THE USE OF POLYMER COMPOSITES IN CONSTRUCTION

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Abstract

The construction sector is one of the world's largest consumers of polymer composites. Unreinforced polymer composite materials have been used by the construction industry for many years in non-load bearing applications such as trimmings, kitchenware, vanities and cladding. In the last decade there has been a concerted effort to migrate reinforced polymer composites (RPCs) into the construction industry for use in primary load bearing applications. Potential advantages commonly expounded by proponents of RPC materials include high specific strength, high specific stiffness, tailorable durability, good fatigue performance, versatile fabrication and lower maintenance costs. As a result reinforced polymer composites are being investigated in applications such as rehabilitation and retrofit, alternative reinforcement for concrete and, in rare cases, entire fibre composite structures. However, to date the number of primary structural applications of RPCs in construction remains relatively low and there appears to be a number of issues contributing to their slow uptake by the construction industry. Issues such as cost, absence of design codes, lack of industry standardisation, poor understanding of construction issues by composites industry, lack of designers experienced with polymer composite materials and civil/building construction are commonly claimed to place these materials at a disadvantage when considered against traditional construction materials. However, this paper proposes that as issues of sustainability become increasingly important to material choice, some fibre composite materials could be at an advantage over traditional materials.

Keywords: polymer composites, fibre composites, natural fibre composites, bio-composites, construction materials, advanced materials, reinforced plastics, civil structures.

1 Introduction

Composite materials combine and maintain two or more distinct phases to produce a material that has properties far superior than either of the base materials. Composite materials have been used in construction for thousands of years. Straw has been used to reinforce bricks for over 2000 years and this method is still used today. There is also evidence of the use of metal to reinforce the tension face of concrete beams in Greece nearly 1000 years ago.

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Polymer composites are multi-phase materials produced by combining polymer resins such as polyester, vinylester and epoxy, with fillers and reinforcing fibres to produce a bulk material with properties better than those of the individual base materials. Fillers are often used to provide bulk to the material, reduce cost, lower bulk density or to produce aesthetic features. Fibres are used to reinforce the polymer and improve mechanical properties such as stiffness and strength. High strength fibres of glass, aramid and carbon are used as the primary means of carrying load, while the polymer resin protects the fibres and binds them into a cohesive structural unit. These are commonly called fibre composite materials.

Polymer composites have enjoyed widespread use in the construction industry for many years in non-critical applications such as baths and vanities, cladding, decoration and finishing. In 1999, the construction sector was the world's second largest consumer of polymer composites representing 35% of the global market [1]. In recent times fibre composite materials have been increasingly considered for structural load bearing applications by the construction industry and have established themselves as a viable and competitive option for rehabilitation and retrofit of existing civil structures, as a replacement for steel in reinforced concrete and to a lesser extent new civil structures.

2 Uses of fibre composite materials in construction

Although the use of structural fibre composites in critical load-bearing applications is relatively rare one of its most common uses in the construction industry is repair of existing structures. The material is also used as a replacement for steel in reinforced and stressed concrete and in very rare cases to produce new civil structures almost entirely out of fibre composites.

2.2 Rehabilitation and retrofit

The widespread deterioration of infrastructure in Canada, the USA and Europe is well documented [2]. The estimated cost to rehabilitate and retrofit existing infrastructure worldwide is around (Canadian) $900B [3]. In Australia it is estimated that $500M per annum is required to repair and upgrade concrete structures [4].

Some traditional rehabilitation and retrofit methods use concrete or external steel sheets to re-introduce or improve structure properties such as strength and ductility. The ability of concrete to form complex shapes and its suitability to submerged installation has seen it used for encapsulation of elements such as bridge piers [5]. Steel can be bonded or bolted to deteriorated concrete structures to provide strength and stiffness improvements with relatively little additional weight. In the last decade the number of instances of fibre composites used as a surface layer that either protects and/or improves on the response of the encapsulated element has been increasing. In these cases the materials are usually bonded externally to the structure in the form of tows (fibre bundles), fabrics, plates, strips and jackets. The advantages offered by composites in these forms include their ability to bond well to many substrate materials and to follow complex shapes. Composites also offer a potential benefit over isotropic retrofit materials, such as steel, by allowing enhancement of strength without increasing stiffness and vice versa.

