STATE OF THE ART OF ADVANCED MATERIALS IN TRANSPORTATION STRUCTURES

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ABSTRACT

Ever so slowly, advanced composite materials are entering the field of traditional civil engineering. This report surveys the current practice and ongoing research into their use in transportation structures. There is a broad spectrum of proposed and applied uses for reinforced plastics, ranging from complete structural systems to the replacement of conventional steel reinforcing or the strengthening and retrofitting of existing superstructures. The impediments to general acceptance of advanced composites include the lack of design standards, the reliance on initial costs in the traditional cost assessment of alternatives, and a lack of awareness that these versatile components and systems can be fabricated and used in construction. Future work at the Virginia Transportation Research Council will include an investigation of the replacement of top reinforcing in bridge decks with reinforced plastics, the use of composites to replace conventional steel stay-in-place forms, and the use of composites in end diaphragms and cross-bracing for bridge framing.

Final Report

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INTRODUCTION

Over the centuries, designers and builders have found ways to take advantage of the unique physical properties of conventional construction materials. Ancient structures used arches to exploit the natural compressive strength of stone and early concrete. The first iron and steel trusses were elegant examples of the relative versatility and fabricability of metals. The forms of modern structures show the evolution of design with concrete and steel. The use of concrete where compressive strength is a priority is often accompanied by steel components that lend their capacity for tension.

Conceptually, there is little difference between steel reinforced concrete and most advanced composite systems. Both are based on the strategic combination of a supporting matrix surrounding a higher strength fiber or bar. The complication when dealing with advanced composites is the nearly unlimited number of possible materials and combinations. Modern composite fabrication techniques permit cross-sections that are impossible with conventional materials. Combine the versatility of fabrication with the numerous options in matrix and fiber constituents, and there is an unlimited array of possibilities.

The many advantages of advanced composite materials for structures and structural systems have now been thoroughly documented. Unfortunately, the advanced materials that have gained broadest acceptance are often very specialized and prohibitively expensive for most civilian-oriented applications, particularly when costs are viewed in the context of the typically larger scale of transportation projects. If composite materials are to become significant in the discipline of civil engineering, it will be through particular applications and will likely incorporate the lower cost materials.

Much of the research relating to advanced composites in transportation structures has focused on the lower cost category of glass fiber reinforced epoxy or polyester matrix materials. These materials are referred to as fiber reinforced plastics (FRP).

Short term behavior, at least for most conventional FRP components, is relatively easy to characterize and has been extensively documented. The long-term, in-service behavior of FRP is much more in question. Perhaps the most intriguing challenge to the composites engineer is matching the unique properties and possible configurations of FRP with the needs of today's civil infrastructure.

PURPOSE AND SCOPE

The accomplishments of academicians studying the capabilities of advanced composite materials are impressive. Often, however, the connection between academic study and practical application is not obvious and the transition from one to the other not graceful. This study evaluated the state-of-the-art in the science and application of advanced composite materials, with a bias toward practical applications. An assessment of real solutions to practical problems was the primary objective.

FRP can be used to improve strength, seismic toughness, and aesthetics, as well as to stop or delay corrosion. This study focuses on the general application of composites and plastics to transportation structures in three areas: 1) the use of total composite structural systems and whole component substitutions for conventional materials, 2) the design and construction of conventional components that incorporate reinforced plastic (primarily, the replacement of conventional rebar and prestressing tendons with FRP in reinforced concrete), and 3) the external reinforcing and encapsulation of conventional structural components.

METHODS

Literature Survey

This state-of-the-art review is based on a comprehensive survey of current relevant literature. The Transportation Research Information Services (TRIS) databases were the starting point. These databases are a collection of abstracts from published articles and reports, including summaries of work in progress. TRIS draws its information from several major sub-files, primarily the Highway Research Information Service (HRIS), the International Road Research Documentation (IRRD), and the Transportation Libraries (TLIB).

The current TRIS databases list approximately 80 abstracts referring to the application of composites to transportation. For the most part, the topics fall within the three categories discussed above. Specific subjects range from the strengthening of beams with fiber composite plates to filament wound light masts and to the development of specifications for the use of composites.

