CHAPTER IV
RESULTS AND DISCUSSION

4.1: Tensile Tests

4.1.1: Introduction

Tensile tests of GFRP bars were performed to obtain the modulus of elasticity, the stress strain behavior, and the ultimate tensile strength and rupture strain for each manufacturer's product. The procedures for completion of the tensile tests are given in Chapter III, and the results from the collected data are presented in Section 1 of this chapter. A total of 47 tensile specimens were tested for this phase of the testing program.

4.1.2: Modulus

The bars strains were measured with three primary types of instrumentation. Two of these measurement systems were used with the tensile tests, and one was used with the bond tests. Even though the third form of measurement was completed with the bond tests, it will be included in this section. The tensile test strain measurements were taken with a clip-on two-inch extensometer, and either one or two strain gages. The bond test strain measurements were taken as the average of two LVDTs. Loads for the tensile tests were taken by the SATEK UTM, and read directly by the computer. Loads for the bond tests were taken by a 222 kN (50 kip) load cell and the measurements were read by the computer data acquisition system.

Stress-strain diagrams were made from the data collected from the all of the instrumentation. The modulus was calculated by finding the slope of these stress-strain diagrams. Due to some cracking and popping of the GFRP bars, jumps occurred in the stress strain diagrams. As a result, the modulus could not be taken over the entire range of load of the stress strain diagram. The modulus was calculated as the slope of the largest portion of the line that had no breaks or jumps. This usually occurred between 0 and 70 per cent of the load. An example of this is shown later in the chapter in Figure 4.1. The modulus results are presented by manufacturer and are broken down into bar sizes. The modulus results for Hughes Brothers Inc. are given in Table 4.1. Similarly the moduli for Marshall and for Pultrall are given in Tables 4.2, and 4.3 respectively.

Table 4.1: Hughes Brothers Inc. modulus summary.

Barsize	Test #	Modulus of Elasticity (E, MPa)				Average E (MPa)
		Gage 1	Gage 2	Extensometer	LVDTs	
#4	UTM					
	17	45900	38200	45700		43300
	18	38700	48400	43000		43400
	19	45700	48600	41900		45400
	20	44400	49100	41700		45100
	21	51400	54500	46400		50800
	Bond Tests					
	1				41500	41500
	2				42000	42000
	3				42700	42700
	4				41900	41900
	5				42800	42800
	6				43000	43000
#5	UTM					
	22			42200		42200
	23	59200	47600	43100		50000
	24	48800	47000	41400		45800
	25	50500	52500	40700		47900
	26	47700	47700	41100		45500
	Bond Tests					
	13				43000	43000
	15				41400	41400
	39				39000	39000
	40				20100 *	
#6	UTM					
	27	58600	37100	36600		44100
	28		38000	42800		40400
	29	69900 *	61100 *	44500		44500
	30	43900	46400	40500		43600
	31	42400	50100	41900		44800
	Bond Tests					
	18				43400	43400
	19				41700	41700
	30				42000	42000
	31				42500	42500
					Average (MPa)	43700
					COV (%)	5.98
					Low (MPa)	39000
					High (MPa)	50800

* Values were determined to be outliers and are not included in the average values

Table 4.2: Marshall Corporation modulus summary.

Barsize	Test #	Modulus of Elasticity (E, MPa)				Average E
		Gage 1	Gage 2	Extensometer	LVDTs	(MPa)
4	UTM					
	1	46100	42600	40800		43200
	2	37300	38600	40900		38900
	3	37800	32100	39500		36500
	4	36900	41000	41400		39700
	5	36500	38700	39700		38300
	6	39800		41000		40400
	9			38100		38100
	Bond Tests					
	7				39300	39300
	8				38100	38100
	9				37700	37700
	10				38200	38200
	16				72300 *	
	17				37900	37900
5	UTM					
	7	51900				45900
	8	41500		42400		41900
	10	42300		37700		40000
	11	40600	39000	40900		40200
	12	42700	44900	42000		43200
	Bond Tests					
	11				40600	40600
	12				39300	39300
	37				41700	41700
	38				20400 *	
6	UTM					
	13	37500	36600	40000		38000
	14	39600	38600	38800		39000
	15	35900	60000			47900
	16	36400	36400			36400
	32	41500	41800	41100		41500
	Bond Tests					
	20				39000	39000
	21				38700	38700
	33				41300	41300
	34				38200	38200
					Average (MPa)	40000
					COV (%)	6.53
					Low (MPa)	36400
					High (MPa)	47900

* Values were determined to be outliers and are not included in the average values

Table 4.3: Pultrall modulus summary.

