

# A Method for Producing Structurally Equivalent Graphite Reinforced Cementitious Composites

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## ABSTRACT

This paper describes a method to duplicate the structural performance of a graphite-reinforced cementitious composite as the mix proportions and constituents of its cementitious matrix are varied. This is accomplished by placing a test specimen constructed using a modified mixture over a reinforcing scheme identical to that of a control standard and then matching the end deflection of these samples.

The method was applied by the American Society of Civil Engineers (ASCE) Student Chapter at the University of Alabama in Huntsville (Team UAH) to design a modified mixture that complied with rule changes established by ASCE and Master Builders for the 2003 ASCE/MBT National Concrete Canoe Competition. The study was highly successful and resulted in a new and improved graphite-reinforced cementitious composite that had the same structural response as the control standard.

## INTRODUCTION

The 17th Annual ASCE/MBT National Concrete Canoe Competition will be held in Washington, DC, on June 17-20, 2004 [1] and teams competing in the event are expected to showcase some of the most exciting and revolutionary concepts being studied in the area of reinforced concrete design [2]. Most people don't realize that concrete canoes are among the most flexible and resilient reinforced concrete structures on Earth. Competitive boats feature amazingly thin composite sections (typically 6-8 mm thick) that are so light that they float without the need for the flotation cavities typically found in their heavier aluminum counterparts [3].

The competition is helping some engineers and scientists realize a vision that cementitious composites may someday replace advanced aerospace composites [4,5]. Cementitious materials and composites are already being targeted for many unique applications ranging from retrofitting commercial airline parts to supporting telescopes in space [6].

In some of these applications, countless hours may have been spent designing reinforced cementitious composite structures that display excellent performance characteristics. But, in some cases, it may be desirable or necessary to duplicate these characteristics as the mix proportions and constituents of the cementitious matrix are varied. While retrofitting aircraft parts, for example, a designer may want to include aggregates to retard flame damage or admixtures to minimize outgas in the event of a crash. In the area of smart materials, it may be desirable to embed computer chips, micro-sensors, and mini-actuators in the matrix.

This paper describes a method to duplicate the structural performance of a graphite-reinforced cementitious composite as the mix proportions and constituents of its cementitious matrix are varied. This is accomplished by placing a test specimen constructed using a modified mixture over a reinforcing scheme identical to that of a control standard and then matching the deflections of end-loaded cantilevered samples.

## PRIOR RESEARCH

Pioneer research in the area of reinforced cementitious composites focused on design considerations for producing a new generation of thin, lightweight, and structurally efficient panels capable of resisting the dangerous stresses produced by reverse loading [7]. The study showed that a very efficient composite structure could be fabricated by placing a flexible polymer-enhanced cementitious matrix having a relatively low elastic modulus over two layers of a rigid steel wire mesh having a relatively high elastic modulus. The design relied on the large difference in stiffness between the constituents in the composite section to drive the internal stress from the cementitious matrix to the steel reinforcement and materials were placed symmetrically to form an “adaptive” section that reacted similarly when bending couples were reversed.

A subsequent investigation revealed that the standard transform section theory applied to study the steel reinforced section failed to provide accurate results when the elastic modulus ratio exceeded 20 and a modified transform section theory was developed to determine the deflections and stresses in such highly compliant cementitious structures [8]. The investigation involved using the rule of mixtures to determine a set of effective material properties for a graphite-reinforced composite. Tensile tests were conducted on composite samples reinforced with a single graphite layer to verify this approach; and, when the effective material properties were used to characterize the deflections of multi-layered composite beams subjected to pure bending, an excellent agreement was obtained.

The study initially focused on a **Graphite Reinforced Cementitious Composite (GRCC)** reinforced with two layers of graphite mesh with fibers aligned along the same directions. But laminated composite plate theory was investigated as a means for analyzing more complex composites having graphite layers oriented in different directions. Multi-layered composite beams were analyzed by incorporating material properties established from tensile tests and finite element modeling was used to verify results. Considering the complexity of the samples, a very good agreement was obtained.

