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**EFFECT OF STRAIN RATES ON STRESS-STRAIN
PROPERTIES AND YIELD PROPAGATION
IN STEEL REINFORCING BARS**

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Abstract

Dynamic loading due to earthquakes alters the stress-strain properties and strain distribution in steel reinforcement. Past research on dynamic load effects has been under constant strain rates, and the applicability of results to variable strain rates caused by earthquakes is uncertain. In the study presented herein, the effect of variable strain rate and distribution of strain along the length of steel bars were studied experimentally. The specimens were ASTM Grade 60 with #3, #8, and #11 sizes, and the strain rates ranged from 0.0001 to 0.1 strain per second. The analysis of data showed that the rate of change in strain rate (second derivative of strain) is an important factor. The data also revealed concentration of strain at higher strain rates. Based on the results new simple equations to estimate the yield and ultimate strength of the bars were proposed and compared with other available data.

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1 INTRODUCTION

1.1 Background

During the last three decades, research has been underway to study the strength of reinforced concrete members particularly after the introduction of the ‘limit state design’ concept for concrete structures in design codes. The variation of material strength and geometrical quantities that affect the strength of reinforced concrete members have been the focus of many research studies. Although in general the reinforcing steel is manufactured based on specific standards, variation between its target and measured yield stress is expected. The following are sources of variation in steel yield stress: (1) variation in the strength of material itself; (2) variation in the area of cross section of the bar; (3) effect of the bar diameter on the properties of the bar; (4) effect of strain at which yield is defined; (5) effect of rate of loading.

The variation in strength within a single bar is relatively small, while the in-batch variation is slightly larger. However, the variability of samples derived from different batches and sources may be high. This is expected since rolling practices and quality measures vary for different manufacturers and different bar sizes.

The actual areas of reinforcing bars tend to deviate from the nominal areas due to rolling process. The designers do not have this information readily available to them and therefore use the nominal areas in their calculations. For this reason, this variation should be incorporated into the strength of steel. Since 1968 the ASTM specifications have based the yield strength on nominal area and thus incorporate this effect directly¹. The static yield strength based on nominal area seems to be desirable because designers use the nominal areas in their calculations.

The data on the effect of the bar diameter on yield strength are contradictory. Allen² and Gamble³ suggested that the mean yield strength of No. 14 and No. 18 bars may be less than that of smaller bars. This phenomenon was not present in the other test series studied by other researchers⁴⁻⁶.

Different values for the yield strength of steel can be obtained depending on how it is defined. The ASTM standards for reinforcing bars define the yield strength as the strength measured at a strain of 0.005. Because concrete crushes at a strain of roughly 0.35%-0.4%, the American Concrete Institute (ACI) Building Code requires that the yield strength of bars having a specified yield strength in excess of 60 ksi (410 MN/m²) be defined at a strain of 0.35%. An alternative method to determine the yield point is to use the proof stress concept. In this method a line is drawn parallel to the initial (elastic) portion of the steel stress-strain curve at a distance corresponding to the prescribed elongation, for instance 0.2%, as used in this study. The ordinate for intersecting point of this line with the curve will give the yield stress.

A literature review on yield strength of reinforcing bars showed that the coefficient of variation was in general in the order of 1%-4% for individual bar sizes and 4%-7% overall for data derived from one source. When data were taken from many sources, the coefficient of variation increased to 5%-8% for individual sizes and 8%-12% overall⁷. Various standards and studies have addressed the static properties of steel reinforcing bars. The static properties are obtained in the quasi static tests at about 10^{-5} to 10^{-4} per second rate of straining. This study investigates the stress-strain properties of reinforcing steel subjected to quasi-static loading rates up to 0.1 strain per second because the structures subjected to earthquake loading could generally experience this high rate of

straining. To cover a range of bar sizes generally used in practice, #3, #8, and #11 ASTM² Grade 60 bar specimens have been used in this study.

1.2 Literature Review on Strain Rate

At high strain rates, the yield stress and ultimate stress increase^{8,9,10} and make the structural response different from that of static loading. However, the steel modulus of elasticity is not significantly influenced by the rate of straining^{8,9,10}. Note that the ultimate stress is defined as the peak stress in the strain-hardening stage, and not necessarily as the stress at failure. A literature review of the effects of high strain rates on the properties of steel reinforcing bars has revealed that steel with lower yield strength is more sensitive to strain rate variation than steel with higher strength⁹⁻¹³.

Previous tests have indicated a logarithmic increase in the yield and ultimate strength of reinforcing steel with increasing strain rates^{8,14}. Soroushian and Choi¹⁵ proposed the following equations for the dynamic to static ratios of the upper yield and ultimate stress for steel, based on regression analysis of the reported data by other researchers^{9,11,16,17,18} :

$$\frac{f'_y}{f_y} = (-6.83 \times 10^{-6} f_y + 1.72) + (-1.37 \times 10^{-6} f_y + 0.144) \log \dot{\epsilon}_{10} \quad (1)$$

$$\frac{f'_u}{f_u} = (-7.71 \times 10^{-7} f_y + 1.15) + (-2.44 \times 10^{-7} f_y + 0.04969) \log \dot{\epsilon}_{10} \quad (2)$$

where f_y, f'_y = static and dynamic yield strength of steel (ksi), respectively;

f_u, f'_u = static and dynamic ultimate strength of steel (ksi), respectively, and

$\dot{\epsilon}$ is the strain per second

If f_y and f'_y are in MPa, the above equations will be as follows:

$$\frac{f'_y}{f_y} = (-9.90 \times 10^{-7} f_y + 1.72) + (-1.99 \times 10^{-7} f_y + 0.144) \log \dot{\epsilon}_{10} \quad (1-1)$$

$$\frac{f'_u}{f_u} = (-1.12 \times 10^{-7} f_y + 1.15) + (-0.35 \times 10^{-7} f_y + 0.04969) \log \dot{\epsilon}_{10} \quad (2-1)$$

Malvar and Crawford¹² obtained the following equation for the dynamic to static stress ratios by regression analysis of experimental data reported in the literature^{11,17-22} for both yield and ultimate stress:

$$\frac{f'_y}{f_y} = \left(\frac{\dot{\epsilon}}{10^{-4}} \right)^\alpha \quad (3)$$

For the yield stress, $\alpha = \alpha_{fy}$, where $\alpha_{fy} = 0.074 - 0.040 \frac{f_y}{60}$

and for the ultimate stress, $\alpha = \alpha_{fu}$, where $\alpha_{fu} = 0.019 - 0.009 \frac{f_y}{60}$

(If f_y is in MPa, the 60 ksi denominator should be replaced by 414 MPa)

Kulkarni and Shah²³ analyzed the reported data^{9,24-26} and suggested the following equations for the dynamic to static yield stress ratios:

$$\text{For 310 MPa (44.9 ksi) steel: } \frac{f'_y}{f_y} = 0.0328 \text{Ln} \left(\frac{\dot{\epsilon}'}{\dot{\epsilon}} \right) + 0.9873 \quad (5)$$

$$\text{For 520 MPa (73.4 ksi) steel: } \frac{f'_y}{f_y} = 0.0124 \text{Ln} \left(\frac{\dot{\epsilon}'}{\dot{\epsilon}} \right) + 0.9832 \quad (6)$$

where $\dot{\epsilon}'$ and $\dot{\epsilon}$ are dynamic and static strain rates respectively.

The above mentioned studies and proposed equations have focused on mechanical properties of reinforcing steel under constant strain rates. The steel properties under

variable strain rates, however, are unknown and need to be studied. The primary purpose of the study presented in this article was to determine the effect of variable strain rate on the characteristics of the stress strain relation for steel reinforcing bars. The study was triggered by the lack of data and procedures to account for variable strain rates experienced by reinforced concrete structure during earthquakes.

1.3 Objectives and Scope

This study is a contribution to the existing knowledge of mechanical properties of reinforcing steel subjected to strain rates expected in an earthquake event. Most of the reported data are based on monotonic constant strain rate tests, whereas seismic excitations put the structure under variable strain rates. Knowledge of dynamic mechanical properties of steel is of significant importance in the numerical analysis of reinforced concrete structures subjected to seismic loads. The primary objective of this research was to study the effect of strain rate on the stress-strain properties of reinforcing bars. The effect of strain rate up to 0.1 strain per second on yield and ultimate stress of #3, #8, and #11 bars was investigated. The results of this study are useful to engineers to help understand the behavior of reinforced concrete members under dynamic loads and to help form a basis for more realistic future seismic design practices.

2 TEST SPECIMENS

2.1 Introduction

To investigate the effect of strain rate on the reinforcing steel response to tensile loads, #3, #8, and #11 ASTM Grade 60 bar specimens have been used in this study. The objective was to investigate the strain rate effect on a range of the most common used bar sizes in practice. The ASTM Grade 60 bar specimens were used for all the bar sizes

because this is the mostly used steel grade in reinforced concrete construction. A typical stress-strain curve for ASTM A615 Grade 60 steel obtained from steel bars loaded monotonically in tension at quasi static rate is shown in Figure 1. The curve exhibits an initial linear elastic portion followed by a yield plateau, i.e. a horizontal portion of the curve where strain continues to increase at constant stress. High –strength bars generally do not have a well-defined yield plateau. However, Grade 60 bars normally have much shorter plateau as compared to Grade 40 steel. With further strains, the stress begins to increase again, though at a slower rate, a process that is known as strain hardening. The curve flattens out when the tensile strength is reached. It then turns down until fracture occurs. Sometimes yielding starts with a high stress level (upper yield) followed by an abrupt decrease in stress (lower yield), which remains for a while before strain hardening portion. At the end of strain hardening portion, all locations in the bar still have the same strain. This strain, called ultimate strain, is the one which characterizes the bar’s energy dissipation potential in numerical analysis. Beyond this point, necking at one location takes place, while the rest of the bar remains with the same strain or unloads elastically. A minimum percent elongation is mostly specified in various standards. ASTM A615¹ requires a minimum percent elongation of 9% in 8 inches (200 mm) for small bars (#3 to #6), 8% for #7 and #8 bars, and 7% for large bars (#9 to #18).

2.2 Test Specimens

Tensile tests were conducted on #3, #8, and #11 ASTM Grade 60 bar specimens. Bar specimens were 508 mm (20 in.) long. They were tested using a MTS servo-controlled machine, which was programmed to apply constant and variable strain rates.

2.3 Instrumentation

2.3.1 Introduction

The basic instrumentation consisted of strain gages and laser to measure the bar specimen elongation.

2.3.2 Data Acquisition System

Data were collected from the tensile tests using a National Instrument control unit. This system had a maximum sampling rate of 2Hz. Analog filters were set up at 4 Hz. Analog output was available for on-line monitoring or control of any selected input parameter. Strain gages and laser were connected to the acquisition system terminals.

2.3.3 Strain Gages

Each specimen was instrumented with three strain gages at three equally spaced locations along the specimen. Strain gages used were the post yield YF-series provided by Texas Measurements Inc²⁷. The specific type that was used is the YFLA-2. They had large strain measurement capacity, which could reach up to 200,000 micro-strains at room temperature. The YFLA-2 strain gage has a small backing size that enabled their adhesion to small surfaces. The backing length of the strain gages is 0.295 in (7.49 mm) and the backing width of 0.157 in (3.99 mm). The CN-Y compatible adhesive was used to fix the strain gages on the bars.

2.3.4 Laser Device

A Laser device was also used to measure bar elongation over a nominally 254 mm (10 in.) gage length. The laser extensometer had a measurement range of 0.2 in (5.08 mm) up to 5.0 in (127 mm). It had a resolution of 0.0001 inches (0.00254 mm). It measured bar elongation by scanning the specimen and detecting the location of reflective tape markings. As the marks move during the test, the laser tracks and records

their exact position. The manufacturer of the laser extensometer used is Mechanical Testing and Simulation (MTS) and the type used is LX 500.

2.4 Test Procedure

All tests were done at the Structural Laboratory at University of Nevada, Reno (UNR). The bar specimens were placed vertically and were held in position with steel grips. Tensile loads were then applied, monitored, and recorded up until failure of specimen. The applied force and the bar elongation were recorded by the testing machine. The elongation of the bars was also monitored by the strain gages and laser readings. The testing machine was programmed to apply pre-selected strain rate histories. The actual strain rates were also calculated at intervals of 0.05 seconds using bar elongation data.

2.4.1 Constant Strain Rate Tests

Monotonic constant strain rate tests were conducted on #3 and #8 bar sizes at different strain rates ranging from 100 to 100,000 $\mu\epsilon/\text{sec}$. Attempts were also made to test #11 bar specimens under similar strain rates used for #3 and #8 bars. However, due to the slippage of the bar at the end grips during the tests at high strain rates, the maximum strain rate was limited to 15000 $\mu\epsilon/\text{sec}$ for #11 bars. In fact for #11 bars, the testing machine was not capable to apply a large enough grip force to prevent the bar specimen from sliding simultaneous with tensile loads at moderate strain rates.

2.4.2 Variable Strain Rate Tests

Variable strain rate and cyclic load tests were performed using pre-selected strain rate patterns. The patterns were chosen to cover a range of possible strain rates that a reinforcing bar may experience under seismic excitations. In practice the yielding of bars is expected to occur when the strain rate is decreasing and the maximum displacement of

the structure occurs at zero strain rate at the end of a quarter of a loading cycle. Thus to simulate the real loading trend, a pattern of decreasing strain rates for variable and cyclic load tests were chosen as shown in Tables 1 and 2. The specimens were tested up to failure. As shown in Table 1, the bar tests started at a high range of strain rates up to the point of 1500 $\mu\epsilon$. Lower range of strain rates were then applied up to the point of 3000 $\mu\epsilon$. The tests were continued to 150000 $\mu\epsilon$ at the decreasing strain rates, ending with 100 $\mu\epsilon$ /sec at failure. The 1500 $\mu\epsilon$ and 3000 $\mu\epsilon$ points were chosen as pre-yield and post-yield representative points for the test specimens respectively. The applied strain rates were changed linearly within the ranges shown in Table 1 for pre-yield, yield and post-yield parts of the tests. Test under constant strain rate of 100 microstrain per second (Test No. 1) was performed to establish a benchmark for static loading rate.

2.4.3 Cyclic Load Tests

In cyclic load tests (Table 2), the specimens were first subjected to five similar half-cycle loads. The tensile load applied up to 4000 $\mu\epsilon$, and then released to zero stress point. The peak tensile strains were then increased by 2000 $\mu\epsilon$ in each subsequent cycle up to the failure. In order to follow the pattern of straining and avoid buckling of the specimen coupons, the testing machine was programmed to perform on both displacement and force control mechanisms. The specimens were loaded at a specified strain rate up to a pre-defined strain point, and then unloaded to the point of zero force. The range of strain rates for the first 5 cycles were smaller than the strain rates for the subsequent cycles as shown in Table 2. The range of strain rates from static to 0.1 per second were chosen based on the strain rate data obtained from longitudinal bars in many

previous RC column shake table tests under different earthquake records performed at University of Nevada, Reno (UNR) structural lab.