Barsize	Test #	Modulus of Elasticity (E, MPa)				Average E (MPa)
		Gage 1	Gage 2	Extensometer	LVDTs	
#4	UTM					
	33	41000	37500	40900		39800
	34	34200	30400	42500		35700
	35	37300	42000	42500		40600
	36	43900	43600	45700		44400
	37	41500	40900	31600		38000
	Bond Tests					
	22				40600	40600
	23				46600 *	
	41				26000 **	
	42				22400 **	
#5	UTM					
	38	37200	37300	40000		38200
	39	45800	38700	41000		41800
	40	38500	35200	40900		38200
	41	40100	43600	41600		41800
	42	40100	43600	43200		42300
	Bond Tests					
	24				41300	41300
	25				41500	41500
	35				40300	40300
	36				20800 *	
#6	UTM					
	43	40800	42200	40700		41200
	44	38500	37000	40700		38700
	45	38300	40200	40700		39700
	46	40200	39500	43000		40900
	47	40900	35000	41300		39100
	Bond Tests					
	26				41000	41000
	27				40200	40200
	28				40400	40400
	29				42900	42900
					Average (MPa)	40400
					COV (%)	4.59
					Low (MPa)	35700
					High (MPa)	44400

* Values were considered outliers and not included in the average values
** Values were considered bad data points and are not included in the average values

Upon comparison of Tables 4.1-4.3, it can be seen that Hughes Brothers Inc. had the highest average modulus at 43,700 MPa (6300 ksi), with the second lowest coefficient of variation at 5.98%. Marshall Corporation had the lowest average modulus at 40000 MPa (5800 ksi) with the highest coefficient of variation 6.53%. Pultrall had an average modulus in between the other manufacturers at 40400 MPa (5900 ksi) with the lowest coefficient of variation at 4.59%.

In each manufacturers' data, some of the data points fell significantly above or below the majority of the results. These values are termed "outliers" and the outliers were discarded from each set of data. One high, and one low data point were discarded from each manufacturers data, and those values were not included in the average values or coefficient of variation. Pultrall's data also had two other values that were determined to be bad, most probably to instrumentation error. They were discarded as a result. The data from test 42 were considered unreliable because of the non-linear behavior of the stress-strain diagram. The data from test 41 indicated linear behavior, but was discarded because the value was so much lower than the others in the data set.

Hughes Brothers Inc. had, overall, the highest modulus performance of all of the manufacturers tested. Although their coefficient of variation was somewhat higher than that of Pultrall, Pultrall's coefficient of variation was greatly improved with the removal of the two outlying points. Marshall bars exhibited the lowest modulus, and the highest coefficient of variation.

4.1.3: Stress-Strain Diagrams

Stress-strain diagrams were made from each tensile test, and each bond test. The stress-strain diagram from the tensile test is composed of measurements from the clip-on two-inch extensometer, and either one or two strain gages. A typical stress –strain diagram is shown in Figure 4.1, with stress-strain diagrams for all of the tests being found in Appendix A.

