Bending and Bond Behavior of Concrete Beams Reinforced with Plastic Rebars

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Corrosion related deterioration of constructed facilities, such as coastal and marine structures, bridge decks, chemical and wastewater treatment plants, results in costly repairs and leads to user inconveniences. To improve the longevity of these facilities, the use of non-corrosive fiber reinforced plastic (FRP) rebars offers an alternative to mild steel rebars as reinforcement in concrete structures. Because the mechanical properties of FRP rebars are different from those of steel rebars, the performance of the FRP rebars embedded in concrete is not fully understood. As an example, the tensile strength varies with the diameter size of the rebar. For an E-glass FRP rebar with 55% glass volume fraction, the ultimate strength is 130 ksi for a #3 rebar and 80 ksi for a #7 rebar, based on gross area of rebar. In addition, the modulus of elasticity is about 7 x 10^3 ksi which is about 1/4 of mild steel. There is an urgent need for information regarding the bending and bond behavior of concrete sections reinforced with FRP rebars. A series of laboratory tests on concrete beams reinforced with FRP rebars is outlined in this paper. The major emphasis of these tests is to evaluate concrete beams reinforced with FRP rebars in terms of the stress-strain behavior, load-deflection variations, load carrying capacities, crack patterns, modes of failure and bond strength.

Recent reports and publications on the use of glass fiber reinforced plastics suggest the desirability of a review of research and development on the use of this material for reinforced concrete (1,2,3,4). In addition, published reports on the prestressing work in West Germany on the UlenBergstrasse bridge were reviewed (5,6). Current engineering reports and publications present very few experiments conducted on the bending and bond behavior of beams reinforced with FRP rebars with inconclusive results and no established design recommendations.

The influence of the following variables of FRP rebars on bending and bond strengths is evaluated on a systematic basis:

1) Rebar surface condition (smooth versus ribbed versus sand coated).
2) Diameter.
3) Fibers and resins types.
4) Fiber volume.

More specifically, this paper synthesizes the experimental results obtained by testing twenty-two rectangular beams under pure bending and twelve tests under bond forces (pull-out) using a stub cantilever test frame. The experimental results of the beams reinforced with FRP rebars tested under bending and bond will be evaluated in terms of the existing theories that are being employed for concrete specimens reinforced with mild steel rods after the completion of the testing program. The mathematical models and design equations of concrete specimens reinforced with mild steel will be modified according to the experimental results generated for FRP reinforced concrete beams.

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EXPERIMENTAL PROGRAM

Specimen Fabrication and Curing

Bending specimens were cast in wood forms whereas the bond specimens were cast in steel forms. In the case of the bond specimens, a thin wall conduit was inserted over and along the unloaded end of the test rebar to eliminate bond, thus giving the desired embedment length, EL.

After assembling the forms, the surfaces were oiled for easy removal. Before redimix concrete was placed in the forms in layers of about one third of the depth of the specimen, the reinforcement was positioned carefully and the overall dimensions were checked. Next, a portable electric vibrator was used to vibrate each layer. The surfaces of the specimens were leveled to a smooth surface. Test cylinders were cast at the same time as the specimens. For each mix of concrete, the slump was measured.

The specimens and cylinders were then covered with plastic sheeting and allowed to cure in the forms for at least seven days. After removing the specimens from the forms, they were allowed to cure at ambient conditions for three weeks. For each bending or bond test, two cylinders were tested. ASTM C-39 test procedure was followed to determine the concrete compressive strength f_c'.

Bending Test

The rectangular beams, Figure 1, were tested under pure bending, (as simply supported under four point bending), using different configurations of FRP reinforcements, such as rebar size, type of rebar (smooth, ribbed), and type of stirrups (steel, FRP smooth, FRP ribbed). The applied force was measured by a load cell connected to a strain indicator, Strain gages were carefully selected and placed on the reinforcement as well as on the concrete top surface. At every load stage, the strains were recorded with the use of strain indicator. A dial gage positioned at the center of the beam was used to measure deflection at each load stage. In addition, cracks were monitored, sketched and measured.

