ABSTRACT

Over the past ten years, Australian researchers have actively pursued the development of new structural systems utilising fibre composites, for the rehabilitation and replacement of deteriorating civil infrastructure. The result has been a range of new systems which offer unprecedented levels of functionality at a cost which is directly competitive with traditional structural materials. Several of these systems have been successfully demonstrated in real world projects. To encourage these developments, the Australian composites industry has been investing in programs to develop codes and standards, and to establish an appropriate regulatory framework to ensure confidence in manufacture, supply and installation of composite products. This paper presents an overview of Australian research into infrastructure applications of fibre composites and associated industry development programs.

KEYWORDS

Composite structures, innovation, bridges, beams, marine structures

INTRODUCTION

As in many other developed nations in Europe and North America, Australian asset owners are actively seeking solutions for the rehabilitation and replacement of deteriorating civil infrastructure. While the reasons for this interest are somewhat different in Australia than in other parts of the world, major asset owners are faced with the same problem of having decreasing budgets to address an ever increasing demand for structural replacements or upgrades.
Over the past ten years, Australian researchers have actively pursued the development of new structural systems utilising fibre composites to address this industry need. While much of this work has gone largely unnoticed by the rest of the world, the research is now paying dividends with a range of new systems providing design solutions which not only offer unprecedented levels of functionality but do so at a cost which is directly competitive with traditional structural materials. Several of these systems have been successfully demonstrated in real world projects and are now being developed into commercial offerings.

In addition to this work, the Australian composites industry has been investing in a program to put composites technology on a more competitive footing with traditional structural materials such as timber, steel and reinforced concrete. Current programs include the development of design documentation such as codes and standards, as well as the establishment of an appropriate regulatory framework which can ensure confidence in manufacture, supply and installation of composite products.

This paper presents an overview of Australian research into infrastructure applications of fibre composites and associated industry development programs.

DEVELOPMENT OF NEW FIBRE COMPOSITE STRUCTURES

Australia’s First Fibre Composite Bridge

While the lack of harsh winters and associated salting of roads removes one of the major causes of bridge deterioration that exists in the USA and Europe, Australia too faces a major bridge replacement program. There are approximately 40,000 road bridges of 7m span or larger in Australia, with a total asset value estimated around $10 billion. Of these, about 10,000 are of timber construction, mostly on the Eastern Seaboard. While old forest hardwood timber is a durable material, many of these bridges, in excess of 60%, were built before the 1940's and were designed to lower loading standards than would be required today. Many of these structures require major rehabilitation or replacement now or in the near future. Hardwood as a structural material is a rapidly diminishing resource and infrastructure owners are actively seeking alternative solutions. With their purported high durability and ability to mimic timber performance through judicious design, fibre composites have become an area of significant interest.

The first fibre composite bridge in the Australian public road network was installed on 19 February 2003 (Figure 1). This installation was the culmination of a development and innovation process lasting over 5 years and involving a wide range of interested parties including; Queensland Department of Main Roads (QDMR), the Roads and Traffic Authority of New South Wales (RTA), the Department of Industry Science and Resources (DISR), Fibre Composite Design and Development (FCDD), Wagners Composite Fibre Technologies (WCFT), the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) and consulting engineers Connell Wagner and Cardno MBK [1].
The project originated with a generic design exercise commissioned by the RTA which sought to identify which particular fibre composite bridge technologies should be encouraged. This involved the development of a performance specification that met RTA requirements and the submission of two conforming design concepts [2].

A design, put forward by the CRC-ACS together with engineering consultant Cardno MBK, was based on a girder-and-deck concept incorporating the latest technology from the United States. The deck was to be formed from 150mm deep pultruded fibreglass profiles, adhesively bonded together. The 600mm deep U-shaped girders were to be manufactured by hand lay-up.

The second proposal based around a traditional plank bridge concept, where individual beams are laterally post tensioned to create a bridge, was proposed by FCDD. The beams combined the high compression capacity of plain concrete with the high strength/low weight characteristics of fibre composites by locating a 100mm deep concrete compression flange on top of 350mm deep box girders formed using glass-reinforced isophthalic-polyester pultruded profiles. Additional carbon fibre reinforcement was incorporated into the base of the deck to enhance stiffness [3-8].