3 TEST RESULTS

3.1 Strain Rate Calculation

The testing machine was programmed to apply pre-selected strain rate histories. The actual strain rates were also calculated at intervals of 0.05 seconds using bar elongation data. The actual strain rates deviated from the target strain rates. The deviation was larger at higher strain rates particularly at the starting point and before and close to yielding, where rapid changes in strain rates were observed. This was because the bar experienced a large change in strain at the starting point and reached the yield strain quickly under high strain rates and the testing machine was not able to adjust the strain rates at high speeds. Therefore, the strain rate at yielding was taken as the average of the actual strain rates between $0.5\varepsilon_y$ to ε_y , calculated at 0.05 second intervals. For ultimate stress the strain rate was taken as the average of strain rates from zero to ultimate stress. This was due to the fact that for variable strain rate tests, the strain rate before yielding is not an appropriate representative for ultimate strength evaluation. The reason for including strain rates from zero stress to $0.5\varepsilon_y$ in average strain rate calculation was the fact that this portion of strain rate history had negligible effect on the average strain rate calculated up to ultimate strength point.

3.2 Constant Strain Rate

The test results are summarized in Tables 3-5 for #3, #8, and #11 bars respectively. The deviation exists between the target strain rates and the calculated strain

rates based on the measured strains. Strain rates equal to 10^{-4} per second or smaller were taken as static rates. This was due to the fact that there is little or no strain rate effect for strain rates below 10^{-4} per second¹¹. In this study the relative strain rate is the dynamic strain rate divided by static strain rate (i.e. 10^{-4} per second). The advantage of using relative strain rate, is that it provides a basis for comparing different reported results with different reference static rates. In general, the yield stress and ultimate strength of reinforcing bars increase with increasing strain rate. The yield strength is more strain rate sensitive than the ultimate strength (see Figs.2 and 3). The amplification factors for yield stress in bars #3 and #8 are shown in Figure 2. For each bar size the measured static yield stress is shown in the graphs. It can be seen in Figure 1 that the yield stress enhancement is increased as the bar size increased from #3 to #8. The increase in the ultimate stresses for different size bars followed the same trend (Figure 3) but with lower slope.

3.3 Variable Strain Rate

Yield Stress - The test results are shown in Table 6. Figure 4 shows the yield stress amplification factors for variable strain rate tests. In general the data points are more scattered. The fitted line slope is comparable for #3 bar but smaller for #8 bar as compared to constant rate test data.

Ultimate Stress - The increase in ultimate stress is shown in Figure 6. The strain rates in this figure are the average strain rates from $0.5 \epsilon_y$ to ϵ_y . To include the strain rate history beyond the yield strain, the average strain rate from zero to ultimate load were also plotted to determine the scatter is reduced (as measured by R^2 value). The results are shown in Figure 7. It can be seen that for ultimate stress enhancement, the average strain

rate which includes strain rates from zero to ultimate is a better representative for strain rate.

3.4 Cyclic Load Tests

Yield Stress – The test results are shown in Table 7. The amplification in the first yield stress versus the strain rates for bar #3 and #8 are shown in Figure 8.

Ultimate Stress The data points and the best fitted line based on the average strain rates from zero to the ultimate stress are shown in Fig. 10. As mentioned earlier, the slope of correlation line is smaller than for yield stress enhancement (Fig.9).

4 ANALYSIS OF TEST RESULTS

4.1 General

By carefully analyzing the data, it appeared that the second derivative of strain with respect to time (the slope of strain rate relative to time) is an important factor that affects the stress amplification. The yield stress enhancement was higher when the strain rate was increasing (positive slope for strain rate) compared with the case with negative slope in the strain rate.

4.2 Strain Rate Index

An index termed ‘Strain Rate Index’ (SRI) was introduced to account for the effect of rate of strain rate. The index is a product of a factor “K” and the average strain rate between half yield strain to the yield strain. The proposed SRI is:

$$SRI = K \dot{\epsilon}_{ave} \quad (7)$$

where: $K = \left(\frac{\dot{\epsilon}_y}{\dot{\epsilon}_{0.5y}} \right)^{0.5}$

$\dot{\epsilon}_y, \dot{\epsilon}_{0.5y}$ & $\dot{\epsilon}_{ave}$ = strain rate at yield, at half yield, and the average strain rate between half yield and yield, respectively.

The factor K is one when the strain rate is constant, more than one for positive rate of strain rate and less than one for negative rate of strain rate.

4.2.1 Yield Stress in Variable Strain Rate Tests

Replacing the strain rate (Figure 4) by SRI (Figure 5), has shown a slightly better correlation for the effect of variable strain rate on yield strength of reinforcing bars, by slightly improving the R-squared value.

4.2.2 Yield Stress in Cyclic Load Tests

The amplification factors as a function of the SRI values are shown in Figure 9. It can be seen that the data point scatter is reduced and a better correlation is achieved with SRI values rather than strain rates at yielding.

4.3 Proposed Equations

Considering the influence of yield strength and bar size on the strain rate sensitivity of the steel mechanical properties, the following expressions were derived in terms of the ratio of dynamic yield stress (f'_y) to static yield stress (f_y) as a function of relative Strain Rate Index (SRI). The expressions were derived by analyzing the best fit line equations and expanding them to include the effect of different types of loading and different size bars for strain rates up to 1 per second.

$$\frac{f_y'}{f_y} = \left(\frac{SRI}{10^{-4}}\right)^\alpha \quad (8)$$

$$\alpha = 0.022\left(\frac{\phi}{\phi_8}\right)^{0.15} - 0.006\left(\frac{f_y}{60}\right) \quad (9)$$

Where: f_y , f_y' = static and dynamic yield stress of steel (ksi), respectively;

(If f_y is in MPa, the 60 ksi denominator should be replaced by 414 MPa)

ϕ = the diameter of the bar and ϕ_8 is the diameter of bar #8;

The ratio of the dynamic to the static ultimate strength is proposed as follows:

$$\frac{f_u'}{f_u} = \left(\frac{\dot{\epsilon}_{ave}}{10^{-4}}\right)^{\frac{2}{3}\alpha} \quad (10)$$

Where $\dot{\epsilon}_{ave}$ is the average strain rate from zero to ultimate strain

4.3.1 Verification of Proposed Equations

The proposed equations were verified using the experimental results obtained from this study. It was found that the proposed equations estimate the increase in yield and ultimate stresses with reasonably good agreement with the experimentally observed values. The proposed fits for estimating yield and ultimate stresses for constant and variable and cyclic strain rates are shown in Figs.11, 12 and 13 respectively. It was found that the difference between estimated yield stress and the best fit line is less than 4% for all cases. A better correlation is achieved for the cyclic strain rates (Fig. 13) as compared to constant and variable strain rates (Figs.11 and 12).

4.3.1.1 Comparison with Previous Test Results

The equations that are proposed in this article were compared with the test data that had formed the basis of the existing equations discussed in previous sections. A comparison was also made with reported data on the ultimate strength for bars with different static yield strength. As shown in Fig. 14, a reasonable correlation exists between the data and the proposed equations. The maximum difference between the best fit line to the reported data and the proposed equation is less than 3%.

4.4 Localization and Propagation of Strain

Comparison between the strain gage readings at different locations of bar specimens shows that in high rate tests, the strain was not uniformly distributed along the bar. Localization of strain started well before peak stress was reached. Figure 15 shows the ratio of peak strain to average strain against ratio of peak strain to yield strain for bar #3 and #8 at different strain rates. For #3 bar, at the strain rate of 0.1 strain per second, the localization started before yielding, decreased until about 40 times the yield strain then increased up to the failure point. For lower rate of straining, the strain localization started after yield strain and almost linearly increased until rupture. Similar behavior was observed for #8 bars. In general the localization of strain was higher for higher rate of straining. On average for different bar sizes at the strain rate of 0.1 strain per second, the ratio of peak strain to average strain at the strain equal to 30 times yield strain (about 7% specimen elongation) was about 1.25. The ratio was approximately 1.70 at 80 times yield strain (about 18% elongation).

Yielding initially takes place at one point in the bar. It will then propagate across the section and then in longitudinal direction. As can be seen in Fig.15, in general the

localization of strain is higher for small size bars (#3) as compared to larger size bars (#8) at similar strain rates. However, larger size bars are more sensitive to the strain rate. As shown in Fig. 15, #8 bars have larger increase in the slope of localization line from low to high strain rates as compared to #3 bars. This is because it takes more time for yield strain to propagate across the larger size bar cross section than for the small bars. It seems that this delay is the cause of higher yield and ultimate stress enhancement in large size bars.

Figure 16 shows the ruptured sections of typical bars failed under low (0.0001/sec) and high strain rates (0.015/sec). At low rate the ruptured section is relatively smooth, while for bars failed at high rate the section is rough with sharp edges. This shows a smoother transverse propagation of strain at low strain rate in comparison to high strain rate loading.

4.4.1 Discussion

The strain localization phenomenon is very important to understand the flexural behavior of reinforced concrete elements subjected to earthquake loadings. Previous studies by several investigators²⁸⁻³⁰ have shown that reinforced concrete members subjected to rapidly applied loads failed in a relatively brittle manner with less cracks as compared to members subjected to lower rate loads. An increase in concrete tensile strength and improved bond strength by 50%³¹⁻³³ have been mentioned as the reasons for formation of less flexural cracks and concentration of strain in steel at crack locations³⁰. The improvement in bond, however, shall cause more cracks because concrete is forced to deform with steel. The new test data presented in this article provide a plausible explanation on the concentration of damage in members that are subjected to high strain

rates. Figure 15 demonstrated the more localization of steel strain as strain rate increased. It is believed that the lack of propagation of steel yield strain is the main cause for concentration of concrete cracking in the vicinity of the point of maximum steel strain. More experimental research work on reinforced concrete elements is required to quantify these effects. This research also shows high sensitivity of the larger size bars to high strain rates as compared to smaller size bars. This requires special care to be taken in extrapolating the results of small scale RC experimental tests to the prototype models.

It shall be noted that yield strain initiation and localization may occur at any point along bare steel, while in a reinforced concrete member, the steel yield strain and localization most likely are initiated at a crack location.

5 SUMMARY AND CONCLUSIONS

5.1 Summary

The main objectives of this study were to determine the effects of high strain rates on the yield and ultimate stresses and yield propagation properties of reinforcing bars.

At high strain rates, the yield stress and ultimate stress increase^{8,9,10} and make the structural response different from that of static loading. A literature review of the effects of high strain rates on the properties of steel reinforcing bars has revealed that steel with lower yield strength is more sensitive to strain rate variation than steel with higher strength⁹⁻¹³. The previous studies have focused on mechanical properties of reinforcing steel under constant strain rates. During earthquake loading strain rate is variable, and it is uncertain if the above equations are applicable. The steel properties under variable strain rates are unknown and need to be studied. The primary purpose of the study presented in this article was to determine the effect of variable strain rate on the

characteristics of the stress strain relation for steel reinforcing bars. The study was triggered by the lack of data and procedures to account for variable strain rates experienced by structures during earthquakes.

To cover a range of bar sizes generally used in practice, #3, #8, and #11 ASTM² Grade 60 bar specimens have been used in this study. The bars were 20 in (508 mm.) long. They were tested using a Material Testing Systems (MTS) servo-controlled machine, which was programmed to apply constant and variable strain rates.

5.2 Conclusions

The following conclusions are drawn from the study:

- 1- The yield stress and ultimate strength of reinforcing bars increase with increasing strain rate. The yield strength is more strain rate sensitive than the ultimate strength.
- 2- The main factors influencing the strain rate effects are the static yield strength of the reinforcing bar and its size.
- 3- The increase in yield and ultimate stress is lower for smaller size bars.
- 4- The yield stress amplification depends not only on the strain rate, but also on the rate of strain rate. A new parameter, the “strain rate index,” was introduced and incorporated in the proposed equations to account for this effect.
- 5- By increasing the strain rate, strain concentration (localization) will be increased. Furthermore, the increase in localization of strain is higher for larger diameter bars.

- 6- The proposed equations in this study for steel subjected to monotonic, variable, and cyclic loadings compare well with test results and data obtained in previous studies.

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Table 1-Variable strain rate loading program

Test No.	No. of Bars	Strain ($\mu\epsilon$)			Type of Strain Rate
		0 to 1500 $\mu\epsilon$	1500 to 3000 $\mu\epsilon$	3000 to 150000 $\mu\epsilon$	
		Strain Rate ($\mu\epsilon/\text{sec}$)			
1	2	100			Constant
2	3	100,000 to 90,000	90,000 to 70,000	70,000 to 100	Non-Linear Variable
3	3	80,000 to 60,000	60,000 to 40,000	40,000 to 100	
4	3	50,000 to 40,000	40,000 to 20,000	20,000 to 100	
5	3	30,000 to 10,000	10,000 to 100	100	
6	2	100,000 to 100			Linear Variable

Table 2- Cyclic strain rate loading program

Test No.	No. of Bars	Strain ($\mu\epsilon$)		Comments
		0---4000---0 (First 5 cycles)	2000 $\mu\epsilon$ increase in each cycle until failure	
		Strain Rate ($\mu\epsilon/\text{sec}$)		
1	2	0---10,000---0	0---30,000---0	No compressive strain, cycles start from zero to the maximum specified strain and then come back to zero, repeatedly. Strain rates are maximum between zero and maximum strain points.
2	2	0---30,000---0	0---50,000---0	
3	2	0---50,000---0	0---80,000---0	
4	2	0---70,000---0	0---100,000--0	
5	2	0---40,000---0 (to failure)		

