CENTER FOR INFRASTRUCTURE ENGINEERING STUDIES

Experimental Investigation of Bond-Slip Relationship between Fiber Reinforced Polymers (FRP) Bars and Concrete

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16. Abstract The aim of the experimental research is to quantify the bonding properties of FRP rods made of carbon (CFRP) and glass (GFRP) with concrete by conducting two sets of experiments. The first set of experiments would involve pullout tests using vertical bond specimens. The tests would be in accordance with the ACI-440k provisions. Provisions of some recommended bond parameters in ACI 440 R.1 (released in 2001), such as K2 and K3 would be evaluated by performing an analytical study on the experimental data.			
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Table of Contents

List of Tables

List of Figures

REPORT

1. Objective:

The aim of the experimental research is to quantify the bonding properties of FRP rods made of carbon (CFRP) and glass (GFRP) with concrete by conducting a set of experiments. The first set of experiments would involve pullout tests using vertical bond specimens. The test would be in accordance with the ACI-440k provisions. Provisions of some recommended bond parameters in ACI 440 R.1 (2003), such as K2 and K3 would be evaluated by performing an analytical study on the experimental data.

This is a preliminary report giving salient features of the tests performed. Full descriptions of the experiments, results and conclusions will be submitted in the final report.

2. Background:

2.1 *Material Details:*

In recent years, FRP materials have been produced in bar shapes to be used in reinforced and prestressed concrete members in place of the conventional steel reinforcement. The material used for this research is manufactured by Hughes Brothers. The Aslan 200 CFRP rebars and Aslan 100 GFRP rebars are used in this research. Please refer to the Hughes Brothers website http://www.hughesbros.com/ for full details of the rods. The bars used in this research are deformed bars with surface features as shown in figure 1.

Figure 1: Surface of Carbon and Glass Rods

2.2 *Places where Aslan 100 GFRP can be used:*

1) Any concrete member susceptible to corrosion of steel reinforcement by chloride ion or chemical corrosion.
2) Any concrete member requiring non-ferrous reinforcement due to electromagnetic considerations.
3) As an alternative to epoxy, galvanized or stainless steel rebar.
4) To strengthen un-reinforced masonry.

2.3 *Places where Aslan 200 CFRP can be used:*

1) New construction in corrosive environments
2) Near surface mount or strengthening of existing masonry, Concrete or wood members (Flexure and shear).

2.4 *Advantages:*

1) FRP bars exceed the strength and fatigue properties of steel.
2) FRP bars offer added resistance to corrosion, even better than the epoxy-coated steel reinforcement.
3) FRP bars have higher tensile strength, which allows the use of a higher compressive strength concrete.
4) FRP bars are also lighter than steel bars.

2.5 *Disadvantages:*

1) FRP bars do not exhibit very good compression properties.
2) In vast majority of reinforced concrete applications, steel bars continue to be the most effective and cost-efficient reinforcing material because of its strength and durability

2.6 *Bond Behavior:*

Bond between FRP reinforcement and concrete depends on several factors including

1) Friction due to surface roughness of FRP rebars.
2) Mechanical interlock of the FRP rebars against concrete.
3) Chemical Adhesion
4) Hydrostatic pressure against the FRP rebars due to shrinkage of hardened concrete.
5) Swelling of FRP rebars due to temperature change and moisture absorption.

3. Methodology:

The experimental techniques (Thiagarajan, 1999) and the methodology of computations of 1/K2 and K3 are based on procedures outlined in Sepeda (2002).

The testing method used is the Direct Pullout Test Method as described in ACI 440 K test no R.4 (2002). The direct pullout specimen consisted of a concrete cube (200 mm x 200mm x 200mm) with the GFRP or CFRP bars placed concentric through the concrete cube. The pictures of the actual experimental setup are given in figure 2. The pullout test specimen and actual test sketches are illustrated in figure2 and figure 3 (http://www.shef.ac.uk/~tmrnet/rrt/index.htm)

Figure 2: Actual Test Snaps

3.1 *Advantages of the Direct Pullout Test:*

1) It offers the advantage of simplicity.
2) The free-end of the rod is accessible which allows for the measurement of the free end slip and also for the placement of instrumentation within the rod.

3.2 *Disadvantages of the Direct Pullout Test:*

The direct pullout test is sometimes viewed with skepticism due to the compressive stresses existing in the concrete near the loaded end of the rod. This stress state in the concrete is more of a concern in steel-reinforced concrete where failure of the concrete governs pullout-behavior. In case of FRP reinforced concrete, however, pullout is primarily governed by the FRP, as the examination of the specimen after bond failure has shown that the concrete does not crush in the vicinity of the reinforcement. The compressive stress at the loading face is very small and hence neglected.

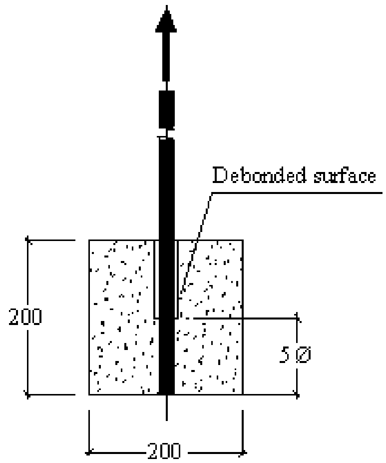

Figure 3: Pullout Test Sample

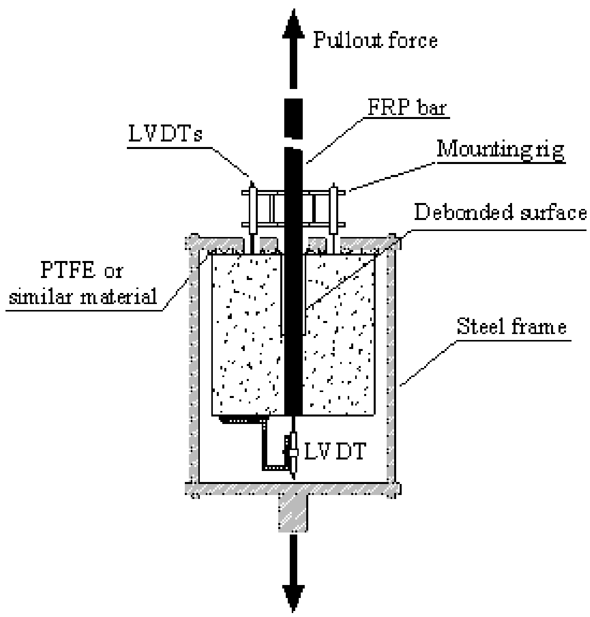

Figure 4: Pullout Test Assemble Sketch

***Scope of Work*:**

The details of various different kinds of specimens used for testing are given below.

Types of Bars Used	Concrete Used	Embedment Lengths	No of Samples
Two types of bars used: 1) ASLAN 100 GFRP 2) ASLAN 200 CFRP	Normal Concrete Used	Two Embedment Lengths used 1) 5 Diameter 2) 10 Diameter	Three samples of each type were tested.

Three samples of each type are tested. Hence a total of 30 samples were tested during the duration of the project.