The work fueled another investigation that quantified the dynamic characteristics of GRCC laminated plates. Each sample had an adaptive section reinforced with three layers of graphite mesh and the study involved plates with aspect ratios ranging from 0.5 to 4.5 [9]. Natural frequencies, damping, and mode shapes were investigated to validate material properties for further theoretical studies and an analytical dynamic finite element model was developed to evaluate the natural frequencies and mode shapes for structures subjected to different boundary conditions.

This model was subsequently applied to study the dynamic performance of “Survivor,” the winning entry fielded by Team UAH in the 2001 ASCE/MBT National Concrete Canoe Competition [10]. Numerical results compared favorably with experimental impact hammer test data. As a result, it was concluded that the classical laminated plate theory developed for composite materials could be applied to quantify the dynamic behavior of highly compliant composite structures made from GRCC materials.

## MOTIVATION

The results taken from “Survivor” helped to answer a lingering question posed earlier in the Wall Street Journal as to why women’s teams fielded by Team UAH had beaten seventy-five percent, on average, of the men’s teams fielded by other competitors. And, in 2002, Team UAH relied on the work described above to design a concrete canoe that had the correct balance of flexibility and strength to further increase their edge over their competition.

The students designed a graphite reinforced cementitious composite section capable of sustaining reverse loading and strategically tuned their hull by lowering its natural frequency so that the forcing function created by their paddlers drove the boat toward resonance. When the flexible hull deformed in response to the torsional and bending moments applied, very large stresses and strains developed. Efforts were made to keep all of the materials elastic so that the structure was absolutely resilient, enabling the strain energy stored in the deformed shape to be recovered. As paddles were pulled from the water, this energy was converted into forward momentum, thereby forcing the boat to surge forward between strokes and swim. And, a new **Strategically Tuned Absolutely Resilient (STAR)** structure [12] was born.

Countless hours were spent in developing empirical and analytical tools to quantify the mode shapes in the boat, and Team UAH knew enough about the properties of the concrete and composite section that experimental and analytical results agreed to within a few percent. The team was extremely satisfied with their boat’s structural and dynamic performances and would have made only slight geometrical modifications to their design. But in 2003, there was a rule change that required adding fly ash and sand to the mix.

Although the reinforcement and geometry of their composite section fell within the rules established for the competition, the design for the concrete mixture did not. Thus, Team UAH faced the possibility of starting from scratch.

This would have been a very time consuming and tedious process that involved placing and testing individual concrete mixtures to determine their tensile strength and elastic modulus, placing composite tensile samples to determine a composite modulus, designing a new composite section using the modified transform section theory, and performing plate tests on samples constructed in this configuration to establish deflection and strength characteristics.

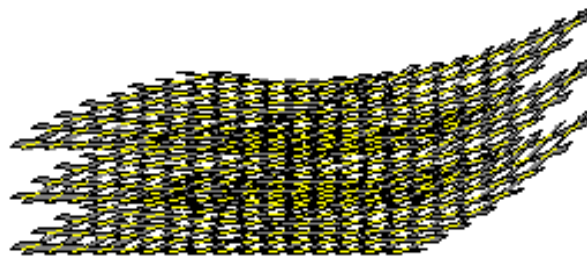
If the deflections were different from those obtained while testing the control standard, Team UAH could not utilize any of the data that they had collected previously from their modal analyses. The team would have needed to perform additional plate tests to establish modal parameters and characterize the mode shapes for the new design. In addition, there was always the possibility that all of this work could result in the production of a composite section and a concrete canoe that did not perform as well as the one that the team had already produced. A more attractive alternative was to find a way to “breed” the same structural response into the design for “Thoroughbred” by taking a different approach altogether.

## DEFLECTION MATCHING METHOD

A method was developed to duplicate the structural performance of a graphite-reinforced cementitious composite as the mix proportions and constituents of its cementitious matrix were varied. This was accomplished by placing test specimens constructed using modified mixtures over a reinforcing scheme identical to that of a control standard and then matching the end deflections of end-loaded cantilevered samples. Since the constituents of the cementitious matrix are the only parameters varied, the elastic modulus of the matrix is assumed to be identical to that of the control standard.