Table 3- Constant Strain Rate Results for # 3 Bars

Test No.	Target Strain Rate.(us/sec)	Calculated Strain Rate (Ave. of 0.85fy to fy) (us/sec)	Calculated Strain Rate (Ave. of 0.50fy to fy) (us/sec)	Yield Stress Ksi (MPa)	Ultimate Stress Ksi (MPa)
1.1.3	100	86	84	72.5 (499)	102 (703)
1.2.3	100	110	99	76.0 (524)	102.5 (706)
1.3.3	100	122	84	74.0 (510)	103.5 (713)
2.1.3	1,000	945	845	71.7 (494)	102.0 (703)
2.2.3	1,000	1,230	1838	71.2 (491)	103.0 (710)
2.3.3	1,000	1,223	1092	73.2 (504)	102.0 (703)
3.1.3	2,000	1,550	1519	75.5 (520)	102.0 (703)
3.2.3	2,000	1,940	1490	72.5 (499)	104.0 (717)
3.3.3	2,000	2,560	2194	74.6 (514)	103.9 (716)
4.1.3	10,000	13,870	11380	76.1 (524)	105.4 (726)
4.2.3	10,000	11,195	10500	78.0 (537)	106.6 (735)
4.3.3	10,000	6,530	7568	77.4 (533)	105.2 (725)
5.1.3	20,000	19,870	19355	76.6 (528)	106.0 (730)
5.2.3	20,000	21,000	19500	75.2 (518)	107.0 (737)
5.3.3	20,000	24,130	22640	74.0 (510)	106.5 (734)
6.1.3	30,000	31,940	30780	75.2 (518)	106.0 (730)
6.2.3	30,000	20,200	18932	76.0 (524)	107.0 (737)
6.3.3	30,000	30,990	27533	79.0 (544)	106.0 (730)
7.1.3	40,000	36,360	32372	80.0 (551)	105.0 (723)
7.2.3	40,000	47,128	39159	76.6 (528)	106.0 (730)
7.3.3	40,000	49,450	25950	75.0 (517)	103.8 (715)
8.1.3	100,000	99,380	71444	76.1 (524)	107.6 (741)
8.2.3	100,000	84,990	76216	79.0 (544)	105.6 (728)
8.3.3	100,000	85,930	71063	80.0 (551)	106.5 (734)

Table 4- Constant Strain Rate Results for # 8 Bars

Test No.	Target Strain Rate	Calculated Strain Rate(Ave. of 0.85fy to fy)(us/sec)	Calculated Strain Rate(Ave. of 0.50fy to fy)(us/sec)	Yield Stress ksi (MPa)	Ultimate Stress ksi(MPa)
1.1.8	100	70	40	61.5 (424)	100.5 (692)
1.2.8	100	20	34	64.7 (446)	101.4 (699)
1.3.8	100	87	62	65.0 (448)	102.5 (706)
2.1.8	1,000	570	451	65.7 (453)	103.8 (715)
2.2.8	1,000	250	340	62.4 (430)	103.0 (710)
2.3.8	1,000	390	326	65.5 (452)	104.0 (717)
3.1.8	2,000	1,700	1530	66.2 (456)	103.0 (710)
3.2.8	2,000	1,800	1580	65.0 (448)	102.2 (704)
3.3.8	2,000	2,300	534	65.0 (448)	102.8 (708)
4.1.8	10,000	9,000	6976	68.6 (473)	106.2 (732)
4.2.8	10,000	3,600	4270	67.8 (467)	105.5 (727)
4.3.8	10,000	1,250	1277	65.5 (452)	105.5 (727)
5.1.8	20,000	6,260	7380	69.5 (479)	104.7 (721)
5.2.8	20,000	23,850	19250	67.2 (463)	105.5 (727)
5.3.8	20,000	24,780	17950	69.0 (476)	106.0 (730)
6.1.8	30,000	12,810	9530	66.7 (460)	107.6 (741)
6.2.8	30,000	16,000	12600	64.9 (447)	101.0 (696)
6.3.8	30,000	19,800	8940	69.0 (476)	105.0 (723)
7.1.8	40,000	29,360	20430	70.0 (482)	105.5 (727)
7.2.8	40,000	20,125	14937	68.0 (468)	107.3 (739)
7.3.8	40,000	46,700	19045	68.5 (452)	104.8 (722)
8.1.8	100,000	117,100	99288	68.8 (474)	106.2 (732)
8.2.8	100,000	69,700	36230	67.6 (466)	106.7 (735)
8.3.8	100,000	47,865	30259	70.0 (482)	105.2 (725)
8.4.8	100,000	84,360	64488	70.0 (482)	107.2 (738)

Table 5- Constant Strain Rate Results for # 11 Bars

Test No.	Target Strain Rate(us/sec)	Calculated Strain Rate (Ave. of 0.85fy to fy) (us/sec)	Calculated Strain Rate (Ave. of 0.50fy to fy) (us/sec)	Yield Stress ksi (MPa)	Ultimate Stress ksi (MPa)
1.1.11	100	11	16	62.0 (427)	104.0 (717)
1.2.11	100	11	26	62.8 (433)	103.3 (712)
1.3.11	100	8	16	61.2 (422)	102.4 (706)
2.1.11	500	226	150	60.0 (413)	102.0 (703)
2.3.11	500	47	189	59.2 (408)	101.5 (699)
3.1.11	1,000	87	189	60.0 (413)	102.0 (703)
3.2.11	1,000	770	144	62.0 (427)	105.7 (728)
3.3.11	1,000	70	347	60.0 (413)	102.0 (703)
4.1.11	1,500	310	144	61.0 (420)	102.8 (708)
4.2.11	1,500	174	345	61.5 (424)	103.0 (710)
4.3.11	1,500	2,590	290	63.3 (436)	106.2 (732)
4.1.11	2,000	174	336	61.9 (427)	103.8 (715)
5.2.11	2,000	269	629	62.8 (433)	105.7 (728)
5.3.11	2,000	1,360	372	63.3 (436)	106.2 (732)
6.1.11	5,000	860	993	61.0 (420)	101.9 (702)
6.2.11	5,000	850	995	62.0 (427)	102.9 (709)
6.3.11	5,000	820	1133	61.9 (427)	104.3 (719)
7.1.11	10,000	1,000	1210	64.5 (444)	105.0 (723)
7.2.11	10,000	1,350	9666	63.3 (436)	105.0 (723)
7.3.11	10,000	3,400	2276	64.5 (444)	108.6 (748)
8.1.11	15,000	2,350	3496	63.6 (436)	106.8 (736)
8.2.11	15,000	2,900	3484	61.9 (427)	103.8 (715)
8.3.11	15,000	5,840	5966	62.4 (430)	105.5 (727)
9.1.11	20,000	890	1867	63.9 (440)	104.4 (719)

Table 6- Variable Stain Rate Results for # 3 and # 8 Bars

Bar Size	Test No.	Calculated Strain Rate (Ave. of 0.85fy to fy)(us/sec)	Calculated Strain Rate (Ave. of 0.50fy to fy)(us/sec)	Yield Stress ksi (MPa)	Ultimate Stress Ksi(MPa)
#3	V.1.1.3	310	77	64.5 (444)	105.0 (723)
	V.1.2.3	270	90.5	65.4 (451)	107.9 (743)
	V.2.1.3	52600	37100	52.4 (361)	94.7 (652)
	V.2.2.3	95670	54700	69.0 (475)	113.2 (780)
	V.2.3.3	454600	66020	67.5 (465)	111.5 (768)
	V.3.1.3	81600	48260	70.5 (486)	110.8 (763)
	V.3.2.3	113960	44710	69.9 (482)	110.8 (763)
	V.3.3.3	107500	47846	65.9 (454)	107.0 (737)
	V.4.1.3	41760	24110	66.3 (457)	111.2 (766)
	V.4.2.3	52100	22220	66.3 (457)	111.2 (766)
	V.4.3.3	31100	18865	70.7 (487)	110.7 (763)
	V.5.1.3	24760	8713	68.8 (474)	108.6 (748)
	V.5.2.3	15000	1780	61.6 (424)	103.0 (710)
	V.5.3.3	26900	12699	61.2 (422)	104.4 (719)
	V.6.1.3	109200	58023	70.0 (482)	112.3 (774)
	V.6.2.3	108647	38283	61.7 (425)	108.2 (745)
#8	V.1.1.8	67	46	61.2 (422)	104.0 (717)
	V.1.2.8	65	40	60.5 (417)	101.9 (702)
	V.2.1.8	60420	36900	61.6 (424)	102.8 (708)
	V.2.2.8	42529	35540	62.9 (433)	104.5 (720)
	V.2.3.8	60180	33690	63.6 (438)	106.3 (432)
	V.3.1.8	29650	19320	66.0 (455)	106.8 (736)
	V.3.2.8	38700	21290	60.9 (420)	102.2 (705)
	V.3.3.8	5849	29260	58.5 (403)	101.8 (701)
	V.4.1.8	26052	9070	63.4 (437)	106.2 (432)
	V.4.2.8	18280	8700	63.0 (434)	107.3 (739)
	V.4.3.8	16088	9060	64.2 (442)	106.0 (730)
	V.5.1.8	6920	3500	60.0 (413)	102.2 (705)
	V.5.2.8	7000	5140	63.9 (440)	104.8 (722)
	V.5.3.8	5778	8630	64.9 (447)	104.9 (723)
	V.6.1.8	74790	56150	61.8 (426)	105.2 (725)
	V.6.2.8	3532	46880	65.2 (449)	108.0 (744)

Table 7- Cyclic Test Strain Rate Results for # 3 and # 8 Bars

Bar Size	Test No.	Calculated Strain Rate (Ave. of 0.85fy to fy)(us/sec)	Calculated Strain Rate (Ave. of 0.50fy to fy)(us/sec)	Yield Stress ksi (MPa)	Ultimate Stress Ksi(MPa)	
#3	C.1.1.3	8540	7259	60.2 (415)	106.7 (735)	
	C.1.2.3	7600	27810	64.6 (445)	106.7 (735)	
	C.2.1.3	20860	41720	63.8 (440)	104.8 (722)	
	C.3.1.3	42800	76600	60.0 (413)	102.0 (703)	
	C.3.2.3	47470	120570	66.6 (459)	107.2 (739)	
	C.4.1.3	71860	180000	63.9 (440)	104.6 (721)	
	C.4.2.3	55800	116630	67.3 (464)	109.6 (755)	
	C.5.1.3	16320	26600	66.7 (460)	110.0 (758)	
	C.5.2.3	36710	53600	65.1 (449)	107.7 (742)	
	C.6.1.3	8610	27000	66.2 (456)	107.2 (739)	
	C.6.2.3	7610	15220	67.3 (464)	108.9 (750)	
	#8	C.1.1.8	40	480	60.5 (417)	101.9 (702)
		C.1.2.8	4691	15527	64.1 (445)	105.8 (729)
C.2.1.8		4878	9463	63.9 (440)	104.9 (723)	
C.2.2.8		13510	23640	63.8 (440)	103.7 (715)	
C.3.1.8		15570	31450	63.6 (438)	105.2 (725)	
C.3.2.8		31820	49957	63.8 (440)	105.5 (727)	
C.4.1.8		28007	56574	66.3 (457)	107.9 (743)	
C.4.2.8		48960	74900	63.2 (435)	105.2 (725)	
C.5.1.8		33942	90625	64.5 (444)	105.4 (726)	
C.5.2.8		24503	39200	63.4 (437)	104.4 (719)	

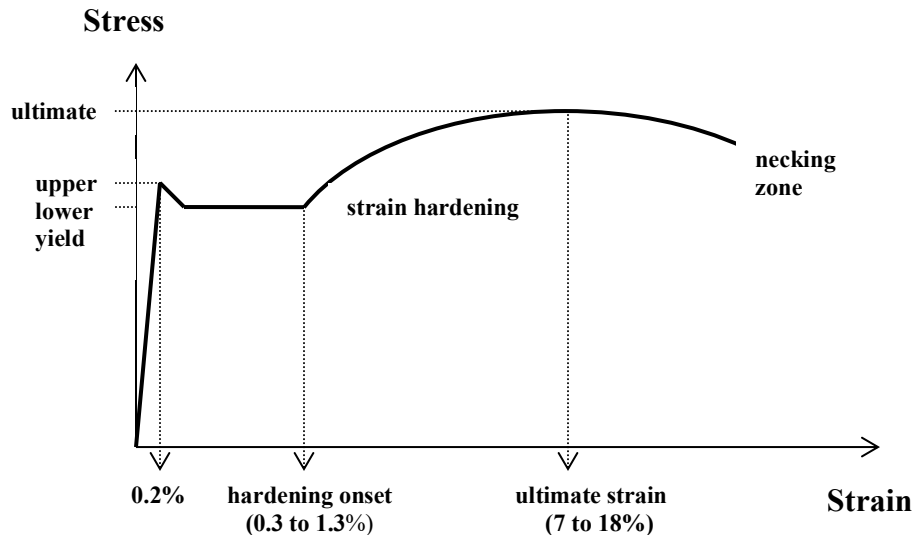


Figure 1- Typical stress-strain curve for ASTM A615 Grade 60 steel

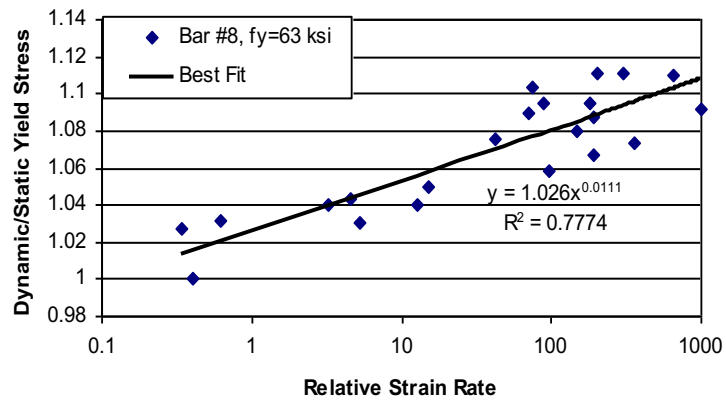
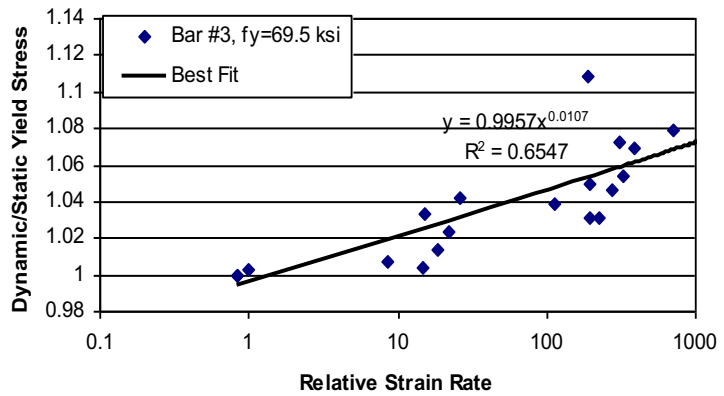