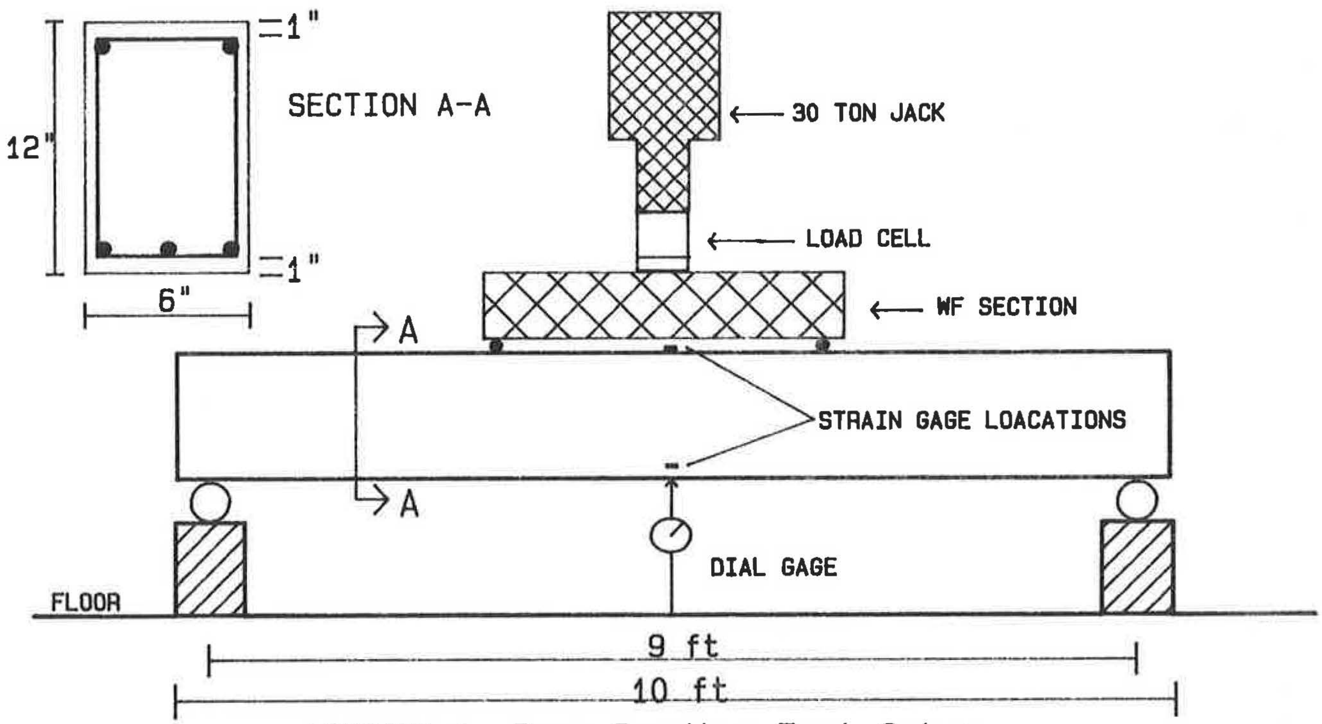

FIGURE 1 Beam Bending Test Setup

Bond Test

All specimens were similar to the WVU modified cantilever type shown in Figure 2. The front concrete end block was cut out in these specimens for modeling the portion of a beam adjacent to a diagonal crack. The compression zone of the beam was designed to prevent premature crushing failure. The specimens were designed so that no shear or moment failures were expected to occur during the tests.

Testing Rig

The specially designed and fabricated testing rig utilized for this study was originally developed by the Civil Engineering Department at WVU in the early 1970's (8). It consisted of a frame and two load reaction systems as shown in Figure 3. One of the load reaction systems was a buildup steel bearing beam, used as the horizontal support at the front end of the specimen. The other load reaction system, used for the vertical support at the rear end of the specimen, was composed of a 100-ton jack, a 60-ton load transducer and a steel bearing plate. The bearing plate was used to reduce the local bearing stresses which might affect the failure mode and crack pattern. At the front end of the specimen was an adjustable WF beam carrying the vertical reaction down by 4 vertical rods to the horizontal girder. Two 1 x 12 x 26 inch steel plates were bolted together to act as load distribution plates with an adjustable gap as shown in Figure 4.

The load distribution plates rested on four bolts. During testing, the bolts were released to avoid any undesirable restraints. For additional details refer to Figure 4.

Loading System

The applied horizontal bar force was produced by a pair of 60-ton jacks and was transmitted to the FRP rebars through the distribution plates and sand coated grips shown in Figure 5. The applied forces were measured by 2 load cells connected to a strain indicator and were increased in increments of 1 kip.

Gripping Mechanism

In earlier stages the design and development of suitable grips to pull FRP rebars embedded in concrete have presented some difficulties. Typically, the FRP rebar is found to fail in the grip itself due to combined effects of local horizontal shear and crushing. An ideal grip must grasp the rebar in a manner as to avoid failure of the rebar at the grip. Several methods for anchoring the FRP rebars have been investigated as a part of this study. However, the sand-coated grips filled with sand are found to be most suitable to transfer axial bar forces, Figure 5.

After placing the FRP rebars between the two sand coated grips, the set of grips are tightened together by six bolts.

Test Procedure

The specimen was seated in its proper position as shown in Figure 3 on the testing frame. After applying the initial load of 5 kip, the bolts which support the distribution plates were released. The test was continued by loading the specimen in an increment of 1 kip per load stage. At each load stage, dial gages were recorded and the crack pattern was sketched on the specimen. The test was stopped when the rebars could not hold any extra load, i.e. slippage was evident.

