Hybrid Beams for Sustainable Replacement of Hardwood Timber in the Construction Industry

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SYNOPSIS

Australian hardwoods are an excellent general purpose building material, however in recent years they have become more expensive, less available, and of poorer general quality than has previously been the case. Many Australian timber bridges will remain in service for the foreseeable future, and the maintenance and potential upgrading of these structures will be an on-going demand, while the availability of traditional resources declines. Compatible alternative timber bridge components are therefore required. Fibre Composites Design and Development (FCDD), a Centre of Excellence at the University of Southern Queensland, in close collaboration with the Forest and Wood Products Research and Development Corporation (FWPRDC) and major timber bridge asset owners, has been developing alternative beam solutions for several years. This paper summarises recent developments, and discusses some of the important issues to be considered.

1 INTRODUCTION

Australian hardwoods are an excellent general purpose building material. This was recognised by early road builders in Australia, and hardwood timber bridges proliferated, particularly during the first half of the 20th century. Timber used in these structures was typically the best of the old growth forests. Australia now has a large number of timber structures (possibly as many as 20,000) that are in the high maintenance phase of their useful life [1]. Many bridge asset owners are confronted with the following realities regarding these timber structures:

1. There are insufficient funds available to construct replacement structures;
2. The assets must remain in a safe usable condition;
3. There is a growing shortage of materials available to repair and rehabilitate these structures.

This situation has created a need for effective alternatives.

While a timber bridge girder is a simple element in practice, it is relatively difficult to define in terms of specified performance requirements. Timber bridge technology has developed with a focus on workable solutions, based on historical evidence that a girder of a specific size and species "works". This approach has not required the development of rational performance criteria, however these criteria are required in order to develop alternative bridge girders.

The development of alternatives to hardwood timber bridge components requires detailed understanding of a range of issues. This paper begins with a discussion of these issues based on the recent experience of FCDD. One of FCDD's hardwood substitute alternatives is then described, along with a summary of the development of this product to-date. Issues and opportunities affecting the further development of timber girder substitutes are then discussed.

2 BACKGROUND

The large section old growth hardwoods that have been traditionally used as components in timber bridge structures are increasingly more expensive and difficult to procure. This is the result of declining physical resources and community pressure to preserve those resources that remain. In order to address this issue the Roads and Traffic Authority of NSW (RTA) and FCDD commenced a collaborative research project in 2001 to develop an effective hardwood alternative for cross girders in timber truss bridges (Figure 1). The alternative had to offer greater strength and durability than current hardwood cross-girders available, and still be acceptable to heritage sensitivities. The ability to drill and trim the girder on site was also a key requirement for this application. During this period, the Queensland Department of Main Roads (QDMR) was also investigating possible alternative replacement girders for their timber bridges, as was the Rail Infrastructure Corporation-NSW (RIC). In addition to alternatives for standard bridge beams, RIC also revealed a desire to obtain longer timber replacement girders (up to 20m). RIC has many three span (road over rail) timber bridges with supports close to the track. Substantial rehabilitation of these bridges generally involves reducing the risk of collapse resulting from an impact between a train and the bridge supports. Elimination of the intermediate supports through the use of long span composite or hybrid/composite girders has the potential to reduce or eliminate this risk. The involvement of these major assets owner in the development of alternatives has been extremely important as has the financial support from the FWPRDC and the Queensland Government. This collaboration is now starting to pay dividends, with close to twenty trial beams being installed in a range of bridges.

