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Abstract

In a collaborative project involving the University of Delaware, the Delaware Department of Transportation (DelDOT), the Federal Highway Administration (FHWA), and industry, Bridge 1-351 on Business Route 896 became one of the first state-owned fiber-reinforced polymer (FRP) composite bridges in the nation. The project was the topic of a doctoral dissertation in the University's Department of Civil and Environmental Engineering.

This project report has been prepared in two parts. The first section is an executive summary of the project, with each major section summarizing the findings detailed in a chapter of the dissertation. The dissertation itself is attached as an appendix and provides a full report of the project, including

- analysis and design,
- large-scale subcomponent testing,
- fabrication and processing of the large-scale subcomponents and the final superstructure sections, and
- construction and erection of Bridge 1-351.

For an overview of these topics, see the executive summary; for more detail, consult the appendix[*].

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[*] Due to its length, the appendix has been included in only selected copies of this report. If your copy of the report does not include the appendix, you may request a copy of it from the Delaware Center for Transportation at (302) 831-1446.

Executive Summary

Background

As the nation's bridge infrastructure deteriorates, authorities from state and federal transportation agencies are searching for more durable construction materials and more efficient erection methods to decrease life-cycle costs and minimize traffic disruptions. Fiber-reinforced polymer (FRP) composites offer increased durability and reduced maintenance costs over traditional construction materials while enabling rapid erection and minimizing traffic disruptions. These advanced materials offer great promise for repair and rehabilitation as well as for new construction.

A study conducted by the National Science Foundation and the Civil Engineering Research Foundation in 1994 showed that nearly 40% of the nation's bridges were classified as structurally deficient and/or functionally obsolete. Thus, of the 575,000 bridges in the nation's bridge inventory in 1994, nearly 230,000 were rated as substandard. With inadequate maintenance and a lack of funding at the county, state, and federal levels, the backlog of structurally deficient and functionally obsolete bridges continues to increase.

Although the advantages of FRP composites make them attractive for rehabilitation, repair, and new bridge designs, major barriers to their use in bridge design remain, including a lack of training, professional practice, and the high initial cost of FRP materials compared to traditional materials. The goal of this project was to design, analyze, fabricate, and erect an all-composite bridge deck to serve as a case study for the use of FRP composites in bridge construction.

Motivation

The bridge chosen for the case study was Bridge 1-351 on Business Route 896 in Glasgow, Del. The original Route 896 bridge was designed and constructed using steel girders and a concrete deck resting on a concrete abutment. The bridge was constructed in 1926 and widened in 1936. In 1994, Route 896 was reconstructed and rerouted around Glasgow, Del.; at that time, the original Route 896, including Bridge 1-351, became a business district route into Glasgow.

With the rerouting of 896 complete and Bridge 1-351 rated as substandard, DelDOT began to evaluate options for continued use of the road. The bridge was seriously deteriorated and required repair to remain in service. Additionally, substantial (and expensive) substructure modifications were required to bring the bridge up to current AASHTO standards. For replacement options, other bridge designs, including steel girder or adjacent prestressed box beams, were considered. A steel-girder bridge was not desirable because of the close proximity to Muddy Run Creek and the potential for corrosion. A decision was made to use lightweight FRP composites, as these materials would enable minimal modifications to be made to the existing substructure, facilitating rapid erection and resulting in minimal traffic disruption and reduced acquisition costs. The project was also motivated by the desire for a testbed to collect long-term data and enable assessment of life-cycle costs, in contrast to making comparisons with traditional materials based on acquisition costs alone. Table 1 shows the team assembled to carry out the project and their respective areas of expertise.