The second concept was selected as the preferred alternative based on a set of agreed selection criteria. The considered advantages of the proposed concept were:

- No joints between deck and girders (the girders are the deck);
- Excellent resistance against flood loading and side impact;
- Significant redundancy in the structure due to large number of beams;
- The concept is well understood by bridge engineers;
- Significant understanding of the bridge behaviour can be obtained through testing of individual beams.

FCDD partnered with Wagners Composite Fibre Technologies, the RTA and QDMR to develop the concept into a working prototype which was installed on a Wagner’s owned quarry site near Toowoomba, Queensland (Figure 2) in early 2002. An extensive series of field tests followed, revealing that the concept exceeded expectations in terms of its technical performance [9]. Based on this development work, RTA developed a project to install one of these new generation bridges for trial purposes.

The selected installation site was an existing timber span (circa 1940) on a bridge over the Orara River at Coutts Crossing in northern New South Wales. Consulting engineers Connell Wagner were engaged by WCFT to review and modify FCDD’s fibre composite bridge concept to suit the site specific requirements at Coutts Crossing. The benefits of the new bridge deck design over traditional bridge deck design were determined to include:

- Installation in only 5 days, instead of 8 to 10 weeks for the conventional alternative,
- 90% savings on traffic control costs, and
- 75% saving on bridge transportation costs.

The bridge was constructed by WCFT under the supervision of FCDD and installed in February 2003. Initial site testing shows that the bridge is performing well. The RTA will continue to periodically monitor the bridge in coming years.

**The Brisbane RiverWalk Project**

RiverWalk is a 34 km long trail along the banks of the inner city reaches of the Brisbane River. The RiverWalk concept caters for jogging, cycling, walking and recreation and joins people and the river together. It is an important transport link catering for nearly 20,000 person trips per day. In keeping with the theme of providing a variety of experiences, a section near the Story Bridge has been designed as a floating walkway (Figure 3). The walkway is 850 m long and 5.4 m wide. It has 600 mm freeboard and is provided with universal access. The walkway consists of 288 individual concrete floats connected by beams called walers.

The original waler design utilised timber and steel which are the traditional materials for this type of structure. However, due to the aggressive marine environment, these walers would require replacement every 10 to 15 years which made them the weak link in the 100 year design life required for the walkway. A Research and Development team, including Brisbane City Council (BCC), International Marine Consultants (IMC), FCDD and Longhouse Green was created to investigate the use of fibre composites as means of achieving the required structural performance and durability demands as well as a detailed set of specifications for vandal resistance, boat impact and aesthetics. This team was able to develop a new waler beam concept using a combination of polymer concrete, 3-dimensional fibre composite reinforcement and a filled resin system. The beam concept was designed to carry a wide range of static and dynamic loads and was extensively tested before being applied in the RiverWalk (Figure 4).

Although having twice the cost of timber and steel, the whole-of-life costs of composite walers are significantly lower. Based on the whole-of-life analysis, the composite solution was determined to provide the best cost-performance benefits, and consequently BCC decided to use this concept for all 600 beams in the walkway project [10,11]. The walers have been installed now for more than a year and are performing well.

**Innovative Fibre Composite Truss Structure for RiverWalk**

One area of the floating walkway that presented a serious structural challenge was the downstream end. This section of the walkway supports a 20m span, 5m wide pedestrian bridge, which provides access from the waterfront onto the floating walkway. In order to distribute the highly concentrated loads from the bridge over a number of pontoons, an 18m long structural member was required. A large part of this member is submersed in saltwater. The extremely high dynamic loads and harsh environment made traditional design solutions a prohibitive option.
A special fibre composite truss was developed for this application (Figure 5). Because of its low weight (5000 kg), the truss offered significant benefits in terms of construction and installation time. Estimates on an alternative stainless steel solution were nearly three times the price of the composite truss. The truss has been designed to carry an ultimate bending moment of 700KNm, is 2.5m deep and has a 1.4m deep cut out to accommodate the pedestrian bridge. It provides an extremely durable and high capacity solution to a difficult engineering problem.

**REHABILITATION OF CONCRETE STRUCTURES**

**Strengthening of West Gate Bridge Approach Spans**

In 2001 one of the world’s largest carbon fibre strengthening programs was undertaken in Melbourne, Victoria. The West Gate Bridge in Melbourne links the western industrial and residential areas to the main city and is one of the city’s busiest transport corridors. The 650m long bridge comprises a pre-cast, segmented box girder with pre-cast, post-tensioned cantilever frames and a composite reinforced concrete deck slab. The structure was designed in the mid 1960’s.