Identify Active Research Programs Using the Internet

Naturally, the bulk of relevant research has been academic. Fortunately, the academic forum enjoys convenient access to modern broad communication mediums such as the Internet. The most active research programs have a presence on the World Wide Web (a fast-growing, multi-media subset of the Internet). Vast amounts of fresh information appear in these sources. Program overviews, project proposals, progress reports, and completed reports are among the materials easily obtained via the Internet.

Conference Proceedings

Because the science is so new and offers so much potential, it is a popular topic for conferences and symposiums. Fortunately, most of these meetings publish proceedings. These proceedings contain many recent studies of design and construction with composite materials. Recent conferences of note include the First International Conference on Advanced Composite Materials in Bridges and Structures (1992), the International Symposium on Fiber-Reinforced-Plastic Reinforcement for Concrete Structures (1993), and the First International Conference on Composites in the Infrastructure (1996).

FINDINGS and DISCUSSION

General Applications

New advanced composite components vary in structural importance from the handrail on top of a parapet wall to complete superstructure systems that replace conventional reinforced concrete decks and steel or concrete girders.

Stay Cables

Stay cables are an area that continues to show promise. In particular, the use of uni-directional carbon fiber reinforced plastic (CFRP) in tension bearing members of large suspension structures has been examined. Among the characteristics that make CFRP particularly suited to stay cables are a very high strength to weight ratio, good fatigue behavior, and extremely low modulus of thermal expansion.[1] The most significant impediment, apart from cost, involves the anchorage systems. Cal State in Long Beach is attempting to address this problem. Their proposal incorporates a link-type FRP anchor.[2] The continuity between the anchor and the load-carrying portion of the cable establishes a bearing stress, avoiding the high shear stresses of the traditional potted-type system.

Deck Panels

Several projects have investigated the use of FRP for bridge deck panels. They offer the obvious advantages of reduced weight, ease and speed of installation, and resistance to corrosion. The researchers at Cal State have actually fabricated and tested a panel. Most other work with deck panel sections has been limited to computer modeling. Examples of those include the earlier work with shape optimization at the University of Virginia[3], and some more recent research with simplified finite element modeling at the University of Illinois.[4]

To date, issues that continue to hamper the practical installation of a FRP bridge deck panel include deck joints, connections, and the fabrication and attachment of crash-worthy parapets. Most of the difficulty with joints will be minimized as pultrusion technology advances to the point where full-width deck sections are produced, thus reducing the number of joints.[5]

Beams/Girders

The combination of conventional materials and advanced composites to produce new structural elements is one of the more interesting fields of contemporary research. For example, one design combines glass fiber reinforced plastic (GFRP), carbon fiber reinforced plastic (CFRP), and conventional concrete to form a box beam.[6] The component starts with a pultruded box section of GFRP. The top portion is shaped to act as form work for a thin conventional concrete slab. This provides an inexpensive medium for compressive forces in the positive moment region of a beam. In the bottom of the section, a thin sheet of CFRP is either pultruded in or bonded on with epoxy. This material, which has a very high tensile capacity, works with the compressive strength of the concrete in the top of the beam to drastically increase the load carrying capacity of the member. The shapes and proportions of the materials can be optimized to take advantage of material strengths and reduce production costs. The optimum combination of materials may also provide an answer to the deflection problem that has always pestered low-modulus FRP composites.

In another example of innovation, researchers at the Georgia Institute of Technology have worked with Morrison Molded Fiberglass (MMFG) to develop a double web I-beam. In addition to the unique cross-section, the flanges are produced from a hybrid carbon and glass system. As in the previous example, the addition of carbon provides significant strength and stiffness to the member in the region of the highest bending stresses. Hybridization in the production of composite materials, that is, the combining of two or more different fiber materials, is a very promising development. Hybridization allows cheaper fiber systems, such as fiberglass, to be combined with high cost fibers such as carbon for enhanced mechanical properties. Thus, not only can a structure be optimally designed, but individual members can be optimized for strength and stiffness.

