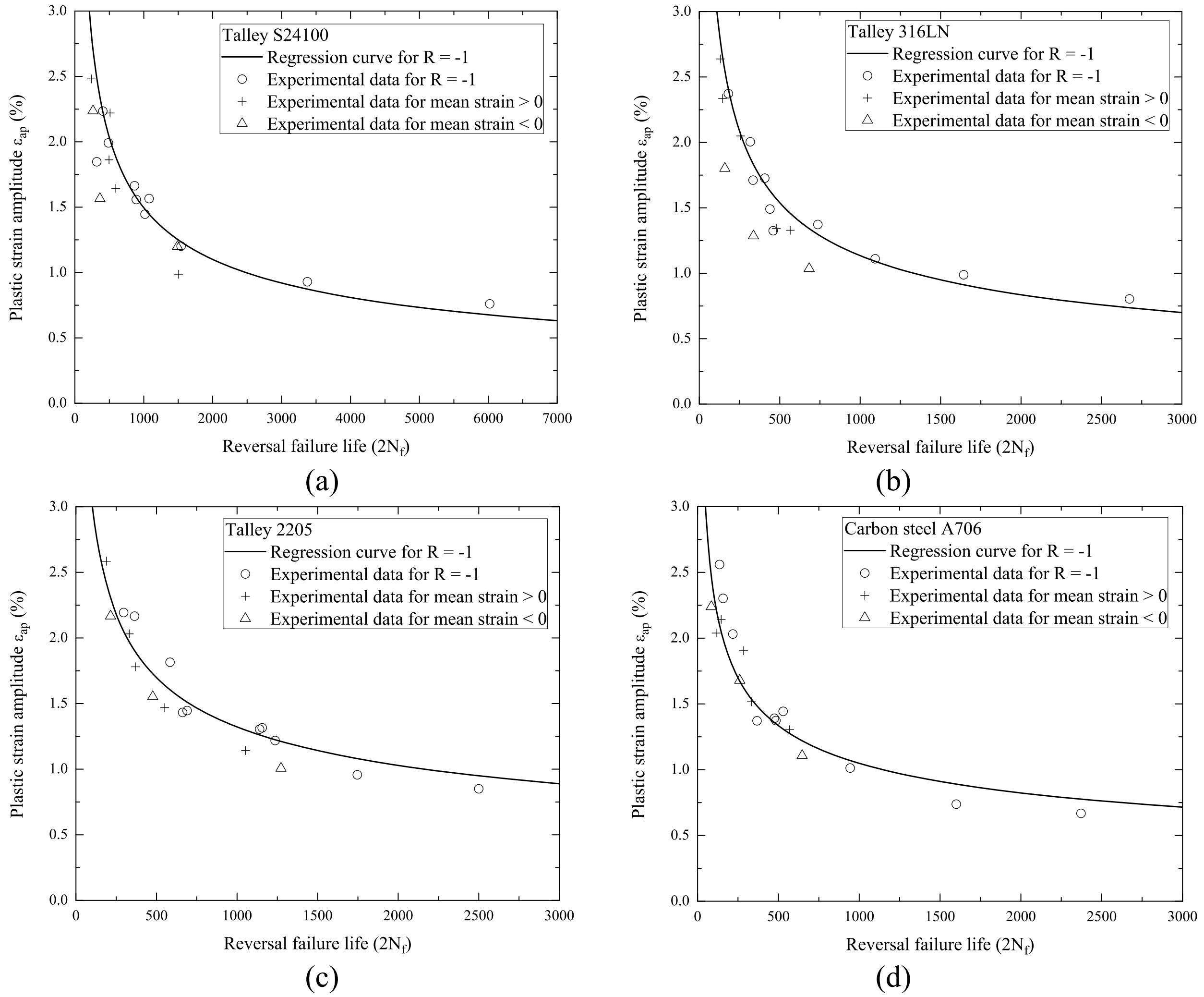
Talley 2205: $$\varepsilon_{ap} = 0.160\left(2N_f\right)^{-0.361} \tag{4}$$

A706: $$\varepsilon_{ap} = 0.116\left(2N_f\right)^{-0.348} \tag{5}$$

MMFX II: $$\varepsilon_{ap} = 0.046\left(2N_f\right)^{-0.201} \tag{6}$$

Figs. 3(a), 3(b), 3(c), 3(d) and 3(e) show experimental plastic strain amplitude vs. reversal fatigue life data for Talley S24100, Talley 316LN, Talley 2205, A706, and MMFX II, respectively. As shown in Fig. 3, by comparing the experimental data for the strain amplitude ratio R equal to -1 with those for R other than -1, it can be seen that the mean strain has little effect on the low-cycle fatigue life. This observation is consistent with that made by other researchers (Mander 1994 et al. and Pellissier-Tanon et al. 1982). Thus, mean strain effects can be ignored in estimating low-cycle fatigue life of the reinforcing steels tested.

It can be seen in Fig. 4, in the large plastic strain amplitude region ($N_f \le 250$), Talley S24100 has the longest fatigue life followed by Talley 2205, Talley 316LN, A706 and MMFX II.

