5-25-2007

CAREER: Framework for Integrating Embedded Sensors in Durability Analysis of FRP Composites in Civil Infrastructure

Roberto A. Lopez-Anido
Principal Investigator; University of Maine, Orono, RLA@Maine.edu

Final Report for Period: 03/2006 - 02/2007
Submitted on: 05/25/2007
Principal Investigator: Lopez-Anido, Roberto A.
Award ID: 0093678
Organization: University of Maine
Submitted By:

Title:
CAREER: Framework for Integrating Embedded Sensors in Durability Analysis of FRP Composites in Civil Infrastructure

Project Participants

Senior Personnel

Name: Lopez-Anido, Roberto

Worked for more than 160 Hours: Yes

Contribution to Project:

Dr. Roberto Lopez-Anido served as PI and directed the research work. He advised graduate and undergraduate students that participated in the project. He was involved in training, teaching and outreach activities. He collaborated with other faculty members associated with the Advanced Engineered Wood Composites Center at the University of Maine.

Post-doc

Graduate Student

Name: Melrose, Paul

Worked for more than 160 Hours: Yes

Contribution to Project:

Paul Melrose started working in the project in January 2002 as an undergraduate research assistant. In May 2002 he entered the graduate program in Mechanical Engineering and continued working in the project as a graduate research assistant. He participated in fabrication of composite panels, instrumention of test coupons, and mechanical characterization experiments. Under the supervision of the PI, he implemented a new hydromat experimental system to characterize sandwich composite panels subjected to uniform pressure.
M.S. Thesis: Elastic Properties of Sandwich Composite Panels using 3-D Digital Image Correlation with the Hydromat Test System. Graduation Date: August 2004.

Name: Fifield, Samantha

Worked for more than 160 Hours: Yes

Contribution to Project:

Samantha Fifield worked as a graduate research assistant. She fabricated composite panels with embedded EFPI fiber optic sensors, conducted laboratory experiments and analyzed and synthesized data. She developed optimal sensor embedment techniques for strain measurement, established the dependability and durability of embedded sensors, and assessed the effects of embedded strain sensors on composite material properties and the structural integrity of panels.
M.S. Thesis: Experimental Methodology for Embedding Fiber Optic Strain Sensors in Fiber Reinforced Composites Fabricated by the VARTM/SCRIMP Process. Graduation Date: Aug. 2002

Name: Michael, Antonis

Worked for more than 160 Hours: No

Contribution to Project:

Antonis Michael, graduate student in the Department of Civil and Environmental Engineering, collaborated with a project application by fabricating and characterizing the structural response of fiber-reinforced polymer composite shells for repairing wood piles. He studied the durability of an underwater curing epoxy adhesive, which is used for bonding composite shells, subjected to freeze-thaw cycles. He was supported by the Sea Grant College Program during 2001-2002.

Name: Herzog, Benjamin

Worked for more than 160 Hours: No

Contribution to Project:

Benjamin Herzog, graduate student in Forestry, participated in the project by exploring a new technique for rapid, accurate analysis in the evaluation of defects and quantitative properties within polymer matrix composite (PMC) materials. He utilized backscattered electron imaging (BEI) to mitigate the somewhat tedious preparation of samples often required for images with conventional light microscopy methods and also improve upon secondary electron microscopy methods which oftentimes do not provide adequate surface resolution. He utilized the BEI technique for evaluation of defects (microvoids) and resin-rich gaps in composite materials fabricated by Vacuum Assisted Resin Transfer Molding (VARTM/SCRIMP) and a novel composites fabrication process called Composite Pressure Resin Infusion System (ComPRIS).

Name: Haskell, Adam

Worked for more than 160 Hours: Yes

Contribution to Project:

Adam Haskell started working in the project in January 2004 as an undergraduate research assistant. In May 2004 he entered the graduate program in Civil Engineering and continued working in the project as a graduate research assistant.
He conducted research on structural health monitoring of a building using composite panels with embedded fiber optic strain sensors. He developed a method to embed fiber optic strain sensors in polymer matrix composite laminates and sandwich composite panels, and he applied this technology to structural health monitoring, and to fatigue durability assessment of sandwich composite panels.
M.S. Thesis Title: A Durability and Utility Analysis of EFPI Fiber Optic Strain Sensors Embedded in Composite Materials for Structural Health Monitoring. Graduation Date: May 2006.

Name: Silva-Munoz, Rodrigo

Worked for more than 160 Hours: Yes

Contribution to Project:

Rodrigo Silva starting working in the project in January 2005. He conducted an analytical and experimental characterization of the bending response of sandwich composite panels. He implemented a structural health monitoring system for buildings using fiber optic strain sensors embedded in composite laminates. He assessed the feasibility of monitoring fatigue crack initiation and propagation using embedded Bragg grating fiber optic strain sensors.
Ph.D. Thesis Title: Structural Health Monitoring Using Embedded Fiber Optic Strain Sensors. Graduation Date: May 2008.

Name: Souza, Benjamin

Worked for more than 160 Hours: No

Contribution to Project:

Characterized fracture mechanics parameters of hybrid composite specimens fabricated by a novel process called Composites Pressure Resin Infusion System (ComPRIS)

Undergraduate Student

Name: Young, Aimee

Worked for more than 160 Hours: No

Contribution to Project:

Aimee Young contributed to the project as an undergraduate research assistant. She was a junior in Civil and Environmental Engineering. She worked with a graduate student in composites fabrication, embedment and instrumentation using fiber optic strain sensors, and material property characterization through tension and compression experiments.

Name: Stephens, Katherine

Worked for more than 160 Hours: No

Contribution to Project:

Assisted in fabrication and preparation of composite specimens in the lab.

Name: Martel, Brian

Worked for more than 160 Hours: No

Contribution to Project:

Assisted in sandwich composite panels fabrication in the lab.

Name: Shawn, Roy

Worked for more than 160 Hours: Yes

Contribution to Project:

Assisted in embedding fiber-optic sensors in composites and instrumenting structural members in a new building facility.

Name: Mundie, Christopher

Worked for more than 160 Hours: Yes

Contribution to Project:

Assisted in composites fabrication and sandwich panel experiments in the lab.

Name: Havu, Chad

Worked for more than 160 Hours: Yes

Contribution to Project:

Participated in fabrication of composite panels with embedded fiber optic sensors

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Name: Johnson, Ericka

Worked for more than 160 Hours: Yes

Contribution to Project:

Ericka Johnson participated in the Research Experience for Undergraduates (REU) program in Advanced Engineered Wood Composites at the University of Maine during the Summer 2001. She was a sophomore in Fiber Engineering at Georgia Institute of Technolgy. She contributed to the project by developing a procedure for experimental characterization of fiber-reinforced polymer composites fabricated by filament winding using embedded fiber optic strain sensors. She implemented a laboratory computer-controlled filament winder and applied it to fabricate carbon/vinyl ester and carbon/epoxy composite cylinders. She utilized Extrinsic Fabry-Perot Interferometric (EFPI) fiber optic strain sensors to monitor residual strains within the composite cylindrical specimens during fabrication and post-curing.

