Appendix E
Fatigue of High-Strength Reinforcing Steel

E.1 Introduction

Fatigue is a process of progressive structural change in a material subjected to transient loads, stresses or strains. Fatigue strength is defined as the maximum transient stress range (S) that may be repeated without causing failure for a specified number of loading cycles (N). The stress range is defined as the algebraic difference between the maximum and the minimum stress in a stress cycle: $S = f_{max} - f_{min}$; that is: the transient stress. Most ferrous materials exhibit an 'endurance limit' or 'fatigue limit' below which failure does not occur for an unlimited number of cycles, N. In general, the concrete material fatigue performance exceeds that of the steel and is not considered in design (Neville 1975).

S-N Relationships and Fatigue Behavior

In order to predict fatigue behavior (in this case to establish appropriate experimental parameters) it is necessary to establish the *S-N* relationship for reinforcing bars in concrete tested under repeated flexure. The *S-N* approach requires numerous fatigue test data points and exhibits considerable scatter and therefore numerous repeated tests are needed to develop the 'best-fit' relationship that describes the fatigue behavior of the material with a reasonable confidence level. There has been a significant amount of research studying fatigue of reinforcing steel and multiple empirical equations have been developed to describe its behavior. Most correspond to the same general form of the equation:

$$S^m \ x \ N = k \tag{E-1}$$

Empirical parameters m and k are dependent upon the units used to express S. Values of m and k are given based on bar size and, in some cases, the expected fatigue life, N. Available models are all based on reinforcing steel having nominal yield strength, f_y, between 40 and 75 ksi. No significant difference in *S-N* behavior is observed over this range of yield values (MacGregor et al. 1971, Mallet 1991). Additionally, some models are based on axial tension tests of bars in air, while others are based on bars in concrete beams tested in flexure. Moss (1982) demonstrated that the fatigue life of bars tested in concrete exceeds that of bars tested in air. Most of the relevant studies have been conducted in Europe (Moss 1980 and 1982, Tilly and Moss 1982, Mallet 1991). Best practices based on these studies have been adopted by the CEB FIB Model Code (1990) and these *S-N* relationships are adopted here. One of the authors (Harries) has conducted over 120 large-scale fatigue tests of reinforced concrete beams; the adoption of Eq. E-2 is supported by the cumulative results of these many studies. The relationships given in Eq. E-2 are for #5 bars embedded in concrete.

$$S^5 \ x \ N = 2.621 \ x \ 10^{17} \ (ksi) \qquad N < 1,000,000 \tag{E-2}$$
$$S^9 \ x \ N = 2.115 \ x \ 10^{26} \ (ksi) \qquad 1,000,000 < N < 100,000,000$$

There are no *S-N* relationships for reinforcing steel prescribed by AASHTO or ACI standards, rather these standards prescribe a maximum transient stress range corresponding to the presumed endurance limit (Eq E-2).

E.2 Fatigue Proof Tests

The limited scope of the fatigue testing program conducted as part of this study served as a 'proof test' to examine whether the existing AASHTO specifications for the fatigue limit state (Eq. E-2) are applicable to members with high-strength reinforcement. Thus it is necessary to select a stress range, S, appropriate to the number of cycles to be tested, N.

The AASHTO fatigue limits are derived largely from tests having $N = 2,000,000$. However, as code-prescribed limits, they must be understood to be appropriate for the 'life of the structure'. AASHTO LRFD (2007) §6.6.1.2.5 provides some guidance as to a) the definition of a fatigue cycle; and b) the expected number of cycles over the life of a structure. Based on AASHTO-recommended values, a deck slab on an urban interstate may undergo approximately 1 million fatigue cycles per year:

$$N = 365 \times n \times ADTT_{SL} = 930,750 \text{ cycles} \tag{E-3}$$

where $ADTT_{SL} = 0.85(ADTT) = 0.85(0.15ADT)$ with $ADT = 20,000$ and $n = 1$.

The supporting girders (assuming the bridge exceeds 40 feet) will undergo twice this number of cycles ($n = 2$). Clearly, not all bridges see this many cycles: A lightly travelled two-lane rural highway bridge may undergo only about 100,000 cycles per year:

$$N = 365 \times n \times ADTT_{SL} = 109,500 \text{ cycles} \tag{E-4}$$

where $ADTT_{SL} = 1.0(ADTT) = 1.0(0.15ADT)$ with $ADT = 1,000$ and $n = 2$.