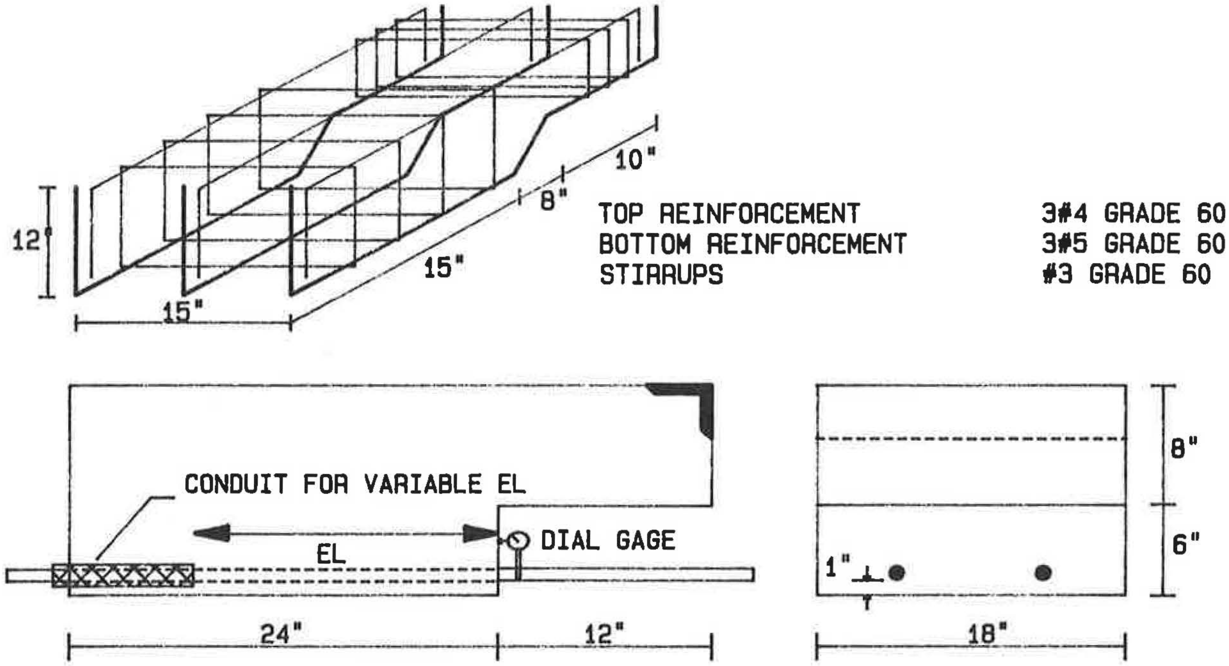

FIGURE 2 Bond Specimen Reinforcement Detail

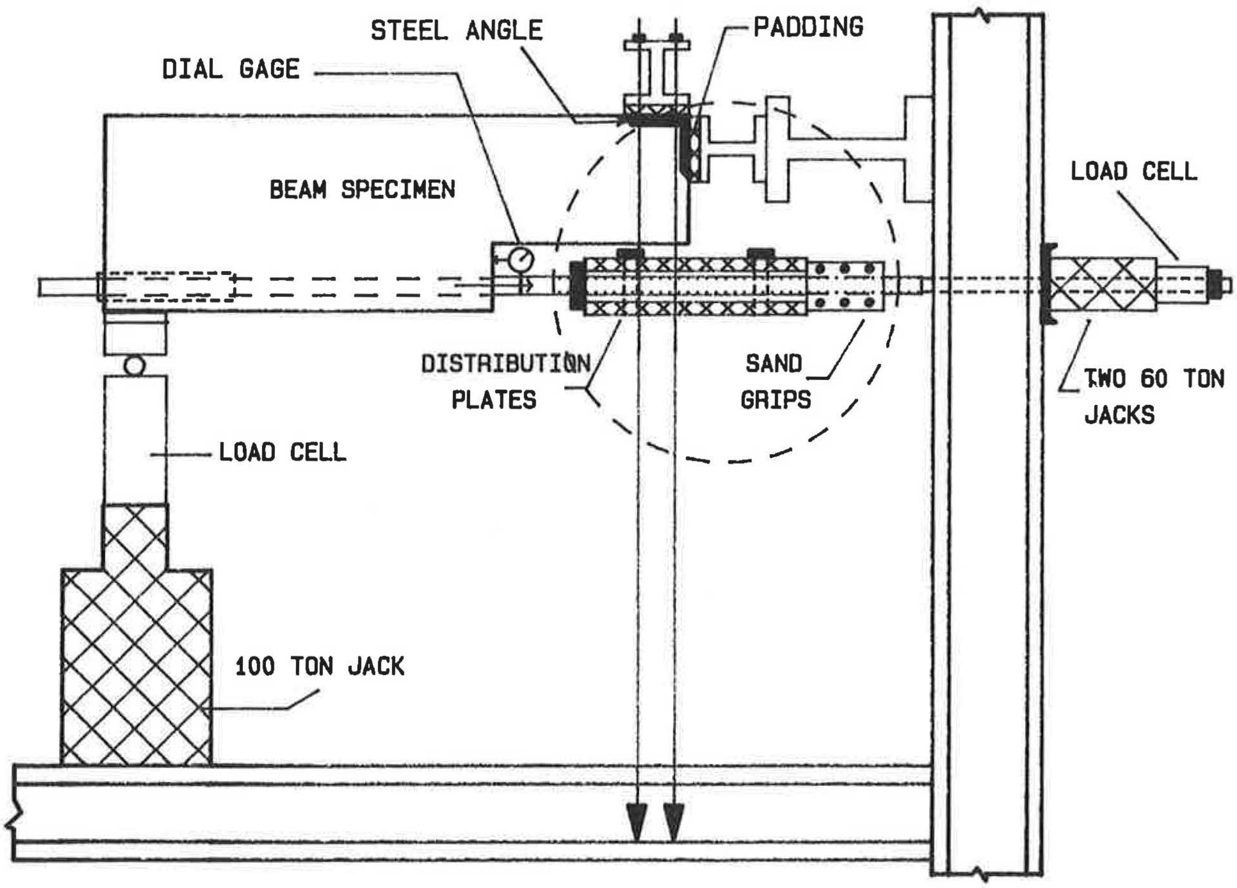

FIGURE 3 Bond Test Setup

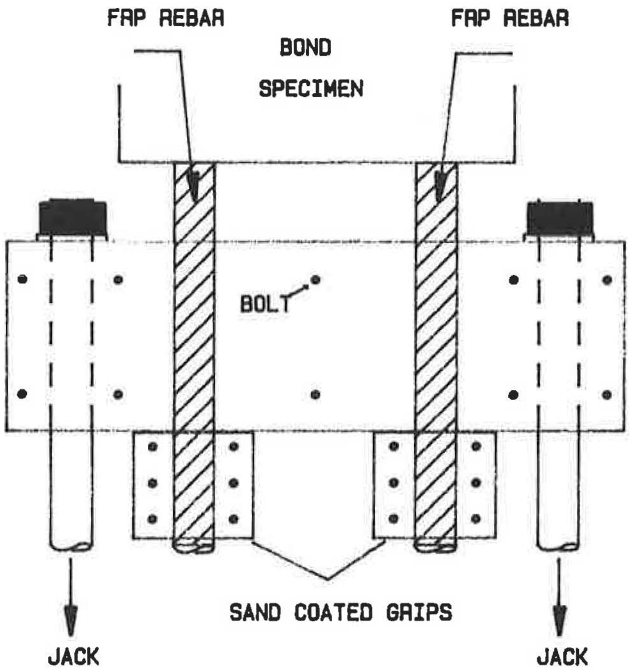

FIGURE 4 Detail of Load Distibution Plates

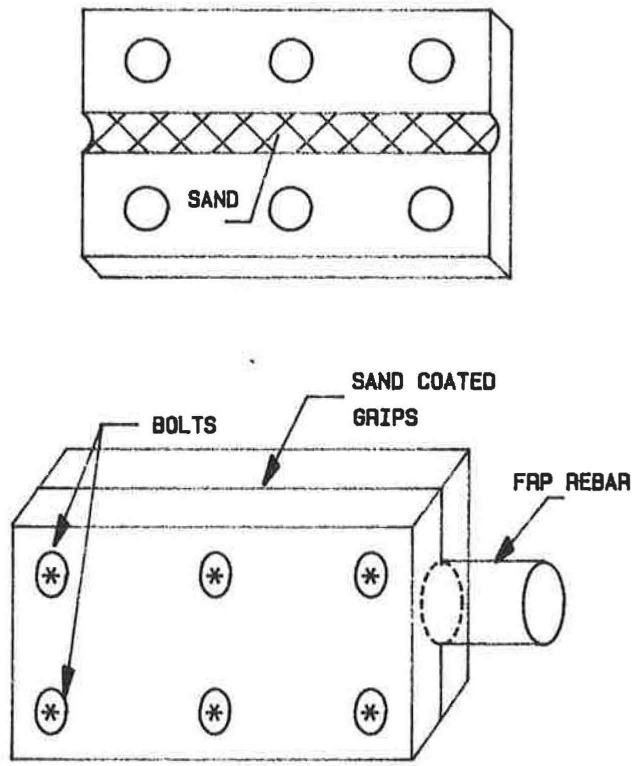

FIGURE 5 Detail of The Sand Coated Grips

EXPERIMENTAL RESULTS

Bending Tests

A series of laboratory tests on concrete beams reinforced with FRP rebars were conducted. The major emphasis of these tests was to investigate whether or not concrete beams reinforced with FRP rebars behave in a manner similar to those reinforced with mild steel rebars in terms of:

* Stress-Strain behavior.
* Load-Deflection variations.
* Load carrying capacities.
* Crack patterns (spacing, width, propagations).
* Modes of failure.

The simply supported rectangular beams of 9 ft lengths, Figure 1, were tested under pure bending, under four point bending load condition, using different configurations of FRP reinforcements. In order to take advantage of the high tensile strength of the FRP rebars, beams with high strength concrete (6500 and 7500 psi) were tested for the purpose of maximizing the bending resistance of the beams. A 90% increase in ultimate moment capacity was obtained when FRP rebars of ultimate tensile strength of 130 ksi were used in lieu of mild steel rods. Cracks in FRP reinforced concrete beams were found to be sudden and crack widths were larger than the corresponding steel reinforced beams; however this behavior has improved by using higher concrete strengths.

In order to compare the beam bending test results and to evaluate the effect of changing some parameters, the results are grouped into five categories, Group A through E. Table 1 summarize the beams reinforcement, and test results.

Group A

This group consists of two beams reinforced with 3#3 FRP rebars with #2 steel stirrups. All other parameters were kept the same for this group except for rebars, which were supplied from two different companies. A maximum difference of 10% was found in the moment capacities of the two beams in this group of which Beam #2 reached an ultimate moment capacity of 27.75 kip-ft