Table 1: Bridge 1-351 Project Team

Team Member	Expertise
University of Delaware (UD)	FRP composites manufacture, design, and analysis tools for the use of FRP composite materials in bridge applications; experimental validation of structural behavior by full-scale structural testing
Delaware Transportation Institute (DTI)[*]	Experience in coordinating joint projects between DelDOT and UD
Delaware Department of Transportation (DelDOT)	Extensive history of designing, constructing, and maintaining bridges
Federal Highway Administration (FHWA)	Funding and identification of Bridge 1-351 as appropriate case study for FRP composites
Hardcore Composites (HC)	Extensive experience in fabrication and processing of FRP composite bridge sections and subcomponents
James Julian, Inc. (JJI)	Substantial history of highway and bridge construction; commitment to explore new and developing technology for bridge construction

FRP Composite Bridge Research at UD

DelDOT sought out the University because of its resident expertise in the design, analysis, fabrication, processing, materials characterization, and full-scale structural testing of FRP composites for bridge applications. The Department of Civil and Environmental Engineering (CEE) and the Center for Composite Materials (CCM) participated in the effort. CCM had a long history of research in composites manufacturing and materials characterization, including comprehensive capabilities to characterize materials behavior through coupon-level and large-scale testing. CEE had the capability to perform experimental structural evaluation of full-scale

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structures. Additionally, the University had experience with the development of design and analysis tools to describe the structural behavior of FRP composite structures via integration of materials behavior, mechanics, and ordinary structural analysis. Finally, CEE had affiliated faculty with substantial experience in bridge design and codification.

Research on the use of FRP composites for bridge applications was initiated as a joint effort between CEE and CCM in the early 1990s. Prior to this effort, UD had designed and built a large-scale load frame with 330 kips of capacity capable of static and high-frequency fatigue loading. The ongoing program resulted in FRP technology for marine applications, railcars, pilings, and FRP composite bridges and bridge decks.

The work included a collaborative project between UD and the Delaware River and Bay Authority (DRBA) on a maintenance bridge owned by DRBA. The original maintenance bridge, known as Magazine Ditch, was a one-lane bridge that served maintenance crews at the Delaware Memorial Bridge. Severe deterioration prompted DRBA to replace the bridge and evaluate the use of FRP composites for a new design. The new bridge consists of post-tensioned channel girders and an FRP deck to transfer loads to the channel sections. John Muller International (JMI) designed the channel section, and UD guided Hardcore Composites (HC) in the design and analysis of the FRP composite deck. The bridge was designed using the AASHTO LRFD bridge design specifications. The University's role included full-scale structural testing.

A theoretical and experimental study to develop and validate design and analysis tools to describe the structural behavior of FRP composite web-core sandwich structures for bridge applications was also performed. Full-scale structural testing included static, fatigue, and strength limit states truck loading. Extensive testing of bridge decks comprising various sizes of sandwich structures fabricated using FRP composites was performed. The buckling performance of web-core sandwich structures was theoretically and experimentally evaluated. This research resulted in a design chart to assist in the future design of web-core sandwich structures for bridge applications. The project also laid the foundation for replacement and repair of numerous bridges and bridge decks in other states, including Maryland, Pennsylvania, New York, and Ohio.

Bridge 1-351 As a Case Study

Bridge 1-351 exemplified the problems associated with the local and national bridge inventory—it was both structurally deficient, due to severe girder deterioration, and functionally obsolete, due to its intended new use as a one-way business route rather than a two-lane throughway and the required re-construction to bring the bridge up to modern design specifications and standards.

Conceptual Design and Requirements

Successful bridge design encompasses bridge design philosophy, conceptual ideas, functional requirements, materials behavior, and structural analysis. When the project began, the team faced a lack of past practice and experience using these nontraditional materials. In addition, standards and specifications using FRP composite materials for bridge design were nonexistent. The engineering systems approach resulted in a list of unique contributions for the conceptual design and requirements for Bridge 1-351, as highlighted below.

The team used and adapted the AASHTO LRFD Bridge Design Specifications to design an FRP composite bridge that would be safe and serviceable for 75 years. The AASHTO bridge design specifications reflect the philosophy of Load and Resistance Factor Design (LRFD) used throughout the steel and concrete industries. LRFD is based on the statistical requirement that factored loads remain less than or equal to factored material resistances. Loads or force effects are statistically factored up or increased to account for the probability that larger than predicted loads are applied. Material resistances are factored down or decreased to allow for degradation of material properties and structural behavior, a measure known as a *knockdown*. For the FRP composite bridge, factored design loads were applied, and implementation of the AASHTO LRFD philosophy remained unchanged. Knockdowns were determined by a comprehensive materials testing program to study the degradation of material properties. Specifically, material resistance factors on modulus and strength were determined for the FRP composite materials subjected to environmental exposure, damage, and static and fatigue loading.

