E90 Final Report:

The Use of Glass Fiber Reinforced Polymer Reinforcement in Concrete Beams

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Abstract

The American Concrete Institute runs a biannual competition to develop an optimized design of a beam reinforced with Fiber Reinforced Polymer bars and mesh. While this competition did not take place this year, the rules from the 2007 competition were used to provide constraints for an investigation of reinforcement layouts within concrete beams. Maintaining a constant quality of workmanship was extremely difficult, leading to results that differ quite widely from the finite element model created, though the relative strengths of the beams in the models was as expected based on an ANSYS model. Overall it appears that simply reinforced beams were most successful.

Key Words: Fiber Reinforced Polymer, Reinforced Concrete, Finite Element Analysis

Acknowledgements

I must thank Kara Peterman ’09 for helping me with my project as a part of her directed reading. She was very helpful in making samples to determine a concrete mix design, as well as helping pour some of the beams. Without her help it would have been nearly impossible to pour as much concrete as we did. She also made the long hours spent in the shop into a much less stressful experience.

I would also like to thank Professor Faruq Siddiqui. His advice kept me on track. Without his help I may never have moved beyond the mix design phase of my project. Professor Siddiqui also provided me with much help in my ANSYS modeling and all failures within that model are entirely my fault.

It is also necessary to thank the people whose help, though limited in extent, was essential to my project. Firstly, Professor Fred Orthlieb who guided me last semester in a project to explore the properties of FRP bars. He also gave me ideas of how to reinforce my beams. While I was unable to implement many of those ideas, they got me thinking of ideas that were possible under the rules of the competition.

Next, I must thank Grant Smith who, despite personal problems, was able to help me procure the necessary components of my concrete. He was able to get me Type III cement at short notice despite the difficulty. Without this help, the pouring of my beams would have been much delayed.

The final group of people I must thank is the student chapter of ASCE, who helped pour my beams. Their help was essential and they gave it even without my asking. Thank you all.

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Introduction

Over the last half century much research has been done on the use of alternative reinforcement methods for concrete. The most important of these materials developed are fiber reinforced polymers (FRP). While not yet widely used in industry, these materials are important to construction in highly corrosive environments. As a result of this importance, recent research has focused on the flexural and shear capacity of beams reinforced using FRP. The American Concrete Institute (ACI) promotes this research by encouraging engineering students to gain experience working on simple FRP reinforced structures. One form of this encouragement is through the use of a competition with the goal of optimizing for load-weight ratio a beam reinforced with FRP bars and grid.

The most recent competition was conducted in 2007 as the ACI FRP Composites competition. An equivalent competition was not conducted this year. Despite the lack of a competition, the principles involved in optimizing a beam design are still significant. These principles include determination of beam dimensions, concrete mix design, and reinforcement layout. Within the rules of the competition all of these are to be determined by the competitor, though some parameters are provided. This makes the rules provided by ACI an ideal way to explore concrete design reinforced with FRP.

The complete competition rules are attached as Appendix A. Of particular importance are the size limitations and reinforcement requirements. These requirements limit reinforcement to two 1000 mm long GFRP bars or two 1000 mm strips of carbon grid, or some combination of these materials not to exceed a combined length of 2000 mm. The reinforcement may be cut to any length as long as the combined length requirement is met.

Also important is the competition's focus on load-weight ratio. To this end it is best to reduce weight of all materials used in the beams. The amount of cementitious material is not directly limited by the rules, but should be limited in design in order to reduce weight. Learning to limit weight in design is important to designing efficient structures.

It is not only necessary to construct the beams, but also to predict the loads under which they will fail. This prediction can be performed using the equations found in the ACI design code, but this is only valid for specific reinforcement layouts and is not very accurate for high strength concrete. As well, these equations are extremely conservative, serving only to provide a lower bound indicator of capacity. Instead, a finite element analysis, using ANSYS, can be performed yielding better results. The creation of an ANSYS model will allow for prediction, not only of ultimate load, but also of deflection behavior under any applied load.

By combining these two elements, the design and construction of FRP reinforced concrete beams and the creation of a model to predict the responses of those beams, this project allows for the application of knowledge from structures courses as well as the exploration of new technologies. It is important for a civil engineer to understand the use of FRP as it is growing popularity. This popularity comes mainly from the lifetime of the reinforced structure, which can be much higher if it does not face corrosion. By increasing the lifespan of the structure, the economic and environmental costs are reduced. Other benefits of FRP include the ability to use it in proximity to MRI machines, and knowing how to design with it efficiently allows for lower cost medical care. One aspect of FRP that has not yet been fully explored is the ability of it to flex elastically. This can allow a structure to remain standing longer after an impact load after the concrete has already failed. Taking into account all of these benefits, it is clear that FRP is going to continue to be important to modern society, and exploring aspects of its design will be important for engineers.

FRP Bars-

The bars stipulated for this project by the ACI competition rules are glass fiber reinforced polymer bars (GFRP) produced by Hughes Brothers, Inc. The manufacturer provides limited physical properties of the bars, including cross-sectional area, tensile strength and tensile modulus of elasticity. Also included is an explanation of the testing used to determine the bond stress when the bars are embedded in concrete. The testing was performed by Penn State University. Other properties of the bars are also provided but are not considered important for this project. The useful properties are shown in Table 1.