Group B

The behavior of the beams reinforced with 2#4 FRP rebars were investigated in terms of the type of stirrups used. The use of smooth FRP stirrups resulted in a bond failure between the smooth stirrup and concrete, thus reducing the moment capacity of the beam by 35%.

Group C

This group of beams was reinforced with either 2#7 or 2#8 FRP rebars. The use of smooth FRP rebars in Beam # 1 reduced the moment capacity of the beam by 60% compared to Beam #8, which was reinforced with ribbed rebars. By using high strength concrete (7.5 KSI) versus regular strength concrete (4.2 KSI) the moment capacity of Beam #C was increased by 50% compared to beam #4, due to better utilization of the rebar high strength.

Group D

In order to take advantage of the high tensile strength of the FRP rebars (130 ksi), the use of high strength concrete (7.5 ksi) was used in beams A & B and (6.5 ksi) was used in beams H1 & H6. The ultimate tensile strength of the FRP rebars were reached in beams H1, H6, A and B, thus increasing the moment capacity of the beams by a factor of TWO. The moment capacities of beams H1 and H6 did not reach the ultimate moment of beam A due to the lower ultimate tensile strength of the rebars, (100 vs 130 ksi), which were supplied from another company. The tensile strengths were also verified by conducting tension test on both rebars.

The use of an additional FRP reinforcement in an arch form in Beam #B has increased the moment capacity of the beam by 60% as shown in Table 1. This increase is attributed not only to the increase in FRP area but also to the shape of FRP, in resisting bending. In addition, the crack width was reduced by 50% when using the arch form.

The effects of changing concrete strength in addition to the use of the arch arrangement are best illustrated by the load versus deflection plot in Figure 6.