Figure 1. Heritage truss bridge (including cross-girders) typical of RTA structures

2.1 Characteristics of traditional hardwood timber and the pursuit of alternatives

Characteristics of traditional hardwood timbers are relatively well understood (at least implicitly) by the bridge engineering community in Australia. They are considered strong, durable, reliable, easy to work with and somewhat variable. There is a strong empirical knowledge base with respect to safe and workable solutions, and the material is considered to be relatively "forgiving". However, a codified approach to the engineering of timber bridges does not exist and there are no generally agreed specifications available for the design of alternative bridge girders. Nevertheless, there is broad agreement on the range of issues that have to be addressed when developing alternative solutions. These issues include:

1. Strength;
2. Stiffness;
3. Durability;
4. Workability;
5. Cost.

Strength and stiffness of timber structures are defined in Australian Standard AS1720.1. However, the strength and stiffness values of old growth timber bridge girders are generally significantly higher than the values defined in AS 1720.1. This results from the higher quality timber that has traditionally been used for bridge girders. The question therefore arises "should code values be used, or values representative of actual bridge girders?" If representative values are preferred, then which values should be used, and what should be the basis for specifying them?

Durability is another characteristic that has been quantified reasonably well in AS 1720.1. However there is general acknowledgment that the durability of bridge timber supplied to asset owners over recent years has declined, even though they have been graded in accordance with AS 1720.1. This has been attributed (among other things) to new growth timber being supplied in lieu of old growth timber, and the difficulty of obtaining hardwoods that truly meet specifications. In more recent years, various chemical treatments have become available to improve the durability of hardwood timber, and the result of these treatments has been reasonably well quantified. However some of these effective durability treatments are under pressure to be phased out as a result of environmental concerns. Thus, specification of durability requirements of hardwood alternatives is more ambiguous than it may at first appear.

Hardwood is considered to be easy to "machine". This is well understood in the context of hardwood practitioners, but relatively difficult to define in terms of performance parameters. Ease of machining is considered essential given that there is considerable dimensional variability between different girders in a bridge and timber bridges in general.

Cost comparisons and viability decisions for alternative solutions have to be based on the total installed cost of the girders rather than the direct purchase price. For example, an asset owner may purchase a hardwood log for about $ 2,000, but the final installed cost may be as high as $ 10,000 due to the significant on-site work involved in shaping a log into a usable bridge girder. In almost all cases, it will not be possible to supply a pre-engineered hardwood substitute for the same price as a virgin hardwood log. However, there is significant potential (through correct detailing) to reduce the on-site labour required for alternative girders, without significantly affecting the adaptability of the girder. In some cases this can result in the installed cost of alternative girders being lower than those of traditional timber girders.

The above points highlight that development of a competitive alternative to hardwood girders is a major challenge and that it requires close collaboration between product developers, asset owners and bridge gangs, particularly with respect to work practices.

2.3 Engineering approaches to hardwood girder substitutes

Based on discussions with asset owners there seem to exist three different philosophies to the engineering of alternative hardwood girders namely:

1. Reference to AS 1720.1 - alternative hardwood girders should be pre-engineered to have mechanical characteristics compliant with AS 1720.1;
2. Reference to AustRoads Bridge Design Code [3, 4] – The bridge loading code specifies loading requirements. Components must be pre-engineered to meet the requirements of this code as demonstrated by a rational design method;
3. Capacity of old growth timber – When an alternative bridge girder is used to replace a hardwood girder in an existing bridge, it is important that the new girder has similar strength and stiffness characteristics as the other timber beams to avoid uneven distribution of loading forces.

For example, RIC uses the first approach and refers to AS1720.1. They specify F22 grade beams to replace their 7m span bridge beams. In order to obtain a better understanding of the performance of current F22 hardwood girders, a 300mm x 300mm girder was tested in four-point bending with a support span of 6600mm and a loading span of 500mm, as shown in Figure 2.

Figure 2. Timber Beam Test Arrangement

The behaviour of the beam was linear until cracking of the timber in the tensile region, which occurred at a load of approximately 220kN. This equates to a moment of 300kNm, which is slightly higher than the characteristic (F22) moment capacity of 290kNm. Initial failure consisted of tensile splitting, and longitudinal delamination of the timber at the bottom corners of the beam. The beam continued to carry some load after initial failure, and continued to be loaded up to the maximum stroke of the loading ram. The stiffness of the timber beam was 10500 MPa, which is marginally lower than the F22 design stiffness of 10800 MPa. Even though only one beam was tested, the result seems to indicate that current hardwood girders struggle to meet AS1720.1 criteria.