The functional requirements for Bridge 1-351 included modifications to the existing substructure for the FRP composite superstructure, deck slope for water runoff, crash barrier design, superstructure anchoring, application of the latex-modified wearing surface (LMC), expansion joints and seals, superstructure transportability and storage, and construction and erection procedures. Innovative ideas and concepts were developed to address these needs.

The geometric cross-section of the bridge superstructure and the subcomponents are constructed as a web-core sandwich structure. The cross-section consists of FRP composite tensile and compressive facesheets separated by a core. Note that the addition and contribution of stiffness from the LMC wearing surface is included to increase flexural rigidity and decrease lateral deformations during in-service use. A structurally redundant longitudinal butt joint with top and bottom splice plates was designed to assist transportability and to join the superstructure into a single bridge.

Due to the lack of design and fabrication standards for FRP composite bridges, QA/QC specifications were developed and implemented. Adherence to the QA/QC guidelines assured the fabricators and owners that the FRP sections were manufactured to provide a high level of proofed structural behavior that would fit within tolerable allowances during erection.

Theoretical Structural Analysis and Design

Design of composite bridges and bridge decks is typically stiffness driven based on the relatively low stiffness (2.5–6 Msi) offered by E-glass laminates to satisfy deflection requirements. Sandwich construction consisting of FRP composite facesheets and a lightweight core comprising FRP composite materials and foam offers high structural stiffness-to-weight at minimal cost.

Flexural and shearing rigidities for the web-core sandwich construction used for Bridge 1-351 were determined using laminated plate theory and simplified sandwich theory. The flexural rigidities were determined for the cross section with and without the contribution of the LMC wearing surface to flexural rigidity using laminated plate theory and simplified sandwich theory. The shearing rigidity was determined from material properties and the actual area of webs in shear. The flexural and shearing rigidities were predicted for the full-scale subcomponents, superstructure proof sections, and final bridge superstructure. Theoretical rigidities were correlated to experimentally measured rigidities from full-scale subcomponent testing. To determine the maximum moments, influence lines were used to determine a family of force effects. A moment envelope was developed for the service and strength I force effects; this would help in determining the position of the design trucks for maximum force effects.

Deformation functions, including the effects of transverse shear deformation, were analytically derived. Lateral deformations were then predicted for the subcomponents, proof sections, and final bridge superstructure. Deformations were predicted for the initial condition and after 75 years of service. Theoretical lateral deformations were shown to satisfy the AASHTO L/800 deflection provision. Theoretical facesheet strains for the FRP composite were far below material allowables, including the effects of degradation using the resistance knockdowns for modulus and strength.

The theoretical transverse bridge moments and shears were analytically predicted. Preliminary finite element modeling assisted in the location of the design trucks to produce maximum resultant moments and shears transversely across the longitudinal joint. Predictions of transverse moment and shear were then correlated to full-scale experimental subcomponent testing.

The buckling response of the web-core sandwich superstructure subjected to ASHTO truck loads was theoretically and experimentally evaluated. The design buckling behavior was subsequently analyzed using a buckling design chart. Full-scale subcomponents were experimentally tested with fatigue- and strength-limit truck loads. The buckling design chart was then updated for these tests. Recommendations based on the design chart, full-scale testing, and theoretical predictions resulted in the recommendation that web thicknesses over the abutments be doubled.

Theoretical predictions of the natural frequencies for the completed bridge were determined. Natural frequencies were then correlated with an experimental vibration modal analysis for the completed bridge. Excellent correlation between the theoretical and experimental first fundamental natural frequency was observed. Modal analysis provided a means to justify QA/QA and the manufacturing defects of fabricated composite structures. Additionally, the in-service structural behavior was captured using the modal analysis.