The experimental deflections of FRP reinforced beams (Beams 9 & 10) were about four times larger than the beam reinforced with steel (beam #11). These larger deflections were expected due to the low modulus of elasticity of the FRP rebars, which is about 7×10^6 psi.

Group E

In this group, the effect of increasing the perimeter of the reinforcement in addition to the use of sand coated rebars was investigated. The use of 5#3 rebars (0.55 in^2) versus 3#4 rebars (0.59 in^2) increased the ultimate moment capacity by 20%. The crack pattern in terms of the crack width, their propagation and distribution has vastly improved by the use of the sand coated rebars. This behavior is related to a better bond between the sand coated rebar and concrete. The crack pattern is very similar to a pattern expected of a beam reinforced with steel rods. The load versus deflection plot in Figure 7 illustrates an increase of 40% in the cracking moment when sand coated rebars are used.

Bond Behavior

Bond strength development is a complicated phenomenon which is influenced by concrete strength, embedment length, concrete cover, rebar spacing and associated shear and flexure. The bond strengths are expected to arise either from the FRP rebar anchorage to concrete or changes in bending moment along the specimen length.

In order to study the bond performance (bond force and failure pattern) of the FRP rebars, a set of experiments were conducted using the cantilever specimen developed by the Civil Engineering Department at West Virginia University, illustrated in Figures 2 and 3.

The cantilever specimen tests are more realistic in simulating bond behavior conditions, less expensive and preferred over the conventional pull-out specimen tests since they provide more realistic strain gradient through the depth of the specimen which is similar to the gradient expected in a flexural member. While the pull-out test does not represent the actual behavior in a beam, subjecting concrete to compression forces and rebars to tension forces, the cantilever specimen produces tension forces in both concrete and rebars.

As shown in Figure 2, the compression zone of the beam is designed to prevent premature crushing failure and is designed to prevent shear or moment failures during experiments. A concrete block is cut out of the specimen for modeling the portion of a beam adjacent to a diagonal crack.

For each experiment in the test program, the loading and slip of the rebar were recorded and plotted. A summary of the bond test experiments and the results are outlined in Table 2. A typical bond stress versus net slip at the loaded end is illustrated in Figures 8 and 9.

CONCLUSIONS

Based on the limited tests (22 in bending and 12 in bond) that were conducted under this program, the following conclusions may be drawn.

1) Cracks in FRP reinforced concrete beams are found to be developing suddenly and crack widths are found to be larger than the corresponding ones in steel reinforced beams.

2) The fact that the bending cracks were developed at uniform intervals is a clear indication that there was no bond failure between deformed FRP rebars and concrete.

3) The crack pattern in terms of the crack width, their propagation and distribution has vastly improved by the use of the sand coated rebars due to a better bond between the sand coated rebar and concrete which has increased the cracking moment by 40%..

4) A 50% increase in ultimate moment was obtained when deformed FRP stirrups were used in lieu of smooth FRP stirrups. Bond failure between smooth FRP rebar and concrete is observed. Therefore, use of smooth FRP rebars and stirrups are ruled out.

5) The ultimate moment capacity of high strength concrete beams ($f_c' = 7.5$ ksi) was increased by 90% when FRP rebars of ultimate tensile strength of 130 ksi were used in lieu of mild steel rods (60 ksi).

6) More bond tests are required before determining the minimum development length for the FRP rebars.

7) Current procedures for steel reinforced beams do not predict ultimate moment capacity of beams reinforced with FRP. However, modifications in the present ACI equations will be made upon the completion of the experimental program.

RECOMMENDED RESEARCH AREAS

In order to reduce the crack width in beams reinforced with FRP rebars and to confine it to the maximum width set by AASHTO specifications (10), the following options will be investigated:

TABLE 1 BENDING TEST RESULTS

GROUP #	BEAM #	FRP REINF.	STIRRUP SIZE	CONCRETE STRENGTH (ksi)	ULTIMATE MOMENT (kip-ft)	MODE OF FAILURE
A	2	3#3	#2 S	4.2	27.75	BEND/COMP/REBAR
A	3	3#3	#2 S	4.2	24.67	BEND/COMP/SHEAR
B	5	2#4	#2 S	4.2	27.75	BEND/SHEAR
B	6	2#4	#3 F	4.2	24.67	BEND/SHEAR
B	7	2#4	#2 fs	5.0	16.96	BOND IN STIRRUP
C	1	2#7SMOOTH	#2 S	4.2	46.50	BOND
C	4	2#8	#2 S	4.2	40.00	COMP/SHEAR
C	8	2#7	#2 S	5.0	41.63	COMPRESSION
C	H5	2#8	#3 F	6.5	54.75	COMP/SHEAR
C	C	2#8	#3 F	7.5	60.00	COMP/SHEAR
D	9	2#3	#2 fs	5.0	12.95	BEND/BOND
D	10	2#3	#2 S	5.0	10.64	TENSION/EX.CRACKING
D	11	2#3 STEEL	#2 S	5.0	13.88	TENSION
D	H1	2#3	#3 F	6.5	18.00	TENSION
D	H6	2#3	#3 F	6.5	16.50	TENSION
D	A	2#3	#3 F	7.5	27.75	TENSION
D	B	2#3/ARCH	#3 F	7.5	43.50	TENSION
E	H2	3#4	#3 F	6.5	31.13	COMPRESSION
E	H4	5#3	#3 F	6.5	37.50	COMP/TENSION
E	D	3#4/SAND	#3 F	7.5	40.50	SHEAR/TENSION
E	E	5#3	#3 F	7.5	40.50	SHEAR/TENSION
E	F	3#4	#3 F	7.5	34.50	SHEAR/TENSION