Main Roads follows the third approach to bridge girder specification and has formulated its own engineering performance criteria based on an extensive testing program on old hardwood girders that were recovered from existing timber bridges. Details of this specification are shown in Table 1.

Table 1. Performance Criteria for Timber Replacement Girder

Performance Criteria : Span 9.1m Nom (8.7m – 9.7m)		
Criteria	**Units**	**Value**
Maximum Dimensions	Width (mm)	350
	Depth (mm)	425
M_{min} at failure (Test to destruction)	kNm	660
-ve BM capacity	kNm	30% +ve BM
V_{max} at failure	kN	350
δ_{max} deflection at failure	mm	170
EI girder	Nmm^2	$2.96e^{13}$
Fatigue Load Testing (2×10^6 cycles, spike load every 2×10^3 cycles)	kN cycle load kN spike load min test span	65 100 8.7m

Each of the approaches to performance specification has its merits. The reality is that different approaches may be required for different situations. Consequently it is important that alternative hardwood girder concepts be flexible enough to accommodate a range of engineering approaches. Over time, it is likely that these concepts will develop further as will other alternative hardwood girder characteristics.

3 HYBRID COMPOSITE ALTERNATIVE HARDWOOD GIRDER

One of the girder alternatives that FCDD has been working on is a hybrid composite softwood beam with properties that exceed those of hardwood beams. This concept was initially developed to comply with the "timber" requirements of the heritage bridge replacements in NSW. However, several other road and rail authorities have since trialled the concept in non-heritage structures.

The philosophy of the hybrid beam concept is based on the optimal use of different materials as shown in Figure 3. The concept uses plantation softwood; either ply or laminated veneer lumber (LVL) for the bulk of the beam, with reinforcement modules to increase the strength and stiffness to a level equivalent to an F22 (or stronger) beam of equivalent dimensions. Ply and LVL engineered timbers have less variability than sawn timber, resulting in more predictable properties. The timber is used to provide the shear capacity for the beam, maintain the separation between the reinforcement modules, and provide the functionality associated with timber.

The reinforcement modules use a patented combination of materials including steel reinforcing, polymer concrete, carbon and glass fibre reinforcing. The steel reinforcing bars are used to provide extra stiffness as they represent the most economical material in terms of cost per unit of stiffness. In some applications, the working strain levels required exceed the capabilities of steel, so carbon fibre is substituted where necessary. Reinforcing bars are typically encased within polymer concrete, which is further encased in fibre composite laminates. This provides an extremely effective barrier against moisture ingress and corrosion of the bars. The FRP provides strength after the steel has yielded. The modules are bonded to the timber using a high strength epoxy adhesive.

Considerable development was necessary to advance this concept towards a pre-engineered alternative hardwood girder. Initially small scale experiments were undertaken to investigate hybrid beam behaviour. For the purpose of comparison, two beams with a constant cross section 186mm wide x 200mm deep were manufactured using ACQ treated plywood timber. The first was made from solid F14 plywood. The second beam was similar however four composite modules were added to it (Figure 3). The beams were tested in four-point bending with a support span of 2500mm and a loading span of 500mm.