Property	Bar Size	Cross-Sectional Area	Nominal Diameter	Tensile Strength	Tensile Modulus of Elasticity	Bond Stress
Value	#4	0.2245 in^2	0.50 in	100 ksi	$5.92 * 10^6$ psi	1679 psi

Table 1. Properties of GFRP used.

The manufacturer also provides some design considerations as compared with concrete. The most important of these differences is the fact that FRP behaves only elastically up to failure, with no ductility or yielding. In steel design, yielding is used to indicate failure and gives warning in actual structures. As FRP lacks this property, it is designed to fail by concrete crushing. The calculations for this design are shown in the beam design section below. In these designs crack width and deflection must also be considered, but this was not considered to be of importance in the competition. Creep is also an important consideration that was ignored for this project.

More information on FRP is provided in the ACI "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures" from 2007. The report provides more information on the various uses of FRP. It also reports on the accepted test methods used to acquire the properties listed in Table 1. Most of the rest of the report discusses design considerations for FRP, such as fire affects, that must be considered in actual usage of the bars, but are not necessary for the competition. While not essential now, the ACI report has a high potential value for the design of FRP structures.

Carbon Fiber Grid-

Most information about carbon fiber grid comes from the manufacturer. ACI has not yet provided a report, as the grid is not used widely except in decorative concrete. The manufacturer chosen by the competition is TechFab, LLC, who provided their 1 in by 1in C3000 grid. The features of the mesh that they emphasize in their literature are the ability of the mesh to minimize crack width and the ease of using it relative to welded wire mesh. They also provide a value for the tensile strength of the carbon grid as being 3300 pounds per foot. As this is low compared to the bars, it seemed most likely that the role of the mesh would be as shear reinforcement due to the relative ease of shaping the mesh. While the mesh is suggested as beam reinforcement, the literature does not say how it should be used. One main aspect of the project was to determine the grid's usefulness in creating beams.

ANSYS-

ANSYS is a finite element analysis software. Finite element analysis is a numerical method for solving complex problems by breaking up the solid body into smaller elements that can be solved separately. For modeling concrete, ANSYS provides an element, Solid65, which replicates the behavior of concrete by adding cracking and crushing abilities to a simple solid element. The element also takes into account the non-linear material properties of concrete as well as the non-linearity of large deflections. It also allows for the modeling of reinforcement smeared within the elements. This capability was used to model the mesh, but it was decided that the bars should be best modeled as axial load elements. A.F. Barbosa and G.O. Ribeiro recommended this substitution in the paper “Analysis of Reinforced Concrete Structures Using ANSYS Nonlinear Concrete Model”. The elements chosen were LINK8 elements according to Verification Problem No. 146 provided by ANSYS. The model for the beams was created by writing a code in the ANSYS Parametric Design Language as opposed to using the GUI. Further discussion of the elements used in the model is included below.

Beam Design Theory

For designing a simply supported normal weight concrete beam with some dimensional limits ACI provides a detailed design method. For the competition this procedure must be highly adapted to yield beam dimensions and preliminary predicted results. The first adjustment that must be made is for the use of high strength concrete. A high strength mix will not be of normal weight and other adjustments must be made to account for this. The procedure also does not account for the restrictions on reinforcement provided by the competition, nor does it allow for the competition's restriction on weight. While the procedure itself is rather limited in its practicality, the equations provided by the design handbook can be employed.

There are four main failure modes expected from these beams, all of which must be examined in beam design and analysis. The first two of these modes are concrete crushing or FRP rupture. Which of these will govern can be determined from comparing the reinforcement ratio (ρ_f) to the balanced reinforcement ratio (ρ_{fb}), which accounts for the condition where both failure modes occur simultaneously. Both of these are calculated according to Equations 1 and 2 below.

$$\rho_f = \frac{A_f}{bd} \tag{1}$$

$$\rho_{fb} = 0.85\beta_1 \frac{f_c'}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}} \tag{2}$$

When $\rho_f > \rho_{fb}$, concrete crushing governs. In this case ACI uses an approximate rectangular stress block to calculate the maximum moment (M_n) as shown in Equation 3 below.

$$
\begin{aligned}
&M_n = A_f f_f (d - \frac{a}{2}) \\
&where, \\
&a = \frac{A_f f_f}{0.85 f_c' b} \\
&f_f = E_f \varepsilon_{cu} \frac{\beta_1 d - a}{a}
\end{aligned}
\tag{3}
$$

When $\rho_f < \rho_{fb}$, FRP rupture governs leading to a very complex analysis as both the concrete compressive strain at failure and the depth to the neutral axis are unknown. Instead of performing this analysis, ACI allows for the calculation of a conservative value for M_n as shown in Equation 4.

$$
\begin{aligned}
&M_n = A_f f_{fu} (d - \frac{\beta_1 c_b}{2}) \\
&where, \\
&c_b = (\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}}) d
\end{aligned}
\tag{4}
$$

Both of these values of M_n are very conservative and must be adjusted by a strength reduction factor, φ. This factor is determined by the reinforcement ratio, and varies in the region where ρ_f is between ρ_{fb} and 1.4 ρ_{fb} as shown in Equation 5.

$$
\phi = \begin{cases} 0.55 \, for \, \rho_f \le \rho_{fb} \\ 0.3 + 0.25 \frac{\rho_f}{\rho_{fb}} \, for \, \rho_{fb} < \rho_f < 1.4 \rho_{fb} \\ 0.65 \, for \, \rho_f \ge 1.4 \rho_{fb} \end{cases}
\tag{5}
$$

