FIBRE COMPOSITES IN INFRASTRUCTURE-APPLICATIONS AND ISSUES

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Abstract

Advanced fibre composites have had significant impact in recent years into a number of industries including aerospace, marine, recreation, and automotive. The reason for the increasing prominence of these materials vary in specifics, but essentially relate to the ability of these materials to be tailored to suit particular environments and structural forms, or functional requirements in different ways compared with conventional materials. There is increasing interest in the use of these materials in Civil Infrastructure, and Fibre Composite Design and Development (FCDD) is a leader in this field, both in Australia, and internationally. FCDD has recently been involved in a number of projects (including the development of Australia's first fibre composite bridge) that illustrate practical applications of the technology, and the issues associated with making available commercial products for asset owners. This paper provides an overview of these activities and discusses the medium term directions for this emerging industry in Australia.

Key Words: Fibre Composites, Beams, Bridges, Trusses, Railway Sleepers

Introduction

Advanced fibre composites were originally developed in the aerospace and marine industries, but have been gaining acceptance in other industries such as recreation, and automotive, and more recently in Civil Infrastructure.

Fibre composites can make available characteristics and performance outcomes that are either difficult or impossible to achieve with more conventional materials such as timber reinforced concrete and steel. However it is important to view composites as an alternative that extends and develops new options, rather than viewing them as a competitor of more conventional materials. Fibre composites are often more expensive than conventional materials when used as a direct substitutes. More economical solutions can be developed when fibre composites are used in combination with traditional materials. Thus the focus needs to be on the development of more optimised and higher performance systems using the right materials in the right applications, rather than engaging in competition between materials (all of which have their limitations). A focussed systems approach can deliver better products.

The University of Southern Queensland's Fibre Composite Design and Development (FCDD) is a leader in this field, both in Australia, and internationally. FCDD has involved in a number of projects that illustrate practical applications of the technology. These show the issues associated with making commercial products available and indicate how astute use of materials can contribute to environmental and economical sustainability.

This paper provides an overview of these projects and discusses the medium term directions for this emerging industry in Australia.

Drivers for composite structures

Fibre composite structures have made significant impacts in aerospace and marine industries primarily because of their superior properties. In those cases the combinations of high performance, light weigh and corrosion resistance have driven developments. In addition the structure of those industries is such that a single organisation conceives, develops and markets products for specific applications. The cost and performance trade-offs required during product development can be made based on a very focussed understanding of product requirements.

Fibre composite materials themselves are more complex systems than conventional civil engineering materials, and realisation of their performance advantages requires quite involved materials and structural engineering. This tends not to be a barrier in the aerospace and marine industries because the engineering input can be made proprietary to protect investments. Specific instructions regarding the use and maintenance of products can also be supplied with the product, so that risks associated with the product life cycle can be clearly articulated and apportioned. The structure of the Civil Infrastructure Industry is not conducive to this approach.

Civil Infrastructure is delivered and maintained through a range of specialised organisations, and strong conventions are in place regarding the distribution of risk and responsibility for delivery. This structure will be a barrier to the introduction of composites because of the complexity of the materials themselves. It will take some time for the necessary systems and procedures to develop to allow composite components to be processed in the same way as other materials for Civil Infrastructure. In the mean time, pre-engineered proprietary systems are likely to be the main means for introducing composites to civil infrastructure.

The main drivers for composites in Civil Infrastructure are cases where there is an advantage in obtaining a product with:

- Light weight;
- Fast installation;
- Corrosion resistance;

Under these circumstances the additional material cost of composites compared with conventional materials is off-set by the costs associated with the above issues.

In the Australian environment, there is a strong additional driver for the development of composites. Australian hardwoods are an excellent engineering material and have been used in a wide range of applications including bridge components, piles, railway sleepers and as structural building elements. However the quality and availability of hardwood components is declining while the cost is increasing. Hence there is increasing demand for a range of alternative engineered products to fill demand for unavailable hardwood. Composites are being increasingly considered as an alternative in many of these applications, and they offer a range of advantages (even over their hardwood predecessors) including significantly reducing the demand on Australia’s native hardwood forests.

The reason for the increasing prominence of these materials relate to the ability of these materials to be tailored to suit particular environments and structural forms, or functional requirements in different ways compared with conventional materials. The examples discussed briefly in this paper illustrate some of the issues associated with using composites in civil infrastructure.

