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Structural Engineering

Behavior and Modeling of Mild and Reinforcing Steel

by
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Research Assistant

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Principal Investigator

Submitted to
The American Institute of Steel Construction
The American Iron and Steel Institute
The National Science Foundation
(MSS-9222064)
Innovative Steel Research For Construction Program

Report No. CE/VPI-ST 96/12

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TABLE OF NOMENCLATURE

F_y = Yield stress

F_u = Ultimate tensile stress

$(F_y)_{mill}$ = Yield stress based on mill tensile test

$(F_y)_{static}$ = Yield stress based on pseudo static tensile test

ε = Strain rate

COV = Coefficient of variation

E = Modulus of elasticity

ABSTRACT

An investigation of the stress-strain behavior of mild structural steel and reinforcing steel is presented in this report. Two grades of mild steel are included in the investigation; ASTM A36 and ASTM A572Gr50. The only reinforcing steel investigated is Grade 60 and specifically #4 bars. Data from existing literature, tensile tests conducted at Virginia Tech (VT), and mill test reports was used as a basis to develop approximate methods for representing the stress-strain behavior of these steels.

1. Introduction

A composite beam-girder connection has two very basic components; steel and concrete. An approximate method of modeling the stress-strain behavior of these components is required for finite element analysis of beam-girder connections. The stress-strain behavior of steel is the subject of this report.

1.1 Mild Steel

Mild steel is the primary material used for beams, girders, and connection elements such as plates and angles. There were two studies on the behavior of mild steel found in the literature Galambos and Ravindra (1978) and Read and Frank (1993).

When the LRFD design method for steel structures was being developed Galambos and Ravindra (1978) studied the properties of hot rolled steel. They considered three sources of data; mill test data, data found in papers designed to determine specific steel properties, and papers that reported steel properties but where the focus was on some other feature of structural steel design. The specified yields for the steels included in the analysis ranged from 33 ksi to 55 ksi.

When considering the yield stress, Galambos and Ravindra (1978) had to deal with the fact that mill yield tests are typically run at a high rate of strain which results in a higher apparent yield stress than the static yield stress. To account for the higher strain rate the authors developed a relationship to transform the mill yield stress to equivalent static yield stress.

$$(F_y)_{mill} - (F_y)_{static} = 3.2 + 0.001\,\varepsilon$$

Where:

ε = Strain rate in micro-inches per inch per second typically taken as 800 μ in. / in.

The strain rate was not really known at the time but because the formula was fairly insensitive to the strain rate the value of 800 seemed reasonable. This strain rate results in approximately a 4 ksi difference.

The results (of interest for this report) are summarized as follows:

- Mean elastic modulus = 29,000 ksi, Coefficient of Variation (COV) = 6%
- Mean yield stress for flanges in rolled shapes = 1.05 Specified Stress, COV = 10%
- Mean yield stress for plates and webs of rolled shapes = 1.10 Specified Stress, COV = 11%
- Mean strain hardening modulus = 600 ksi, COV = 25%

The large quantity of structural steel being produced from recycled steel in recent years, which is approximately 85% (Bell, 1995), has changed the characteristics of structural steel. A mill survey was conducted (Read & Frank, 1993) to evaluate the properties of steel currently being supplied. Mill test data for rolled W sections from six steel companies was provided over a 12 month period. Table 1 summarizes the results of a statistical analysis of the data which included some 57,930 mill tests. Only the results for A36 and A572Gr50 steel have been included.

Table 1 Results of Recent Mill Survey

	Steel Grade Number of Data	A36 36,570	A572 13,536
Yield (ksi)			
	Mean	49.2	57.6
	Standard Deviation	4.9	5.1
Ultimate (ksi)			
	Mean	68.5	75.6
	Standard Deviation	4.6	6.2
Yield/Ultimate			
	Mean	.720	.763
	Standard Deviation	.057	.048

1.2 Reinforcing Steel

Standard deformed bar reinforcing steel is available in grade 40, 60 and 75 with nominal yield stresses of 40 ksi, 60 ksi, and 75 ksi respectively. The most common reinforcing steel used in buildings is grade 60. A review of mill test data by Mirza and MacGregor (1979) determined the following results for Grade 60 reinforcing steel.

- Yield Stress: Mean = 71 ksi, COV = 9.3%
- Ultimate Stress: Mean = 110.8 ksi, COV = 8.73%
- Elastic Modulus: Mean = 29,200 ksi, COV = 3.3%

The stress-strain behavior of reinforcing bars is usually taken as elastic plastic (Collins and Mitchell 1991); but, because #4 Grade 60 bars typically have a very short yield plateau, a more detailed representation of the stress-strain behavior is desired by the writer. Four of the key points of an ideal stress-strain curve for grade 60 reinforcing bars, as given by Wang and Salmon (1985), are shown in Table 2.

Table 2 Ideal Stress Strain Points For Grade 60 Reinforcing Steel

Point	Stress (ksi)	Strain (in/in)
Yield	60	0.002
Begin Strain Hardening	60	0.01
Ultimate	110	0.08
Rupture	95	0.125

2. Focus And Objective

The objective of this investigation is to develop an approximate method of numerically representing the stress-strain behavior of mild and reinforcing steels. The stress-strain behavior will later be used in composite connection analysis. A multi-linear representation is probably the simplest method of representing the behavior.

A multi-linear representation of the stress-strain behavior consists of key points on the stress-strain curve that are connected with straight line segments. The number of key points required to adequately represent the stress-strain curve depends on the basic shape of the curve as well as the degree of accuracy sought. A minimum of five points and preferably six points are needed to adequately represent the stress-strain behavior of mild and reinforcing steel. These points include yield, start of strain hardening, one or two points between start of strain hardening and ultimate, ultimate, and rupture.

Typical tensile tests are designed to obtain the yield point (both stress and strain values), the ultimate stress (no strain value), and the percent elongation (rupture strain, no stress). Tensile test reports typically only include the yield and ultimate stress values (no corresponding strain values) and percent elongation. These are only three out of the 10 to 12 values (5 to 6 stress and 5 to 6 strain) that are necessary to adequately represent the stress-strain behavior. However, these three values are probably the most important in defining the boundaries of the stress-strain behavior. Consequently, readily available tensile test reports were collected and included in the analysis. These include tensile tests conducted at VT and mill test data.

To fill in the missing stress-strain values needed to define an adequate multi-linear representation special tensile tests that report the full stress-strain behavior were performed on mild and reinforcing steel coupons.

The most commonly used mild structural steels are ASTM A36 and ASTM A572Gr50 steel. In addition, all previous and subsequent research by the writers on composite beam-girder connections only utilizes #4 Grade 60 reinforcing bars. Consequently, this report only deals with these particular steels.

It should be noted that the primary intent of this work is to develop estimates for the average behavior of mild structural steel for use in finite element models. It is not the intent of the this work to develop a new statistical basis for the prediction of steel behavior for use in design codes.

3. Mill Survey of Angles and Plates

Mill tests reporting yield stress, ultimate stress, percent elongation, and chemical analysis for hot rolled angles and plates were supplied by a steel mill. These tests covered approximately a six month time period from 6/25/95 to 12/20/95. The mill that supplied the mill test data uses electric arc furnaces and scrap steel to produce the angles and plates.

Data from the mill test reports was entered into a commercial database program and then analyzed with a commercial spreadsheet program. The data included 15 angle shapes and 40 plate shapes, a summary of the shapes included in the analysis is presented in Appendix A Table A-1. The data also included 14 different grades of steel. Only A36 and A572Gr50 steels have been included in the analysis.

A summary of steel property statistics including the mean, median, coefficient of variation, minimum values, maximum value, and number of data is presented in Appendix A Table A-2. These statistics are grouped by shape (plate or angle) and steel grade. The mean values are also presented in Table 3 below.

Table 3 Mean Values of Mill Survey Data

	F_y	F_u	% Elongation	F_u/F_y
	(ksi)	(ksi)		
A36 Structural Angles	46.1	67.3	34.9	1.46
A36 Plates	45.7	67.2	32.0	1.47
A572Gr50 Structural Angles	57.7	79.3	30.4	1.37
A572Gr50 Plates	54.7	77.1	29.6	1.41
A36 Angles & Plates	45.8	67.2	32.7	1.47
A572Gr50 Angles & Plates	55.8	77.9	29.9	1.40

As can be seen in Table 3 the properties for A36 angles differed very little from those for A36 plates. Consequently, it does not seem necessary to distinguish between angles and plates when considering A36 steel properties. The properties for A572Gr50 angles did differ some from those for A572Gr50 plates. There were only 50 mill test reports available for A572Gr50 angles and plates. The small number of tests is the likely reason for the difference seen in the properties between A572Gr50 angles and plates. Consequently, the writer believes distinguishing between angles and plates when considering A572Gr50 steel is also not necessary.

4. Tensile Tests Conducted at Virginia Tech

The following describes the collection and compilation of various tensile test data available from recent work at VT. In addition, a description of special tensile tests which reported the entire stress-strain behavior is presented.

4.1 Miscellaneous Tensile Test Data Collected

Data from tensile tests that were performed at VT was collected and compiled. The amount of stress-strain data available varied depending on the particular tensile test. The available data was analyzed to determine as many key points for the stress-strain behavior as possible. Tensile tests for plates and angles made of A36 steel, wide flange shapes made from A572Gr50 steel, and #4 Grade 60 reinforcing steel were found. This test data is summarized in Appendix B Table B-2 and Table B-4 for mild steel and for reinforcing steel respectively.

4.2 Tensile Tests With Full Stress-Strain Data

Typical tensile tests only measure enough strain data to determine the steel yield stress and occasionally extend into the start of the strain hardening region. To determine additional strain values needed to define an adequate multi-linear representation of the stress-strain curve, special tensile tests that report the full stress-strain behavior were performed on 42 mild and 20 reinforcing steel coupons.

4.2.1 Tensile Coupon Specimens

The 42 mild steel coupons came from rolled steel plate that had a nominal grade A36. This plate was purchased at varying times from a local supplier. Because of this and the fact that the plate thickness varied it is assumed that these coupons came from various different steel heats.

The 20 reinforcing steel coupons were taken from #4 Grade 60 bars. These bars were all purchased at the same time from a local supplier. Although not guaranteed, because these bars came from the same supplier at the same time and are all the same size and grade it is very likely they all came from the same heat of steel.

The nominal dimensions of the tensile coupons are shown in Figure 1. These dimensions are in accordance with ASTM A370 (1988) guidelines. The measured dimensions are presented in Table C-1 and Table D-1 found in Appendix C and Appendix D for the mild steel and reinforcing steel coupons respectively.

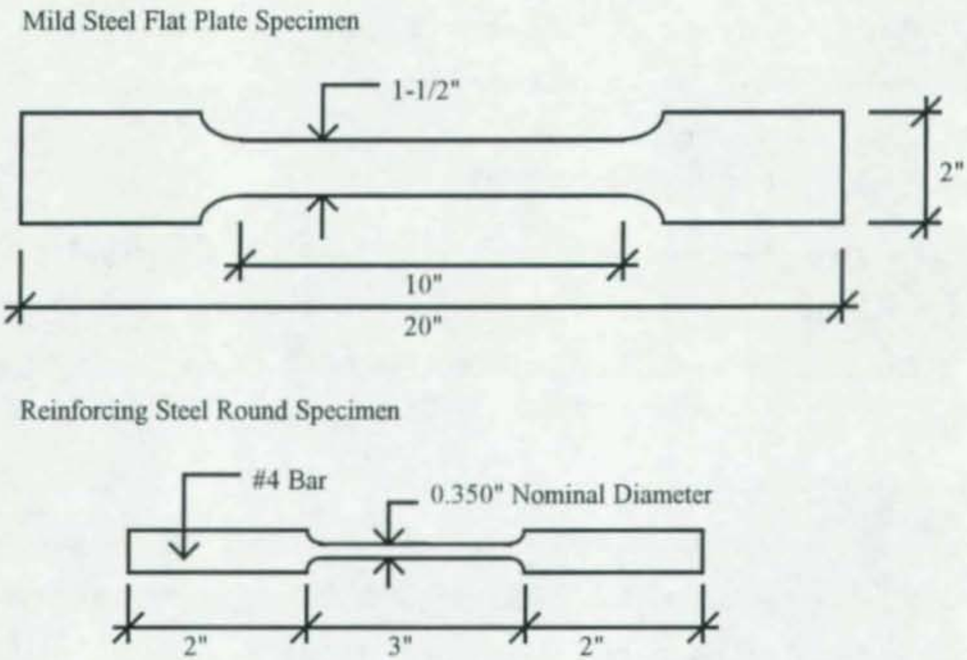

Figure 1 Nominal Dimensions of Tensile Coupons

4.2.2 Instrumentation

An Instron extensometer was used to measure the strain over a 2-in. gage length. This extensometer was capable of strain measurements up to 50%. Calipers were used to measure initial and final gage lengths for purposes of calculating percent elongation. The mild steel coupons had gage lengths of 8-in. and the reinforcing steel coupons had gage lengths of 2-in.

4.3 Results

Tabular summaries of all key stress-strain and statistical values for both mild and reinforcing steel are presented in Appendix B. Full stress-strain plots for the tensile tests described in Section 4.2 are presented in Appendix C and D for mild steel tests and reinforcing steel tests respectively. A discussion of these results is reserved for the following sections.

5. Summary and Comparison of Data

The purpose of this section is to summarize and compare the mean values of the steel properties determined from work described in Sections 3 and 4 as well as any pertinent existing literature.

5.1 Yield and Ultimate Stress

Yield and ultimate stress values are probably the most important values for defining the stress-strain behavior. Data for these values was reported in existing literature and in the work described in Sections 3 and 4. A summary of this data is presented in Table 4.

Table 4 Mean Values of Yield and Ultimate Stress Data

	F_y (ksi)	F_u (ksi)	F_u/F_y	No. Data
A36 Mild Steel				
Tensile Tests on Wide Flange Shapes				
Mill Survey (Read & Frank 1993)	49.2	68.5	1.39	36570
Tensile Tests on Plates & Angles				
Mill Survey	45.8	67.2	1.47	760
Tensile Tests Conducted @ VT	45.9	67.8	1.48	90
A572 Gr. 50 Mild Steel				
Tensile Tests on Wide Flange Shapes				
Mill Survey (Read & Frank 1993)	57.6	75.6	1.31	13536
Tensile Tests Conducted @ VT	46.0	62.7	1.36	10
Tensile Tests on Plates & Angles				
Mill Survey	55.8	77.9	1.40	50
Grade 60 Reinforcing Steel				
Mill Survey (Mirza & MacGregor 1979)	71.0	110.8	1.56	3042
Tensile Tests Conducted @ VT (#4 Bars)	70.5	114.6	1.63	25

When considering A36 mild steel there appears to be a difference in mean yield stress values between wide flange shapes and plates and angles. Part of this difference may be attributable to variations in test strain rates associated with the mill survey. However, a comparison of the two sets of mill survey data indicates this is most likely not the case. It is unclear why this apparent difference exits. Despite the difference in the yield stress values there is very little difference seen in the ultimate stress values.

When considering A572Gr50 mild steel there is a large difference for both yield and ultimate stress values for wide flange shapes between the mill survey by Frank and Read (1993) and the data found on tensile tests at VT. This difference is attributed to the particularly small number of data from tensile tests conducted at VT and it is assumed that a larger base of data would tend to give values more in line with those determined by Read and Frank (1993). When comparing wide flange shape properties to angle and plate properties there is a very small difference between the yield and ultimate stress values which is most likely explained by the few number of tests in the mill survey on plates and angles.

When considering Grade 60 reinforcing steel there is very little difference between the yield stress values from the two sources; however, there is a small difference in the ultimate stress values. This is attributed to the fact the tests at VT are believed to come from the same heat and same bar size while the mill survey data comes from a much larger number of heats and bar sizes.

5.2 Other Key Stress-Strain Values

In addition to the yield and ultimate stress values other key values are required to properly represent the stress-strain behavior. These values include:

- The modulus of elasticity
- Strain at start of strain hardening

- Two stress-strain points between start of strain hardening and the ultimate stress
- The strain at ultimate stress (percent elongation)
- The stress and strain at rupture

A summary of these key points is presented in Table 5. Based on the data, distinctions between steel grades and shapes does not required for the steel properties listed. Consequently, the data presented in Table 5 are the mean values without regard to steel grade or shape.

Based on a visual inspection of the typical stress-strain behavior the writer choose the intermediate stress-strain values at 5% and 10% strain were chosen. The stresses corresponding to these strains were determined and normalized by dividing the value by the ultimate stress. The stress at rupture was also normalized by the ultimate stress.

Table 5 Mean Values For Key Stress-Strain Strain Points For Mild Steel

	Galambos & Ravindra (1978)	Plate & Angle Mill Survey	Tensile Tests Conducted @ VT
Modulus of elasticity (ksi)	29000	-	30000
Strain @ start of strain hardening (in./in.)	-	-	0.0219
Stress @ 5% strain (normalized by F_u)	-	-	0.846
Stress @ 10% strain (normalized by F_u)	-	-	0.957
Strain @ ultimate stress (in./in.)	-	-	0.1894
Stress @ rupture (normalized by F_u)	-	-	0.833
Strain @ rupture (in./in.)	-	0.325	0.296

The only values that can be compared between sources are the modulus of elasticity and the strain at rupture. The commonly accepted value of the elastic modulus for mild steel is 29,000 ksi. The difference between this and what was determined from tensile tests at VT can be attributed to the small number of tests and the lack of accuracy with which the extensometer used can measure small strains. The difference in rupture strains is small and can easily be attributed to the wide variability seen in percent elongation measurements.

A summary of the mean values for the key points of the stress-strain behavior for reinforcing steel is presented in Table 6. Based on a visual inspection of the typical stress-strain behavior the intermediate stress-strain values at 3% and 7% strain were chosen. The stresses corresponding to these strains were determined and normalized by dividing the value by the ultimate stress. The stress at rupture was also normalized by the ultimate stress.

Table 6 Mean Values For Key Stress-Strain Strain Points For Reinforcing Steel

	Mirza & MacGregor (1979)	Wang & Salmon (1985)	Tensile Tests Conducted @ VT
Modulus of elasticity (ksi)	29200	30000	32500
Strain @ start of strain hardening (in./in.)	-	0.01	0.0074
Stress @ 3% strain (normalized by F_u)	-	-	0.832
Stress @ 7% strain (normalized by F_u)	-	-	0.976
Strain @ ultimate stress (in./in.)	-	0.08	0.101
Stress @ rupture (normalized by F_u)	-	-	0.837
Strain @ rupture (in./in.)	-	0.125	0.167

A comparison of the data presented in Table 6 reveals some minor differences between the three sources. For the most part these differences may be explained by the limited variety of reinforcing steel used in the tensile tests conducted at VT. However, the source of the ideal stress-strain behavior given by Wang and Salmon (1985) is not known. Consequently, it is difficult to say which set of values is more accurate.

6. Multi-Linear Approximation

The objective of this report is to develop a method of representing the stress-strain curves for typical mild structural steel and for #4 Grade 60 reinforcing bars. In particular a multi-linear representation of the stress-strain curve is sought. For clarity, methods to do this for mild steel and reinforcing steel are developed separately below. After the methods are developed a comparison of the multi-linear representations to the measured stress-strain data is discussed.

6.1 Mild Steel

The first step in defining all the required key points in the stress-strain curve for a multi-linear approximation is to determine the elastic modulus. Next, the values of the yield and ultimate stresses must be determined. And finally, all remaining key values must be determined.

6.1.1 Elastic Modulus

The only statistically significant work that was done on mild steel with regard to the elastic modulus was by Galambos and Ravindra (1978). They determined the mean value of the elastic modulus to be 29,000 ksi. Because of the many changes in the steel making process since this work it is questionable whether or not the mean value of the modulus has changed. The only recent data available to try to resolve this question is the data collected in this report. The mean value of the elastic modulus based on the combined results for the A36 and A572Gr50 steels is 30,000 ksi. As discussed previously, this difference is most likely attributable to errors in measurement and the small number of data points. Consequently, without any additional data a value of 29,000 ksi should be assumed.

6.1.2 Yield and Ultimate Stresses

If both the yield and ultimate stresses have not been determined by a tensile test then they must be approximated. The following possible scenarios will be considered.

- Case 1: Don't know either F_y or F_u
- Case 2: Only know F_y or F_u

Consider Case 1. There are two possible methods for determining both F_y and F_u. Conservatively (conservative in this research but not necessarily in other research) F_y and F_u can be assigned the nominal minimum ASTM properties for the grade of steel being used. These values are given in Table 7. A second alternative would be to use the mean values determined in the recent mill surveys and data collected in this report. The suggested values are also given in Table 7. Note that for A36 steel a distinction is made between wide flange shapes and angles and plates. However, this distinction is not necessary for A572Gr50 steel.

Table 7 Suggested Yield and Ultimate Stress Values

Steel Grade	A36	A572Gr50
Nominal F_y (ksi)	36	50
Nominal F_u (ksi)	58	65
F_y for wide flange shapes (ksi)	49.2	57.6
F_u for wide flange shapes (ksi)	68.5	75.6
F_u/F_y for wide flange shapes	1.39	1.31
F_y for plates & angles (ksi)	45.8	57.6
F_u for plates & angles (ksi)	67.3	75.6
F_u/F_y for plates & angles	1.47	1.31

Consider Case 2. If F_y or F_u is unknown then it could be assumed that neither value is known and the method outlined for Case 1 could be used. Alternatively, an estimate of the unknown quantity could be obtained by using the mean ratio of F_u to F_y determined in the recent mill surveys and data collected in this report. These values are also given in Table 7.

6.1.3 Remaining Key Values

Once the elastic modulus, yield stress, and ultimate stress have been determined then the remaining values needed to complete the multi-linear approximation to the stress-strain curve are:

- The strain at which strain hardening begins
- Two stress and strain values between the beginning of strain hardening and the ultimate stress
- The strain at the ultimate stress

- The stress and strain at rupture

Based on the mean values of the data collected in this report and general observations of the full stress-strain curves the following recommendations for estimating these remaining values are given.

- Strain at start of strain hardening = 2%
- Intermediate strain and stress values
    - Strain = 5%, Stress = 85% of F_u
    - Strain = 10%, Stress = 95% of F_u
- Strain at ultimate stress = 20%
- Rupture strain = 30% and stress = 83% of F_u

6.2 Reinforcing Steel

The only reinforcing steel considered is #4 Grade 60 reinforcing bars. Consequently, the key values of the stress-strain curve will be estimated with the statistical mean values obtained from the mill survey by Mirza and MacGregor (1979) and those obtained from the data collected in this report. The value for the elastic modulus, yield stress, and ultimate stress are taken from the mill survey while the remaining values are based on the data collected in this report and observation of the full stress-strain data collected at VT.

- Elastic Modulus = 29,000 ksi
- Yield Stress = 71 ksi
- Ultimate Stress = 111 ksi
- Strain at start of strain hardening = 0.8%
- Intermediate stress and strain values
    - Strain = 3%, Stress = 83% of F_u
    - Strain = 7%, Stress = 98% of F_u

- Strain at ultimate stress = 10%
- Rupture strain = 16% and stress = 84% of F_u

These values are slightly different than the ideal values suggested in Wang and Salmon (1985).

6.3 Comparison of Multi-Linear Estimate to Measured Data

The multi-linear estimates are plotted against the measured data for the mild steel and reinforcing steel tensile tests in Appendix C and D respectively. There are two plots presented for each test: the full stress-strain curve and a view of the initial region of the curve. The only full stress-strain curves available for mild steel are for A36 plates. Consequently, only the method for approximating the stress-strain behavior for A36 angle and plate steel can be evaluated.

In general, the multi-linear estimates of the mild steel stress-strain behavior, when the yield and ultimate stresses are known, and the reinforcing steel stress-strain behavior are excellent. As is expected, without knowing F_y or F_u or both, the approximation becomes worse but is still generally acceptable. Using nominal F_y and F_u values clearly gives a conservative estimate of the behavior.

The strain values for the approximations are constants and a visual comparison of the approximations to the measured data shows that the chosen strain values accurately represent the data. The reader may observe that the strain data for the mild steel coupons typically extends beyond the predicted rupture strain. This is because the extensometer used to measure the strain uses a 2-in. gage length but an 8-in. gage length is used to determine the percent elongation. The later was used to estimate the strain at rupture. This is not a problem for the reinforcing steel coupons because the gage for the extensometer is the same as the gage for determining the percent elongation.

7. Summary, Conclusions, and Recommendations

7.1 Summary

Readily available tensile test data and mill test data for common mild structural steels and #4 Grade 60 reinforcing bars was collected and analyzed. In addition, special tensile tests that measured the entire stress-strain behavior were conducted on these same types of steel. Based on this data, as well as previous studies on the behavior of structural and reinforcing steel, methods were developed to create multi-linear representations of the stress-strain behavior for these steels. These methods are summarized in Figures 2 and 3.

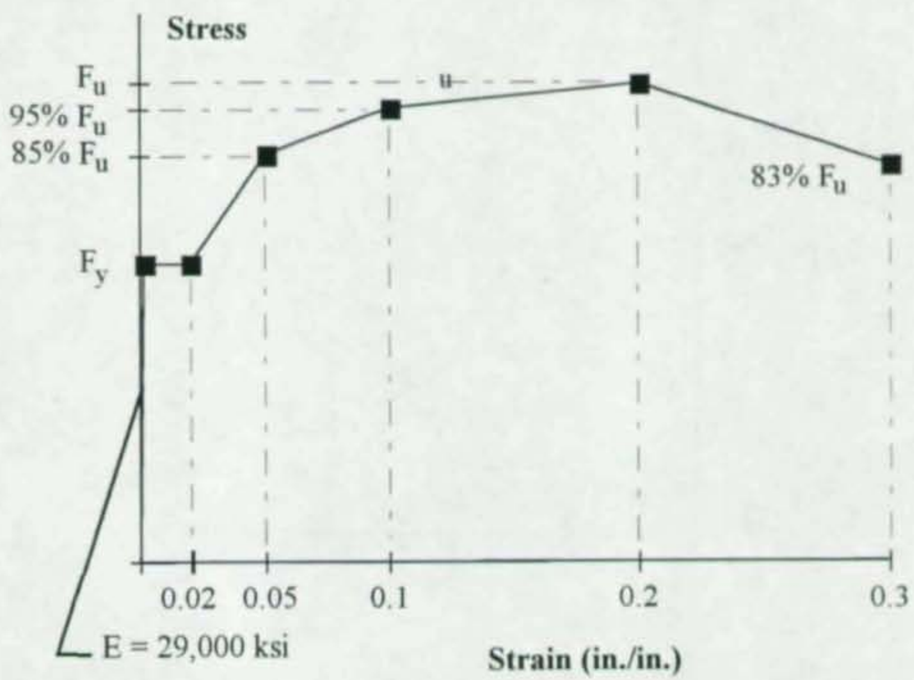

Figure 2 Multi-Linear Approximation For Mild Steel Stress-Strain Behavior

The rules for determining F_y and F_u if either or both are unknown are as follows:

A36 Steel

F_y & F_u Unknown

Use Nominal Values $F_y = 36$ $F_u = 58$

Use Mean Values

	Wide Flange Shapes	$F_y = 49.2$	$F_u = 68.5$
	Plates & Angles	$F_y = 45.8$	$F_u = 67.3$
F_y or F_u Unknown			
	Use Mean F_u/F_y Values		
	Wide Flange Shapes	$F_y = Fu/1.39$	$F_u = 1.39\ Fy$
	Plates & Angles	$F_y = Fu/1.47$	$F_u = 1.47\ Fy$
A572Gr50 Steel			
F_y & F_u Unknown			
	Use Nominal Values	$F_y = 50$	$F_u = 65$
	Use Mean Values	$F_y = 57.6$	$F_u = 75.6$
F_y or F_u Unknown			
	Use Mean F_u/F_y Values	$F_y = F_u/1.31$	$F_u = 1.31\ F_y$

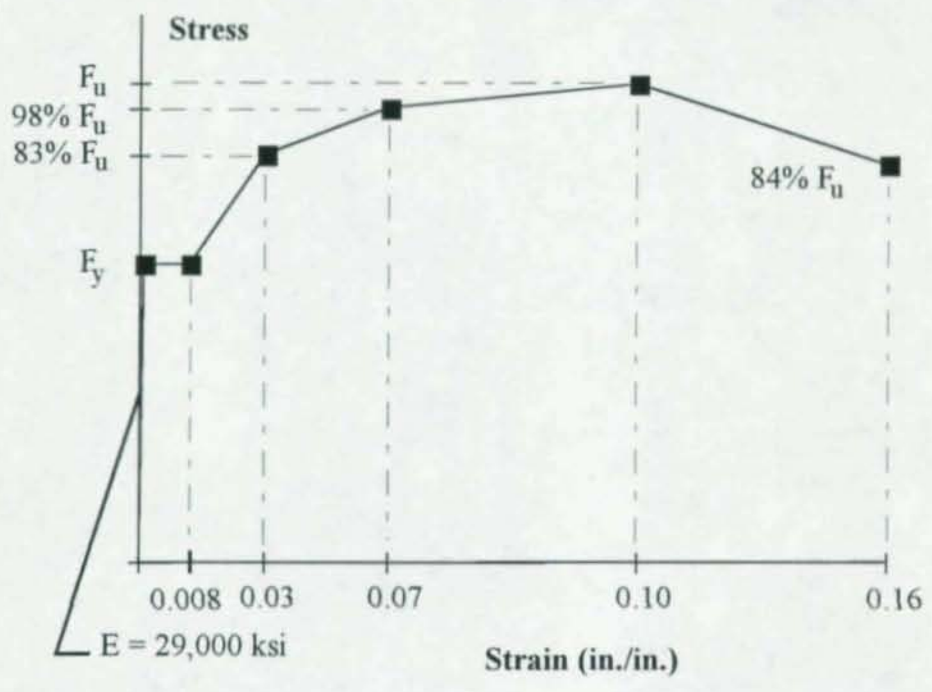

Figure 3 Multi-Linear Approximation For Reinforcing Steel Stress-Strain Behavior

If F_y and or F_u are unknown then the mean values 71 ksi and 111 ksi respectively are recommended.

7.2 Conclusions

This report outlines a method for developing a multi-linear approximation a stress-strain curve for the most common mild structural steels and for #4 Grade 60 reinforcing bars. The agreement between the multi-linear approximation and the actual stress-strain curve data is very good when both yield and ultimate stresses are known. As would be expected, the approximation compares less favorably when either F_y or F_u are unknown.

7.3 Recommendations

The accuracy with which an approximation to the stress-strain behavior is needed depends on the intended use of the approximate behavior. In many cases, highly accurate approximations are not necessary because the intended use is fairly insensitive to variations in the approximate behavior.

If the intended use is very sensitive to small variations in the approximate material behavior then the following recommendations are given:

A much larger base of data needs to be collected

A statistical study of this data should be conducted to find the following for each key point of the stress-strain behavior.

- The mean value
- The shape of the variation
- Confidence interval values

The results of such a study would allow investigators to properly account for the effects that the variation in the steel behavior has on their particular work.

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Appendix A

Mill Survey of Angles & Plates

Table A-1
Summary of Angle And Plate Shapes Included In Mill Survey

Plates	Angles
1-3/4 x 1/2	4 x 4 x 3/8
1-3/4 x 3/4	4 x 4 x 0.344
2 x 1/4	4 x 4 x 5/16
2 x 3/8	4 x 4 x 1/2
2 x 1/2	4 x 3-1/2 x 1/4
2 x 5/8	4 x 3 x 3/8
2 x 3/4	4 x 3 x 5/16
2 x 1	4 x 3 x 1/4
2-1/4 x 1/4	3-1/2 x 3-1/2 x 3/8
2-1/2 x 3/8	3-1/2 x 3-1/2 x 5/16
2-1/2 x 1/2	3-1/2 x 3-1/2 x 1/4
2-1/2 x 5/8	4 x 4 x 7/16
2-1/2 x 3/4	
2-1/2 x 1	
3 x 5/8	
3 x 3/4	
3 x 1	
3-1/2 x 1/4	
3-1/2 x 1	
3-3/4 x 5/16	
4 x 1/4	
4 x 5/16	
4 x 3/8	
4 x 1/2	
4 x 5/8	
4 x 3/4	
4 x 1	
4-1/2 x 1/4	
4-1/2 x 3/8	
4-1/2 x 1/2	
5 x 1/4	
5 x 5/16	
5 x 3/8	
5 x 1/2	
5 x 5/8	
6 x 1/4	
6 x 3/8	
6 x 1/2	
6 x 3/4	
6 x 1	

Table A-2
Summary of Steel Property Statistics From Mill Survey

	F_y (ksi)	F_u (ksi)	%Elongation	F_u/F_y
A36 Structural Angles				
Mean	46.1	67.3	34.9	1.46
Median	45.8	67.3	35.0	1.47
Coeff. of Variations	6.3%	5.5%	5.6%	3.2%
Minimum Value	40.2	59.0	29.4	1.20
Maximum Value	56.8	75.8	40.0	1.56
Number of Data	174	174	174	174
A36 Plates				
Mean	45.7	67.2	32.0	1.47
Median	45.8	67.4	32.0	1.48
Coeff. of Variations	7.5%	6.8%	10.0%	5.6%
Minimum Value	38.2	7.2	23.8	0.16
Maximum Value	82.6	79.8	40.0	1.75
Number of Data	586	586	586	586
A572Gr50 Structural Angles				
Mean	57.7	79.3	30.4	1.37
Median	58.1	80.2	30.6	1.37
Coeff. of Variations	6.8%	6.2%	9.5%	1.8%
Minimum Value	52.0	73.1	26.0	1.35
Maximum Value	64.5	88.3	33.8	1.43
Number of Data	18	18	18	18
A572Gr50 Plates				
Mean	54.7	77.1	29.6	1.41
Median	54.1	76.0	29.8	1.39
Coeff. of Variations	4.8%	5.0%	9.5%	4.6%
Minimum Value	50.3	72.4	22.5	1.31
Maximum Value	60.8	83.3	35.0	1.54
Number of Data	32	32	32	32
A36 Plates and Structural Angles				
Mean	45.8	67.2	32.7	1.47
Median	45.8	67.4	32.6	1.47
Coeff. of Variations	7.3%	6.5%	9.8%	5.2%
Minimum Value	38.2	7.2	23.8	0.16
Maximum Value	82.6	79.8	40.0	1.75
Number of Data	760	760	760	760
A572Gr50 Plates and Structural Angles				
Mean	55.8	77.9	29.9	1.40
Median	55.3	76.7	30.0	1.38
Coeff. of Variations	6.2%	5.6%	9.5%	4.0%
Minimum Value	50.3	72.4	22.5	1.31
Maximum Value	64.5	88.3	35.0	1.54
Number of Data	50	50	50	50

Appendix B

Summary Tables & Statistics For
Tensile Tests Conducted At Virginia Tech

Table B-1 Summary Statistics For Mild Steel Coupons

	Elastic Modulus (ksi)	Yield *Stress* .2% Offset (ksi)	Begin *Strain* Hardening	Stress @ 5% Strain (ksi)	% of Fu	% of Fu - Fy	Stress @ 10% Strain (ksi)	% of Fu	% of Fu - Fy	Ultimate Stress (ksi)	Strain @ Ultimate Stress	Rupture Stress (ksi)	% of Fu	% of Fu - Fy	% Elongation (8" Gage)	Fu/Fy
A36 & A572 Gr. 50																
No. Data	58	100	64	64	64	64	53	53	53	101	42	62	62	62	101	100
Mean	30050	45.9	0.0219	56.3	84.6%	50.3%	64.4	95.7%	86.7%	67.2	0.1894	55.3	83.3%	46.6%	29.6%	1.47
COV	17.5%	6.7%	25.3%	7.2%	2.5%	18.1%	6.3%	1.4%	4.1%	5.8%	9.8%	8.7%	6.6%	36.8%	6.6%	4.9%
A36 Angles & Plates																
No. Data	48	90	54	54	54	54	53	53	53	90	42	52	52	52	90	90
Mean	30528	45.9	0.0210	57.1	84.9%	53.0%	64.4	95.7%	86.7%	67.8	0.1894	55.7	83.0%	47.2%	29.8%	1.48
COV	17.3%	6.9%	18.5%	6.6%	2.3%	11.3%	6.3%	1.4%	4.1%	5.5%	9.8%	9.1%	6.9%	37.5%	3.9%	4.3%
A572 Gr. 50 Wide Flange Sections																
No. Data	10	10	10	10	10	10				11		10	10	10	11	10
Mean	27757	46.0	0.0264	52.0	83.1%	35.9%				62.7		53.3	85.2%	43.8%	28.5%	1.36
COV	16.8%	5.3%	37.4%	4.3%	3.0%	27.1%				2.4%		4.9%	4.7%	33.0%	17.5%	4.0%

Table B-2 Summary of Tensile Data For Mild Steel Coupons

Coupon Designation	Shape	Nominal Steel Grade	Elastic Modulus (ksi)	Yield Stress .2% Offset (ksi)	Begin Strain Hardening	Stress @ 5% Strain (ksi)	Stress @ 10% Strain (ksi)	Ultimate Stress (ksi)	Strain @ Ultimate Stress	Rupture Stress (ksi)	Elongatio (8" Gage)
1-1	Plate	A36		45.0				65.0			31.0%
1-2	Plate	A36		46.0				65.0			31.0%
2-1	Plate	A36		46.0				65.5			30.0%
2-2	Plate	A36		45.5				65.5			31.0%
3-1	Plate	A36		44.0				67.0			29.0%
3-2	Plate	A36		45.0				68.0			30.0%
5-1	Plate	A36	43831	43.7	0.0149	60.1	67.3	70.0	0.1817	56.3	30.0%
5-2	Plate	A36		43.0				70.0			29.0%
6-1	Plate	A36		43.0				67.0			30.0%
6-2	Plate	A36		44.0				67.0			31.0%
7-1	Plate	A36		45.0				67.0			29.0%
7-2	Plate	A36		45.0				67.0			30.0%
8-1	Plate	A36		45.0				68.0			31.0%
8-2	Plate	A36		45.0				68.0			30.0%
9-1	Plate	A36		45.5				69.0			29.0%
9-2	Plate	A36		46.0				69.0			30.0%
10-1	Plate	A36		51.0				74.0			32.0%
10-2	Plate	A36		51.0				74.0			31.0%
11-1	Plate	A36		52.5				74.5			29.0%
11-2	Plate	A36		54.0				75.0			30.0%
12-1	Plate	A36		51.0				74.5			31.0%
12-2	Plate	A36		52.0				74.5			30.0%
13-1	Plate	A36		47.0				70.0			29.0%
13-2	Plate	A36		46.5				70.0			31.0%
15-1	Plate	A36	21856	42.9	0.0209	52.2	58.2	60.9	0.1995	43.5	32.0%
15-2	Plate	A36	29640	44.2	0.0260	52.0	58.8	61.8	0.2043	53.7	31.0%
16-1	Plate	A36	23876	43.7	0.0274	51.6	57.9	60.7	0.1943	54.8	29.0%
16-2	Plate	A36	22615	43.7	0.0227	52.3	58.6	61.5	0.1954	41.8	29.0%
17-1	Plate	A36	24041	44.1	0.0195	52.8	59.3	62.0	0.1911	55.5	29.0%
17-2	Plate	A36	26000	43.6	0.0201	53.0	59.5	62.0	0.1963	54.7	32.0%

Table B-2 Summary of Tensile Data For Mild Steel Coupons

Coupon Designation	Shape	Nominal Steel Grade	Elastic Modulus (ksi)	Yield Stress .2% Offset (ksi)	Begin Strain Hardening	Stress @ 5% Strain (ksi)	Stress @ 10% Strain (ksi)	Ultimate Stress (ksi)	Strain @ Ultimate Stress	Rupture Stress (ksi)	Elongatio (8" Gage)
18-1	Plate	A36	23762	47.9	0.0245	57.0	64.3	66.9	0.1739	60.8	29.0%
18-2	Plate	A36	27960	47.1	0.0256	56.3	63.3	66.5	0.1900	57.9	29.0%
19-1	Plate	A36		47.1	0.0260	56.5	64.1	66.8	0.1803	59.0	29.0%
19-2	Plate	A36	25961	46.6	0.0240	56.2	63.4	66.4	0.1984	57.5	29.0%
20-1	Plate	A36	17699	45.7	0.0256	55.9	63.5	66.4	0.2309	60.0	28.0%
20-2	Plate	A36		46.4	0.0274	55.2	62.9	65.9	0.1727	59.7	31.0%
21-1	Plate	A36		43.7				63.7			29.0%
21-2	Plate	A36	33544	43.1	0.0202	53.9	60.9	63.6	0.2083	43.4	29.0%
22-1	Plate	A36		44.3	0.0217	54.7	61.6	63.8	0.1839	47.8	30.0%
22-2	Plate	A36	33411	42.6	0.0180	54.7	61.3	63.9	0.1742	56.5	29.0%
23-1	Plate	A36	31707	44.2	0.0202	54.9	61.4	63.8	0.1724	52.4	29.0%
23-2	Plate	A36	33568	43.8	0.0207	54.6	61.2	63.8	0.1842	56.6	29.0%
24-1	Plate	A36	35093	42.9	0.0192	54.5	61.3	63.7	0.1788	56.1	29.0%
24-2	Plate	A36	31517	43.8	0.0225	54.0	61.1	63.6	0.1693	53.6	29.0%
25-1	Plate	A36		43.3	0.0140	56.2	61.8	63.7	0.2301	54.9	30.0%
25-2	Plate	A36	31879	44.0	0.0214	54.3	61.0	63.7	0.2041	54.1	30.0%
26-1	Plate	A36	32023	43.2	0.0251	53.4	61.7	64.3	0.1805	51.9	31.0%
26-2	Plate	A36	34543	44.3	0.0223	54.5	61.5	64.6	0.2015	51.0	30.0%
27-1	Plate	A36	35496	44.9	0.0179	59.0	66.2	68.4	0.1773	53.3	30.0%
27-2	Plate	A36		44.8	0.0183	58.0	65.4	67.8	0.1567	52.5	29.0%
27a-1	Plate	A36	32638	45.0	0.0192	58.3	65.9	68.5	0.1863	52.6	30.0%
27a-2	Plate	A36	39317	45.7	0.0177	58.5	66.1	68.3	0.1703	52.5	29.0%
28-1	Plate	A36		44.7	0.0158	60.9	66.4	68.9	0.1710	54.8	29.0%
28-2	Plate	A36	27482	44.9	0.0165	59.0	66.6	69.2	0.1710	54.7	31.0%
29-1	Plate	A36	27678	44.6	0.0148	59.8	66.6	68.7	0.1908	54.0	29.0%
29-2	Plate	A36		44.5				68.9			30.0%
30-1	Plate	A36	29899	40.1	0.0152	55.8	63.5	66.3	0.1802	51.7	30.0%
30-2	Plate	A36	31217	40.6	0.0147	56.9	62.7	66.4	0.2301	59.1	32.0%
31-1	Plate	A36		41.8				67.9			32.0%
31-2	Plate	A36	39591	42.5	0.0137	58.7	65.8	67.7	0.1934		31.0%