F : FRP STIRRUP S : STEEL STIRRUP fs : SMOOTH FRP STIRRUP

TABLE 2 BOND TEST RESULTS

BEAM #	REBAR SIZE	EMBEDMENT LENGTH (in)	ULT. LOAD @ FAILURE (kip)	EXP. BOND STRESS (psi)	REMARKS
BO.1.1	#8	16	22.46	450	BOND
BO.1.2	#8	16	24	480	BOND
BO.1.3	#8	24	29	387	BOND
BO.1.4	#8	24	30	400	BOND
BO.2.1	#3	16	*	*	FAILURE IN GRIP
BO.2.2	#3	16	*	*	FAILURE IN GRIP
BO.2.3	#3	24	11	>389	REBAR FAIL./NO SLIP
BO.2.4	#3	24	10.9	>389	REBAR FAIL./NO SLIP
BO.H1	#3	12	8.2	>580	REBAR FAIL./NO SLIP
BO.H2	#3	12	8.1	>573	REBAR FAIL./NO SLIP
BO.H3	#3	8	9.4	>997	REBAR FAIL./NO SLIP
BO.H4	#3	8	8	>849	REBAR FAIL./NO SLIP

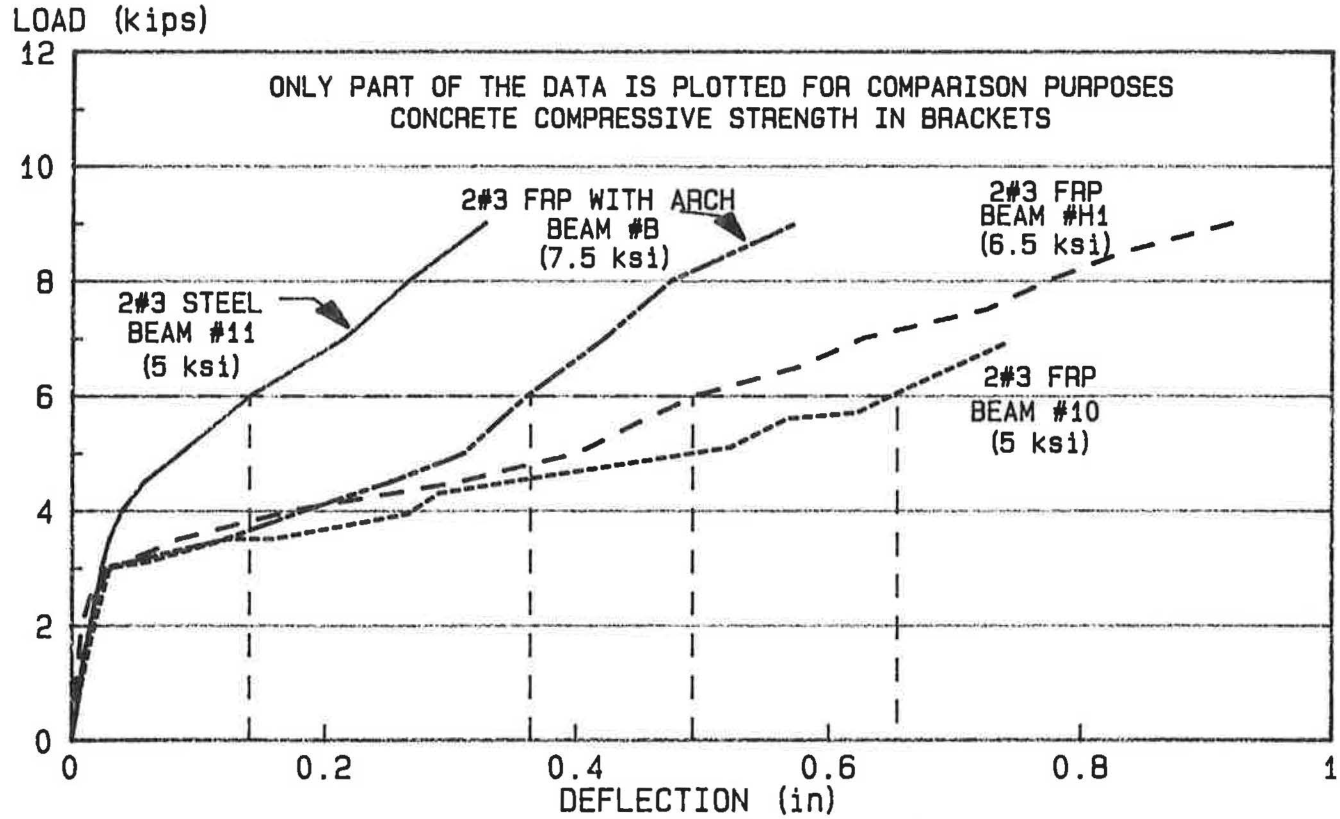

FIGURE 6 Load vs Deflection (GROUP D)