Years of schooling completed: Sophomore

Home Institution: Other than Research Site

Home Institution if Other: Georgia Institute of Technology

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported:

REU Funding: REU site award

Name: Florea, Micah

Worked for more than 160 Hours: Yes

Contribution to Project:

Micah Florea participated in the Research Experience for Undergraduates (REU) program in Advanced Engineered Wood Composites at the University of Maine during the Summer 2002. He was a junior in Civil Engineering at Tulane University. He contributed to the project by developing a fiber-reinforced polymer (FRP) composite drain system for concrete bridges. He conducted experiments to evaluate the FRP drains subjected to ice formation pressure, fatigue cycling simulating wheel load repetitive action, and ultimate quasi-static loading. He instrumented the FRP drains with embedded fiber optic sensors to monitor strains. He analyzed and summarized the experimental data and proposed improvements to the FRP drain system.

Years of schooling completed: Junior

Home Institution: Other than Research Site

Home Institution if Other: Tulane University

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2002

REU Funding: REU site award

Organizational Partners

Other Collaborators or Contacts

Dr. Thomas Sandford, Associate Professor of Civil Engineering, collaborated with a project application by evaluating durability of fiber-reinforced polymer composite shells for repairing wood piles. He was supported by the Sea Grant College Program.

Dr. Barry Goodell, Professor of Wood Science and Technology, collaborated with interdisciplinary research on electron microprobe imaging for the characterization of polymer matrix composites. He also contributed to research work on durability of fiber reinforced polymer composites for wood reinforcement exposed to preservative chemicals and exterior environments. He collaborated with the P.I. on a novel composites fabrication process called Composites Pressure Resin Infusion System (ComPRIS).

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

K-12 SCHOOL ACTIVITIES

1. Supervisor. High-School Student Internship: Meredith Kirk-Lawlor from Maine School of Science and Mathematics, 2 weeks, May-Jun. 2001.
2. Mentor. Upward Bound Regional Math-Science Center, Summer 2001. Student: Vireak Gilpatrick, Sanford High-School. Publication: 'Basswood Bridges,' Journal of Explorations, College of Education and Human Development, University of Maine, Ed. S. Stevens, Vol. 10, pp. 108-113, 2001.
3. Operation Breaking Stereotypes: Volunteer during the exchange program between Walton High School in the Bronx, NY and Orono High School. Program focused on breaking stereotypes created by race and ethnicity, Feb. 2002.
4. Maine Engineers Week Expo: Learning Activity using the West Point Bridge Design Software, University of Maine, Orono, March 2, 2002.
5. High-School Student Science Project: Study of temperature effect on shear strength of epoxy adhesive for wood bonding. Matthew Stephens, from Mt. Ararat High School, Topsham, ME. Presentation at Maine Science and Technology Fair: May 11, 2002.
6. Hampden Academy seniors: AEWC Lab Tour, Dec. 6, 2002.
7. Maine Engineers Week Expo: Learning Activity using the West Point Bridge Design Software, Gorham High School, Gorham, March 1, 2003.
8. Maine Engineers Week Expo: Learning Activity using the West Point Bridge Design Software, University of Maine, Orono, February 28, 2004.

UNDERGRADUATE STUDENTS

1. NSF funded Research Experience for Undergraduates (REU) during 9 weeks in the Summers of 2001 and 2002. As part of the NSF-REU program the PI advised one minority female student.
2. Supervised and trained undergraduate student research assistants from Civil Engineering and Mechanical Engineering in the AEWC Center laboratories (2001-present).
3. Participated in an Honor Thesis Committee of an undergraduate student that was supported by this grant: Stephens, Katherine, Thesis Title: Feasibility of Recycling Polypropylene Rope into Wood-Plastic Composites, Honors College, University of Maine, June 2005.

GRADUATE STUDENTS

Graduate students that were supported by this grant:

1. Samantha Fifield. M.S. Thesis Title: Experimental Methodology for Embedding Fiber Optic Strain Sensors in Fiber Reinforced Composites Fabricated by the VARTM/SCRIMP Process. Graduation Date: Aug. 2002. Current Employer: New Hampshire DOT.
2. Paul Melrose. M.S. Thesis Title: Elastic Properties of Sandwich Composite Panels using 3-D Digital Image Correlation with the Hydromat Test System. Graduation Date: August 2004. Current Employer: Naval Undersea Warfare Center (NUWC).
3. Adam Haskell, M.S. Thesis Title: A Durability and Utility Analysis of EFPI Fiber Optic Strain Sensors Embedded in Composite Materials for Structural Health Monitoring. Graduation Date: May 2006.
4. Rodrigo Silva-Mu±oz, Ph.D. Thesis Title: Structural Health Monitoring Using Embedded Fiber Optic Strain Sensors. Graduation Date: Dec. 2007.

TEACHING: APPROACH AND ACTIVITIES

Education is the foundation for this CAREER program with the goals of increasing recruitment and retention of minorities and women students, developing a teaching style compatible with students' learning style dimensions, promoting a cooperative learning environment, and introducing advanced multi-disciplinary research training for graduate students. The learning style implemented by the PI is student-centered

teaching that seeks to help students grasp the development of engineering knowledge as an interactive process, rather than a product. This teaching û learning strategy requires understanding how students process information and the effect of other important factors in Maine, such as regional attitudes, cultural values, and learning motivation.
The combination of this integrative approach, with a focus on balancing theories, applications, and ethics, and a locus of an interdisciplinary world-class research Center has resulted in the integration of education and research into a learning and discovery environment. Through the CAREER project the PI recruited and retained a diverse pool of students that are being educated to become engineers with a broad vision toward the needs for renewing the civil infrastructure. In this way the project has contributed to further increase the participation of minority students in research and science. Specifically, one minority female student graduated with an M.S. degree in Civil Engineering, one minority female student completed a summer research experience, and one minority male student has been recruited in the Ph.D. program in Civil Engineering.