Each cantilevered test specimen had a length of 13.97 cm (5.5 in.); the width and depth were 2.54 cm (1 in.) and 7.62 mm (0.3 in.), respectively. The span to depth ratio of 18.33 exceeds the minimum ASTM standard of fifteen.

Figure 1 depicts the adaptive reinforcement scheme employed by Team UAH in 2002 to build their canoe. The three graphite layers are placed symmetrically in a 7.6 mm (0.30 in.) thick section. Two of the layers are positioned as close as possible to the upper and lower surfaces of the section with the third layer placed between. In the case illustrated, the fiber orientation of the reinforcement is the same for all three of the fiber layers.



**Figure1.** An adaptive section was designed with three graphite layers.

Each layer of reinforcement consisted of a non-impregnated graphite mesh with 3,000 fibers per tow, spaced at 0.125 in. (3.18 mm) intervals. Each tow was 0.19 mm (0.0075 in.) thick by 1.07 mm (0.042 in.) wide. The elastic modulus and tensile strength of the graphite are 231 GPa (33.5 msi) and 3.65 GPa (530 ksi), respectively.

The reinforcement was placed within a polymer-modified cementitious matrix that had the mix proportions and material properties listed in Fig. 2 under the column designated as “2002.” The rules specified that a minimum of 80% (by weight) of the binding material should be Portland cement. The small and uniformly sized micro-balloons, used as the only aggregate in the cementitious matrix, created a dense grain structure that prevented the graphite fibers, used to reinforce the section, from buckling. The addition of latex helped keep the elastic modulus low. It also improved the bond between the concrete and the reinforcement, thereby improving the strength of cold joints. The acrylic fortifier stiffened the concrete but made it water resistant and increased the tensile strength. A summary of the mix proportions for the cementitious matrix used to prepare the control samples is included in the mix table shown as Fig. 3.

The team modified the control mix to meet the new rule requirements. They specified that a minimum of 70% (by weight) of the binding material should be Portland cement. Sand was added in a minimal quantity (15% by volume of the aggregate particles) primarily because of its high density. The non-uniform size and varying shape of the sand particles also made it difficult to control the failure mode and quantify bond strength of the reinforced composite samples.

The team offset these detriments by adding two different types of small and uniformly sized micro-balloons to the mix. They added as many of these aggregates as possible and blended them to create the strongest and lightest mix possible. Latex was added to obtain the required flexibility and a mix was designed with a dense grain structure to prevent the graphite fibers used to reinforce the section from buckling under the service load and force a controlled failure if higher loads should occur.

The rules specified that a minimum of 20% (by weight) of the binding materials should be fly ash. Although preliminary studies indicated that the highest strength and best match to the control standard was obtained when fly ash was added to the mix at 10%, the mix designated in the column labeled “2003” was selected because it met all rule specifications. A summary of the mix proportions for the cementitious matrix used to prepare the modified samples is included in the mix table shown as Fig. 4.

<b>Mix Designation:</b>	<b>2002</b>	<b>2003</b>
<b>Binding Materials</b>	kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) [%]	kg/m <sup>3</sup> (lb/ft <sup>3</sup> ) [%]
Portland Cement	266.2 (16.6) [80%]	211.6 (13.2) [72%]
Latex	51.7 (3.2) [15%]	21.6 (1.3) [7.4%]
Acrylic Fortifier	16.4 (1.0) [5%]	0
Class "C" Fly Ash	0	60.4 (3.8) [20.6%]
Mass of Cementitious Materials	334.3 (20.8)	293.6 (18.3)
<b>Aggregates</b>	kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	kg/m <sup>3</sup> (lb/ft <sup>3</sup> )
K25 Spheres	104.3 (6.5)	36.3 (2.3)
K20 Spheres	0	27.2 (1.7)
Sand	0	167.4 (10.4) [15.5%]
Weight of Combined Aggregates	104.3 (6.5)	230.9 (14.4)
<b>Additive</b>	kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	kg/m <sup>3</sup> (lb/ft <sup>3</sup> )
Water	318.4 (19.9)	323.5 (20.2)
<b>Properties</b>		
Elastic Modulus [GPa (ksi)]	0.793 (115)	0.758 (110)
7 Day Tensile Strength [MPa (psi)]	1.77 (256)	2.12 (307)
28 Day Compressive Strength [MPa (psi)]	4.8 (696)	5.8 (835)
Poisson's Ratio	0.28	0.28
Unit Weight [kg/m <sup>3</sup> (lb/ft <sup>3</sup> )]	757 (47.3)	848 (52.9)
Water / Cement	1.20	1.53
Water / Cementitious Materials	0.95	1.10