Fig. 2- Yield stress enhancement of bars tested under constant strain rates

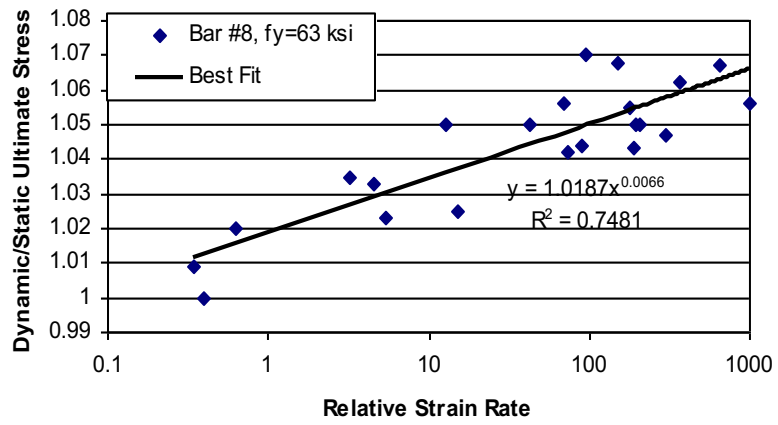
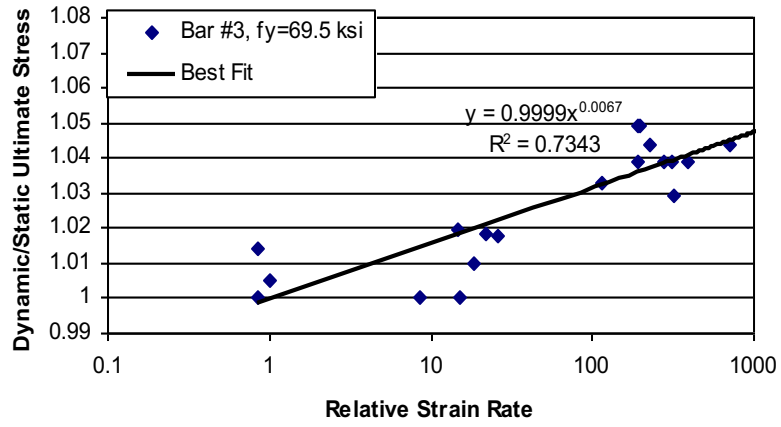


Fig.3- Ultimate stress enhancement of bars tested under constant strain rates

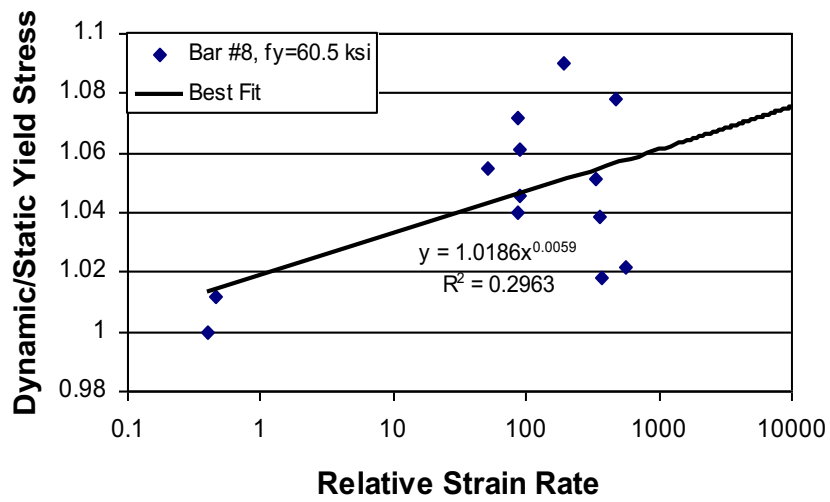
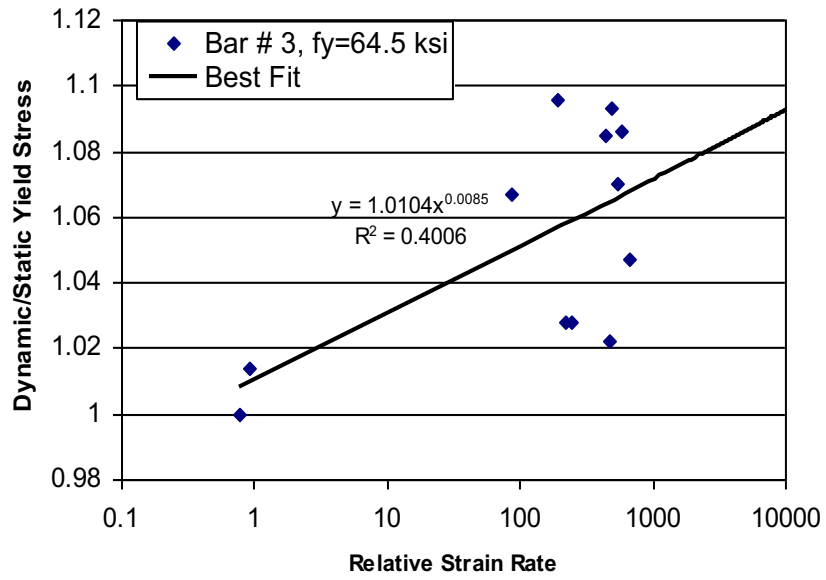


Fig.4- Yield stress enhancement versus relative strain rate for bars tested under variable strain rate

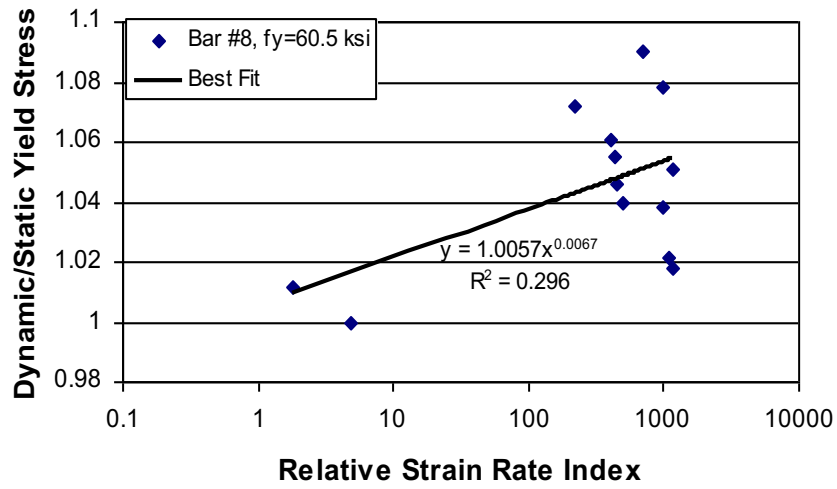
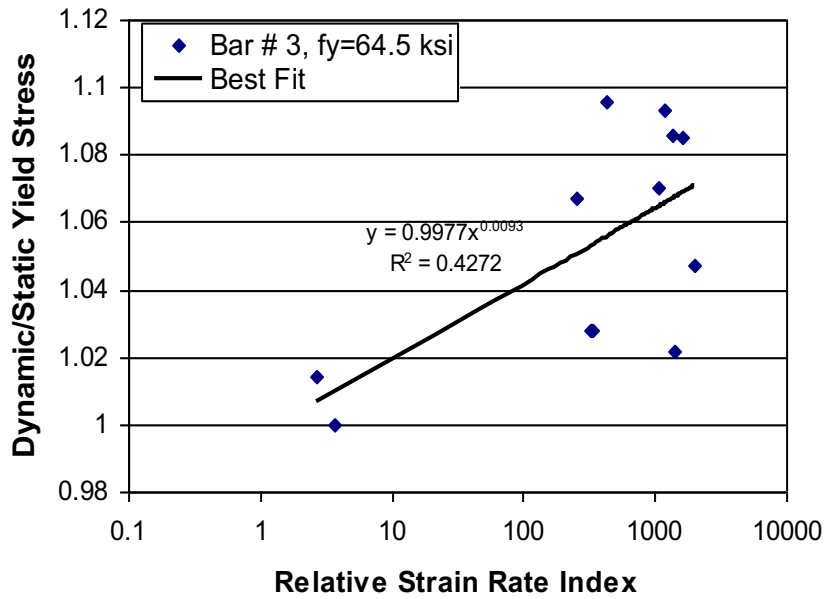


Fig.5- Yield stress enhancement versus relative strain rate index for bars tested under variable strain rates

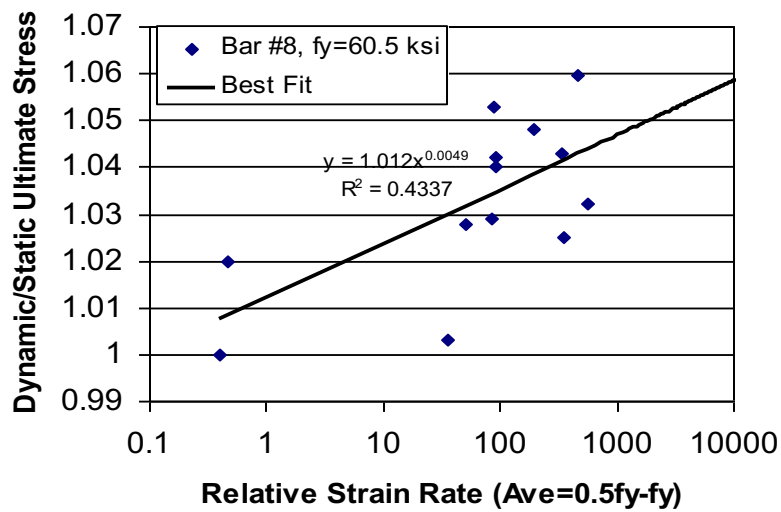
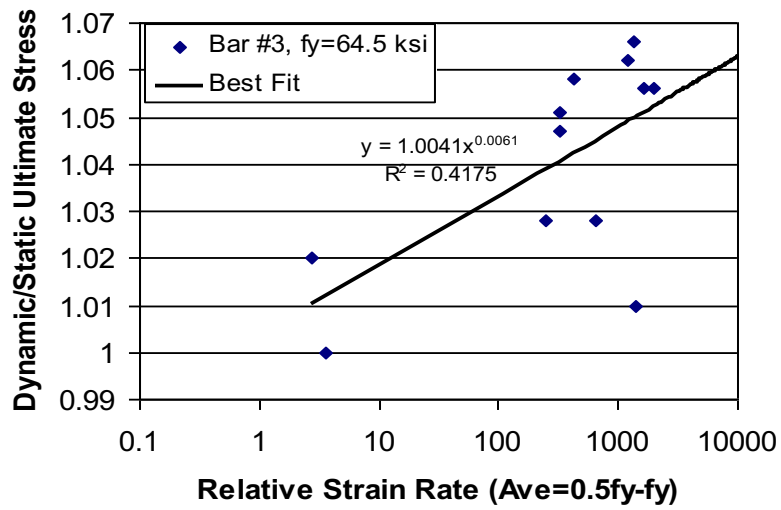


Fig 6- Ultimate stress enhancement versus average strain rates from $0.5\varepsilon_y$ to ε_y for variable strain rate tests

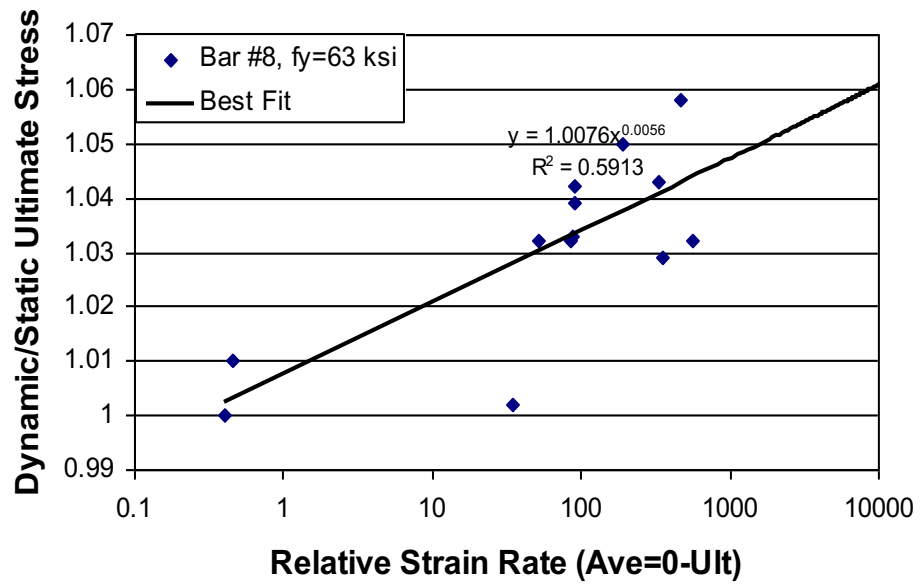
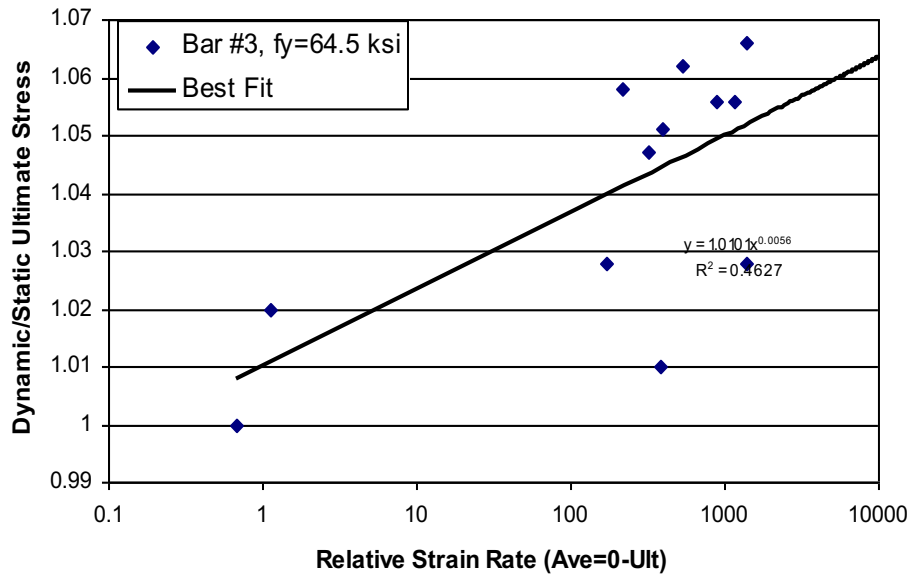


Fig.7- Ultimate stress enhancement versus average strain rates from 0 to ϵ_{ult} for variable strain rate tests