Outreach Activities:

MULTICULTURALISM
The PI has been actively involved in a number of multicultural activities.
1. He has collaborated with Operation Breaking Stereotypes, which is a program focused on lifting barriers and promoting cultural exchanges between high school students from the State of Maine and from the Bronx in New York.
2. He has served on the University Commission on the Status of Racial and Ethnic Minorities, which addresses the need to develop new programs and strengthen existing ones, in such areas as student, faculty and staff recruitment and retention, curricular and co-curricular programs, and public service.
3. He prepared a summary of recommendations for the 2002 Diversity Action Plan for four units on Campus.
4. He has served on the University/Community/Diversity Committee, which integrates University diversity efforts across the campus and with surrounding communities.
5. He was the Guest Speaker at the 8th Annual Latino Heritage Celebration, University of Maine, Orono, ME, Oct. 29, 2004. His talk was titled: 'A Roadmap for Advancement of Hispanics in Science and Engineering.'
6. He was an Invited Speaker at the Faculty of Physical Sciences and Mathematics, Universidad de Chile. His talk was titled: 'Fulbright Fellowships for Graduate Studies in the United States,' Santiago, Chile, May 30, 2006.
7. Reviewer of Foreign Student Fellowships, Engineering Panel, Fulbright Commission, Santiago, Chile, Aug. 17, 2006.

K-12 EDUCATIONAL ACTIVITIES
The PI has a special interest in K-12 educational activities for discovering engineering. During the statewide Engineers Week event, the PI has organized a middle-school level truss bridge design activity using educational computer software, and an elementary-school level building set activity. The PI has also served as mentor of high-school students as part of the Upward Bound Regional Math-Science program and other high-school internship and visiting programs.

PARTICIPATION IN SEMINARS, WORKSHOPS AND MEETINGS
1. International Workshop - Composites in Construction: A Reality. Invited speaker. Sponsored by the University of Naples. Title of presentation: 'FRP-Glulam Structures: From Material and Processing Issues to a Performance-Based Evaluation Methodology.' Capri, Italy, July 20-21, 2001.
2. Second International Conference on Advanced Engineered Wood Composites. Speaker. Title of presentation: 'Material Qualification of FRP Reinforcement Bonded to Glulam Members.' Session Moderator. Title of session: 'New Products/Processes.' Bethel, Maine, August 14-16, 2001.
3. Panel Member, 'Evaluation Panel: FRP Composite Bridge Decks', HITEC Evaluation Plan, Civil Engineering Research Foundation, ASCE, Washington, DC, 2001.
4. Panel Member, Composites Education Workshop (government, high school, and university), Northeast Composites Conference, Portland, ME, June 25-26, 2001.
5. Workshop: Analytical Modeling of Composite Ship Structures during and after Fire, Office of Naval Research, Arlington, VA, 16-18 July 2002.
6. Sensor Workshop, Homeland Security Lab, University of Maine, Orono, ME, Nov. 6, 2003.
7. Invited Participant. 'NSF Workshop on Performance and Design of Fiber Reinforced Polymer Composites at Very Cold Temperatures,' Fairbanks, Alaska, August 13-14, 2004. Funded by the National Science Foundation.
8. Panelist, 'Preparing for Promotion and Tenure,' Luncheon for new faculty members, Center for Teaching Excellence, Feb. 17, 2005.
9. Co-Chairman, 3rd International Conference on Advanced Engineered Wood Composites, Jul. 10-14, 2005, Bar Harbor, ME.
10. Invited Participant. 'Workshop on Prediction of the Degradation of Advanced Materials for Emerging Facilities and Equipment for the Army,' Urbana, IL, August 30-31, 2005. Funded by the US Army Corps of Engineers - Construction Engineering Research Laboratory (CERL).
11. Workshop Speaker. 'Structures of Fiber-Reinforced Polymer (FRP) Composite Materials,' Institute of Research and Testing of Materials

(IDIEM), Faculty of Physical Sciences and Mathematics, Universidad de Chile, Santiago, Chile, 8 sessions, May 30-June 8, 2006.
12. Workshop Speaker. 'Wood-Plastic Composites for Construction: Perspectives and Opportunities,' Institute of Research and Testing of Materials (IDIEM), Faculty of Physical Sciences and Mathematics, Universidad de Chile, Santiago, Chile, 3 sessions, June 20, 2006.
13. Workshop Speaker. 'Wood-Plastic Composites for Construction: Perspectives and Opportunities,' Universidad TÚcnica Federico Santa MarÝa, Valparaiso, Chile, August 2, 2006.

Journal Publications

Lopez-Anido, R., Michael, A.P., and Sandford, T.C., "Experimental Characterization of FRP Composite-Wood Pile Structural Response by Bending Tests", Marine Structures, p. 257, vol. 16 (4), (2003). Published,

Lopez-Anido, R., Michael, A.P., and Sandford, T.C., "Fiber Reinforced Polymer Composite-Wood Pile Interface Characterization by Push-Out Tests", Journal of Composites for Construction, ASCE, p. 360, vol. 8 (4), (2004). Published,

Lopez-Anido, R., Michael, A.P., and Sandford, T.C., "Freeze-Thaw Resistance of Fiber-Reinforced Polymer Composites Adhesive Bonds with Underwater Curing Epoxy", Journal of Materials in Civil Engineering, ASCE, p. 283, vol. 16 (3), (2004). Published,

Herzog, B., Goodell, B., and Lopez-Anido, R., "Electron Microprobe Imaging for the Characterization of Polymer Matrix Composites", Composites Part A: Applied Science and Manufacturing, p. 1075, vol. 35 (9), (2004). Published,

Lopez-Anido, R., and Fifield, S., "Experimental Methodology for Embedding Fiber Optic Strain Sensors in Fiber Reinforced Composites Fabricated by the VARTM/SCRIMP Process", Proc. of the 4th Int. Workshop on Structural Health Monitoring, Ed. F-K Chang, DEStech Publications, Lancaster, PA, p. 247, vol. , (2003). Published,

Pirvu, A., Gardner, D.J., and Lopez-Anido, R., "Carbon Fiber-Vinyl Ester Composite Reinforcement of Wood Using the VARTM/SCRIMP Fabrication Process", Composites Part A: Applied Science and Manufacturing, p. 1257, vol. 35 (11), (2004). Published,

Herzog, B., Goodell, B., Lopez-Anido, R., Muszyñski, L., Gardner, D., Halteman, W., and Qian, Y., "The Effect of Creosote and Copper Naphthanate Preservative Systems on the Adhesive Bondlines of FRP/Glulam Composite Beams", Forest Products Journal, p. 82, vol. 54 (10), (2004). Published,

Herzog, B., Goodell, B., Lopez-Anido, R., Muszyñski, L., Gardner, D., and Tascioglu, C., "Effect of Creosote and Copper Naphthenate Preservative Treatments on Properties of FRP Composite Materials Used for Wood Reinforcement", Journal of Advanced Materials, SAMPE, p. 25, vol. 36 (4), (2004). Published,