The embedment length is chosen to be short enough not to develop high stresses in the bars and, hence, no special devices should be needed in the testing machine grip. It is also long enough to be representative of the bar surface deformations. Two different types of bond breakers like the Duct Tape and the cPVC tubes were used and results show relative similarity.

4. Experimental Measurements:

Measurements of the slips (both top and bottom) are done using LVDT's placed by the following scheme.

4.1 End slip, Top Slip and Load

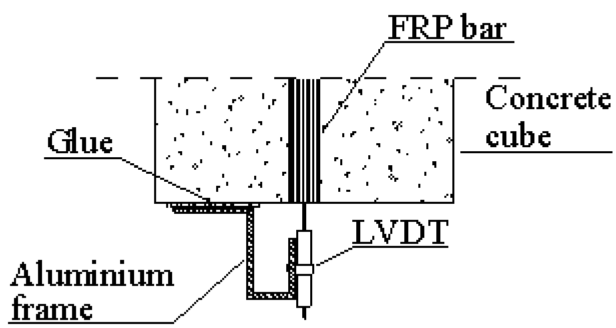

Figure 5: LVDT at the bottom face of the cube (vertical section)

- The load is measured using a 30000 lbs GEOKON load cell placed between the cube and the loading frame.
- To avoid crushing of the rod, a steel tube held together by epoxy at the grips surrounds the rod.
- The results are collected using a National Instruments 'Data Acquisition System'. All the LVDT's and the Load cells are connected to this Data Acquisition System and then calibrated
- A single VI reading the values of all 3 LVDTs and load cells is developed. The value of the load cell is measured directly as the load values. The readings of the LVDT's are to be multiplied by a pre-calculated factor to get the values of the displacements

5. Other Test Details:

1) Loading rate used: max 0.1 KN/sec

2) We use the PTFE plate between the reaction area and the testing rig to reduce the friction effects and also help to form a better contact surface for the load cell.

3) The specimens are cast vertically.

4) Curing of 28 days is allowed for the test.

5) Debonding material of Duct tape and CPVC tubes is used.

6. DATA:

6.1 *Nomenclature:*

CF – Carbon Fibers
GF – Glass Fibers
L05 - 5 diameters embedment length
L10 - 10 diameter embedment length

Hence a CFL05 means carbon fiber with 5 diameters embedment length.

Hughes Brothers provided all the CFRP and GFRP bars. The manufacturer reported the following data for the rods.

ASLAN 100 GFRP Rods:

Bar Size	Nominal Diameter (in)	Cross Sectional Area (in^2)	Guaranteed Tensile Strength (ksi)	Tensile Modulus of Elasticity (psi 10^6)
# 2	0.25	0.0515	120	5.92
# 3	0.375	0.1307	110	5.92

Table 1: Properties of Aslan 100 GFRP Rods

ASLAN 200 CFRP Rods:

Bar Size	Nominal Diameter (in^2)	Cross Sectional Area (in^2)	Guaranteed Tensile Strength (ksi)	Tensile Modulus of Elasticity (psi 10^6)
# 2	0.254	0.0464	300	18
# 3	0.362	0.1010	300	18

Table 2: Properties of Aslan 200 CFRP Rods

The data obtained from the tests is as follows.

1) Load Values
2) Top Slip (Loaded end slip)
3) Bottom Slip (Free end slip)

At each of the load levels, the slip at the loaded end is calculated as the average of the readings of the LVDTs minus the elongation Sc of the FRP rod in the length Lc between the top surface of the bonded length and the point of attachment of the measuring device on the FRP rod, the latter being calculated as

$$Sc = (F \times L_c) / (E_l \times A)$$

Where Sc = elastic elongation (in)
F = Tensile Load (Lbs)
L_c = length from the top of the embedded rod to the point of the attachment of the measuring device (in)
E_L = Longitudinal modulus of elasticity of FRP Rod (psi)
A = Cross sectional area (in^2)

From these values the bond stress is calculated. The graphs of 1) Load vs Slips and 2) Load vs bottom slip are then plotted.

The bond parameters of K_2 and K_3 are calculated using the following formulas (ACI 440.1R-03 equations 11-5 and 11-6)

$$l_{bf} = K_2 \frac{d_b^2}{\sqrt{f_c^{'}}} \times f_{fu}$$

$$l_{bf} = \frac{d_b}{K_3} \times f_{fu}$$

Where l_{bf} = Embedment Length
d_b = Diameter of rod
f_{fu} = Bar Stress

The various computed results are expressed in the form of tables. Table 3 gives the pullout test data. The concrete strength was not available at the time of computations and hence it is assumed to be 5500 psi which is pretty close to the actual values. Table 4 gives the details regarding the top and bottom slips occurring during the experiments. The computations of K2 and K3 and given in table 5. The average values for a particular type of test are given in table 6. The tables are given below.

Test Name	Embedment Length (in)	Concrete Strength (psi)	Max Pullout Load (lbs)	Remarks
	Glass Rods	***3/8 in Diameter***		
	10 Diameter Embedment			
G 3/8 L10T1	3.75	5500	10451	
G 3/8 L10T2	3.75	5500	10695	
G 3/8 L10T3	3.75	5500	10401	
	5 diameter embedment			
G3/8 L5T4	1.875	5500	5980	
G3/8 L5T5	1.875	5500	5145	
G3/8 L5T6	1.875	5500	6684	
	Carbon Rods	***3/8 in Diameter***		
	10 Diameter Embedment			
C 3/8L10T7	3.75	5500	6774	
C 3/8L10T8	3.75	5500	5817	
C 3/8L10T9	3.75	5500	5898	
	5 diameter embedment			
C 3/8 L5T10	1.875	5500	4416	
C 3/8 L5T11	1.875	5500	4482	
C 3/8 L5T12	1.875	5500	4261	
	Glass Rods	***1/4 in Diameter***		
	5 diameter embedment			
G 1/4 L5T13	1.25	5500	3459	
G 1/4 L5T14	1.25	5500	3262	
G 1/4 L5T15	1.25	5500	3412	
	10 Diameter Embedment Length			
G 1/4 L10T18	2.5	5500	4973	
	Carbon Rods	***1/4 in Diameter***		
	5 diameter embedment			
C 1/4 L5T16	1.25	5500	1731	
C 1/4 L5T17	1.25	5500	1414	
	10 Diameter Embedment			
C 1/4 L10T21	2.5	5500	2125	
C 1/4 L10T22	2.5	5500	2394	
C 1/4 L10T23	2.5	5500	2214	
T20				Grip failure