The construction of additional approach lanes to the bridge required the placement of an additional traffic lane within the existing roadway. The bridge was originally designed for a maximum of 8 traffic lanes and thus it was determined that strengthening of the structure was required to accommodate the new lanes.

URS Australia Pty Ltd undertook a structural assessment of the concrete approach spans on behalf of the Victorian state road authority (VicRoads). This assessment determined that the bridge had insufficient capacity for:

- Global hog of the box girder over piers at serviceability limit state
- Combined shear and torsion near the piers at ultimate limit state
- Local sag moments in the deck slab at ultimate limit state
- Local bending capacity in the cantilever frame at ultimate limit state.

VicRoads decided to undertake the necessary strengthening works via a Design and Construct contract. The overall project cost was of the order of A$10 million. URS Australia Pty Ltd joined with Abigroup and Savcor to launch a successful bid for the project, which was awarded in May 2001. The use of fibre composite laminates was a key component in the winning bid.

Strengthening of the structure was achieved through a combination of external post-tensioning using longitudinal steel tendons, as well as the application of bonded FRP strips and sheets (Figure 6). BBR Systems Ltd (Zurich) supplied the FRP products for the project. FRP was used for both flexural, shear and torsional strengthening. To achieve adequate anchorage, the shear and torsional laminates were slotted into the concrete deck using a special concrete cutting saw.
The cantilever frames were strengthened for flexure. FRP was placed near the top of the pre-cast concrete frame to increase the tensile capacity, however due to the over-reinforced nature of the cantilever, it was also found necessary to provide bottom flange compression strengthening in the form of steel plates.

The scale and complexity of the FRP strengthening undertaken in this project was unprecedented at the time and has demonstrated the cost effectiveness of FRP for strengthening large span concrete bridges in Australia.

Research Into Externally Bonded Plates for Rehabilitation of Concrete Members

In addition to real world applications such as the West Gate Bridge, Australian researchers are also involved in fundamental research to better understand this type of system. The Centre for Infrastructure Diagnosis, Assessment and Rehabilitation at the School of Civil and Environmental Engineering, University of Adelaide is involved in research into retrofitting using externally bonded plates [12-16]. Areas of research include:

- Seismic retrofitting of rectangular columns
- Critical crack debonding of adhesively plated beams (Figure 7)
- Intermediate crack debonding of adhesively plated beams
- Debonding of adhesively plated masonry
- Bolted plated beams

The centre is also working on the development of generic design rules for all forms of plating which allow the designer to develop their own application techniques. Research in this area encompasses:

- plate fixing techniques including adhesive bonding and/or bolting
- plate materials including steel, aluminium, carbon FRP and glass FRP
- plate positioning such as tension face, side and compression face plates
- plate geometry including flat plates, and angle or channel sections
- plate function such as the enhancement of the strength or ductility

Comprehensive design rules have now been developed for plating RC beams and slabs which covers all forms of plating and can be used to quantify both the strength and ductility [17].

Researchers within the Department of Civil Engineering at Monash University, Melbourne, are also investigating bonded FRP / concrete systems [18-27]. Research has included:

- investigation of end cover separation and shear crack debonding failure mechanisms in rectangular concrete beams with bonded FRP plates
- shear strengthening of reinforced concrete T-beams with L-shaped CFRP strips (Figure 8), and
• torsional strengthening of rectangular concrete beams with externally bonded CFRP sheets.

REHABILITATION OF TIMBER STRUCTURES

Replacement of Hardwood Timber Beams

The decreasing access to hardwood timber, both in terms of volume and quality, has created strong national demand for alternatives solutions from asset owners with large inventories of hardwood timber structures. FCDD has been developing hybrid composite/timber beams for several years, and is in the process of commercialising a range of products to meet the needs of specific markets [28-31].

The concept is based on the use of plantation softwood for the bulk of the beam with composite reinforcement modules being used to increase the strength and stiffness up to that of a typical Australian hard wood beam (see Figure 9). The plantation timber is laminated veneer lumber (LVL), because this type of timber product has less variability than sawn timber, resulting in more predictable properties. The main function of the timber is to provide the shear capacity to the beam, as well as maintaining the separation between the reinforcement modules.