The value of φM_n is related to the applied load by Equation 6. This is based on the approximation of a simply supported span.

$$
P = 4 \frac{\phi M_n}{L}
\tag{6}
$$

Flexure is not the only cause of failure for beams though, with shear being an important case. ACI also provides guidance for shear analysis. For a beam lacking shear reinforcement, V_c is given in Equation 7.

$$\begin{aligned} & V_c = 5\sqrt{f_c{}'} b_w c \\ & where, \\ & c = kd \\ & k = \sqrt{(2\rho_f n_f + (\rho_f n_f)^2)} - \rho_f n_f \\ & n_f = \frac{E_f}{E_c} \end{aligned} \tag{7}$$

The code then dictates that V_c be adjusted by a factor of 0.75 and then compared to P/2. The above equation for shear is one that is still under investigation and other studies provide other equations. The ACI code used here is the most recent, though it is possible that in the future there will be further changes in these calculations.

The last failure mode to be examined is bond failure. The value calculated from this failure is the development length, which determines the necessary length a reinforcing bar must be to prevent it from pulling out of the concrete. ACI does not recommend a length of less than 20 bar diameters for any beam. This minimum value will be used.

Beam Dimensions

Determining the beam dimensions created an interesting optimization problem. The limiting feature was the weight restriction of a maximum of 33 lbs. The unit weight of the concrete was estimated at 150.75 lb/ft^3. A spreadsheet was created for all possible values of beam width and height with an assumed length of 39 inches. In the chart, the load at failure was calculated using both flexure and shear. The complete table is included as Appendix B. A summary of the dimensions that fit the weight requirement is shown as Table 2.

Base (in)	Height (in)	P (Rupture) (lbs)	P (Shear) (lbs)
4	2.5	11024.777	2683.08435
3	3	13229.7324	2526.26477
2	5	22049.5541	2683.08435
2	4	17639.6433	2360.66292
2	3	13229.7324	1995.84901

Table 2. Loads for sample dimensions.

Most of the dimensions that satisfied the weight requirement were found to be impractically small. To provide another constraint, it was decided that pre-existing beam molds would be adapted for these beams, giving the beams a height of 2.5 inches. With this value determined, the only logical option for the base was 4 inches.

Mix Design

The mix design was determined based on previous mixes created for the regional ACI beam competition. To determine the final mix, each potential mix design was tested by creating 3 cylinders using type III cement, which were tested at 7 day strength. It was initial thought that Hydrocure©, a lightweight aggregate sand due to presumed benefits to the cured strength of the concrete, but it was determined that the mixes with simple concrete sand performed better. In all of the sand only mixes the water cement ratio was intended to be approximately 22%. This value, though, was difficult to achieve with such small quantities.

The overall goal of the mix testing was to find a mix that gave an f'$_c$ of greater than 9000 psi that was workable and used as little cement as possible. The results and mix designs for all of the tests are shown in Appendix C. In Table 3, below, is the final mix design used adjusted for pouring two beams and four cylinders. The calculations done to achieve these values from the original mix are shown in Appendix D. The testing results for this design are shown in Table 4.

	Weight
Cement	10.65538
H2O	3.09901
FA	20.24522
CA	18.11414
SP	0.266384
SF	0.799153
Total	53.17929

Table 3. Final Mix Design

Cylinder	Diameter (in)	Weight (lbs)	Load (lbs)	f'c
6-1	3.005	3.771	75500	10646
6-2	3.005	3.7065	66440	9368
6-3	3.01	3.7	72660	10211

Table 4. Test results for final mix design.

Reinforcement Layouts

A total of 8 beams were produced. Of these, two, beams 1 and 7, were simply reinforced using 2 FRP bars placed a half inch from the bottom of the beam. This design is the normal design used in test beams and for the regional ACI beam competition. One beam, beam 2, was reinforced using entirely mesh layered within the bottom half of the beam. This was chosen as a way to understand the use of Carbon mesh without the complication of adding FRP. The four of the remaining five beams were reinforced with one FRP bar and sheets of mesh, in varying arrangements as shown in Figure 1. These arrangements were designed with the intention of increasing the shear resistance of the beams. The final beam, beam 8, used only FRP bars, but they were cut and arranged as shown in Figure 2. Angling the reinforcement was considered as it increases the surface area of reinforcement through which a shear crack must pass. This surface area was also the reason for adding layers of horizontal mesh in Beams 5 and 6. It was expected that, of these two, beam 5 would perform best due to the increased presence of mesh below the center of the beam where it added to the tensile capacity of the beam.