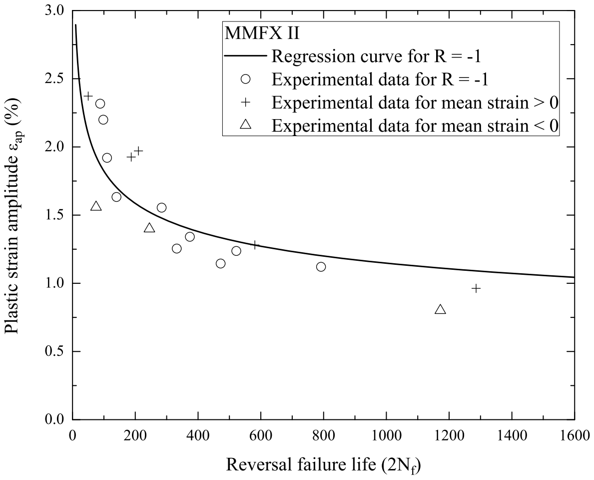


(a)

(b)

(c)

(d)



(e)

Figure 3. Plastic strain amplitude vs. fatigue life for (a) Talley S24100; (b) Talley 316LN; (c) Talley 2205; (d) A706; (e) MMFX II.

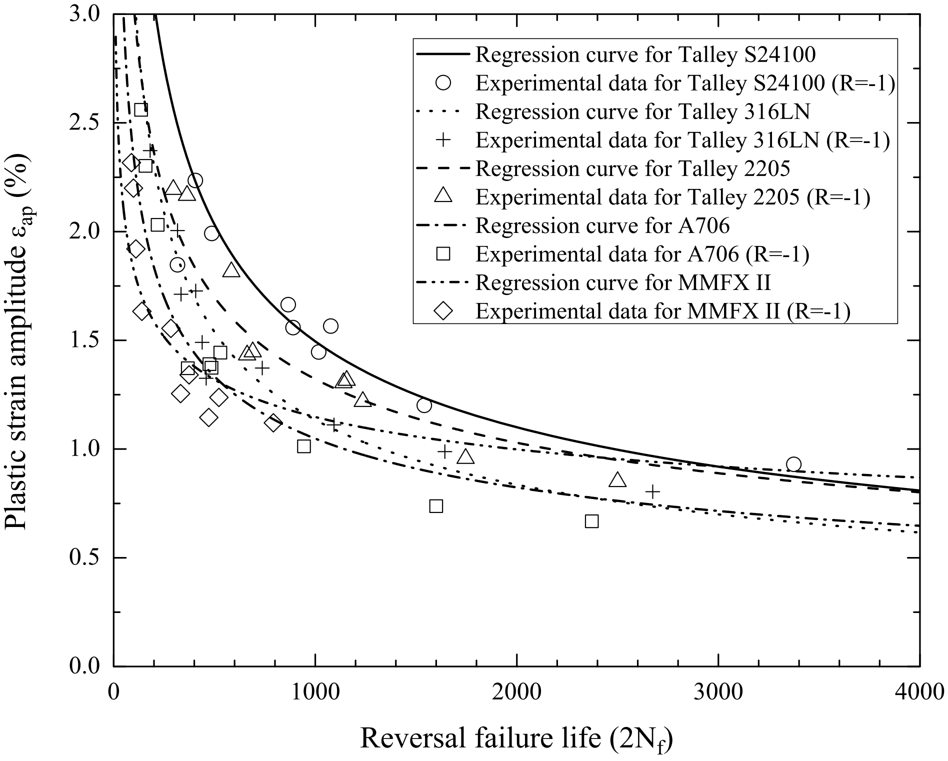


Figure 4. Regression curves for plastic strain amplitude vs. fatigue life

Conclusions

Mechanical properties and low-cycle fatigue behavior of Talley S24100, Talley 316LN and Talley 2205 stainless reinforcing steels, A706 carbon reinforcing steel, and MMFX II high strength, corrosion resistant reinforcing steel were investigated in this paper. Important conclusions are summarized as follows.

(1) The values of the modulus of elasticity, *E*, for Talley S24100, Talley 316LN and Talley 2205 and stainless reinforcing steels are 1.3%, 4.2% and 8.4% lower than that of A706; in contrast, the modulus of elasticity for MMFX II is 4.3% higher than that of A706.
(2) All five types of reinforcing steels tested satisfy the requirements of the ACI 318 code on the lower limit of the tensile to yield strength ratio. Except Talley 2205, the rest four types of reinforcing steels investigated meet the requirement by ACI 318 that the actual yield strength does not exceed the specified yield strength by more than 18 ksi.
(3) Under monotonic tensile loading, the uniform elongations before necking of the three types of stainless reinforcing steels are substantially higher than those of A706 and MMFX II.
(4) Mean strain effect can be ignored in estimating low-cycle fatigue life of the reinforcing steels tested.
(5) In large plastic strain amplitude region ($N_f \leq 250$), Talley S24100 stainless reinforcing steel has the longest fatigue life followed by Talley 2205, Talley 316LN, A706, and MMFX II.

Acknowledgements

Financial support for this project is provided by the Federal Highway Administration (contract No. DTFH61-07-R-00121) and industry through MCEER, University at Buffalo. The support of International Molybdenum Association, Nickel Institute, Talley Metals - A Carpenter Company, North American Stainless and Salit Specialty Steel is sincerely appreciated. Dr. Frank Smith, P. Eng. served as project manager for the consortium. MMFX Technologies Corp is acknowledged for providing reinforcing steel bar samples for testing.

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