Table B-2 Summary of Tensile Data For Mild Steel Coupons

Coupon Designation	Shape	Nominal Steel Grade	Elastic Modulus (ksi)	Yield Stress .2% Offset (ksi)	Begin Strain Hardening	Stress @ 5% Strain (ksi)	Stress @ 10% Strain (ksi)	Ultimate Stress (ksi)	Strain @ Ultimate Stress	Rupture Stress (ksi)	Elongatio (8" Gage)
32-1	Plate	A36	30779	41.3	0.0233	52.4	63.7	67.4	0.1890	51.4	30.0%
32-2	Plate	A36	35682	42.3	0.0283	52.1	59.7	67.7	0.2387	51.7	31.0%
33-1	Plate	A36	26346	52.9	0.0169	65.2	71.8	73.8	0.1777	59.0	28.0%
33-2	Plate	A36	28708	53.7	0.0255	64.0	71.6	74.1	0.1777	62.2	28.0%
34-1	Plate	A36	30385	51.5	0.0232	62.6	70.7	73.3	0.1757	58.3	29.0%
34-2	Plate	A36	31554	52.3	0.0239	63.8	71.8	74.4	0.1686		28.0%
35-1	Plate	A36	34993	52.8	0.0243	63.8	71.5	73.8	0.2052	63.4	27.0%
35-2	Plate	A36	30071	52.4	0.0245	62.7	70.6	73.4	0.1998	60.2	28.0%
40-1	Plate	A36		47.9				66.6			31.0%
40-2	Plate	A36		47.9				67.3			30.0%
41-1	Plate	A36		47.6				65.9			31.0%
41-2	Plate	A36		47.9				70.6			31.0%
42-1	Plate	A36		47.1				71.1			30.0%
42-2	Plate	A36		46.5				70.5			29.0%
43-1	Plate	A36		44.2				64.0			31.0%
43-2	Plate	A36		43.2				62.6			31.0%
44-1	Plate	A36		44.2				67.7			30.0%
44-2	Plate	A36		44.7				67.8			31.0%
2WV	WF	A572 Gr. 50	28825	48.9	0.0378	52.7		62.9		55.3	26.0%
2WH	WF	A572 Gr. 50	30249	48.5	0.0301	54.5		62.9		52.3	26.0%
3WH	WF	A572 Gr. 50	26111	45.9	0.0327	48.3		61.9		56.2	29.0%
2BF-1	WF	A572 Gr. 50	29790	45.0	0.0254	52.2		61.6		49.0	28.0%
2BF-2	WF	A572 Gr. 50	24635	44.5	0.0258	51.8		61.4		55.2	25.0%
3BF-1	WF	A572 Gr. 50	25418	41.5	0.0048	50.4		61.2		50.3	28.0%
3BF-2	WF	A572 Gr. 50	23577	43.5	0.0171	48.6		60.6		51.6	27.0%
GWV	WF	A572 Gr. 50	33322	48.7	0.0370	54.1		64.1		56.8	24.0%
GWH	WF	A572 Gr. 50	35496	47.6	0.0308	53.1		64.7		52.2	42.0%
GTF-1	WF	A572 Gr. 50						64.4			32.0%
GTF-2	WF	A572 Gr. 50	20143	46.2	0.0230	54.3		64.4		53.6	26.0%
SA-1	Angle	A36	32314	42.4	0.0185	54.5		65.4		51.9	30.0%

Table B-2 Summary of Tensile Data For Mild Steel Coupons

Coupon Designation	Shape	Nominal Steel Grade	Elastic Modulus (ksi)	Yield Stress .2% Offset (ksi)	Begin Strain Hardening	Stress @ 5% Strain (ksi)	Stress @ 10% Strain (ksi)	Ultimate Stress (ksi)	Strain @ Ultimate Stress	Rupture Stress (ksi)	Elongatio (8" Gage)
SA-2	Angle	A36	43393	42.6	0.0192	54.4	61.9	65.4		53.8	30.0%
PL-1	Plate	A36	36823	48.4	0.0227	59.5	67.4	71.3		59.0	29.0%
PL-2	Plate	A36	30238	49.6	0.0200	60.3	68.2	71.5		63.8	29.0%
50a	Plate	A36	28747	44.8	0.0204	56.7	63.7	67.1		56.7	29.7%
50b	Plate	A36	26655	45.5	0.0228	57.4	64.4	67.8		57.5	30.3%
51a	Plate	A36	27252	44.9	0.0241	55.6	62.7	65.4		58.2	28.4%
51b	Plate	A36	24435	44.1	0.0284	53.5	61.3	65.5		56.9	28.9%
A1a	Angle	A36	29799	49.1	0.0199	62.9	70.8	73.9		64.7	26.9%
A1b	Angle	A36	32177	48.8	0.0193	62.6	70.6	73.1		62.7	26.8%
A2a	Angle	A36	25139	48.8	0.0211	61.2	70.1	73.8		64.7	29.5%
A2b	Angle	A36	32000	49.2	0.0164	64.5	72.1	74.4		63.4	28.3%

Table B-3 Summary Statistics For #4 Grade 60 Reinforcing Steel Coupons

	Elastic Modulus (ksi)	Yield Stress .2% Offset (ksi)	Begin Strain Hardening (in./in.)	Stress @ 3% Strain (ksi)	% of Fu	% of Fu - Fy	Stress @ 7% Strain (ksi)	% of Fu	% of Fu - Fy	Ultimate Stress (ksi)	Strain Ultimat Stress (in./in.)	Rupture Stress (ksi)	% of Fu	% of Fu - Fy	% Elongation (2" Gage)	Fu/Fy
No. Data	24	25	24	24	24	24	20	20	20	25	20	24	24	24	21	25
Mean	32451	70.5	0.0074	95.3	83.2%	56.1%	111.1	97.6%	93.8%	114.6	0.1010	96.0	83.7%	57.6%	16.7%	1.63
COV	17.5%	2.7%	20.4%	2.6%	1.2%	5.3%	1.2%	0.6%	1.6%	1.9%	6.0%	6.8%	5.8%	21.6%	10.8%	2.5%

Table B-4 Summary of Tensile Data For #4 Reinforcing Steel Coupons

Designation	Elastic Modulus (ksi)	Yield Stress 0.2% Offset (ksi)	Begin Strain Hardening (in./in.)	Stress @ 3% Strain (ksi)	Stress @ 5% Strain (ksi)	Stress @ 7% Strain (ksi)	Stress @ 10% Strain (ksi)	Ultimate Stress (ksi)	Strain @ Ultimate Stress (in./in.)	Rupture Stress (ksi)	% Elongation (2" Gage)
1-1&2a	40,471	69.9	0.0062	96.0	107.6	112.4	114.8	115.1	0.1026	91.5	17.8%
1-3&4a	29,178	71.5	0.0093	93.8	105.1	110.2	112.9	113.1	0.1061	93.5	16.2%
1-3&4b	29,599	71.2	0.0095	93.9	104.6	109.6	112.2	112.6	0.1017	92.3	16.1%
1-3&4c	24,604	72.4	0.0102	92.9	104.2	109.9	112.4	112.8	0.0925	92.1	15.2%
2-1&2a	38,360	70.3	0.0059	95.7	107.6	112.8	115.2	114.7	0.1061	93.9	17.6%
2-1&2b	31,176	69.9	0.0063	95.9	106.5	112.3	114.5	114.9	0.0959	92.7	16.2%
2-1&2c	31,574	69.9	0.0076	93.9	105.3	111.9	114.4	115.3	0.1006	90.1	17.5%
2-3&4a	41,161	68.3	0.0044	97.6	107.5	113.1	115.3	115.2	0.1020	92.4	18.8%
3-1&2a	31,481	72.0	0.0089	94.0	105.2	110.3	113.5	114.2	0.1093	90.6	17.3%
3-1&2b	35,942	72.8	0.0086	93.9	104.6	110.7	113.3	113.3	0.1067	95.1	16.8%
3-1&2c	26,924	71.9	0.0091	94.7	105.2	110.3	113.7	113.6	0.1027	94.0	16.8%
3-3&4a	30,475	68.8	0.0091	92.3	103.0	109.0	108.4	110.3	0.0829	102.4	10.9%
3-3&4b	34,257	70.4	0.0082	93.2	104.0	108.9	111.4	111.4	0.0987	98.5	13.5%
3-3&4c	30,196	71.1	0.0073	95.2	105.9	110.8	113.3	113.2	0.1055	91.8	17.4%
4-1&2a	30,609	69.6	0.0061	94.8	106.4	111.6	114.3	114.9	0.0978	91.4	16.2%
4-3&4a	44,127	68.5	0.0053	95.1	106.4	112.5	114.6	114.1	0.0964	93.5	16.8%
4-3&4b	44,729	67.5	0.0060	93.0	104.4	110.7	113.3	113.6	0.1000	91.1	17.6%
4-3&4c	34,664	69.9	0.0068	94.9	106.2	112.6	114.9	115.0	0.1006	95.5	16.8%
5-1&2a	32,273	68.3	0.0076	93.2	105.2	109.9	113.2	113.1	0.1084	95.0	18.4%
5-3&4a		67.6						114.1			19.1%
6-3&4a	*28,511*	*68.3*	*0.0072*	*94.1*	*105.3*	*112.3*	*114.8*	*115.3*	*0.1028*	*90.7*	*17.1%*
R-01	27,929	72.5	0.0063	100.6	112.9			116.7		104.7641	
R-02	25,817	73.8	0.0085	99.8	111.8			118.8		107.9186	
R-03	28,773	73.6	0.0067	99.4	111.3			119.4		114.461	
R-04	25,989	73	0.0063	100	113			120		107.6264	

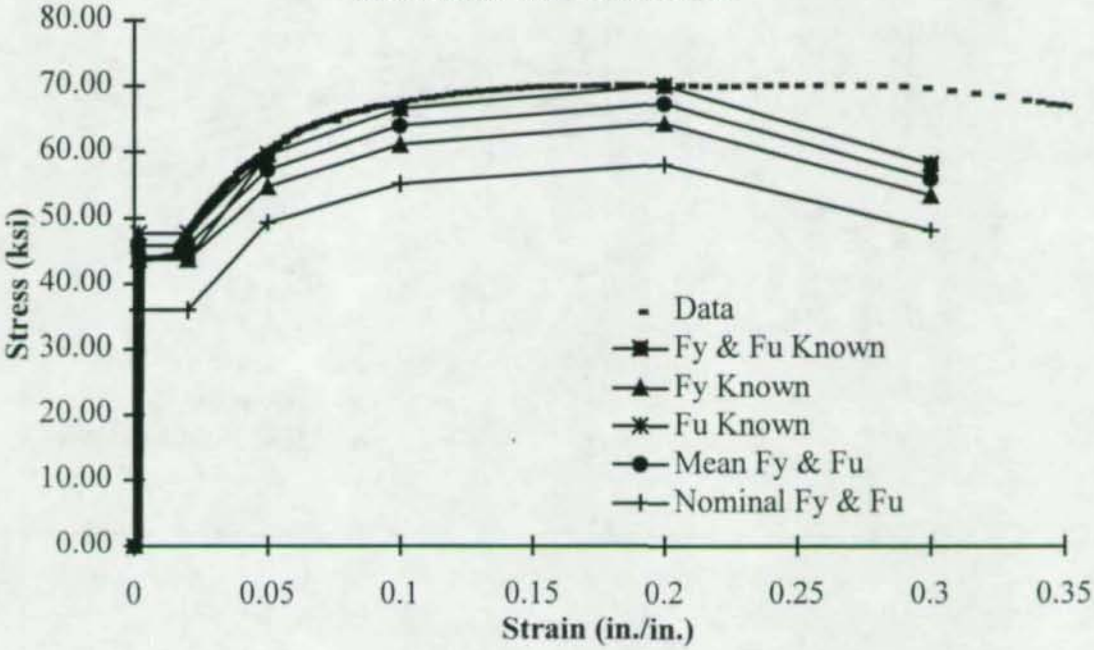
Appendix C

Tensile Tests Conducted At Virginia Tech
Reporting Full Stress-Strain Data
Mild Steel

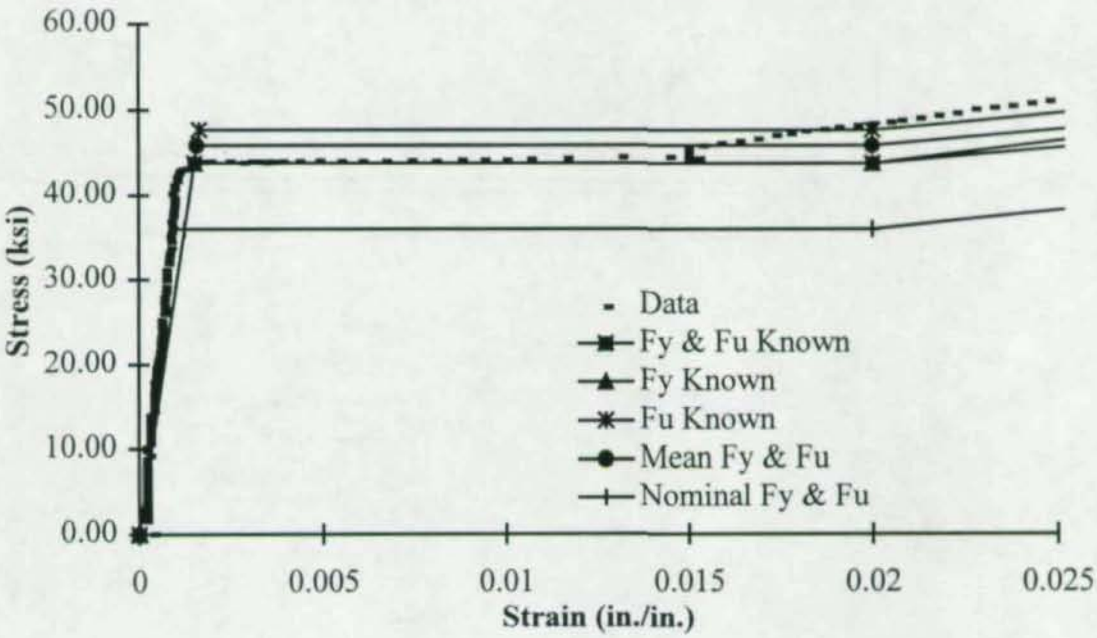
Table C-1
Mild Steel Coupon Dimensions

Coupon Designation	Average Width (in.)	Average Thickness (in.)	Area (in.^2)	Initial Gage (in.)
5-1	1.499	0.993	1.489	8
15-1	*1.497*	*0.121*	*0.181*	8
15-2	1.497	0.120	0.180	8
16-1	1.498	0.121	0.181	8
16-2	1.498	0.120	0.179	8
17-1	1.498	0.120	0.180	8
17-2	1.497	0.120	0.180	8
18-1	*1.500*	*0.249*	*0.374*	8
18-2	1.497	0.248	0.371	8
19-1	1.501	0.246	0.370	8
19-2	1.499	0.249	0.374	8
20-1	1.497	0.248	0.372	8
20-2	1.498	0.250	0.375	8
21-1	*1.498*	*0.367*	*0.550*	8
21-2	1.499	0.370	0.555	8
22-1	1.500	0.367	0.550	8
22-2	1.498	0.370	0.554	8
23-1	1.501	0.368	0.552	8
23-2	1.499	0.370	0.555	8
24-1	*1.501*	*0.369*	*0.554*	8
24-2	1.501	0.367	0.550	8
25-1	1.501	0.371	0.557	8
25-2	1.501	0.368	0.552	8
26-1	1.498	0.500	0.749	8
26-2	1.499	0.500	0.749	8
27-1	*1.500*	*0.625*	*0.937*	8
27-2	1.500	0.623	0.934	8
27a-1	1.500	0.627	0.940	8
27a-2	1.499	0.624	0.935	8
28-1	1.501	0.750	1.125	8
28-2	1.500	0.749	1.124	8
29-1	*1.500*	*0.750*	*1.125*	8
29-2	1.500	0.749	1.124	8
30-1	1.500	0.997	1.496	8
30-2	1.501	0.999	1.499	8
31-1	1.500	1.000	1.500	8
31-2	1.500	1.001	1.502	8
32-1	*1.500*	*1.001*	*1.502*	8
32-2	1.501	1.000	1.501	8
33-1	1.499	0.491	0.736	8
33-2	1.499	0.491	0.736	8
34-1	1.499	0.493	0.740	8
34-2	1.501	0.494	0.741	8
35-1	*1.500*	*0.486*	*0.729*	8
35-2	1.502	0.486	0.729	8