The selection of an appropriate fatigue proof test must consider at least the following:

1. **Practical value of N.** Two million cycle tests are most common and may be considered 'standard'. At 1.2Hz, a 2 million cycle test takes three weeks. Generally there is more scatter in results as N is taken less than 1 million cycles. Larger values of N are impractical for large-scale laboratory tests and few such tests are reported in the literature. A 2 million cycle protocol is adopted in the present study.

2. **A minimum stress, f_{min},** must be used that is adequate to represent 'dead load' and to permit safe and efficient control of the test protocol. A value $f_{min} = 0.10f_y$ is commonly used and is adopted in the present study.

3. **The value of the stress range, S,** is selected to 'match' the value of N selected using an established S-N relationship. The relationship given by Eq. E-2 is used in the present study.

Considering the previous discussion and assuming nominal values $f_y = 60$ ksi and $f_{min} = 0.10f_y$, Eq. E-2 yields $f_r = S \leq 22$ ksi. The same value is found using Eq. E-3 regardless of the value of f_y used. Based on the S-N relationships give in Eq. E-2, $S = 22$ ksi corresponds to $N = 20,000,000$ which correlates reasonably well with the expected range of fatigue life anticipated by AASHTO. For example, a deck slab on an urban interstate will undergo approximately 20

million fatigue cycles over a 20 year life. Using Eq. E-2, setting a test value of $S = 28$ ksi for a 2 million cycle test is equivalent to a 20 million cycle test having $S = 22$ ksi. The latter is the AASHTO 'proof protocol' but would take upwards of 7 months to complete, while the former may be conducted in a practical time frame (3 weeks). The specimen protocols described below were selected considering these factors. Thus the protocol adopted for Fatigue Test 1 was selected to exceed the $S = 28$ ksi at $N = 2,000,000$ criteria; S was selected to be 32 ksi.

SEM of Fatigue Test 2 Failure

The failure of a bar at N = 155,005 under S of 45.5 ksi is very close to the prediction which is thought to be conservative. Therefore an investigation of the fatigue failure surface using scanning electron microscopy (SEM) was conducted (Figure E-1). The SEM revealed aluminum (Al) inclusions in the fracture surface (E-1b) and a significant silicon (Si) inclusion at the edge of the bar section thought to have served as a crack initiator (E-1c and E-1d). Figure E-1 provides both the SEM image and backscatter spectral analysis for each image. The spectra shown in Figure E-1a are of the A1035 material and agree well with the specified composition of this material (ASTM A1035 2007).

The spectra shown in Figure E-1b are taken from the dark inclusion shown in the image. This is clearly pure aluminum. The aluminum cannot be accounted for. A1035 contains no aluminum but the inclusion was apparently embedded in the section and therefore unlikely to be contamination occurring following the fracture. Figures E-1c and E-1d show the same location on opposite faces of the fracture. A 0.3 mm (0.012 in.) diameter inclusion is evident in these images. The spectra indicate that this inclusion is silicon. A1035 steel is specified to have a maximum silicon content of 0.50% (ASTM A1035 2007). Therefore the presence of silicon should not be a surprise. The size of the inclusion, however, and its location at the edge of the bar may have resulted in a stress concentration that initiated the fatigue failure of this bar.

E.3 Previous Studies of Reinforcing Bar Fatigue

In order to establish the validity of AASHTO-established fatigue limits (Eq. E-2) and to assess the effects of yield strength on fatigue performance, a review of available fatigue data was conducted. Table E-1 summarizes these studies. While few studies report on bars having $f_y > 75$ ksi, the fact that these studies report different steel grades (i.e. 40, 60 and 75 ksi) permit some trends to be established. Figure E-2 shows the reported fatigue endurance limits as a function of yield strength. Although stress range is the critical parameter affecting fatigue, this data has been sorted by the value of f_{min} which is shown to have little effect on the results. Figure E-2 shows no values of the endurance limit falling below 24 ksi. Thus the present AASHTO recommendations for f_f are felt to be conservative for tension-tension fatigue (i.e.: f_{min} positive). Additionally, a correlation between endurance limit and f_y is evident. Thus the penalty paid by using Eq. E-2 with high strength steel is unjustified. While Eq. E-3 does not recognize the correlation between f_f and f_{min}, it does remove this penalty in a justifiable manner.