2.3 Concrete structures reinforced with fibre composites

Concrete reinforced with fibre reinforced polymer (FRP) materials has been under investigation since the 1960's. Unstressed FRP reinforcement has been developed in a number of forms including ribbed FRP rod similar in appearance to deformed steel reinforcing bar, undeformed E-glass and carbon fibre bar bound with polyester, vinylester or epoxy resin, E-glass mesh made from flat FRP bars and prefabricated reinforcing cages using flat bars and box sections [6]. Stressed FRP reinforcement is also available, usually consisting of bundles of rods or strands of fibre-reinforced polymer running parallel to the axis of the tendon. These are used in a similar fashion to conventional steel tendons [7].

The durability performance of FRP reinforcements is considered by some [6, 8] to offer a possible solution to the problem of corrosion of steel reinforcement, a primary factor in reduced durability of concrete structures. Other reported advantages of FRP rebar include enhanced erection and handling speeds [9] and suitability to applications which are sensitive to materials which impede radiowave propagation and disturb electromagnetic fields.

2.4 New fibre composite civil structures

A small number of new load bearing civil engineering structures have been made predominantly from FRP materials over the last three decades. These include compound curved roofs [10] pedestrian and vehicle bridges and bridge decks [11], energy absorbing roadside guardrails [12], building systems, modular rooftop cooling towers [13], access platforms for industrial, chemical and offshore [14], electricity transmission towers, power poles, power pole cross-arms and light poles and marine structures such as seawalls and fenders [1].

The potential benefits offered by fibre composites include high specific strength and specific stiffness, tailorable durability, good fatigue performance and the potential to reduce long-term costs. However, in many cases these potential benefits are difficult to realise and are sometimes based on specious fact and irrelevant data. In addition to this, the lack of bona-fide applications has caused many constructors to be sceptical of the material's ability to provide a viable alternative to traditional materials. Many of the existing applications are experimental in nature and are aimed at demonstrating the ability of fibre composite materials to perform in certain applications. To this end they may be successful in terms of structural performance, but offer little by way of meaningful financial performance data.

3 Issues slowing the adoption of fibre composite materials in construction

There is little doubt that fibre composite materials are structurally capable, however their ingress into the construction industry has been slow to date. Literature suggests a number of reasons for this. Issues of cost, structural performance and durability are discussed below.

3.1 Cost

Cost can be considered in terms of short-term costs, such as design, construction and installation, and long-term costs such as maintenance, modification, deconstruction and disposal. These can be further grouped into direct costs, such as materials and production, and indirect costs, such as interruptions to traffic, depreciation, resale value and impact on the environment. Difficulties can arise in determination of the lowest cost of competing solutions when interested parties place different levels of importance on these different types of cost.

3.1.1 Short term costs of fibre composites

Currently, fibre composite materials are expensive when compared to conventional construction materials on an initial cost basis. There are a number of factors contributing to the high cost of composite materials including; high cost of raw materials and processing, the use of imported materials, the general acceptance of high prices in markets such as marine and aerospace and occasional low availability of material [15].

In line with the evolution of other composites uses, such as sporting equipment, some researchers believe it is likely that production volume increases resulting from the use of fibre composites in civil engineering applications will lead to decreased cost of materials [16]. However, locally this may be an optimistic outlook as the majority of fibre composites materials used in Australia are imported and are therefore subject to a range of international economic variables such as fluctuations in overseas production costs, transport and import costs and fluctuations in the exchange rate between Australia and countries such as Europe, United States and Japan, which supply us with carbon, aramid, E-glass fibres and many resins. When this is considered in conjunction with the tendency of suppliers to provide price reductions based on quantity purchased, accurate costing of an FRP construction project can seem difficult and suggest that it could be some time before anticipated price drops could significantly influence project cost.

3.1.2 Fabrication cost

In addition to relatively high material costs, the short-term cost of FRP materials is dependant on fabrication. Most fibre composite manufacturing techniques were originally developed for the aircraft, marine and/or car industry. The construction industry is vastly different to these, as constructors tend to be concerned with the design and construction of rather large-scale structures. Also, design specifications usually differ from project to project and therefore very little duplication of design solutions occurs. As a result most construction projects tend to be ‘one-off’ jobs. This situation is in contrast with the manufacturing industries, where mass production of one design solution is common. As a result, design and manufacturing methods that are highly successful in the manufacturing industry are often not viable in civil engineering.