Lopez-Anido, R., Lech Muszyñski, L., Gardner, D., Goodell, B., and Herzog, B., "Performance-Based Material Evaluation of Fiber-Reinforced Polymer-Wood Interfaces in Reinforced Glulam Members", Journal of Testing and Evaluation, ASTM Int., p. 385, vol. 33 (6), (2005). Published,

Hong, Y., Muszyñski, L., and Lopez-Anido, R., "Modeling and Calibration of a Laminating Press Prototype for Fiber-Reinforced Polymer-Glulam Billets", Journal of Testing and Evaluation, ASTM Int., p. 395, vol. 33 (6), (2005). Published,

Herzog, B., Goodell, B., Lopez-Anido, R., and Gardner, D.J., "Durability of Fiber-Reinforced Polymer (FRP) Composite - Wood Hybrid Products Fabricated Using the Composites Pressure Resin Infusion System (COMPRIS)", Forest Products Journal, p. 54, vol. 55 (11), (2005). Published,

Herzog, H., Gardner, D.J., Lopez-Anido, R., Goodell, B., "Glass-Transition Temperature Based on Dynamic Mechanical Thermal Analysis Techniques as an Indicator of the Adhesive Performance of Vinyl Ester Resin", Journal of Applied Polymer Science, p. 2221, vol. 97 (6), (2005). Published,

Melrose, P., Lopez-Anido, R., and Muszyñski, L., "Elastic Properties of Sandwich Composite Panels using 3-D Digital Image Correlation with the Hydromat Test System", Proc. of the SEM XI Int. Congress and Exposition on Experimental and Applied Mechanics, Society for Experimental Mechanics, p. 490, vol. , (2004). Published,

Walter, T.R., Miskioglu, I., Bertelsen, W.D., Lopez-Anido, R. Haskell, A., Trofka, S., and Baylor J.S., "ASTM D6416 Round Robin Testing of Sandwich Panels,", Proc. of the SEM XII Int. Congress and Exposition on Experimental and Applied Mechanics, Society for Experimental Mechanics., p. 175, vol. , (2005). Published,

Dutta, P.K., Lopez-Anido, R., and Kwon, S.K., "Fatigue Durability of FRP Composite Bridge Decks at Extreme Temperatures", International Journal of Materials and Product Technology, p. 198, vol. 28, (2007). Published,

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Product Type:

Award for Composites Excellence

Product Description:

The PI received the 2002 Award for Composites Excellence (ACE) from the Composites Fabricators Association (CFA) - American Composites Manufacturers Association (ACMA), Arlington, VA. The category of the award was Market Expansion. The title of the application was: FRP Composite Drain for Highway Concrete Bridge Decks.

Sharing Information:

An FRP composite drain was developed and evaluated using embedded fiber optic strains sensors as an application of the project. The PI collaborated with the Maine Department of Transportation and one composites company to fabricate and install FRP composite drains in three highway bridges in the State.

Product Type:

Instruments or equipment developed

Product Description:

The PI developed, fabricated, and validated a smart and robust composite sheet with embedded fiber optic sensors that can be easily attached to structural members to monitor strains.
The smart composite sheets were implemented in a structural health monitoring system in the University of Maine AEWC Center office building expansion in 2005. This system contributed to the Leadership in Energy and Environmental Design (LEED) Certification of this building in the Category Innovation and Design Process.

Sharing Information:

The smart composite sheets can be used for reliable long-term structural health monitoring of building and bridge structures.

Contributions

Contributions within Discipline:

The research work has contributed to advance knowledge in fiber-reinforced polymer composites with emphasis on durability, experimental mechanics and structural composites health monitoring using embedded fiber optic sensors (FOS). The project contributed to the development of techniques for integrating embedded FOS in composites fabrication by vacuum assisted resin transfer molding (VARTM/SCRIMP). Furthermore, the research effort has led to advances in the field of durability of sandwich composite structures.
Specifically, the research work contributed to:
a) Develop optimal embedment techniques for FOS in FRP composites for sandwich panel construction;
b) Establish dependability of embedded sensors during fabrication and laboratory testing to simulate service life; and
c) Characterize effects of embedded EFPI strain sensors on host composite tensile and compressive properties.

The project contributed to develop techniques for integrating embedded FOS in composites fabrication by vacuum assisted resin transfer molding (VARTM/SCRIMP), as follows:

a) Devised lead routing strategies through panel edges;
b) Adopted techniques for FOS alignment and attachment to fabric reinforcement;
c) Designed ingress/egress lead reinforcement;
d) Prevented air leak during fabrication; and
e) Avoided resin contamination of leads and connector heads during fabrication.

The project contributed to understanding the effect of embedded EFPI sensors on mechanical properties of E-glass/vinyl ester composites, as follows:
a) No changes in elastic modulus in the fiber direction and perpendicular to the fiber direction for tensile and compressive loading were found;
b) Tension tests of specimens in the fiber direction with embedded sensors experienced premature grip failure;
c) No changes in tensile strength perpendicular to the fibers (matrix dominated property) was observed; and
d) No changes in compressive strength in the fiber direction and perpendicular to the fibers were found.

A first main project outcome is a smart and robust FRP composite sheet with embedded FOS that can be easily attached to structural members to monitor strains. The PI and his graduate students developed, fabricated, and validated the smart composite sheet, which was applied to monitor engineered wood beams in a new building facility as part of a structural health monitoring system.

A second main project outcome was the implementation of embedded FOS in a sandwich composite panel subjected to uniformly distributed pressure to monitor strains during fatigue loading and to validate with full-field strain measurements using a digital image correlation (DIC) system.

Contributions to Other Disciplines:

Contribution to Building Construction:
Smart FRP composite sheets with embedded fiber optic sensors were implemented in a structural health monitoring system in the University of Maine AEWC Center office building expansion in 2005. This building received the Leadership in Energy and Environmental Design (LEED) Certification.

In addition to the FOS strain gages, temperature and relative humidity sensors were installed as part of a comprehensive structural health monitoring system. Structural members representative of different building locations and loading conditions were selected. The research contributed to address installation issues, including routing of sensors leads and cables, attachments and connections and designing a central hub for continuous data collection. The location of the smart FRP composite sheets was determined to measure maximum tensile and compressive longitudinal strains without interfering with other building components.

Contributions to Human Resource Development:

The project has contributed to human resource development in science and engineering, as follows:
a) Two new interdisciplinary graduate courses were developed to support education and training in the area of composite materials for civil engineers and wood scientists. The courses are integrated in the curricula of the new graduate certificate in Advanced Engineered Wood Composites at the University of Maine.
b) The PI participated during two summers in the NSF Research Experience for Undergraduates (REU) site in Advanced Engineered Wood Composites at the University of Maine.
c) Educational activities for discovering engineering were planned and conducted by the PI during the statewide Engineers Week event (2002, 2003 and 2004). The PI also served as mentor of high-school students as part of the regional math-science program and other high-school internship and visiting programs.
d) The PI recruited and retained a diverse pool of students that are being educated to become engineers with a broad vision toward the needs for renewing the civil infrastructure. The project has contributed to further increase the participation of minority students in research and science by graduating one minority female student with an M.S. degree in Civil Engineering, supervising one minority female during a summer NSF-REU program, and recruiting a minority male Ph.D. student in the Civil Engineering program.