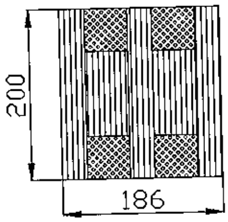


Figure 3. Cross Section of 3m Hybrid Test Beam

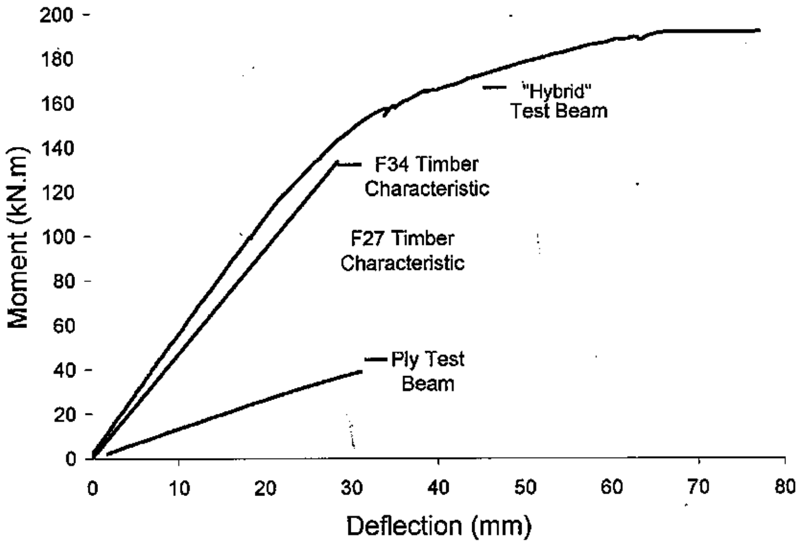


Figure 4. Moment-Deflection Graph of Results from 3m Beam Tests

The first (plywood) beam closely matched the characteristic stiffness of 8E11 N.mm², but had an ultimate strength 40% higher than the characteristic bending strength of 20MPa. The results for this test are shown in Figure 4. Typical code results for F22 and F34 timber are also given in this figure.

The Hybrid beam had a stiffness greater than the characteristic stiffness of an equivalent F34 timber beam, and a strength 44% higher than the characteristic strength of F34. The hybrid beam also had a ductile failure mode (Figure 4), providing significant warning of failure through cracking of the ply and the associated large deflections.

The initial test beams utilised plywood cores, while more recently beams have been produced using LVL, for example the hybrid girder developed to meet the Main Roads performance criteria in Table 1. The 310mm wide and 385mm deep girder consisted primarily of LVL strengthened with four reinforcement modules. This beam had a stiffness slightly below that of a characteristic F32 of the same dimensions, and a strength in excess of F27 characteristic, as shown in Figure 5. The beam had a semi-ductile failure, with significant warning of failure through cracking of the LVL.

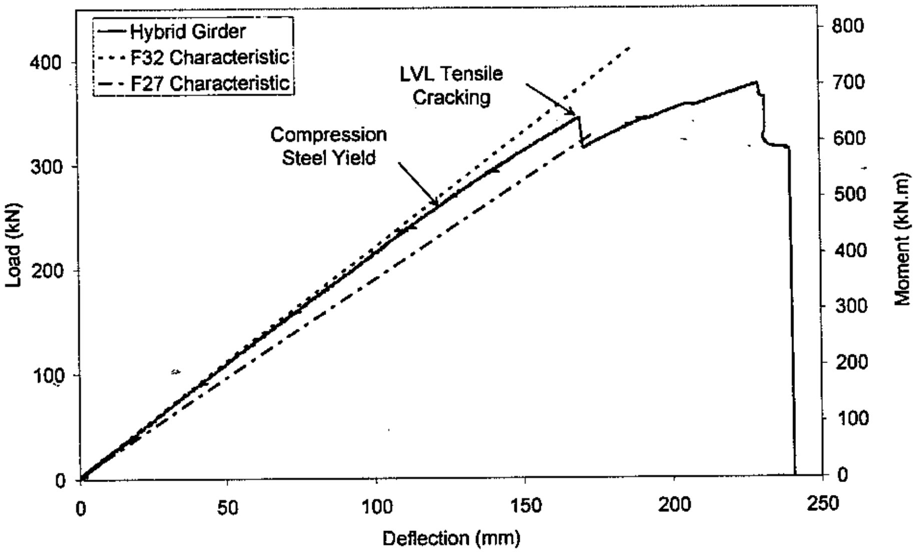


Figure 5. Load and Moment-Deflection Graph of Results from 9m Beam Tests

The test results reveal that there is potential to engineer a "pseudo-ductile" behaviour into hybrid beams. That is initial rupture of the timber can correspond to a "plastic" response rather than a sudden loss of capacity. Most engineers would prefer to avoid a sudden loss of capacity; however this potential raises a series of questions, namely:

1. Should such capacity be included in engineering calculations;
2. If so, on what basis should it be included;
3. How should such behaviour be specified/quantified;
4. What is the value of such behaviour?

In summary, a series of questions arise when determining target girder behaviour. Given that conventional timber girders do not exhibit pseudo-ductile behaviour, should alternative timber girders be required to exhibit it (just because they can), how should this be specified and utilised, and what is the relationship between cost and benefit for this improved behaviour?

4. DEVELOPMENT OF PRODUCTS

Many issues are yet to be resolved with respect to alternative hardwood timber girders. FCDD continues to work with road and rail authorities to resolve these issues, and in the process, develop products that meet the needs of these authorities. Alternative girders have already been supplied to the RTA, RIC and QDMR. Each of these authorities has different requirements; however on-going collaboration should allow appropriate methodologies and products to emerge. One example of a demonstrator beam is shown in Figure 6. This beam has been used as a cross girder in the heritage bridge shown in Figure 1.

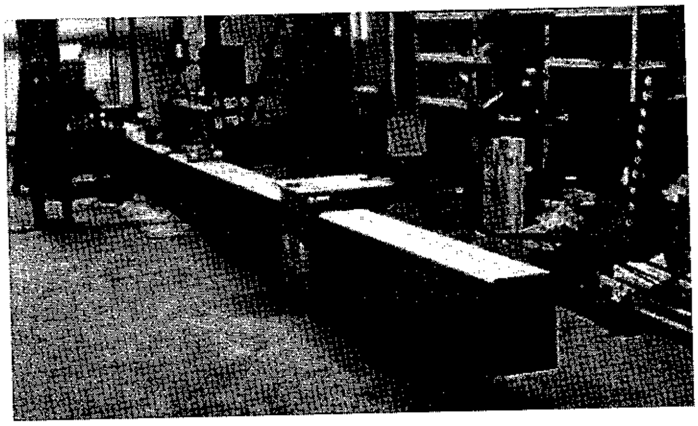


Figure 6. RTA cross beam under test loading.

Other examples of typical hybrid girder demonstrator projects are discussed in the next section

4.1 Short span (7 metre) girders for RIC

The standard timber overbridge beam used by RIC is an F22 hardwood girder with a cross-section of approximately 300mm x 300mm, and a length of approximately 7 m. FCDD has developed an alternative beam to match the AS1720.1 requirements (Figure 7). The alternative beam is also 300 x 300 mm in cross section, and consists of LVL strengthened with four reinforcement modules, and is designed to match the strength and stiffness of an equivalent F22 girder. The beam has a design stiffness of 1.3E13 N.mm^2 (an equivalent Modulus of Elasticity of 18,900 MPa), and a design strength of 300kNm (giving an equivalent bending strength of 67 MPa).

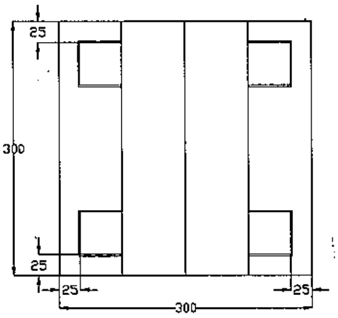


Figure 7. Cross section of short span RIC beam.