Some short-term costs, such as transport and erection may benefit from production of large, lightweight, modular components. Lower weight can translate into reduced transport and cranage costs, while the use of fewer large modular components can reduce erection time. Meier [17] points out that although it is difficult to quantify indirect savings, they have a cost that is present. He believes that savings can be accrued at the systems level due to faster construction thereby causing less distress and disruption to the community, lower dead weight requiring smaller and lighter substructure as well as lighter construction equipment. Others, such as Shapira et al [18] and Ehlen [19], claim that road closure in busy areas, traffic congestion, detours, environmental costs, administrative costs, downtime in industrial applications, and reduced maintenance can represent substantial benefits.

3.1.3 Costing of fibre composite materials

Techniques used to cost civil infrastructure projects can vary from project to project depending on individual circumstances. Often times, parties with financial interests in building projects will base cost decisions on the initial cost of the structure. This is primarily due to project budget limits and the tendency for the owner to be more concerned with obtaining the best structure possible for their money and less concerned with its long-term performance.

Two techniques claim to consider most of the critical issues in the application of composites in civil applications. The first has been developed by El-Mikawi and Mosallam [20] and uses the Analytical Hierarchy Process (AHP) to provide various levels of focus to evaluate options for project needs, management, manufacture and maintenance. However, their method does not allow comparison of tangible and non-tangible factors, such as impact on amenity, or cost/benefit analysis of the options important in a realistic evaluation of composite materials. The second approach is known as the Whole Of Life (WOL) approach [16], which is derived from lifecycle costing. WOL costing appears to be more comprehensive and includes initial cost, maintenance cost, operating cost, replacement and refurbishment costs, retirement and disposal costs and other costs such as taxes, depreciation and additional management costs. Ongoing costs are allocated a value based on the expected lifespan of the building. This method could be used to compare, in economic terms, the advantages of new and existing materials in structures which are designed to equal performance criteria such as minimum service life, strength and stiffness.

3.2 Structural performance

3.2.1 Specific strength and specific stiffness

Fibre composite materials are often claimed to offer potential benefits to construction projects through high specific stiffness and high specific strength. This is primarily based on the ability of materials that possess high specific strength and high specific stiffness to produce structures with low self-weight in some applications. The potential benefits arising from low structure weight include the freedom to produce larger structures, larger components in the factory, reduced transport and erection costs and reduced size of substructure and foundations.

Judicious use of some fibre composite materials instead of traditional construction materials could potentially produce a lighter structure and lead to a number of cost savings, but these may be difficult to realise. Currently a proprietary FRP bridge deck can cost as much as ten times that of traditional precast concrete planks for a single span two-lane road bridge. The use of a lighter deck could result in transport costs decreasing by as much as 75%. However, the saving would probably amount to a few thousand dollars for installations close to the point of manufacture. Small cost savings may also be made through reduction in lifting costs and savings on concrete substructure, although these would not be considered significant in most cases.

3.2.2 Low stiffness

Civil structures are commonly governed by stiffness performance and the use of materials with low gross elastic moduli, such as FRP materials, can cause these structures to become significantly over-designed for strength, making them economically uncompetitive. Whilst reasonably stiff laminates can be produced using carbon fibres, they tend to be expensive and have a lower failure strain which limits their usefulness. As reinforcing fibres evolve it is possible that higher modulus laminates will be produced at a lower cost and which won't require expensive consolidation techniques to increase fibre volume fraction to give higher gross moduli.

3.2.3 Tailorable mechanical properties

It is often claimed that fibre composite materials offer designers of civil structures increased versatility over traditional materials through freedom to engineer the material as part of the design process. This may be achieved by varying the type of fibre and resin and the orientation and location of reinforcing fibres to produce structures with a combination of performance characteristics such as strength, stiffness, durability, impact and fatigue well suited to a particular application, potentially using material more efficiently.

But this level of tailorability in fibre composite materials requires a fabrication process that allows localised variations of laminate composition. This tends to preclude the use of some automated procedures, such as pultrusion, which allows some variation in reinforcing fibre type on a ply-by-ply basis, but it does not allow variation in resin composition or localised changes in laminate layup.

3.3 Durability

Enviro-mechanical durability is often cited as a key advantage of FRP composites materials over traditional materials [21]. The large range of constituent materials potentially allows design of a material which exhibits very good resistance to long-term deficiencies which can result from environmental influence of moisture, ultraviolet radiation, chemical attack, dynamic loading, freeze thaw cycles and deterioration of material properties through physical aging.