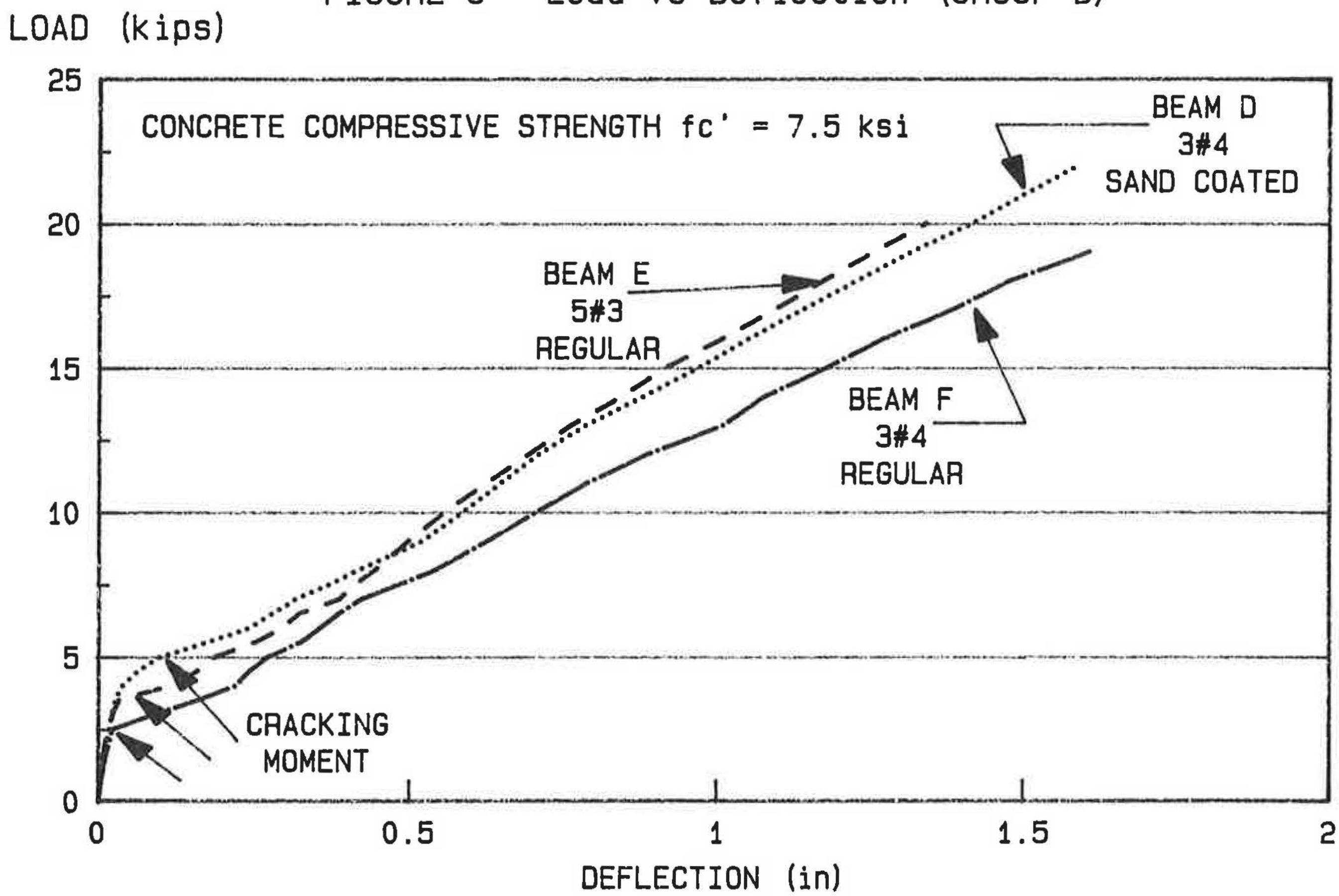

FIGURE 7 Load vs Deflection (GROUP E)