The reinforcement modules use a combination of composite materials and have a Modulus of Elasticity of 60GPa and a failure strength of around 200MPa. The modules are bonded to the timber using a high strength epoxy adhesive. The stress in the adhesive is relatively low due to the large surface area of the module.

Figure 10 shows a comparison between the load-displacement behaviour of a typical hybrid composite/timber beam and that of a range of Australian hardwood beams. F34 hardwood has a characteristic flexural strength of 100MPa and a Modulus of Elasticity of 21500MPa. This type of beam used to be readily available but is very rare these days. Figure 10 also shows that the hybrid beam can be designed to have a ductile failure mode which gives significant warning of failure.

The Rail Infrastructure Corporation of NSW has identified a number of applications for this type of beam. These include:

• shorter span beams with a typical cross section of 300x300mm² and a span of 7m, and
• longer span girders (18m and 23m) which require shallow abutment depth and a flat soffit, to minimise earthworks and retain minimum track clearances.

A number of tests have been carried out in the development of these hybrid composite/timber beams, aimed at verifying the strength, stiffness, failure mode, and predictability. The first 5 hybrid beams have been installed in two separate bridges early in 2004.
DESIGN CODE DEVELOPMENT PROGRAM

The market growth restrictions imposed by the lack of appropriate design codes and standards from composites in civil infrastructure applications have been well documented. Recognising this significant barrier to broad utilisation of fibre composites in civil engineering, Fibre Composites Design and Development (FCDD) embarked on a major initiative to develop an Australian Code of Practice for the structural design of fibre composites. This initiative was developed as part of a broader program of industry development with the Composites Institute of Australia and key civil engineering industry stakeholders. Funding for this program has been provided by the Australian Federal Government and the Queensland State Government, with additional support from a range of industry stakeholders.

The primary objective of the Australian code development program was to create a platform whereupon practicing structural engineers could begin to employ fibre composite materials in their design solutions. It was believed that by opening up the world of composites to a wider segment of the structural engineering community, new and innovative structural forms would emerge to incorporate these materials in a more functional and economically viable manner.

Recognising that most current design codes for timber, steel and reinforced concrete, have evolved from an established technology base and history of application, Australian developers believed that the most appropriate initial step in creating a regulated design system was the preparation of an industry based Guide of Best Practice. The aim of this document is not to provide highly prescriptive design guidance on specific structural elements like the more established material codes due to the relative infancy of the infrastructure composites technology. Instead, the document has been developed to provide engineers with sufficient foundational guidance to begin exploring new structural systems utilising composites.

As documented earlier in this paper, researchers have demonstrated that cost effective, real-world structures using fibre composites are achievable. However most of these new composite systems take a significantly different form than those traditionally targeted at the infrastructure market. It is thought that as more engineers explore ways of using composites in their particular applications, a range of other forms and techniques will also emerge. Furthermore, it is considered likely that many of these new systems will also be distinctly different from those currently in the marketplace. Over time improved knowledge and market forces will result in some of these concepts becoming accepted practice while others will fall by the wayside. As this occurs, the successful forms and practices will be incorporated into more prescriptive design codes.

The key at this early stage is to provide the framework necessary for these new forms to be explored and it is believed that the cornerstone of this framework is the provision of accurate and reliable materials data.
One of the core assumptions underlying the Australian work is that the true potential of fibre composites can only be exploited through the use of sophisticated analysis techniques such as finite element analysis. Research experience at USQ has shown that, with correct material data and in the hands of suitably skilled personnel, these tools can be effectively used to develop new structural systems within acceptable levels of confidence. However, to effectively utilise these tools, there is a need to provide engineers with materials data which they can have confidence in.

Australian researchers have moved to address this need on two fronts:

- the development of the National Composites Certification Scheme; and

A handbook to assist practicing engineers in interpreting and using the Guide of Best Practice is also under development.

**The National Composites Certification Scheme**

The National Constituent Certification Scheme (NCSS) is designed to provide a mechanism for standardising the determination and reporting of materials data. The aim is to establish a scheme wherein a central industry body monitors and certifies the performance of all composite materials and constituents sold into the Australian civil infrastructure market. The adopted approach is quite similar to that established by the Australian plywood industry [32].