Table E-1 Fatigue Stress Ranges (f_r) Corresponding to a Fatigue Life of 2 Million Cycles.

| Bar Size	No. tests	f_y (ksi)	f_{min}	f_r (ksi)	reference
#8	157	40	0.10f_y	38	Pfister, J.F. and Hognestad, E. 1964
		60		34	
		75		39	
		40	0.30f_y	33	
		60		31	
		75		32	
		40	0.10f_y	32	
		75		35	
		40	0.30f_y	28	
		75		30	
#5	19	40	0.25f_y	27	Lash, SD. 1969
		60		31	
		75		38	
#8	72	40	0.10f_y	30	MacGregor, J.G., et al. 1971
		60		30	
		75		30	
		40	0.40f_y	25	
		60		25	
		75		25	
#5	not reported	40	0.10f_y	32	
		60		33	
		75		36	
#10	not reported	40	0.10f_y	31	
		60		29	
		75		30	
		49	0.17f_y	28	Wascheidt, H. 1965
		53	0.16f_y	28	
		64	0.13f_y	28	
		88		31	
		50	0.10f_y	30	Kokubu, M. and Okamura, H. 1965
		57		30	
		70		31.5	
#3, #4 & #5	n.r.	120	0	45[1]	DeJong 2005
#5	1	120	0.10f_y	32	present study

[1] One million cycle fatigue life
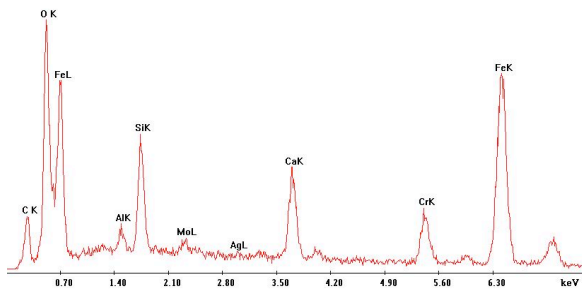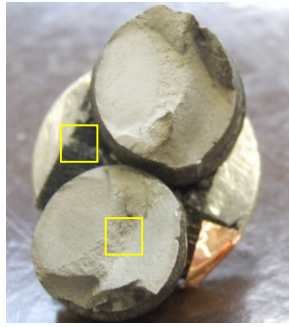
(a) Fracture and backscatter spectra of MMFX steel (boxes indicate region of images c and d)
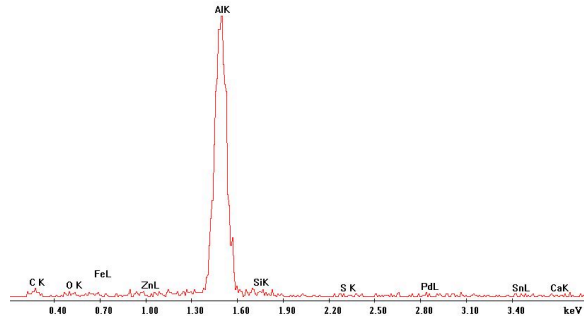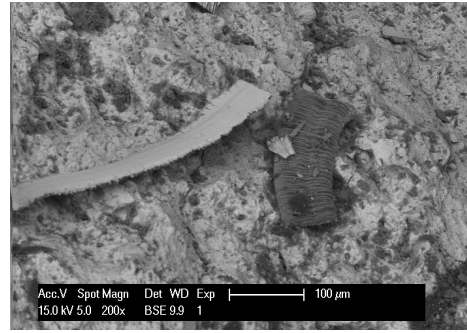
(b) Aluminum inclusion (darker inclusion right of center; long thin piece is steel)
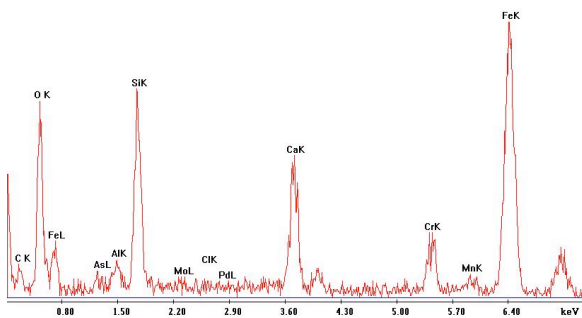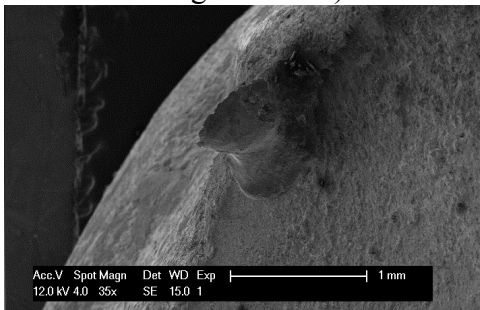
(c) 'Male' side of Silicon inclusion
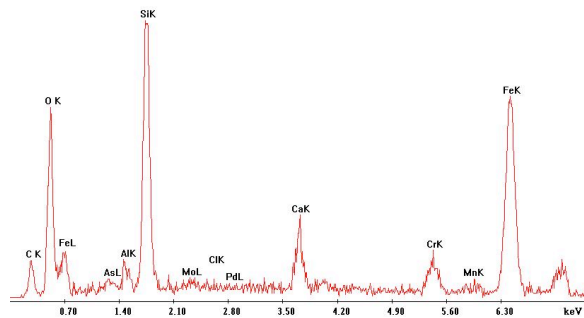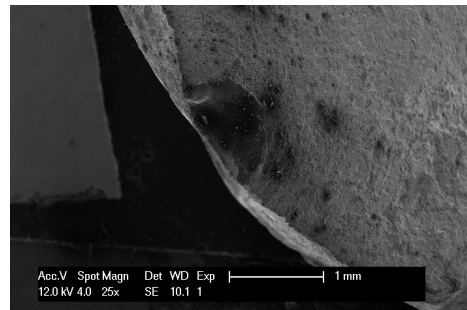
(d) 'Female' side of Silicon inclusion