Handrails

The handrail system is the most susceptible component to corrosion from deicing salts, on many conventional highway bridges. Generally, this part of the parapet system lacks the protection of concrete coverage, and many times is not adequately treated with corrosion inhibitors (galvanizing, painting, etc.). Replacement of original or conventional handrail pipe with composite systems would be more expensive, but in the long run would be cost-effective on structures where salt splash is common.[24]

Access Platforms

Work at Northwestern University [24] identified inspection access systems, such as catwalks and ladders, as a priority for the demonstration of composites. Lightweight, non-corrosive composite walkways, platforms, and ladders may be an ideal solution to the problems often associated with inspecting very large, complicated structures. There are structures that, during original design and construction, have been equipped with such systems. In these cases, the fabrication and attachment issues, not to mention any additional load, were dealt with, if not from conception, at least early in the design process. Many more structures could benefit from fixed, or partially fixed, access systems. Unfortunately, most bridges were not constructed to accept them easily and in many cases are not accessible enough to allow a convenient retrofit to address that shortcoming. Extending the alternatives to include lighter weight composite systems greatly increases the options available. In addition to the reduced weight and increased design flexibility, the resistance to corrosion reduces the additional inspection burden that would accompany most conventional (i.e., steel or timber) alternatives.

All-Composite Bridge Systems

Working models of total composite systems for pedestrian structures are numerous.[7,7,24] Examples of composite bridges built for vehicular traffic, however, are uncommon. Most have been constructed in Europe and the Far East, with very little information widely circulated or available concerning them.[8]

One of the most recent domestic projects was prompted “in response to a need expressed by the Department of Defense (DOD) and the Advanced Research Projects Agency (ARPA) for a government-industry dual-use product development and demonstration strategy”.[9] In this effort, the Lockheed Martin Missiles and Space (LMMS) Research and Development Division demonstrated a quarter-scale model of a short span, all-composite bridge superstructure. The superstructure was manufactured by two local companies in the San Francisco Bay area. One company, a sail boat manufacturer, constructed the u-shaped bottom support beams. The other company fabricated the top sandwich deck plates. The two components were assembled using steel splice plates and fasteners. Most of both components were hand lay-ups. The core of the deck panels was 100mm x 100mm (4”x 4”) pultruded tubes. The final superstructure was 5.8 m wide (18 ft), 9.1 m long (30 ft), and weighed 10,433 kilograms (23,000 lb.). It was proof tested to over 59 tonnes (130,000 lbs). Future work will concentrate on cost reduction. One method will investigate adding stiffness through continuous carbon fibers.

Another project that looks toward the fabrication of all-composite highway bridges is underway at the University of California, San Diego (USCD).[10] This study is part of a cooperative venture with the California Department of Transportation and the Federal Highway Administration. Its intention is also to demonstrate the cost and construction characteristics of complete composite structural systems for highway structures. Their project is focusing on a cable-stayed highway traffic bridge over Interstate 5 in La Jolla. In their design, all components, including the deck, superstructure, pylon, and cables are manufactured using advanced composite materials and automated manufacturing techniques. Currently, their research is looking at two design alternatives. In one, the structure is a mass-manufactured, erector-set type in which components are assembled with adhesives in the field. The second alternative uses segmental construction with transverse joints or continuous in-situ resin transfer molding techniques. Transfer molding is a common technique in the processing of polymer materials. In transfer molding, material is fed into the pot of a mold, heated, and then forced under pressure into an adjoining cavity of the same mold.

Highway Tunnels

To further illustrate the grand schemes that composite researchers and practitioners are pondering, consider the suggestion a few years back that structural composites be applied to establish a fixed transportation link across the Strait of Gibraltar.[11] This proposal stressed the fatigue and fracture resistance of commercial composites, as well as their energy-absorbing and thermal insulative capabilities. These attributes, combined with the material’s light weight, resistance to corrosion, and unique fabricability, make plastic composites ideal for long, underwater highway tunneling. Kaempen presented a detailed discussion of the twined-strand unidirectional (principal fiber orientation in one direction) composites that could be used and proposed high-strength couplers and sealing assemblies that could only be economically feasible with modern commercial composites.