Table 3: Pullout Test Data for Normal Concrete

Test Name	Load when Bottom started slipping (psi))	Max Top Slip (in)	Max Bottom Slip (in)	Remarks
	Glass Rods 3/8 Diameter			
	10 Diameters Embedment			
G 3/8 L10T1	4867	0.2925	0.1487	
G 3/8 L10T2	3696	0.3883	0.1666	
G 3/8 L10T3	4241	0.3364	0.135	
	5 Diameters Embedment			
G3/8 L5T4	1500	0.5379	0.5011	
G3/8 L5T5		0.5047	0.4727	
G3/8 L5T6	1453	0.3389	0.2774	
	Carbon Rods 3/8 Diameter			
	10 Diameters Embedment			
C 3/8L10T7	2763	0.2665	0.2269	
C 3/8L10T8	2411	0.5669	0.5547	
C 3/8L10T9	2722	0.5714	0.5419	
	5 Diameters Embedment			
C 3/8 L5T10	1862	0.5556	0.5203	
C 3/8 L5T11	1633	0.5622	0.5582	
C 3/8 L5T12	2015	0.5589	0.5563	
	Glass Rods 1/4 Diameter			
	5 Diameters Embedment			
G 1/4 L5T13	2010	0.4645	0.3531	
G 1/4 L5T14	1200	0.4902	0.366	
G 1/4 L5T15	1412	0.5481	0.4106	
	10 Diameters Embedment			
G 1/4 L10T18	1225	0.3618	0.2273	
	Carbon Rods 1/4 Diameter			
	5 Diameters Embedment			
C 1/4 L5T16	900	0.5679	0.4499	
C 1/4 L5T17	580	0.5354	0.5666	
	10 Diameters Embedment			
C 1/4 L10T21		0.5897	0.5714	
C 1/4 L10T22	356	0.4663	0.4635	
C 1/4 L10T23	765	0.4926	0.4838	

Table 4: Data for Slips for Normal Concrete

Test Name	Max pullout Load (lbs)	Bar Stress (ksi)	Average Bond(psi)	1/K2	K3	Remarks
		Glass Rods	**3/8 Diameter**			
		10 Diameters Embedment				
G 3/8 L10T1	10451	79.96	2458	38.7	7996	
G 3/8 L10T2	10695	81.83	2497	39.6	8183	
G 3/8 L10T3	10401	79.58	2426	38.5	7958	
		5 Diameters Embedment				
G3/8 L5T4	5980	45.75	3243	44.3	9150	
G3/8 L5T5	5145	39.36	2743	38.11	7873	
G3/8 L5T6	6684	51.14	3321	49.51	10228	
		Carbon Rods	**3/8 Diameter**			
		10 Diameters Embedment				
C 3/8L10T7	6774	67.1	1743	32.4	6707	
C 3/8L10T8	5817	57.59	1627	27.8	5759	
C 3/8L10T9	5898	58.4	1637	28.2	5840	
		5 Diameters Embedment				
C 3/8 L5T10	4416	43.72	1971	42.3	8745	
C 3/8 L5T11	4482	44.37	1997	42.9	8875	
C 3/8 L5T12	4261	42.18	1919	40.8	8438	
		Glass Rod	**1/4 Diameter**			
		5 Diameters Embedment				
G 1/4 L5T13	3459	67.16	2662	65.0	13433	
G 1/4 L5T14	3262	63.33	2535	61.3	12668	
G 1/4 L5T15	3412	66.25	2656	64.1	13250	
		10 Diameters Embedment				
G 1/4 L10T18	4973	96.56	2518	73.2	9656	
		Carbon Rods	**1/4 Diameter**			
		5 Diameters Embedment				
C 1/4 L5T16	1731	37.3	1742	56.5	7461	
C 1/4 L5T17	1414	30.43103448	1459	46.1	6086	
		10 Diameters Embedment				
C 1/4 L10T21	2125	45.77	1088	34.7	4577	
C 1/4 L10T22	2394	51.59	1221	39.1	5159	
C 1/4 L10T23	2214	47.71	1130	36.1	4771	

Table 5: Pullout Test Variables for Normal Concrete

Test Type	Average Bond Stress (psi)	1/K2	K3
G 3/8 L10	2460	38.9	8045
G 3/8 L5	3102	43.9	9084
C 3/8 L10	1669	29.5	6099
C 3/8 L5	1962	42	8686
G1/4L10	2518	73.2	9656
G1/4L5	2617	63.5	13117
C1/4L10	1600	51.4	6773
C1/4L5	1146	36.7	4836

Table 6: Average Values for Normal Concrete

Conclusions:

1) With reference to table 6, it can be seen that the values of 1/K2 and K3 are higher for ¼ in diameter rods than that for 3/8 in diameter rods. Hence they show diameter dependability.

2) Values for 1/K2 and K3 as seen in table 5 are similar for all the samples of each type. This demonstrates a greater degree of confidence in the reliability of the test results.

3) These values are significantly higher than those previously published. This may be due to the surface texture of the rod.

4) From figure 1, which shows the surface characteristics of the two rods, it can be seen that the woven fabric on the glass rod can provide a higher degree of mechanical bonding compared to carbon rods. This is clearly reflected in the 1/K2 and K3 values, wherein all 1/K2 and K3 values of glass rods are consistently higher than the carbon rods values.

References:

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Thiagarajan, G. (1999). “Flexural Behavior of Carbon Fiber Based Rods in Concrete Beams: An Experimental and Analytical Investigation”, A report to Louisiana State Transportation Research Center, Louisiana Department of Transportation and Development, S.P. No. 736-99-0686.

“Guide Test Methods for Fiber Reinforced Polymer (FRP) Rods and Sheets”, Draft prepared by ACI Subcommittee 440 K. (2002).

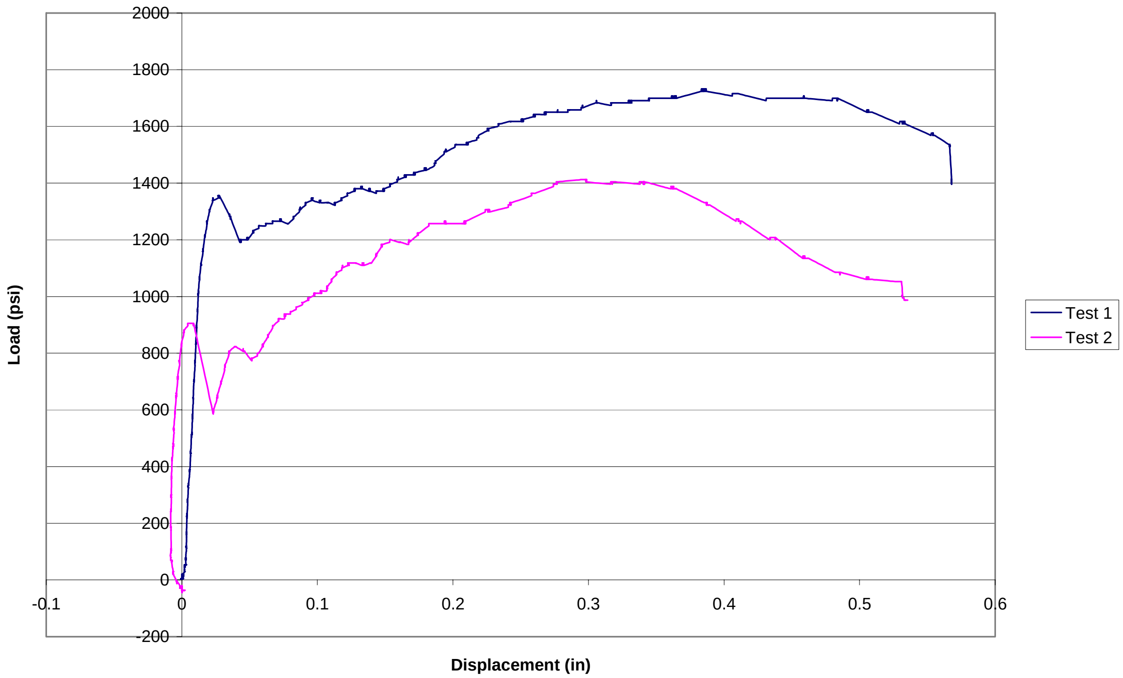
Focacci, F., Nanni, A., Bakis, A.E., (2000). “Local Bond-Slip Relationship for FRP reinforcement in Concrete”