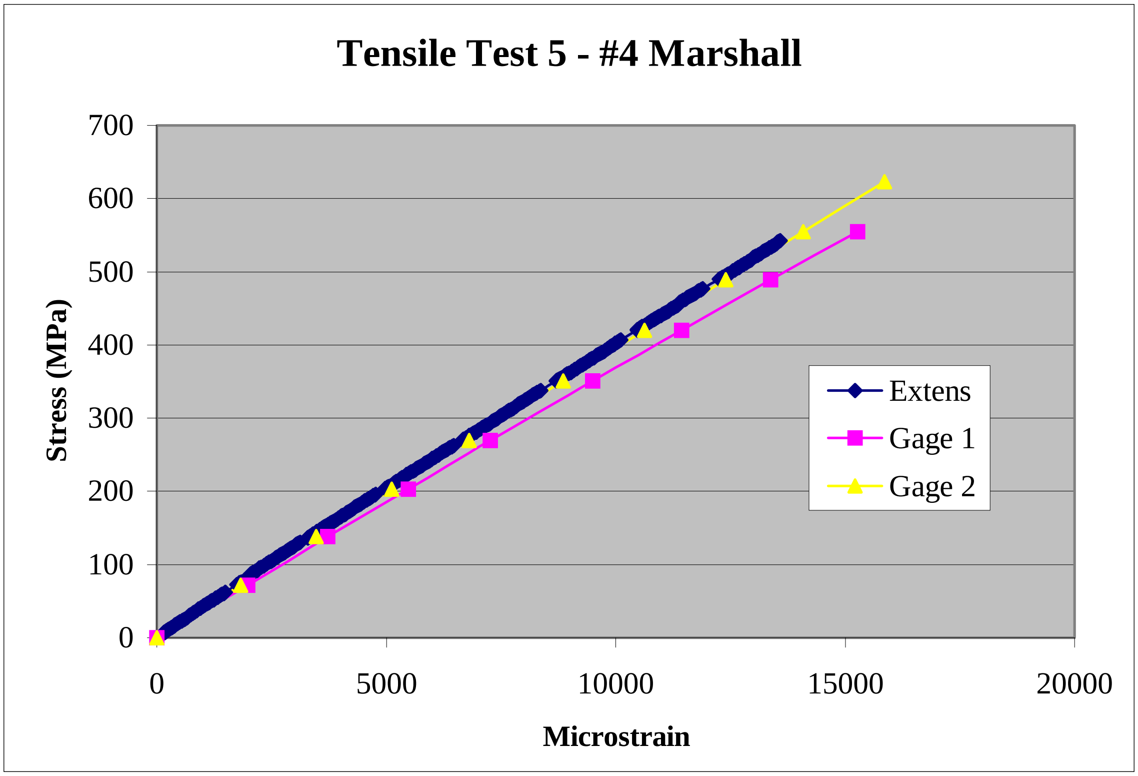

Figure 4.1: Typical stress-strain curve

As can be seen from Figure 5.1, the GFRP bars exhibited linear-elastic stress-strain behavior. This behavior is consistent until failure. There is no yield plateau as with steel. The three measurements in Figure 5.1 are very close to each other. The breaks in the continuity of the extensometer data represent pauses in the load to take the readings for gage 1 and gage 2 by hand. The divergence of gage 1 from gage 2 and the extensometer data toward the end of the test could have been caused for several reasons. The first possibility is that the loading of the bar could have been slightly eccentric causing one side of the bar to elongate more than the other. Another reason is the pausing of the load. As the SATEK reached higher loading it took longer for the load to pause so that hand reading for the two strain gages could be taken. Toward the end of the test, load would not come to a complete stop. So readings were taken as fast as possible, so that the most accurate strain could be matched with a given load. Even so, this becomes more difficult toward the end of the test, and more error can be introduced.

From some of the other test results presented in Appendix A, it can be seen that the extensometer, and/or the strain gages occasionally exhibit jumps in the graphs. The jumps correspond to a popping sound heard while testing. This popping noise is caused by some of the fibers and/or the resin failing on the outer perimeter of the bar. When this happened within the gage length of either of the two measuring devices, the stress-strain curve shifts, and then continues the same upward slope.

All of the graphs in Appendix A present measurements from all the measuring devices utilized for the particular test shown on the graph. If a measuring device does not appear on the graph, then either it was not present during the test or the data from that device was considered unreliable and not included in the graph. All of the stress-strain diagrams for the tensile test are shown individually, and are present in the format of Figure 4.1. The bond tests only have one measuring device for stress-strain behavior (The average of two LVDTs over a 191 mm (7.5 in.) gage length), therefore the stress-strain diagrams from the bond tests are grouped by manufacturer and bar size in Appendix A. Each of the stress-strain curves for the bond tests are denoted in the legend by a block number (B1, B2, etc), the embedment length (5 or 7.5 times the bar diameter), and the side of the block (west or east).