Bridges

Numerous large-scale demonstration projects around the world have shown that composites are viable structural materials for bridge applications [Brailsford *et al*, 1995, GangaRao *et al*, 1999]. The Department of Main Roads (Queensland), and the Roads and Traffic Authority of NSW (RTA) expressed interest in the deck unit bridge concept developed at USQ’s Fibre Composite Design and Development (FCDD). Wagners Composite Fibre Technologies (CFT) obtained funds from AusIndustry under the START programme to develop the bridge concept in conjunction with FCDD to proof of concept stage.

A convenient way of explaining the structural behaviour of this hybrid structure is to consider it a development from conventional reinforced concrete (Figure 2).

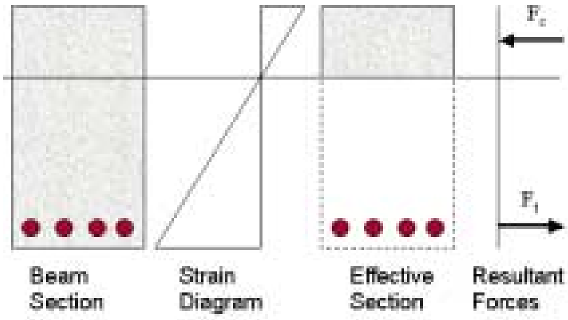
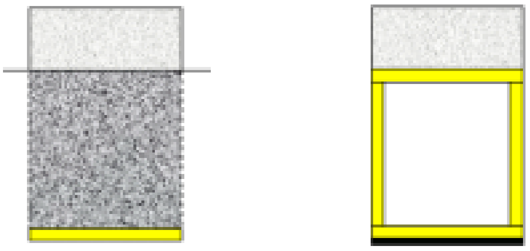


Figure 1 Reinforced concrete beam concept

The main load carrying elements of the beam consist of the concrete compression zone (approximately 20-25% of the cross section) and the steel reinforcement. The two main disadvantages of reinforced concrete beams are the potential corrosion of the reinforcement and the high self weight.

The concept of the new hybrid beam is shown on Figure 2. The compression zone remains as with normal reinforced concrete. A continuous tensile flange can be easily positioned using a single or double web as is common for steel beam cross sections (Figure 2a). By orientating the fibres in the web members at +45° and -45° the webs are ideally suited to carry the shear forces in the beam (Figure 2b).



(a) (b)

Figure 2 Transition to new beam concept

In this approach, the FRP top flange has been designed to carry significant compressive loads. As a result the cross section reduces to an FRP box section after crushing of the concrete. By ensuring that the ultimate load carrying capacity of the box section exceeds the crushing load of the concrete flange by a safe margin, a very ductile behaviour is obtained. Due to the low stiffness of the FRP box section in comparison to the hybrid section, large deflections will occur prior to ultimate failure. The combined compression capacity of the FRP top flange and the post failure strength of the concrete, enable the beam to carry significant additional load after initial failure of the concrete (Figure 3).

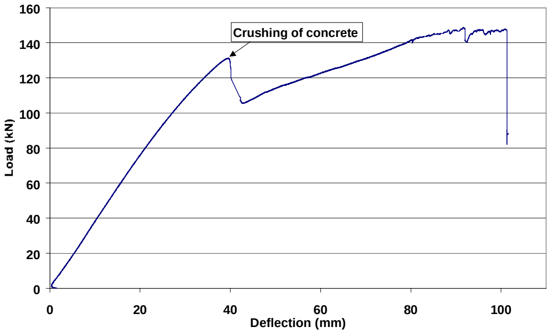


Figure 3 Load-displacement behaviour of 3m test beam

The design for the prototype bridge was governed by the deflection requirement of less than span/500 under serviceability traffic loading. This resulted in considerable excess strength in the beam. The serviceability traffic moment for each beam is 65kNm, while the design moment capacity of the beam at initial failure of the concrete is in excess of 550kNm (at a theoretical deflection of 160mm). The residual composite box section left after compression failure of the concrete has an ultimate design moment capacity of almost 700kNm, at a deflection of approximately 550mm. A prototype test beam (Figure 4) was constructed to prove the full scale beam concept prior to construction of the bridge.

Trucks in excess of three times the legal limit have been detected on roads in remote parts of Australia. To replicate the effects of these extreme loads on the test beam, a periodic overload was applied to the beam every 100,000 cycles as part of a test programme that exceeded 2 million cycles. During the initial 1 million cycles applied to the beam, a periodic overload of 100kN (about three times serviceability) was applied to the beam every 100,000 cycles. There were no indications of damage. The load spike was then increased to 150kN, 5 times serviceability, every 100,000 cycles for the next 500,000 cycles. As there were still no indications of damage, the periodic overload was increased to 220kN, approximately seven times serviceability. This overload was applied every 100,000 cycles for another 500,000 cycles. This level of overload is 2.5 times the ultimate design load and generated a deflection of 100mm in the beam. Once again there were no indications of deterioration or damage either visually, or in the deflection and strain readings.