Contributions to Resources for Research and Education:

The project has contributed to resources for research and education, as follows:
a) In order to build research capacity, the PI has led the effort in designing and outfitting the new state-of-the-art Resin Infusion Composites Reliability (RICoR) lab in the AEWC Center at the University of Maine. The RICoR lab completed in 2004 is an environmentally controlled 48 ft x 32 ft clean room space, which supports the PI's laboratory activity on advanced composites processing and instrumentation.
b) By serving as Associate Editor of the Journal of Materials in Civil Engineering, ASCE, the PI has contributed to define the editorial guidelines of one of the main journals in the field.
c) The PI has contributed to institutional resources for the broader community of engineers by serving as chairman of the Advanced Materials Research Committee of the American Society of Civil Engineers.

Contributions Beyond Science and Engineering:

Contribution to standard test methods for industry:
The PI actively participated in ASTM Committee D30 with a task group formed by Industry and Academe that has investigated a new experimental method for characterizing mechanical properties and fatigue durability of sandwich composite panels. Through this effort the PI has been disseminating the results of the project by enhancing a standard test method for sandwich composite panels that has potential to be used to assess durability.

Categories for which nothing is reported:

Organizational Partners

Any Book

Any Web/Internet Site

SUMMARY

CAREER: Framework for Integrating Embedded Sensors in Durability Analysis of FRP Composites in Civil Infrastructure - Award No.CMS-0093678
Roberto Lopez-Anido, University of Maine.
Duration: Feb 2001 - Feb 2007.

Contributions with Discipline:
The research work contributed to advance knowledge in fiber-reinforced polymer composites with emphasis on durability, experimental mechanics and structural composites health monitoring using embedded fiber optic sensors (FOS). Techniques for integrating embedded FOS in composites fabrication by vacuum assisted resin transfer molding (VARTM) were developed. Furthermore, the research effort led to advances in the field of durability of sandwich composite structures.
Specifically, the research work contributed to: a) Develop optimal fabrication techniques for FOS embedded in FRP composites; b) Characterize effects of embedded EFPI strain sensors on host composite mechanical properties; and c) Develop structural health monitoring system using embedded sensors.

Contributions to Human Resources Development:

a) Two new interdisciplinary graduate courses were developed to support education and training in the area of composite materials for civil engineers and wood scientists. The courses are integrated in the curricula of the new graduate certificate in Advanced Engineered Wood Composites at the University of Maine.
b) The PI participated during two summers in the NSF Research Experience for Undergraduates (REU) site in Advanced Engineered Wood Composites at the University of Maine.
c) Educational activities for discovering engineering were planned and conducted by the PI during the statewide Engineers Week event (2002, 2003 and 2004). The PI also served as mentor of high-school students as part of the regional math-science program and other high-school internship and visiting programs.
d) The project contributed to further increase the participation of minority students in research and science by graduating one minority female student with an M.S. degree in Civil Engineering, supervising one minority female during a summer NSF-REU program, and recruiting a minority male Ph.D. student in the Civil Engineering program.
e) The project supported 3 M.S. students and 1 Ph.D. student and several undergraduate students.

Contributions to Resources for Research:

a) In order to build research capacity, the PI has led the effort in designing and outfitting the new state-of-the-art Resin Infusion Composites Reliability (RICoR) lab in the AEWC Center at the University of Maine. The RICoR lab completed in 2004 is an environmentally controlled 48 ft x 32 ft clean room space, which supports the PI's laboratory activity on advanced composites processing and instrumentation.
b) Smart FRP composite sheets with embedded fiber optic sensors were implemented in a structural health monitoring system in the University of Maine AEWC Center office building expansion in 2005. This work was conducted as part of the Leadership in Energy and Environmental Design (LEED) Certification of the building.

Selected publications from this NSF support:

Integrate embedded sensors in composites fabrication by VARTM/SCRIMP:

1. Lopez-Anido, R., and Fifield, S. "Experimental Methodology for Embedding Fiber Optic Strain Sensors in Fiber Reinforced Composites Fabricated by the VARTM/SCRIMP Process," Proc. of the 4th Int. Workshop on Structural Health Monitoring, DEStech, Lancaster, PA, pp. 247-254, 2003.
2. Pirvu, A., Gardner, D.J., and Lopez-Anido, R. "Carbon Fiber-Vinyl Ester Composite Reinforcement of Wood Using the VARTM/SCRIMP Fabrication Process," Composites Part A: Applied Science and Manufacturing, Vol. 35, No. 11 pp. 1257-1265, 2004.

Durability analysis of FRP composite materials:

3. Lopez-Anido, R., Michael, A.P., and Sandford, T.C. "Freeze-Thaw Resistance of FRP Composites Adhesive Bonds with Underwater Curing Epoxy," J. Materials in Civil Engineering, ASCE, Vol. 16, No. 3, pp. 283-286, 2004.
4. Herzog, H., Gardner, D.J., Lopez-Anido, R., Goodell, B. "Glass-Transition Temperature Based on Dynamic Mechanical Thermal Analysis Techniques as an Indicator of the Adhesive Performance of Vinyl Ester Resin," Journal of Applied Polymer Science, Vol. 97, No. 6, pp. 2221-2229, 2005.

Durability analysis of FRP composite-wood interfaces:

5. Lopez-Anido, R., Lech Muszyński, L., Gardner, D., Goodell, B., and Herzog, B. "Performance-Based Material Evaluation of Fiber-Reinforced Polymer-Wood Interfaces in Reinforced Glulam Members," Journal of Testing and Evaluation, ASTM Int., Vol. 33, No. 6, pp. 385-394, 2005.
6. Herzog, B., Goodell, B., Lopez-Anido, R., and Gardner, D.J. "Durability of Fiber-Reinforced Polymer (FRP) Composite - Wood Hybrid Products Fabricated Using the Composites Pressure Resin Infusion System (COMPRIS)," Forest Products Journal, Vol. 55, No. 11, pp. 54-60, 2005.