However, fibre composites have been used in civil engineering applications for a relatively short period of time and full understanding of their durability is yet to be achieved. Liao [22] showed that substantial consideration has been afforded to the durability of FRP composite materials in infrastructure applications. However Karbhari [23] identified a lack of long-term data relevant to civil structures with a service life of 75 – 100 years. An international study undertaken by the Civil Engineering Research Fund (CERF) to bridge gaps in long-term durability data related to civil engineering applications identified areas which are lacking such as; moisture effects, alkaline solution, fatigue, creep and physical degradation [24].

4 A long-term view

Although an enormous effort is underway to migrate fibre composite materials to construction applications they appear to be struggling to compete with traditional construction materials. However, some fibre composite materials may be preferred over traditional construction materials as environmental sustainability becomes more important in the long-term.

The "long-term" could be more than fifty years if steel and reinforced concrete are any indication of the construction industry's attitude towards new materials. This would provide a significant amount of time for issues of environmental sustainability in construction to mature and is likely to see a change in the criteria with which evaluation of material options is undertaken. It is likely that material choice will become more focussed on environmental issues such as reduced use of non-renewable natural resources and lower embodied energy.

This trend towards increased environmental responsibility for materials is already occurring in other industries. For example, the European automobile industry is taking steps towards adoption of a "cradle to the grave" (or the "cradle to the cradle" if materials are recycled) philosophy for material use [25]. It is not unreasonable to suggest that a similar model could be developed for the construction industry. If such as model were to be adopted then much more emphasis would need to be placed on the use of materials which do not use non-renewable natural resources and which are recyclable or biodegradable.

In terms of construction material choice, the “green” requirements would be in addition to practical material characteristics such as stiffness, strength, affordability, durability, versatility and easy of use. Our three traditional construction materials each possess some of these characteristics, but none possess all. The ultimate goal would be to develop a material that not only possesses the basic requirements of construction materials, but also the characteristics of an environmentally sustainable material. Composite materials may offer a solution. Their unique tailorability allows virtually any combination of properties, but the cost of this versatility is high. However, of significantly greater concern is that the current range of materials can not be considered environmentally sustainable, despite some claims by the composite industry to the contrary. For example, the production of reinforcing fibres such as glass, carbon and aramid, requires an enormous amount of energy and, in the case of glass is derived from a non-renewable resource. Resins are sometimes claimed to be more environmentally friendly than materials such as metal because they are derived from by-products of the petroleum industry. However, the petroleum industry itself is not sustainable. Similarly some filler materials used to provide bulk to some resin systems are derived from the waste of coal-fired power stations; this industry may not be sustainable in the long term due to public awareness of pollution despite vast coal reserves.

A feature of composite materials is their ability to combine two or more basic constituents to produce a bulk material with characteristics improved over the base materials. This may allow a suitable construction material to be produced from basic materials that are environmentally sustainable. Bio-composites, or bio-fibres, is not a new concept; natural fibres such as linen, cotton, hemp and straw have been used as reinforcing materials for many years. On the other hand, natural matrix materials with suitable properties may present more of a challenge. A small number of natural resin products are available, such as rubber, plant resin, and animal glues. However these generally lack the processing and performance characteristics sought after in a matrix resin.

This is not to say that the effort spent on development of current fibre composite technology is being wasted. On the contrary, it will be critical to facilitate the migration to “bio-composites” technology in the future. Methods, systems and standards need to be developed which are generally applicable to fibre composite materials in the construction industry and which will be applicable to new types of fibre composite materials as they become available.

By the time that natural materials and associated design methods are sufficiently mature to allow their widespread use, issues related to construction material sustainability are likely to have become paramount in material choice. The coincidence of these three factors could see natural composite materials at a distinct advantage over traditional materials.

There is a significant research effort underway to develop natural materials and explore their use in construction applications. This research needs to continue in conjunction with development of conventional composite materials in order to provide a solution in the future which will allow wider use of the natural composite materials by the construction industry.

References

[1] Weaver, A., 1999, "Composites: Worldwide Markets and Opportunities", Materials Today, Available March 2003: http://www.materialstoday.com/

[2] Karbhari, V. M., Zhao, L., 2000, "The Use of Composites for Twenty-First Century Civil Infrastructure", Fibre Composites: Who Needs Them?, A Workshop for Civil and Structural Engineers, University of Southern Queensland, Australia

[3] ISIS Canada, 1998, ISIS Annual Report 1997/1998, The University of Manitoba, Canada

[4] Oehlers, D. J., 2000, "Development of Design Rules for Retrofitting by Adhesive Bonding or Bolting Either FRP or Steel Plates to RC beams in Bridges and Buildings", ACUN2, UNSW, Australia