Figure 4 Laboratory testing of 10m beam

The load-displacement behaviour of the beam continued to be linear and consistent even at high levels of overload. At seven times overload, the concrete had a maximum compressive strain of 0.14% (1400$\mu\varepsilon$) and the laminate had a maximum strain of 0.3%.

In total the prototype 10m beam underwent 2 million cycles (4 times the requirement of the Draft Australian Bridge Design Code) at the serviceability traffic load, as well as being loaded 16 times to 100kN, 10 times to 150kN, and 12 times to 220kN.

The bridge design is based on the traditional plank bridge concept, in which a number of individual beams are placed side by side to create a bridge. The 10 m span prototype bridge was constructed from beams similar to that shown in Figure 4. Traditionally, transverse stressing is used to make the individual bridge beams work together as a plate. In the current design, plate behaviour is achieved by adhering the beams together using a high quality epoxy adhesive. By combining two sets of 7 beams each, 2 sections with a width of approximately 2.5m are created. Each 2.5m section is provided with a strong composite laminate in transverse direction along the bottom of the beams in order to give the section adequate transverse stiffness (Figure 5).

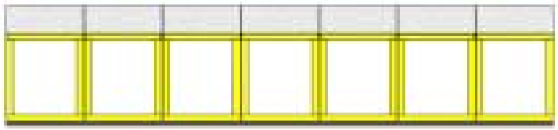


Figure 5 Cross section of 2.5m bridge section

Figure 6 Transportation of bridge sections

Figure 7 Extreme loading: 75 tonne mining truck with over 45 tonne on rear axle.

The 2.5m wide sections can be easily transported to site on a standard truck (Figure 6) and assembled into a bridge using simple field joints. The total bridge weighs approximately 20,000kg and was installed in less than 30 minutes. A range of vehicles were used to test the bridge including an off-road mine truck (Figure 7). This could be loaded to a total mass of approximately 75 tonnes (representing a rear axle load in excess of 45 tonnes).

Beams

The deck unit bridge described above is clearly based on assembling a number of beams. These types of beam can also be used individually as flexural members, for example as replacement timber girders in existing timber structures. These beams are currently under development using a number of different technologies, and prototypes for evaluation are planned for the public road network by mid 2003.

Given the increasing difficulty of sourcing consistent and reliable Australian hardwood structural members, there is increasing interest in the use of composite members as replacement timber beam elements to be used in conjunction with other materials (including existing hard wood structures). A good example of the issues involved is evident in the current project that FCDD is undertaking for the Brisbane City Council (BCC).

BCC are constructing a “river-walk” approximately 800 m long, consisting of a series of reinforced concrete floating pontoons approximately 3 m long, 5 m wide and 1.5 m deep. Each pontoon must be tied to adjacent pontoons to form a structure. Passing river traffic will generate waves that will cause adjacent pontoons to move vertically with respect to each other. To control this movement, the pontoons are joined with beams (walers) that act as flexural springs. Normally timber (hardwood) walers are used. These will require replacement every 10 to 15 years. In addition, shrinkage of the timber means that the stainless steel bolts used to fix the walers to the pontoons must be re-tensioned annually.

BCC approached FCDD to investigate the possibility of using polymer composite walers. FCDD developed a concept that fulfilled the functions of waler (beam), rubbing strip, and “kick” rail in one structural element.

Figure 8 BCC waler under primary flexural test.

Figure 9 BCC waler under transverse flexural test.

Figure 10 BCC waler under burn test.

The waler developed was tested extensively including primary flexure (Figure 8), transverse flexure (Figure 9) and burn testing (Figure 10).

Given the project timelines, the lack of available manufacturing skills in general industry, and the significant research issues associated with the project, FCDD entered into an agreement with BCC to complete the engineering, fabricate production prototypes, fabricate sufficient product for the project (approximately 1.6 km of waler), and develop and manufacture specialist walers to ensure that the project is successfully completed. This is scheduled to occur towards the end of 2002.

The waler concept was engineered to meet specific project requirements, in particular, a long life with minimum maintenance. Given the relatively harsh marine environment in which the walers are installed, these properties are difficult to achieve with alternative materials.

Trusses

Figure 11 Prototype truss joint.