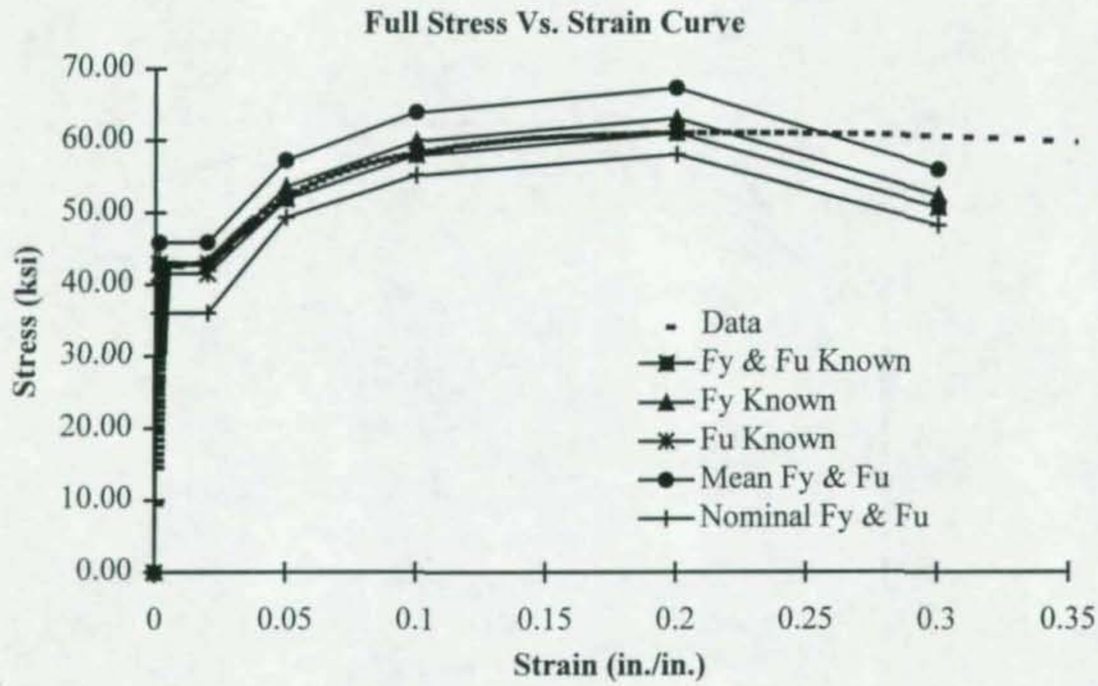
Full Stress Vs. Strain Curve

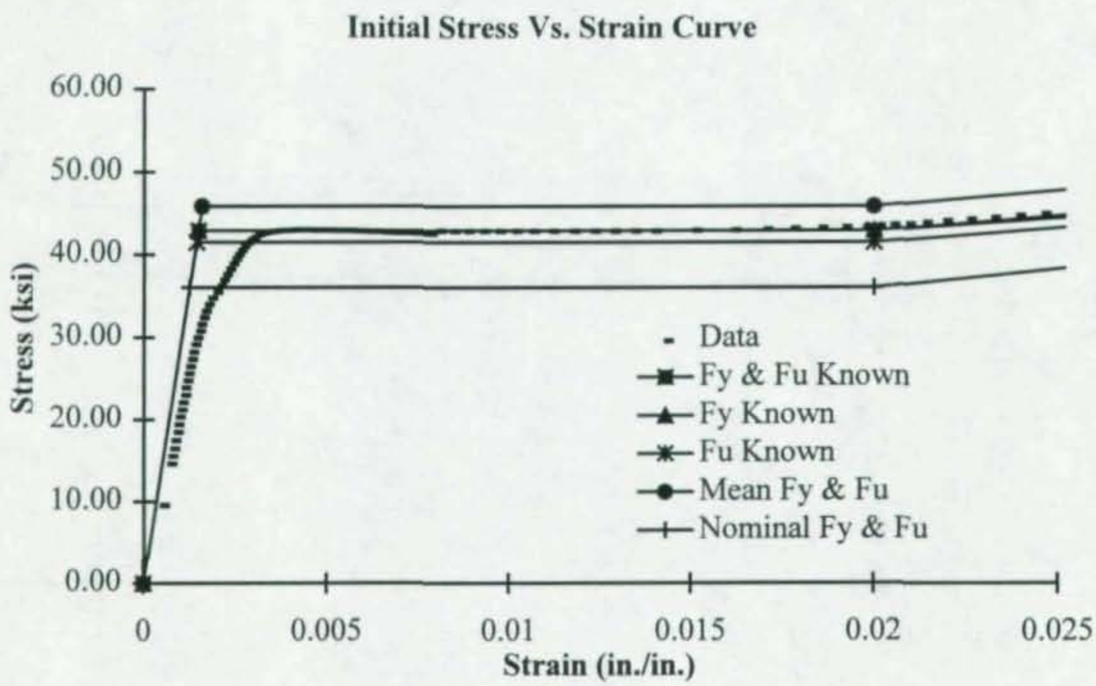


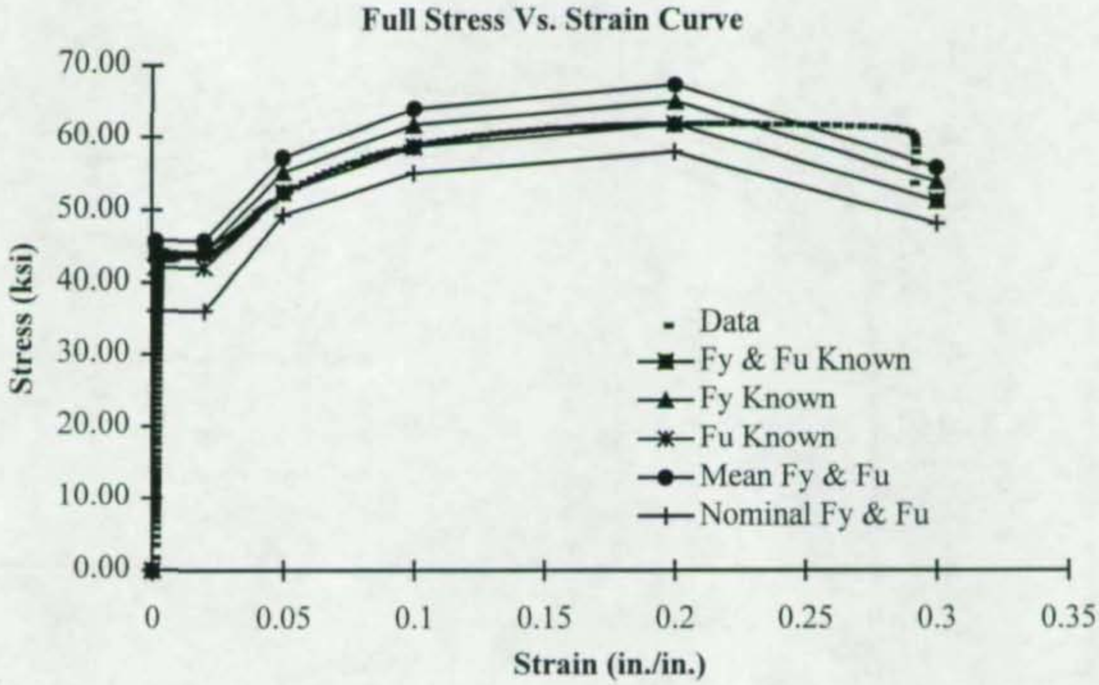
Initial Stress Vs. Strain Curve

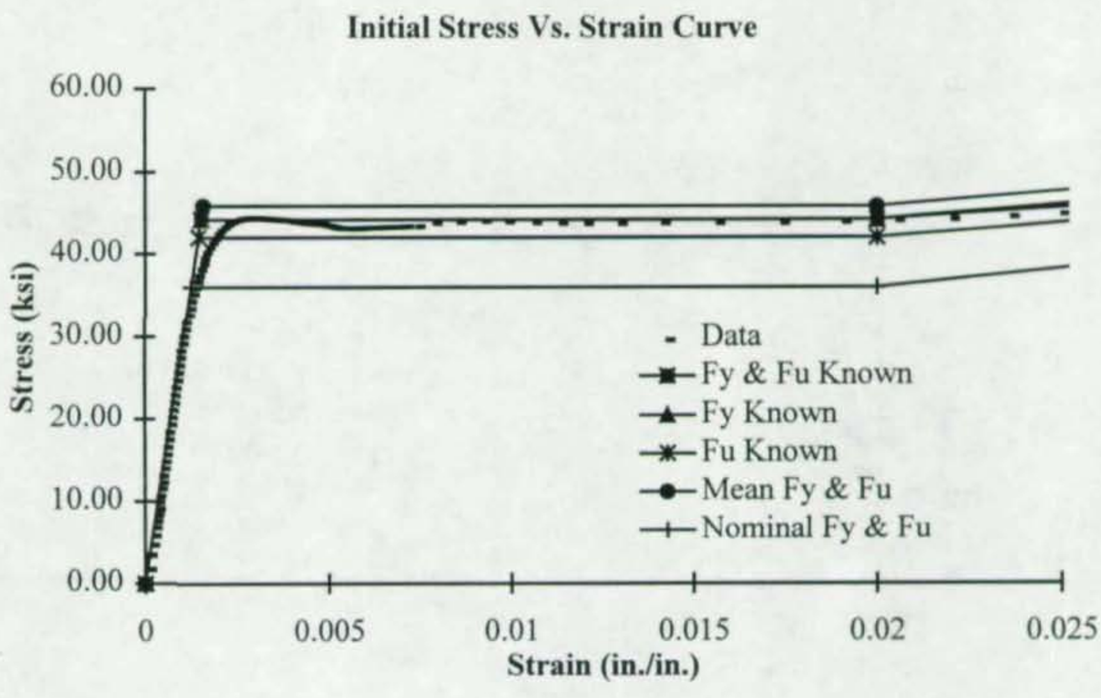


Mild Steel Stress-Strain Plots **Tensile Test: 15-1**

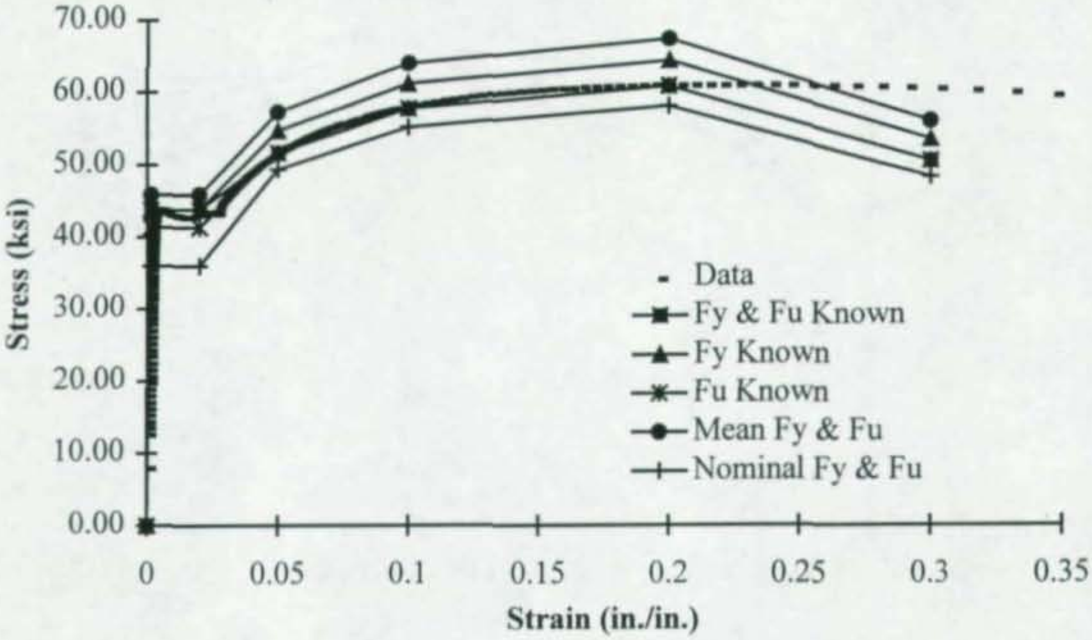




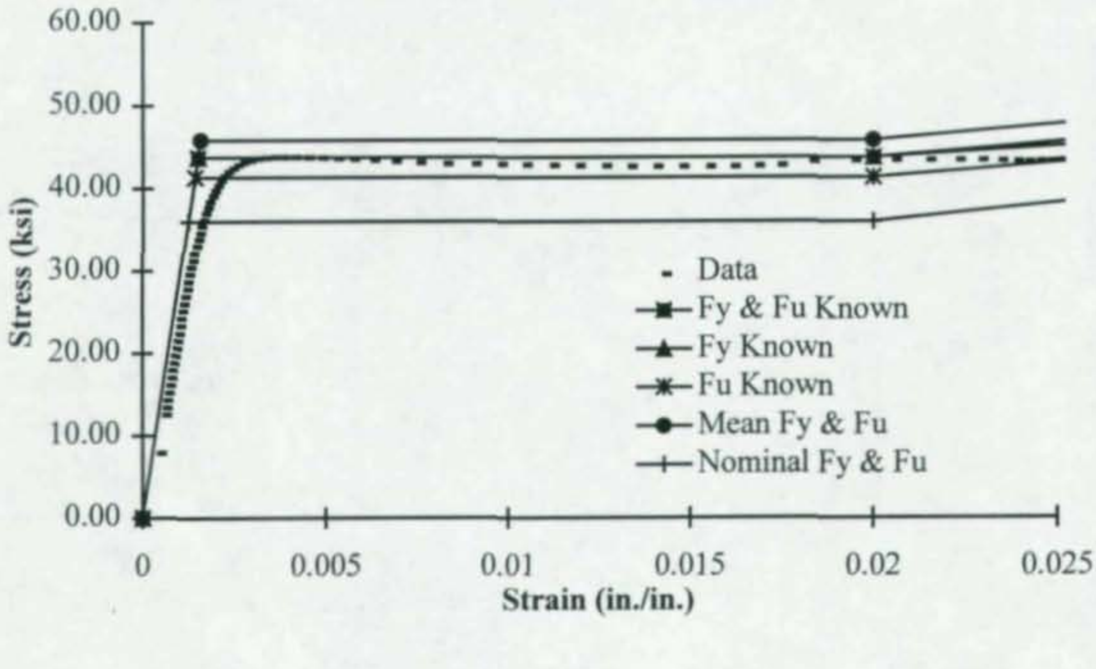

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

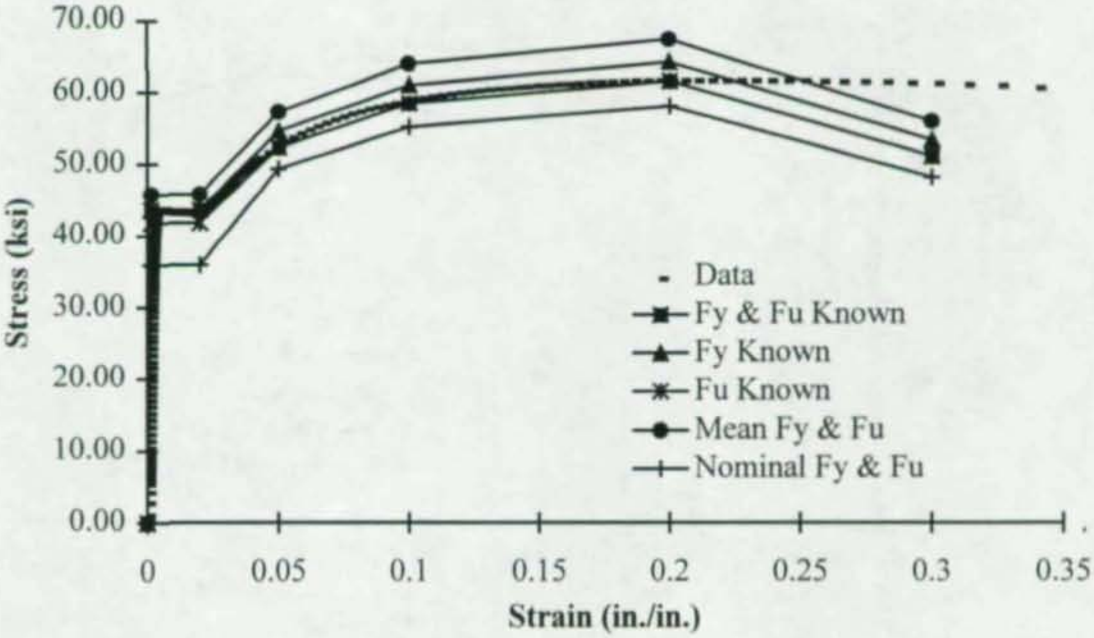
Full Stress Vs. Strain Curve



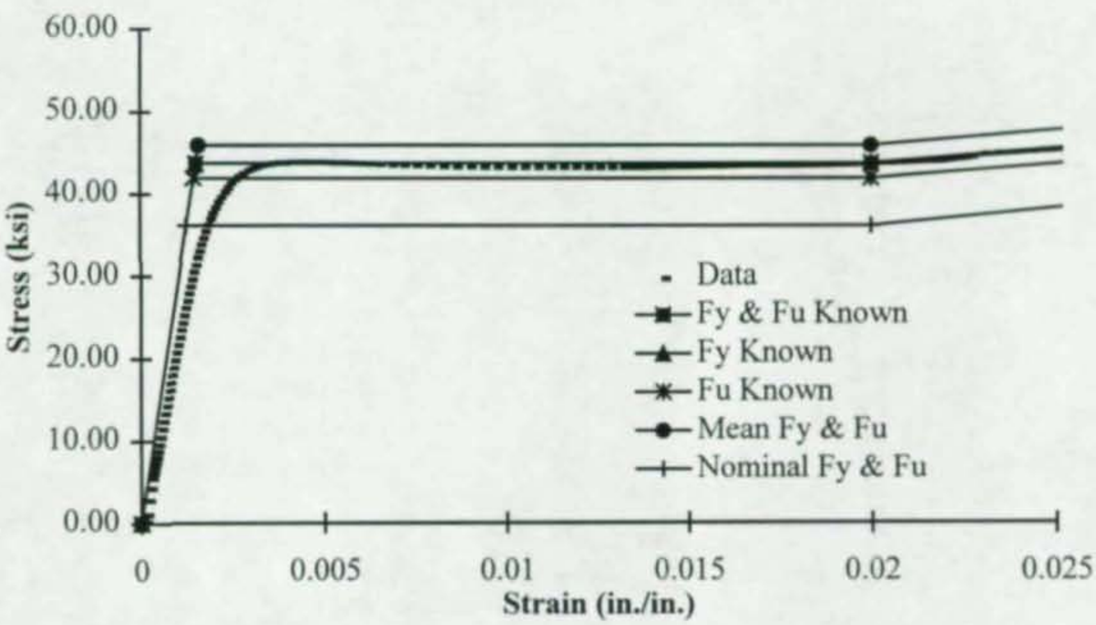
Initial Stress Vs. Strain Curve

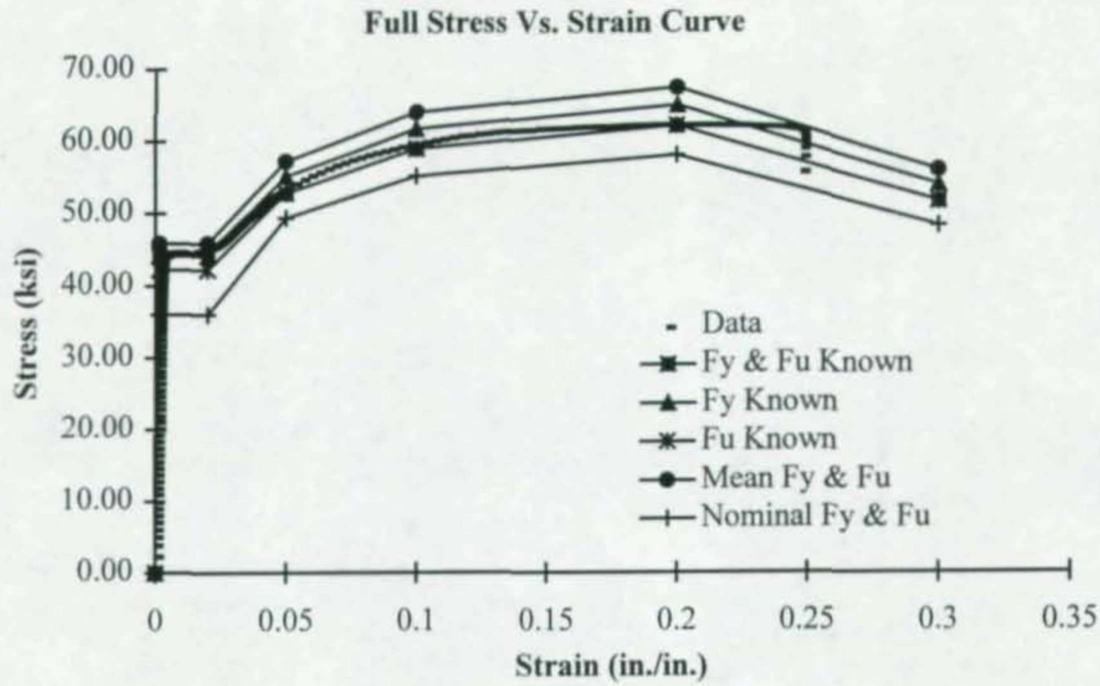


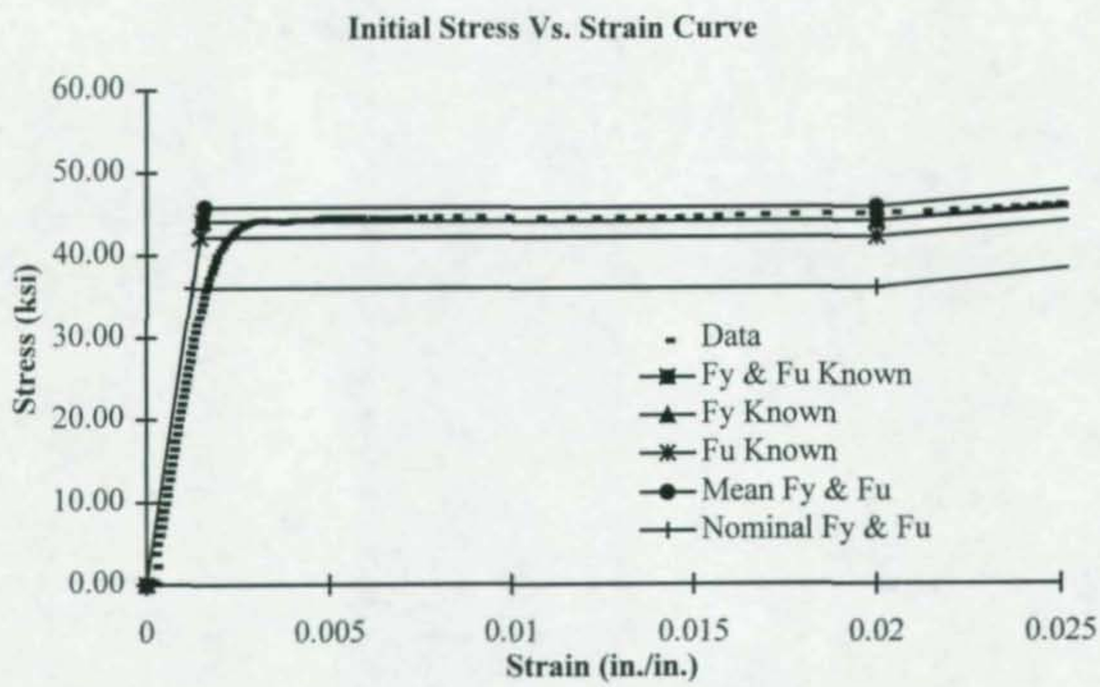
Full Stress Vs. Strain Curve



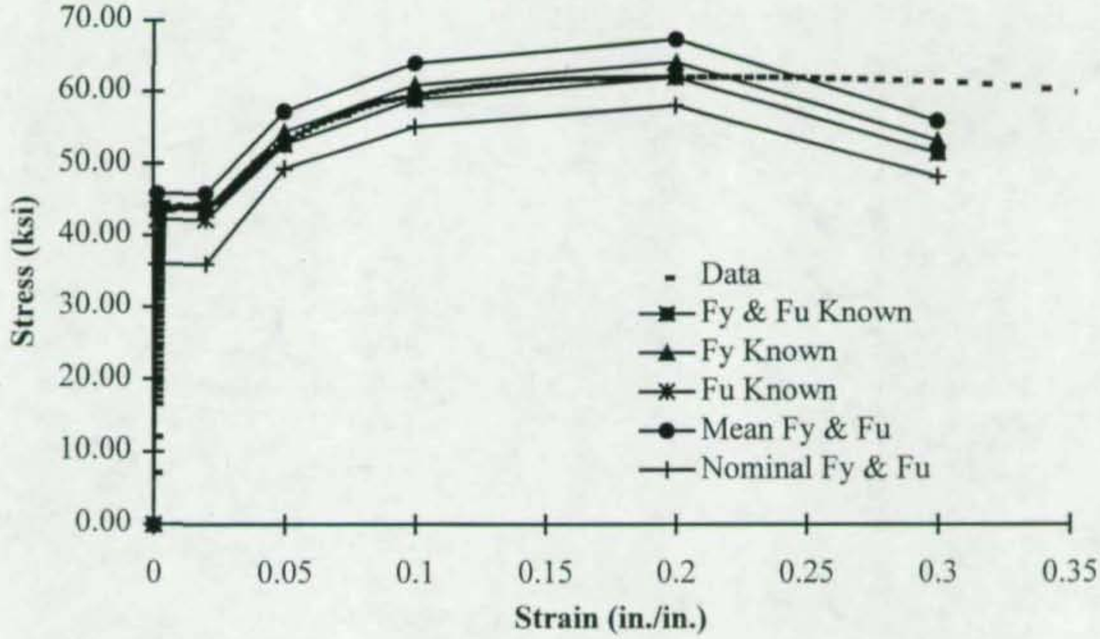
Initial Stress Vs. Strain Curve



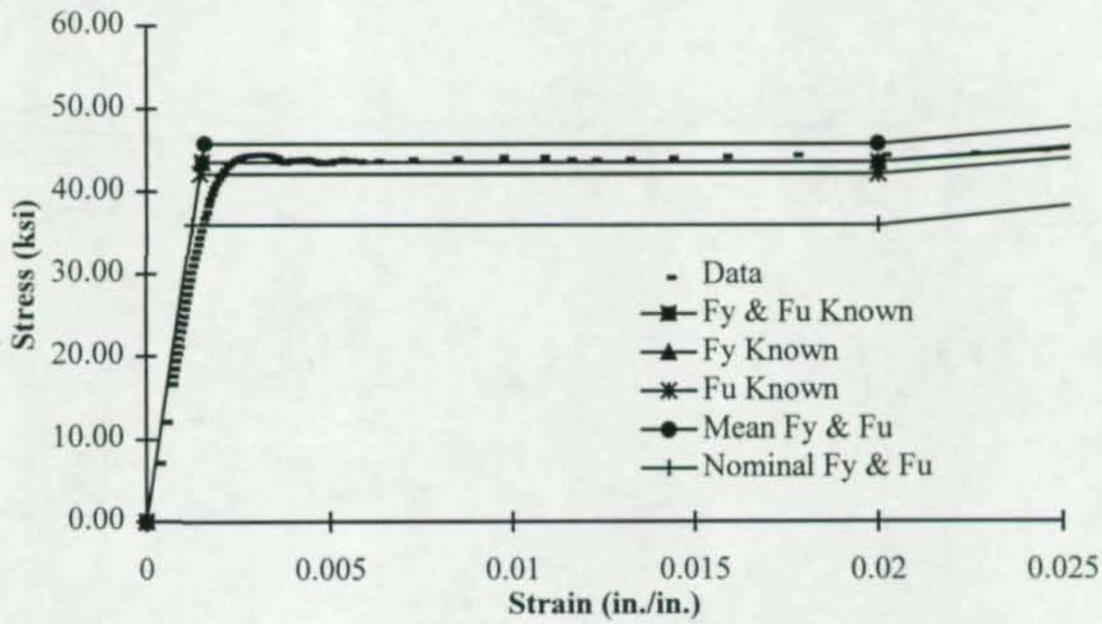

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

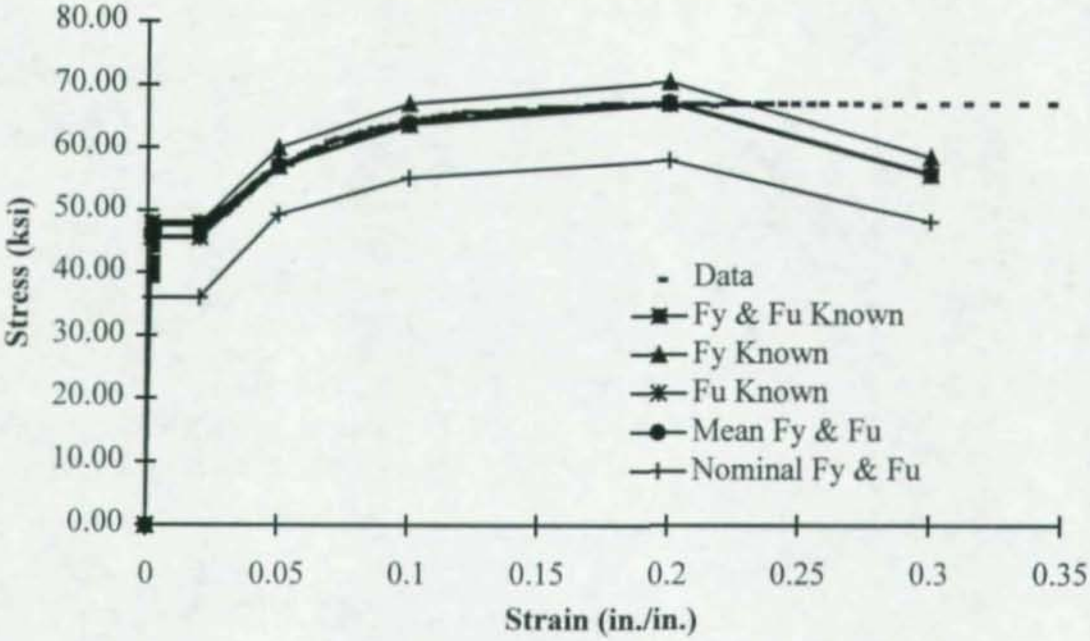
Full Stress Vs. Strain Curve



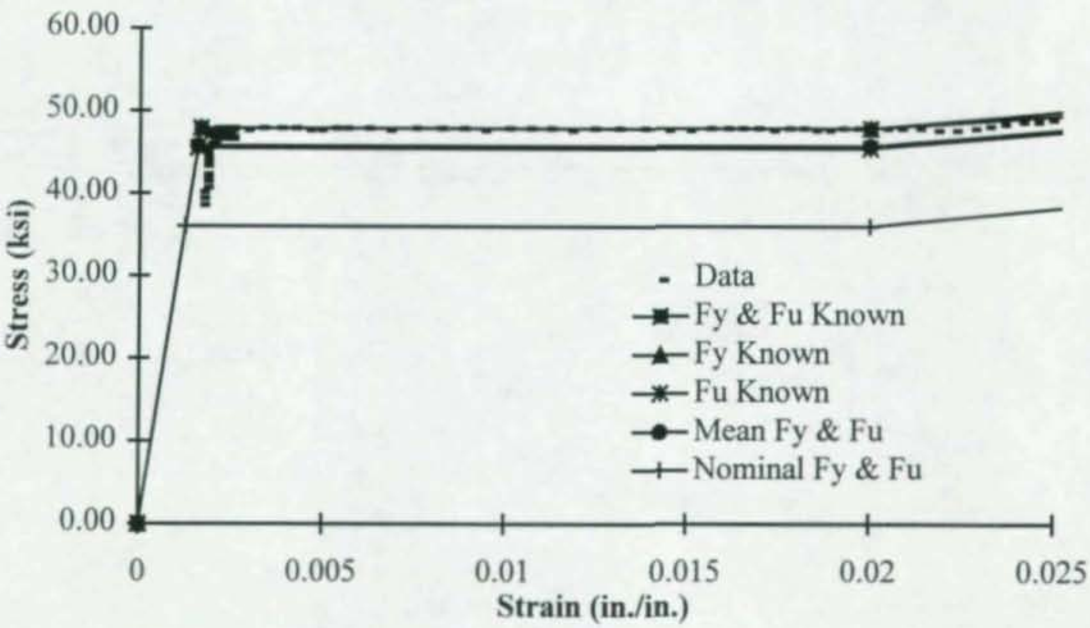
Initial Stress Vs. Strain Curve



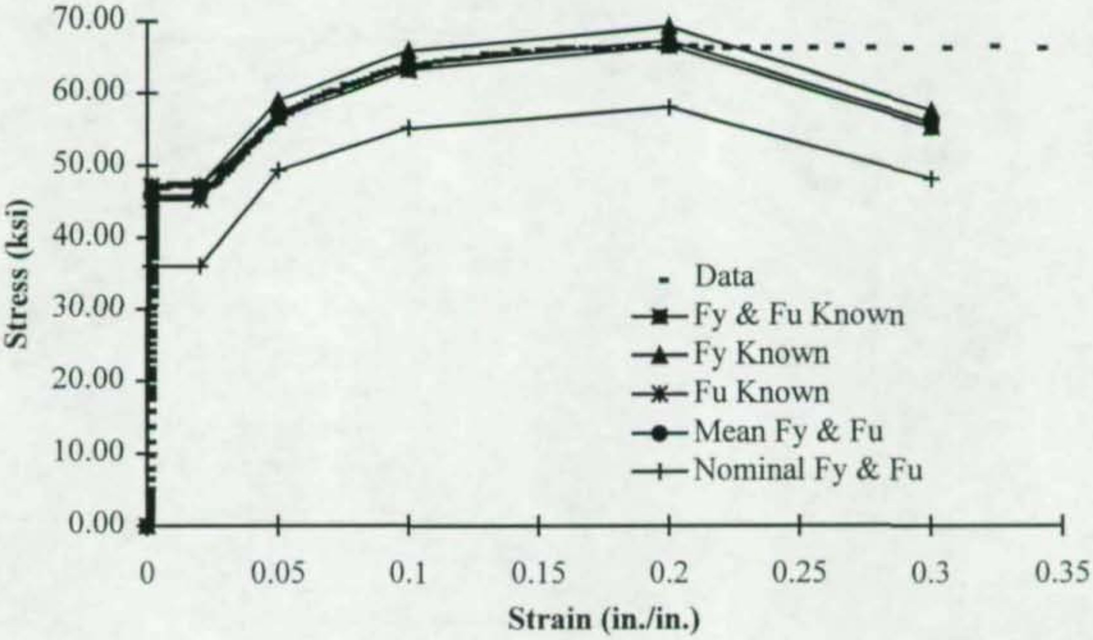
Full Stress Vs. Strain Curve



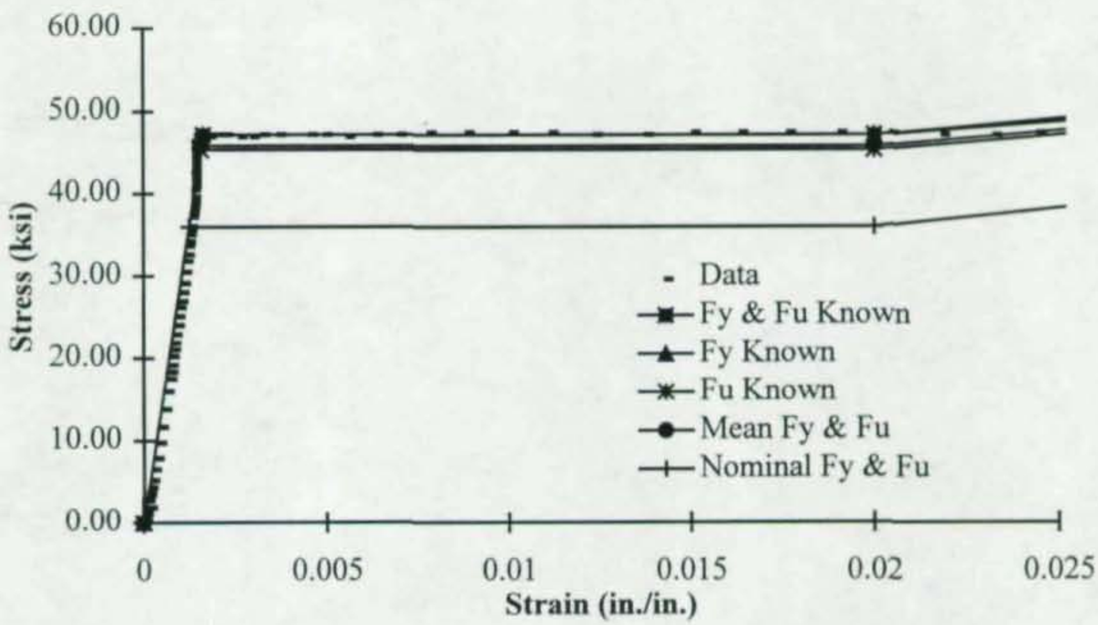
Initial Stress Vs. Strain Curve

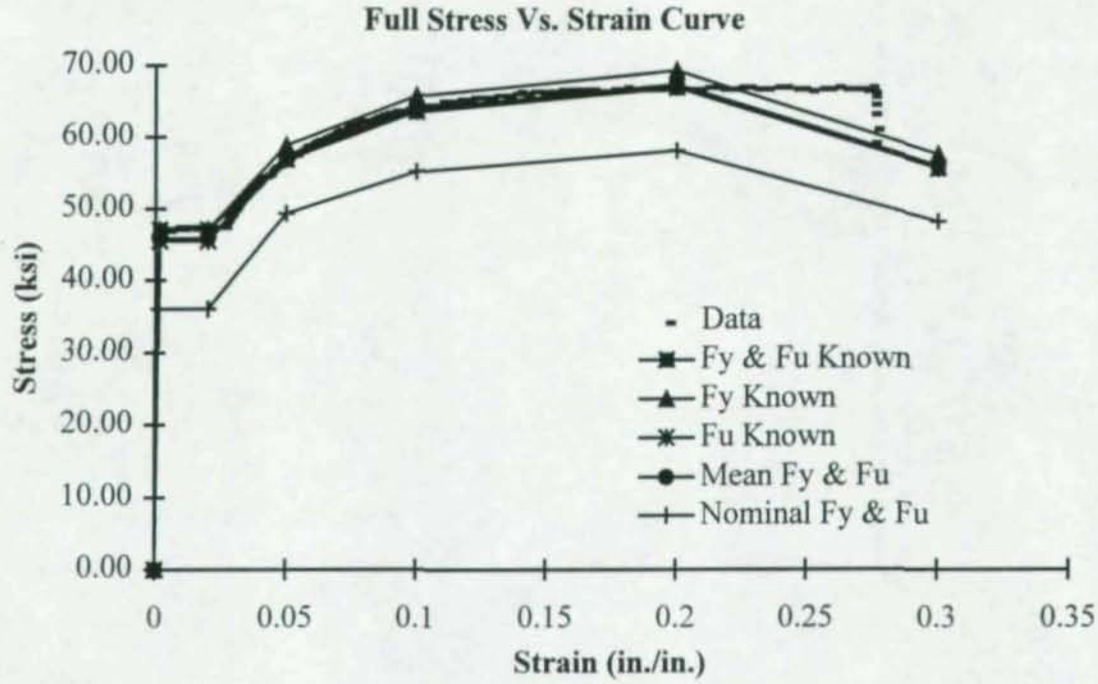


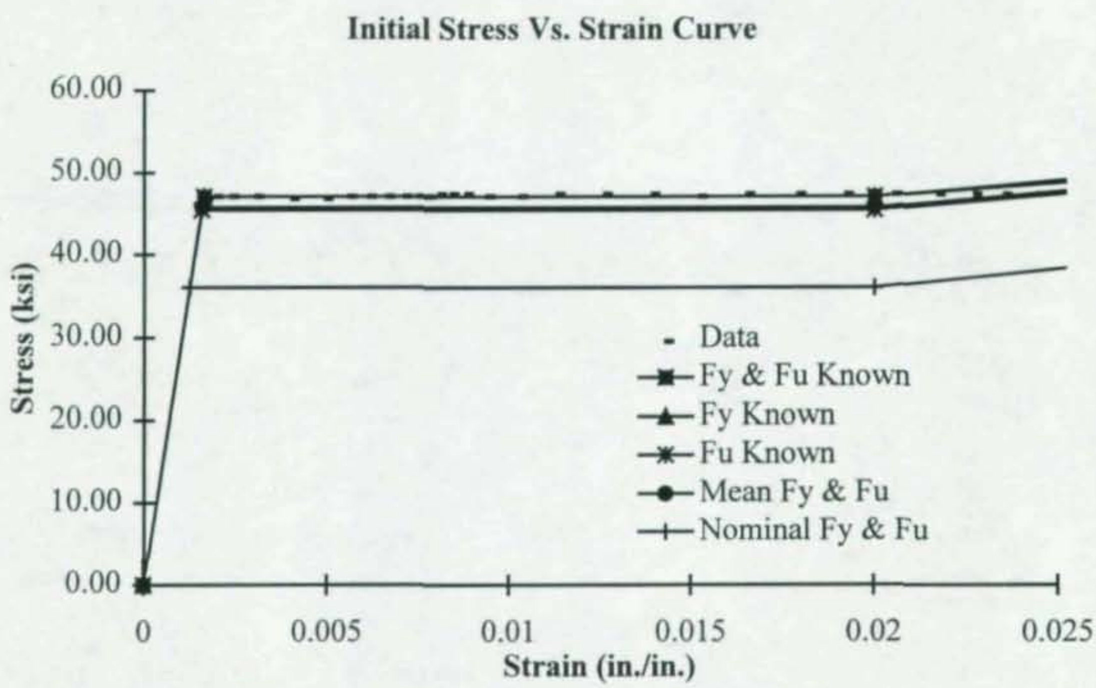
Full Stress Vs. Strain Curve



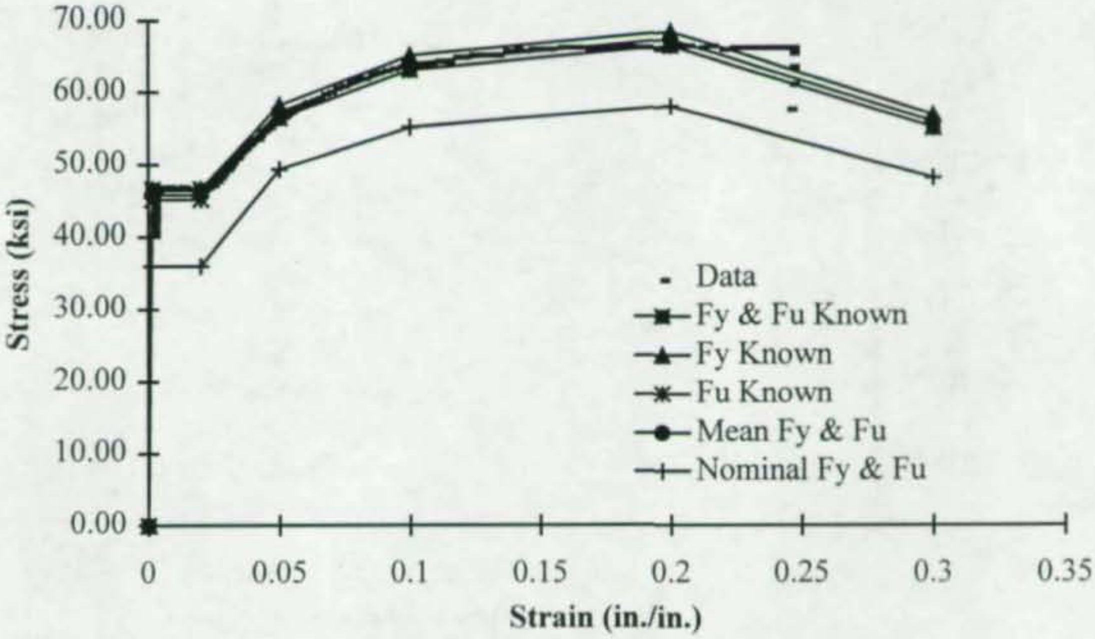
Initial Stress Vs. Strain Curve



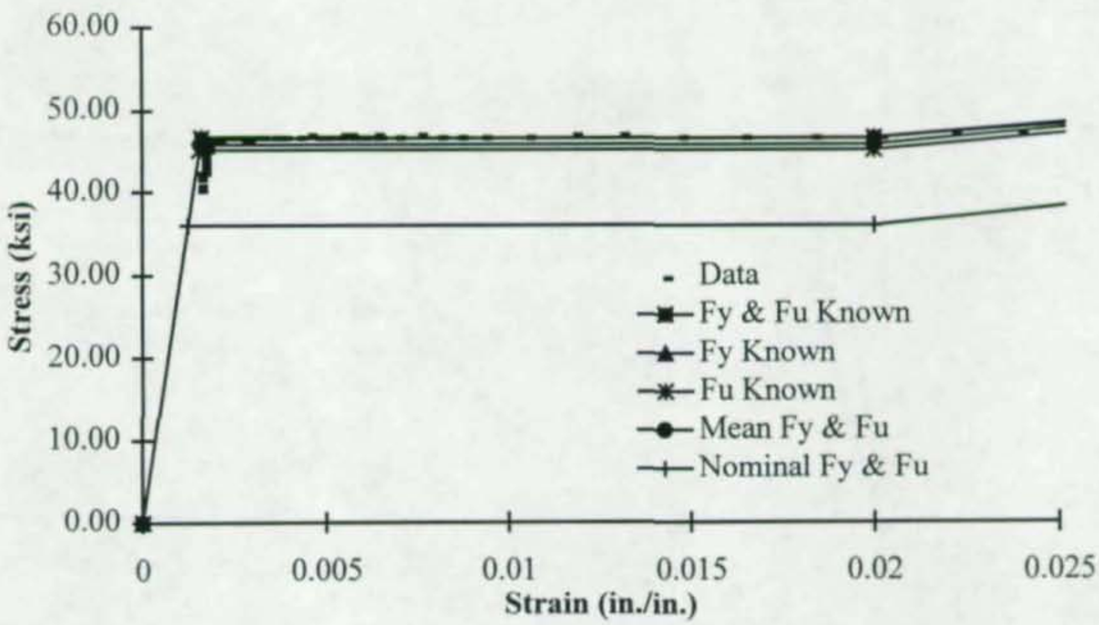

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

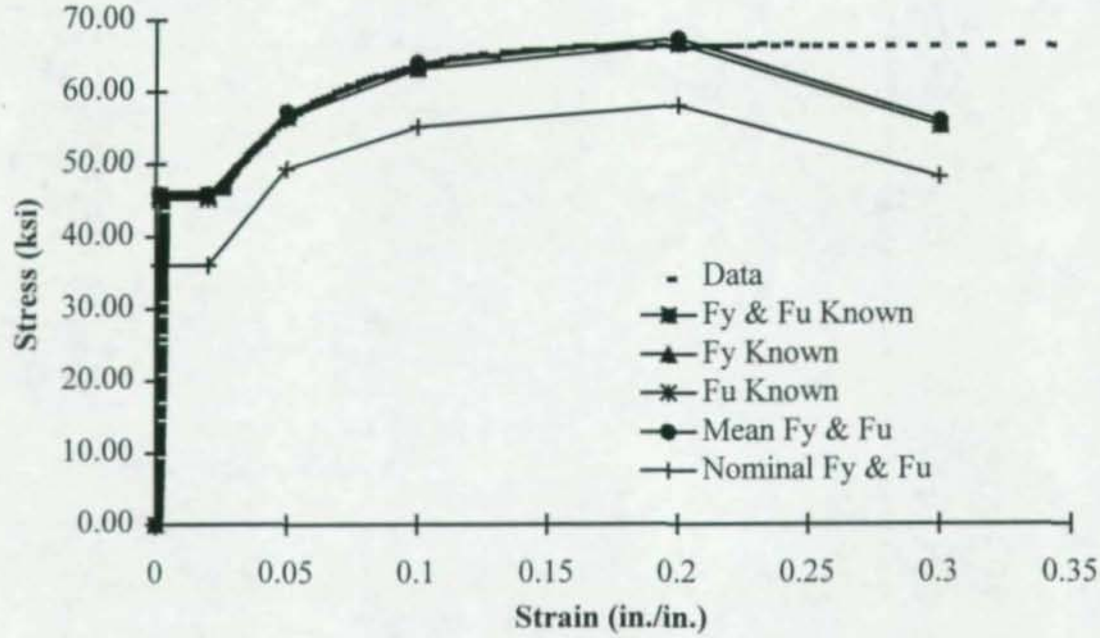
Full Stress Vs. Strain Curve



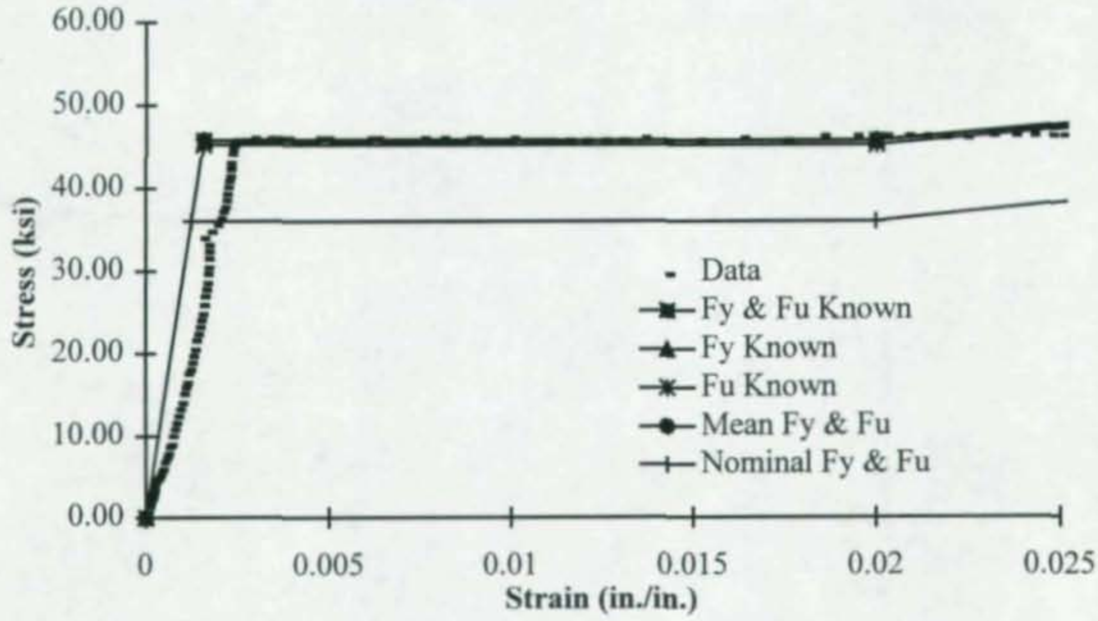
Initial Stress Vs. Strain Curve



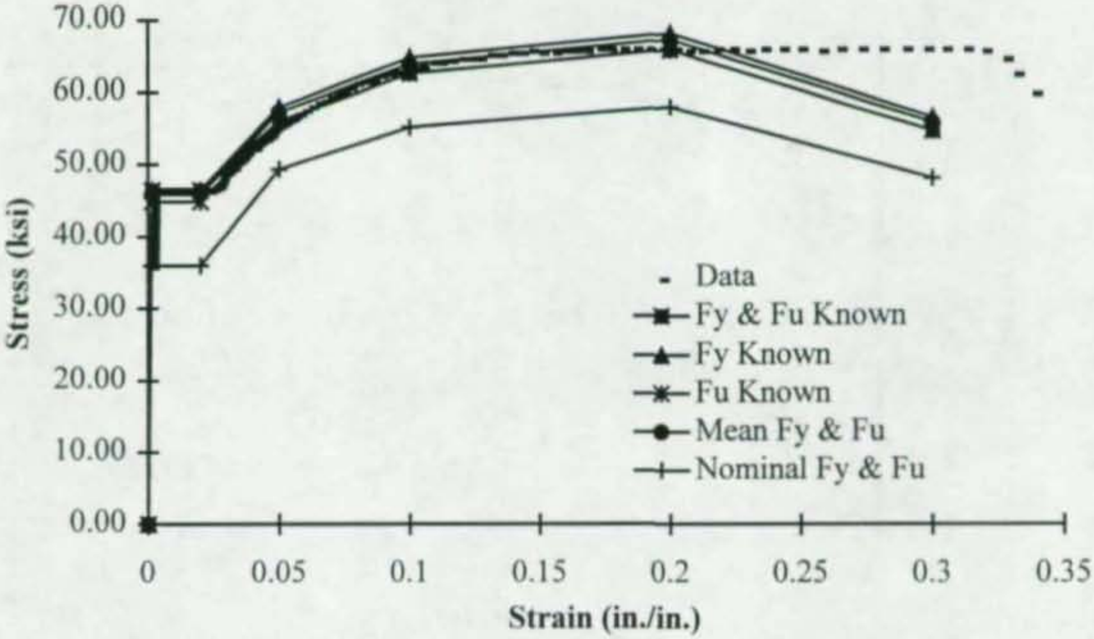
Full Stress Vs. Strain Curve



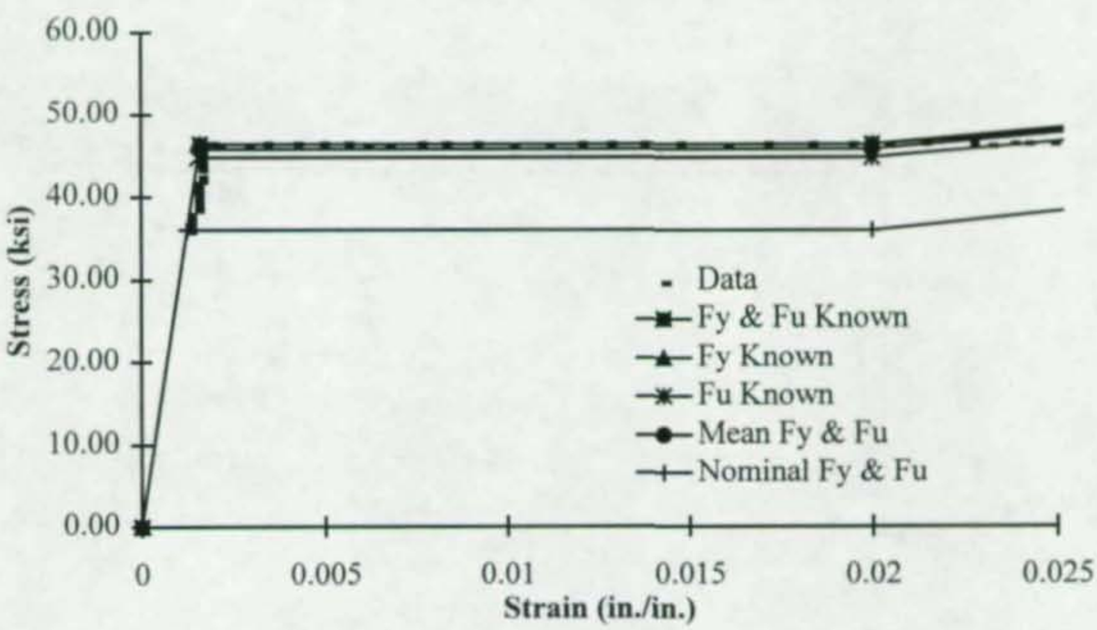