4.1.4: Average Ultimate Tensile Strength & Rupture Strain

Ultimate tensile strength, or breaking strength data was recorded with each tensile test. The ultimate tensile strength data is compiled for each test under manufacturer, and bar size and is shown in Table 4.4

Table 4.4: Tensile strength data by manufacturer and bar size.

Manufacturer	Bar Size	Measured Tensile Strength, (MPa)					Average (MPa)	COV* (%)
Hughes Bros	#4	Test 17	Test 18	Test 19	Test 20	Test 21		
		823	811	859	804	792	818	3.12
	#5	Test 22	Test 23	Test 24	Test 25	Test 26		
		721	762	793	705	779	752	5.00
	#6	Test 27	Test 28	Test 29	Test 30	Test 31		
		642	692	656	698	682	674	3.58
Marshall	#4	Test 1	Test 2	Test 3	Test 4	Test 5		
		732	780	769	751	723	751	3.23
	#5	Test 7	Test 8	Test 10	Test 11	Test 12		
		821	689	677	731	768	737	8.01
	#6	Test 13	Test 14	Test 15	Test 16	Test 32		
		740	790	781	660	773	749	7.10
Pultrall	#4	Test 33	Test 34	Test 35	Test 36	Test 37		
		546	575	645	656	607	606	7.62
	#5	Test 38	Test 39	Test 40	Test 41	Test 42		
		575	560	601	571	571	576	2.62
	#6	Test 43	Test 44	Test 45	Test 46	Test 47		
		529	545	588	577	532	554	4.83

* Coefficient of Variation.

It can be seen from Table 4.4 that Hughes Brothers No. 4 bars exhibited the highest average ultimate tensile strength at 818 MPa (119 ksi), and Pultrall's No. 6 bars exhibited the lowest average ultimate tensile strength at 554 MPa (80 ksi). One general trend apparent in Table 4.4 is that the ultimate tensile strength decreases with an increase in bar diameter. This does not hold true for the Marshall GFRP bars. The ultimate tensile strength drops from the No. 4 to the No.5, but then increases with the No. 6 bars to almost the same tensile strength and the No. 4 bars. This may be in part due to the large coefficient of variation with the No. 5, and No. 6 Marshall bars. A smaller coefficient of variation could reveal a lower average ultimate tensile strength for the No. 6 Marshall bars. Table 4.4 also indicates that the Hughes Brothers bars had the highest average ultimate tensile strength, and the lowest coefficient of variation. Conversely, the Pultrall bars have the lowest average ultimate tensile strength, but their coefficient of variation is overall lower than that of Marshall's bars.

Another characteristic of the GFRP bars obtained from the tensile test is the rupture strain. This value is calculated using the ultimate tensile strength, and the modulus for each individual tensile test. Equation 4.1 gives the rupture strain calculation.

$$\varepsilon_{rupture} = \frac{\sigma_{ult}}{E} \qquad (4.1)$$

Where: $\varepsilon_{rupture}$ = rupture strain, microstrain
σ_{ult} = ultimate tensile strength, MPa
E = modulus of elasticity, MPa

The rupture strain for each test as well as the average by bar size and manufacturer is given in Table 4.5.

Table 4.5: Calculated rupture strain by bar size and manufacturer.