http://www.shef.ac.uk/~tmrnet/rrt/index.htm

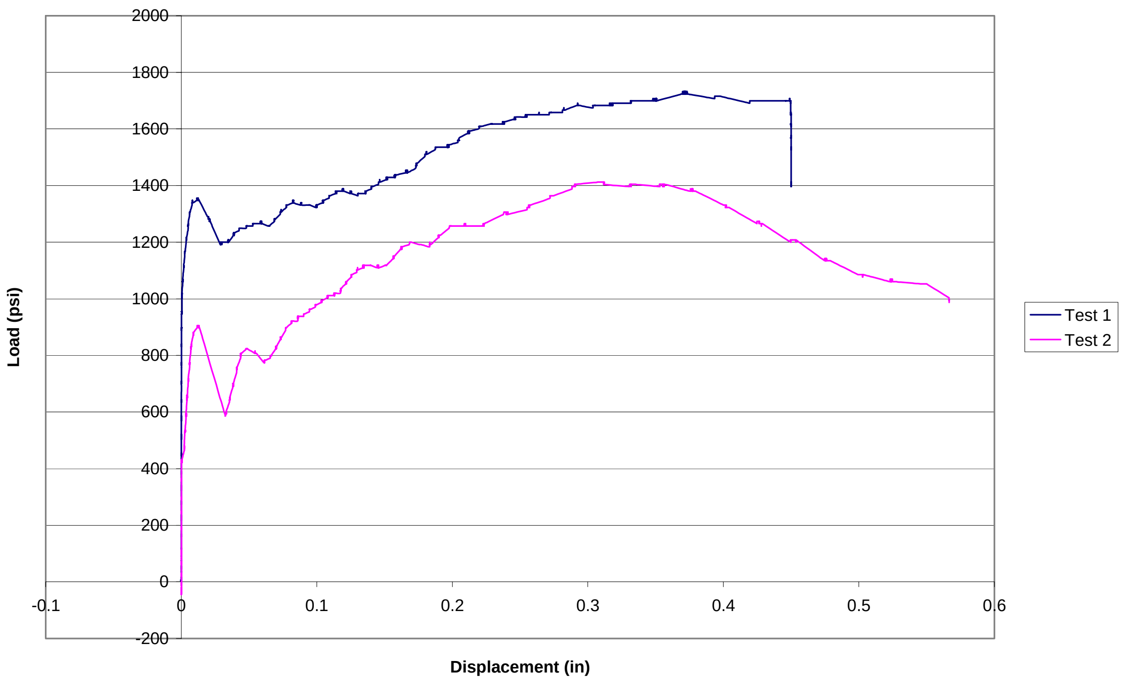
Appendix A (Graphs)