Replacement of Internal Reinforcing

Conventional rebar replacement

In conventionally reinforced concrete bridge decks, the primary distress mechanism typically involves the corrosion of the top layer of steel. A previously referenced survey conducted by the Industrial Research Laboratory (BIRL) at Northwestern University [24] indicated that the bridge deck was the number one priority for bridge maintenance needs, and that deicing salts were far and away the number one enemy of bridges in general. This is particularly pertinent to structures in which the steel is not epoxy-coated or where poor quality concrete results in highly permeable surfaces. Obviously, the corrosion resistance of fiber reinforced plastics make them attractive for this application. In situations where high stiffness is a secondary requirement, such as most top deck steel, research has looked into the use of GFRP reinforcing bars and grid systems as an alternative to steel.[12, 13]

Researchers at Carlton University in Ottawa, Ontario have developed a hybrid composite system reinforcing bar as a potential replacement for traditional steel reinforcing bars. The hybrid material consists of a high strength, high modulus carbon fiber reinforced plastic inner core, with a low modulus, high strength polymeric outer wrap. The resulting hybrid bar matches the stress-strain behavior of traditional carbon steel, thus providing identical ductile behavior when placed in concrete.[14]

Aramid fibers are known for their strength in the longitudinal direction. Kevlar, by DuPont, is one well-known aramid product. Although Kevlar provides considerably less transverse-direction strength, it has been used experimentally as tensile reinforcement in concrete beams. In one reported test application , two very modest sheets of an aramid mesh improved toughness and increased the strength of an otherwise unreinforced beam.[15]

Finally, the use of dowel bars made from composite material in rigid pavements has been reported. Dowels are placed at transverse joints in rigid pavements to insure shear force transfer between adjoining pavement slabs. They are exposed to water and deicing chemicals and are thus very susceptible to corrosion. The corrosion not only leads to dowel bar degradation but also causes the bars to bind, thus restricting thermal movements. In the reported test results, dowels made from GFRP performed as well as those made from steel.[16]

Pre-Stressing Tendons

The use of composites for pre-stressing is probably the most widespread application of reinforced plastics to large, civil-sized structural components. High-strength FRP is especially well suited to pre-stressing applications. Corrosion resistance and light weight are complimenting factors, but perhaps the most unique feature of reinforced plastics that lends them to pre-stressing is their low modulus to strength ratio. Ironically, this characteristic of FRP tends to be a significant impediment in most structural applications. The advantage in pre-stressing involves a combination of the reinforced plastic's large elongation when stressed, with the normal shrinkage associated with curing concrete. The shortening of the stressed FRP tendon, as a result of concrete shrinkage, does not result in the same proportion of stress loss that is generally associated with the equivalent shortening of high-strength steel.

Exterior Strengthening/Retrofit

Beams and Girders

One popular trend in strengthening or repairing existing bridges involves bonding composites to conventional structural elements. The bonding is accomplished by adhesives, mechanical fasteners, or both. A number of research projects have experimented with ultra-thin and lightweight plates applied to aging and damaged beams and girders to either supplement or restore load-carrying capacity. The research done under the direction of Urs Meier at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) provides several examples. Among them is the substitution of carbon fiber-reinforced plastic laminates for steel plates to retrofit the Ibach Bridge near Lucerne.[17, 18] This multi-span box-beamed bridge was the first real structure retrofitted in Switzerland with advanced composite materials. In this example, the original pre-stressing was damaged while mounting some additional traffic control devices. Calculations indicated that steel plates weighing approximately 175 kg would be necessary to restore the load carrying capacity of the structure. As an alternative, it was proposed that an equivalent repair could be made with carbon fiber-reinforced plastic (CFRPs). At the time, the price of CFRP was approximately fifty times more expensive, per kilogram, than the steel typically used to repair structures. However, the 6.2 kg of CFRP necessary was less than 4% of the weight of steel required. Meier also pointed out that often the price of the materials in a situation such as this is only 20% of the total cost of the procedure. The ease of handling the lighter weight material can easily reduce total project costs and make the expensive advanced composite materials very competitive. The repair was ultimately made using three CFRP sheets, two 150 x 5000 x 1.75 mm, and one 150 x 5000 x 2.0 mm.