Manufacturer	Bar Size	Calculated Rupture Strain (microstrain, με)					Average (με)	COV* (%)
Hughes Bros	#4	Test 17	Test 18	Test 19	Test 20	Test 21		
		19000	18700	18900	17900	15600	18000	7.89
	#5	Test 22	Test 23	Test 24	Test 25	Test 26		
		17000	15300	17300	14700	17100	16300	7.32
	#6	Test 27	Test 28	Test 29	Test 30	Test 31		
		14600	17100	14700	16000	15200	15500	6.73
Marshall	#4	Test 1	Test 2	Test 3	Test 4	Test 5		
		17000	20000	21000	18900	18900	19200	7.77
	#5	Test 7	Test 8	Test 10	Test 11	Test 12		
		17900	16400	16900	18200	17800	17400	4.35
	#6	Test 13	Test 14	Test 15	Test 16	Test 32		
		19500	20300	16300	18100	18700	18600	8.17
Pultrall	#4	Test 33	Test 34	Test 35	Test 36	Test 37		
		13700	16100	15900	14800	16000	15300	6.78
	#5	Test 38	Test 39	Test 40	Test 41	Test 42		
		15100	13400	15700	13700	13500	14300	7.34
	#6	Test 43	Test 44	Test 45	Test 46	Test 47		
		12800	14100	14800	14100	13600	13900	5.32

* Coefficient of Variation.

The rupture strain data exhibits some of the same results as the ultimate tensile strength. Generally, the rupture strain decreases with an increase in bar diameter. This again is not true for the Marshall bars which decrease from the No. 4 to No. 5 bars but then increase from No. 5 to No. 6. And as with the ultimate tensile strength, the rupture strain for the No. 4 Marshall bars is greater than that of the No. 6 Marshall bars. This result may again be attributed to the large coefficient of variation. Due to its low strength and relatively high modulus, Pultrall has the lowest rupture strain values at 13900 microstrain. Marshall had high strength and low modulus, which resulted in the highest rupture strain values at 19200 microstrain.

In conclusion, the behavior from the tensile tests of the three manufacturers bars is quite similar. Even so, there are some general trends observed in the data. Hughes Brothers exhibited the highest average values for all of the tensile test characteristics, while Pultrall yielded the lowest. Marshall had average values somewhere in the middle of the other two manufacturers, and they had the highest coefficient of variation of all the manufacturers with respect to tensile test characteristics.

4.2: Bond Tests

4.2.1: Introduction

The bond tests that were performed in the experimental program had several objectives. One objective was to use the gathered data to develop load versus slip charts for the live end of the block, and load versus slip charts for the free end of the block. Another objective was to obtain the maximum bond stress for each manufacturer's bar. The last objective was to make a comparison between the max bond stress resulting from tests with the two embedment lengths used, 5 bar diameters and 7.5 bar diameters. An auxiliary result of the testing is stress-strain diagrams used to calculate the modulus. The stress-strain diagrams were discussed in the previous section, and will not be discussed in this section. However the modulus calculated from the stress-strain diagram for each test is used in the development of the load versus live end slip chart for that test. The focus of this section will be on the calculation of, and behavior exhibited in the load versus slip charts, along with the calculation of the maximum bond stress, and the embedment length comparison.

4.2.2: Load versus Slip Graphs

The load versus live end slip curves were created using the data collected for the bond tests. First the modulus was calculated from the slope of the stress-strain diagram, which was produced for each test. The stress-strain curves came from data collected by the two elongation LVDTs that measured the elongation of the bar over a specified gage length. Next, the data from the two live end displacement LVDTs was averaged. The raw data collected from the displacement LVDTs included slip of the bar as well as the elongation of the bar over the unbonded length within the test block. The elongation of the bar was subtracted from the overall movement of the bar to obtain the actual slip. The elongation of the bar, d, was calculated using Equation 4.2.

$$\delta = \frac{PL}{AE} \tag{4.2}$$

Where: P = applied load, kN
L = unbonded length of bar, m
A = cross-section area of the bar, m^2
E = modulus of elasticity, kPa

The elongation was calculated for each load reading, and subtracted from each of the LVDTs averaged measurements. Then the load was plotted against the calculated live end slip. A typical load versus live end slip plot is shown in Figure 4.2.