**Figure 2.** Mix proportions and properties of the cementitious matrix.

A total of twelve composite samples were tested to failure, six for each of the mixes listed in Fig. 1. A load versus deflection plot was obtained for each sample and the average slope of the curves generated for each class of specimen was calculated. These values were combined with the modified transform section theory and the elastic curve to determine the elastic modulus of the cementitious matrix.

The modulus found for the control sample agreed to within a few percent of that measured in tensile tests conducted on un-reinforced cementitious samples. The average slope of the plots generated for the modified samples was slightly lower than that of the control samples and the rule of mixtures was applied to estimate the elastic modulus of the cementitious matrix. Tensile tests were conducted on un-reinforced cementitious samples to verify this result. Strengths and material properties are listed in Fig. 1.

## CONCLUSION

A method was developed to duplicate the structural performance of a graphite-reinforced cementitious composite as the mix proportions and constituents of its cementitious matrix were varied. This was accomplished by placing a test specimen constructed using a modified mixture over a reinforcing scheme identical to that of a control standard and then matching the end deflection of these cantilevered samples. Since the constituents of the cementitious matrix are the only parameters varied, the elastic modulus of the matrix is assumed to be identical to that of the control standard.

The method allows constituents of a cementitious matrix to be varied while capitalizing on data banks previously logged for structures constructed from a control standard. It has the added advantage that it completely eliminates the need to quantify the elastic modulus of individual concrete mixes, thereby significantly simplifying the test procedure ordinarily associated with reinforced concrete composite design. The only other issues that need to be addressed are strength and bonding characteristics.

## ACKNOWLEDGEMENT

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AIR AND CEMENTITIOUS MATERIALS			
Component	Quantity		Units
air content by volume of concrete		12.7	%
Portland Cement	Type I-II Blend	266.2	kg/m <sup>3</sup>
Latex	Binding Material	51.7	kg/m <sup>3</sup>
Acrylic Fortifier	Binding Material	16.4	kg/m <sup>3</sup>
mass of all cementitious materials	334.3		kg/m <sup>3</sup>
cement to cementitious materials ratio	0.8		
AGGREGATES			
	Base Quantity	Batch Quantity	
mass of K25 Microspheres	104.3	104.3	kg/m <sup>3</sup>
weight of combined aggregate	104.3	104.3	kg/m <sup>3</sup>
WATER			
water	318.4	167.4	kg/m <sup>3</sup>
volume of Latex	137,376		ml/m <sup>3</sup>
volume of Acrylic Fortifier	69,235		ml/m <sup>3</sup>
water from Latex		96.1	kg/m <sup>3</sup>
water from Acrylic Fortifier		54.9	kg/m <sup>3</sup>
total of free (surplus) water from all aggregates		0	kg/m <sup>3</sup>
total water	318.4	318.4	kg/m <sup>3</sup>
concrete density { [1]+[2]+[3] }	757	757	kg/m <sup>3</sup>
water to cement ratio	1.20		
water to cementitious material	0.95		

Figure 3. Mix table corresponding to the control mix used in 2002.

AIR AND CEMENTITIOUS MATERIALS			
Component	Quantity		Units
air content by volume of concrete		5.5	%
Portland Cement	Type I-II Blend	211.6	kg/m <sup>3</sup>
Latex	Binding Material	21.6	kg/m <sup>3</sup>
Fly Ash	Binding Material	60.4	kg/m <sup>3</sup>
mass of all cementitious materials	293.6		kg/m <sup>3</sup>
cement to cementitious materials ratio	0.72		
AGGREGATES			
	Base Quantity	Batch Quantity	
mass of K20 Microspheres	27.2	27.2	kg/m <sup>3</sup>
mass of K25 Microspheres	36.3	36.3	kg/m <sup>3</sup>
mass of Sand	167.4	167.4	kg/m <sup>3</sup>
weight of combined aggregate	230.9	230.9	kg/m <sup>3</sup>
WATER			
water	323.5	284.7	kg/m <sup>3</sup>
volume of Latex	19,608		ml/m <sup>3</sup>
water from Latex		38.8	kg/m <sup>3</sup>
total of free (surplus) water from all aggregates		0	kg/m <sup>3</sup>
total water	323.5	323.5	kg/m <sup>3</sup>
concrete density { [1]+[2]+[3] }		848	kg/m <sup>3</sup>
water to cement ratio	1.53		
water to cementitious material	1.10		