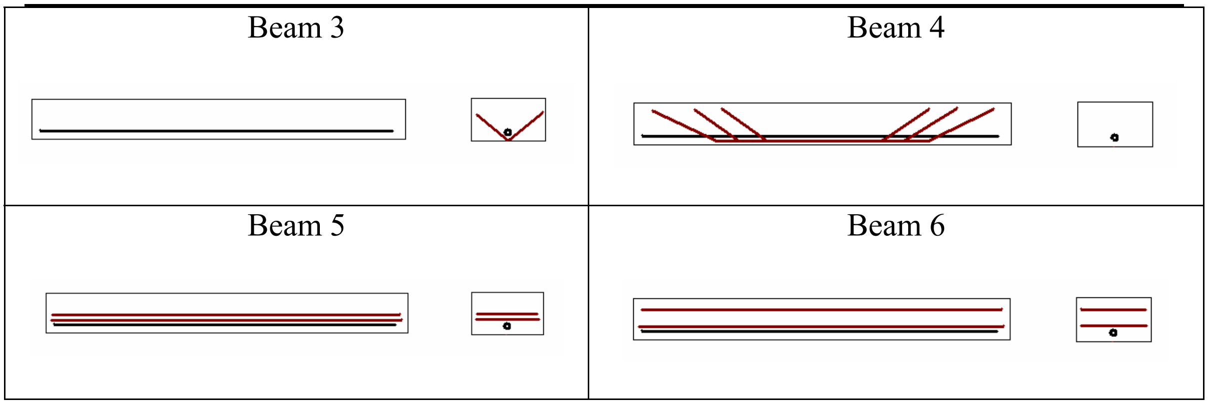
Beam 3
Beam 4
Beam 5
Beam 6

Figure 1. Reinforcement Layouts (Black is FRP bars, Red is mesh)

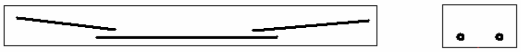

Figure 2. Reinforcement Layout for Beam 8

Results

Of the eight beams produced, only six were testable due to fabrication problems. The beams that were not tested are beams 3 and 4 above. The results for the other six beams are shown in Table 5.

Beam	Height (in)	Width (in)	Weight (lbs)	Average Cylinder Strength (psi)	Load (lbs)	Failure Type	Normalized Load Parameter
1	2.6	4.1	36	8461.689308	2400	crushing/bond failure	26.09051815
2	2.575	4.25	35.5	8232.70263	1760	shear	19.39730763
3	N/A	N/A	N/A				
4	N/A	N/A	N/A				
5	2.75	3.875	34.875	8943.887699	2190	crushing	23.15692804
6	2.5	4.5	36.75	8943.887699	1810	crushing	19.13883094
7	2.5	4.125	35.813	10679.01423	2380	crushing	23.03092465
8	2.5	4.375	37.188	10679.01423	1650	bond failure	15.96681751

Table 5. Beam results.

The normalized load parameter was found by dividing the measured load by the square root of the 28-day compressive strength for that batch. Based on these results the simply reinforced beams are significantly stronger than the beams employing more complex layouts. Based on that conclusion then it is unimportant that beams 3 and 4 were un-testable, as both contained a mixture of FRP bars and mesh.

The beams broke with three different mechanisms. The most common was crushing, which occurs when the concrete reaches above its compressive strength. An example of this failure is shown in Figure 3. While this is the mode designed for according to the code, it was not expected based on the calculations performed in the beams size determination. It probably occurred at a much lower load than expected due to the large deflection, which increases the load due to the p-delta effect.

The mechanism that was expected was shear. Only one beam, 2, failed in this manner. It is possible that this occurred due to the lower tensile strength of the mesh relative to the FRP. The mesh also, when placed in the lower half of the beam, provided less area than the bars in the shear plane. This failure appears as a crack at a 45^{o} angle, and can be seen in Figure 4.

The final mechanism that could be seen was bond failure. This appears as an initial horizontal crack along the reinforcement in most cases. The crack could be seen in Beam 1, but it initiated at a crack caused by crushing. It is most apparent in Beam 8, where it appeared in a different form. The initial crack was instead a perfectly vertical crack at the junction of two of the FRP bars. Clearly not enough overlap was provided, though it had been calculated to be the development length. If longer bars had been allowed this would have been adjusted. The crack can be seen in Figure 5.

These conclusions are rather tenuous. Not enough beams of each layout were tested to account for the large amount of variation in the quality of workmanship. Many other factors also affected the results, as well, and without running more tests it would not be possible to classify them all. While more tests would have allowed for better results, it was not possible due to time constraints and the constraints of manpower. One person can not easily or consistently make beams alone, and it was difficult to get the necessary help more than a few times a semester.

Figure 3. Crushing Failure (Beam 6)

Figure 4. Shear Failure (Beam 2)

Figure 5. Bond Failure (Beam 8)

ANSYS Model

Two ANSYS models were created. Both models used the SOLID65 element. This is an 8-node brick-like element as shown in Appendix F. It is best used for representing concrete or similar materials as it allows for cracking and crushing behavior. In order to utilize this feature, the CONCR material data table specified and certain parameters are entered. These parameters include shear transfer coefficients for both closed and open cracks, the tensile cracking stress and the biaxial crushing stress. Values for these were recommended in the article "Nonlinear Models of Reinforced and Post-tensioned Concrete Beams" by P. Fanning.

From that same article, as well as from the ANSYS verification problem 146, it was recommended that reinforcing bar should be represented as LINK8 elements. This element is defined by two nodes, and has only axial properties. Fanning recommends this, as it means a coarser mesh can be used on the rest of the beam. The only values required for this element are the Young's modulus and the cross-sectional area. For modeling the mesh, a property of the SOLID65 element was used. It allows up to 3 reinforcement types to be included as smeared reinforcement within the element. All that must be specified is tensile strength and average ratio of reinforcement.

The first model generated replicated Beam 1, by modeling the FRP as LINK8 elements. The second model was similar to Beam 2 and used smeared reinforcement in the lower half of the beam. Both models were loaded the same way, as shown in Figure 6.