List of Graphs

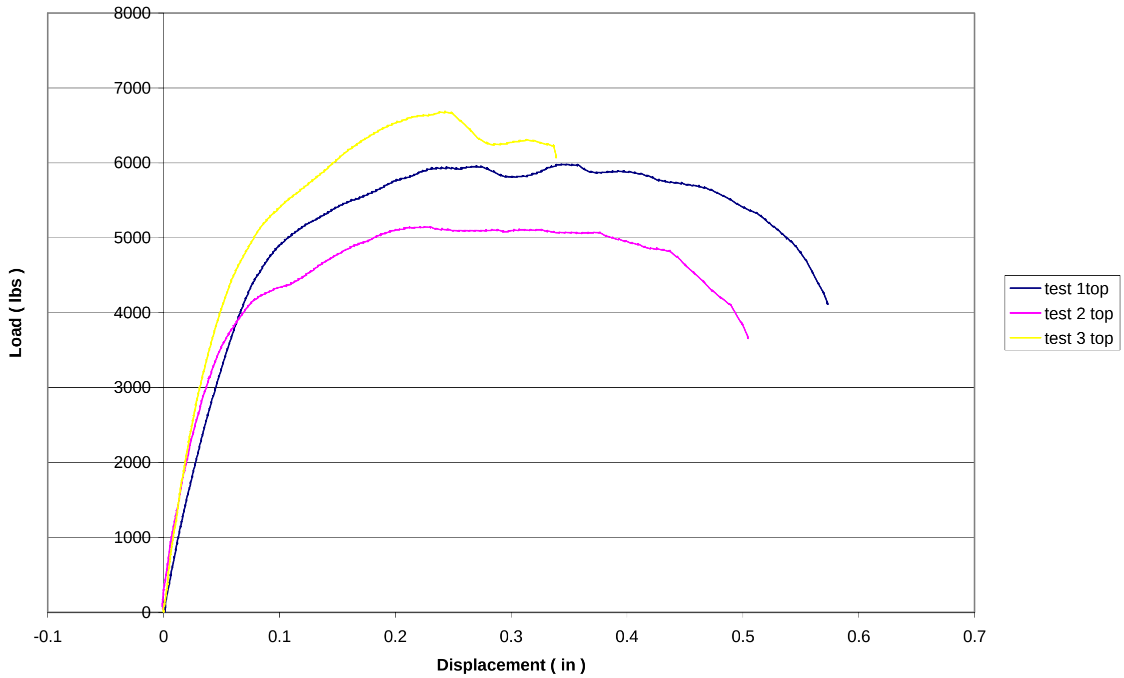
Graph 1: C1by4L5 Top Slip



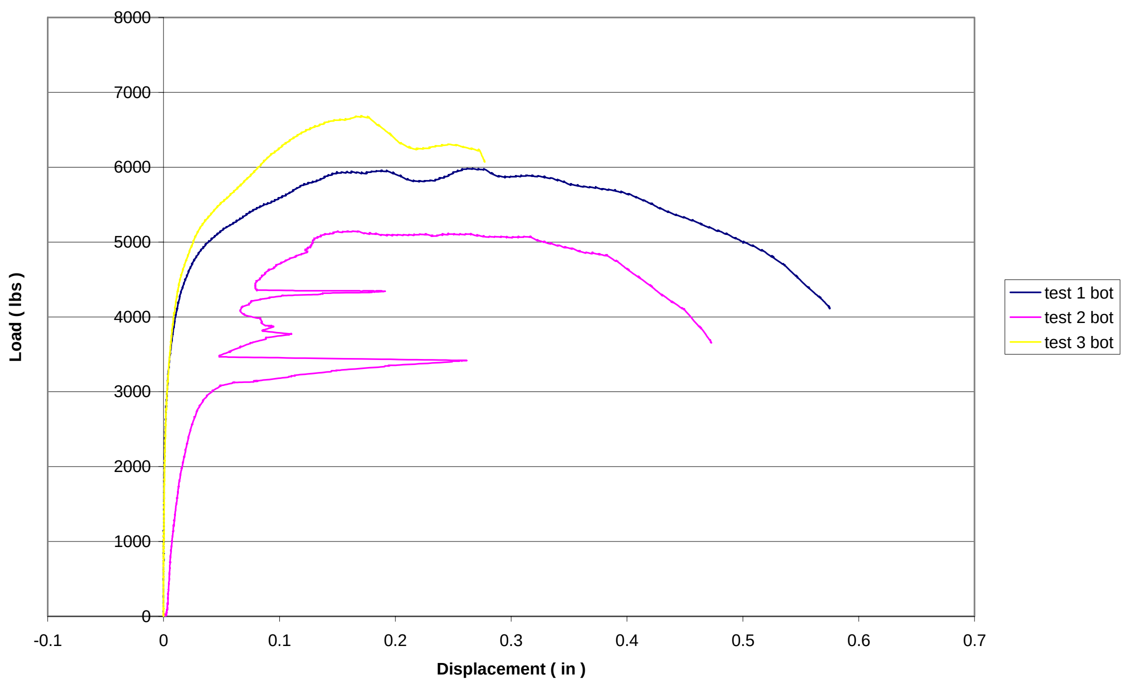
Graph 2: C1by4L5 Bottom Slip



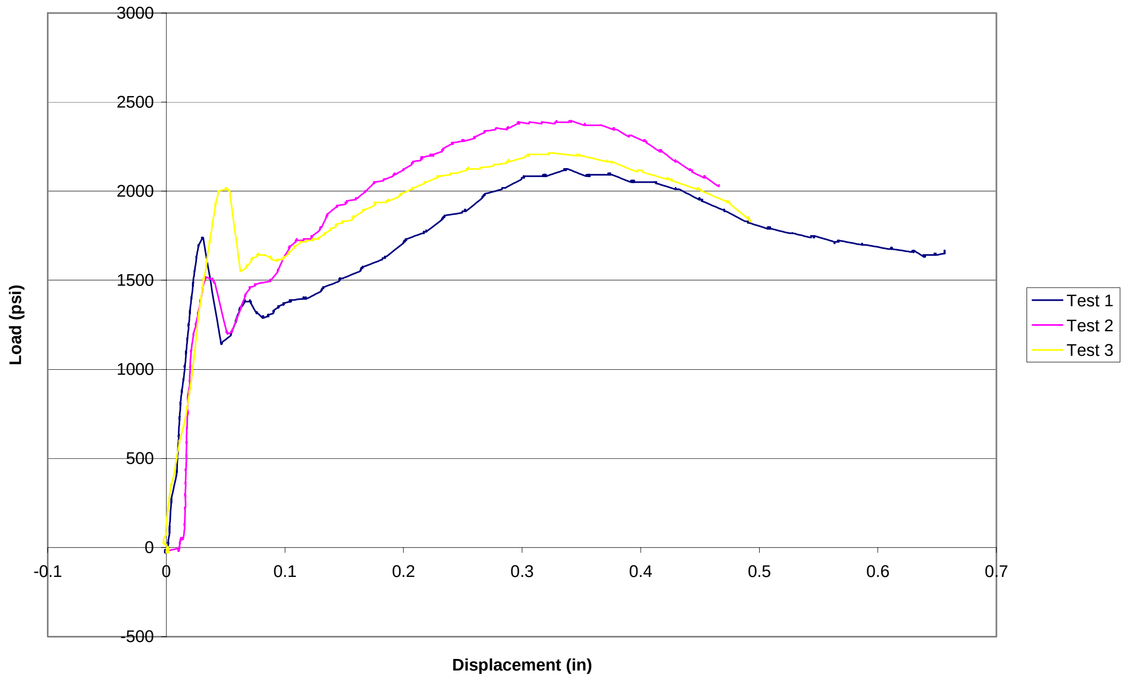
Graph 3: G3by4L05-Top Slip Comparision



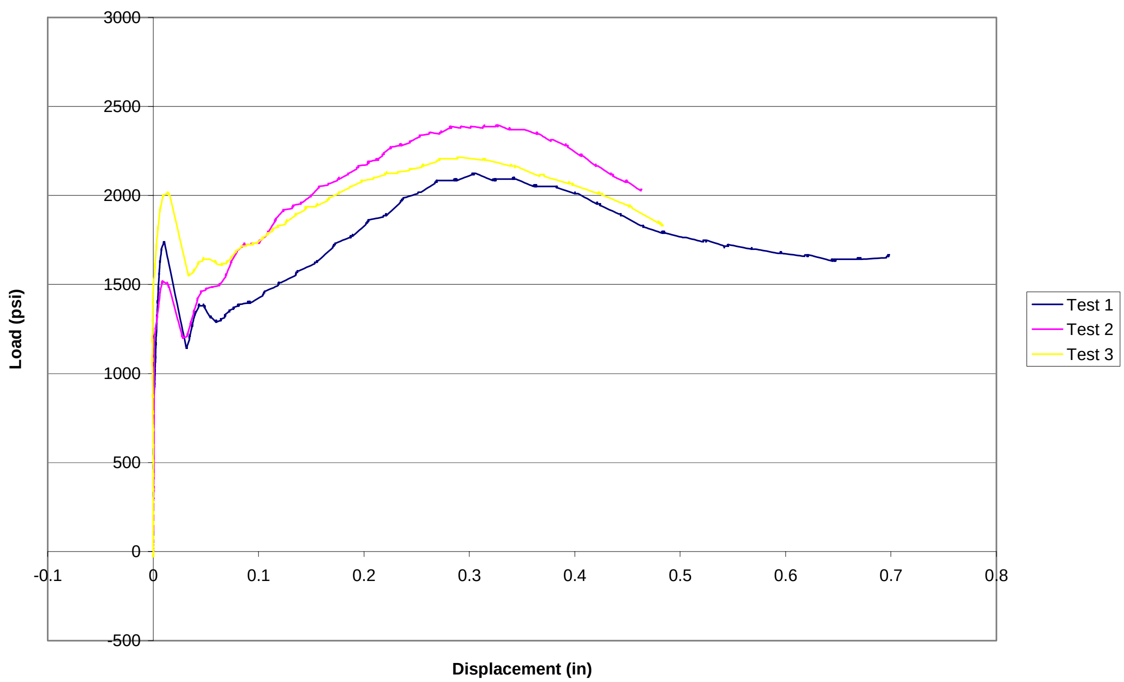
Graph 4: G3by8L05-Bottom Slip Comparision