Fabrication of Full-Scale Subcomponents and Bridge Superstructure Sections

To validate the design, analysis, and structural behavior of the completed bridge, full-scale subcomponents were fabricated and experimentally tested. Using the AASHTO Bridge Design Specifications, the subcomponents were subjected to AASHTO-type truck loading and the Service I, Fatigue, and Strength I limit states. The subcomponent testing also included structural validation of the buckling performance of the web-core section. A full-scale section of the longitudinal joint was assembled to validate the transverse structural performance of the loads across the longitudinal joint. The transverse section resulted in assembly procedures defined for the erection of the final bridge superstructure.

A methodology was required to define the QA/QC of the fabricated subcomponents and the subsequent final bridge superstructure. The standards were repeatable processing of quality sections and maintenance of geometric tolerances for the final superstructure. To assist in the QA/QC for the subcomponents, the final bridge superstructure sections, and future designs using the SCRIMP® processing technique, a methodology was defined to measure processing parameters during processing. Fiber-optic sensors, thermocouples, and an infrared camera were positioned in the subcomponent sections during fabrication and processing. The thermal strains, temperatures, and heat transfer during fabrication and processing of the subcomponents were measured. The structural performance of the full-scale subcomponents and final sections was experimentally measured to complement the processing parameter measurements. Validation of the theory with the structural performance enables the baseline fabrication and processing parameters to be used for rapid redesigns without the need for full-scale testing. Future redesigns of web-core sandwich sections can simply apply baseline processing data, resulting in confidence in manufacture along with a greater probability of structural performance. In addition, the use of a vibration modal analysis technique can assist in identifying additional manufacturing defects not seen with baseline processing parameters.

Fiber-optic sensors were placed in the subcomponents to measure processing parameters as well as to develop sensor placement techniques. Survivability of the delicate sensors during the SCRIMP® process was a major issue. Baseline testing was performed on the sensors, including subjecting them to an elevated-temperature environment (400°F). The cables and sensors remained intact and functional. The thermal testing validated that the 88 fiber-optic sensors to be placed in the final superstructure would survive the exotherm in the hollowed-out containment cell during processing.

After the structural performance of the subcomponents was validated to the AASHTO design philosophy and to theory, the final superstructure sections were fabricated. Final documents including shop drawings and bridge construction drawings were completed and placed out for bid. The final superstructure sections were then fabricated and proof-tested to the Strength I limit state. The subcomponents and final superstructure sections were successfully fabricated with only slight defects and out-of-tolerance concerns that were deemed acceptable.

The final bridge sections were fabricated by Hardcore Composites using E-glass/vinyl-ester materials via a vacuum-assisted resin transfer molding process (SCRIMP®). The bridge decks were designed and fabricated as classic web-core sandwich construction.

Experimental Validation of Structural Behavior

To validate the design and structural behavior of the all-composite bridge, full-scale bridge subcomponents were fabricated and experimentally tested with AASHTO truck loading. The bridge superstructure was designed and fabricated as a web-core sandwich construction. The bridge sections and subcomponents were fabricated using E-glass/vinyl-ester materials. Bridge 1-351 consists of two 29.4 in. x 13 ft. x 32 ft. FRP superstructure sections joined by a longitudinal butt joint with top and bottom splice plates.

The fundamental questions to be addressed included the overall bridge deck stiffness, strength, fatigue, web-core buckling, and the transverse behavior of the longitudinal joint. The subcomponents and superstructure sections were subjected to AASHTO truck loading and the Service I, Fatigue, and Strength I limit states. The bridge longitudinal joint was designed with comparable stiffness and strength in the direction of traffic. Transverse truck loading at the edges of the bridge create resultant shear and moments transverse to the longitudinal joint.

Construction and erection procedures resulted from full-scale testing of the transverse section of the longitudinal joint.