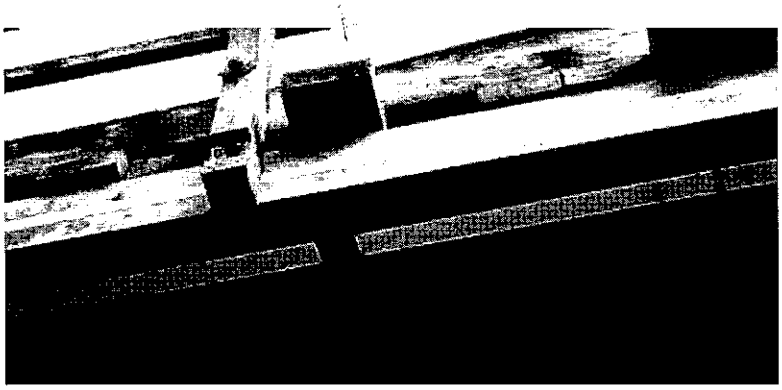
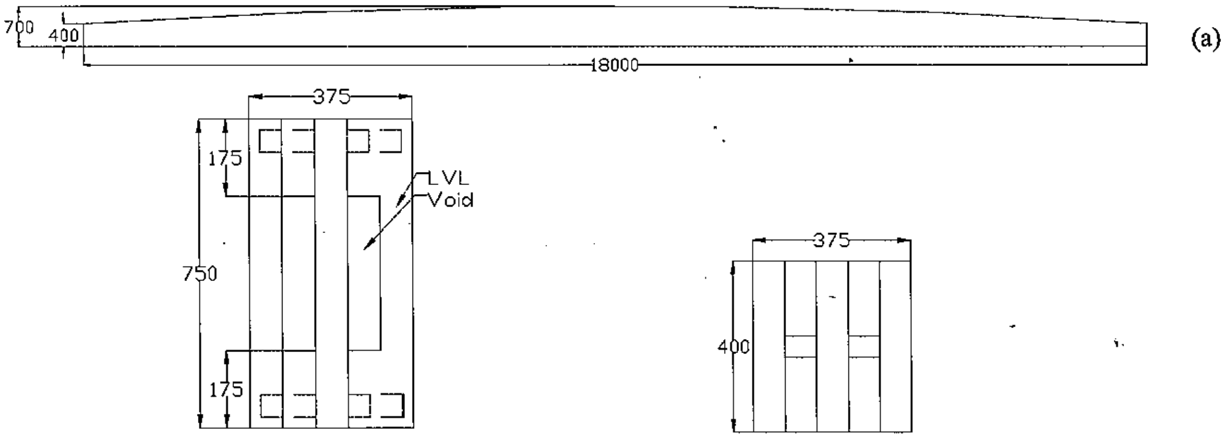


Figure 8.example of installed short span RIC beam

4.2 Long span (18+ metre) girders for RIC



(b) (c)

Figure 9.Long span road-over-rail beam (a) Elevation (b) Mid-span Section (c)End of Beam

Figure 9 and Figure 10 show an example of 18m long hybrid girders that have been produced for RIC. These girders have been designed with flat soffits and a curved top surface, with a typical rise over the length of the girder of 350 mm. This shape provides reasonable depth of girder at mid span while minimising abutment depth.