EMPA has also performed a similar retrofit to a wooden structure. In 1992, shortly after completing the Ibach bridge repair, they participated in the retrofit of an 185-year-old covered timber bridge.[18] In addition to the pre-stressed bonded wooden planks used to improve the load-carrying capacity of the deck, EMPA used CFRP epoxy resin sheets to strengthen two of the most highly loaded cross-beams. Very thin but very stiff CFRP sheets were able to improve the strength of the bridge with minimal detraction from the aesthetic or historical value of the structure.

Column Wraps

The traditional means of retrofitting a damaged or brittle column has been the use of steel jackets. More recently developed systems have applied advanced composites to add strength and ductility to existing columns. The system developed in a joint effort between Fyfe Associates and Hexcel Corporation [19] wraps columns in either glass or carbon reinforced polymer impregnated sheets. The composite material wrap offers several advantages. It is less labor and equipment intensive and can be field cut to fit any existing cross section and length. With a coating of ultra-violet inhibitor paint, colored to look like concrete, the composite wrap column is much more aesthetic than the traditional jackets.

The principal application of column wrapping has been in the retrofitting of existing structures identified as vulnerable to seismic activity. California DOT (CALTRANS) has been the leader in this application. However, Nevada, Washington, and Pennsylvania have all initiated at least one project to retrofit an existing highway structure because of its seismic vulnerability. The 1994 Northridge Earthquake in California demonstrated the effectiveness of the composite wrap system. Fifteen wrapped columns in a major interchange in the Los Angeles area survived this magnitude 6.8 event without serious damage.[19]

Other applications for the composite wrap system have surfaced. Wisconsin DOT has used the system to repair concrete columns damaged from exposure to de-icing chemicals and cycles of freezing and thawing. Many concrete structures have been constructed with aggregates that react with the cement alkalis, resulting in alkali-silica reactivity (ASR). ASR leads to accelerated deterioration, both within the concrete itself, and through exposing the reinforcing steel to chloride attack. Several states have used the column wrap system to hold ASR-damaged columns together as a strengthening mechanism. Additionally, the FRP wrap has been used to minimize the infiltration of water, a catalyst for ASR, into the damaged column. Traditionally, badly damaged concrete columns are subjected to a costly and time-consuming full-depth removal and replacement of material.[19] In Virginia, a series of bridge columns were retrofitted with the composite wrap after a 500-year flood event. The flood caused damage to the upstream structure carrying Route 29 over the Rappahannock River in Madison County. The bridge was closed for a period of time to assess and repair the damage. The columns were found to have suffered cracking and some loss in material. It was decided to first repair the columns by conventional means. The composite wrap system was employed as a preventive maintenance measure.

In terms of the general application of advanced composites to strengthen and retrofit existing structures, a recently initiated study from the U.S. Army Construction Engineering Research Laboratories and the Composites Institute of the Society of Plastics Industry, Inc.[20] is particularly relevant. In this cooperative venture, they proposed to develop fiber reinforced polymer systems specifically for the repair and strengthening of in-place concrete columns, beams and decking. The study will look at glass, aramid, and carbon fiber reinforcing. The intended products will include material specifications, design protocols and standards for each of the developed systems. Ultimately, the project will demonstrate each of the systems actually applied to civil engineering structures.

Construction Applications

One promising scheme for gently introducing composites into traditional civil engineering construction may involve the construction process itself. A recent emphasis in

Japan towards streamlined construction and reduced environmental threats has led to the testing of permanent concrete forms that incorporate high-strength FRP reinforcement.[21] These forms are constructed of panels that incorporate 3-directional aramid fiber mesh for reinforcement and high-strength mortar as the supporting matrix. Successful life-size tests of these high-tech forms have been conducted.

Additionally, stay-in-place forms made of GFRP to replace galvanized steel forms are being considered.[22] Stay-in-place construction, using galvanized steel forms, has become a well accepted construction practice for concrete bridge decks. However, recently there are reports of the forms corroding to the point where they have fallen completely out of the structure, creating a road hazard if the bridge is over another roadway.

For now, plastic concrete column forms are also available.[22] The advantages of these polyurethane forms include reduced operator and equipment involvement, simplified form cleanup and repair, and easier (outside) storage without rusting.