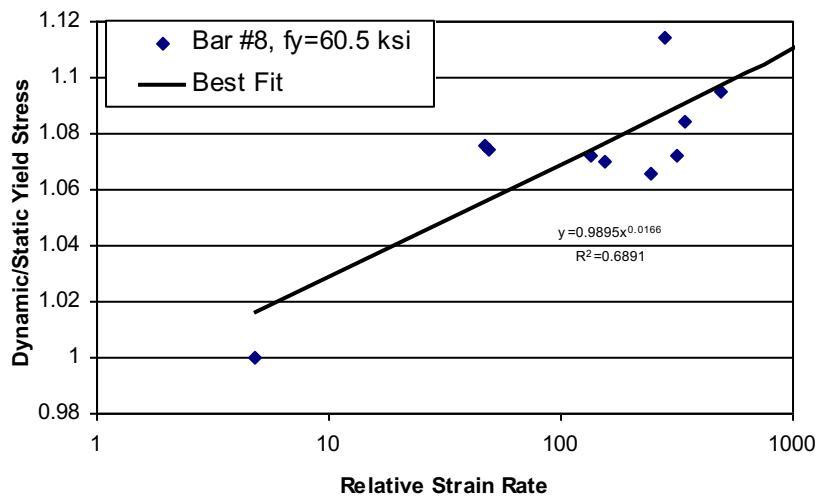
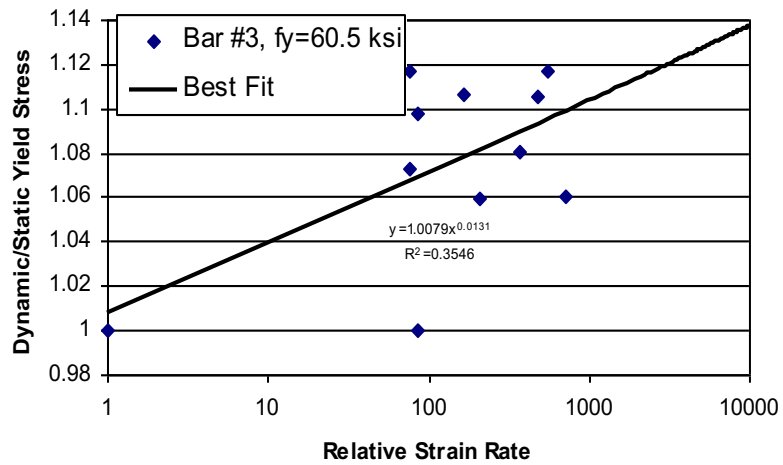


Fig.8- Yield stress enhancement versus relative strain rate for bars tested under cyclic strain rates

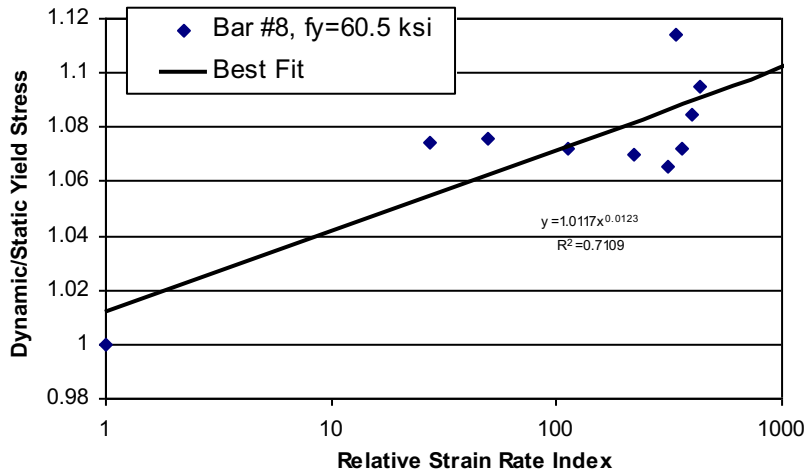
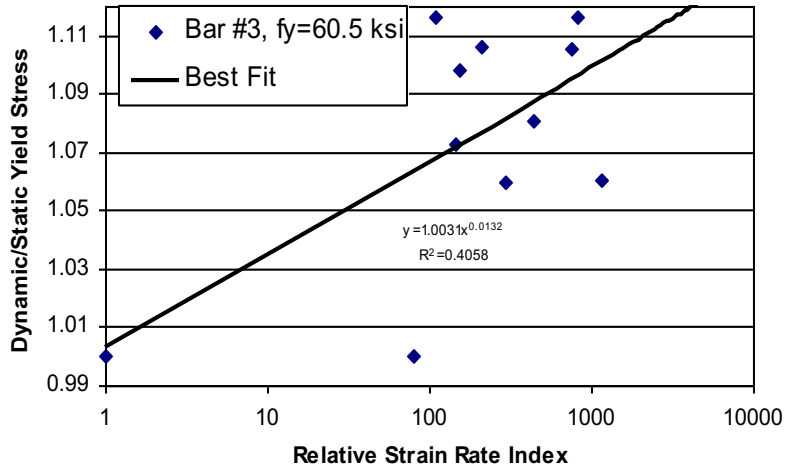


Fig.9- Yield stress enhancement versus relative strain rate index for bars tested under cyclic strain rates

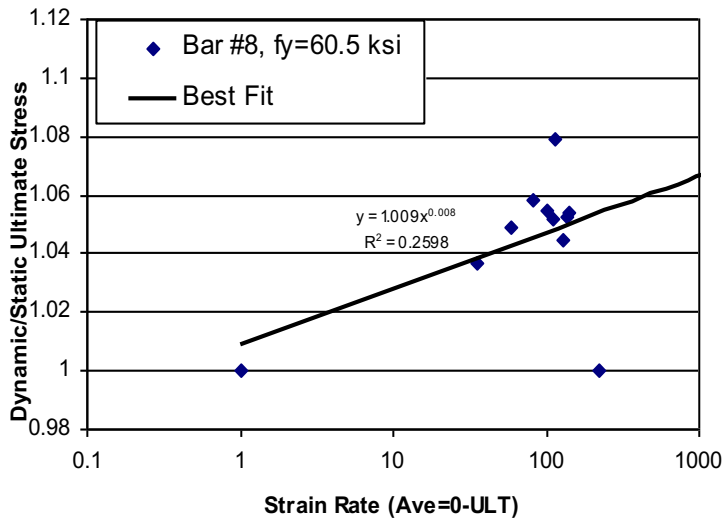
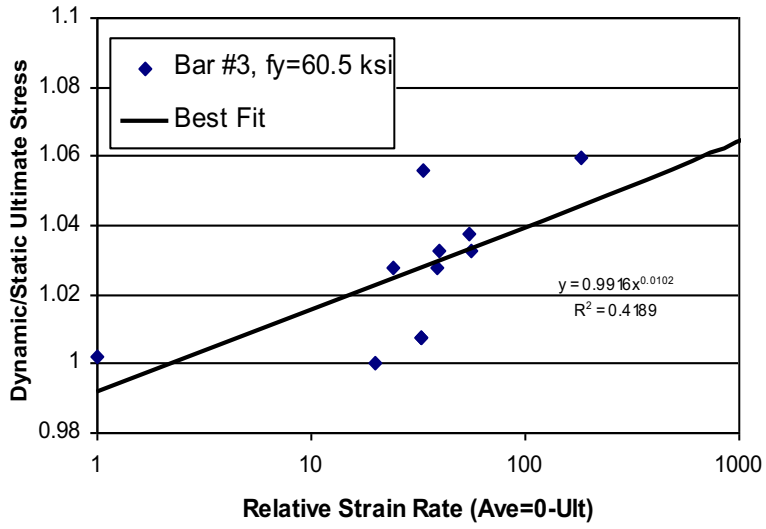


Fig. 10 - Ultimate stress enhancement versus average strain rates from 0 to ϵ_{ult} for cyclic strain rate tests