A standardised program of material characterisation will be established and a centralised laboratory will evaluate all submitted materials in accordance with the prescribed methods. The results obtained will be compared against an established set of objective performance criteria and on the basis of this comparison materials will be awarded a performance grading. The allocated grade will be ratified by an independent certification committee operating under the NCSS. The manufacturer will then be given the right to market the product with tradmarked product labelling indicating the allocated grade.

Certification of a product will be for a 5 year period with potential for renewal after that time. During the period of certification, the product may be periodically checked by the NCSS. Products found to deviate significantly from original certification will then be subject to review and possible revocation of their certification. Disqualification of a product will require removal of tradmarked grading signage from all products and associated literature.

The NCSS will operate under the auspices of the Composites Institute of Australia’s Polymer Composites in Construction (PCiC) division. The scheme will be overseen by a committee with representation from key industry stakeholders.
The initial stage in establishing the NCSS has been the development of a characterisation and grading program for polymer matrix materials used in fibre reinforced laminates. A draft characterisation program has been prepared and is currently under review. This project was undertaken with the support of six of Australia’s largest resin suppliers.

The project also involved an experimental investigation of around twenty five matrix systems put forward by the participating manufacturers. The systems have been subject to a wide array of characterisation testing to evaluate proposed test methods and to assist in developing property data for the Guide of Best Practice. This initial program for matrix systems will be used as a model for further work on reinforcements, adhesives and core materials.

Guide of Best Practice on Material Properties for Design

The Guide of Best Practice on Material Properties for the Design of Fibre Composite Structures builds on the work of the NCSS by providing design engineers with the information necessary to begin exploring structural systems involving fibre reinforced composites [33]. The guide has been designed to provide engineers with the material data necessary for input into standard finite element analysis software. It sets out procedures for determining characteristic material properties either from standardised material tables contained within the guide or through direct testing of a specific material combination.

The guide contains a number of standardised material property tables for basic lamina forms. The fundamental forms addressed are:

- Unidirectional laminae
- Woven laminae (based on unidirectional laminae but modified by the direction percentage of fibre and a weave factor)
- Random fibre laminae

This is consistent with the approach of the earlier British tank design standard BS4994 [34].

There are several points worth noting about the adopted approach. Firstly, strength and stiffness properties parallel to the fibre axis are defined in terms of Normalised Unit values (N/mm per kg/m$^3$ of reinforcement). These properties are fibre dominated and this system is seen to better characterise fibre dominated behaviour [35]. Properties perpendicular to the fibre axis remain in traditional stress units. The guide provides for simple conversion between the two systems of units.

Secondly material capacities are primarily defined in terms of strain limits not strengths. Strength values are determined as a product of the modulus and strain values. This has been done to encourage a focus on strain based design which it is felt is more
appropriate to composite materials where multiple materials are often combined within the one system.

The procedure adopted in the guide for determination of characteristic properties has been deliberately kept simple to encourage wider adoption of guide by practicing engineers. It is acknowledged that a significant number of simplifying assumptions have been made in this process, however it is believed that the end result retains acceptable levels of engineering accuracy while facilitating ease of use.

The current guide document is an initial draft and it is recognised that there are still a range of fundamental materials issues and implementation issues which must be addressed. A consultation process with key industry stakeholders is currently underway and research work to improve fundamental knowledge is ongoing. However, while there is still much work to do, it is believed that this document represents a significant step forward for the Australian engineering and composites communities, finally providing interested engineers with a real way forward into the realm of composites technology.

CONCLUSION

This paper has presented a brief survey of development efforts into infrastructure composites within Australia. It has been shown that several new and innovative structural systems using composites are reaching a point of commercial reality within the Australian market. It is believed that the continuing development of these systems and others like them, in combination with national programs to provide engineers with necessary design guidance, will see composites gain an increasing foothold in the Australian civil engineering market over the coming years.

REFERENCES


FIGURES

Figure 1. Installation of Australia’s first fibre composite bridge

Figure 2. Full scale prototype of composite bridge under test

Figure 3. Brisbane's Floating Walkway
Figure 4. Testing of fibre composite walers

Figure 5. 18m long fibre composite truss

Figure 6. Inspection of strengthening system
Figure 7. Investigations into critical crack debonding of adhesively plated beams

Figure 8. Experimental investigation of shear strengthening of concrete T-beams with CFRP strips at Monash University

Figure 9. Example of hybrid beam cross-section
Figure 10. Behaviour of new hybrid composite beam compared with Australian timbers