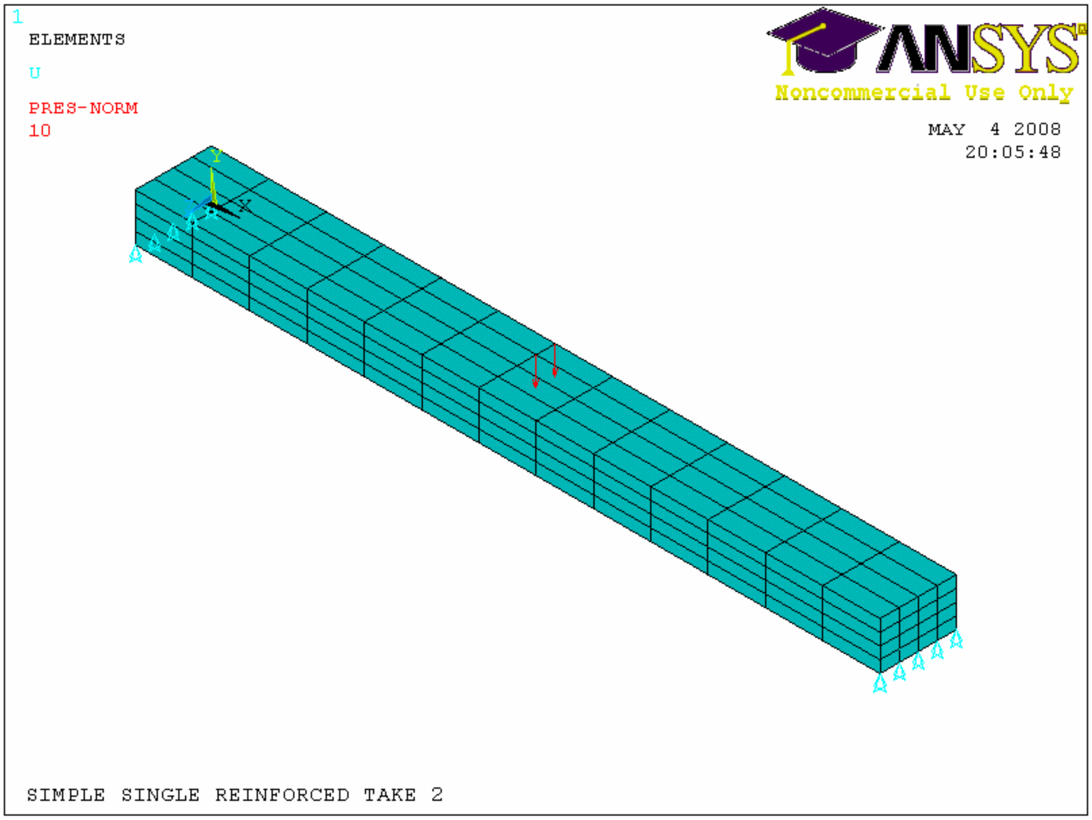

Figure 6. Loading Diagram for ANSYS.

Under this load, using the parameters given, it proved impossible to get convergence for the FRP reinforced beam once open cracks formed. 90 lbs/in^2 was the last load that was possible to apply before the model failed. While this does not allow for comparison to the actual beams, it does allow for a comparison between the deflected shapes of the two models. The first beam is shown as Figure 7, and the second as Figure 8. By comparing the maximum deflection of both, it can be seen that the mesh-reinforced beam, at .01273 inches, is significantly more curved than the FRP, at .01195 inches, under the same load. This reflects what would be expected given the actual mesh-reinforced beam failed under a lower load. With more time, it would have been good to find the correct parameters that allowed for open cracks without failure, but even so there would not have been a good comparison to the actual beams, which did not have measured deflections.

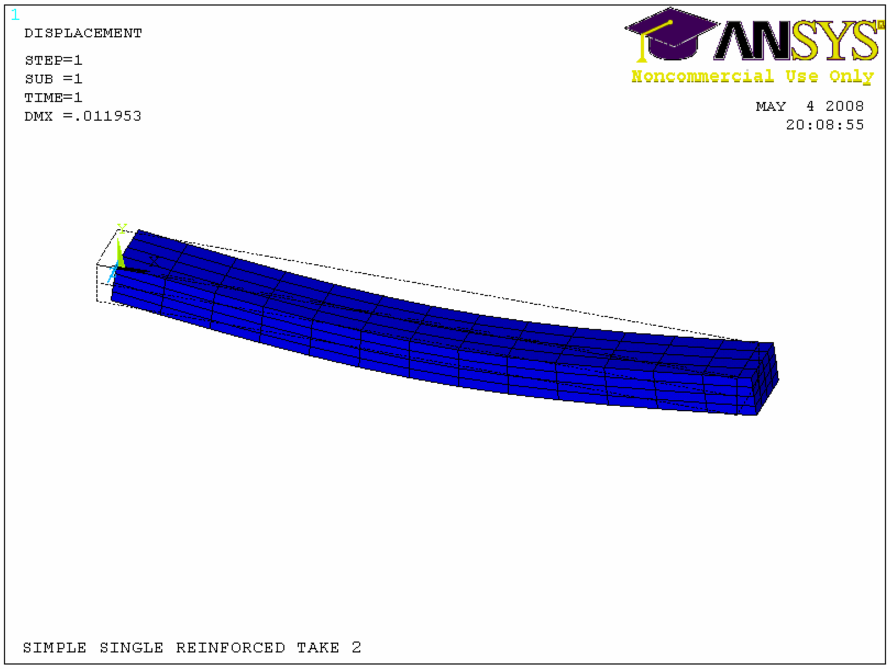

Figure 7. ANSYS model of FRP reinforced beam.