Initial Stress Vs. Strain Curve



Full Stress Vs. Strain Curve

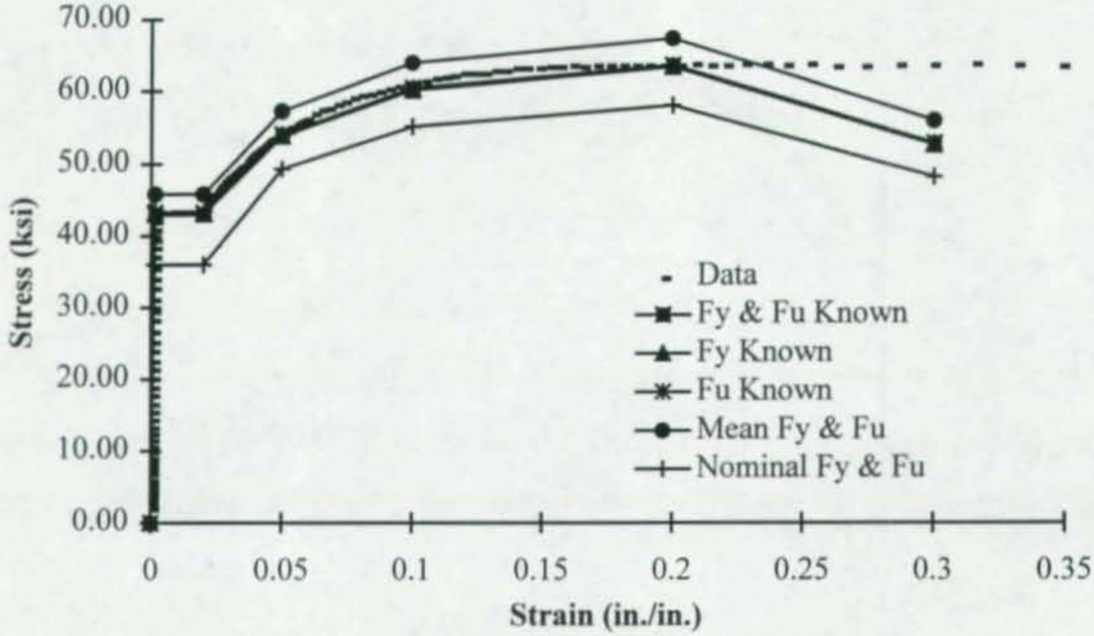


Initial Stress Vs. Strain Curve

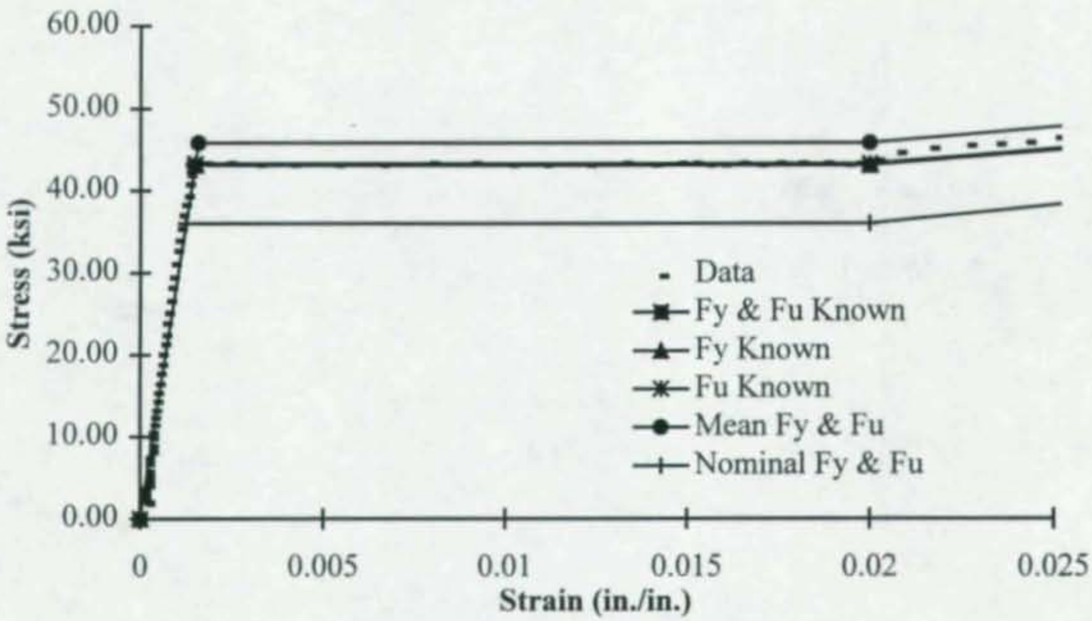


Mild Steel Stress-Strain Plots **Tensile Test: 21-2**

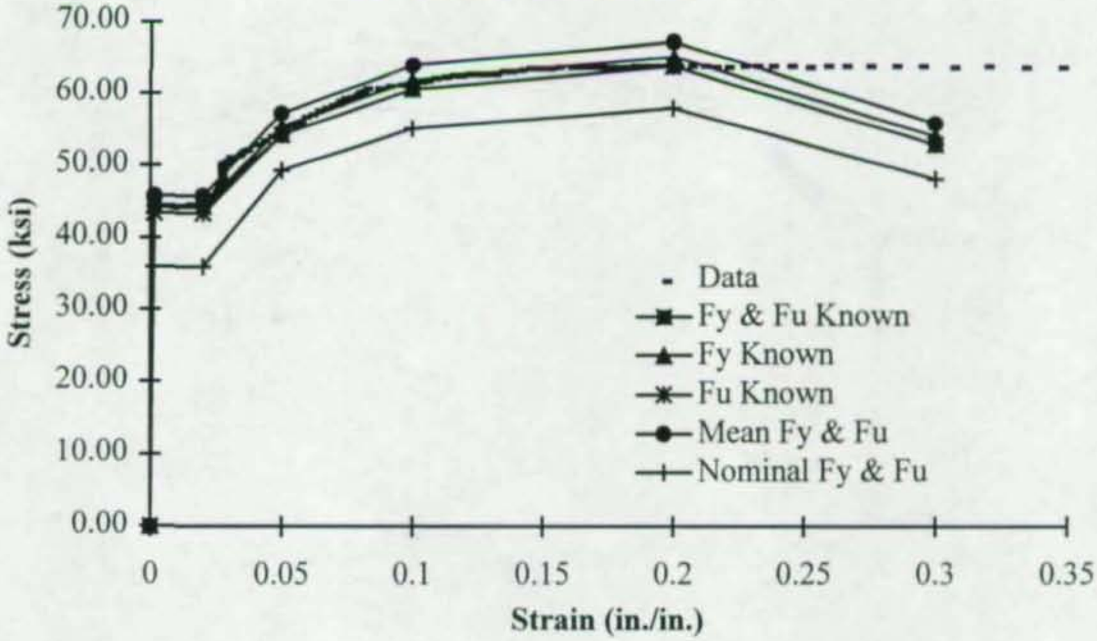
Full Stress Vs. Strain Curve



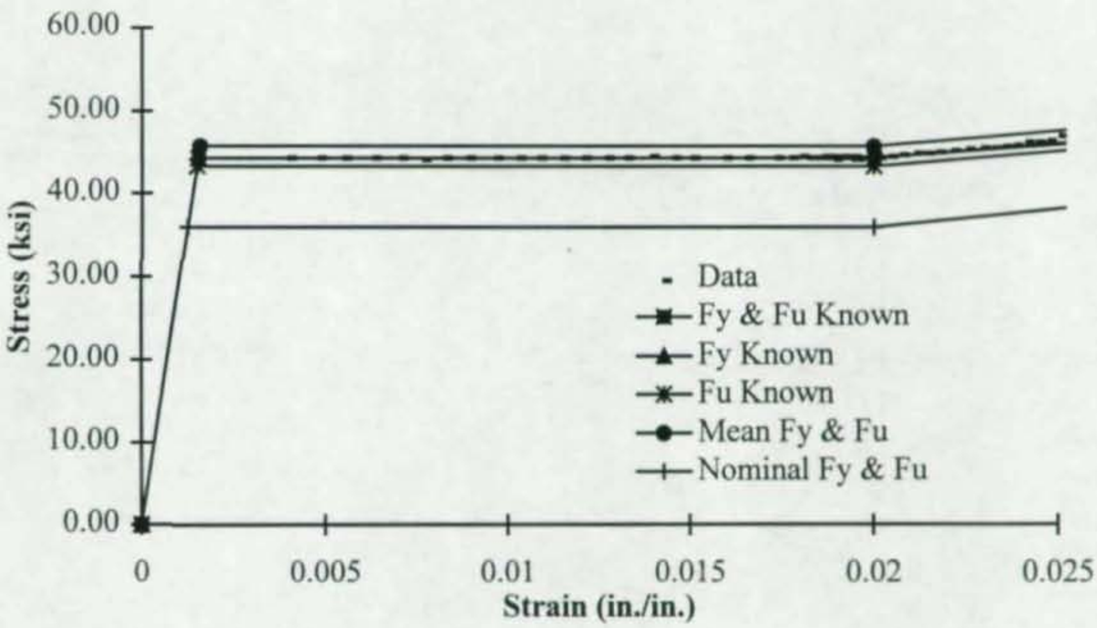
Initial Stress Vs. Strain Curve

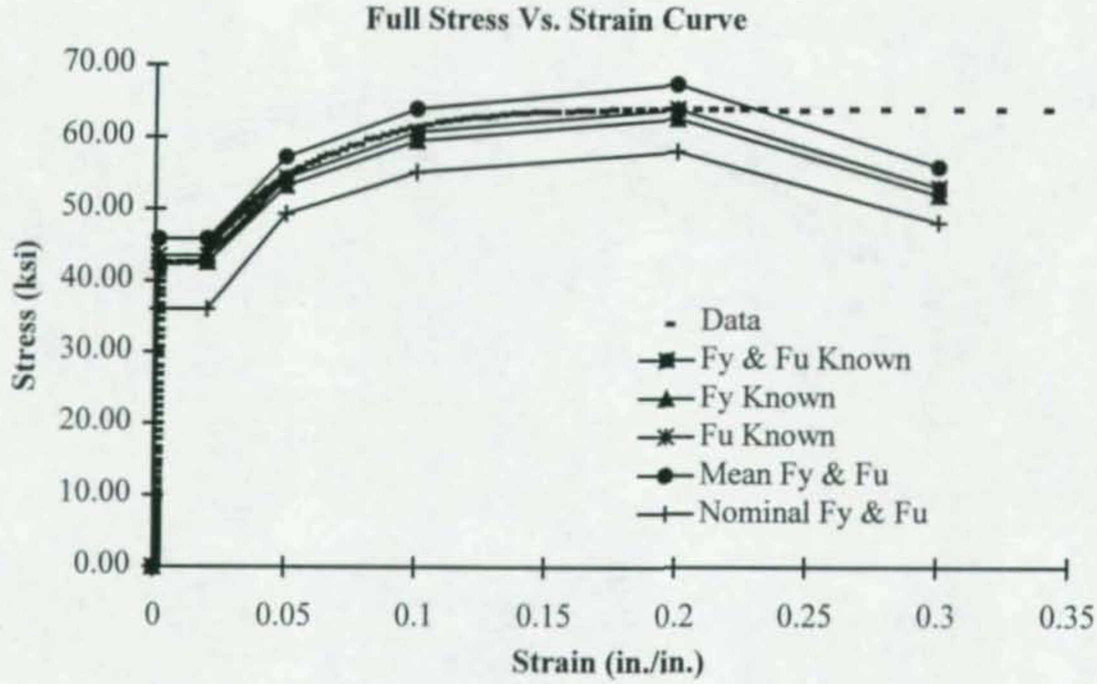


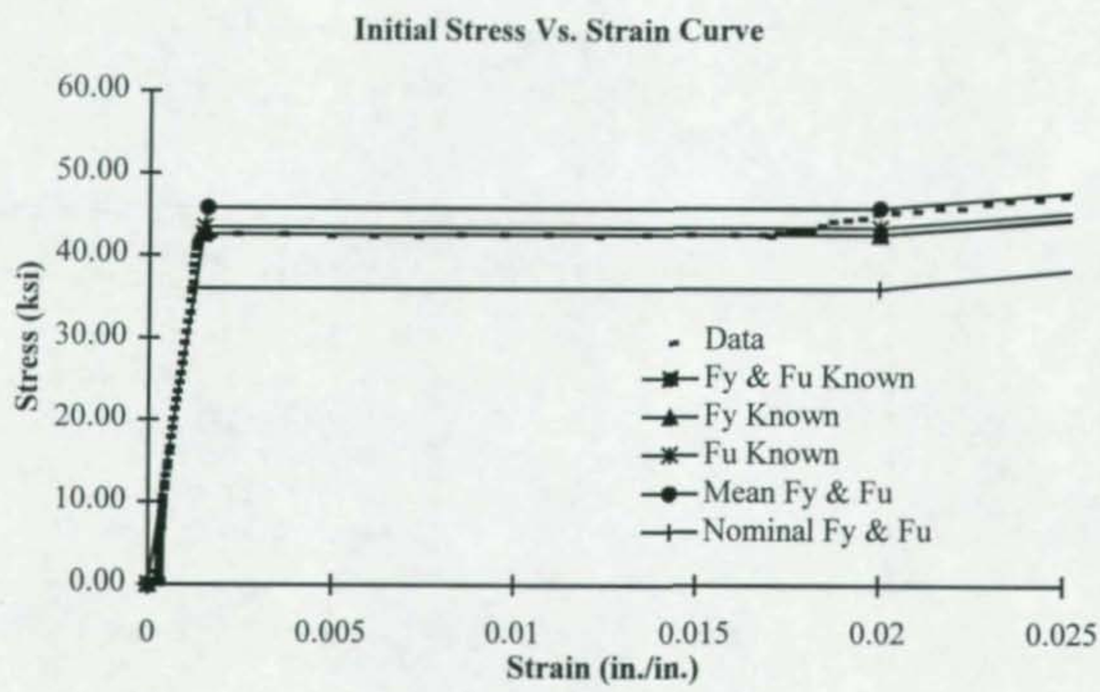
Full Stress Vs. Strain Curve

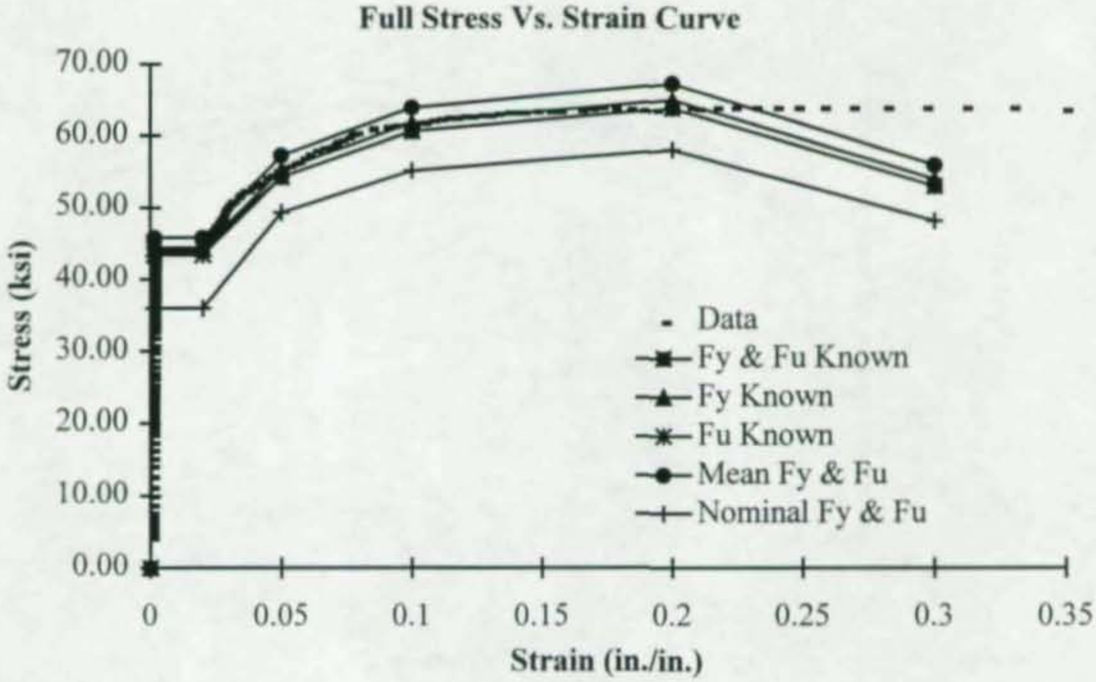


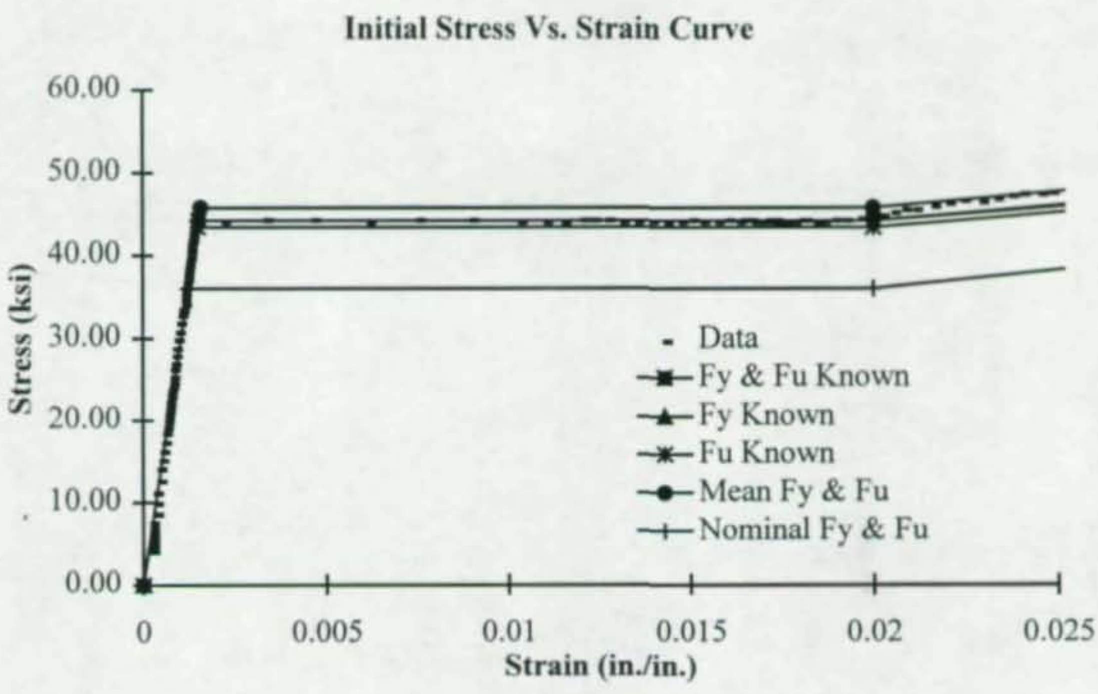
Initial Stress Vs. Strain Curve

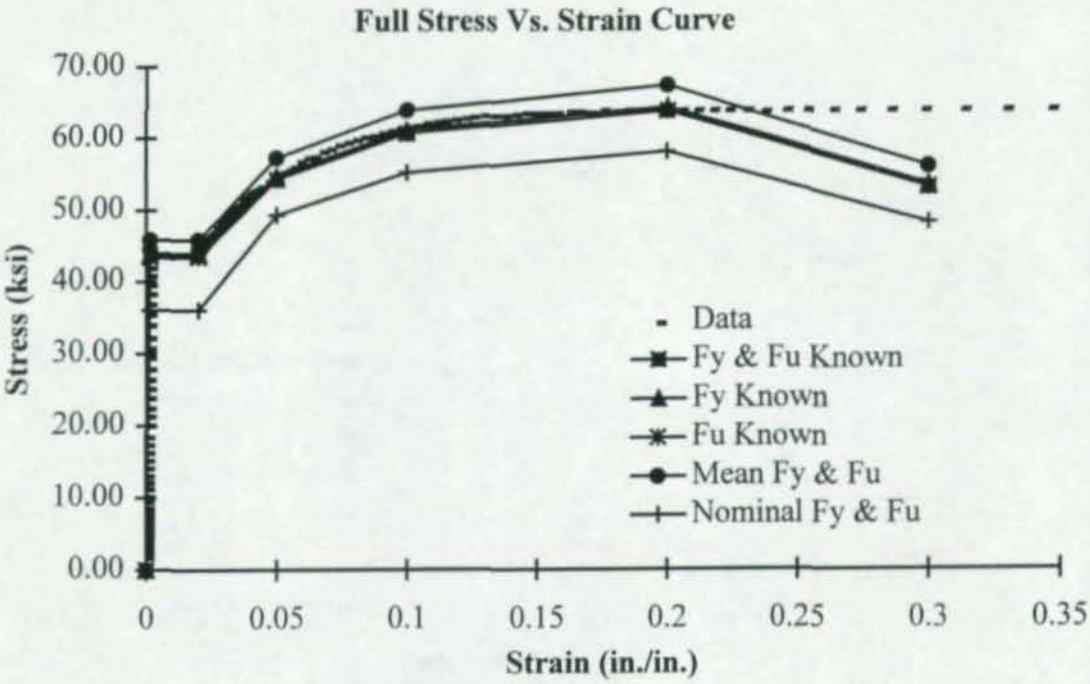


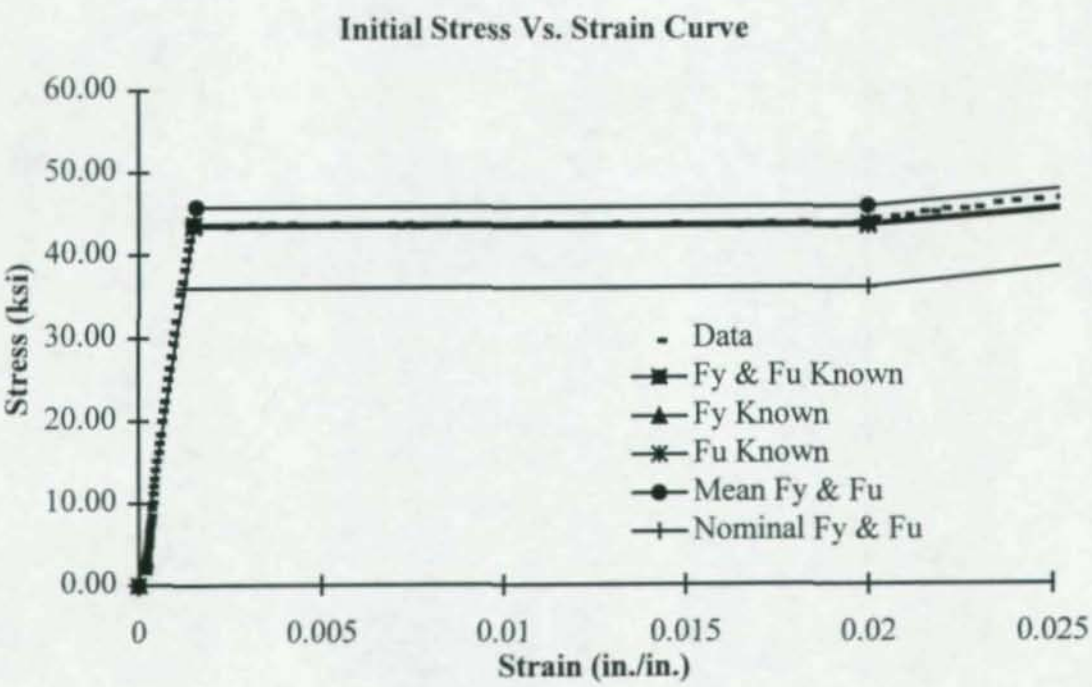

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

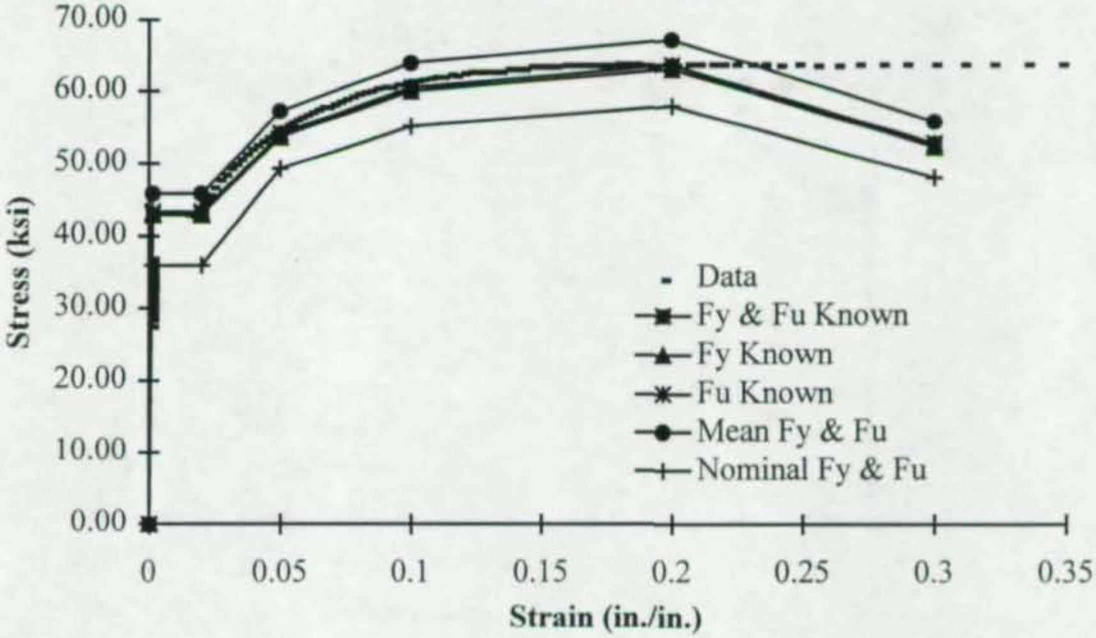

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

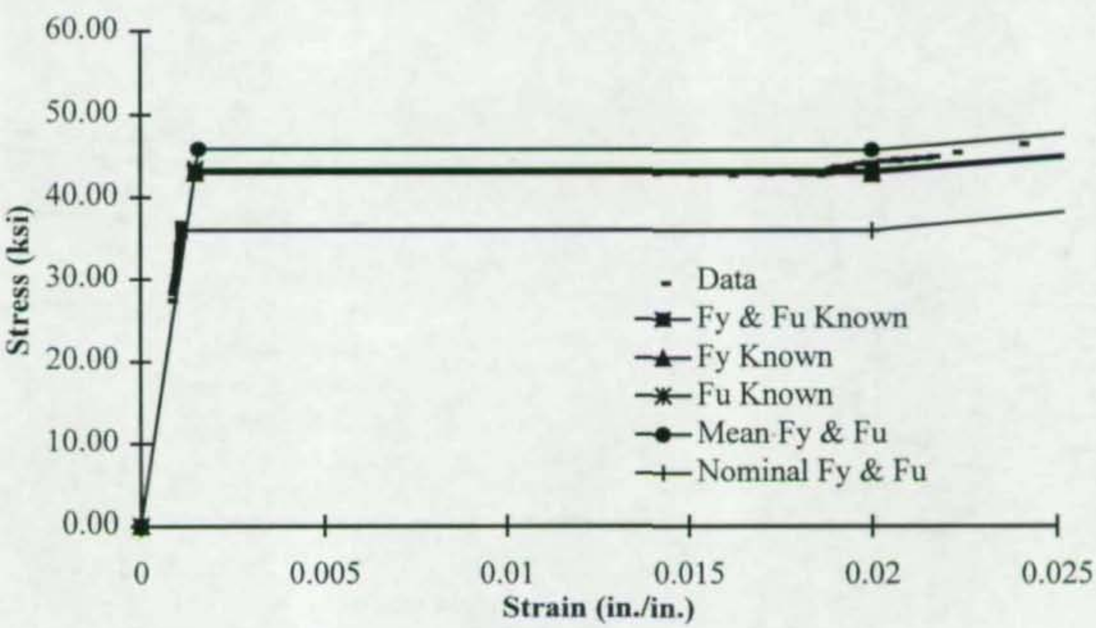

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

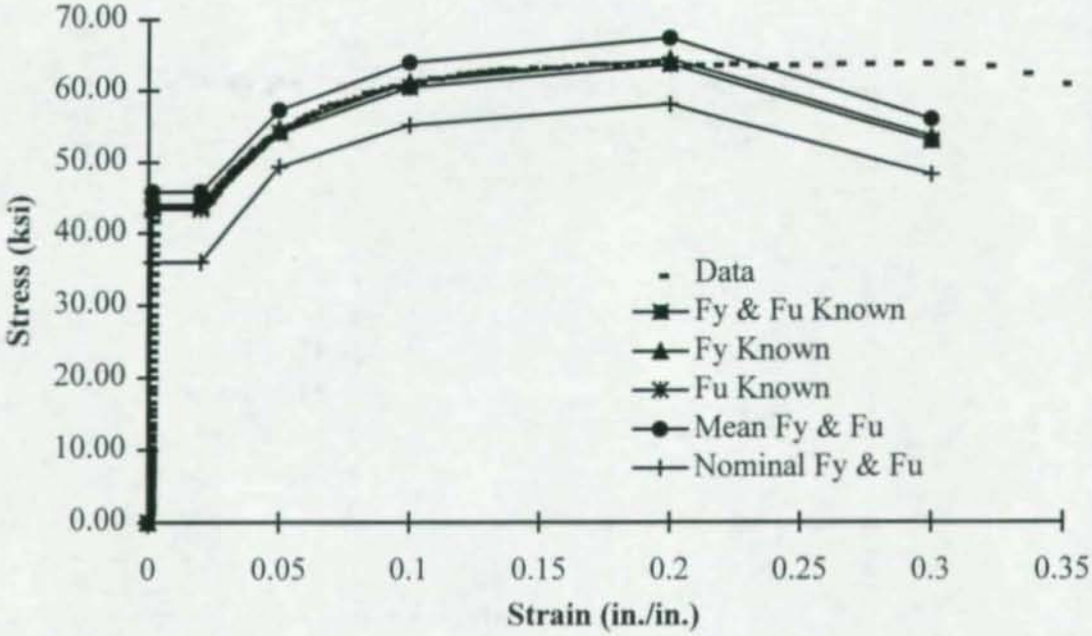
Full Stress Vs. Strain Curve



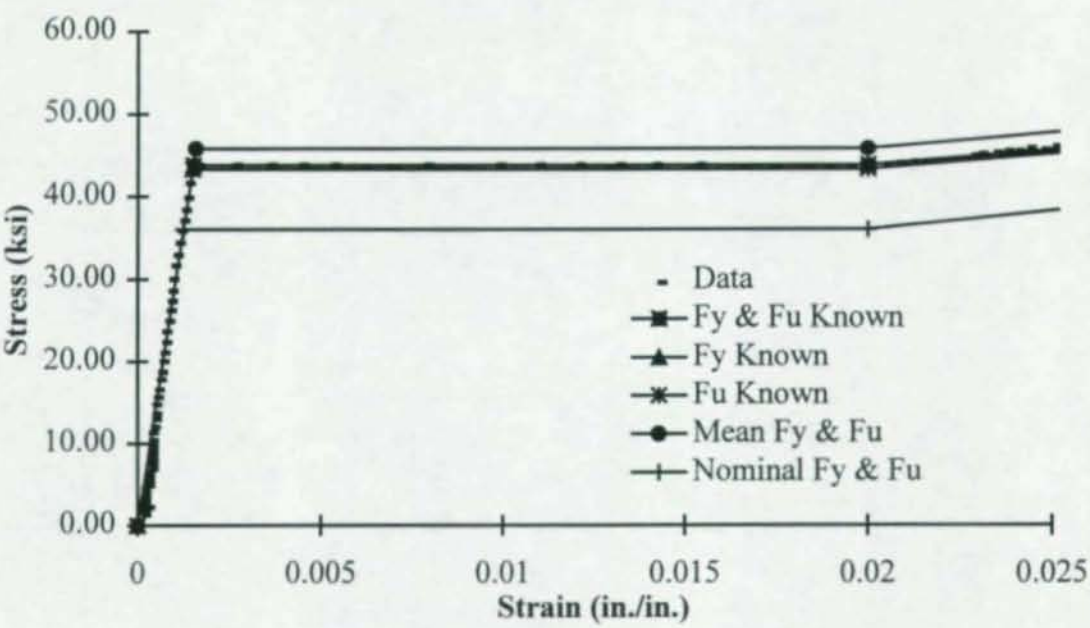
Initial Stress Vs. Strain Curve



Full Stress Vs. Strain Curve

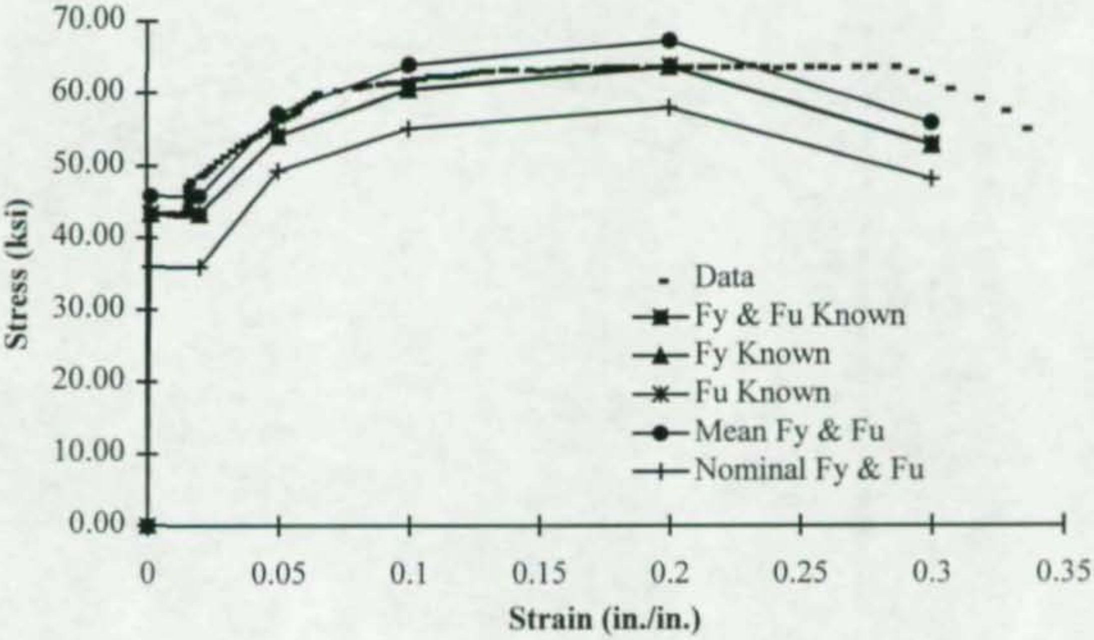


Initial Stress Vs. Strain Curve

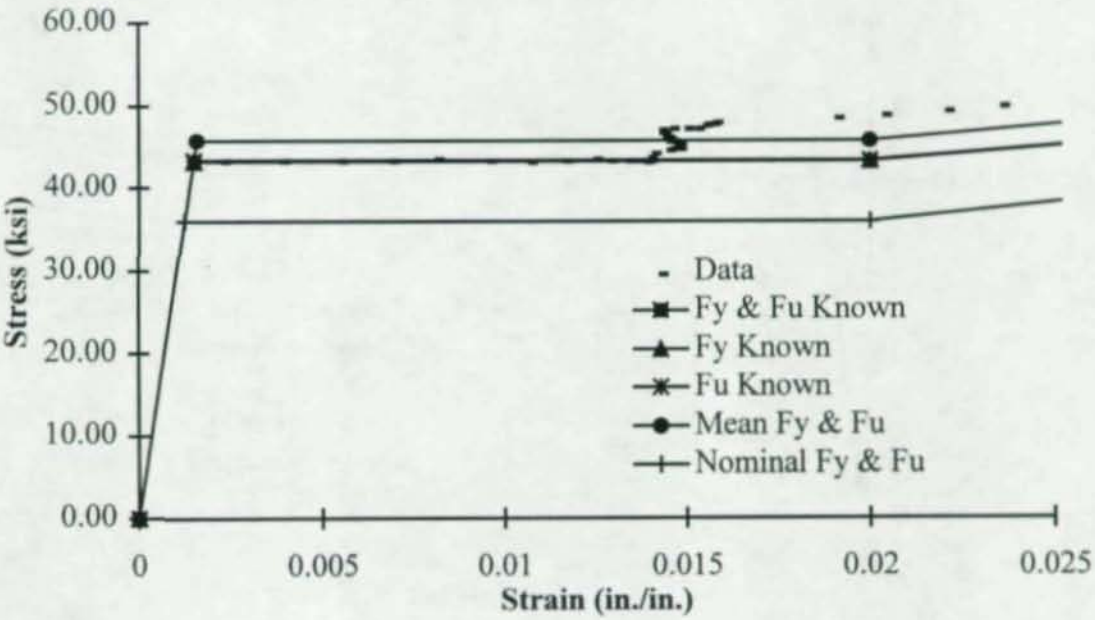


Mild Steel Stress-Strain Plots **Tensile Test: 25-1**

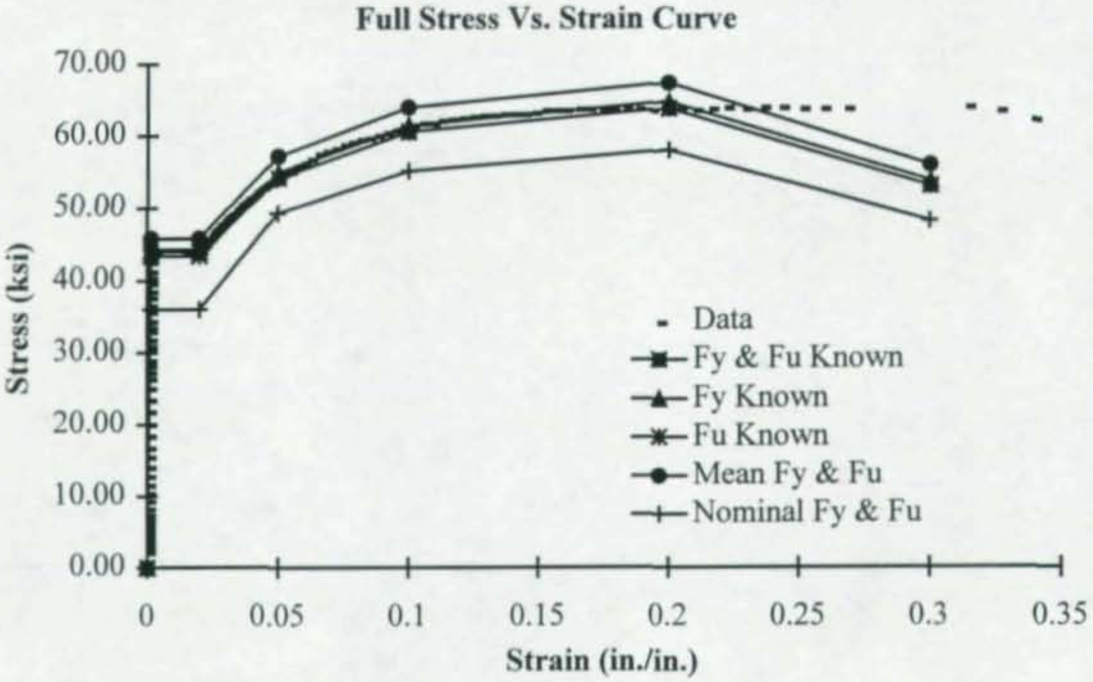
Full Stress Vs. Strain Curve

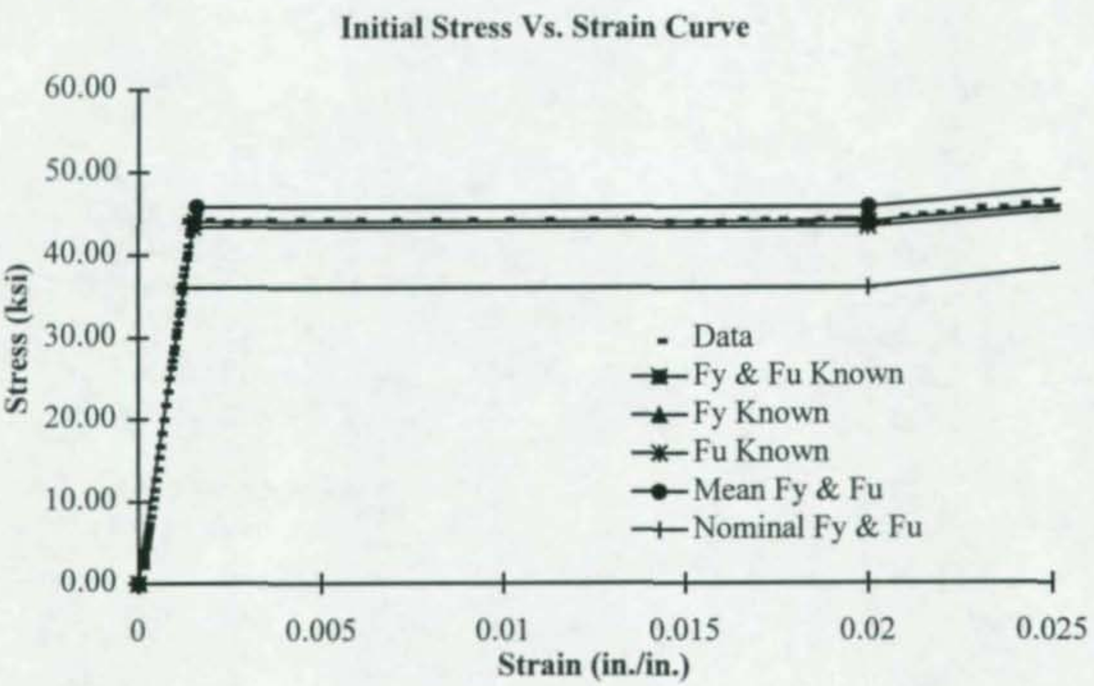


Initial Stress Vs. Strain Curve

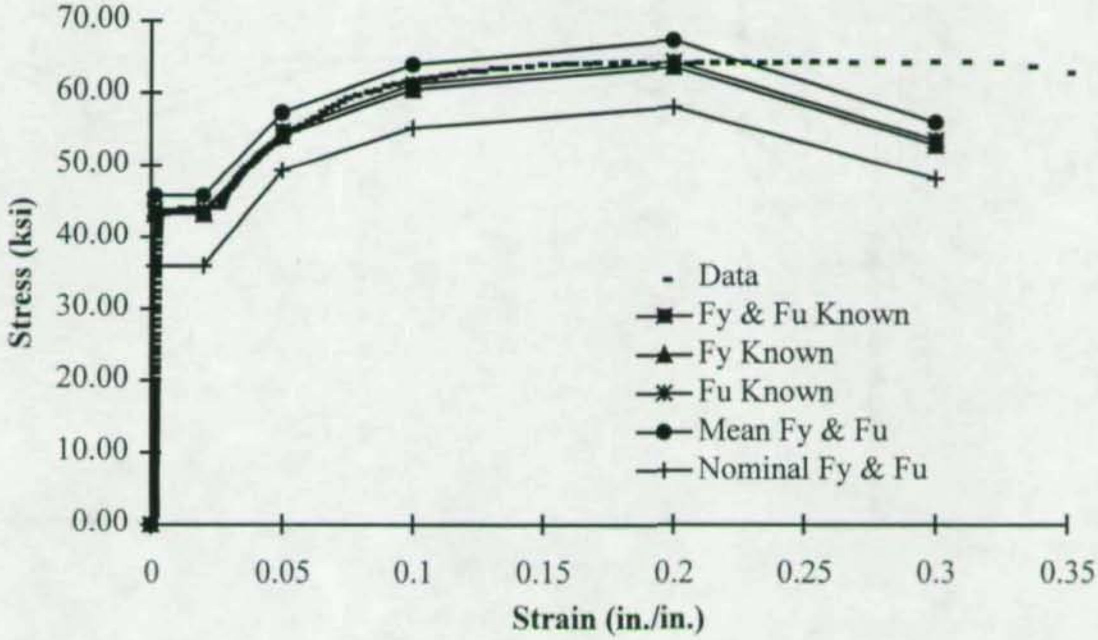


Mild Steel Stress-Strain Plots **Tensile Test: 25-2**

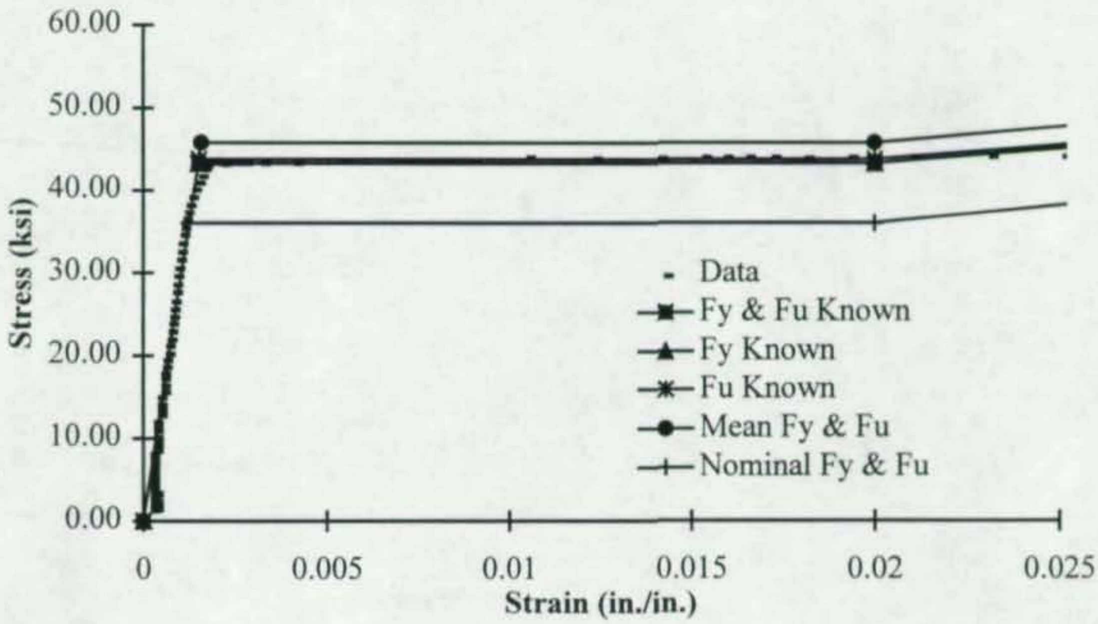


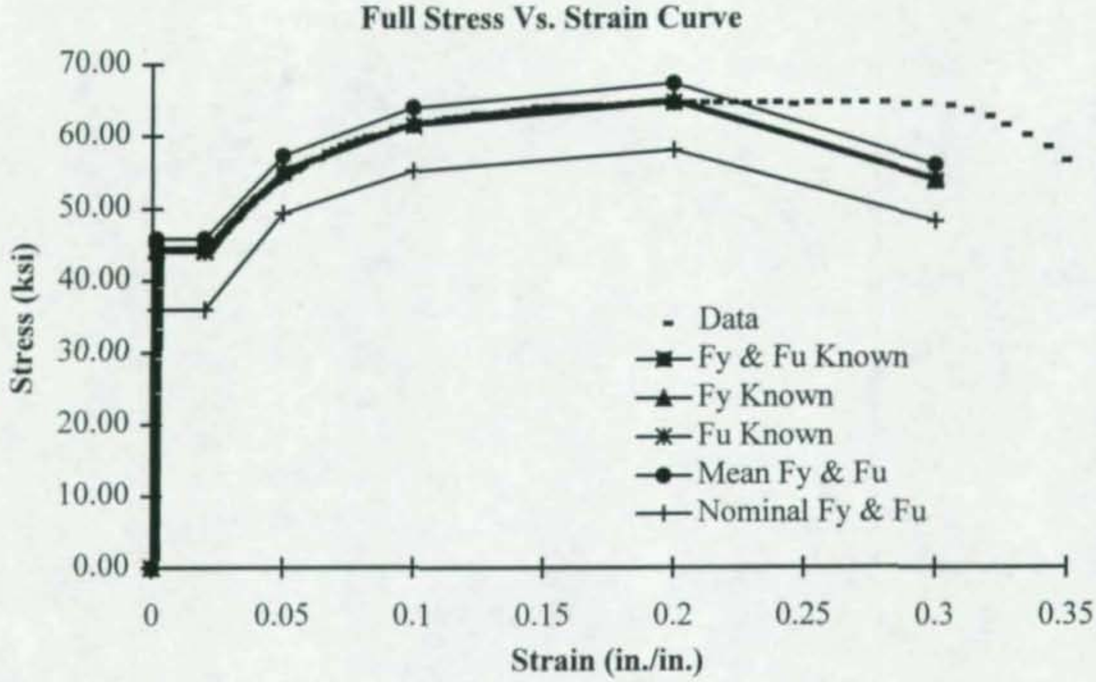


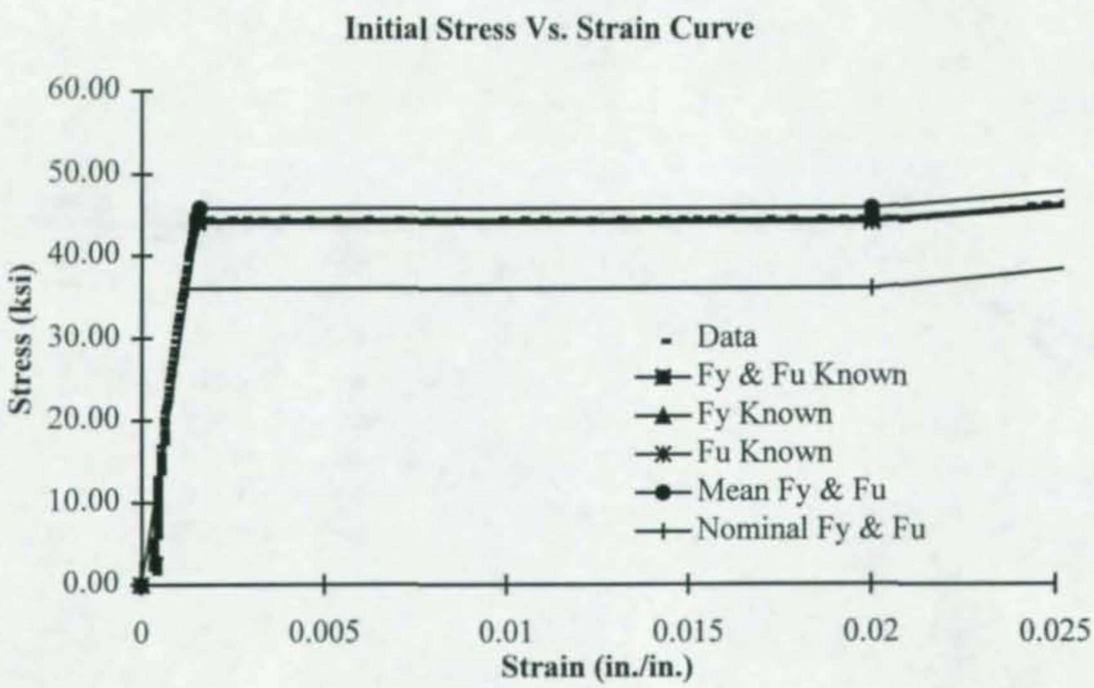
Full Stress Vs. Strain Curve



Initial Stress Vs. Strain Curve