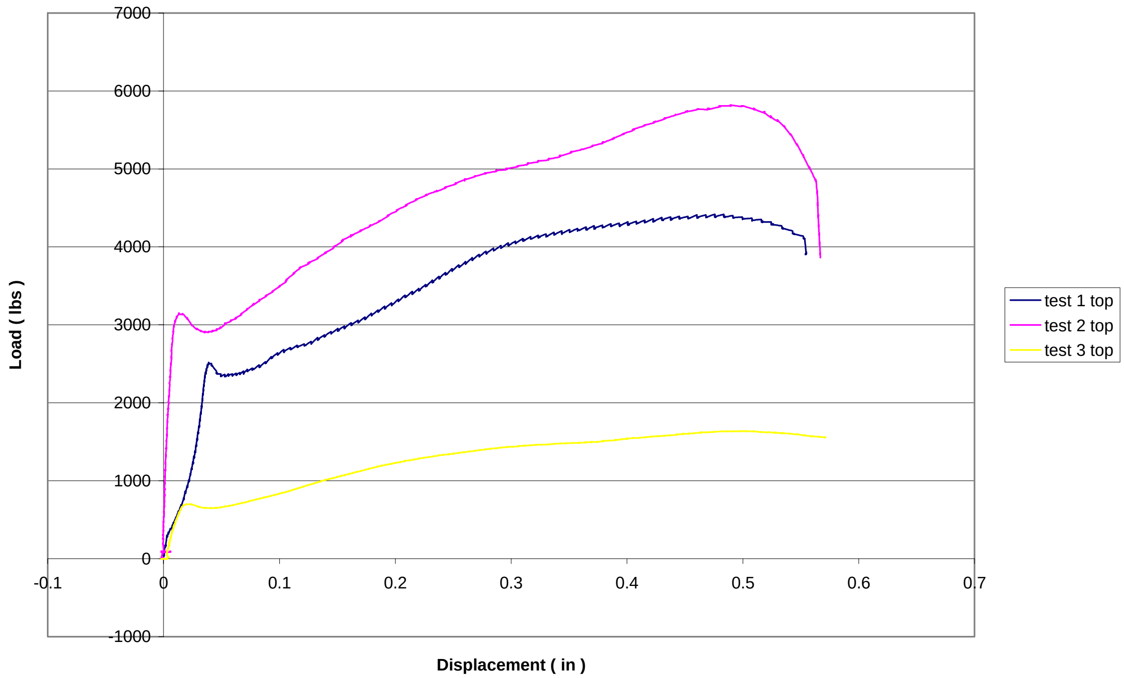
Graph 5: C1by4 L10 Top Slip



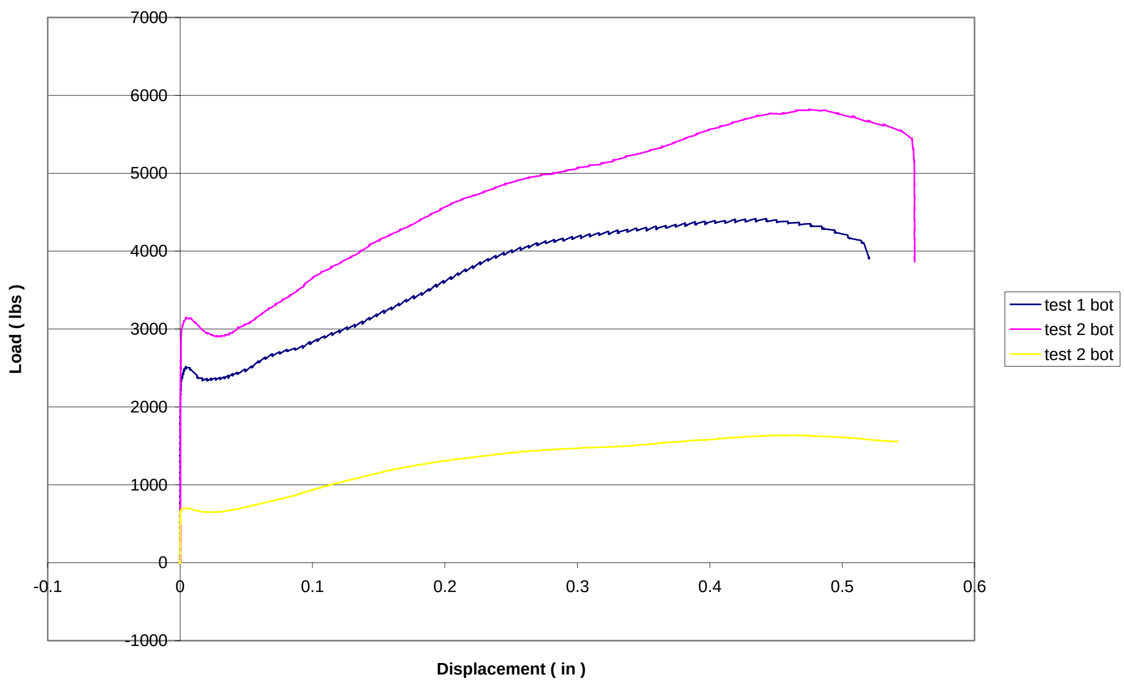
Graph 6: C1by4 L10 Bottom Slip



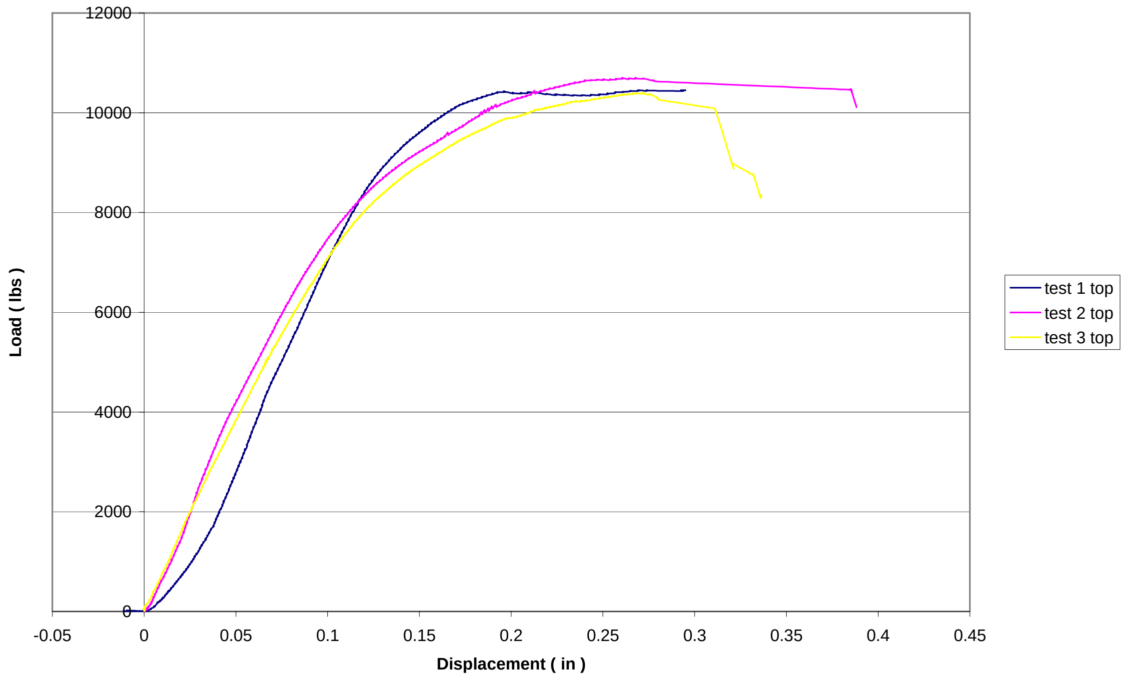
Graph 7: C3by8L10-Top Slip Comparision