Develop a structural mechanics model for durability analysis:

7. Melrose, P., Lopez-Anido, R., and Muszyński, L. "Elastic Properties of Sandwich Composite Panels using 3-D Digital Image Correlation with the Hydromat Test System," Proc. of the SEM XI Int. Congress and Exposition on Experimental and Applied Mechanics, Paper No. 490, Jun. 7-10, 7 pp., Costa Mesa, CA, 2004.
8. Walter, T.R., Miskioglu, I., Bertelsen, W.D., Lopez-Anido, R. Haskell, A., Trofka, S., and Baylor J.S., "ASTM D6416 Round Robin Testing of Sandwich Panels," Proc. of the SEM XII Int. Congress and Exposition on Experimental and Applied Mechanics, Paper 175, 7 pp., Jun 7-9, Portland, OR, 2005.

Assessment of composite structures - sandwich composite panels and bridge decks:

9. Hong, Y., Muszyński, L., and Lopez-Anido, R. "Modeling and Calibration of a Laminating Press Prototype for Fiber-Reinforced Polymer-Glulam Billets," Journal of Testing and Evaluation, ASTM Int., Vol. 33, No. 6, pp. 395-405, 2005.
10. Dutta, P.K., Lopez-Anido, R., and Kwon, S.K. "Fatigue Durability of FRP Composite Bridge Decks at Extreme Temperatures," International Journal of Materials and Product Technology (IJMPT), Vol. 28, No. 1/2, pp. 198-216, 2007.

CAREER: Framework for Integrating Embedded Sensors in Durability Analysis of FRP Composites in Civil Infrastructure - Award No.CMS-0093678

Roberto Lopez-Anido, University of Maine

Findings

Integration of Embedded Sensors in Composites Fabrication by VARTM/SCRIMP

A methodology for embedment of Extrinsic Fabry-Perot Interferometric (EFPI) fiber optic strain sensors (FOS) into polymer matrix composite panels was demonstrated. E-glass/vinyl ester panels with embedded FOS were fabricated by the Vacuum Assisted Resin Transfer Molding (VARTM) process based on the Seemann Composites Resin Infusion Molding Process (SCRIMP) licensed technology (See Fig. 1). The efficiency of the FOS embedment method was demonstrated by evaluating tensile and compressive mechanical properties in the longitudinal and transverse material directions. Tension and compression experiments were conducted using specimens with and without embedded fiber optic sensors to determine: a) optimal embedment techniques; b) dependability of embedded sensors; and c) effects of embedded EFPI strain sensors on host composite properties. It was found that embedded EFPI sensors did not cause significant effects on the longitudinal and transverse elastic modulus and strength of the composite material. In general, strain measurements with EFPI sensors correlated well with bonded resistance foil gages. Strategies for lead routing of embedded FOS sensors through the edges of tension and compression test specimens were devised. The greatest challenge faced in the embedment of EFPI fiber optic sensors in VARTM/SCRIMP composites was prevention of sensor lead damage during panel fabrication, specimen cutting and mechanical testing. A fabrication process to produce sandwich composite panels with embedded fiber optic sensors was further developed.

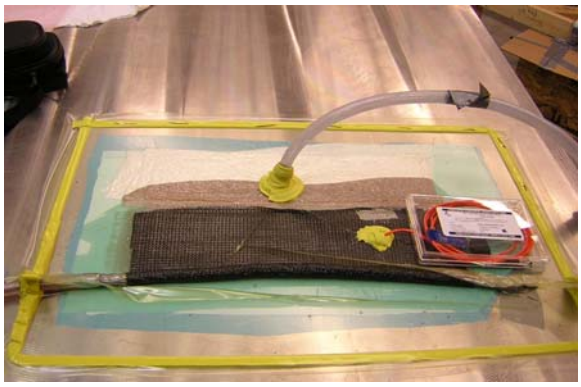

Figure 1. Integration of embedded fiber optic strain sensor in composites fabrication

Integration of Embedded Sensors in Composites Fabrication by Filament Winding

A procedure for experimental characterization of fiber-reinforced polymer (FRP) composites fabricated by filament winding using embedded fiber optic strain sensors was also developed. A laboratory computer-controlled filament winder was applied to fabricate carbon/vinyl ester and carbon/epoxy composite cylinders. EFPI fiber optic sensors were utilized to monitor residual strains within the composite cylindrical specimens during fabrication and post-curing.

The proposed procedure for embedment of FOS proved to be practical and consistent to measure residual strains experienced by filament-wound composite structures. It was found that carbon/epoxy filament wound composites absorbed less water than carbon/vinyl ester composites. However, the difference in moisture content between the epoxy matrix and the vinyl ester matrix composite specimens decreased with the exposure time. The filament winding fabrication process can be further improved by controlling ambient temperature and relative humidity to reduce variations in the resin pot-life.

Electron Microprobe Analysis for Characterizing Features of FRP Composite Materials

Using the electron microprobe in the backscatter mode, the surfaces of the FRP composites fabricated by the two processes could be easily imaged. Microvoids were observed in the composite specimens fabricated by the

VARTM/SCRIMP process, which is a vacuum-driven resin infusion process. No significant microvoids were observed in the composite specimens fabricated by the ComPRIS process, which is a pressure-driven resin infusion process. The apparent difference in void content is attributed to the difference in the resin infusion driving force, i.e. vacuum versus pressure. It is hypothesized that the microvoids were due to apparent outgassing and/or solvent ablation caused by the applied vacuum. In addition, the mechanical consolidation process associated with ComPRIS resulted in a more uniform fiber packing distribution than the VARTM process resulting in fewer resin-rich areas observed in the analysis.

Durability Analysis of FRP Composite-Wood Interfaces

Durability of adhesive bonds between FRP composites and wood substrates subjected to hygrothermal cycling was investigated. Two FRP composites fabrication process were studied: the VARTM/SCRIMP process and the ComPRIS process. The effect of surface conditioning and chemical preservative treatments applied to wood on the interface durability was characterized. Glass-transition temperature based on dynamic mechanical thermal analysis techniques was implemented as an indicator of the adhesive performance of vinyl ester resin.

Durability Analysis of FRP Composite Doubler-plate Joints

A distributed sensing system based on embedded Bragg grating fiber optic strain sensors has potential to monitor crack initiation and propagation in composite joints subjected to fatigue loading. A finite element model is required to correlate the fiber optic strain measurements with crack lengths.

Development of Structural Mechanics Model for Durability Analysis

A sandwich composite plate model was accurate in predicting the level of load and pressure corresponding to yielding of ductile foam cores or fracture of brittle end-grain balsa wood cores. The model predicted the failure location for both materials; however, the model could not predict the ultimate failure load for the foam panel since the core yielded and carried a significant amount of load above the predicted failure load. A non-linear material model would be needed to accurately model the yielding response of the foam core.