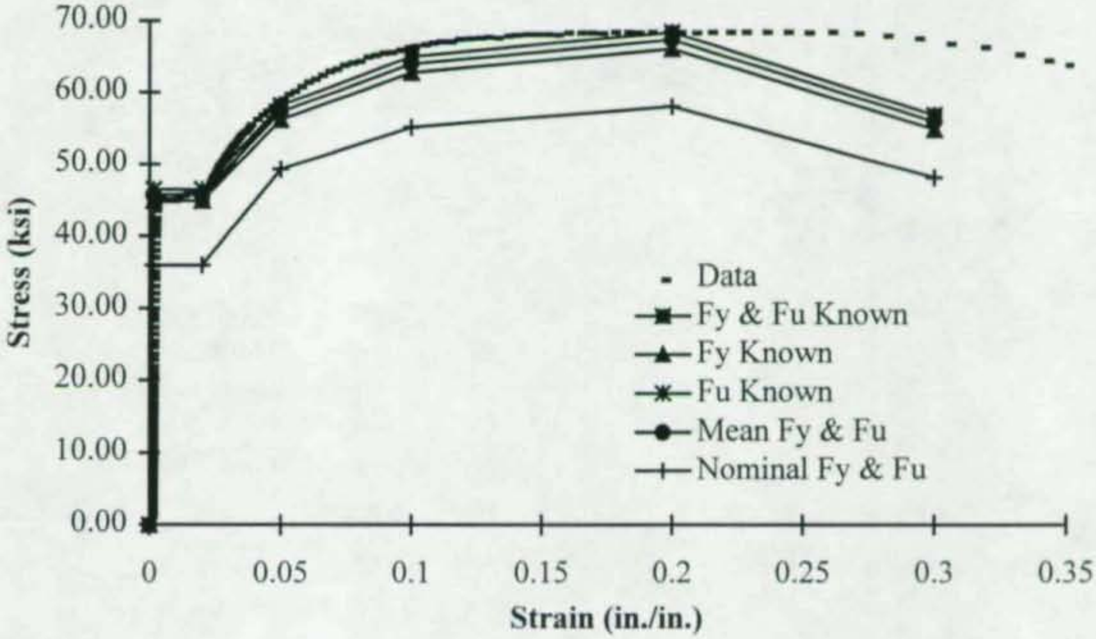



Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

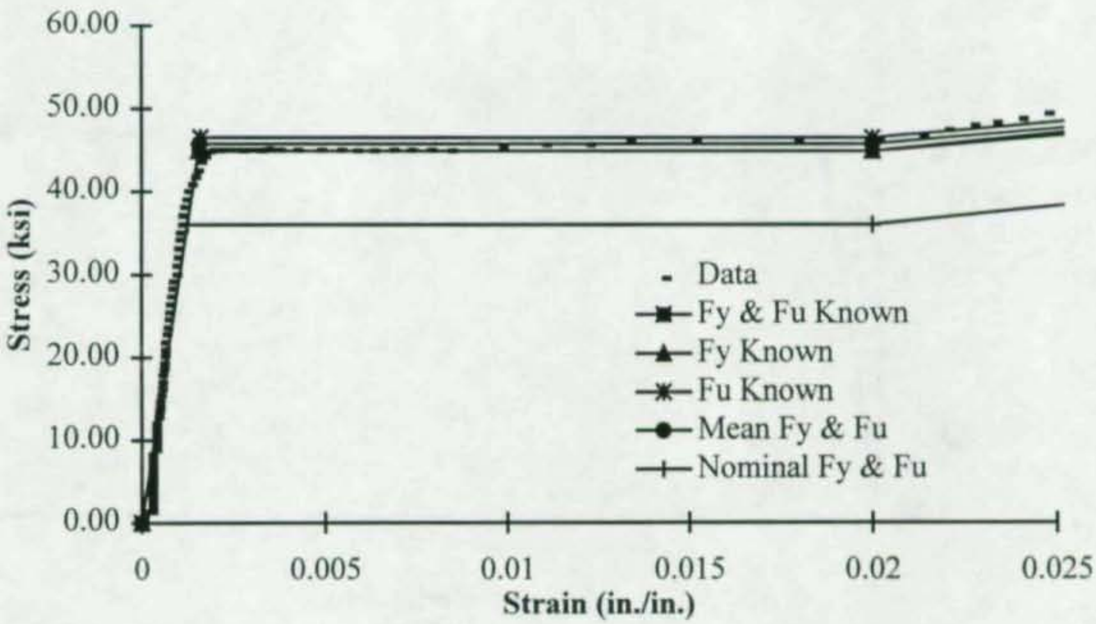

Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

Mild Steel Stress-Strain Plots **Tensile Test: 27-1**

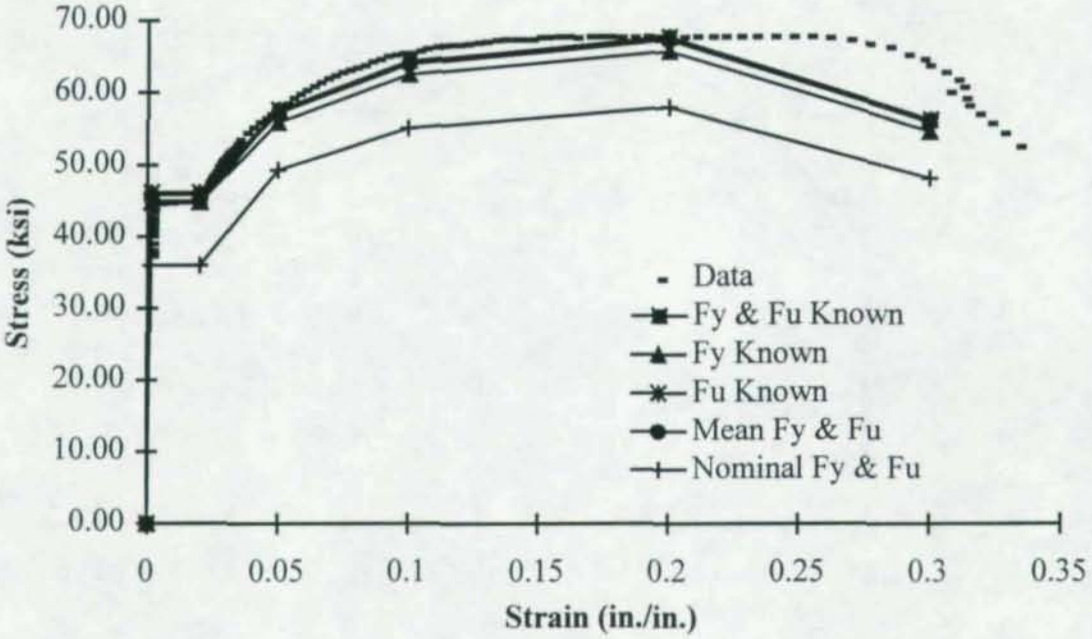
Full Stress Vs. Strain Curve



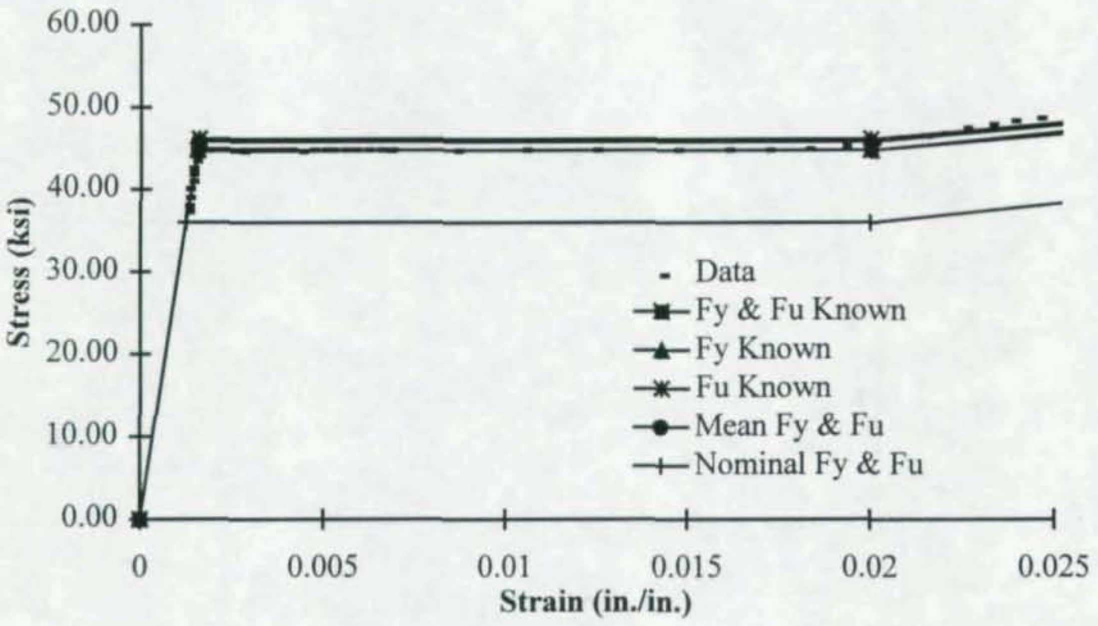
Initial Stress Vs. Strain Curve



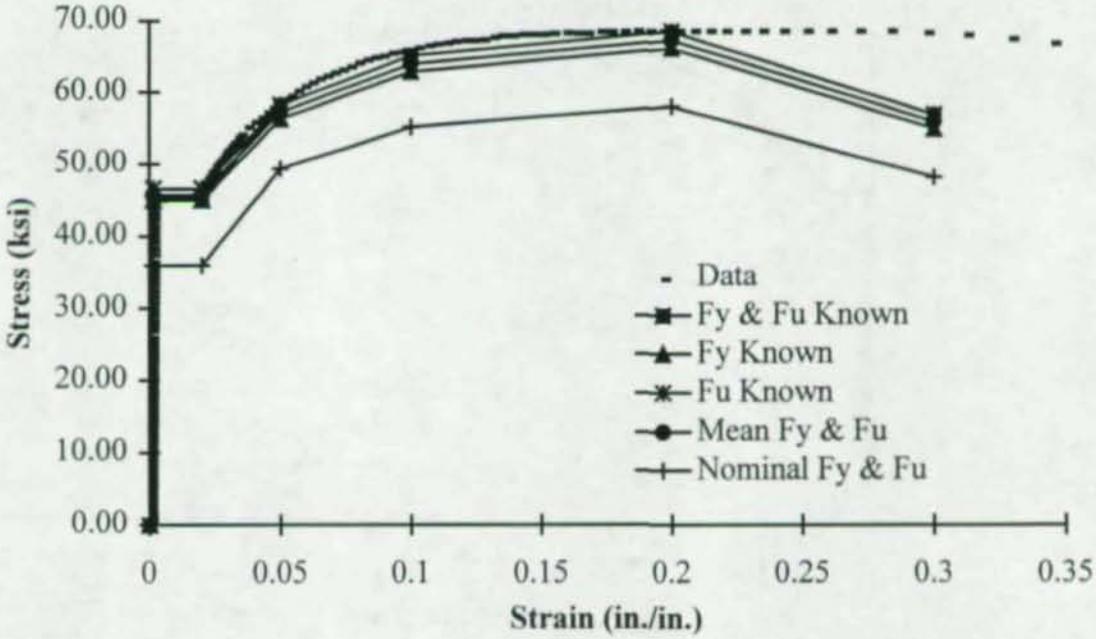
Full Stress Vs. Strain Curve



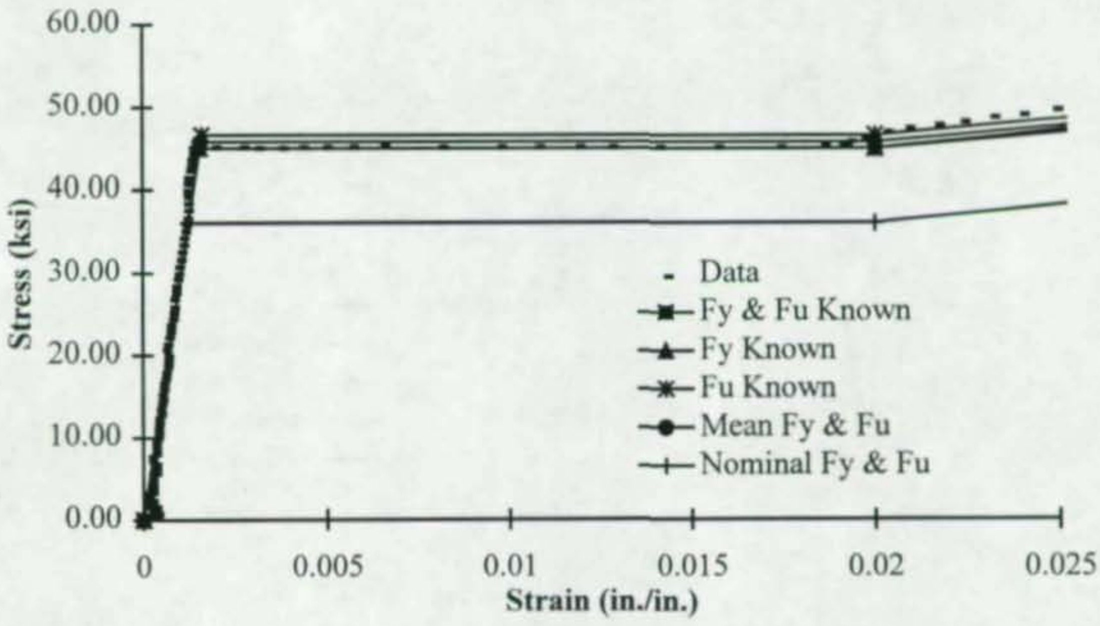
Initial Stress Vs. Strain Curve

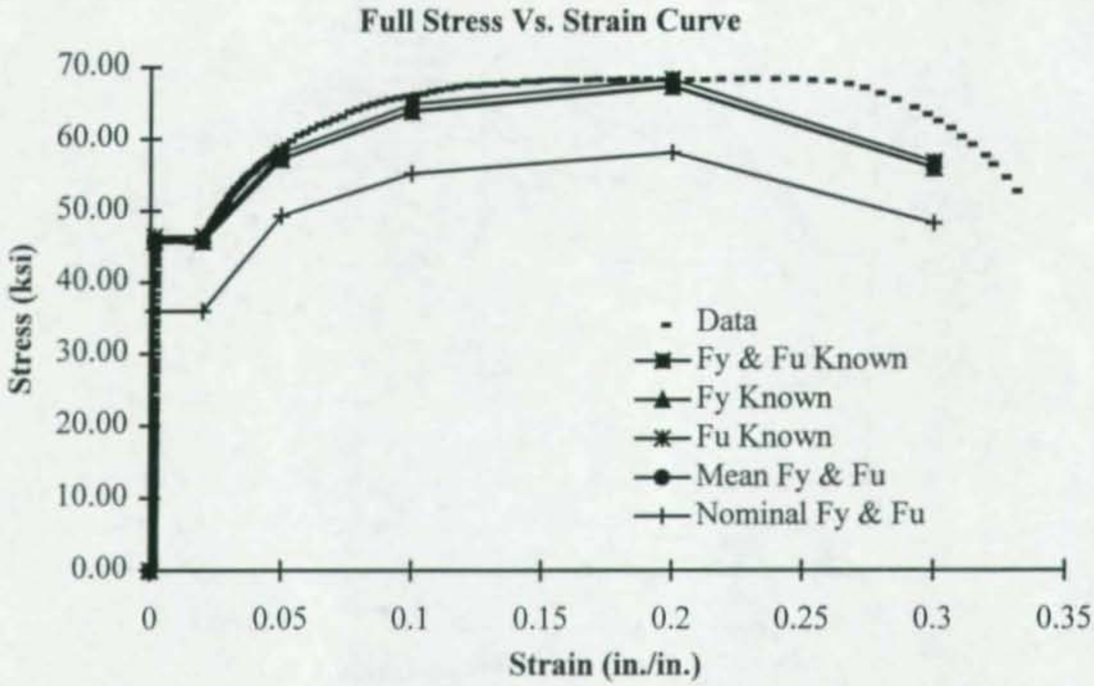


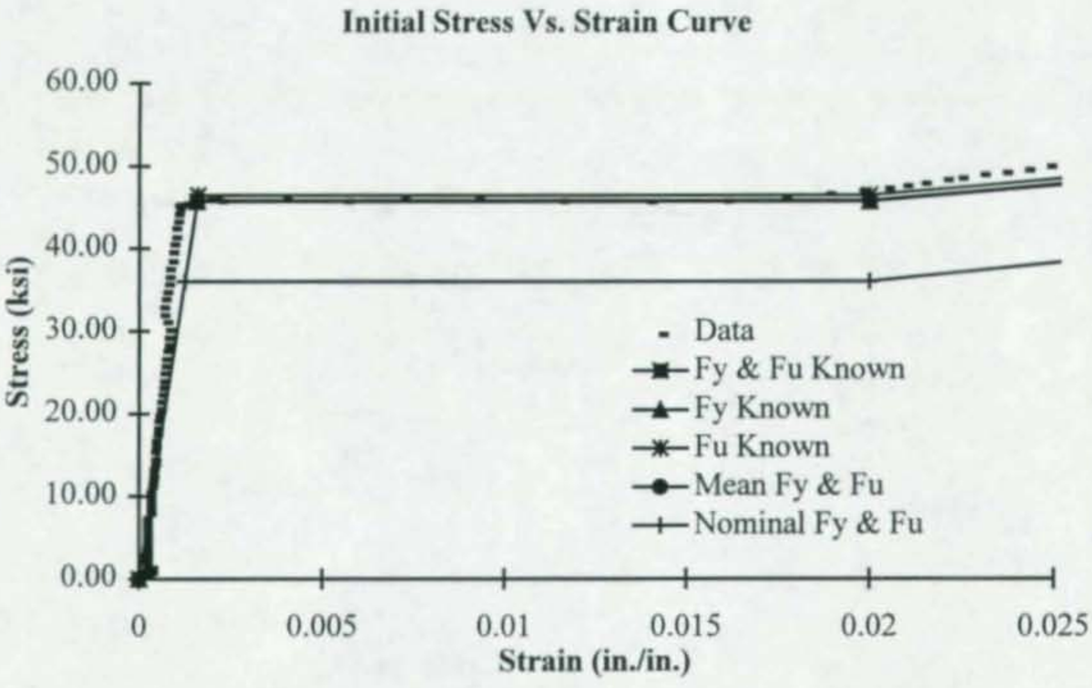
Full Stress Vs. Strain Curve



Initial Stress Vs. Strain Curve

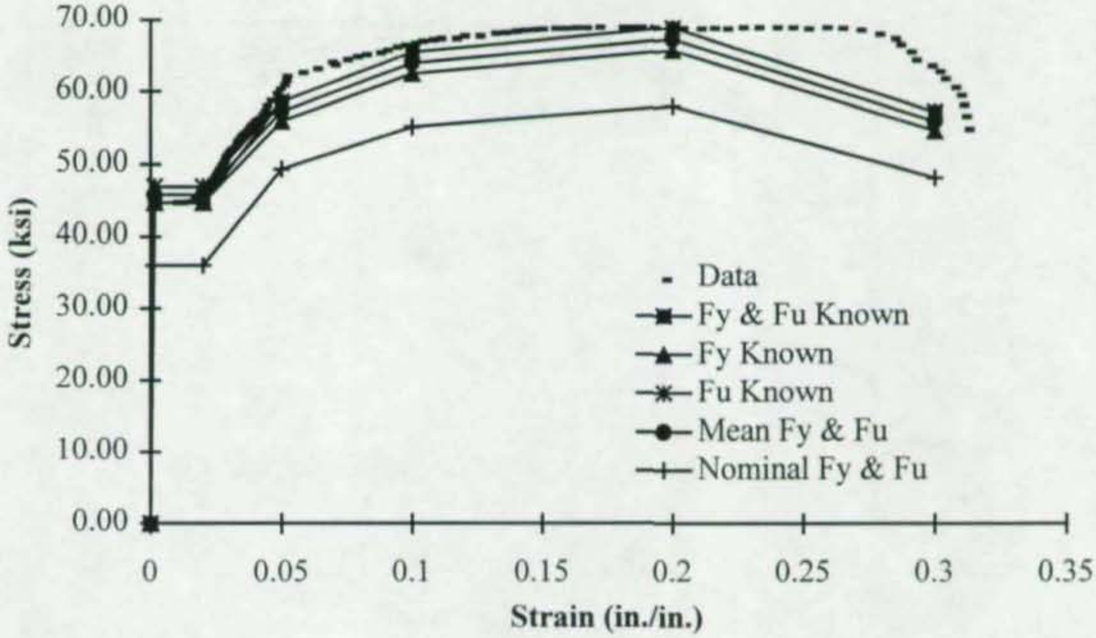



Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

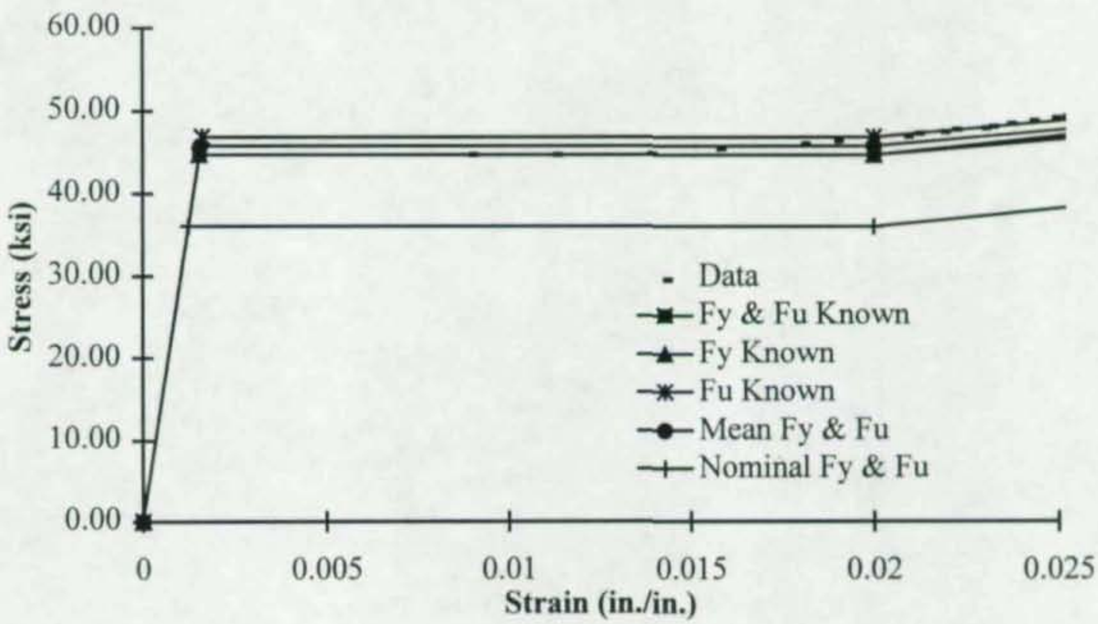

Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

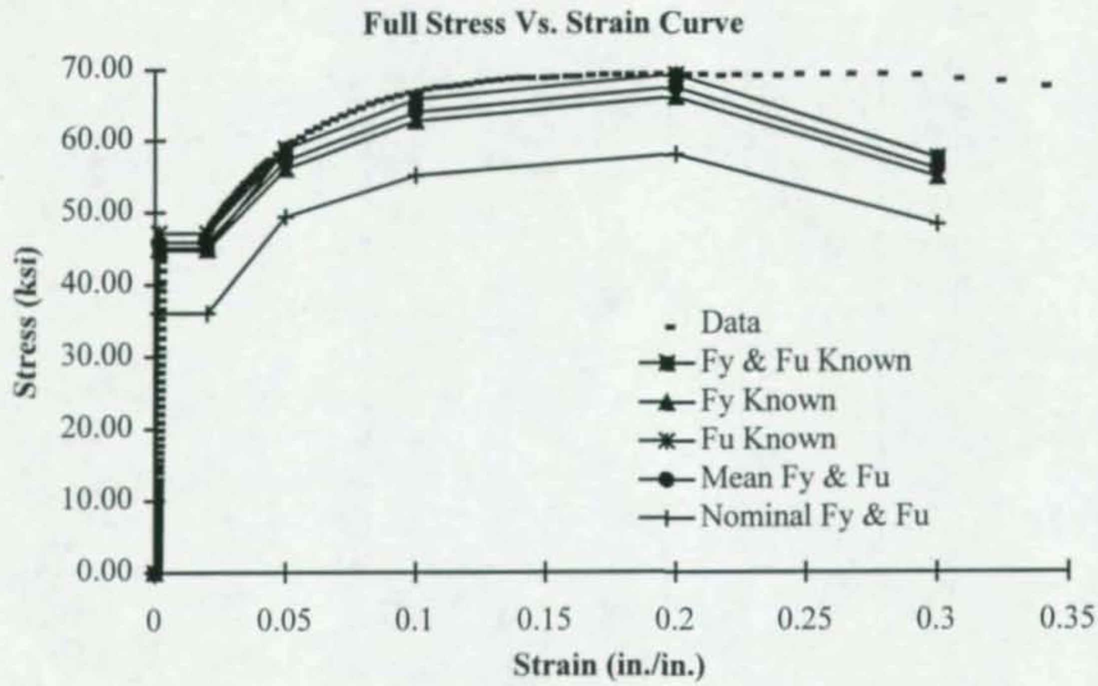
Mild Steel Stress-Strain Plots **Tensile Test: 28-1**

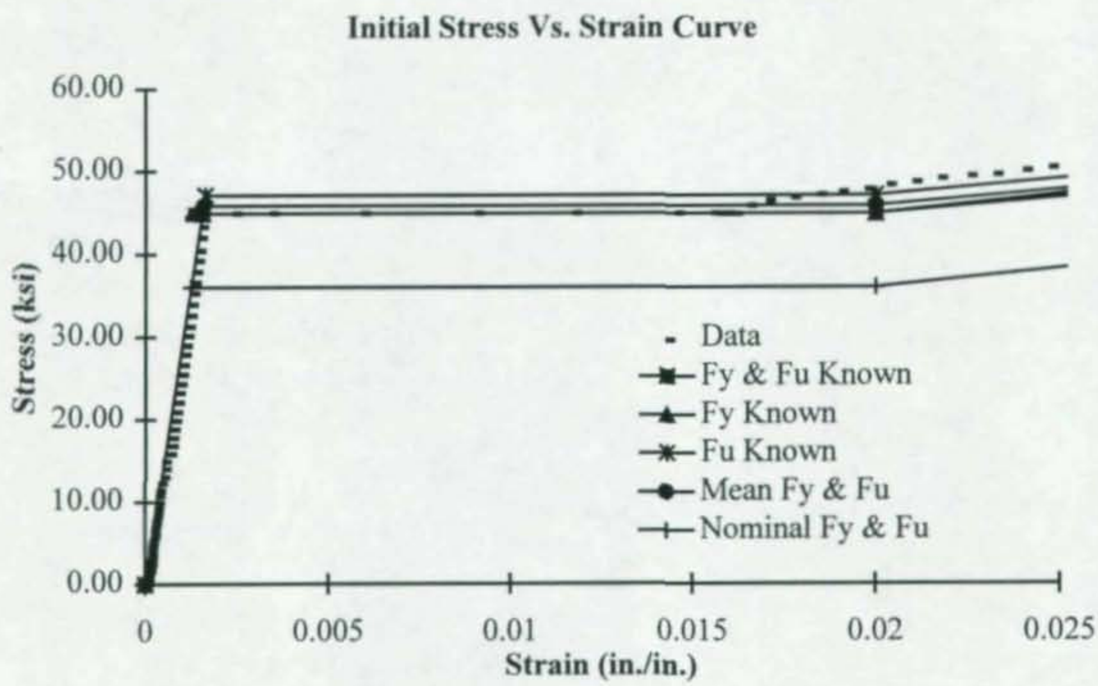
Full Stress Vs. Strain Curve



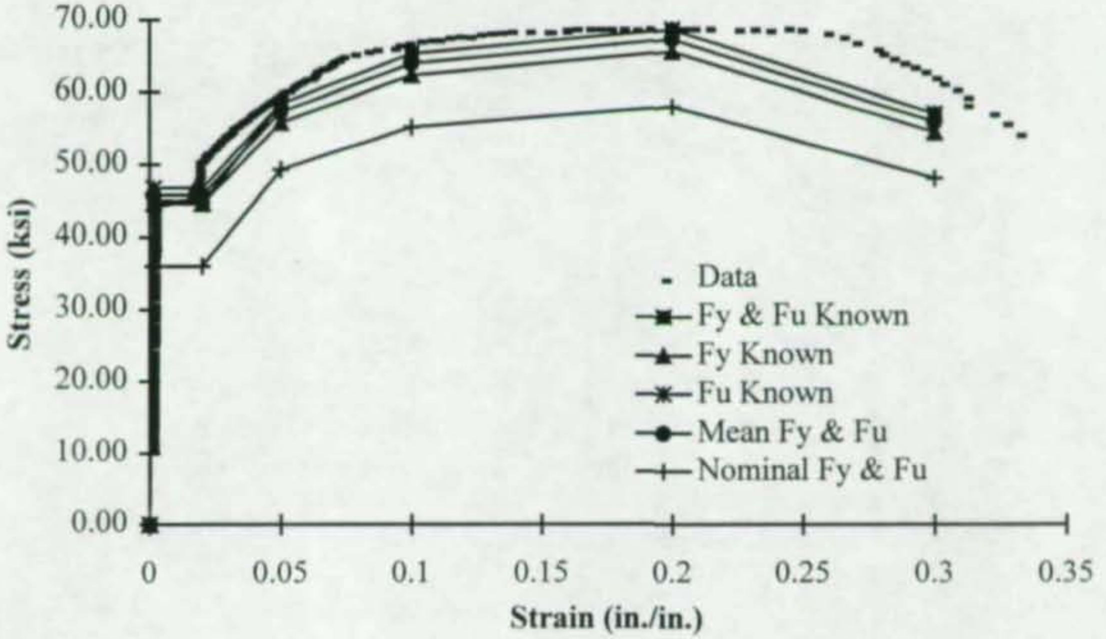
Initial Stress Vs. Strain Curve



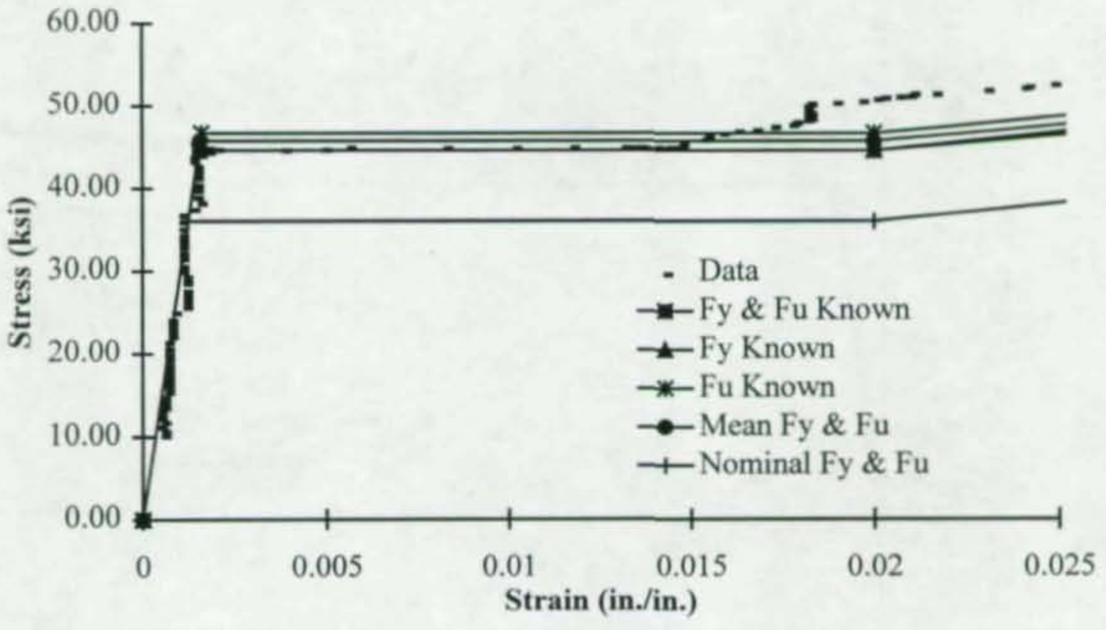

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

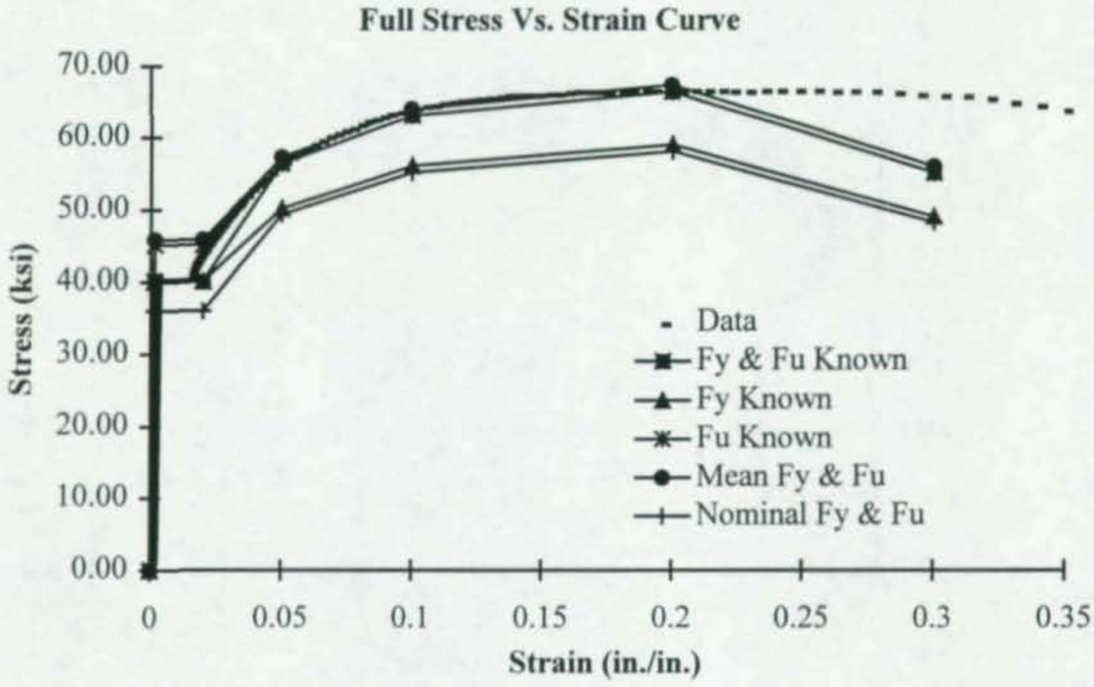

Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

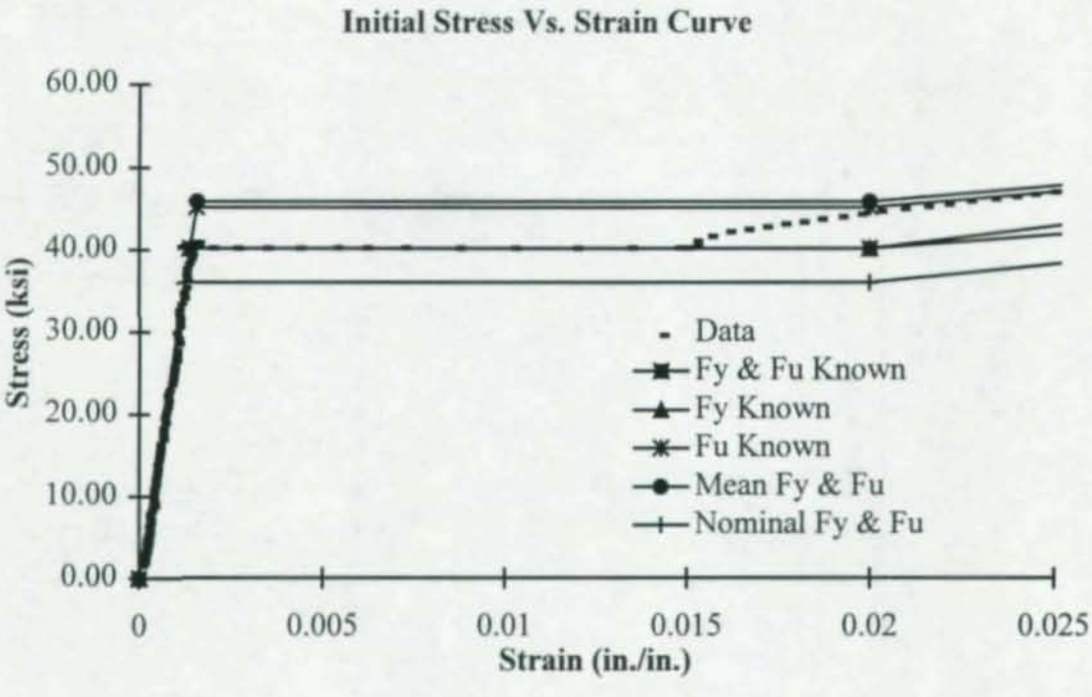
Full Stress Vs. Strain Curve

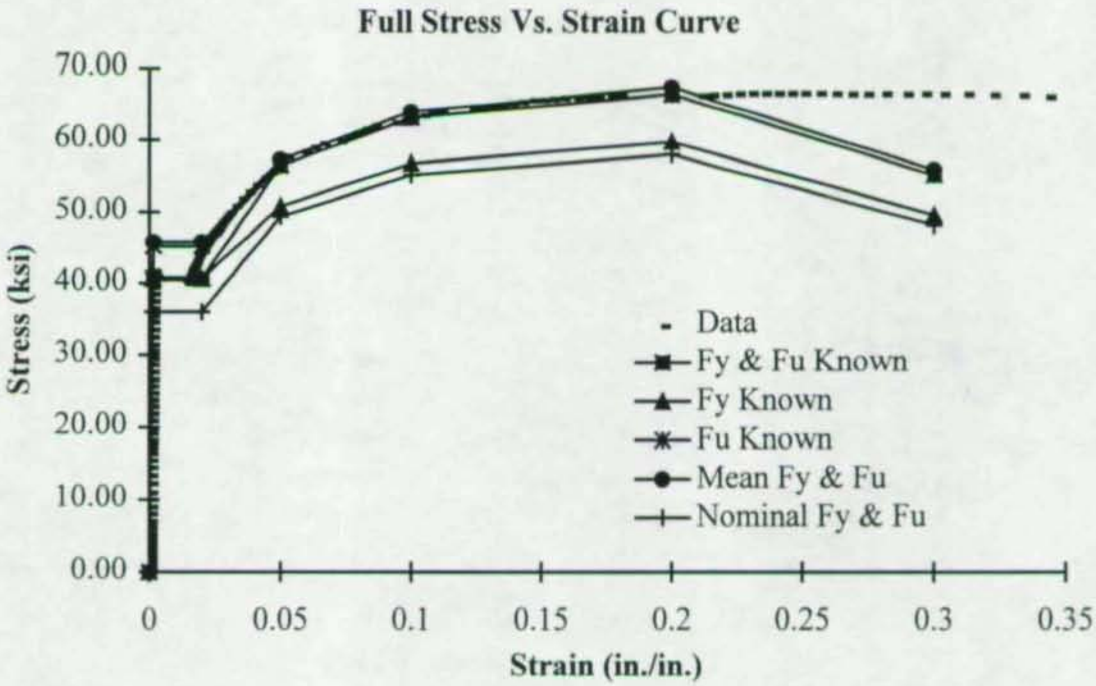


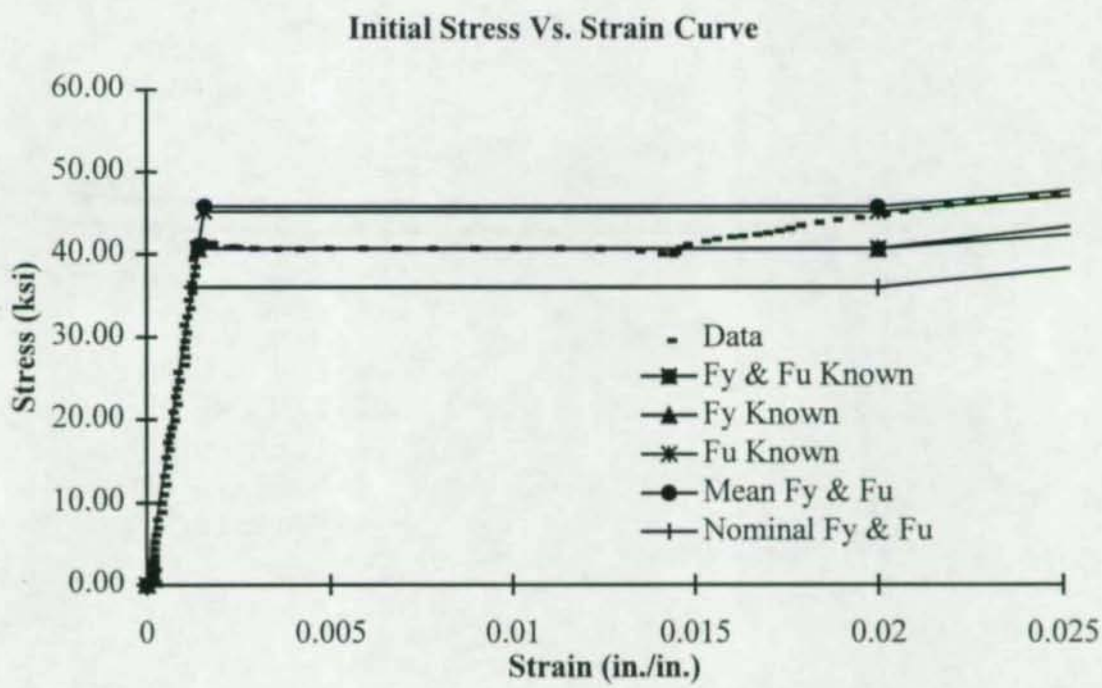
Initial Stress Vs. Strain Curve



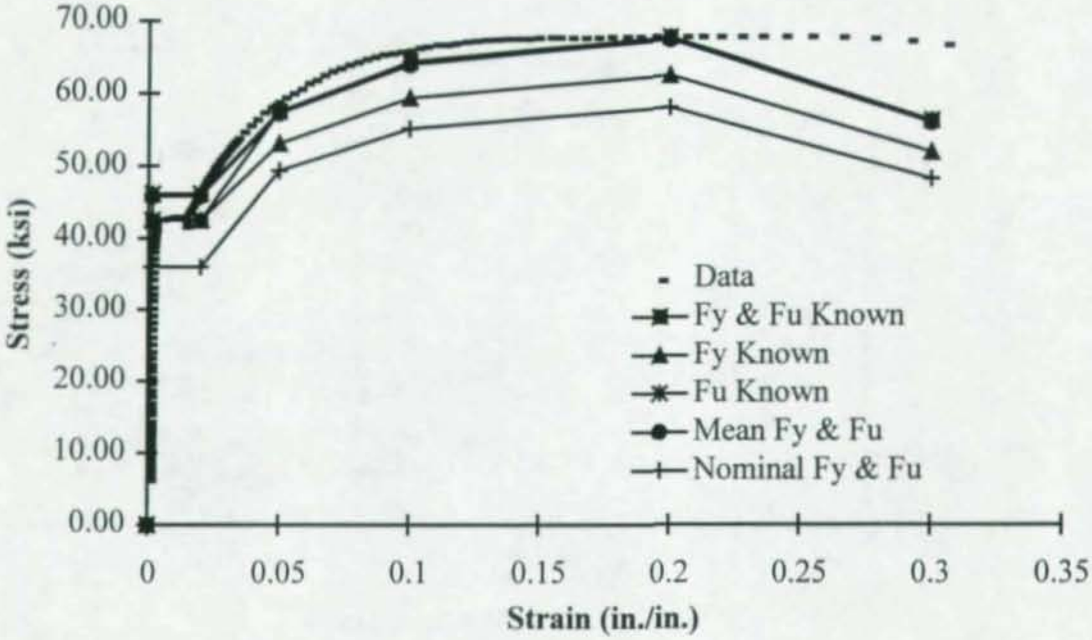

Full Stress Vs. Strain Curve
Stress (ksi)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
Stress (ksi)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