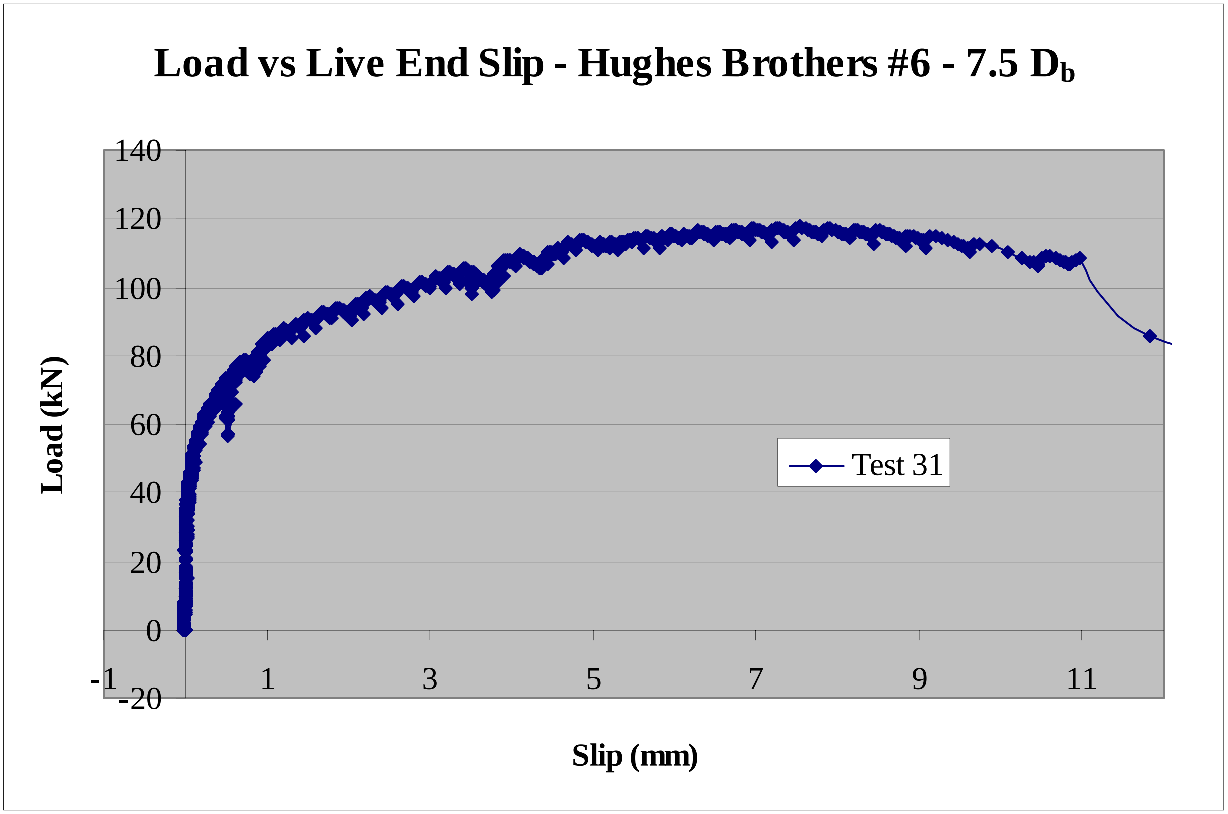

Figure 4.2: Typical load vs. live end slip plot.

The load versus free end slip plots were more simple to construct because there was no bar elongation on the free end. Therefore the slip data collected by the free end LVDT could be directly used to construct the curve. A typical load versus free end slip plot is shown in Figure 4.3. Load versus slip plots for all of the tests are paired together, live end and free end slip, and shown in Appendix B. Appendix B is organized by manufacturer, with Hughes Brothers tests first, followed by Marshall and then Pultrall.