Active Research Projects

In addition to the continued research programs discussed previously, several recently initiated projects are being conducted around the country. For bridges, the recent Fourth National Workshop on Bridge Research in Progress[23] lists some examples:

- The University of California, San Diego, is continuing the development of FRP composite bridge decks. They have also begun to look at carbon shell/tube systems that are filled on-site, either partially or fully, and used as arch and truss components for bridges. Finally, their work includes a continued study of the performance of advanced composite cable stay anchor systems.
- Researchers at the University of Windsor, in Ontario, Canada, are conducting tests on a pre-cast concrete bridge system that uses glass and carbon-fiber reinforced bars and cables as reinforcing. This work is in preparation for an actual composite pre-stressed highway bridge for the City of Southfield, Michigan.
- The Florida Department of Transportation and the University of Central Florida are involved in a very interesting study of an FRP-encased bridge pier column. In this unique assemblage, the encasing system not only acts as the pour form, but also serves as a protective jacket and confining mechanism, and may even replace conventional internal reinforcement.
- The University of Texas at Austin is working to optimize the design of a bridge deck railing system that incorporates pultruded glass FRP. The designs have targeted bridges on secondary roads. As is typically the case with GFRP, deflection criteria are proving to be the limiting constraint.

Although not listed in the aforementioned proceedings, research at West Virginia University's Constructed Facilities Laboratory should be noted. They are currently working on the development of the necessary data for the design of structures with FRP structural shapes. They are also investigating the use of composite materials to replace steel reinforcing in bridge decks. WVU has recently initiated a study of the applicability of composite materials to replace steel bars used in the post-tensioning of timber bridge deck systems as well in the use of composite sheets sandwiched between timber planks to form a hybrid bridge girder.

CONCLUSIONS

Research like that done at BIRL[24] suggests that there are four needs that should be addressed with composites. They are: 1) corrosion mitigation, 2) reinforcement of degraded bridge components, 3) seismic protection, and 4) low-cost erection/maintenance.

If advanced composites are to be implemented, a number of changes in conventional thinking will have to take place:

1. Design standards will have to be developed **and accepted** by the traditional engineer for the design and construction of transportation-related structures using composite materials.
2. Current methods of economically assessing a construction, rehabilitation, or repair alternative will need to evolve to allow engineers to consider life cycle costs. It is unlikely that, using first costs alone, advanced composites will compete very well with traditional materials, at least in the near term.
3. An increased emphasis on *constructability* and *fabricability* of designs. Reduced weight, toughness, ductility, and corrosion resistance means that composites can enjoy greater flexibility in construction. Combined with the variety of sections and shapes possible, an immeasurable variety of design/construction scenarios can be explored.

RECOMMENDATIONS

Many of the most impressive feats of engineering are performed during the construction process. Often, the true extremes of structural and environmental stress and strain are experienced midway through a project. In that sense, the greatest benefit from the combination of strength, stiffness, light weight, and corrosion resistance may very well come prior to the completion of a structure. Perhaps one angle on the introduction of FRP and other advanced materials to conventional civil engineering should incorporate the construction process.[25] For example, temporary walkways, scaffolding, shoring, temporary form work and sheet-piling may all present opportunities. The use of rigid CFRP systems for crane masts and aramid and flexible carbon fiber composites for cabling may represent an application to construction equipment in which the significantly higher first costs would be offset by easier assembly and longer fatigue lives.

Based on this research, the Research Council has recommended that the Virginia Department of Transportation (VDOT) pursue the use of composite materials in three areas. The Council has formed a partnership with researchers at the Virginia Polytechnic Institute (Virginia Tech) and Morrison Molded Fiberglass and is seeking FHWA funding to support a research project on the use of composite materials to replace top steel reinforcing in bridge decks. Funding is also being sought to replace cold-formed steel stay-in-place forms used in deck construction with forms fabricated from composite materials. This proposal is also seeking to study the applicability of parapets cast with no conventional steel reinforcing but with stay-in-place forms made from composite materials. Finally, it has been proposed to investigate the use of end diaphragms and cross-bracing made from composite materials as a replacement for those fabricated from steel.

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