Assessment of Composite Structures: Sandwich Composite Panels

The hydromat test system proved to be a versatile method for testing sandwich composite panels (See Fig. 2). Necessary changes in the hydromat test setup, such as changing bladder sizes or load cell positioning, were made with relatively ease. Sandwich composite plate modeling was used in conjunction with the hydromat test system to verify the structural response of two types of sandwich panels. This correlation between experimental results and a predictive model opens the door for inverse solution methods that allow back computation of sandwich panel stiffness properties.

Figure 2. Hydromat test system with digital image correlation system

A combined experimental and numerical approach for determining bending and shear stiffness parameters of a sandwich composite panel evaluated with the hydromat test system was developed. The solution was verified using

simulated full-field data, which was perturbed using additive random noise. With this verification approach, the solution method was proven to be robust although additional relationships between stiffness parameters should be investigated to improve the stability of the solution. Additionally, it was found that the solution converged for initial seed values containing significant error from the actual stiffness parameters.

The new combined experimental and numerical method for computing stiffness parameters from a sandwich composite panel bending test was successfully implemented. The method combines digital image correlation with the hydromat test system and numerical optimization techniques developed as part of this project. The method produced consistent results for sandwich composites with E-glass vinyl ester face sheets and both balsa wood and PVC foam cores. The majority of the variability was observed in the core transverse shear stiffness parameters with the balsa core having the largest variation.

Assessment of Composite Structures: Cylindrical Shells

A technique for fabricating FRP composite shells utilizing VARTM/SCRIMP was implemented in the laboratory. A durable method for adhesive bonding of composite shells using an underwater curing epoxy adhesive was developed and evaluated through exposure to freeze-thaw cycles. These project findings were applied to demonstrate the feasibility of using FRP composite shells for strengthening of wood piles.

Assessment of Composite Structures: Carbon Composite Cable Structures

Currently, there are not reliable methods for measuring longitudinal strains in carbon composite strands made of twisted wires. The method developed using fiber optic strain sensors embedded in a composite cylindrical shell has potential to be robust and reliable for long-monitoring of cable structures made of carbon composite strands.

CAREER: Framework for Integrating Embedded Sensors in Durability Analysis of FRP Composites in Civil Infrastructure - Award No.CMS-0093678

Roberto Lopez-Anido, University of Maine

Research and Education Activities

Implementation and Calibration of Fiber-Optic Strain Sensor Systems

Initially, a fiber optic sensor (FOS) system manufactured by Luna Innovations from Blacksburg, Virginia, was selected and implemented in the laboratory. Extrinsic Fabry-Perot Interferometric (EFPI) strain gages with polyimide-coated leads and Teflon-sheathing were utilized. The operation temperature of the EFPI sensors used ranges from -100°C to 350°C. The FOS strain measurement range is ±5,000με. The monitoring system used generates light waves and reads changes in the phase of the light that travels through the fiber optic sensors.

A second FOS system manufactured by Roctest-Fiso, called BUS system, was procured and implemented to support structural health monitoring. The BUS system is a simultaneous fiber-optic multi-channel signal conditioner. Four channel modules with 1000 Hz sampling rate were installed. This system was used in conjunction with a FISO Commander BUS/Veloce Edition software to read, gather and record data from the FOS gages. In addition, a portable FOS system manufactured by Roctest-Fiso, called UMI system, was procured for structural health monitoring of bridges and building structures.

Integration of Embedded Sensors in Composites Fabrication by VARTM/SCRIMP

A technique was devised to integrate embedment of FOS in the Vacuum Assisted Resin Transfer Molding (VARTM/SCRIMP) composites fabrication process. EFPI fiber optic sensors for structural health monitoring were embedded in composite specimens for laboratory experiments. Composite specimens were instrumented with bonded foil strain gages and correlated with the fiber-optic outputs. In general, strain measurements with EFPI sensors correlated well with bonded resistance foil gages applied on the test specimens. However, for laminates subjected to compressive loads, embedded FOS are more accurate to measure in-plane strains than surface bonded foil gages, since bending effects are minimized.

The focus of this research task was on the placement of the sensors to minimize the impact on the fiber-reinforced polymer (FRP) composite properties. The effect of the sensor layer on the structural response of the composite subjected to static loading regimes was established. The mechanical properties investigated were longitudinal and transverse tension, and longitudinal compression. Techniques to integrate the sensor layer into the laminate and manufacturing process were developed. In particular, the following issues were investigated: 1) Method of attachment of sensor layer to reinforcing fibers (stitching, binding); and 2) Effect resin impregnation on the sensors and curing conditions (temperature, shrinkage).

Integration of Embedded Sensors in Composites Fabrication by Filament Winding

A procedure for experimental characterization of FRP composites fabricated by filament winding using embedded fiber optic strain sensors was investigated. A laboratory computer-controlled filament winder was implemented for fabricating carbon/vinyl ester and carbon/epoxy composite cylinders. EFPI fiber optic strain sensors were utilized to monitor residual strains within the composite cylindrical specimens during fabrication and post-curing. Hygro-thermal strain due to vacuum-pressure moisture saturation and equilibrium conditioning were measured following standard test procedures ASTM D1101 and ASTM D5229. The proposed procedure for embedment of fiber optic strain sensors proved to be practical and consistent to measure residual strains experienced by filament-wound composite structures.

Electron Microprobe Analysis for Characterizing Features of FRP Composite Materials

A new electron microprobe analysis (EMPA) technique for rapid and accurate characterization of features, and evaluation of defects and quantitative properties within FRP composite materials was developed. The PI and collaborators utilized backscattered electron imaging (BEI) to mitigate the somewhat tedious preparation of samples often required for images with conventional light microscopy methods and also improve upon secondary electron microscopy methods which oftentimes do not provide adequate surface resolution. He utilized the BEI technique for evaluation of defects (microvoids) and resin-rich gaps in composite materials fabricated by Vacuum Assisted Resin

Transfer Molding (VARTM/SCRIMP) and the Composite Pressure Resin Infusion System (ComPRIS). ComPRIS is a composites fabrication process developed as an application of the project.

Durability Analysis of FRP Composite-Wood Interfaces

Durability of adhesive bonds between FRP composites and wood substrates subjected to hygrothermal cycling was investigated. Two FRP composites fabrication process were studied: the VARTM/SCRIMP process and the ComPRIS process. The effect of surface conditioning and chemical preservative treatments applied to wood on the interface durability was characterized. Glass-transition temperature based on dynamic mechanical thermal analysis techniques was implemented as an indicator of the adhesive performance of vinyl ester resin.

Durability Analysis of FRP Composite Doubler-plate Joints

Fatigue fracture tests of secondary bonded composite doubler-plate joints in tension have been investigated. The main objective of this research task is to assess feasibility of monitoring crack propagation using embedded Bragg grating fiber optic strain sensors. A finite element simulation has been developed to support the design of the experiment and the post-process of the experimental measurements.