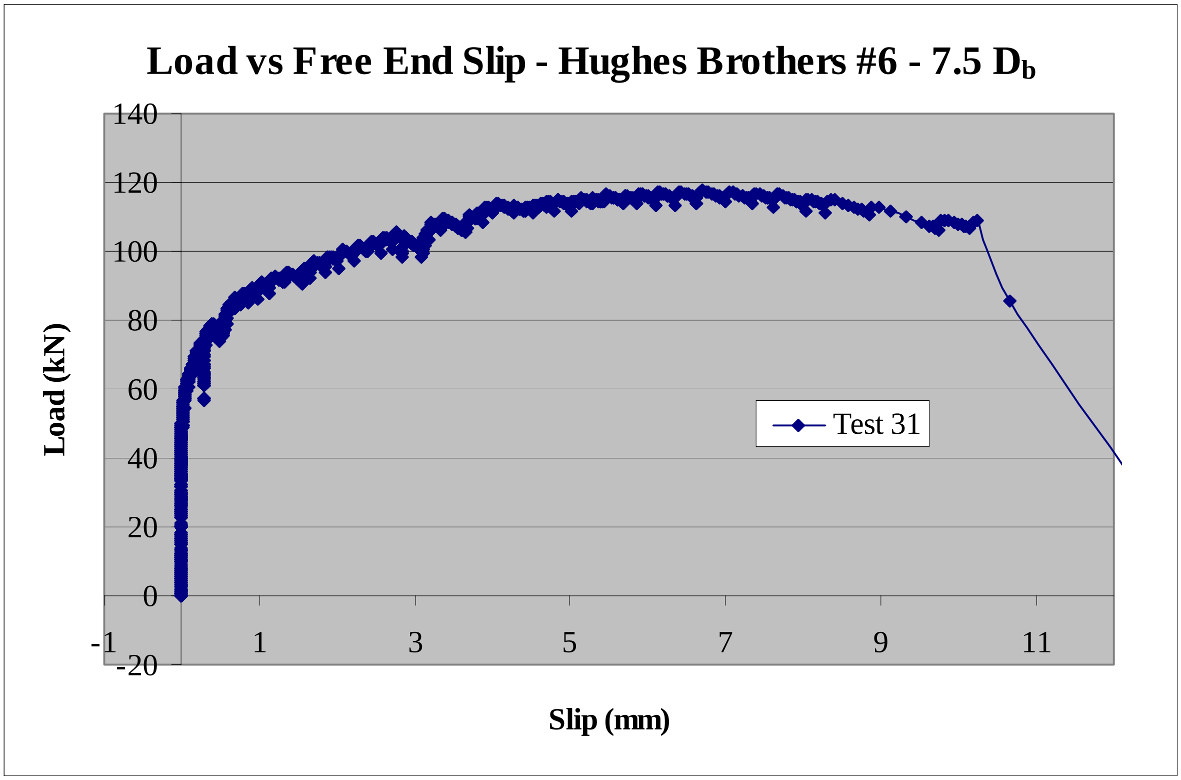

Figure 4.3: Typical load vs. free end slip plot

Upon review of the graphs in Appendix B, it can be seen that each manufacturer generally exhibits a different type of bond behavior. The Hughes Brothers' bars typically show a large amount of slip (approximately 4 to 5 mm) before the peak load is reached. Then the bars continue to hold a relatively high load (approximately 80 to 90% of the peak bond stress) for continued slipping before the load is finally shed. Conversely, Marshall's bars exhibit a small amount of slip, typically less than a 1 mm (0.04 in.), when the peak load is reached. Once the peak load is reached, the majority of the load is shed, or lost. Then as slip continues small peaks in bond stress occur. Pultrall bars exhibit the same pre-peak behavior as Marshall with a small amount of slip at peak load, typically less than 1 mm (0.04 in.). The difference is that after the peak Pultrall bars lose some load, but hold a lower load as slip continues.

Many of the graphs in Appendix B show negative slips through some of the loading regime. In reality, this behavior in highly improbable, and is likely the result of some type of error. There are a few possible reasons for this type of behavior. The first reason is that there is some inadvertent misalignment in the test setup. If the hydraulic ram that applies load to the bar was not in line with the block, then the ram could have pulled the bar at a small angle so that the LVDTs would shift slightly closer to the block. Another possible reason for the error could have been some small rotation of the block. As load was being applied to the bar by the ram, the other compression ram and load cell that provided the reaction that kept the block level could have moved just enough to allow some small rotation. It is also possible that this rotation could have come from a test frame that wasn't stiff enough to prevent those small deflections. Still another possible reason could be that some cement paste leaked into the bond breaker tubes causing the unbonded length to be shorter than what was measured. This would in turn affect the elongation of bar, and the calculation to determine the final end slip. Regardless of the reason, the accuracy of the measured live end slip at peak bond stress is questionable for the graphs that exhibit the negative slip behavior.