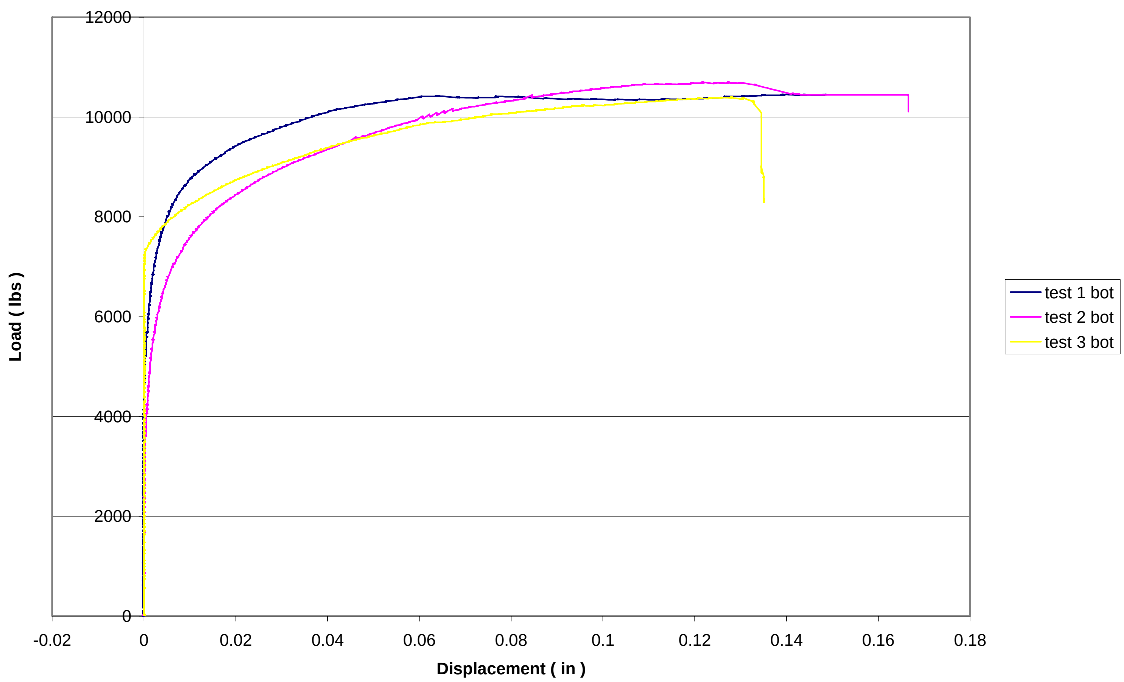
Graph 8: C3by8L10-Bottom Slip Comparision



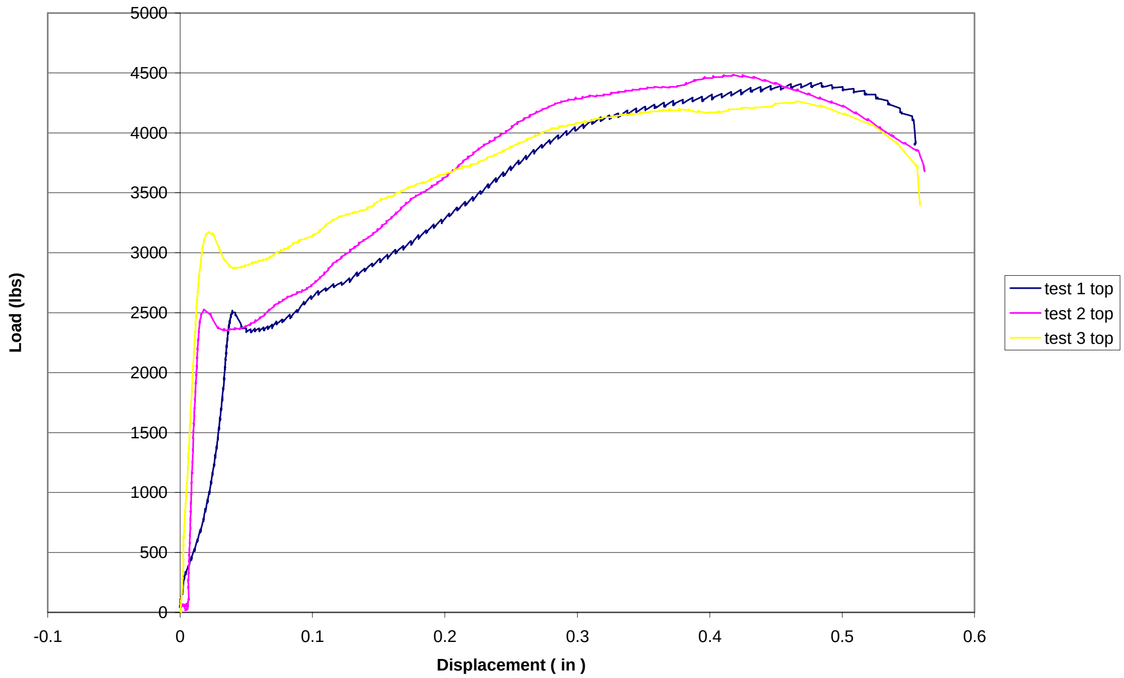
Graph 9: G3by8L10-Top Slip Comparision



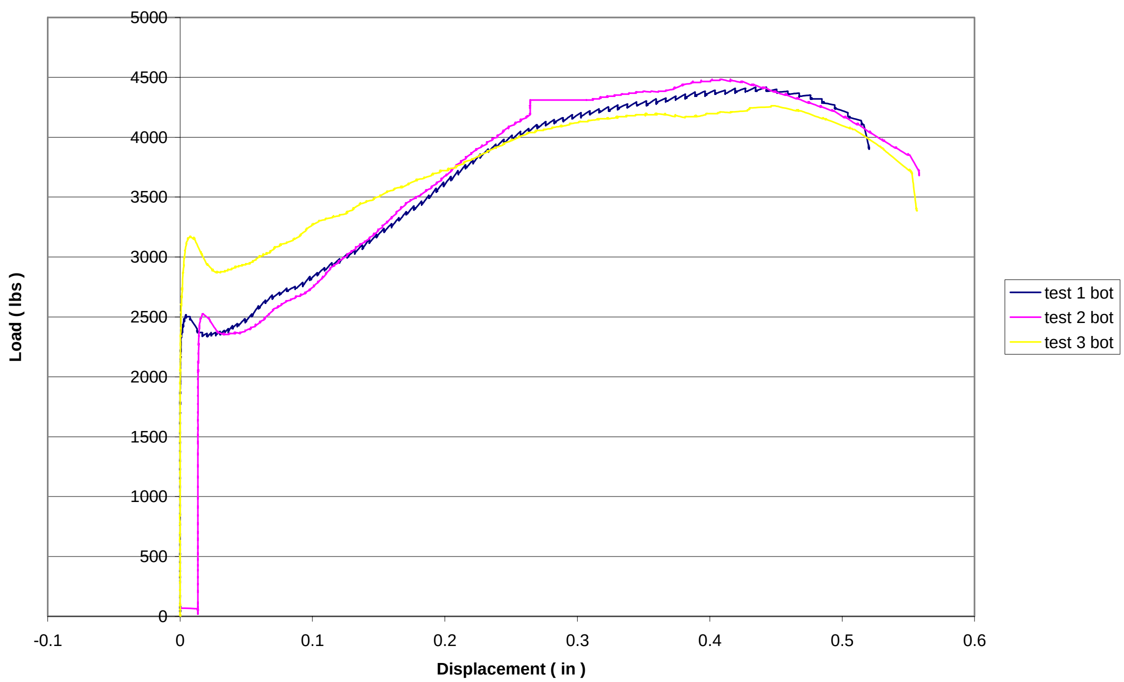
Graph 10: G3by8L10-Bottom Slip Comparision