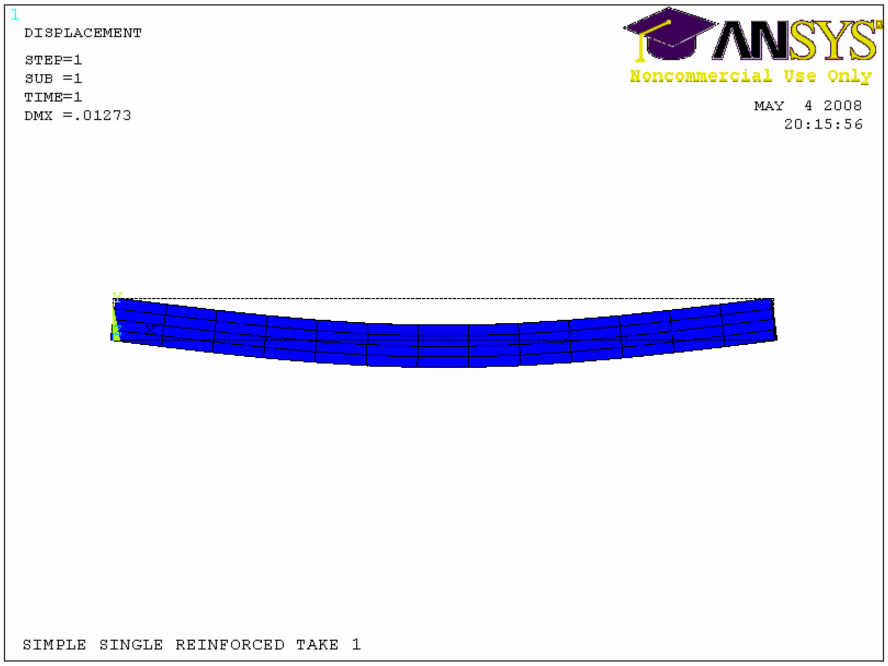

Figure 8. ANSYS model of mesh-reinforced beam.

Conclusions

As discussed above, it is difficult to draw to many conclusions from the limited data that could be collected. What data could be found indicated that beams reinforced with two linear FRP placed near the bottom of the beam held the highest load. This seems reasonable when the strength of the carbon grid is considered. With more beams this could be verified. The ANSYS model confirms the relative weakness of the mesh beam, though it cannot guarantee that there were not some other factors affecting the results of the actual beams.

Appendix Listing

References

ACI FRP Composites Competition Rules 2007, http://www.concrete.org/students/st_FRPcomposites.htm, Accessed 11/14/07

ACI 440-06. "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars"

ACI 440R-07. "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures"

ANSYS. ADPL Programmer's Guide: Release 10.0 Canonsburg, PA. August 2005.

ANSYS. Release 11.0, Documentation for ANSYS 2007\

Barbosa, A. F. and Ribeiro, G. O., "Analysis of Reinforced Concrete Structures Using ANSYS Nonlinear Concrete Model," Computational Mechanics: Barcelona, Spain, 1998

Fanning P., "Nonlinear Models of Reinforced and Post-tensioned Concrete Beams," Electronic Journal of Structural Engineering, 2 (2007)

Hughes Brothers Specifications Sheet for Aslan 100 GFRP Rebar, from ACI FRP Composites Competition Website

Kentucky Transportation Center, "GFRP Reinforced Concrete Bridges", July 2000, www.ktc.uky.edu/Reports/KTC_00_09_SPR96_169.pdf, Accessed 11/15/07

Tech-Fab Specifications Sheet for C-3000 Carbon Grid for Concrete Reinforcement, from ACI FRP Composites Competition Website

Appendix A

ACI FRP Composites Competition

Objective

These are the challenges in this competition:

Design, construct, and test a concrete structure reinforced with fiber-reinforced polymer (FRP) bars and/or grids to achieve the optimal load-to-weight ratio.

Predict the ultimate load.

Predict the load that will result in a piston deflection of 2.5 mm (0.1 in).

Rules

THE MATERIALS AND THE SPECIMEN GEOMETRY (See Structure Geometry Requirements Diagram)

1. The structure's cross section must fit into a 200 mm (7.87 in) wide by 350 mm (13.75 in) high envelope. The cross section may vary over the length, provided the structure can be mounted on supports and loaded as shown in the attached sketch. The structure's overall length may not be less than 950 mm (37.4 in) nor more than 1000 mm (39.4 in) on a 900 mm (35.4 in) center-to-center span. Dimensional tolerances are ± 6 mm (1/4 in) on the length and ± 3 mm (1/8 in) on all other dimensions. If time permits, structures not meeting this requirement may be tested, but the teams submitting such specimens will not be eligible for prizes.

2. The specimen must be constructed using a minimum of one and a maximum of two of the following reinforcement forms: 1000 mm (39.4 in) long #4 FRP reinforcing bars and/or 300 mm (11.8 in) wide by 1000 mm (39.4 in) long sheet of C3000 carbon/epoxy thin grids. Note that the width of the carbon/epoxy thin grids may be slightly less than 300 mm to insure that a continuous strand of carbon/epoxy borders the width. Other reinforcing materials are not allowed. Reinforcing bars and grids may not be prestressed. Mechanical anchorages of bars and grids are not permitted. Bars and grids may be cut to provide a larger number of shorter pieces, as long as a minimum of 1000 mm (39.4 in) and a maximum of 2000 mm (78.8 in) of FRP reinforcing bars and /or grids are used in the structure. The grid may be cut to any width as long as the limitation on total length (minimum of 1000 mm and maximum of 2000 mm) is satisfied. Reinforcement may be used in any combination of bars and/or grids as long as the limitation on total length (minimum of 1000 mm and maximum of 2000 mm) is satisfied.