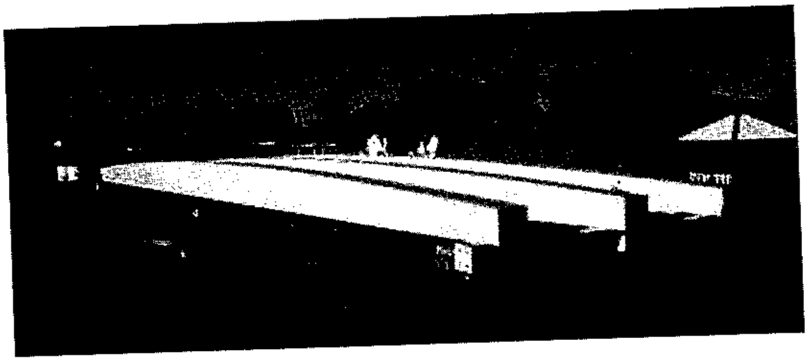


Figure 10. Example of 18m span RIC road-over-rail beams

4.2 10m girder for Queensland Main Roads

Early in 2005 Queensland Main Roads installed two 10m hybrid girders in a bridge over Heifer Creek near Gatton. These hybrid beams were designed to meet the specification shown in Table 1. A detailed inspection after six months found that the beams are performing well. Figure 11 shows one of the hybrid girders being installed.

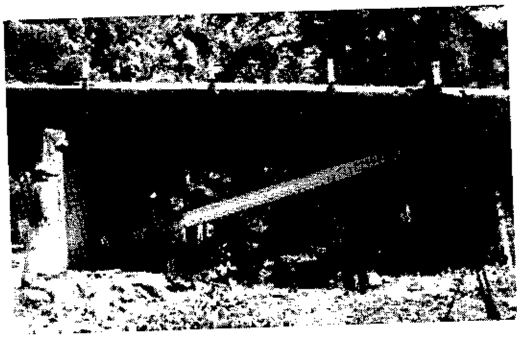


Figure 11. Installation of Hybrid beams at Heifer creek.

5 SUMMARY AND CONCLUSION

The need to develop alternatives to hardwood bridge girders has caused a range of questions to be raised that have not been evident while conventional hardwood girders have been used to construct and rehabilitate timber bridges. The potential to obtain engineered products brings with it questions about the appropriate design approach that should be used, particularly with the introduction of the new SM1600 bridge load model. Alternatives can be broadly summarised as:

1. Use the characteristic design values from AS1720.1 as target characteristic values;
2. Use the bridge loading code, and a rational design methodology;
3. Specify that new alternatives must match the behaviour of old growth hardwood girders.

Alternatives other than (1) to (3) may also exist. Currently products are being developed using each of the above approaches.

Similar issues to the above exist when considering the durability of alternative girders, and there is even less clarity regarding specification of machining characteristics of alternatives. In both cases, progress is being made, and it is likely that new options will arise as these issues are dealt with.

Alternatives can provide failure mechanisms other than the brittle elastic failure modes associated with traditional timber girders. This possibility raises questions including whether such improved performance is cost-effective, and (if so), how should it be treated analytically and practically.

These ambiguities regarding alternatives to hardwood timber girders can either be seen as a barrier to the development of alternatives, or as an opportunity to create improved solutions. However, the need for alternative girders is likely to increase as fewer hardwood logs are made available to asset owners. There is much to be gained for all concerned by exploring new possibilities, and this requires collaboration between asset owners, product developers, bridge maintenance staff, manufacturers, and indeed the community. This paper demonstrates that alternative solutions can be found, and that these provide exciting opportunities for new products.

6 ACKNOWLEDGEMENTS

The authors wish to acknowledge the support and assistance provided by the RTA, RIC, QDMR, FWPRDC and Qld Department of Environment. Without the involvement of these authorities these developments would not have been possible. In addition to this support, FCDD has also greatly benefited from a $7.5M infrastructure grant made available by the Queensland Government from the Smart State Research Facilities Fund (SSRFF) support scheme.

7 REFERENCES

(1) DUTTON S. and CARTWRIGHT B., "Findings of a study into the feasibility of building a polymer composite bridge as a technology demonstrator project – Technology Diffusion Program: FINAL REPORT", CRC-ACS, January 2001

(2) STANDARDS ASSOCIATION OF AUSTRALIA "AS1720 Timber Structures Code", Standards Association of Australia, 1974.

(3) AUSTROADS, "Australian Bridge Design Code", AustRoads, 1996.

(4) STANDARDS AUSTRALIA, "Draft Code AS 5100.1-200X Bridge Design", Standards Australia, 2003.