FCDD conducted research into the development of fibre composite trusses (Humphreys et al, 1999) and more recently Connell Wagner Consulting Engineers (another FCDD partner) have identified an opportunity to use this concept. Connell Wagner are currently working with FCDD on a feasibility study to prove this concept for a specific application. The key issue to be addressed in fibre composite trusses is the reliable behaviour of the joints. Prototype joints have been constructed and tested. A number of other truss applications have been identified and FCDD is actively pursuing these in conjunction with other partner organisations.

Railway sleepers

Railway sleepers are another large consumer of Australian hardwoods. Queensland Rail approached FCDD in 2000 to discuss the possibility of developing fibre composite sleepers that could be used as substitutes for timber sleepers (Figure 12). Currently FCDD is undertaking a significant feasibility study to quantify the issues associated with composite sleepers. The study will be completed by the end of 2002, and an Australian composites fabricator has expressed strong interest in commercialising such a product should if it is shown to be commercially viable.

Figure 12 Prototype duo-block railway sleeper.

Resins from plant oils

The majority of the world polymer resins currently used in the production of composites are derived from petrochemical feed stocks. Resins produced from plant oils can offer a low-cost, environmentally attractive alternative to traditional resins. Benefits associated with these developments are:

- Environmental – the use of plant sources for resin production is environmentally sound. Their production leads to a net decrease in greenhouse carbon dioxide (CO_2) emissions. Oilseed crops act as CO_2 "sinks". Even if plant-oil based fibre composites are burned at the end of their useful life, they can release no more CO_2 to the environment than the plants removed when growing.

- Decreased reliance on fossil-fuels – nearly all resins used in fibre composites are currently derived from petroleum products. The price of these resins is therefore highly dependent on world oil prices that can undergo large variations, especially in uncertain political times. Dependence on these types of products has significant implications for the national economy. Plant oil-based resins will help in reducing national dependence on these products.

- Sustainable high tech building products – plant oil-based resins can be combined with plant fibres such as flax and hemp, resulting in advanced building products from renewable resources.

Successful development of this plant resin technology and involvement of the local agricultural and manufacturing industries has the potential to create significant economic growth in the region, leading to a large number of sustainable jobs. Regional exploitation of this technology will create employment opportunities in a range of industries including crop production, oil refinement, composite resin production, and civil construction.

Directions

The project examples described above illustrate that composite materials can be used in a wide range of structures, but that their uses needs to be specifically targeted and engineered, in many cases in combination with more traditional materials. A summary of these projects serves as an indicator for successful fibre composite structural projects in the immediate future.

A systems approach is required when developing composite structural elements, and the result is a specialised product, rather than a commodity item. The main attributes of the developed product tends to be:

- Light weight;
- Corrosion resistance;
- Rapid installation;
- Hardwood substitution.

Input from end users (clients) is important to ensure that appropriate properties are engineered into the structure for the life cycle of the structure.

These structures can contribute to more sustainable systems in a number of ways including:

- Longer life products
- Reduced maintenance;
- Lower energy inputs to manufacture;
- Reduce demand for hardwood;
- Increase renewable constituents in engineered materials.

Conclusion

Advanced fibre composites have been gaining acceptance in the civil infrastructure industry. Where specific requirements are identified, engineered structures can be produced from composites that achieve performance not possible with conventional materials. Composites can also make substantial contributions to improving the sustainability of engineered structures. There is great scope for the further development of these materials.

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Author Biography

Tim Heldt graduated with a BEng (Civil) in 1986 and joined Queensland Railways. From 1988 till 1991 Tim worked in both design and construction (private) industries including the design of grain storages and the construction of industrial process plants. Tim joined the full time lecturing staff at QUT in 1994, lecturing in construction and design and completed his PhD in 1996. In 1998, Tim joined Infratech Systems and Services where he worked on monitoring and instrumentation of bridges, dams and other structures. In 2001 he joined FCDD as a senior engineer, working on a range of fibre composite projects.

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Gerard Van Erp is a Professor in fibre composites at the University of Southern Queensland (USQ). He is the Executive Director of Fibre Composites Design and Development (FCDD), a Centre of Excellence in Engineered Fibre Composites at USQ. Gerard has more than 25 years experience in civil and structural engineering, the last 7 years in fibre composites. During this time he has developed a range of new and innovative fibre composite structures, including Australia's first full scale fibre composite bridge. Gerard is the holder of the Composites Institute of Australia Research Chair in Fibre Composites. He recently received the 2002 IEAust Qld Professional Engineer of the Year award.

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Craig Cattell joined FCDD in 2000 as a structural analyst specialising in the Finite Element analysis of fibre composite structures. Craig has also been heavily involved in materials and process development since joining FCDD. Craig was also involved in FCDD developments during his undergraduate studies, and had considerable construction experience before and during his engineering studies.

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