3. A student team may use any combination of these bars and/or grids in their structure, but the competition specimen must be fabricated with a least one (1) and not more than two (2) of these bars and/or grids. Additional bars and grids are supplied for student experimentation. Reinforcing bars and grids from other sources are not permitted. Participating manufacturers have agreed to provide FRP reinforcement free of charge to

the schools, in reasonable quantities consistent with the contest rules. Students and advisors, in return for receiving the FRP bars and grids free of charge, must agree to only use the FRP reinforcement supplied to them for purposes directly related to the competition. Failure to comply with the requirement prohibiting the use of FRP bars and grids supplied for the competition in other projects will disqualify the student team from the competition and may also disqualify the faculty advisor from participation in future competitions. Faculty advisors are required to sign a statement on the Preregistration Form stipulating they will not use the bars and grids for purposes (research or others) not directly related to the competition. Should faculty advisors desire to use these types of reinforcements in other projects, they are encouraged to directly contact the manufacturers.

4. Total structure weight must be between 5 kg (11.0 lbs) and 15 kg (33.1 lbs).
5. The cementitious materials shall consist of any combination of portland cement meeting ASTM C 150, blended cement meeting ASTM C 595 or ASTM C 1157, ground-granulated blast furnace slag meeting ASTM C 989, fly ash meeting ASTM C 618, and/or silica fume meeting ASTM C 1240. Any type of nonmetallic aggregate may be used. Chemical admixtures meeting ASTM C 494 are allowed. Epoxies and other polymers, glue, and binders may NOT be used.
6. Teams must provide the actual measured batch weights of all materials (including admixtures) used in their concrete mix, as specified on the Official Registration Form. Teams must also provide a diagram showing placement and dimensions of reinforcements used. The diagram must accompany the specimen to the competition and be identified with the specimen beam mark.
7. Curing shall be at atmospheric pressure, and the curing temperature must not exceed the boiling point of water at atmospheric temperature.
8. No structure shall be more than 56 days old at the time of the test.
9. Reinforcing support wires and/or chairs are not permitted in the clear span area. Any manner of nonmetallic bar support may be used outside the clear span, as long as the bar support does not act to enhance the behavior of the structure, such as by anchoring the bar in the concrete.

THE TESTING PROCESS:

1. Entries will be weighed and measured, and those judged acceptable by the FRP Competition Committee will be positioned in the testing apparatus, which will apply a midspan concentrated load by means of a pivoting load plate. The center-to-center span is 900 mm (35.4 in) and reaction forces are through bearing surfaces measuring not less than 50 mm (2 sq in) by 50 mm (2 sq in) and providing no restraint against rotation at the ends of the specimen.
2. Once seated in the testing apparatus, a seating load of approximately 0.25 kN (56 lbs)

will be applied and recorded. Additional load will be applied until the structure fails or is loaded to the test fixture's capacity of 67 kN (15,000 lbs). The maximum load achieved will be recorded as the maximum load prior to failure or 67 kN (15,000 lbs), whichever is smaller. In lieu of obvious physical signs of failure, failure will be assumed to have occurred when total load on the structure has decreased to 50% of the maximum load achieved by that specimen. The loading rate will be determined by adjusting the cylinder's manual speed setting so that the manual speed valve is closed hand tight. This setting will correspond to a piston movement of approximately 1 mm/minute, but may be affected by the stiffness of the specimen. Deflection will be measured as the movement of the loading piston, which is assumed to correspond to deflection of the specimen at the loading plate.

3. If a structure fails to reach a deflection of 2.5 mm (0.1 in) prior to either failing or reaching the test fixture's capacity of 67 kN (15,000 lbs), that entry shall be disqualified for the Most Accurate Prediction prizes but will be permitted to compete for the Highest Ultimate Load-to-Weight Ratio prizes.

4. To arrive at the actual load corresponding to a 2.5 mm (0.1 in) deflection, the total load at 2.5 mm (0.1 in) deflection will be reduced by the 0.25 kN (56 lbs) seating load (for which no deflection was measured).

5. The maximum load achieved (as specified in paragraph 3b), without deduction of the seating load, will be recorded as the measured ultimate load.

THE EVALUATION PROCESS:

1. Load-to-weight ratios will be calculated as the ultimate load, as defined in paragraph 3e, divided by the weight of the structure. Any structure that does not fail prior to reaching the 67 kN (15,000 lb) test fixture capacity will have its load-to-weight ratio calculated as 67 kN divided by the weight of the structure.