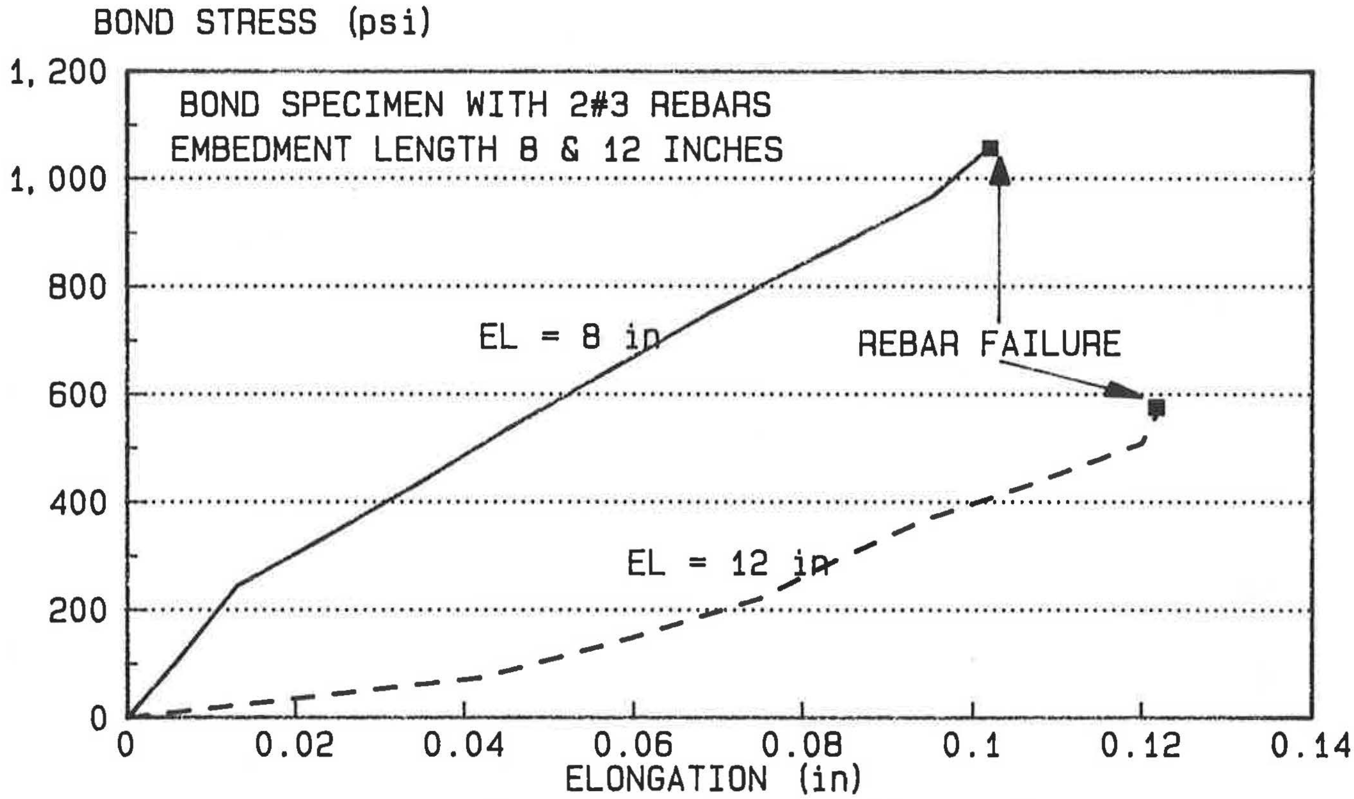

FIGURE 8 Bond Stress vs Elongation

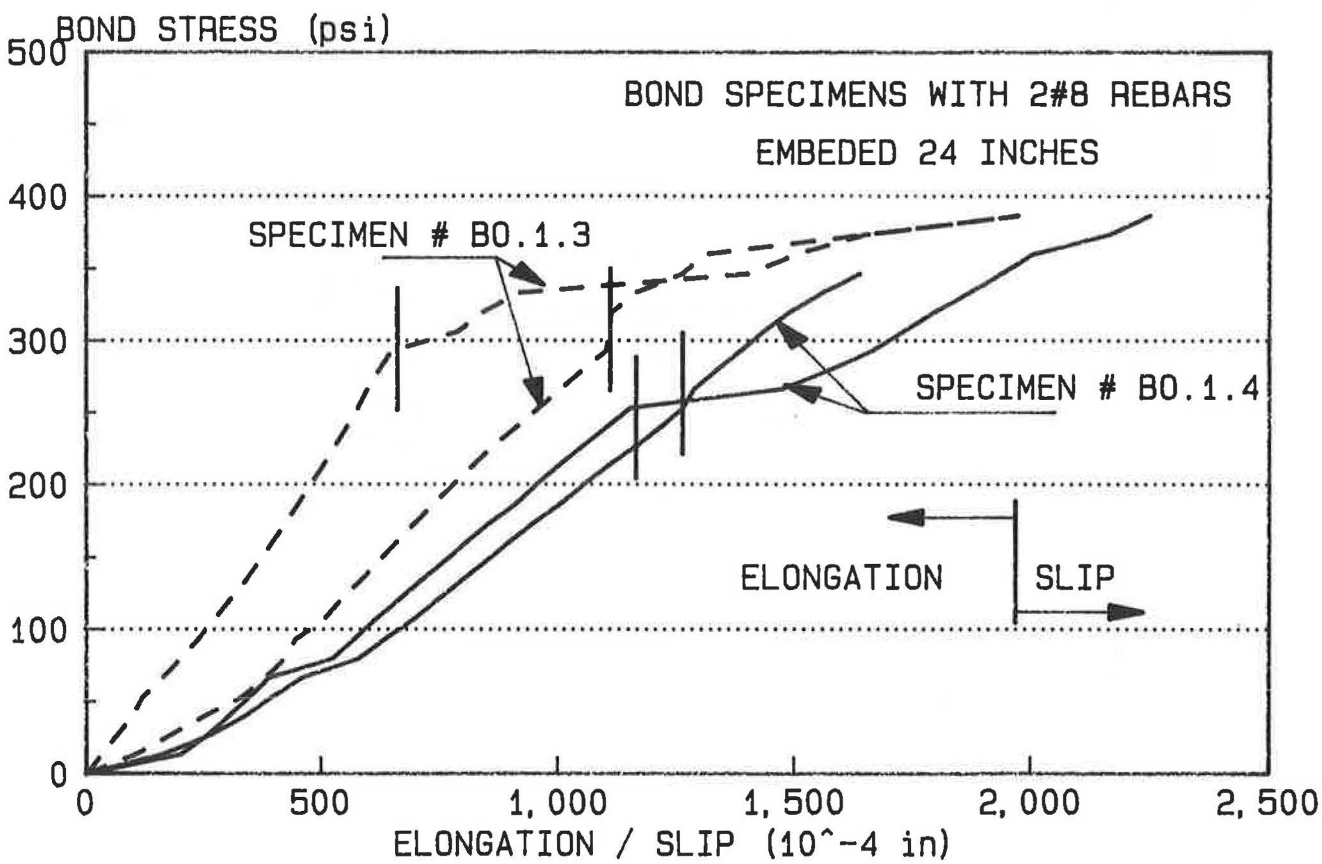

FIGURE 9 Bond Stress vs Net Slip

a) Reduce the elongation mismatch between the FRP rebar and concrete by either increasing the ductility of concrete or increasing the stiffness of the rebar by using different kind of fiber, i.e. kevlar, or byincreasing the strength of concrete, i.e. 8 ksi inlieu of 4 ksi.
b) Increase the stiffness of the beams by using 2 to 3 times the required cross-sectional area of the FRP rebar needed.
c) Increase the perimeter of the reinforcement.
d) Introduce a new detailing idea in the reinforcing of the beams.

Acknowledgement

This study was part of the effort of the Constructed Facilities Center of West Virginia University, Morgantown, West Virginia. This work was supported in part by the National Science Foundation (NSF) under grant No. 861010. The support of the Federal Highway Administration (FHWA), the West Virginia Department of Highways (WVDOH), and industry are also gratefully acknowledged.

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