Figure 4. Mix table corresponding to the modified mix used in 2003.

## REFERENCES

- [1] ASCE/MBT 2004 National Concrete Canoe Competition, on line at: <http://www.asce.org/inside/nccc2004/>
- [2] Gilbert, J.A., "In pursuit of a national concrete canoe title," *Oldcastle News*, 2(1), 11, 2004, on line at: [http://www.uah.edu/student\\_life/organizations/ASCE/Articles/OldcastleNewsletter2004/OldcastleArticle.htm](http://www.uah.edu/student_life/organizations/ASCE/Articles/OldcastleNewsletter2004/OldcastleArticle.htm)
- [3] Behar, M., "Like a rowing stone," *Smithsonian Magazine*, December 2002, on line at: <http://www.smithsonianmag.com/smithsonian/issues02/dec02/poi.html>
- [4] UA Press, "Concrete: a promising space technology," *Space.com*, June 1, 2001, on line at: [http://www.space.com/business/technology/space\\_concrete\\_010601.html](http://www.space.com/business/technology/space_concrete_010601.html)
- [5] Knapp, L., "Canoe cements a place in history," *Wired News*, July 4, 2001, on line at: <http://www.wired.com/news/technology/0,1282,44800,00.html>
- [6] Burr, A., "Concrete canoes: the start of things to come," *The Structural Engineer*, pp. 28-29, December 2003, on line at: <http://concretecanoe.org/FeatureArticles/TheStructuralEngineer.htm>
- [7] Biszick, K.R., Gilbert, J.A., "Designing thin-walled, reinforced concrete panels for reverse bending," *Proc. of the 1999 SEM Spring Conference on Theoretical, Experimental and Computational Mechanics*, Cincinnati, Ohio, June 7-9, 1999, pp. 431-434.
- [8] Vaughan, R.E., Gilbert, J.A., "Analysis of graphite reinforced cementitious composites," *Proc. of the 2001 SEM Annual Conference and Exposition*, Portland, Oregon, June 4-6, 2001, pp. 532-535.
- [9] Ooi, T.K., Vaughan, R.E., Gilbert, J.A., Engberg, R.C., Bower, M.V., "Dynamic characteristics of highly compliant graphite reinforced cementitious composite plates," *Proc. of the 2003 SEM Annual Conference & Exposition on Experimental and Applied Mechanics*, Charlotte, North Carolina, June 2-4, 2003, Paper No. 133, 7 pages.
- [10] Ooi, T.K., Engberg, R.C., Vaughan, R.E., Gilbert, J.A., Bower, M.V., "Experimental and numerical investigation of the dynamic response of highly compliant, polymer-enhanced, graphite reinforced cementitious composites," *Proc. of the 2003 SEM Annual Conference & Exposition on Experimental and Applied Mechanics*, Charlotte, North Carolina, June 2-4, 2003, Paper No. 135, 6 pages.
- [11] Johnson, R., "Row, row, row your (concrete) boat," *Wall Street Journal*, Marketplace, June 18, 1999, on line at: [http://www.uah.edu/student\\_life/organizations/ASCE/Articles/Wall%20Street%20Journal/wsarticletext.htm](http://www.uah.edu/student_life/organizations/ASCE/Articles/Wall%20Street%20Journal/wsarticletext.htm)
- [12] Gilbert, J.A., Vaughan, R.T., Ooi, T.K., Toutanji, H., "Creating "STARS" for advanced propulsion with cementitious composites," *Proc. of the HATS/TABES Exposition*, Huntsville, Alabama, May 15-16, 2001.