Fiber-optic sensors placed in the midplane of the subcomponent tensile facesheet during fabrication and processing were also used to measure mechanical strains induced by transverse loads. The strains measured using the fiber-optic sensors were then correlated to strains measured with ordinary strain gages as well as to theoretically predicted strains. The subcomponents and final superstructure proof sections satisfied AASHTO truck loading requirements.

Experimental results showed that the designed sections for the final bridge should exceed the 75-year bridge life span. The experimental program also provided a means to validate the design tools used for scaleup or scaledown of web-core sections for future redesigns by state transportation departments. Overall, excellent correlation of theoretical predictions to experimental results of structural behavior was achieved.

Construction and Erection

The construction phase included abutment modifications, removal of fiber optics, FRP section placement and assembly, application of the LMC wearing surface, parapet and backwall construction, and highway construction.

The final bridge consists of two 13-ft. wide by 32-ft. long sections joined by a longitudinal joint, yielding final overall bridge dimensions of 26 ft. width by 32 ft. length. The longitudinal joint was connected with top and bottom splice plates using an industrial-grade structural adhesive.

Construction and erection procedures were based on validated conceptual design and the subcomponent experimental program. The University provided on-site engineering support through completion of the construction. The use of FRP composites for Bridge 1-351 required new construction and erection procedures. Questions were addressed and guidance provided with regard to section transportation, storage, lifting, placing and erection, placement and anchorage. Concerns regarding assembly of the longitudinal joint were also addressed to assist in the erection of the FRP composite superstructure. Guidelines and assistance with placement of the LMC wearing surface were also provided.

The bridge opened on November 20, 1998, and in February 1999 it received the 1998 ASCE Delaware Section Project of the Year Award.

Inspection and Maintenance Guidelines, Load Rating, and Modal Analysis

The condition evaluation and load ratings developed under this project were based on the 1994 AASHTO Bridge Design Specifications and the 1994 revised AASHTO Manual for Condition Evaluation of Bridges. Because Bridge 1-351 was designed using the Load and Resistance Factor Design (LRFD), the load ratings are determined using the LRFD philosophy. Therefore, modifications to the rating formula found in the Condition Evaluation Manual (LFD) were made to include the LRFD philosophy. Because the AASHTO specifications and the condition manual were written for bridges designed using traditional materials, both the bridge specifications and the condition manual were adapted for the use of FRP composite materials.

Bridge rating factors and bridge ratings were determined using the LRFD philosophy and structural failure modes. Potential failure modes of the superstructure include limitations in the FRP facesheet capacities, shearing failure of the facesheet-to-core interface, crushing strains in the latex-modified concrete wearing surface, and crushing of the webs forming the web-core sandwich structure. Maintenance guidelines were developed to provide the owner with the necessary procedures to prolong the in-service life of the FRP composite bridge. Itemized bridge components were listed to assist the owner in the inspection and corrective and preventive maintenance of Bridge 1-351. Load rating factors and load ratings were calculated to enable safe and serviceable passage of truck traffic. The potential FRP composite failure modes were identified, resulting in the governing rating factor based upon the crushing strain in the latex-modified concrete. Bridge ratings were calculated to assist in determining safe truck loads, permit loads, and overweight loads.

The initial in-service structural behavior of Bridge 1-351 was evaluated using a vibration modal analysis technique and algorithm. Using the modal analysis, actual in-service structural behavior was measured by excitation of the bridge using a force transducer and accelerometers. The modal analysis also offers the potential to detect structural defects or damage due to in-service use or from processing and fabrication.