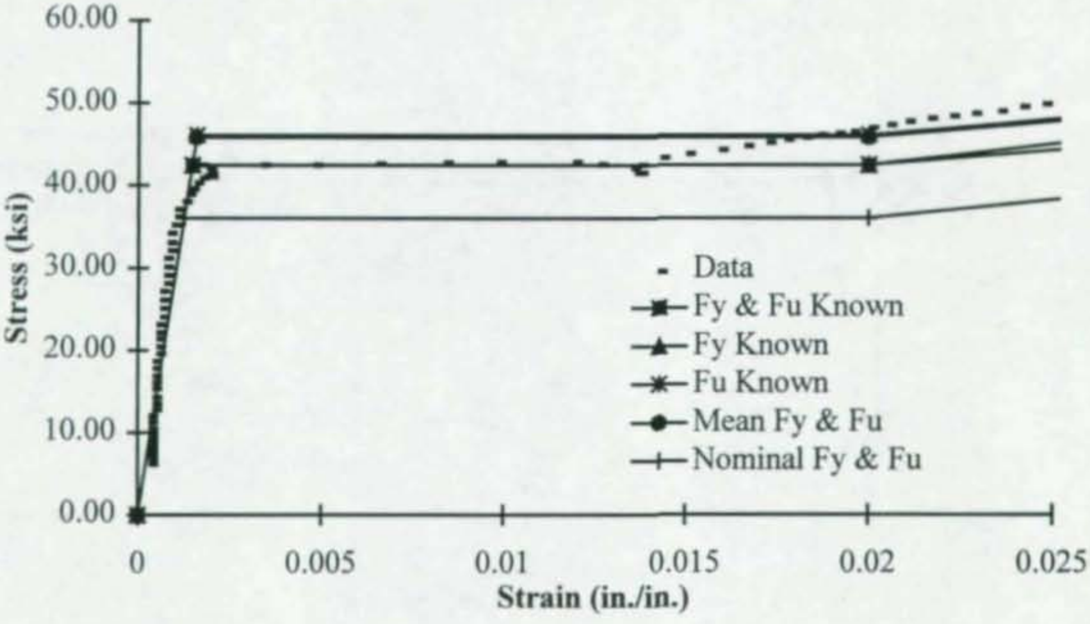

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

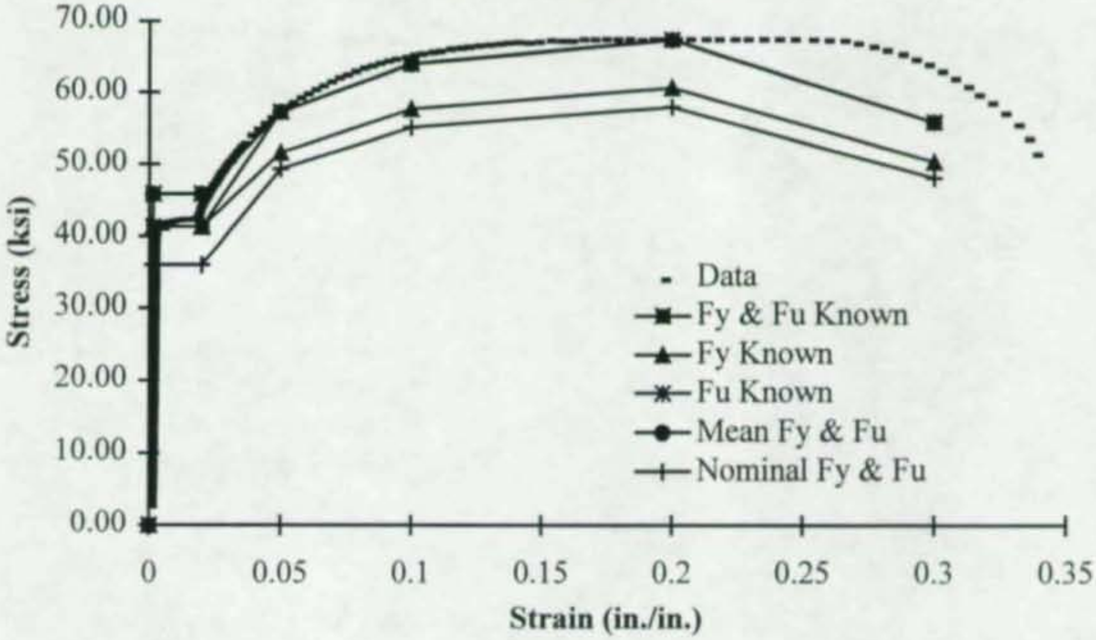
Full Stress Vs. Strain Curve



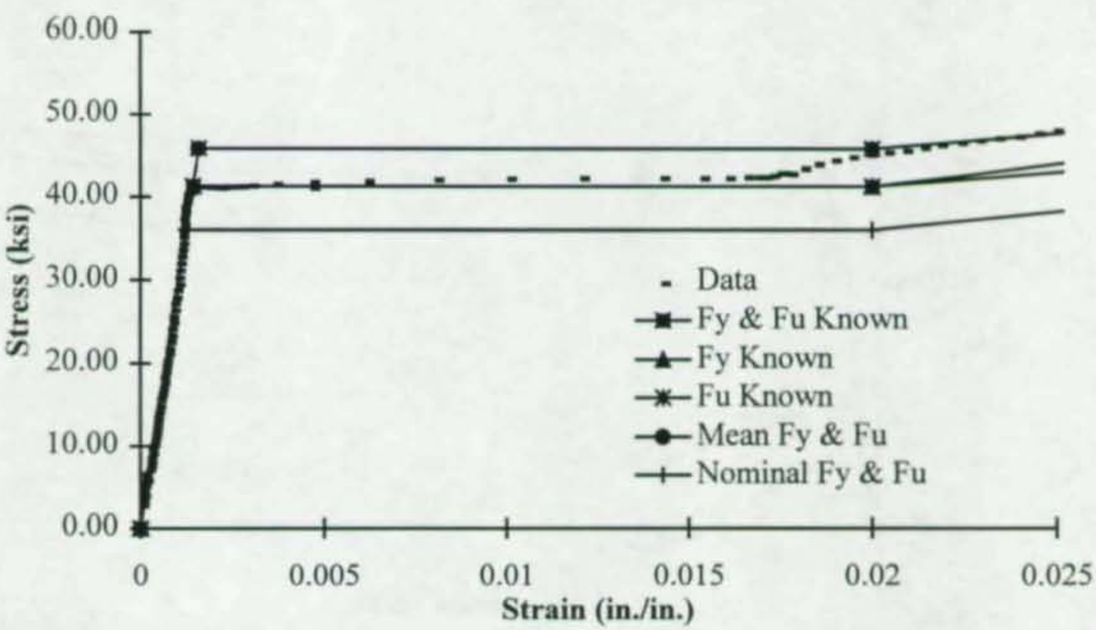
Initial Stress Vs. Strain Curve

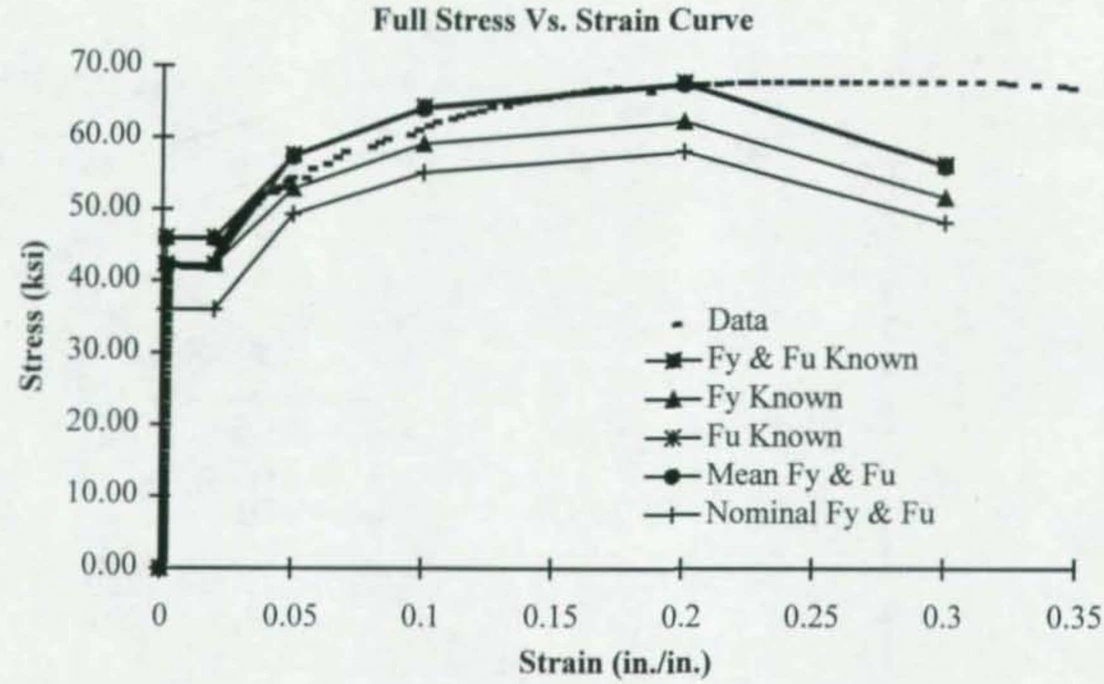


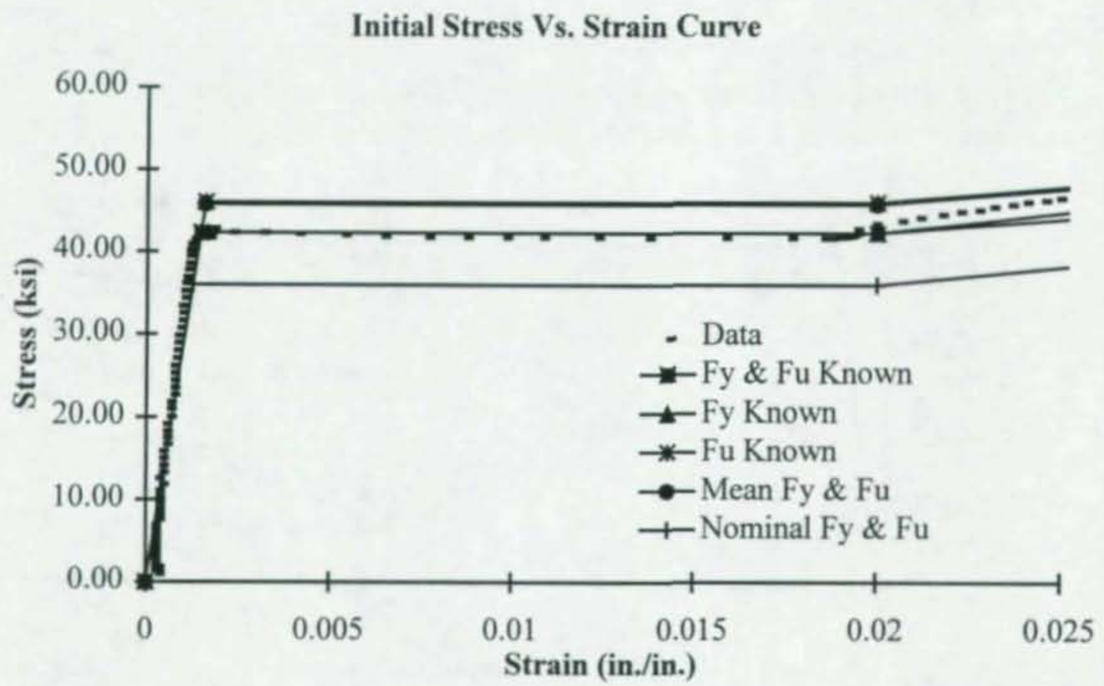
Full Stress Vs. Strain Curve

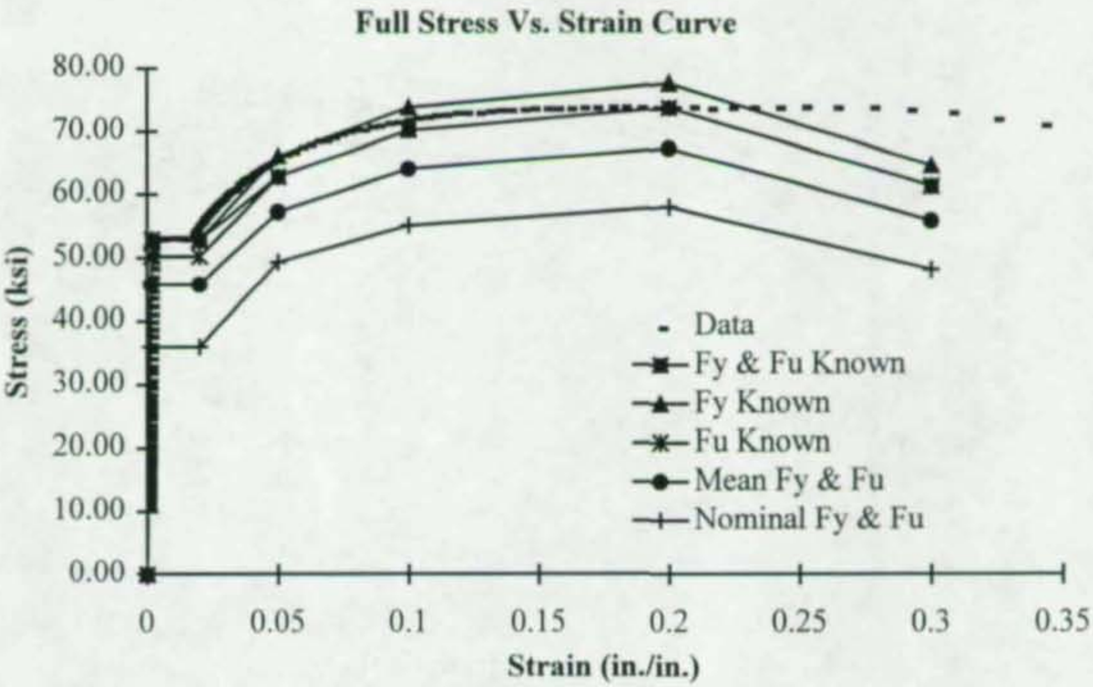


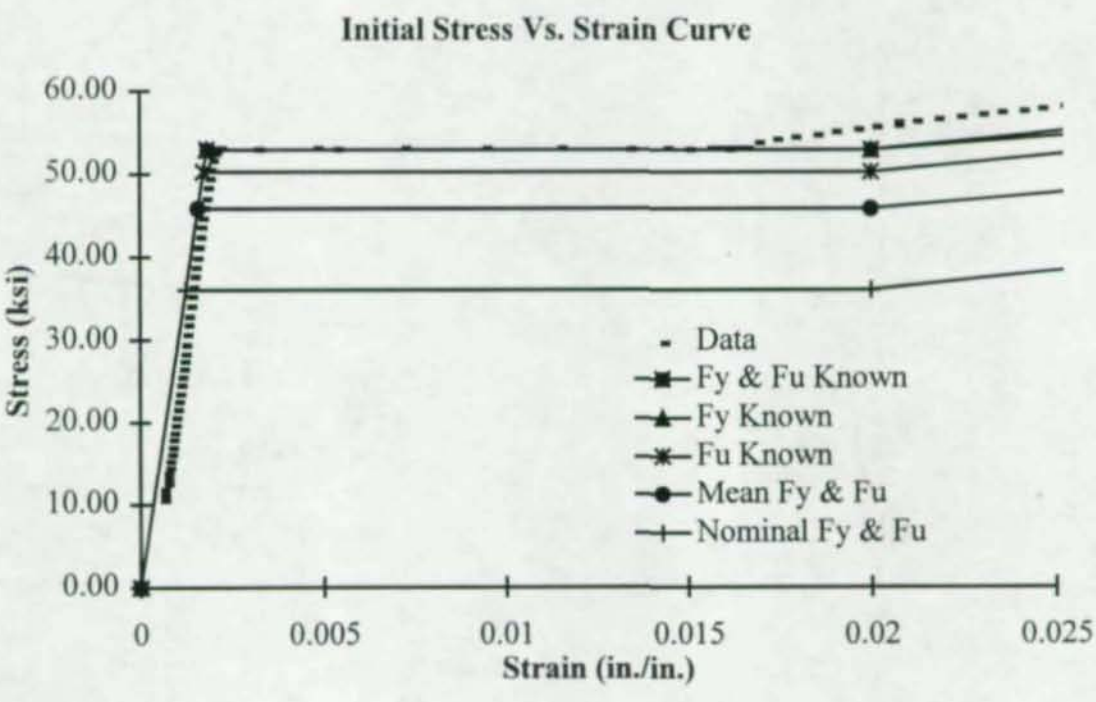
Initial Stress Vs. Strain Curve

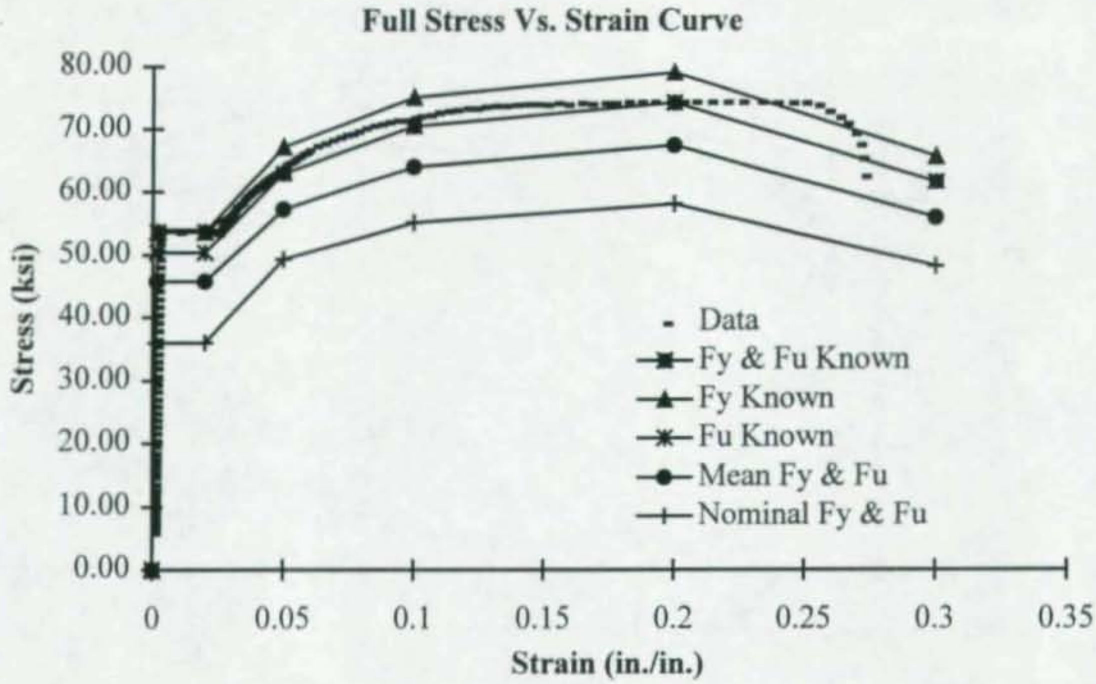


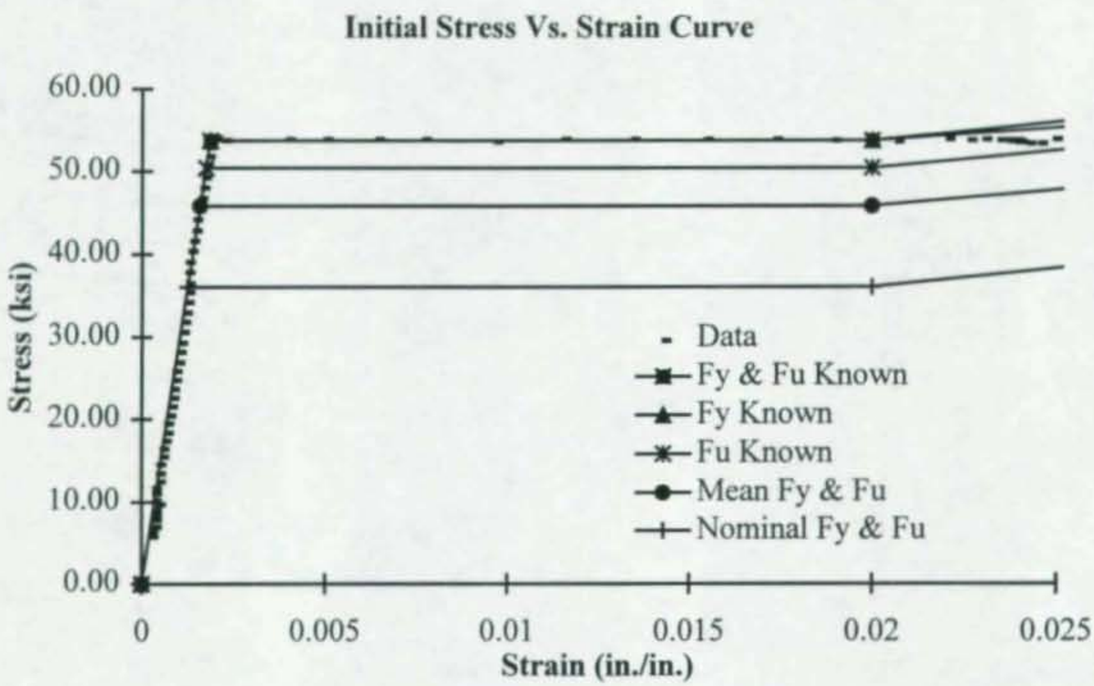

Full Stress Vs. Strain Curve
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

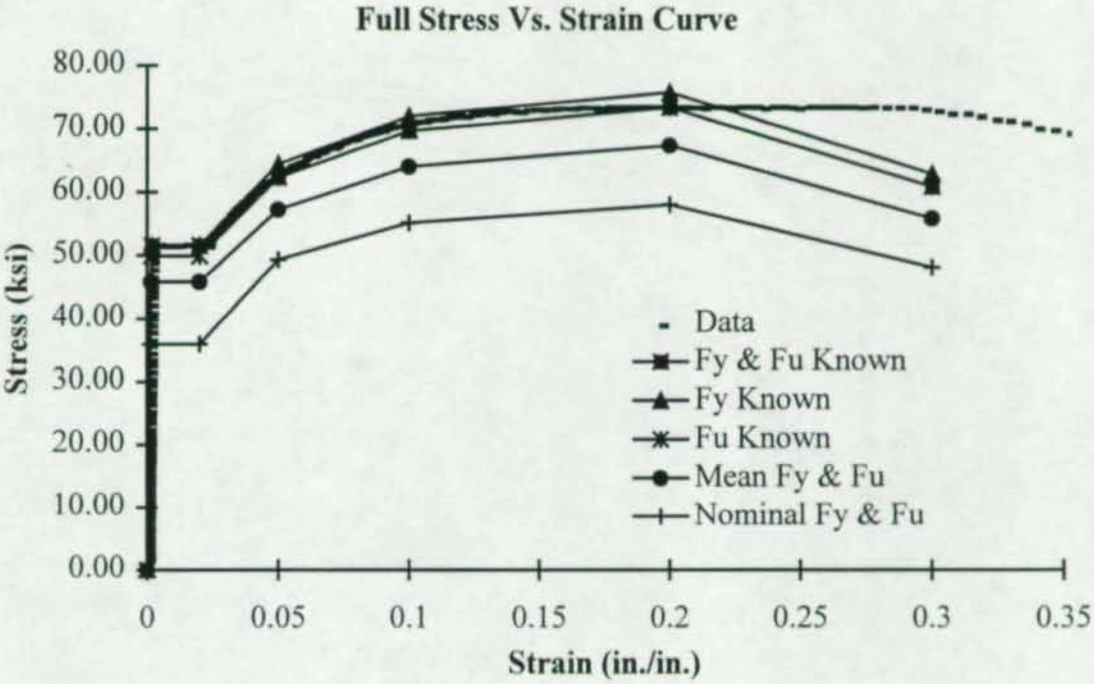

Full Stress Vs. Strain Curve
Stress (ksi)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

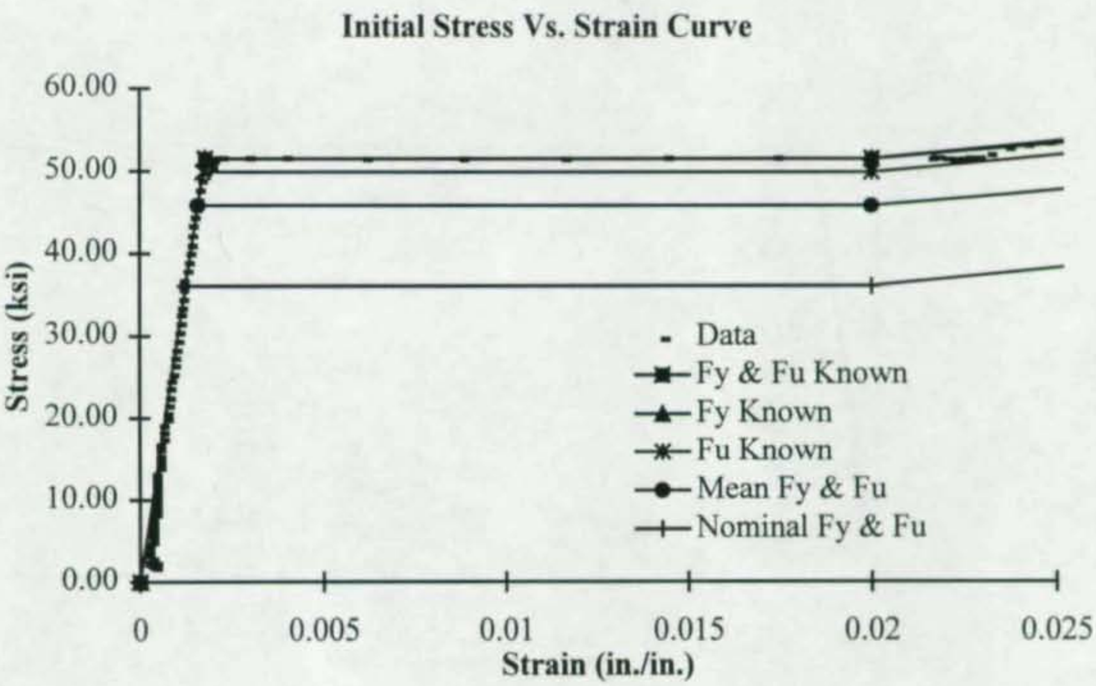

Initial Stress Vs. Strain Curve
Stress (ksi)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

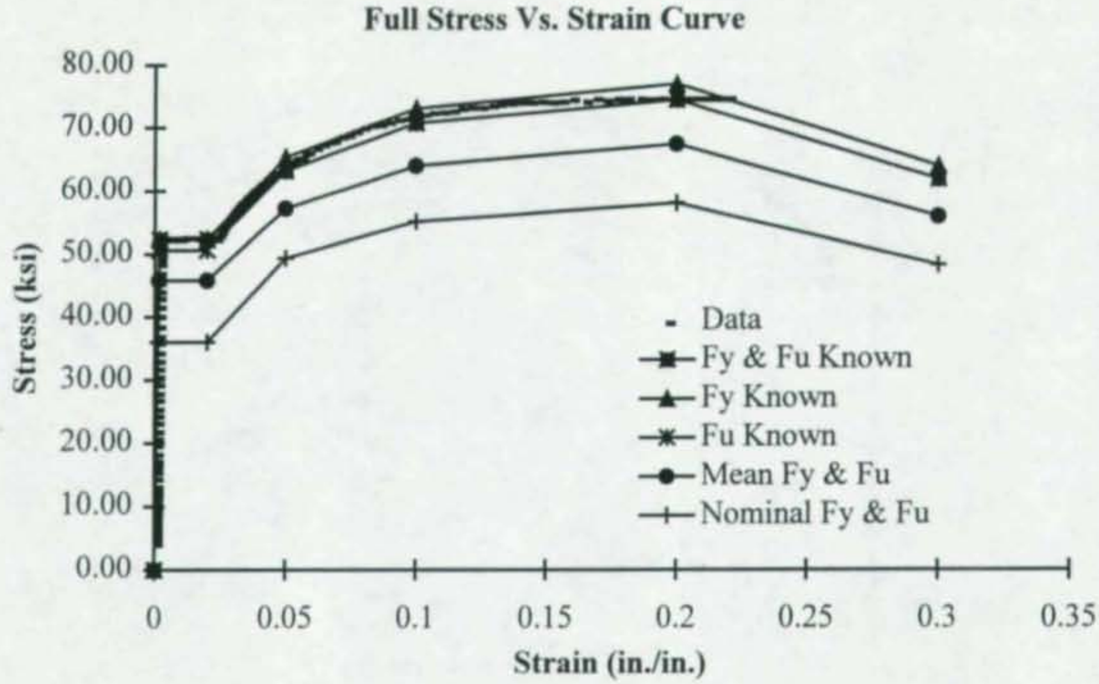

Full Stress Vs. Strain Curve
Stress (ksi)
Strain (in./in.)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

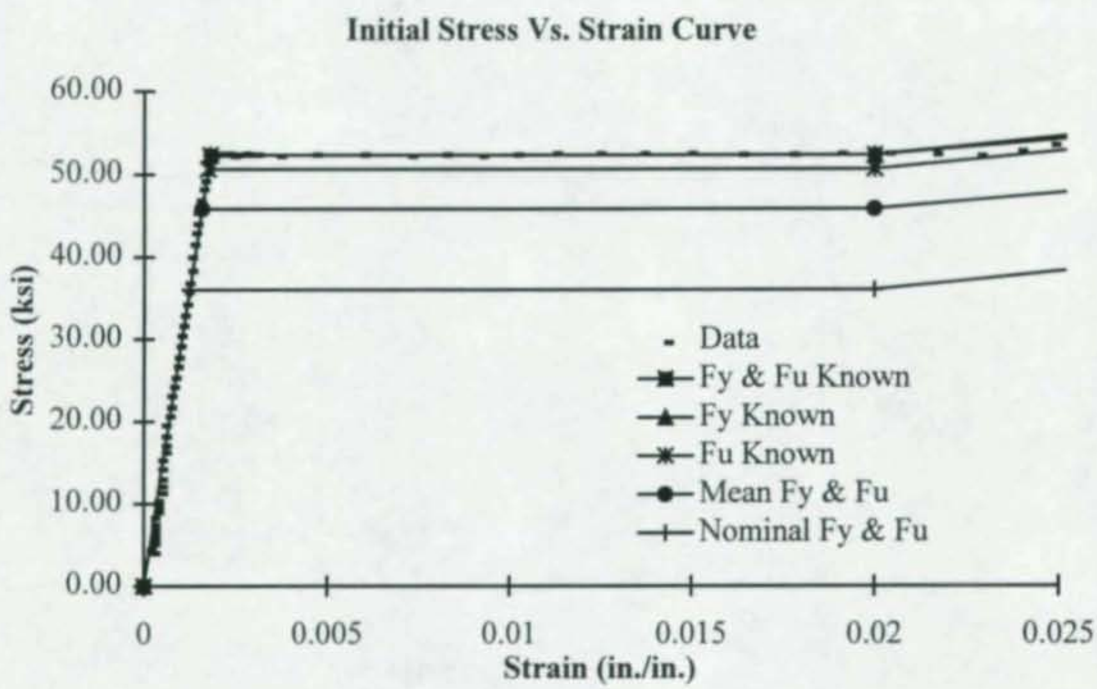

Initial Stress Vs. Strain Curve
Stress (ksi)
Strain (in./in.)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
0
0.005
0.01
0.015
0.02
0.025
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

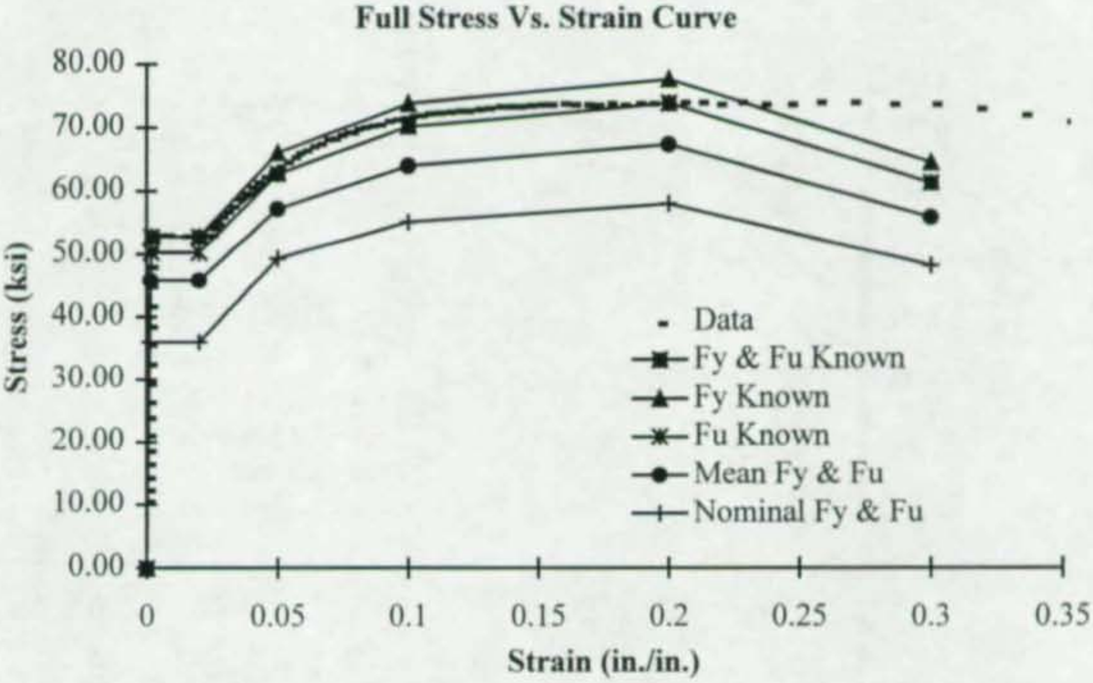
Mild Steel Stress-Strain Plots **Tensile Test: 34-1**

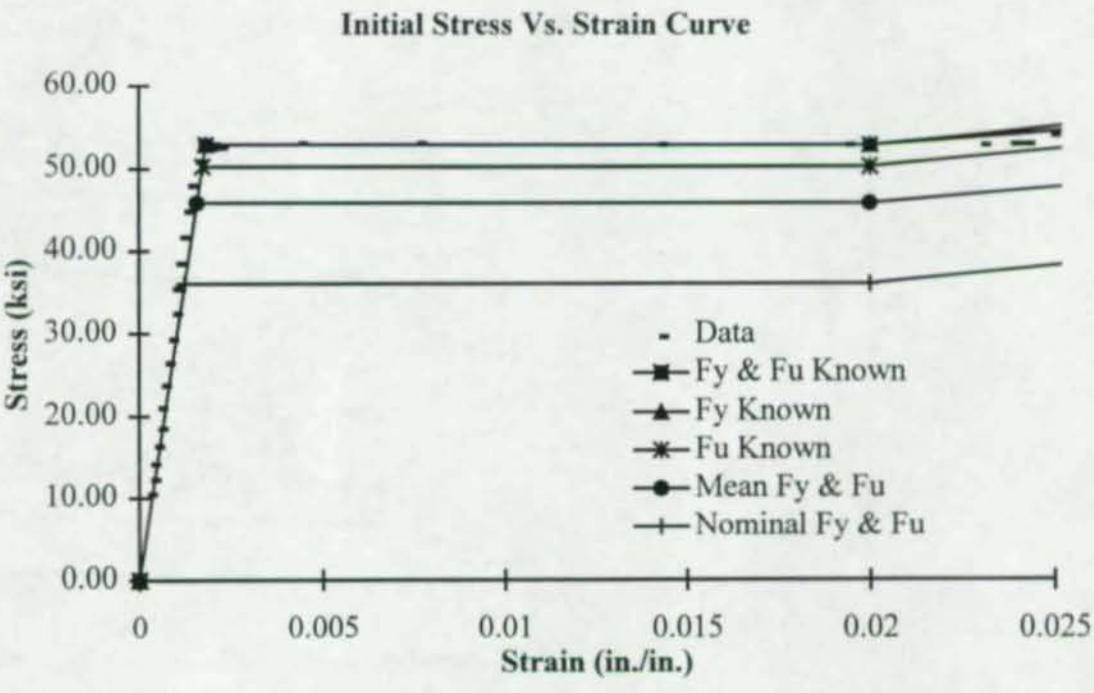


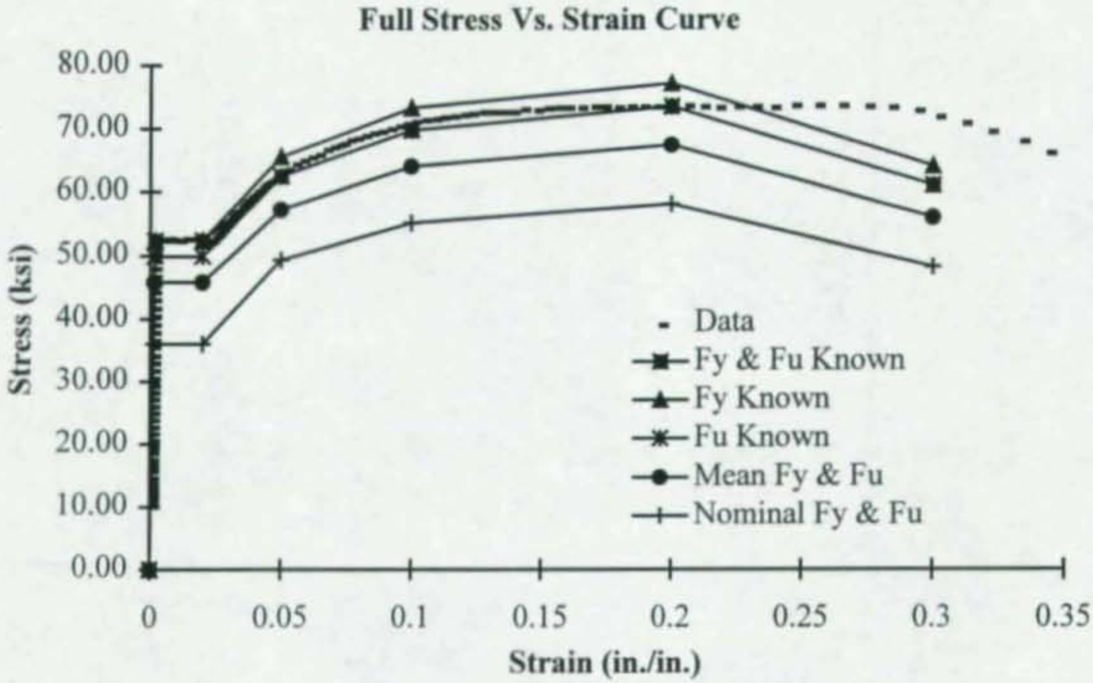


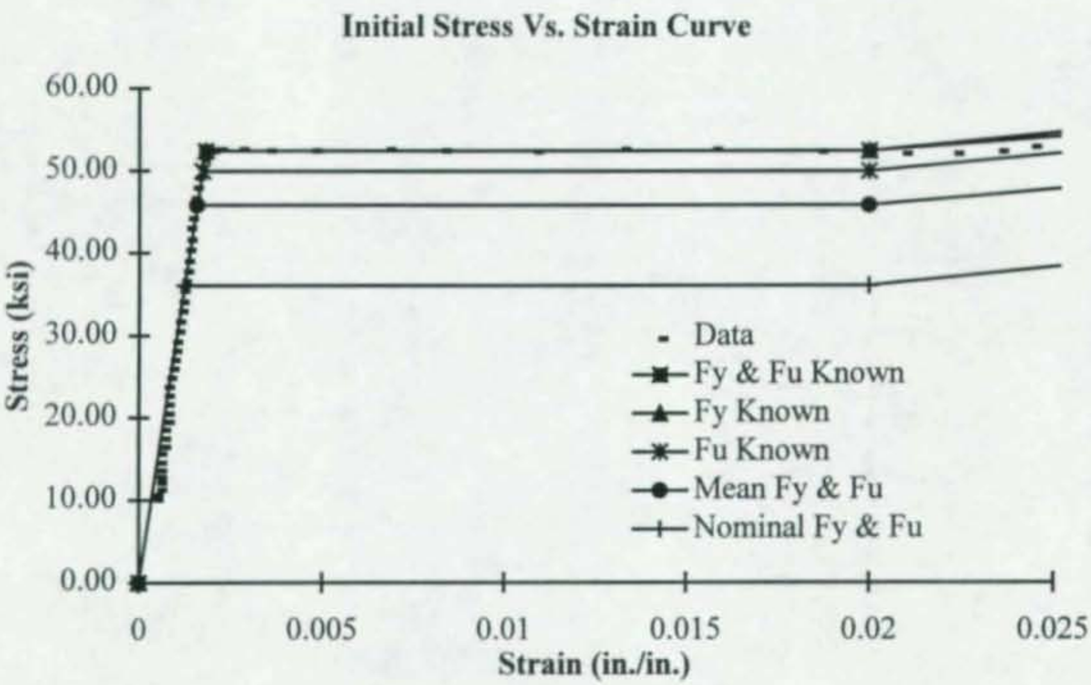

Full Stress Vs. Strain Curve
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)


Full Stress Vs. Strain Curve
Stress (ksi)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
Stress (ksi)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Full Stress Vs. Strain Curve
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu


Initial Stress Vs. Strain Curve
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Stress (ksi)
0
0.005
0.01
0.015
0.02
0.025
Strain (in./in.)
Data
Fy & Fu Known
Fy Known
Fu Known
Mean Fy & Fu
Nominal Fy & Fu

Appendix D

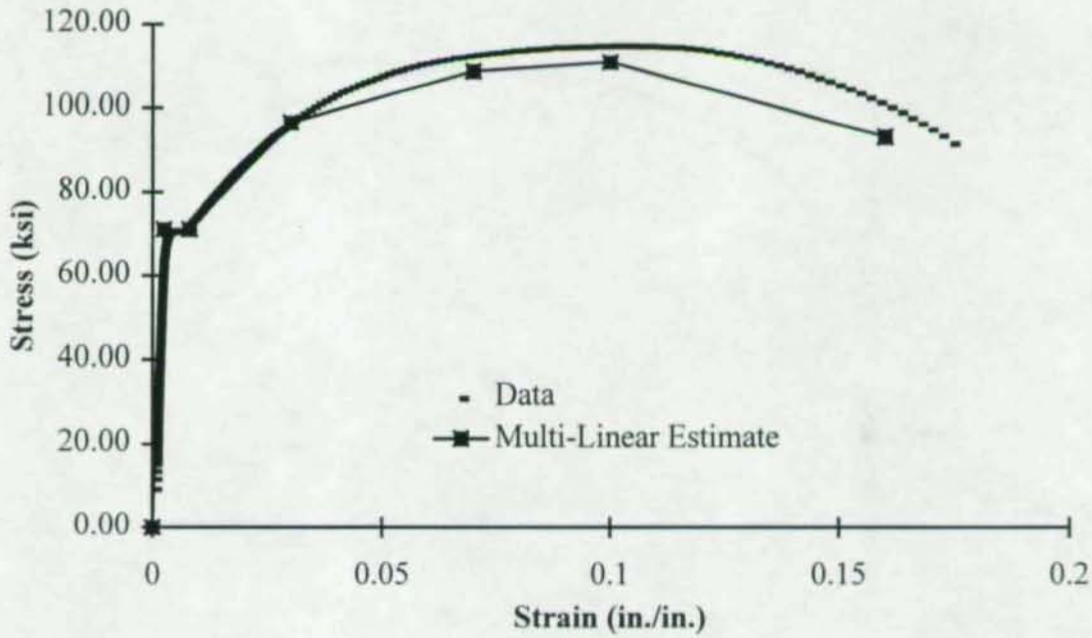
Tensile Tests Conducted At Virginia Tech
Reporting Full Stress-Strain Data
Reinforcing Steel

Table D-1
Reinforcing Steel Coupon Dimensions

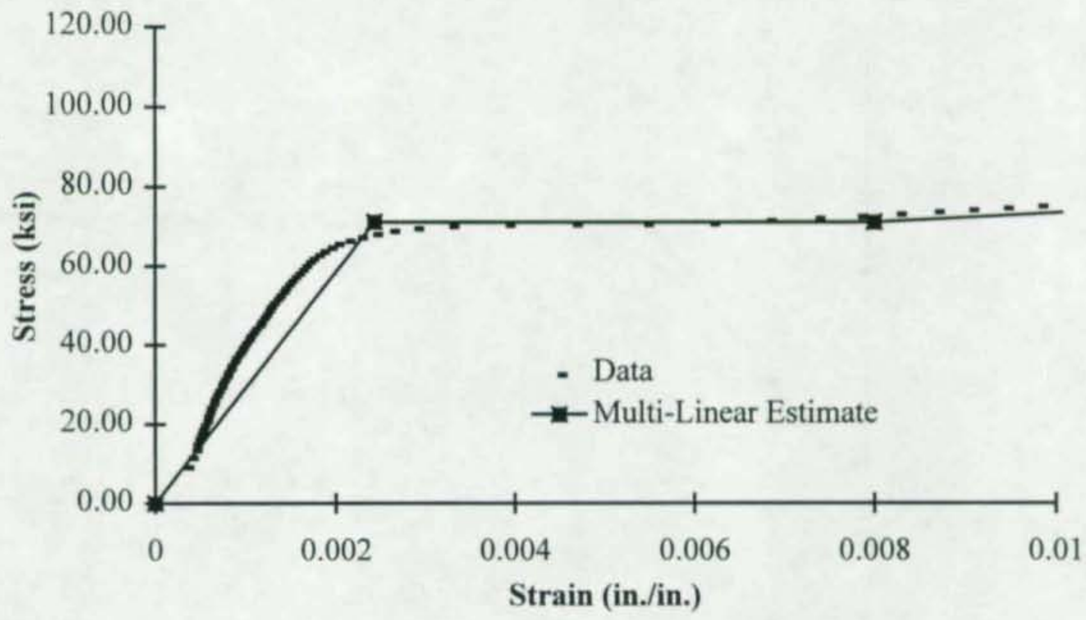
Coupon Designation	Average Diameter (in.)	Average Area (in.^2)	Initial Gage (in.)
1-1&2a	0.346	0.094	1.980
1-3&4a	0.340	0.091	1.983
1-3&4b	0.340	0.091	2.032
1-3&4c	0.342	0.092	2.056
2-1&2a	0.345	0.093	2.042
2-1&2b	0.349	0.096	2.067
2-1&2c	0.334	0.088	2.071
2-3&4a	0.344	0.093	2.050
3-1&2a	0.340	0.091	2.065
3-1&2b	0.335	0.088	2.074
3-1&2c	0.344	0.093	2.040
3-3&4a	0.344	0.093	1.989
3-3&4b	0.329	0.085	2.018
3-3&4c	0.341	0.091	2.102
4-1&2a	0.338	0.090	2.044
4-3&4a	0.343	0.092	2.026
4-3&4b	0.347	0.095	2.047
4-3&4c	0.346	0.094	2.109
5-1&2a	0.345	0.093	2.028
5-3&4a	0.350	0.096	2.079
6-3&4a	0.334	0.088	2.057