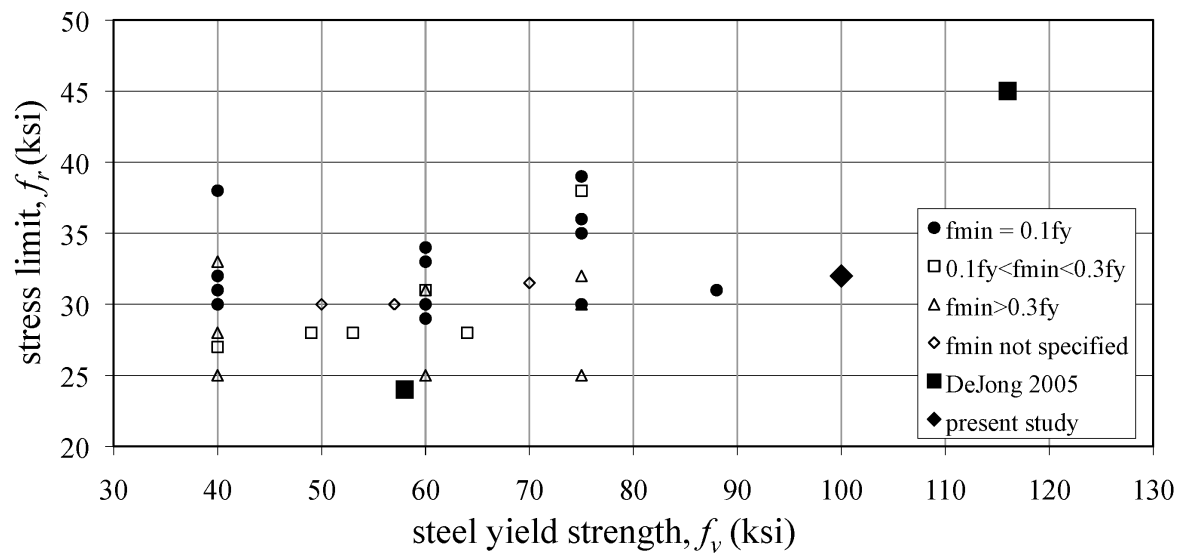**Figure E-1 SEM Images of Failure Surface.**

Figure E-2 Observed Stress Limits as a Function of Minimum Stress Level, f_{min}.