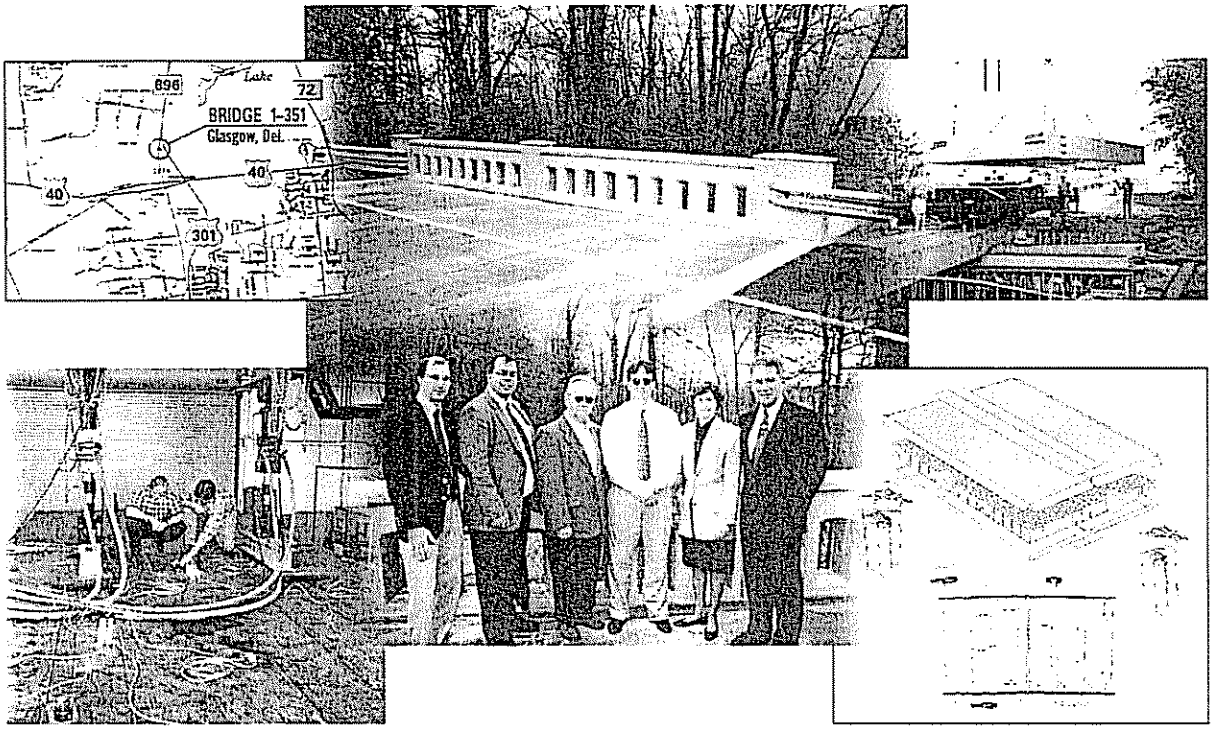
Training Recommendations

Using FRP composites for bridge applications may require DOT and AASHTO training workshops to completely disseminate the theory for design and analysis procedures for advanced composite bridges. Lectures and seminars at DOTs can offer the in-house training required for using FRP composites for bridge applications. Workshops may be set up at structural engineering and bridge conferences. Finally, publications (journals and textbooks) coupled with training will more completely disseminate the knowledge required for the future design of bridges with FRP composite materials.

Conclusions and Future Work

An engineering and systems approach for the use of FRP materials in bridge applications culminated with the successful opening of Bridge 1-351 in Glasgow, Del., in November 1998. AASHTO provisions and truck loading, complemented by experimental validation of structural performance, resulted in a bridge that is expected to have a service life of 75 years. Using FRP composites for Bridge 1-351 enabled rapid erection with minimal modifications to the existing bridge layout and substructure, while also minimizing traffic disruptions. These materials also offer the potential for low maintenance and life-cycle costs through increased durability.

Future work should include additional research and analysis for different cross-sections and superstructure joining techniques. More detailed analysis of structural behavior should be carried out using plate theory and FEM. Experimental validation for these proposed concepts is required. Additional testing is required for longer term environmental exposure, fatigue effects, and local wheel loading on full-scale FRP composite structures and proposed designs. Full-scale experimental validation is required for cyclic loading exceeding 75 million cycles for higher truck traffic conditions. Using FRP composites for bridge designs beyond short spans (31 ft.) is next.



An engineering and systems approach for the use of FRP materials in bridge applications culminated with the opening of Bridge 1-351 in Glasgow, Del., on November 20, 1998. The bridge received the ASCE Delaware section Project of the Year Award.

Appendix

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