Reinforcing Steel Stress-Strain Plots **Tensile Test: 1-1&2a**

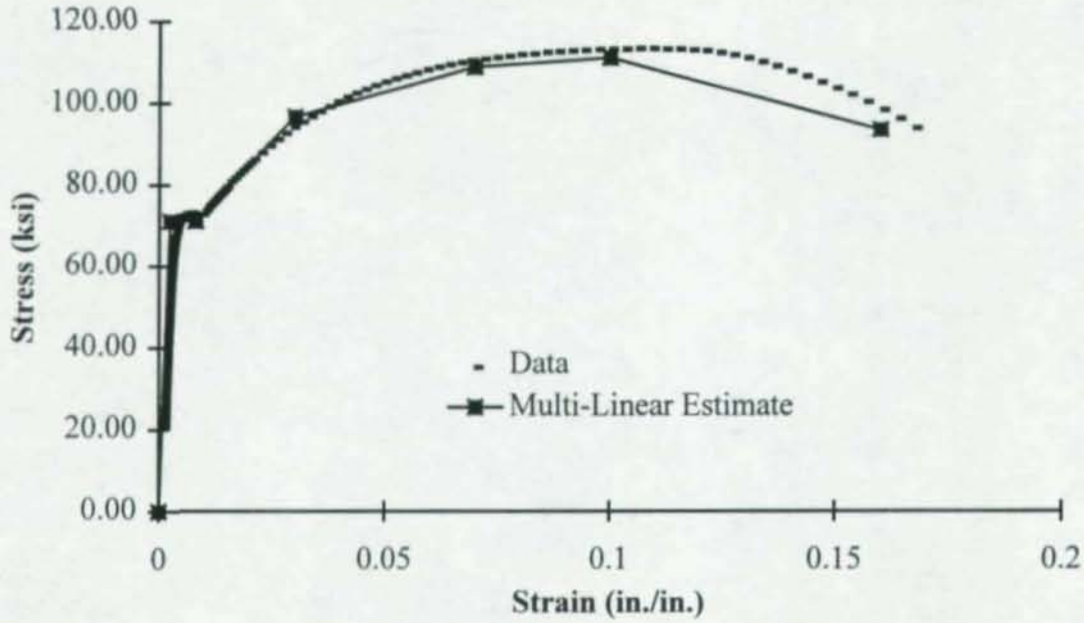
Full Stress Vs. Strain Curve



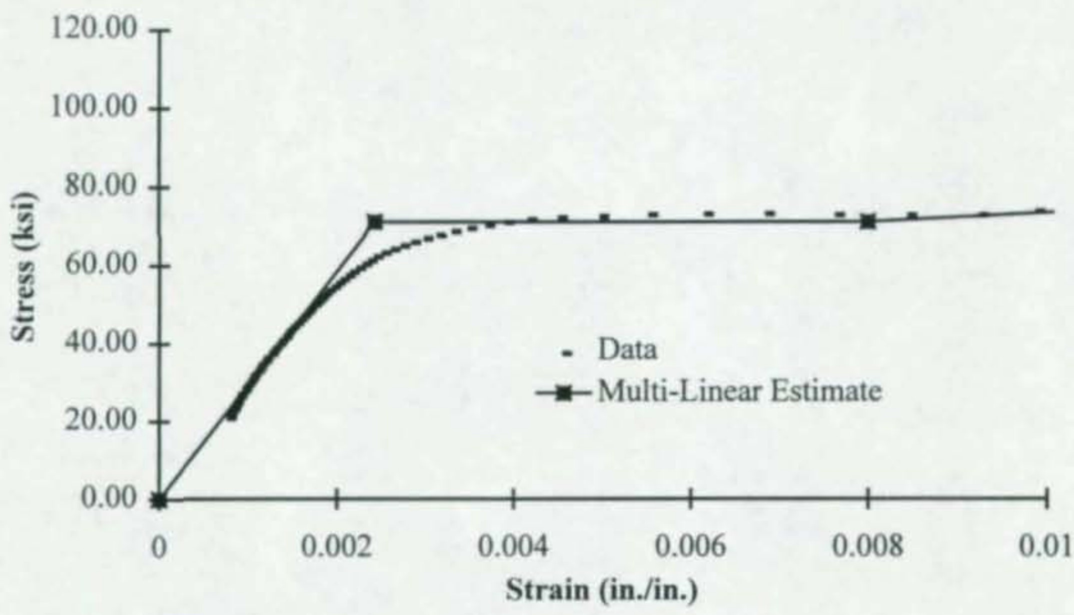
Initial Stress Vs. Strain Curve



Full Stress Vs. Strain Curve

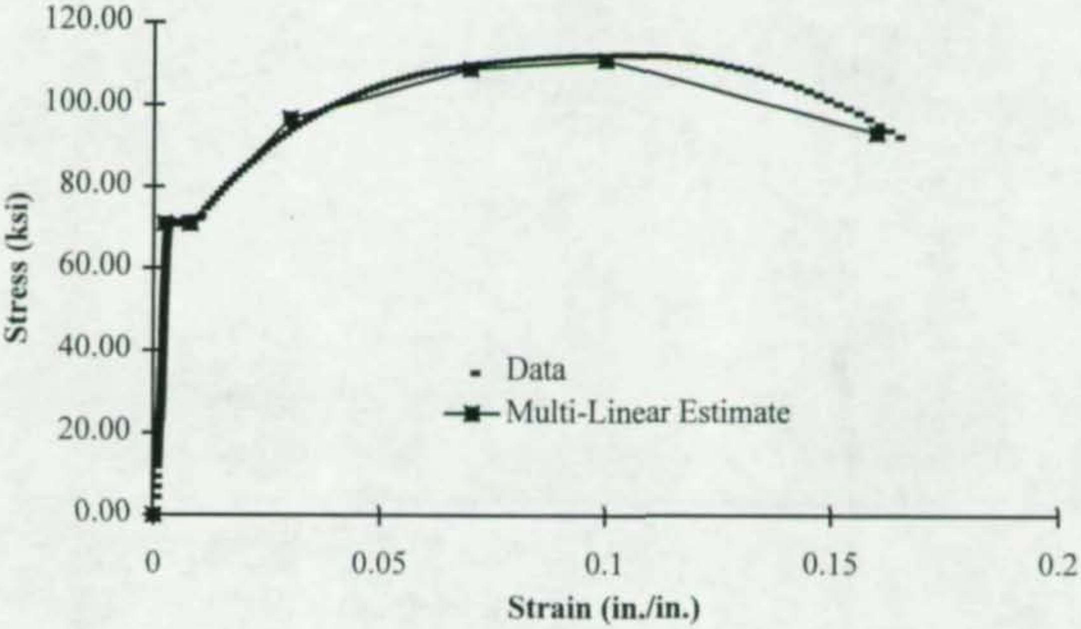


Initial Stress Vs. Strain Curve

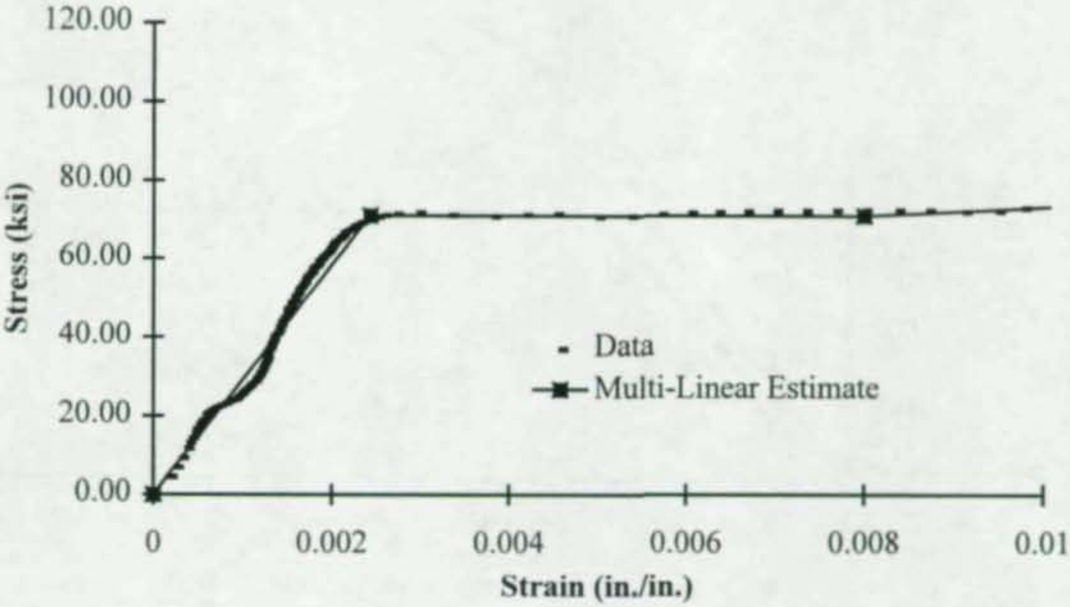


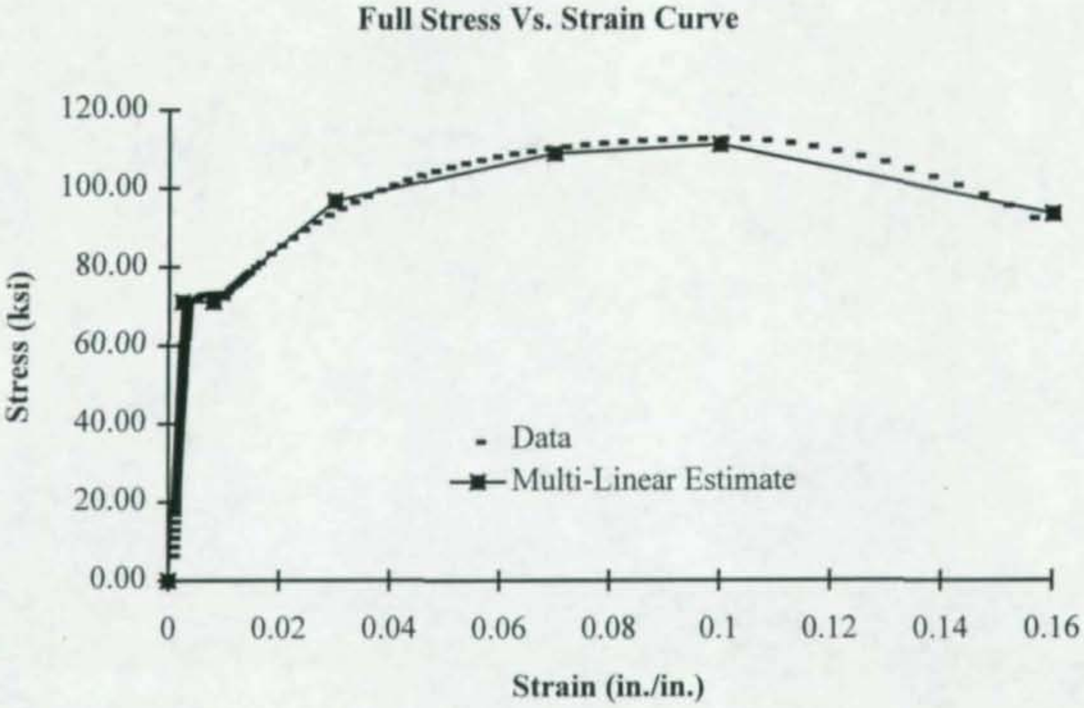
Reinforcing Steel Stress-Strain Plots Tensile Test: 1-3&4b

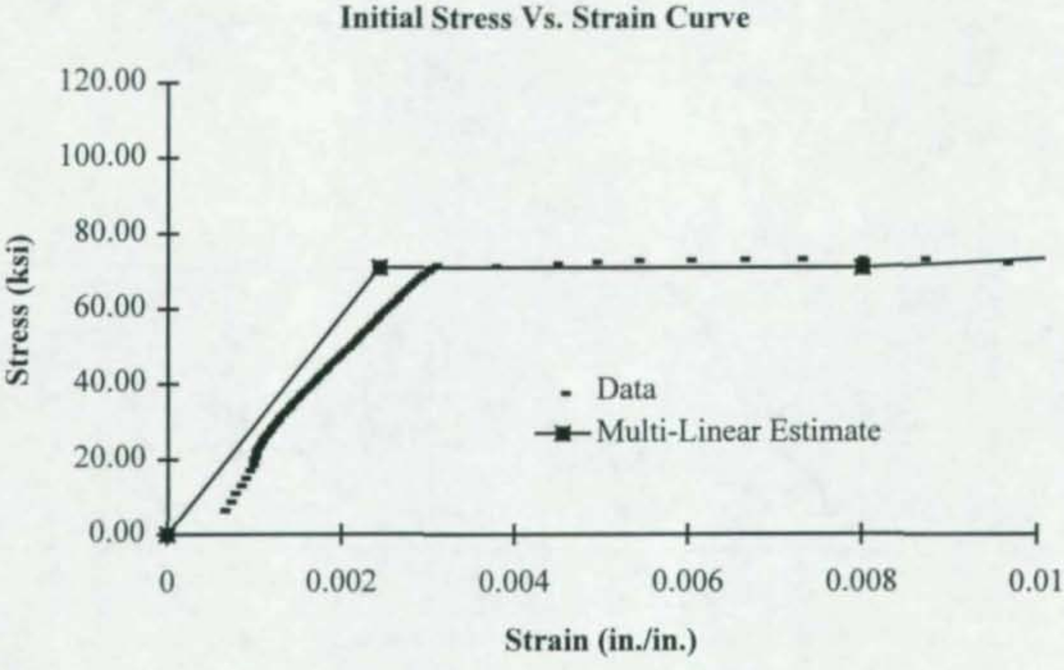
Full Stress Vs. Strain Curve



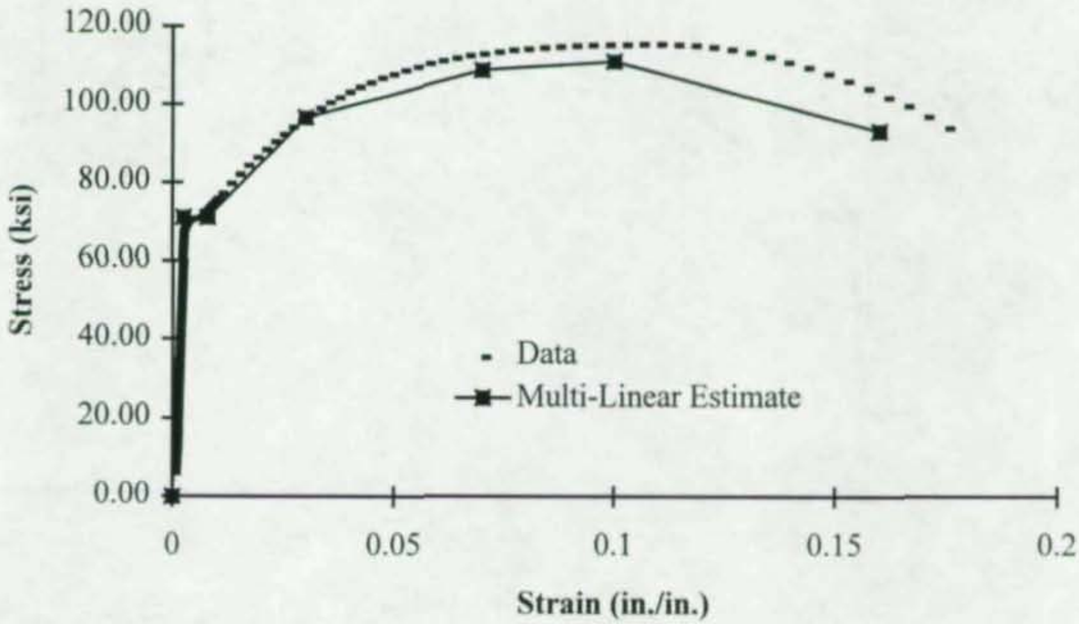
Initial Stress Vs. Strain Curve



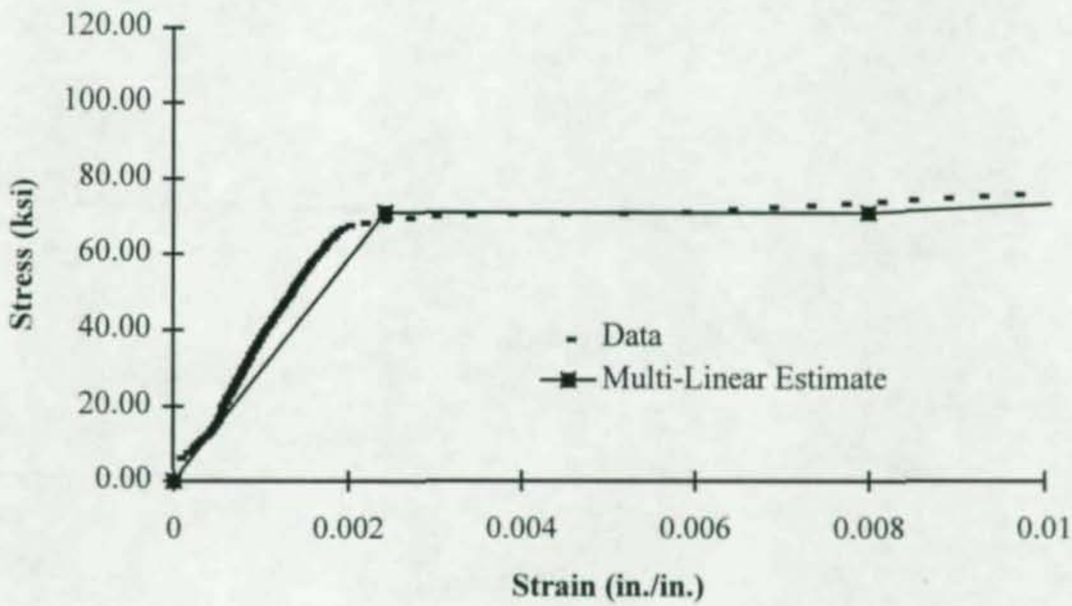

Full Stress Vs. Strain Curve
Stress (ksi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Strain (in./in.)
Data
Multi-Linear Estimate


Initial Stress Vs. Strain Curve
Stress (ksi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
0.002
0.004
0.006
0.008
0.01
Strain (in./in.)
Data
Multi-Linear Estimate

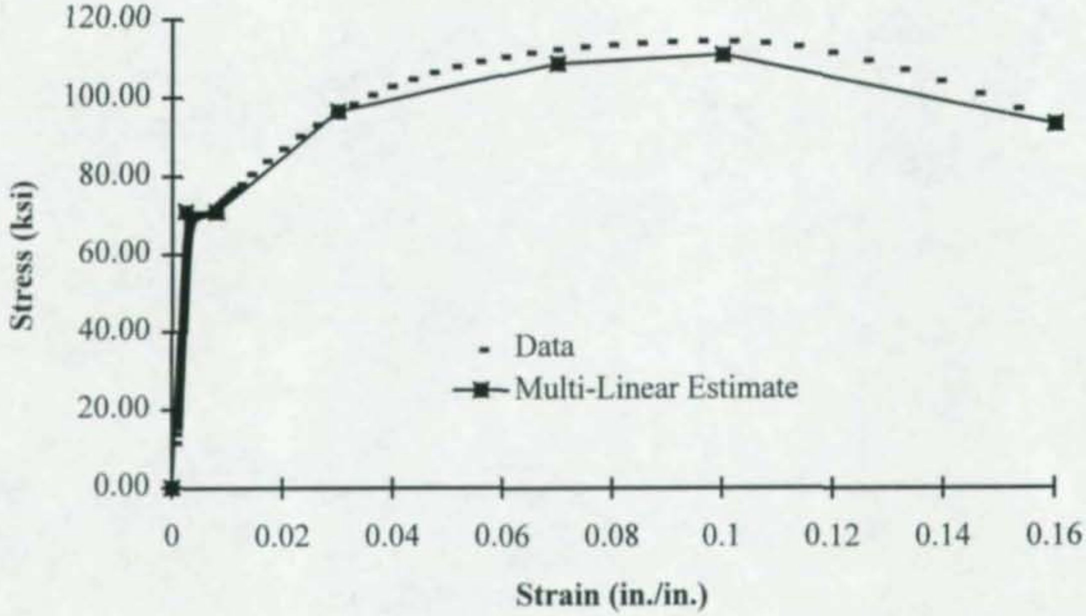
Full Stress Vs. Strain Curve



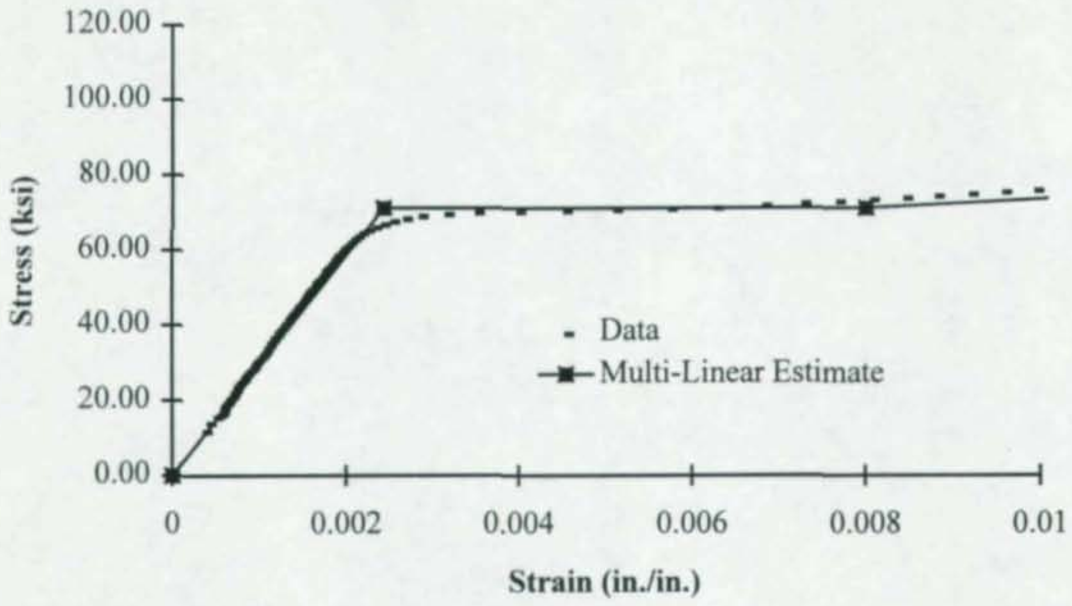
Initial Stress Vs. Strain Curve



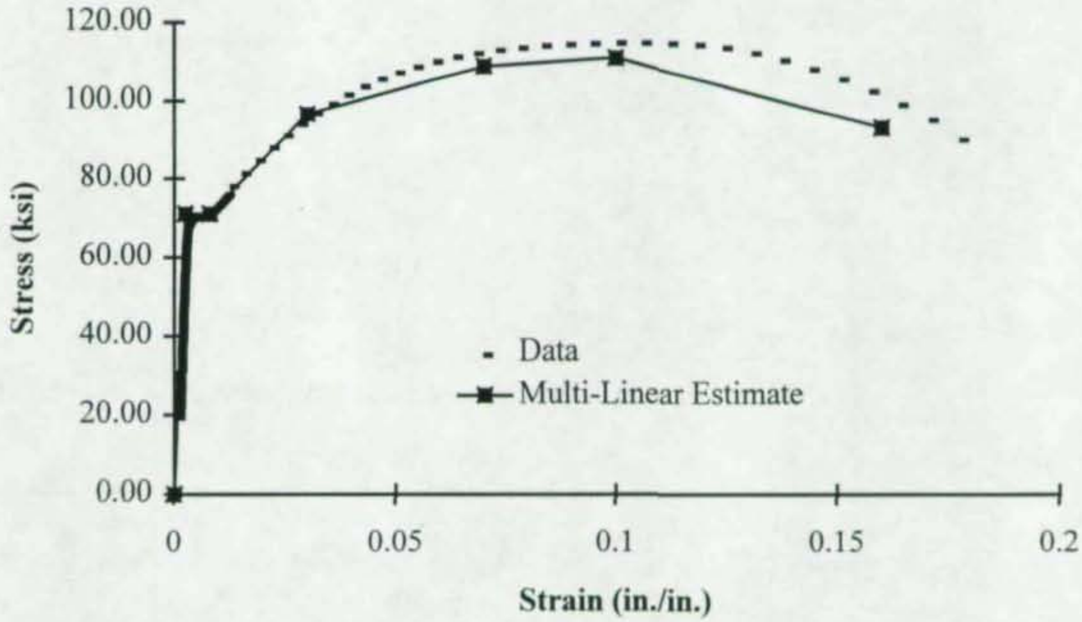
Full Stress Vs. Strain Curve



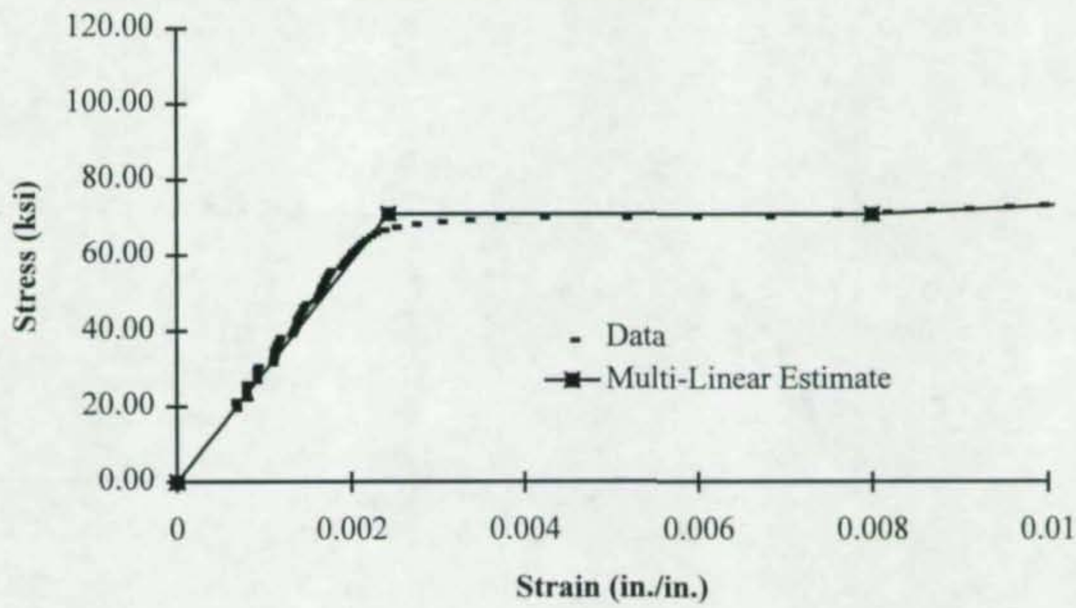
Initial Stress Vs. Strain Curve

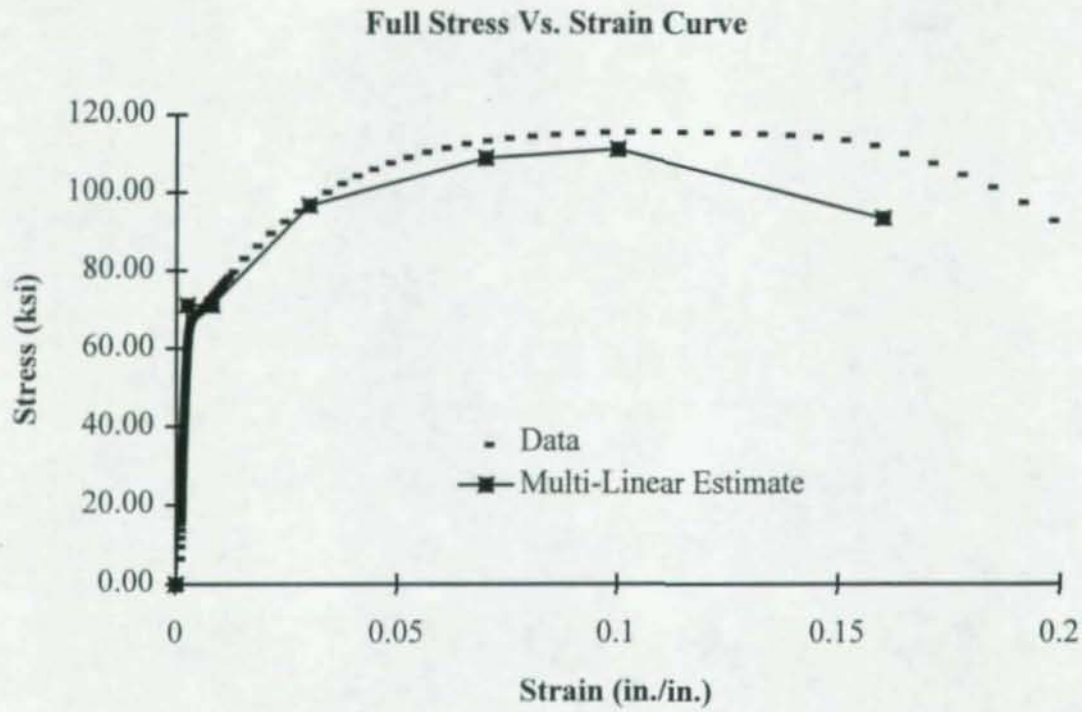


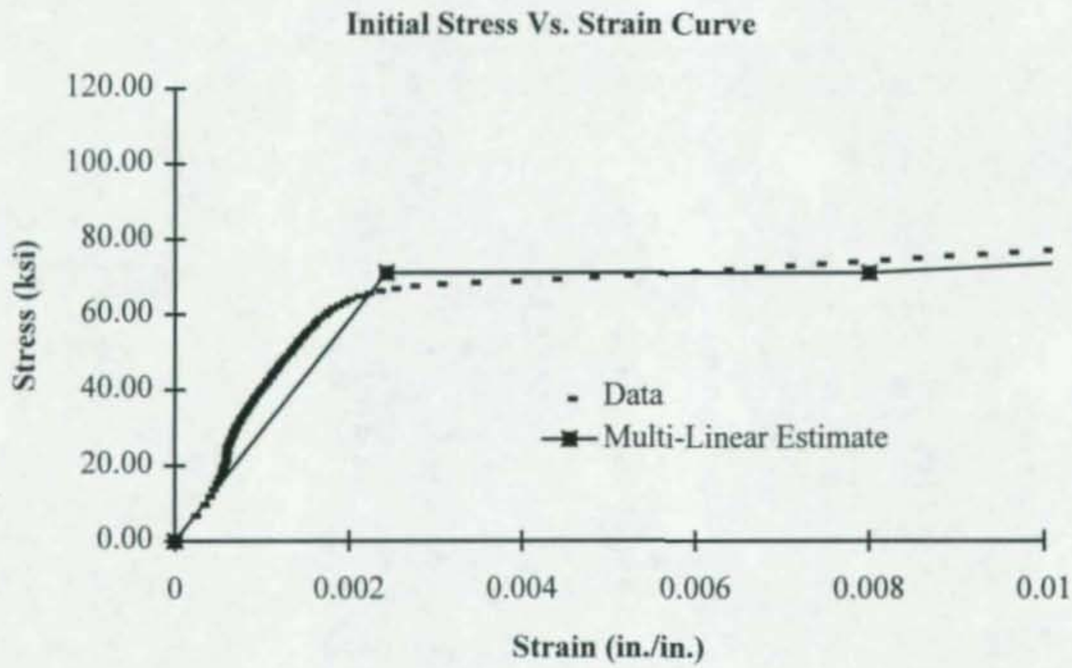
Full Stress Vs. Strain Curve

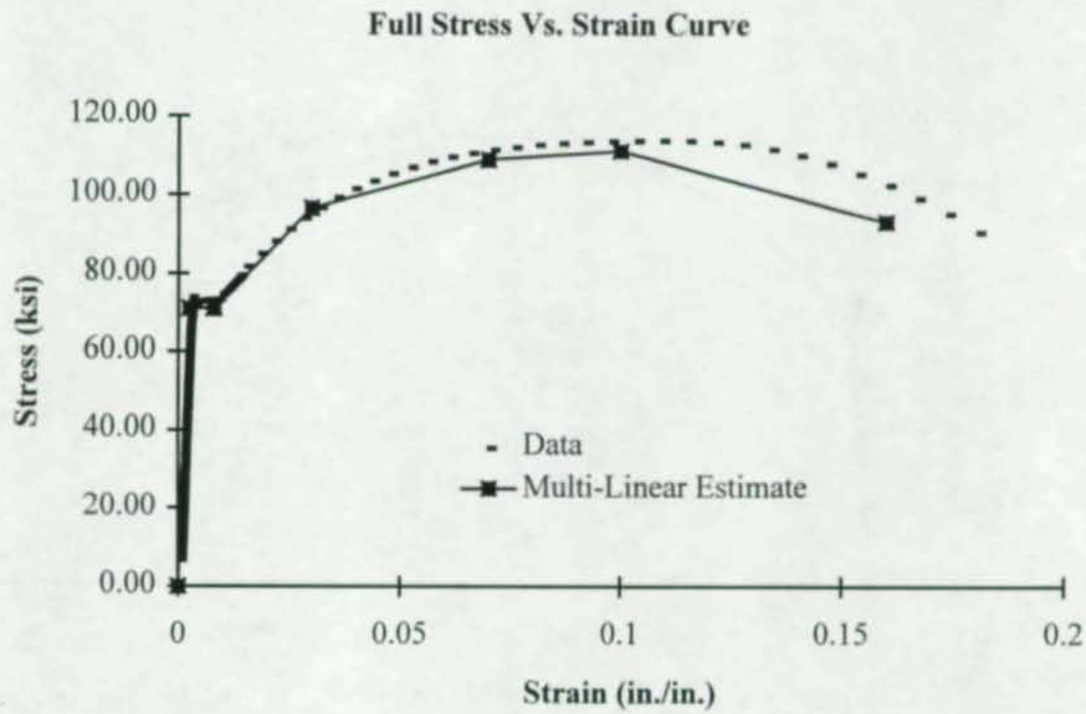


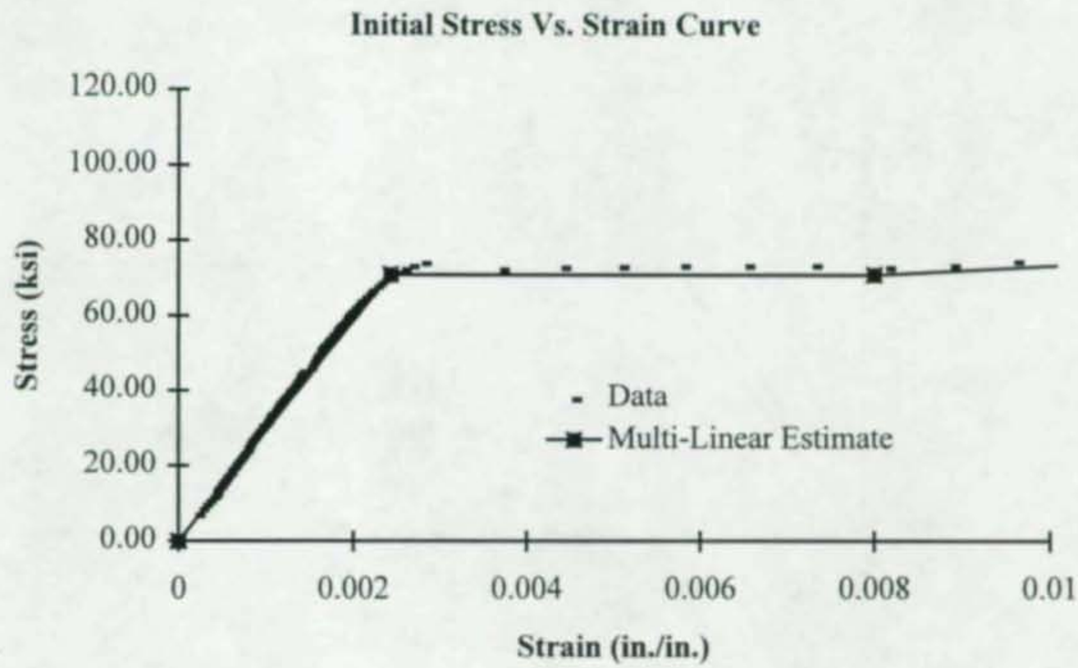
Initial Stress Vs. Strain Curve



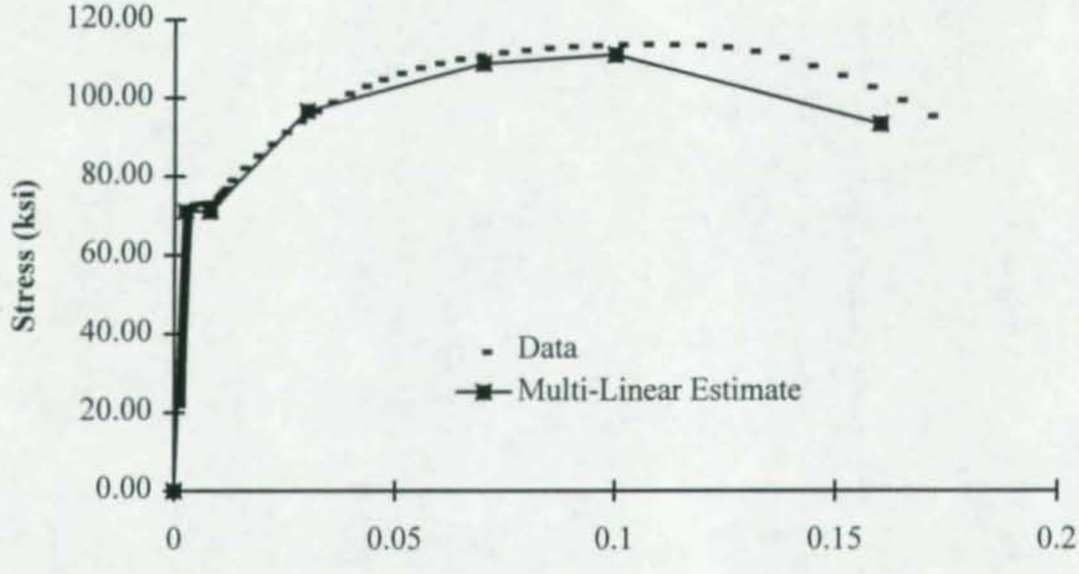

Full Stress Vs. Strain Curve
Stress (ksi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
0.05
0.1
0.15
0.2
Strain (in./in.)
Data
Multi-Linear Estimate


Initial Stress Vs. Strain Curve
Stress (ksi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
0.002
0.004
0.006
0.008
0.01
Strain (in./in.)
Data
Multi-Linear Estimate

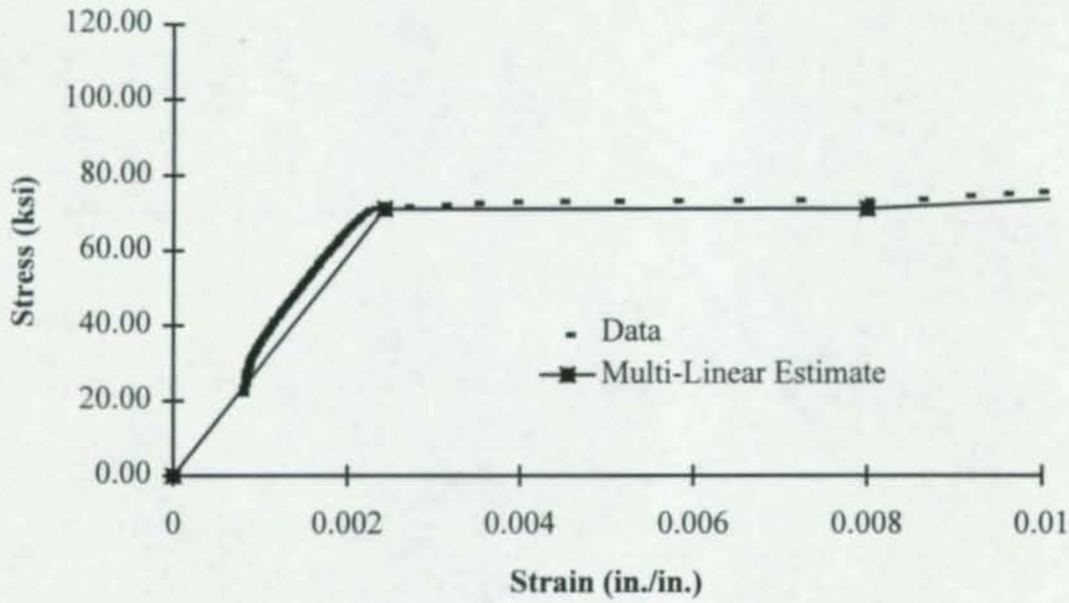

Full Stress Vs. Strain Curve
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Stress (ksi)
0
0.05
0.1
0.15
0.2
Strain (in./in.)
Data
Multi-Linear Estimate


Initial Stress Vs. Strain Curve
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Stress (ksi)
0
0.002
0.004
0.006
0.008
0.01
Strain (in./in.)
Data
Multi-Linear Estimate