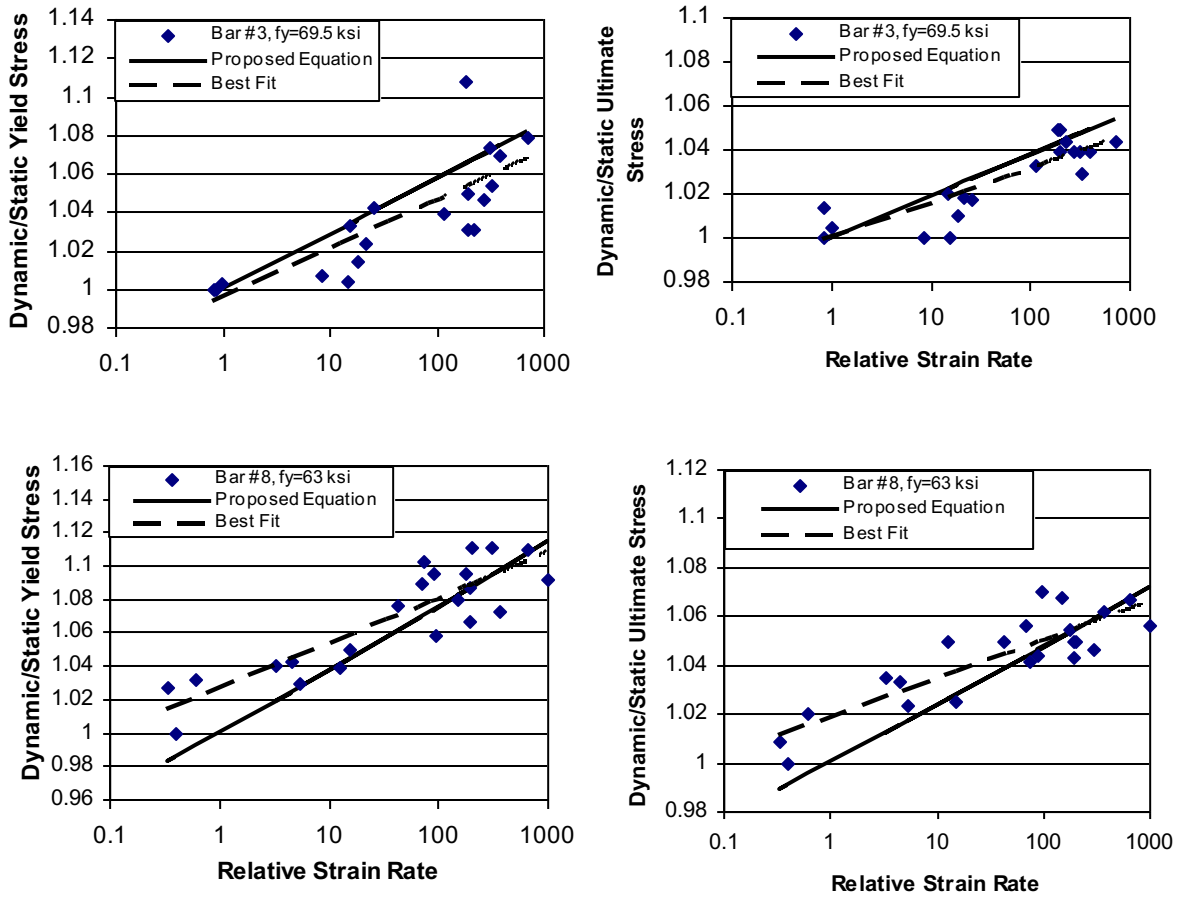


Fig. 11- Comparison of proposed Equation to results of constant strain

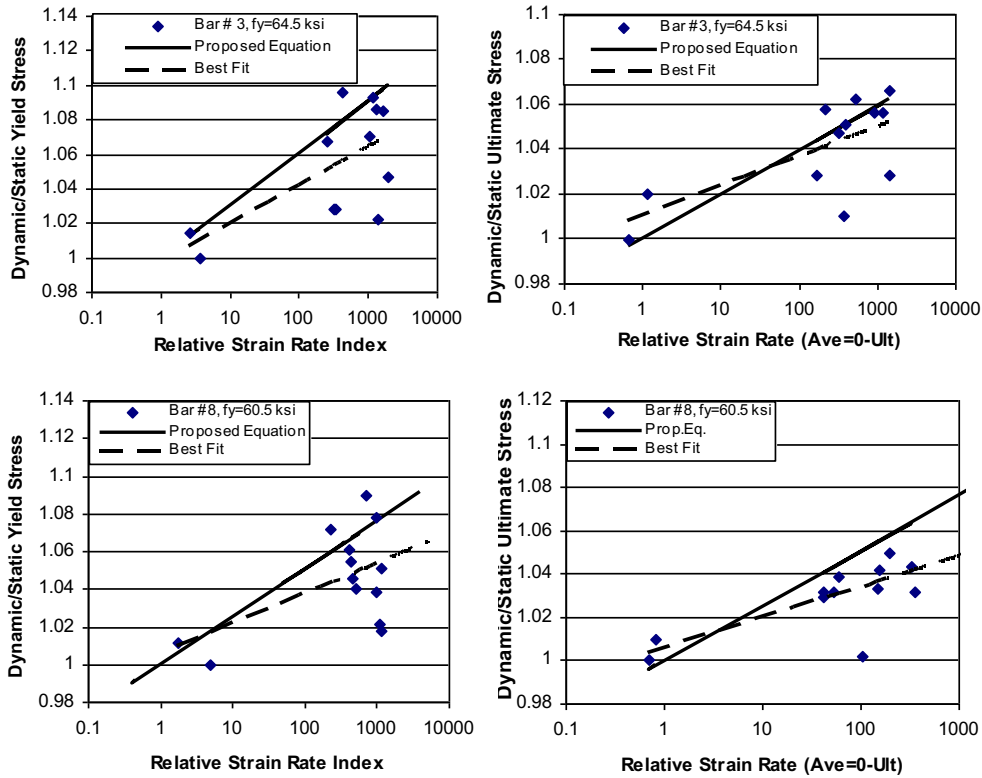


Fig. 12- Comparison of proposed Equation to results of variable load tests

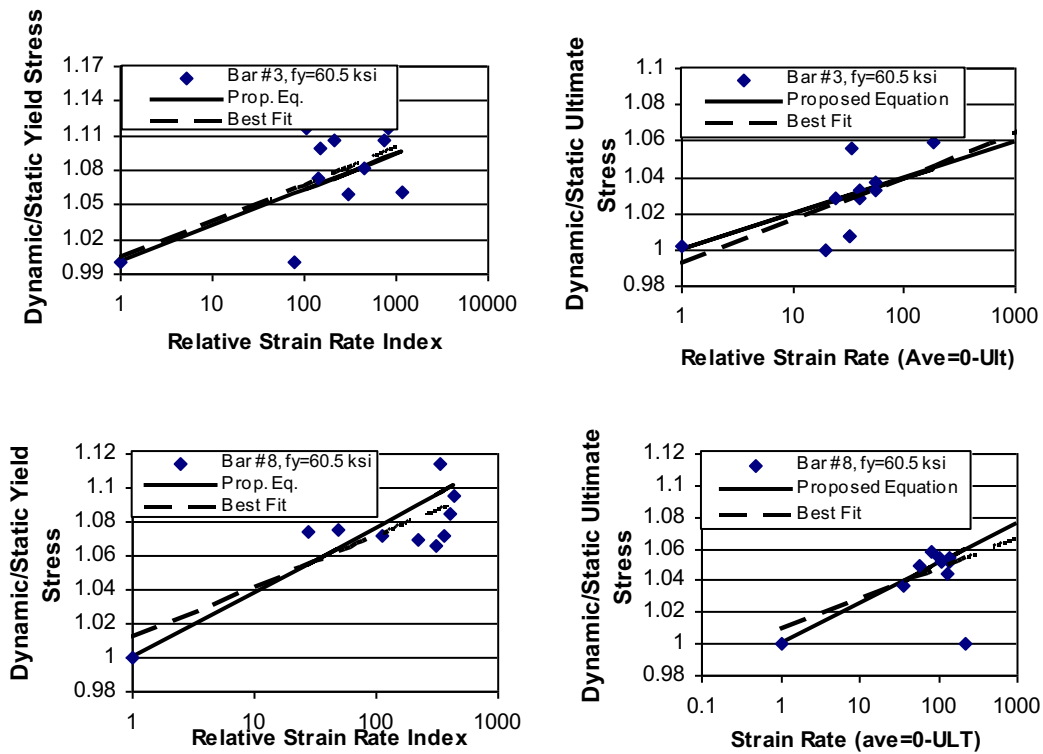


Fig. 13- Comparison of proposed Equation to results of cyclic load

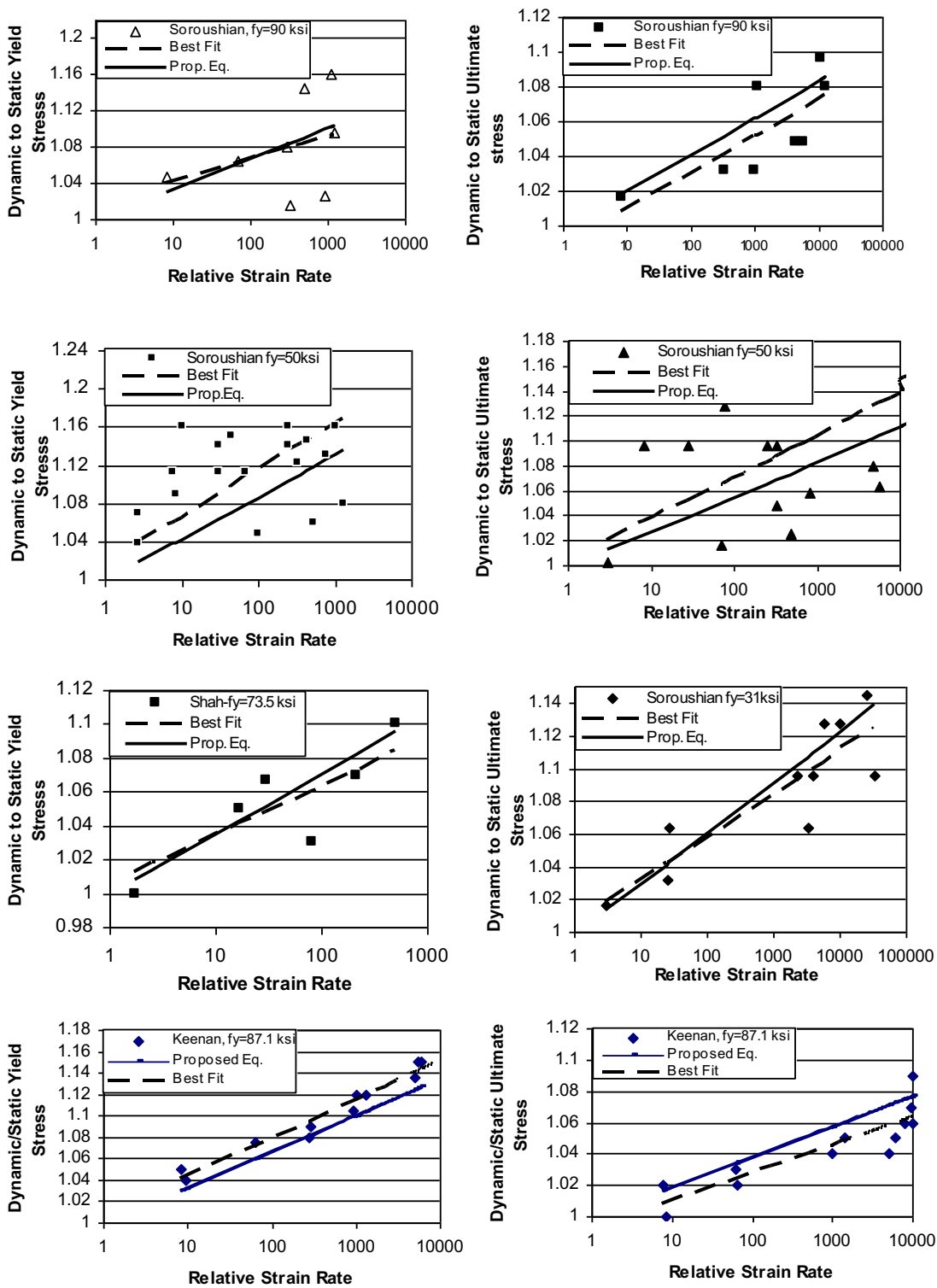
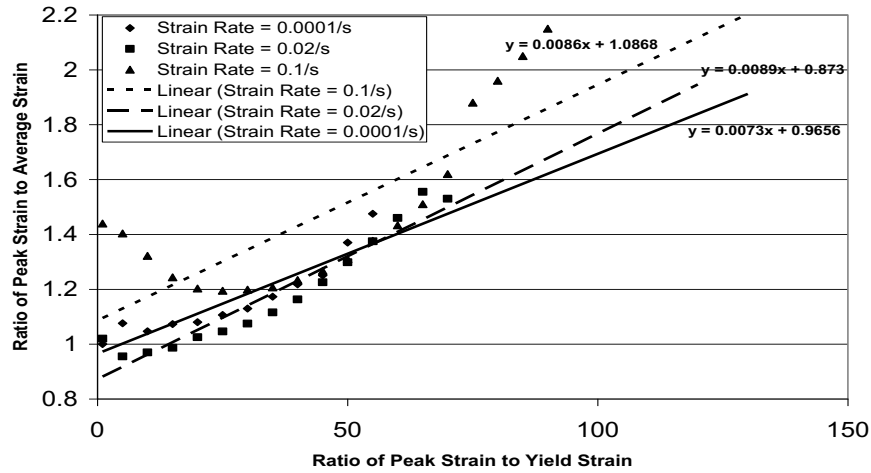
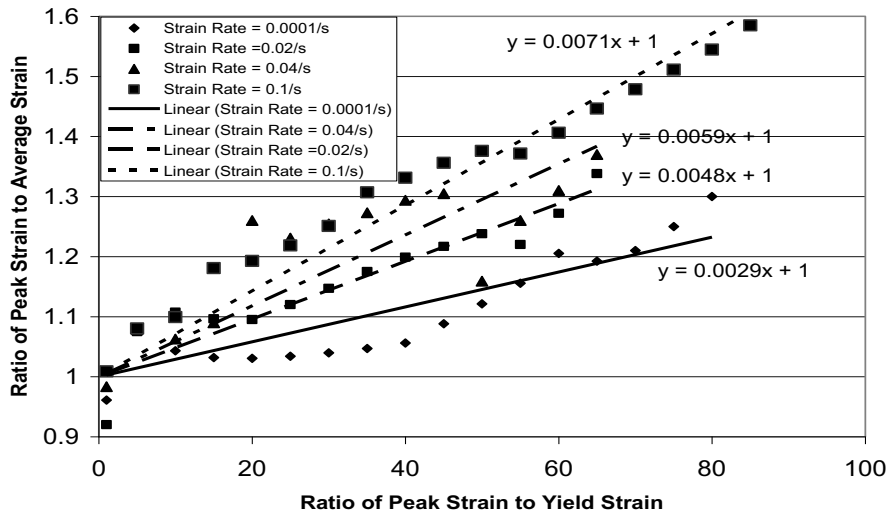


Fig. 14- Comparison of proposed fit to reported data

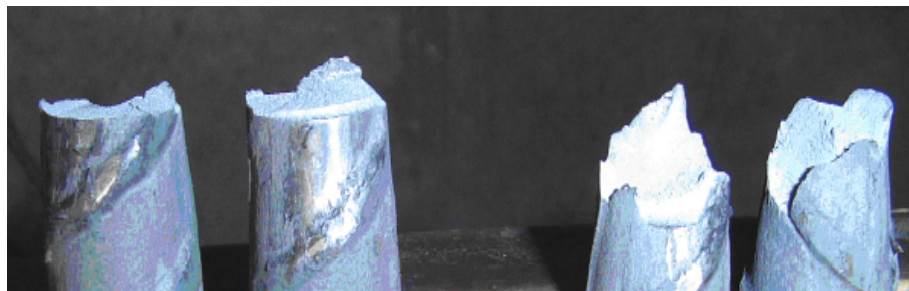


A) # 3 Bars



B) # 8 Bars

Fig. 15- Localization of strain for different size bars at low to high strain rates



a) Strain Rate = 0.0001/sec

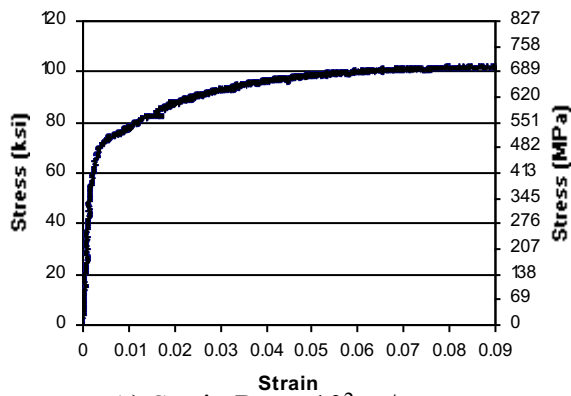
b) Strain Rate = 0.015 /sec

Fig. 16- Ruptured sections of bars failed under low and high strain

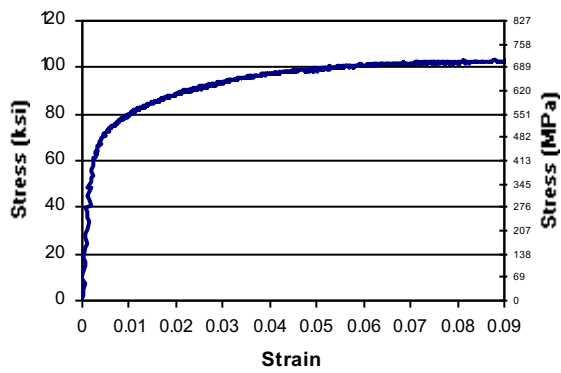
APPENDIX A

PLOTS OF STRESS-STRAIN CURVES OF BAR SPECIMENS

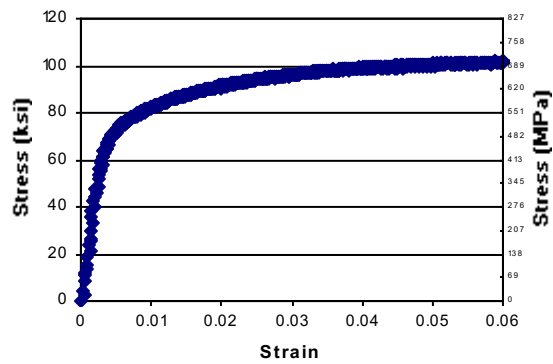
Appendix A presents plots of experimental results that are not presented in the previous sections. The plots represent the stress-strain curves for the bar specimens tested at different strain rates. The strains used in the plots are the average of the strains measured by three strain gages installed on each specimen.



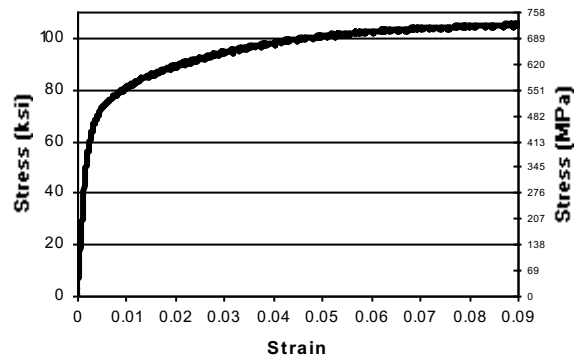
A) Strain Rate= $10^2 \mu\epsilon/\text{sec}$



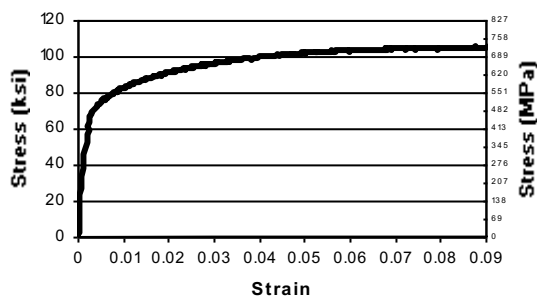
B) Strain Rate= $10^3 \mu\epsilon/\text{sec}$



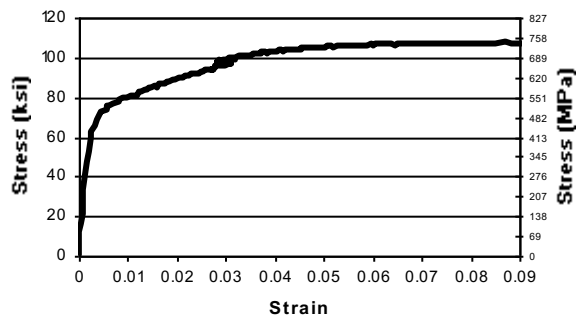
C) Strain Rate= $2 \times 10^3 \mu\epsilon/\text{sec}$



D) Strain Rate= $10^4 \mu\epsilon/\text{sec}$

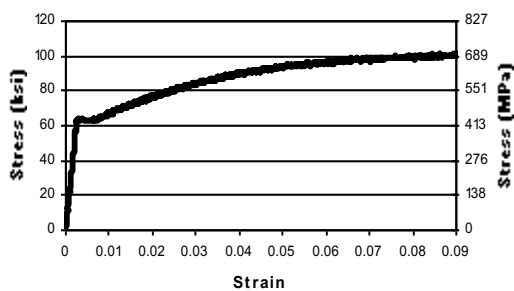


E) Strain Rate= $4 \times 10^4 \mu\epsilon/\text{sec}$

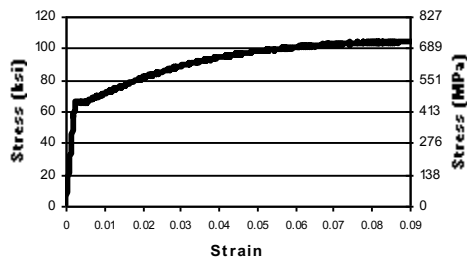


F) Strain Rate= $10^5 \mu\epsilon/\text{sec}$

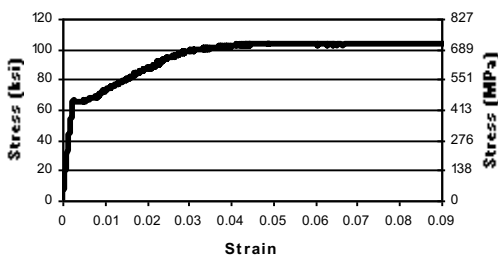
Fig. A-1 Stress-Strain Curves for # 3 Bars at Different Constant Strain Rates