4.2.3: Maximum Bond Stress & Embedment Length Comparison

The maximum bond stress was calculated for each bond test in the experimental program. It was calculated by dividing the largest load held by the bar by the circumference of the bar times the bonded length. The maximum bond stresses for all of the tests are shown in Table 4.6. In Table 4.6, the maximum bond stress is group by manufacturer, and bar size. The average maximum bond stress was found for each bar size per manufacturer, and each manufacturer.

Table 4.6: Bond stresses, and averages for all bond tests.

Manufacturer	Bar Size	Test Number	Max Bond Stress (MPa)	Average Max Bond Stress (Bar Size) (MPa)	High Max Bond Stress (Manufacturer) (MPa)	Low Max Bond Stress (Manufacturer) (MPa)	Average Max Bond Stress (Manufacturer) (MPa)	COV (%)
Hughes Brothers	#4	1	17.8	17.5	24.9	12.3	17.3	19.1
		2	14.9					
		3	21.4					
		4	19.4					
		5	15.2					
		6	16.3					
	#5	13	18.9	19.1				
		15	20.1					
		39	24.9					
		40	12.3					
	#6	18	15.7	15.4				
		19	16.6					
		30	14.5					
		31	14.7					
Marshall	#4	7	20.3	19.7	22.8	11.1	18.1	18.4
		8	21.0					
		9	19.2					
		10	21.7					
		16	17.3					
		17	18.4					
	#5	37	17.4	18.3				
		38	11.1					
		11	21.9					
		12	22.8					
	#6	33	15.4	15.5				
		34	16.9					
		20	14.4					
		21	15.5					
Pultrall	#4	41	21.2	17.2	21.2	9.2	16.3	21.3
		42	11.2					
		22	18.3					
		23	18.2					
	#5	24	19.3	16.2				
		25	17.1					
		35	19.1					
		36	9.2					
	#6	28	15.6	15.4				
		29	14.7					
		26	16.4					
		27	14.8					

It can be seen from Table 4.6 that all of the manufacturers' bars behaved similarly. They all had close to the same average maximum bond stress for all bar sizes, with Marshall having the highest bond stress at 18.1 MPa (2.6 ksi), and Pultrall having the lowest at 16.3 MPa (2.4 ksi). The variation throughout the bars was also similar with Pultrall having the highest coefficient of variation at 21.3%, and Marshall having the lowest at 18.4%. A general trend in the data is that the average maximum bond stress decreases with an increase in bar diameter. This is true for all of bars except the Hughes Brothers No. 5 bars. Even so, in general the behavior for all of the bars is closely matched.

The last objective of the bond tests was the comparison between embedment lengths. The embedment lengths were set at 5 times the bar diameter (D_b), and 7.5 times the bar diameter (D_b). The embedment length comparison is shown in Table 4.7.

Table 4.7: Embedment length comparison.

Manufacturer	Bar Size	Average Max Bond Stress	
		5 Db (MPa)	7.5 Db (MPa)
Hughes Brothers	#4	18.4	15.7
	#5	19.5	18.6
	#6	16.2	14.6
Marshall	#4	20.6	17.9
	#5	14.3	22.4
	#6	16.2	14.9
Pultrall	#4	16.2	18.2
	#5	18.2	14.2
	#6	15.2	15.6

Table 4.7 shows a general pattern of behavior of the average maximum bond stress decreasing with an increase in the embedment length. This holds true for all of the bars tested with the exception of Marshall's No. 5 bars, and Pultrall's No. 4 bars. Only

two tests were done per embedment length for those two types of bar. The behavior of these two types of bars could be a result of some unexplained anomalies, and could be a reflection of the small sample size and high variability.

The bond tests performed in the experimental program yielded great insight into the behavior of each manufacturer's bar. A general pattern of load slip behavior was established for each manufacturer's bar. Also, the maximum bond stress was determined for all bars, and averaged by bar size, and manufacturer. Finally, a comparison was drawn between the maximum bond stresses of the same bars at different embedment lengths.