Development of Structural Mechanics Model for Durability Analysis

A method to determine properties of sandwich composite panels by integrating digital image correlation analysis, plate bending experiments and numerical techniques was developed. Sandwich composite panels were evaluated as a simply supported plate under uniform lateral pressure using a Hydromat test system according to ASTM D6416 standard method. The panel was modeled using sandwich composite plate theory with a Navier's solution. A 3-D digital image correlation system capable of full field measurements of strains and displacements was utilized with the Hydromat test system. The experimental displacement and in-plane strain measurements were correlated to the sandwich composite plate solution. Based on this correlation, an inverse analysis technique was developed to compute properties of the sandwich panel components (face sheets and core). A numerical optimization method based on non-linear least squares was utilized to minimize the error in the computation of properties.

Assessment of Composite Structures: Sandwich Composite Panels

Two types of sandwich composite panels were studied: 1) Deck panels fabricated by contact molding hand lay-up with glued-laminated wood core (FRP-glulam); and 2) Panels fabricated by VARTM/SCRIMP with end-grain balsa wood and polyvinyl chloride (PVC) foam cores. The sandwich composite panels were subjected to different types of mechanical loading and environmental exposure that may be expected in civil structures.

FRP-glulam deck panels were instrumented with FOS for strain monitoring and installed in the Union-Washington Skidmore Bridge, Maine in 2001. This highway bridge received in 2002 an Award of Merit from the National Timber Bridge Awards Program, APA-Engineered Wood Systems, Tacoma, WA.

Assessment of Composite Structures: Cylindrical Shells

Three types of FRP composite cylindrical shells were studied: 1) FRP cylindrical shells fabricated by VARTM/SCRIMP for rehabilitating wood piles; 2) FRP cylindrical shells fabricated by filament winding; 3) FRP cylindrical shells fabricated by hand lay-up contact molding for bridge drains. The composite structures were subjected to different types of mechanical loading and environmental exposure that may be expected in civil structures.

A project application based on utilizing FRP composite shells for rehabilitation of wood piles was developed. A technique for fabricating FRP composite shells utilizing VARTM/SCRIMP was implemented in the laboratory. The interfaces in wood piles repaired with FRP composite shells and grout materials were characterized through push-out and bending tests. A simplified piecewise linear model was proposed to represent the apparent interface shear stress versus slip response. The durability of an underwater curing epoxy adhesive, which is used for bonding composite shells, subjected to freeze-thaw cycles was also investigated.

As an application of the project, an FRP composite drain system for concrete bridges was developed. The PI and collaborators conducted experiments to evaluate the FRP drains subjected to ice formation pressure, fatigue cycling simulating wheel load repetitive action, and ultimate quasi-static loading. The FRP drains were instrumented with embedded fiber optic sensors to monitor strains. Improvements to the FRP drain system were proposed based on the research work and demonstration drains were installed in three highway bridges in Maine.

Assessment of Composite Structures: Carbon Composite Cable Structures

A method to evaluate the long-term deformation response of carbon composite strands for cable structures using embedded fiber optic strain sensors has been developed. The method is suitable for field monitoring of cable-stayed bridges. Fiber optic sensors are embedded in a composite cylindrical shell in the lab environment using the VARTM/SCRIMP fabrication process. The composite shell is made of a thin and flexible laminate and it has a longitudinal slit to facilitate the attachment to a strand prior to tensioning of the cable structure. The structural health monitoring system has potential for long-term monitoring of strains due the thermal effects and dynamic loading, as well as to characterizing creep deformation of carbon composite strands.

Teaching: New Courses Developed

The PI developed two new interdisciplinary graduate courses to support education and training in the area of composite materials for civil engineers and wood scientists. The development and implementation of the courses was funded by the NSF CAREER project.

1. CIE 543 - Introduction to Composite Materials in Civil Engineering. This course provides an introduction to the mechanics of fiber-reinforced polymer (FRP) composite materials in civil engineering with a view to structural design. Students are expected to gain an understanding of material properties, fabrication processes, fundamental mechanics, experimental procedures and methods of analysis and design.
2. CIE 644 - Advanced Composite Materials in Civil Engineering. This is an advanced course on material science and mechanics of composite materials. Students are exposed to the application of fiber reinforced composites in civil-infrastructure including durability; failure criteria -strength and design, temperature and environmental effects, and repair and retrofit of existing structures.

Teaching: New Graduate Program Developed

The PI co-developed the interdisciplinary Graduate Certificate Program on Advanced Engineered Wood Composites (AEWC). The general objective of the AEWC Graduate Certificate is to provide students with a firm foundation in wood-polymer and fiber-reinforced hybrid composite materials. The development and implementation of the graduate program was funded by the NSF CAREER project. The AEWC Graduate Certificate is a 16 credit graduate program with a coordinated curriculum of courses in Composite Materials Engineering and Wood Science and Technology. The three specific objectives of the program and coursework, which cover the six levels of Bloom's Taxonomy of Educational Objectives for the Cognitive Domain, are:

1. Students acquire knowledge and demonstrate comprehension on processing and manufacturing.
2. Students conduct and analyze material property characterization.
3. Students develop skills in assessing technology and systematizing application of the interdisciplinary graduate training to product development of low-cost, high-performance wood-polymer and fiber-reinforced hybrid composites.

The PI served as co-coordinator of the AEWC Graduate Certificate program since its inception in 2001. Already, one graduate student has completed the program and several other graduate students are currently enrolled. The current interactions and partnerships of the AEWC Center with Wood and Composites industries have provided an industrial network for job placement.

Teaching: Innovation

The PI used technology to produce significant improvements in teaching techniques and learning strategies, as part of the CAREER project. The PI developed a set of class notes in electronic format in the junior level course CIE 340. In addition, the PI used an educational computer program (Dr. Beam) to teach methods of structural analysis in the laboratory sessions. The PI also implemented computer activities on truss bridge design in CIE 100 - Introduction to Civil and Environmental Engineering.

In the graduate course CIE 547, the PI has trained students in analysis and design of prestressed concrete structures using an interactive computer program. In the new graduate course CIE 543, the PI has developed computer worksheets for laminated composite beam analysis using MathCad software to facilitate students understanding the relationships between mechanical and hygro-thermal loading, and the structural mechanics response.

The PI was selected the Professor of the Year by the UMaine ASCE Student Chapter in 2001 and in 2005.

Teaching: Student Recruitment

The PI contributed as a mentor to the McNair Scholars Program proposal, which prepares participants from disadvantaged backgrounds that have demonstrated strong academic potential for doctoral studies through involvement in research and other scholarly activities. The PI participated in minority recruitment activities in engineering with support from the Northeast Alliance for Graduate Education and the Professoriate (NEAGEP).