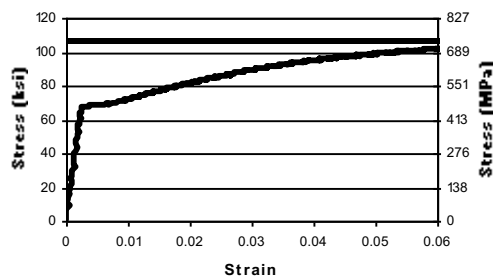
A) Strain Rate= $10^2 \mu\epsilon/\text{sec}$



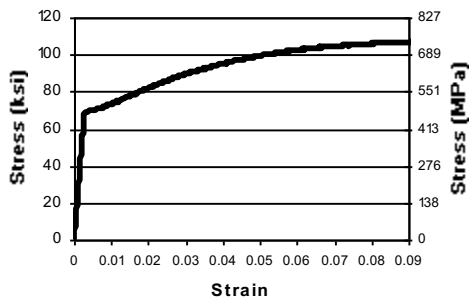
B) Strain Rate= $10^3 \mu\epsilon/\text{sec}$



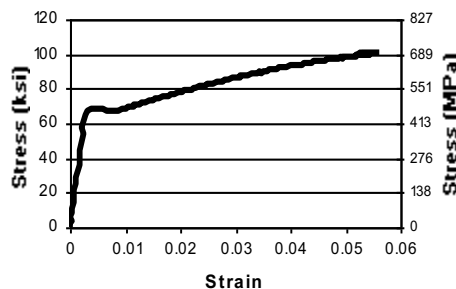
C) Strain Rate= $2 \times 10^3 \mu\epsilon/\text{sec}$



D) Strain Rate= $10^4 \mu\epsilon/\text{sec}$

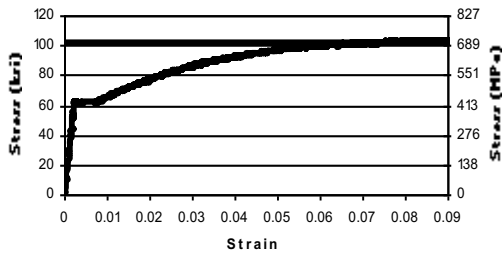


E) Strain Rate= $4 \times 10^4 \mu\epsilon/\text{sec}$

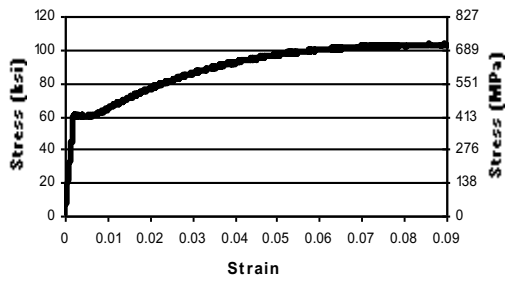


F) Strain Rate= $10^5 \mu\epsilon/\text{sec}$

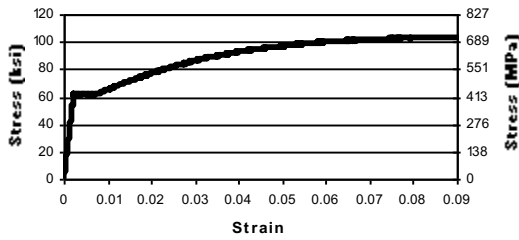
Fig. A-2 Stress-Strain Curves for # 8 Bars at Different Constant Strain Rates



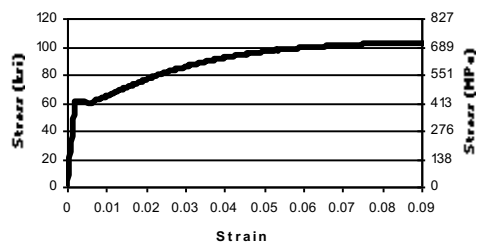
A) Strain Rate= $10^2 \mu\epsilon/\text{sec}$



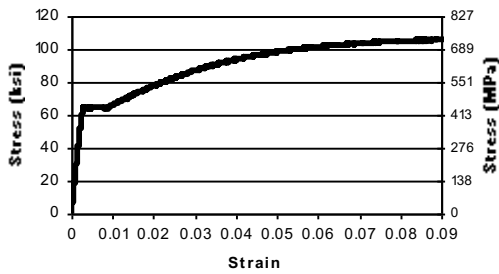
B) Strain Rate= $10^3 \mu\epsilon/\text{sec}$



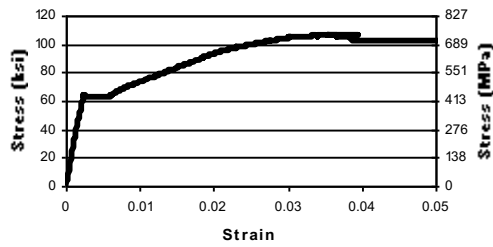
C) Strain Rate= $2 \times 10^3 \mu\epsilon/\text{sec}$



D) Strain Rate= $5 \times 10^3 \mu\epsilon/\text{sec}$

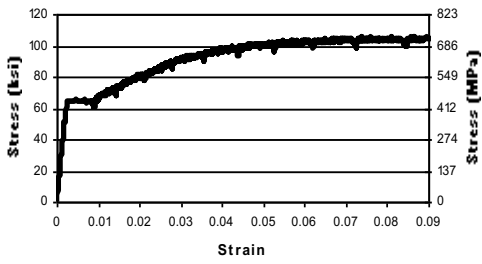


E) Strain Rate= $10^4 \mu\epsilon/\text{sec}$

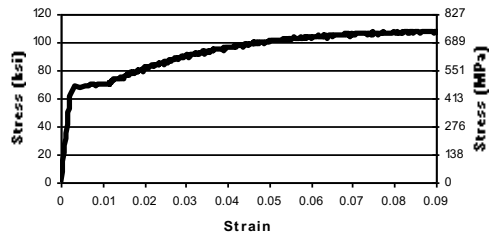


F) Strain Rate= $1.5 \times 10^4 \mu\epsilon/\text{sec}$

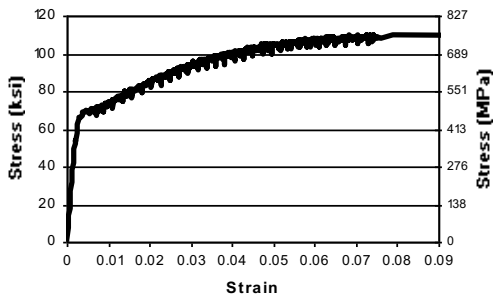
Fig. A-3 Stress-Strain Curves for # 11 Bars at Different Constant Strain Rates



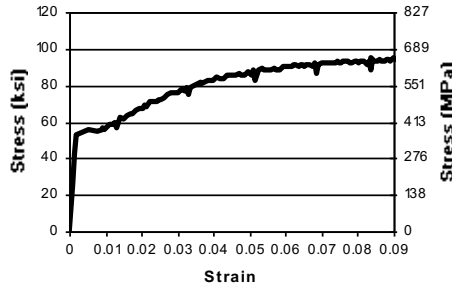
A) Ave. Strain Rate=310 $\mu\epsilon/\text{sec}$



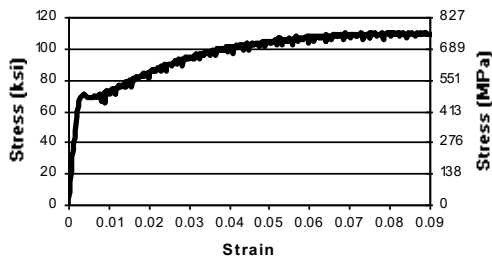
B) Ave. Strain Rate=24760 $\mu\epsilon/\text{sec}$



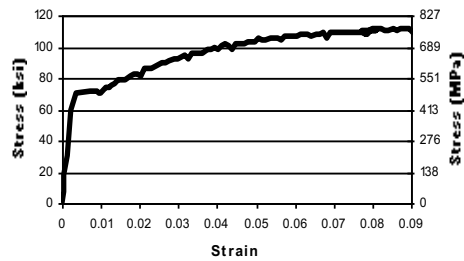
C) Ave. Strain Rate=41760 $\mu\epsilon/\text{sec}$



D) Ave. Strain Rate=52600 $\mu\epsilon/\text{sec}$

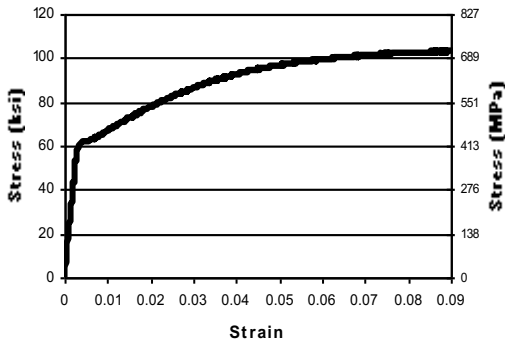


E) Ave. Strain Rate=81600 $\mu\epsilon/\text{sec}$

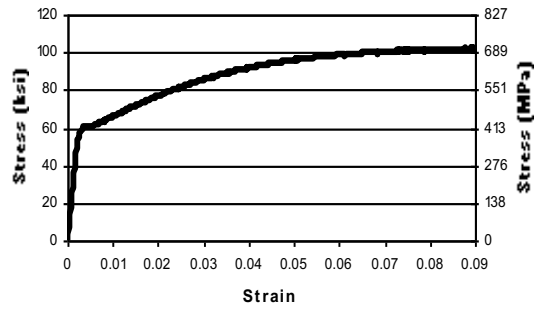


F) Ave. Strain Rate=109200 $\mu\epsilon/\text{sec}$

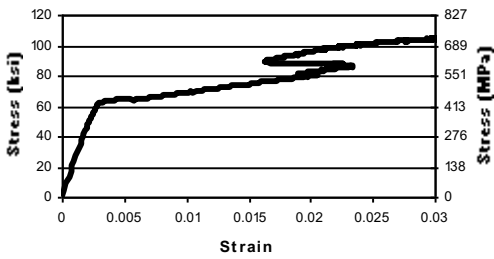
Fig. A-4 Stress-Strain Curves for # 3 Bars at Different Variable Strain Rates



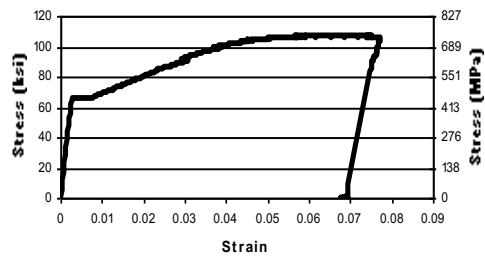
A) Ave. Strain Rate=66 $\mu\epsilon/\text{sec}$



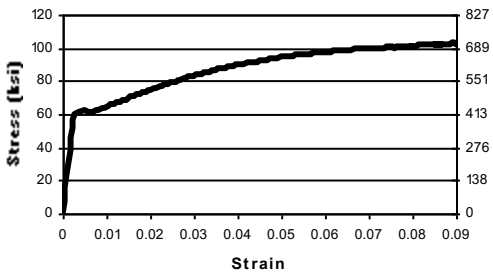
B) Ave. Strain Rate=6920 $\mu\epsilon/\text{sec}$



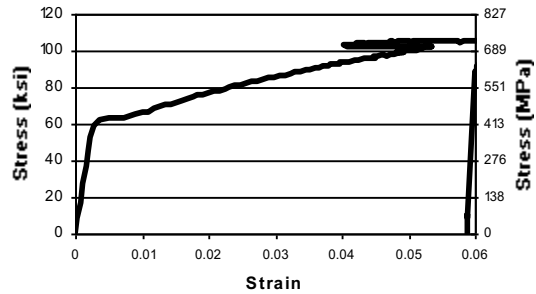
C) Ave. Strain Rate=26050 $\mu\epsilon/\text{sec}$



D) Ave. Strain Rate=29650 $\mu\epsilon/\text{sec}$

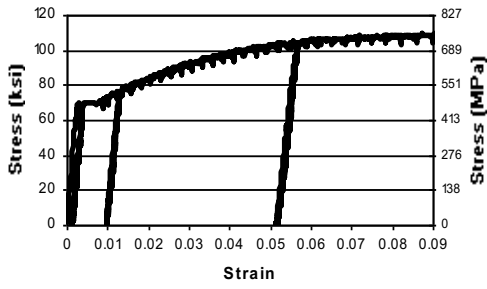


E) Ave. Strain Rate=60420 $\mu\epsilon/\text{sec}$

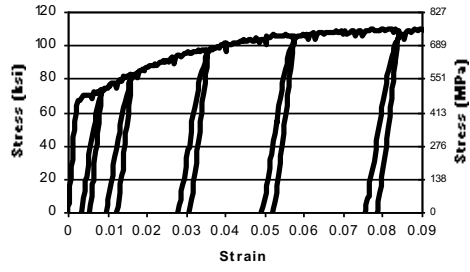


F) Ave. Strain Rate=74790 $\mu\epsilon/\text{sec}$

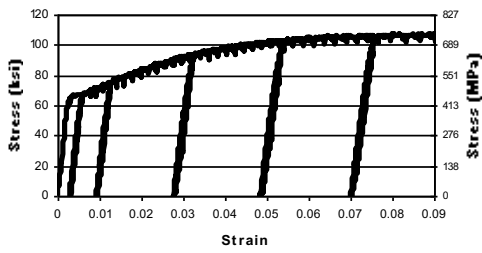
Fig. A-5 Stress-Strain Curves for # 8 Bars at Different Variable Strain Rates



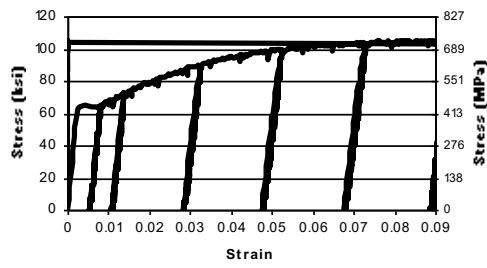
A) Ave. Strain Rate=7259 $\mu\epsilon/\text{sec}$