[5] Carse, A., 1997, "The Asset Management of a Long Bridge Structure Affected by Alkali-Silica Reaction", Proceedings of Concrete '97 Conference, Concrete Institute of Australia, Adelaide

[6] Gowripalan N., 1999, "Fibre reinforced Polymer (FRP) Applications for Prestressed Concrete Bridges", Proceedings of ACUN 1 Conference Composites: Innovations and Structural Applications, UNSW, Australia

[7] Gowripolan, N., 2000, "Design Considerations for Prestressed Concrete Beams with Fibre Reinforced Polymer (FRP) Tendons", Fibre Composites: Who Needs Them?, A Workshop for Civil and Structural Engineers, University of Southern Queensland, Australia

[8] Ko, K., et al, 1997, "Fibre Architecture Based Design of Ductile Composite Rebar for Concrete Structures", Proceedings of ICCM-11: International Conference on Composite Materials, Australian Composites Structures Society, Australia.

[9] Karbhari, V. M., et al, 1999, "Structural Characterization of Fiber-Reinforced Composite Short- and Medium-Span Bridge Systems", Developments In Design Standards, CRC-ACS, Australia

[10] Hollaway, L., 2002, "The Development and the Future of Advanced Polymer Composites in the Civil Infrastructure", Proceedings of the International Conference on Advanced Composites in Construction, University of Southampton, Available November 2002:
http://www.cosacnet.soton.ac.uk/ACIC2002/Monday/m0930Hollaway.pdf

[11] FHWA, "Fibre Reinforced Polymer Composites Bridge Technology", US Department of Transport Federal Hyway Administration, Available March 2002:
http://www.fhwa.dot.gov/bridge/frp/index.htm

[12] Bank, L.C. and Gentry, T. R., 2000, "Composite Materials for Roadside Safety Structures", Proceedings of ACUN-II International Composites Conference, University of New South Wales, Australia

[13] Barbero, E., GangaRao, H.V.S., 1991, "Structural Applications of Composites in Infrastructure", SAMPE Journal, Vol 27, No 6, SAMPE, USA.

[14] Hale, J. M., 1997, "Strength Reduction of GRP Composites Exposed to High Temperature Marine Environments", Proceedings of ICCM11 International Conference on Composite Materials, Australian Composites Structures Society, Australia

[15] Goldstien, H., 1996, "Catching up with Composites", Civil Engineer, March, p47, ASCE, New York
[16] Hastak, M., Halpin, D. W., 2000, "Assessment of Life-cycle Benefit-cost of Composites in Construction", Journal of Composites for Construction, Vol 4 No.3, August, ASCE, USA
[17] Meier, U., 2000, "State of the Practice of advanced composite materials in structural engineering in Europe with emphasis on transportation", Proceedings of ACUN-II International Composites Conference, University of New South Wales, Australia
[18] Shapira, A., et al, 1997, "Constructability and Economics of FRP Reinforcement Cages for Concrete Beams", Journal of Composites for Construction, Vol 1 No. 3, August, ASCE, USA
[19] Ehlen, M., 1999, "Life-Cycle Costs of Fibre–Reinforced-Polymer Bridge Decks", Journal of Materials in Civil Engineering, August.
[20] El-Mikawi, M., Mosallam, A.S., 1996, "A Methodology for Evaluation of the use of Advanced Composite in Structural Civil Engineering Applications", Composites, Oxford , UK Vol 27 Issue 3.
[21] Hayes, M. D., et al, 2000, "Laboratory and Field Testing of Composite Bridge Superstructure", Journal of Composites for Construction, Vol 4 No.3, August, ASCE, USA
[22] Liao, K., et al, 1998, "Long-term Durability of Fiber-Reinforced Polymer-Matrix Composite Materials for Infrastructure Applications: A Review", Journal of Advanced Materials, Issue 4, Society for the Advancement of Material and Process Engineering, USA
[23] Karbhari V.M. and Zhang S., 1999, "Durability of Fibre Reinforced Composites in Civil Infrastructure – Issues, Results and Implications", Developments in Design Standards for Advanced Composites in Infrastructure Applications, CRC-ACS, Australia
[24] Karbhari V., et al, 2001, "Gap Analysis for Durability of Fibre Reinforced Polymer Composites in Civil Infrastructure", CERF, ASCE
[25] Verband Der Automobilindustrie, 2003, Available March 2003: http://www.vda.de/en/vda/intern/organisation/abteilungen/umwelt_02.html