Full Stress Vs. Strain Curve

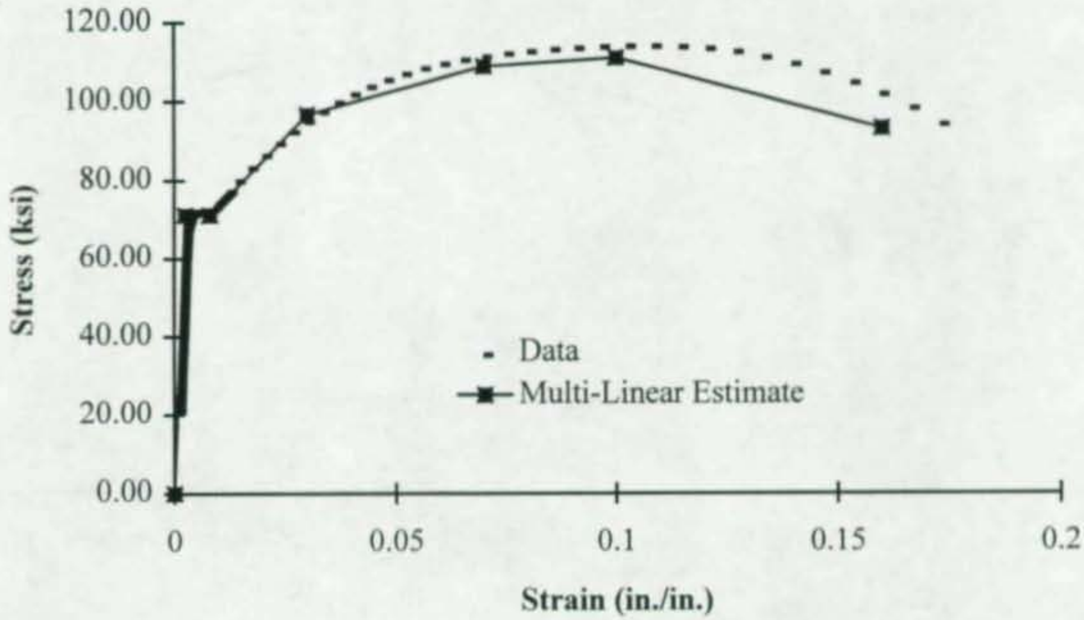


Initial Stress Vs. Strain Curve

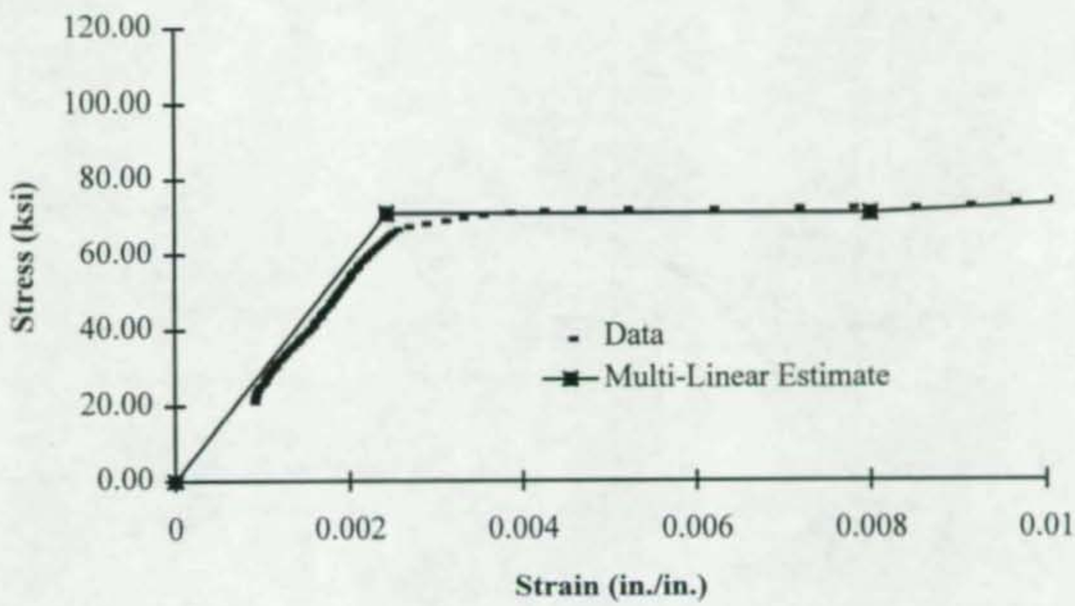


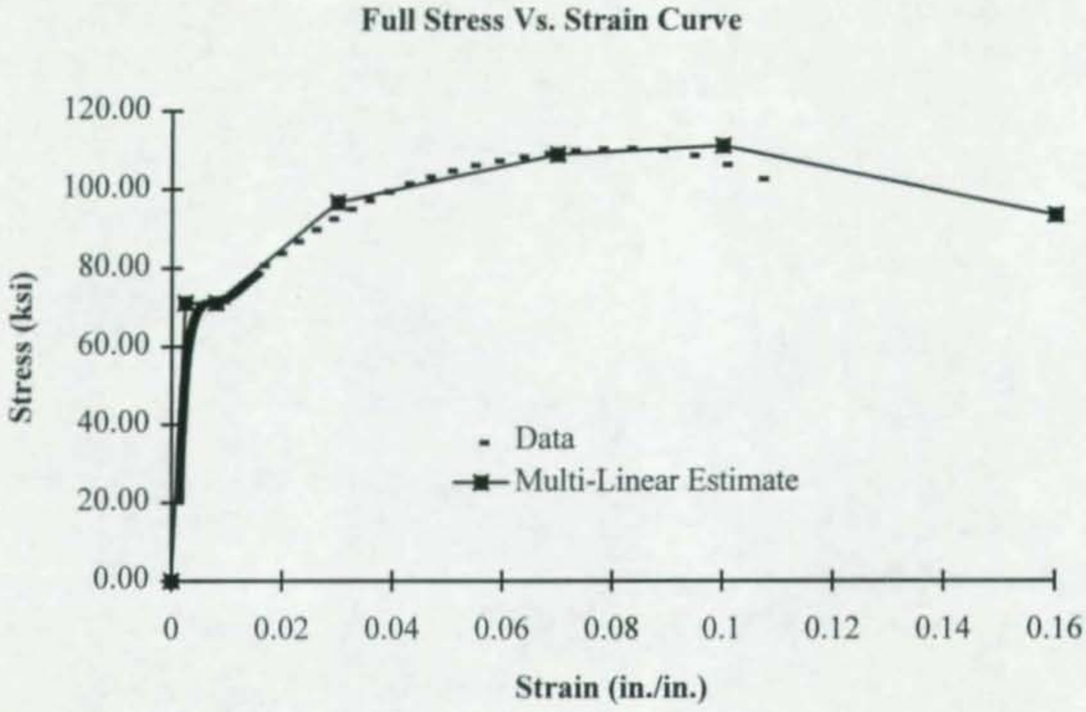
Reinforcing Steel Stress-Strain Plots **Tensile Test: 3-1&2c**

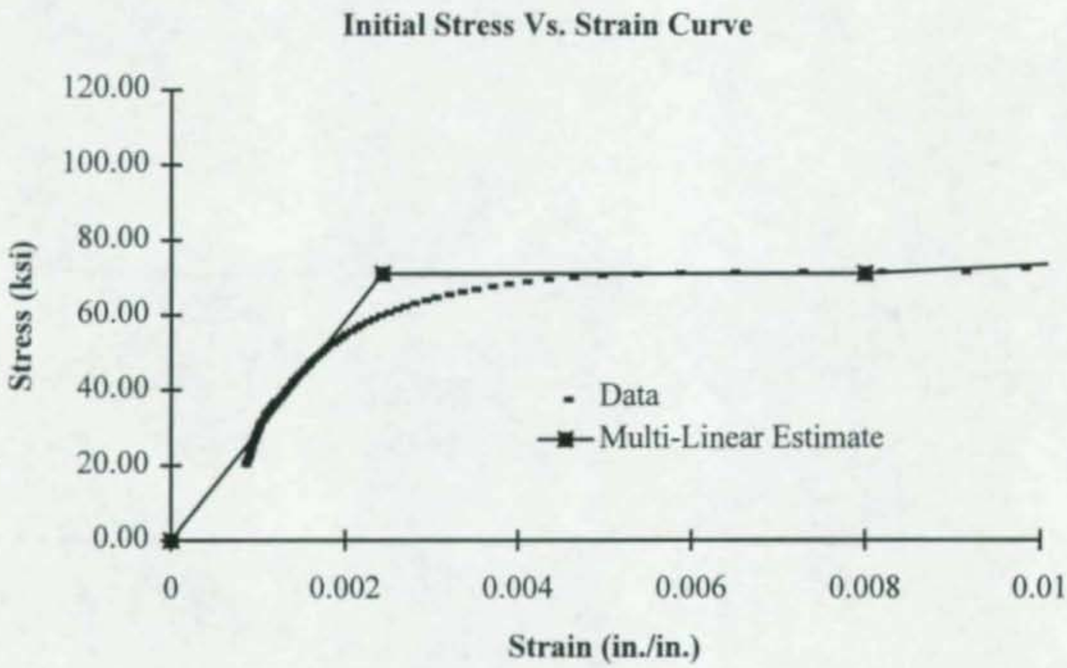
Full Stress Vs. Strain Curve

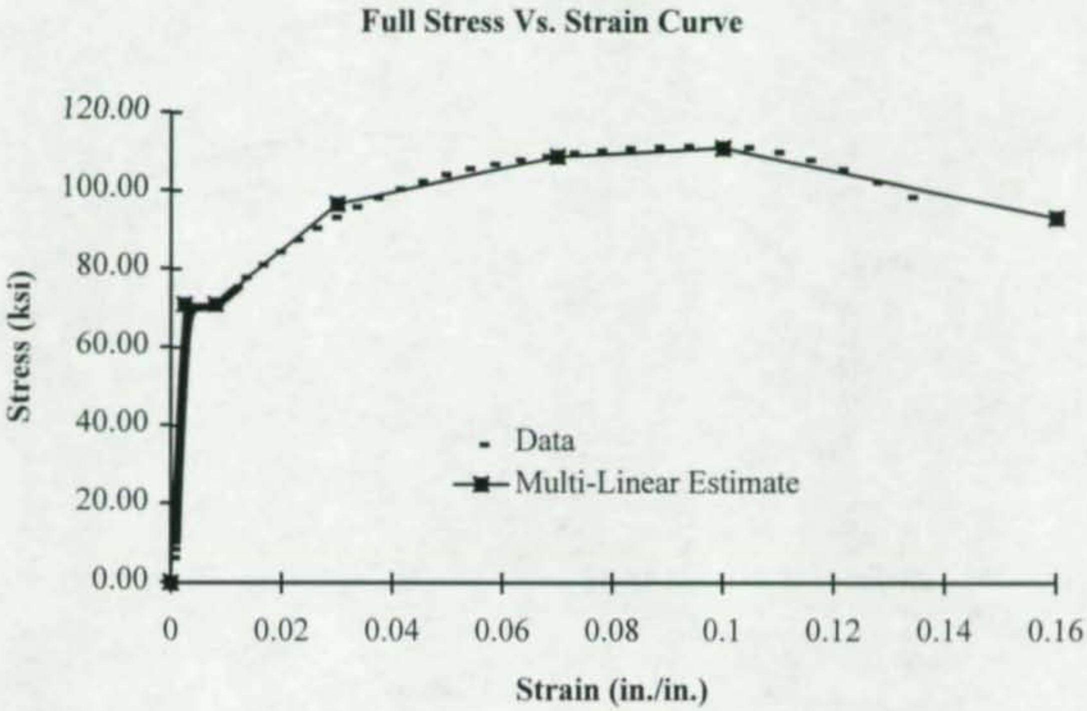


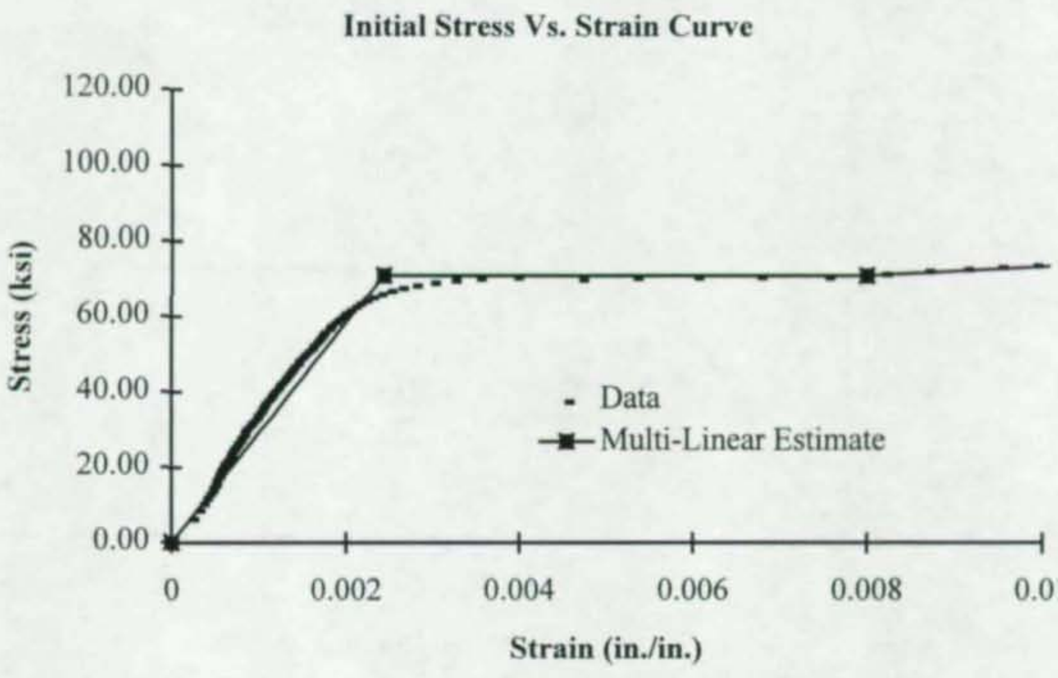
Initial Stress Vs. Strain Curve



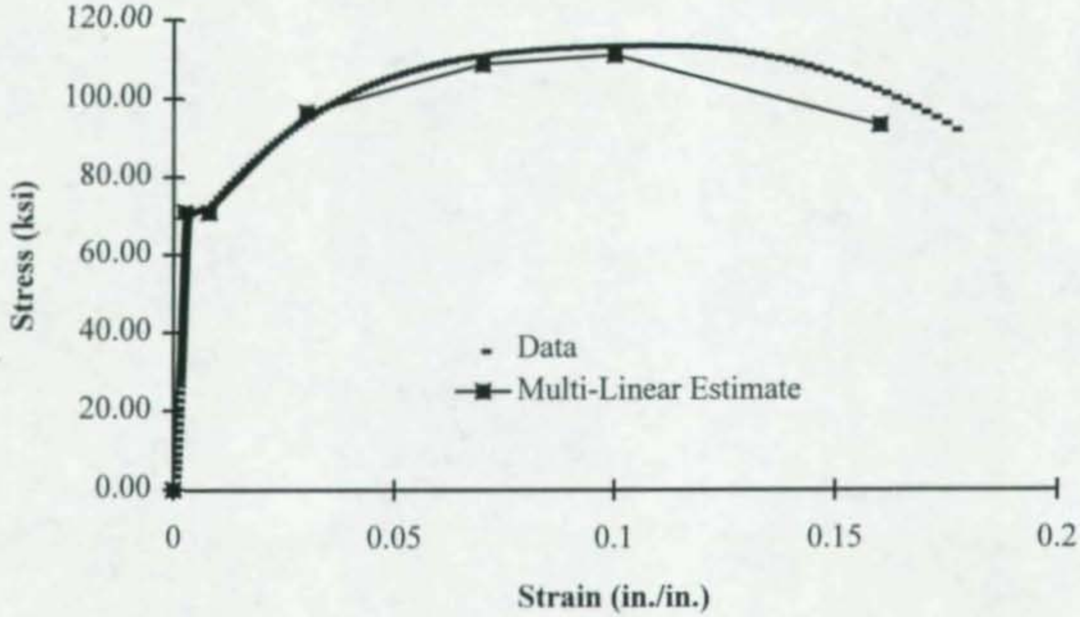

Full Stress Vs. Strain Curve
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Stress (ksi)
Data
Multi-Linear Estimate
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Strain (in./in.)


Initial Stress Vs. Strain Curve
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Stress (ksi)
Data
Multi-Linear Estimate
0
0.002
0.004
0.006
0.008
0.01
Strain (in./in.)

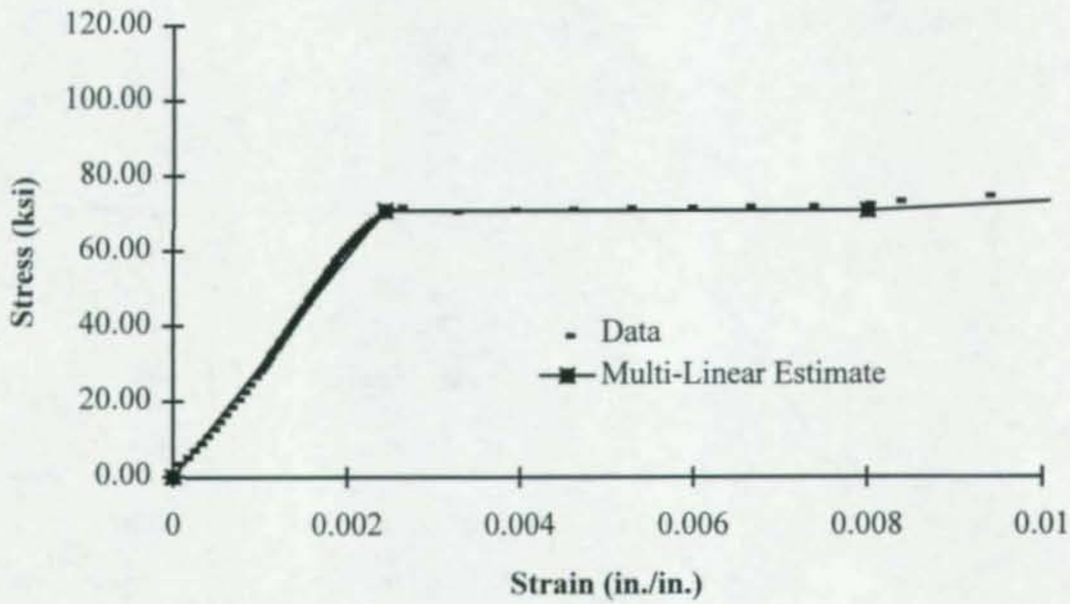

Full Stress Vs. Strain Curve
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Stress (ksi)
Data
Multi-Linear Estimate
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Strain (in./in.)


Initial Stress Vs. Strain Curve
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Stress (ksi)
Data
Multi-Linear Estimate
0
0.002
0.004
0.006
0.008
0.01
Strain (in./in.)

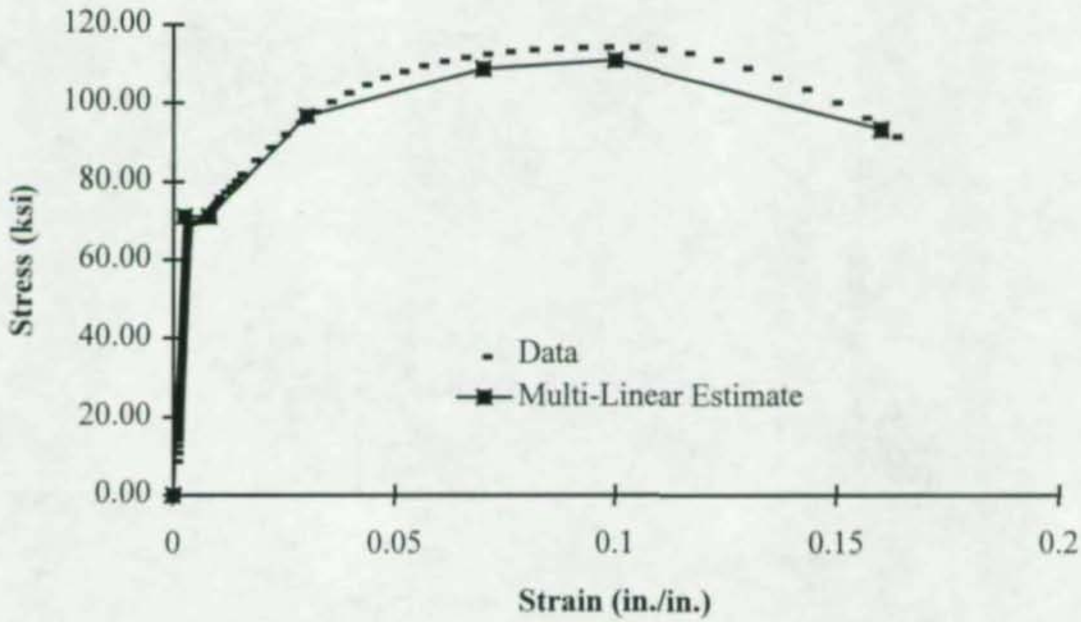
Full Stress Vs. Strain Curve



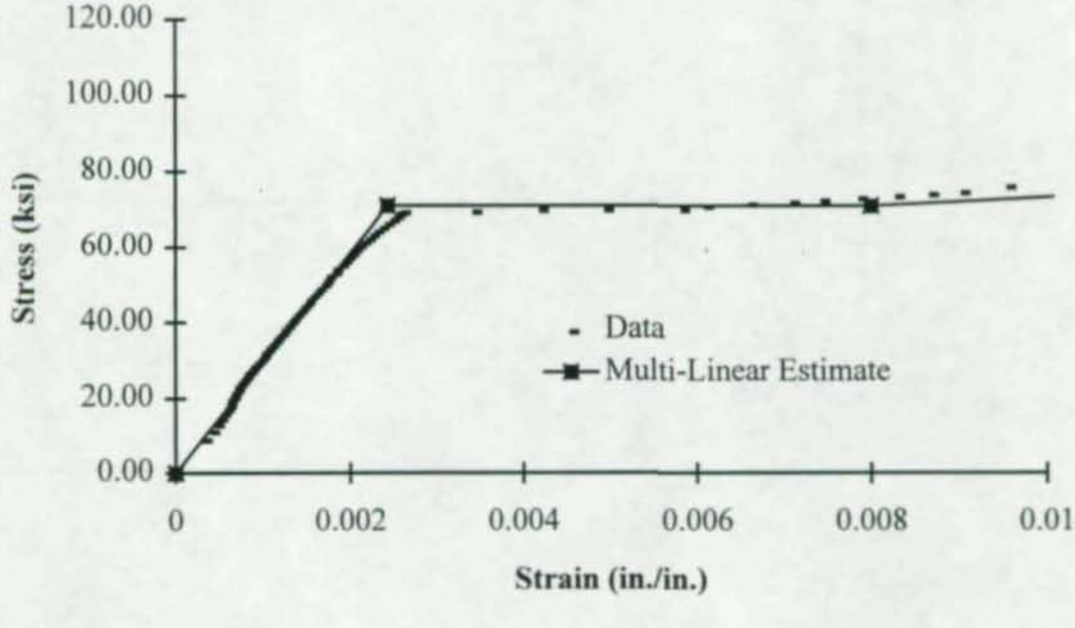
Initial Stress Vs. Strain Curve



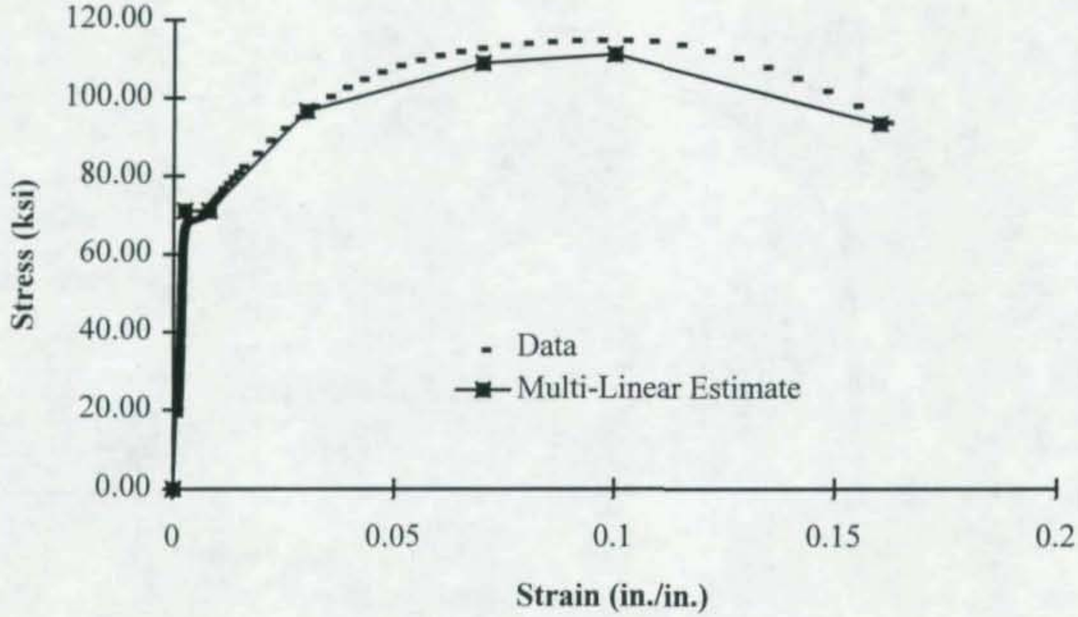
Full Stress Vs. Strain Curve



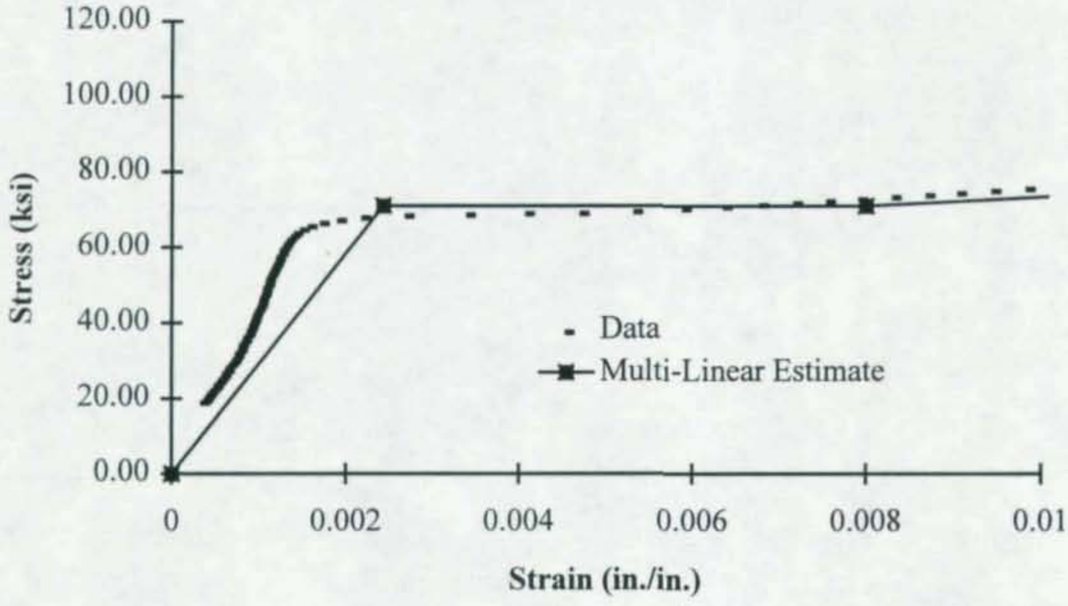
Initial Stress Vs. Strain Curve



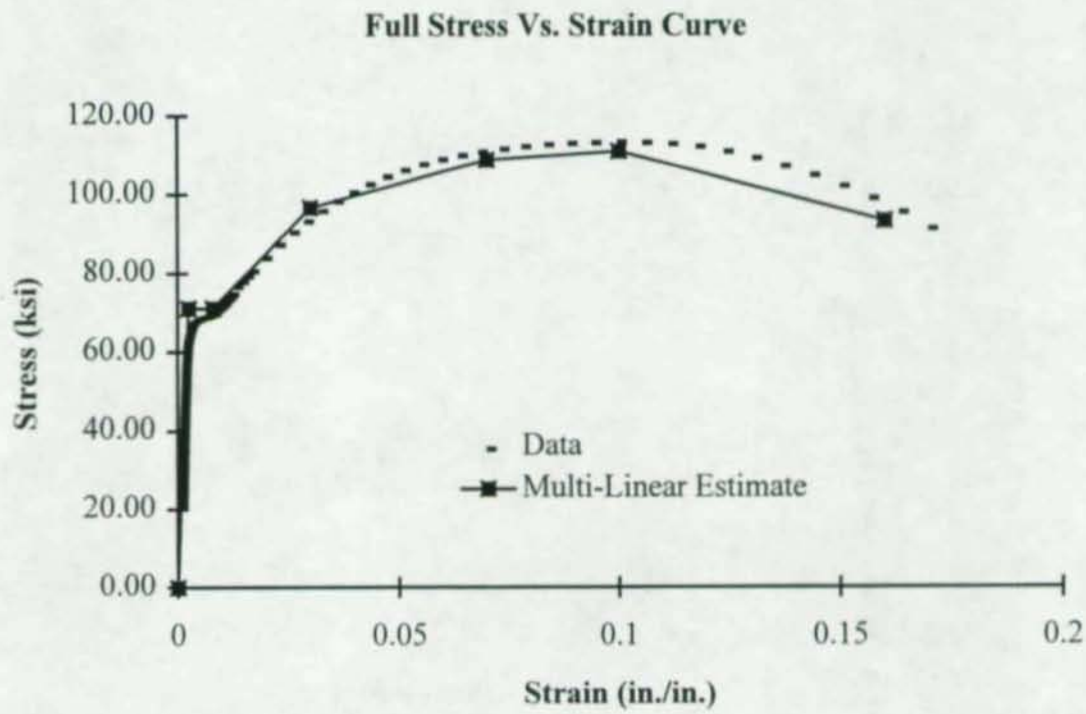
Full Stress Vs. Strain Curve

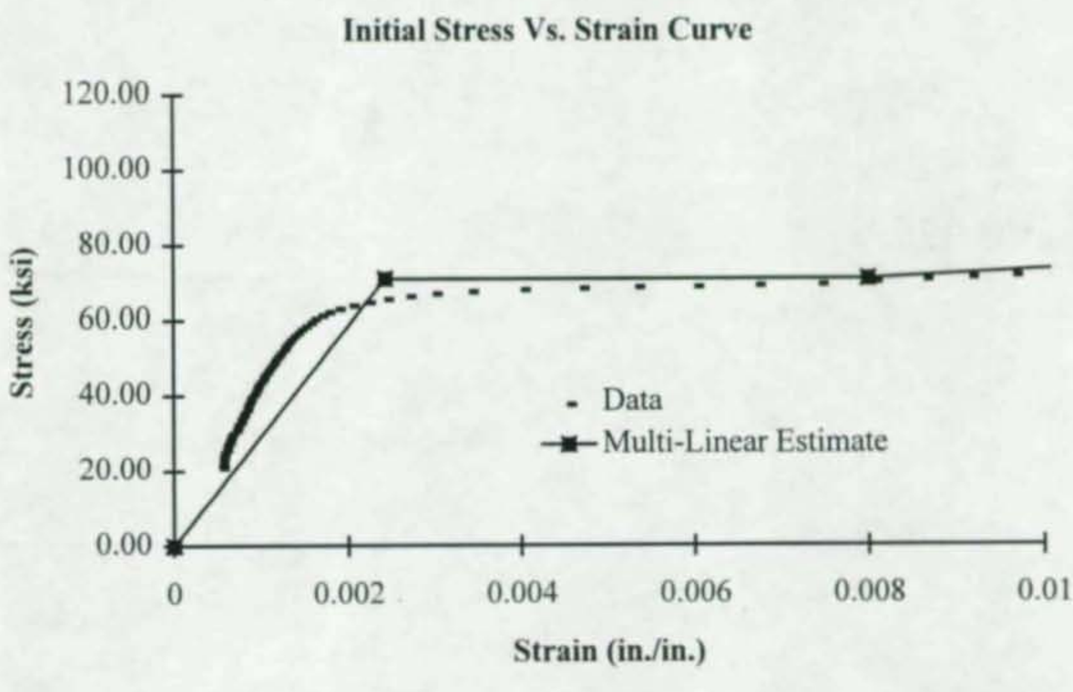


Initial Stress Vs. Strain Curve

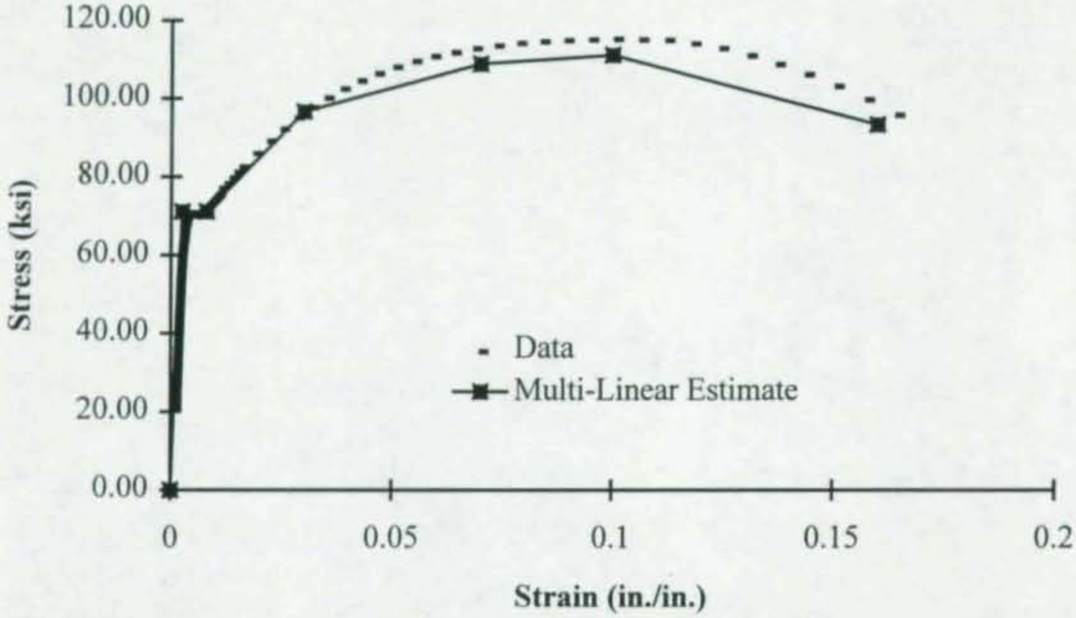


Reinforcing Steel Stress-Strain Plots **Tensile Test: 4-3&4b**

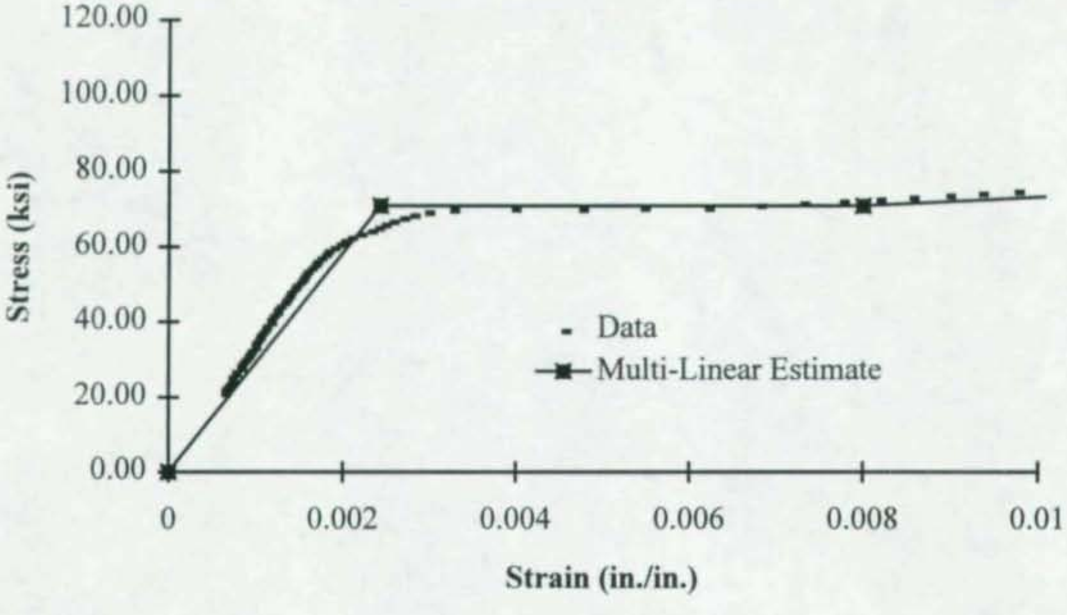


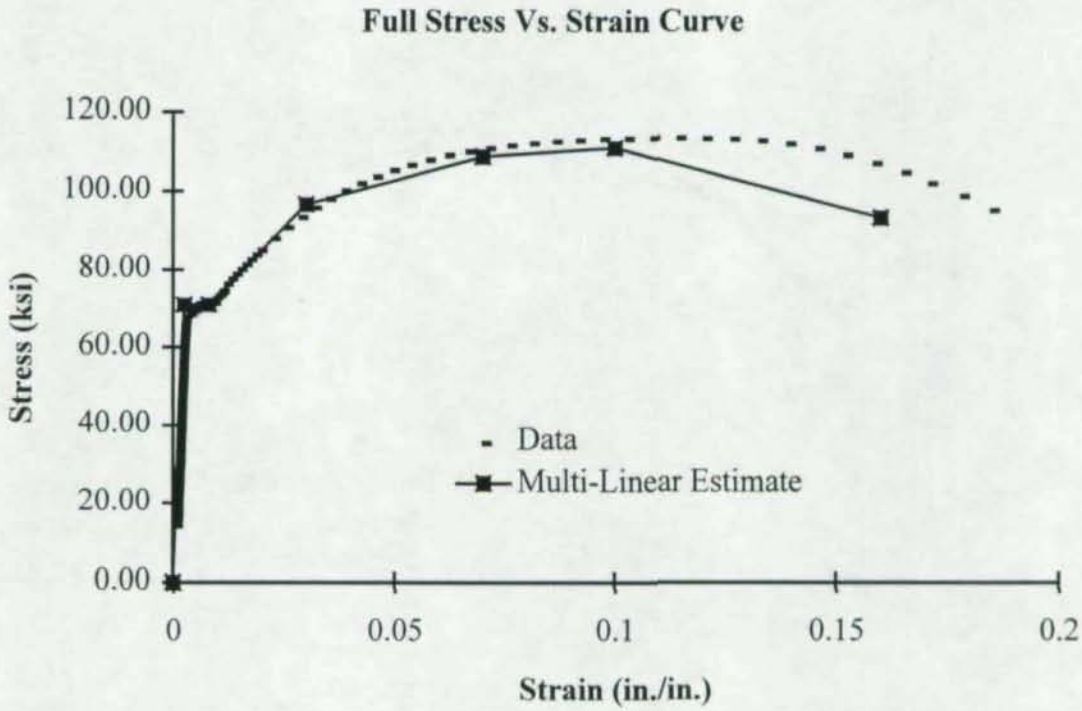


Full Stress Vs. Strain Curve

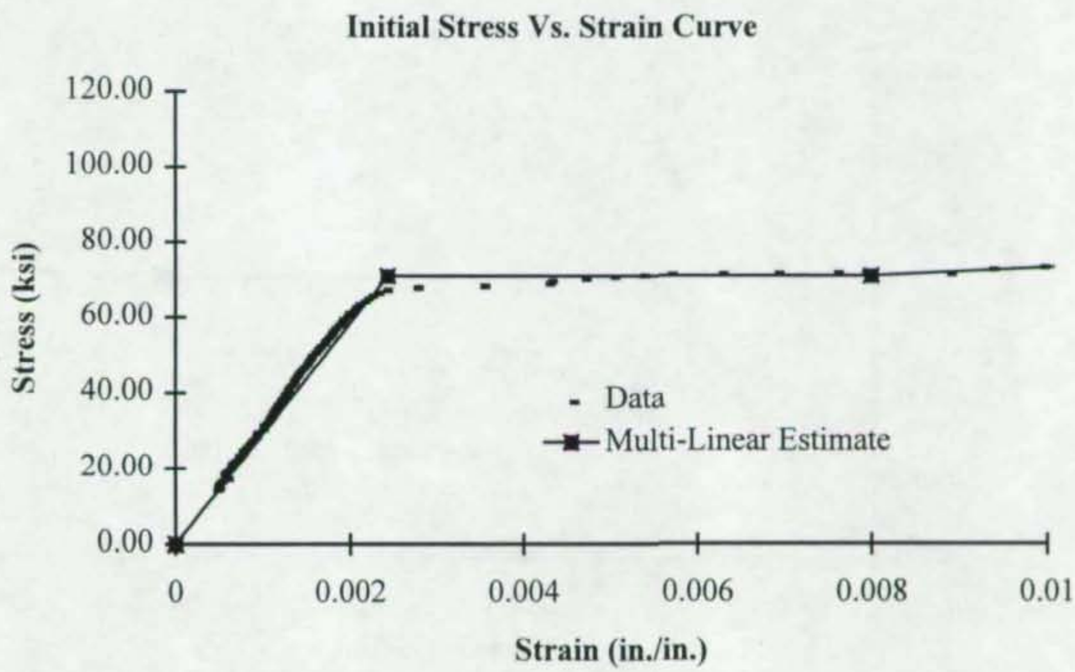


Initial Stress Vs. Strain Curve



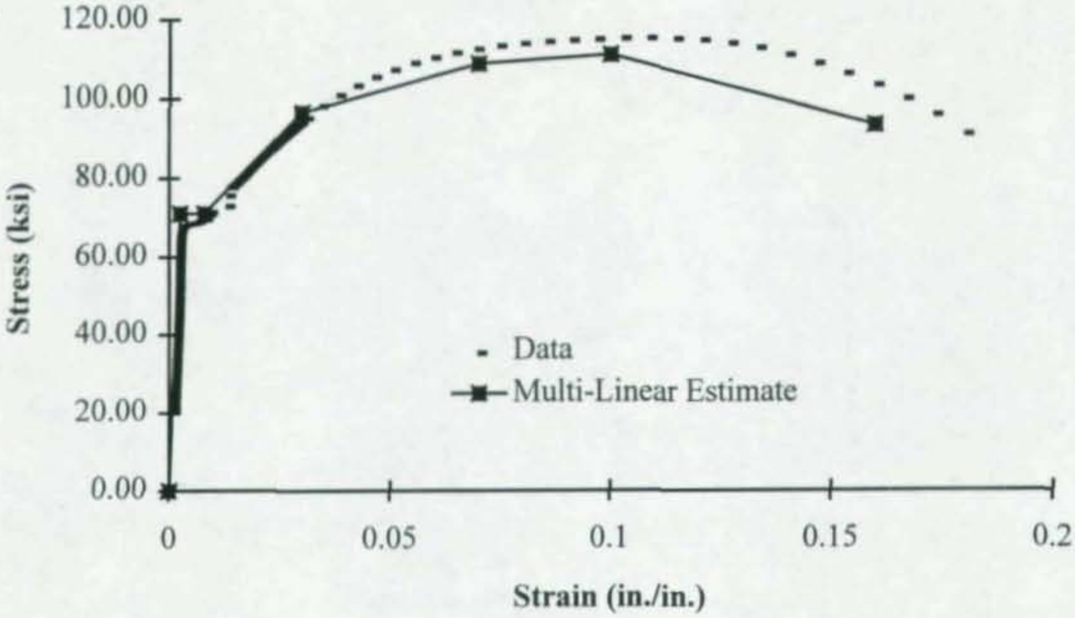


Full Stress Vs. Strain Curve
Stress (ksi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
0.05
0.1
0.15
0.2
Strain (in./in.)
Data
Multi-Linear Estimate



Initial Stress Vs. Strain Curve
Stress (ksi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
0.002
0.004
0.006
0.008
0.01
Strain (in./in.)
Data
Multi-Linear Estimate

Full Stress Vs. Strain Curve



Initial Stress Vs. Strain Curve