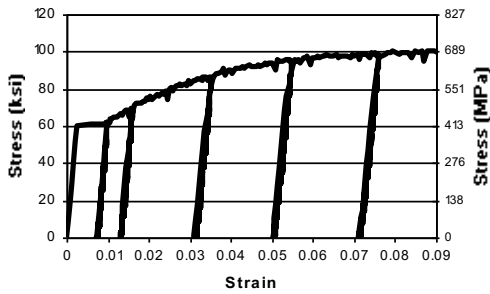
B) Ave. Strain Rate=26600 $\mu\epsilon/\text{sec}$



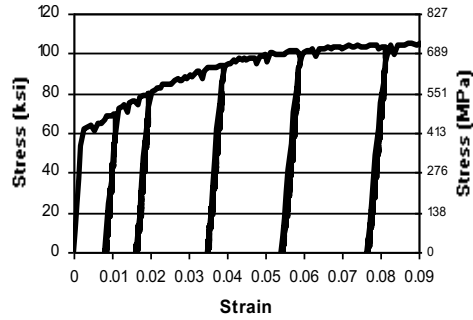
C) Ave. Strain Rate=27000 $\mu\epsilon/\text{sec}$



D) Ave. Strain Rate=41720 $\mu\epsilon/\text{sec}$

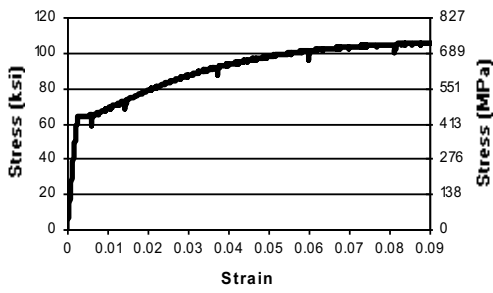


E) Ave. Strain Rate=76600 $\mu\epsilon/\text{sec}$

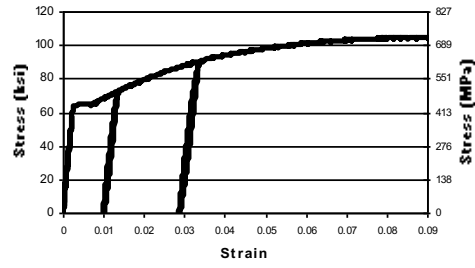


F) Ave. Strain Rate=180000 $\mu\epsilon/\text{sec}$

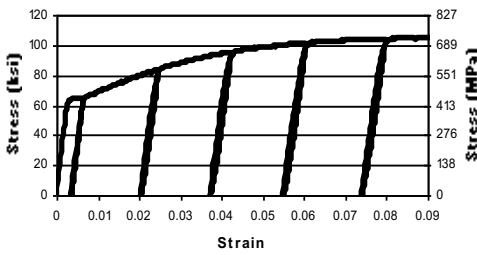
Fig. A-6 Stress-Strain Curves for # 3 Bars at Different Cyclic Load Strain Rates



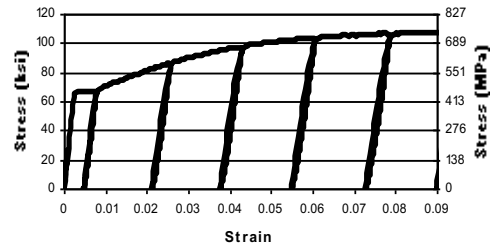
A) Ave. Strain Rate=480 $\mu\epsilon$ /sec



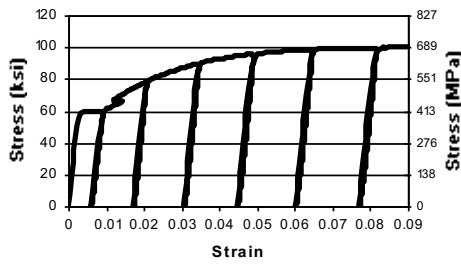
B) Ave. Strain Rate=15527 $\mu\epsilon$ /sec



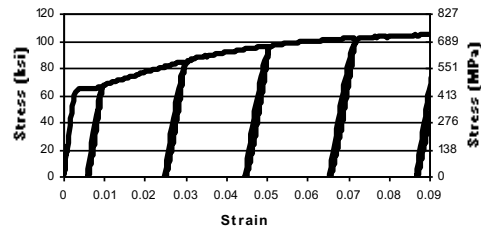
C) Ave. Strain Rate=23640 $\mu\epsilon$ /sec



D) Ave. Strain Rate=49957 $\mu\epsilon$ /sec



E) Ave. Strain Rate=56570 $\mu\epsilon$ /sec



F) Ave. Strain Rate=90625 $\mu\epsilon$ /sec

Fig. A-7 Stress-Strain Curves for # 8 Bars at Different Cyclic Load Strain Rates

APPENDIX B

PLOTS OF EXPERIMENTAL MEASUREMENTS OF # 11 BAR SPECIMENS

Appendix B presents the plots of yield and ultimate stress enhancement of #11 bars at different strain rates and the strain localizations. Because of the slippage of some of the # 11 bar specimens at the MTS testing machine grips, the stresses seems to be underestimated for this size of bars particularly at high strain rates. However the test results are presented here to show the large size bars measured properties at high strain rates which support the conclusions drawn in this study for different size bars.

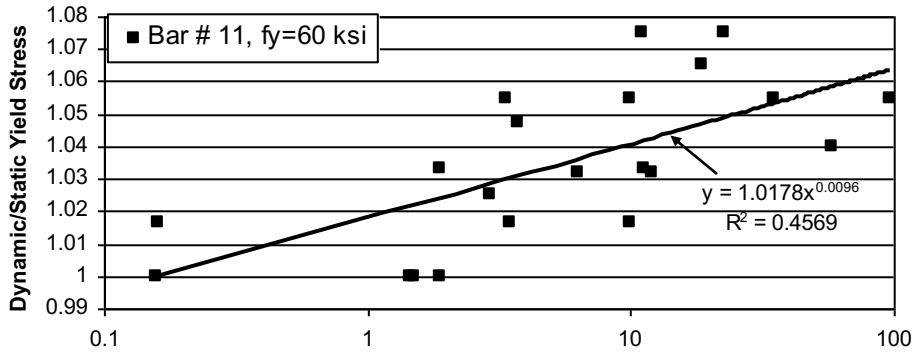


Fig. B-1 Yield stress enhancement of #11bars tested under constant strain rates

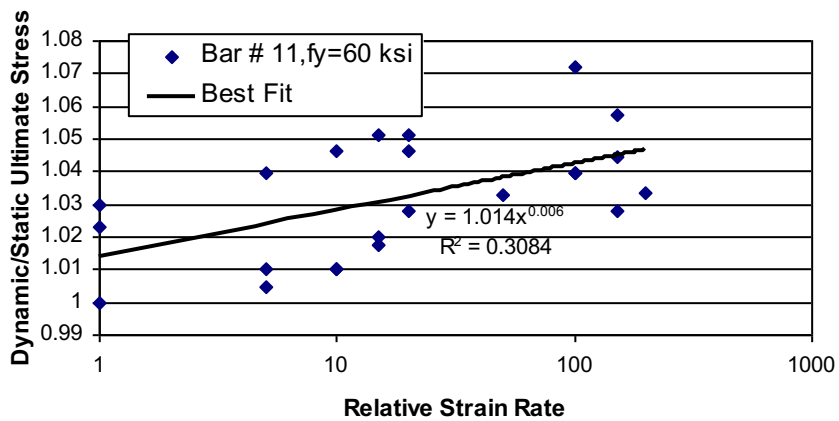


Fig.B-2 Ultimate stress enhancement of #11 bars tested under constant strain rates

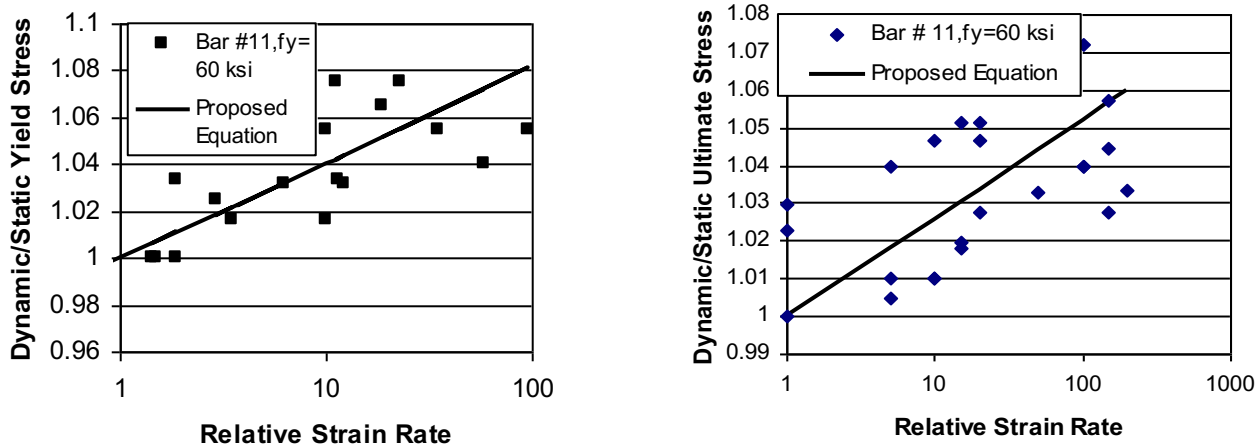


Fig. B-3 Comparison of proposed Equation to results of #11 constant strain

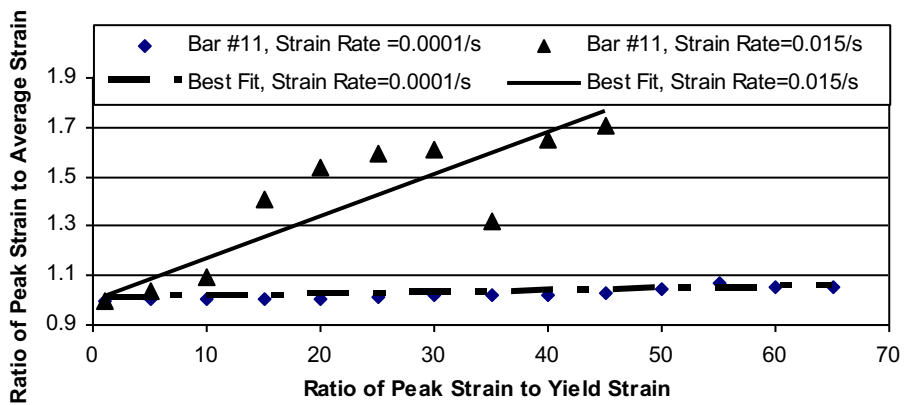


Fig. B-4 Localization of strain for #11 size bars at low and high strain rates

LIST OF CCEER PUBLICATIONS

- | Report No. | Publication |
|------------|--|
| CCEER-84-1 | Saiidi, M., and R. Lawver, "User's Manual for LZAK-C64, A Computer Program to Implement the Q-Model on Commodore 64," Civil Engineering Department, Report No. CCEER-84-1, University of Nevada, Reno, January 1984. |
| CCEER-84-2 | Douglas, B. and T. Iwasaki, "Proceedings of the First USA-Japan Bridge Engineering Workshop," held at the Public Works Research Institute, Tsukuba, Japan, Civil Engineering Department, Report No. CCEER-84-2, University of Nevada, Reno, April 1984. |
| CCEER-84-3 | Saiidi, M., J. Hart, and B. Douglas, "Inelastic Static and Dynamic Analysis of Short R/C Bridges Subjected to Lateral Loads," Civil Engineering Department, Report No. CCEER-84-3, University of Nevada, Reno, July 1984. |
| CCEER-84-4 | Douglas, B., "A Proposed Plan for a National Bridge Engineering Laboratory," Civil Engineering Department, Report No. CCEER-84-4, University of Nevada, Reno, December 1984. |
| CCEER-85-1 | Norris, G. and P. Abdollaholizadeh, "Laterally Loaded Pile Response: Studies with the Strain Wedge Model," Civil Engineering Department, Report No. CCEER-85-1, University of Nevada, Reno, April 1985. |
| CCEER-86-1 | Ghousn, G. and M. Saiidi, "A Simple Hysteretic Element for Biaxial Bending of R/C in NEABS-86," Civil Engineering Department, Report No. CCEER-86-1, University of Nevada, Reno, July 1986. |
| CCEER-86-2 | Saiidi, M., R. Lawver, and J. Hart, "User's Manual of ISADAB and SIBA, Computer Programs for Nonlinear Transverse Analysis of Highway Bridges Subjected to Static and Dynamic Lateral Loads," Civil Engineering Department, Report No. CCEER-86-2, University of Nevada, Reno, September 1986. |
| CCEER-87-1 | Siddharthan, R., "Dynamic Effective Stress Response of Surface and Embedded Footings in Sand," Civil engineering Department, Report No. CCEER-86-2, University of Nevada, Reno, June 1987. |
| CCEER-87-2 | Norris, G. and R. Sack, "Lateral and Rotational Stiffness of Pile Groups for Seismic Analysis of Highway Bridges," Civil Engineering Department, Report No. CCEER-87-2, University of Nevada, Reno, June 1987. |
| CCEER-88-1 | Orie, J. and M. Saiidi, "A Preliminary Study of One-Way Reinforced Concrete Pier Hinges Subjected to Shear and Flexure," Civil Engineering |

Department, Report No. CCEER-88-1, University of Nevada, Reno, January 1988.

- CCEER-88-2 Orié, D., M. Saiidi, and B. Douglas, "A Micro-CAD System for Seismic Design of Regular Highway Bridges," Civil Engineering Department, Report No. CCEER-88-2, University of Nevada, Reno, June 1988.
- CCEER-88-3 Orié, D. and M. Saiidi, "User's Manual for Micro-SARB, a Microcomputer Program for Seismic Analysis of Regular Highway Bridges," Civil Engineering Department, Report No. CCEER-88-3, University of Nevada, Reno, October 1988.
- CCEER-89-1 Douglas, B., M. Saiidi, R. Hayes, and G. Holcomb, "A Comprehensive Study of the Loads and Pressures Exerted on Wall Forms by the Placement of Concrete," Civil Engineering Department, Report No. CCEER-89-1, University of Nevada, Reno, February 1989.
- CCEER-89-2 Richardson, J. and B. Douglas, "Dynamic Response Analysis of the Dominion Road Bridge Test Data," Civil Engineering Department, Report No. CCEER-89-2, University of Nevada, Reno, March 1989.
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