2. Prediction accuracy will be measured by the relative difference between predicted and actual results. The Most Accurate Predictions of load will be the teams that achieve the smallest absolute value for "Delta", the estimated percentage difference, computed as follows:□□$D = 50\{DP_{2.5}/P_{2.5} + DP_{ult}/P_{ult}\}$□□Where□□$DP_{2.5} = ½P_{\text{est @ 2.5 mm midspan deflection}} - P_{2.5}½$ = the absolute value of the difference between the predicted load at 2.5 mm (0.1 in) deflection and the measured load corresponding to 2.5 mm (0.1 in) deflection, where the measured load is defined in paragraph 3d.□□$P_{2.5}$ = measured load corresponding to 2.5 mm (0.1 in) deflection, defined in paragraph 3d.□□$DP_{ult} = ½P_{\text{est @ ult}} - P_{ult}½$ = the absolute value of the difference between the predicted ultimate load and the measured ultimate load as defined in paragraph 3e.□□P_{ult} = the measured ultimate load as defined in paragraph 3e. Any structure that does not fail prior to reaching the 67 kN (15,000 lb) test fixture capacity will have D calculated with P_{ult} taken equal to 67 kN.□

Appendix B – Table for Determining Beam Dimensions

Appendix C- Mix Designs and Cylinder Results

	Weight (lbs)					
Component	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Cement	4.07	3	2.5	2	2.5	2.5
Water	1.36	1	1.25	0.66	0.75	0.7271
Hydrocure	2.035	0	3	0	0	0
Sand	4.07	6	5	4.5	5	4.75
Coarse Aggregate	8.14	6	5	3.5	4	4.25
Super Plasticizer	0.02725	0.02	0.04	0.0625	0.0625	0.0625
Silica Fume	0.0285	0.02	0.04	0.0625	0.25	0.1875
Cylinder Strengths (psi)	8523.07	8110.8	5375.18	7921	> 10000	10646
	6802.96	7869.02	5233.9	8338		9368
	6166.58	8480.9				10211
Average	7164.2033	8153.573	5304.54	8129.5	Unbreakable	10075

Appendix D- Table for Converting Mix Design to New Volume

E90 Beam Mix Design

Weights (found experimentally)

	Weights	Ratio
Cement	2.5	0.200367072
H2O	0.7271	0.058274759
FA	4.75	0.380697438
CA	4.25	0.340624023
SP	0.0625	0.005009177
SF	0.1875	0.01502753
Total	12.4771	1

Total Volume

Beam	390	in^3
Cylinder	42.4115	in^3
Total	559.646	

Production Volume	600	in^3
	0.347222222	ft^3

Calculated Weights for Production

Cement

Density	196.5748
Volume Ratio	0.001019292
Adjusted Ratio	0.156111017
Volume	0.054205214
Weight	10.65537913

H2O

Density	62.4
Volume Ratio	0.00093389
Adjusted Ratio	0.143031252
Volume	0.049663629
Weight	3.099010467

FA

Density	163.47
Volume Ratio	0.002328852
Adjusted Ratio	0.356678501
Volume	0.123846702
Weight	20.24522035

CA

Density	165.4
Volume Ratio	0.002059396
Adjusted Ratio	0.31540953
Volume	0.109517198
Weight	18.11414453

SP

Density	62.4
Volume Ratio	8.02753E-05
Adjusted Ratio	0.012294668
Volume	0.004268982
Weight	0.266384478

SF

Density	139.7
Volume Ratio	0.00010757
Adjusted Ratio	0.016475031
Volume	0.005720497
Weight	0.799153435

Total	0.006529	1
		0.347222222

Summary

Cement	10.65538
H2O	3.09901
FA	20.24522
CA	18.11414
SP	0.266384
SF	0.799153
Total	53.17929

Appendix E: Sample ANSYS Code

```
/FILE, E90
/TITLE, SIMPLE SINGLE REINFORCED TAKE 2
!ANALYST: REBECCA BURROW
!DATE: 4/30/08
!CONCRETE BEAM ANALYSIS
/PREP7
ET, 1, SOLID65,,,2,,2
ET, 2, LINK8
R, 1
R, 2, 0.2245
R, 3, 1, .5
MP, EX, 1, 6691096.516
MP, NUXY, 1, 0
TB, CONCR, 1
TBDATA, 1, 0, 1, 1000, 10000

MP, EX, 2, 5920000
MP, NUXY, 2, 0.33

!NODES
N, 1, 0, 0, 0
N, 14, 39, 0, 0
N, 57, 0, 0, 4
N, 70, 39, 0, 4
N, 281, 0, 2.5, 0
N, 294, 39, 2.5, 0
N, 337, 0, 2.5, 4
N, 350, 39, 2.5, 4
FILL, 1, 281, 3, 71, 70, 2, 13, 1
FILL, 57, 337, 3, 127, 70, 2, 13, 1
FILL, 1, 57, 3, 15, 14, 5, 70, 1
FILL, 14, 70, 3, 28, 14, 5, 70, 1
FILL, 1, 14, 12, 2, 1, 25, 14, 1

!ELEMENTS
TYPE, 1
REAL, 1
E, 1, 2, 16, 15, 71, 72, 86, 85
EGEN, 4, 14, 1
EGEN, 13, 1, 1, 4
EGEN, 4, 70, 1, 52

TYPE, 2
REAL, 2
```

```
E, 85, 86
EGEN, 13, 1, 209
EGEN, 2, 28, 209, 223

!SUPPORT RESTRAINTS
D, 1, UY, 0, 0, 57, 14
D, 14, UY, 0, 0, 70, 14

!LOADS
SFE, 183, 6, PRES, 0, 50
SFE, 182, 6, PRES, 0, 50


SAVE, REVIEW
FINISH
/SOLU
SOLVE
SAVE, REVIEW
FINISH
```

Appendix F- ANSYS Element Model