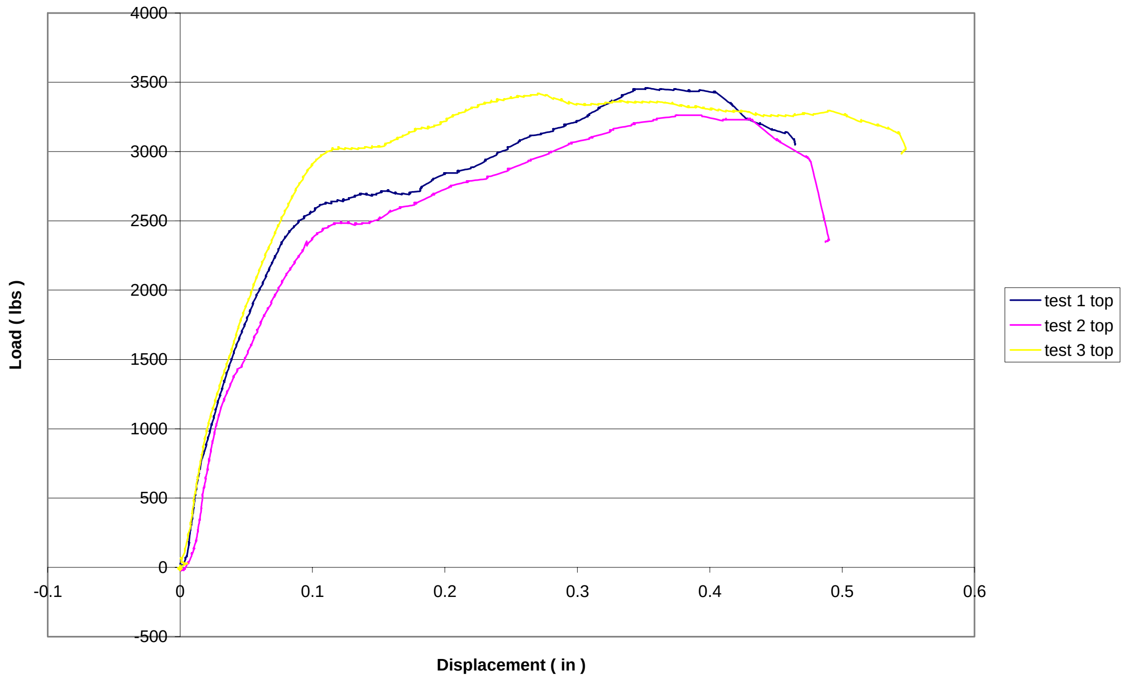
Graph 11: C3by8L5-Top Slip Comparision



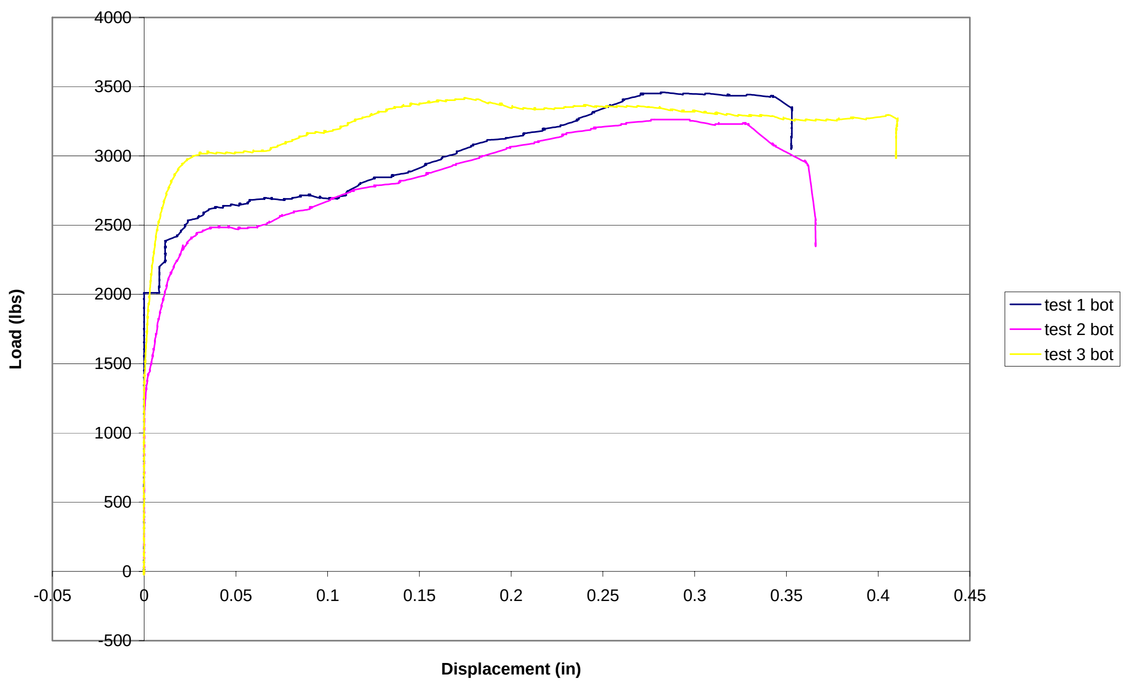
Graph 12: C3by8L5-Bottom Slip Comparision



Graph 13: G1by4L5-Top Slip Comparision



Graph 14: G1by4L5-Bottom slip Comparision



9. Conclusions:

5) With reference to table 6, it can be seen that the values of 1/K2 and K3 are higher for ¼ in diameter rods than that for 3/8 in diameter rods. Hence they show diameter dependability.

6) Values for 1/K2 and K3 are similar for all the samples of each type. This demonstrates a greater degree of confidence in the reliability of the test results.

7) These values are significantly higher than those previously published. This may be due to the surface texture of the rod.

8) From figure 1, which shows the surface characteristics of the two rods, it can be seen that the woven fabric on the glass rod can provide a higher degree of mechanical bonding compared to carbon rods. This is clearly reflected in the 1/K2 and K3 values, wherein all 1/K2 and K3 values of Glass rods are consistently higher than the carbon rods values.