

Alternative Hardwood Girders – An Innovation with Composites

Tim Heldt - Fibre Composite Design and Development, University of Southern Qld
Craig Cattell - Fibre Composite Design and Development, University of Southern Qld
Rod Oates (RTA) - Roads and Traffic Authority, New South Wales
Peter Prasad (RIC) - Rail Infrastructure Corporation, New South Wales
Wade Arthur (DMR) - Department of Main Roads, Queensland
Gerard Van Erp - Fibre Composite Design and Development, University of Southern Qld

SYNOPSIS

Australian hardwoods are an excellent general purpose building material, however in recent years they are becoming 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.

FCDD has been developing hybrid composite/timber beams for several years in collaboration with major timber bridge asset owners, and is now in the process of specialising products to meet the needs of specific asset owners. This collaborative process has revealed a range of philosophical approaches to the establishment of “target parameters” for hardwood alternatives that vary significantly in terms of product behaviour and performance. This is compounded by the lack of a recognised national approach to timber bridge design and evaluation, and the additional structural behaviour possibilities associated with emerging technologies.

This paper begins by discussing some of the contemporary issues to be considered in timber bridge engineering and management, which leads to the pursuit of hardwood alternatives. Recent developments at FCDD are then described, and some typical cases are illustrated. A series of questions are raised as a result of this discussion, and these are summarised. These and other issues require further detailed consideration.

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 a performance

specification. Timber bridge technology has developed with a focus on workable solutions rather than performance specifications. Ascribing performance specifications to timber bridge components that are generic enough for other materials to be considered as alternatives is relatively difficult.

While the shortage of hardwood timber bridge components is relatively easy to define as a problem, development of solutions to this problem requires a relatively detailed understanding of a range of issues. This paper begins with a discussion of these issues based on the recent experience of Fibre Composite Design and Development (FCDD). One of FCDD's hardwood substitute alternatives is then described, along with a summary of 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 high quality sections 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 (fewer source trees) and community pressure to preserve those resources that remain. Asset owners such as the Roads and Traffic Authority of NSW (RTA) can be presented with conflicting requirements, for example:

1. Heritage listing demands that structures be maintained close to original condition;
2. Environmental regulations limit the availability of materials required to achieve (1);
3. Increasing load requirements mean that safety margins are eroded even when traditional (sound) material sources are used.

FCDD has been involved in discussions with a number of authorities (summarised here). Based on these discussions there are large numbers of structures that will continue to require replacement members made from hardwood (or alternative materials), to maintain them into the future.



Figure 1. Heritage Truss Bridge (including cross-girders) Typical of RTA Structures

The RTA and FCDD commenced a collaborative 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 Department of Main Roads-

Queensland (DMR) was also investigating possible alternative replacement timber girders for their timber bridges, as was the Rail Infrastructure Corporation-NSW (RIC). Typically RIC hardwood girders were of sawn square section rather than round (as used by DMR).

FCDD began developing alternatives to meet RTA's general requirements, and had identified a possible solution by November 2002. FCDD proposed a hybrid softwood beam with properties that exceed those of hardwood beams, incorporating a patented fibre composite and steel hybrid module. This alternative used plantation timber and had the potential to be commercially competitive.

Subsequently, discussions between FCDD and RIC revealed a desire to obtain longer timber replacement girders. RIC has many three span (road over rail) timber bridges with supports close to the tracks. Substantial rehabilitation of these bridges should incorporate the possibility of managing the risk of collapse resulting from a collision between a train and the bridge supports. Use of long span hybrid girders has the potential to reduce or eliminate this risk using simple and economically effective technology.

Based on interactions between FCDD and these asset owners, some alternative timber girders can be considered direct timber substitutes with fitness-for-purpose based on current hardwood timber components. However in other cases, timber substitutes are required to have the general characteristics of traditional hardwood timber, but have technical or functional performance exceeding traditional timber. This situation is complicated by some gaps and inconsistencies with respect to codes and standards for timber bridge design and assessment. These issues are outlined in Section 2.1, before the pursuit of alternatives is discussed.

2.1 Bridge Code and Assessment Issues

The generally accepted document currently used for the design and assessment of bridges is the 1996 Australian Bridge Design Code [3], which uses a loading model collectively known as T44. Over recent years, a new loading code has been developed and is currently in draft form as Draft Code AS 5100.1-200X [4]. This is a substantial revision compared with the earlier document [3] and is still being debated. The draft code [4] has a new loading model collectively known as SM1600. While SM1600 is part of the draft code, it is now generally used by most road authorities for the design of new bridges (replacing the older T44 loading), since it is anticipated that it (SM1600) will be accepted once the draft code is ratified. Thus many road authorities are currently using the new SM1600 loading with the older 1996 Australian Bridge Design Code [3].

Neither of the above documents [3,4] have sections dealing specifically with the design or evaluation of timber structures. Consequently there is no current comprehensive "code coverage" of timber bridge structures, so asset owners must develop their own approach to this problem. For example, the RTA reverts to the 1976 NAASRA Bridge Design Specification [5] as being the most recent relevant code with a section on timber bridges. This section is relatively brief, and calls up the contemporary timber code AS1720 [6]. This was a working stress code, whereas the current timber structures code AS1720.1 [2] is a limit states code, and is not considered to be as compatible with the older NAASRA document. To comply with Clause 10.2 (i) in NAASRA [5] the RTA does not utilise the Impact Effect Factor from the T44 loading model and the load duration (k_1) in the old timber code [6] is taken as unity. Other organisations may have different approaches, and will therefore produce different solutions to what may be considered similar design or evaluation problems. This situation means that there is not a consistent approach (nationally) to the engineering and

assessment of timber bridges using the (traditional) materials currently available, which adds to the difficulty of specifying alternatives.

2.2 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, even if this does not extend to a codified approach to the engineering of timber bridges. They are considered strong, durable, reliable, easy to work with, somewhat variable, and (until recently) readily available. There is a strong empirical knowledge base with respect to safe and workable solutions, and the material is considered to be relatively “forgiving”.

Some characteristics are relatively easy to quantify, in particular:

1. Strength;
2. Stiffness;
3. Cost.

In the case of (1) and (2) the Australian Timber Structures Code [2] quantifies these characteristics, while (3) has traditionally been stable and accessible through a range of databases. In the case of (1) and (2), the values suggested by AS 1720.1 are significantly less than values known to apply to bridge girders. This probably 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 how should they be specified?

Durability is another characteristic that has been quantified reasonably well in AS 1720.1, and has been based on visual grading and species identification. 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 hardwood that truly meet specifications (without heartwood). 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 difficult 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 to be a desirable characteristic, and is essential given that there is considerable dimensional variability in traditional hardwood girders supplied to road authorities. However changes in work practices are desirable if hardwood alternatives are to be seriously considered. For example an asset owner may purchase a hardwood bridge girder for \$ 2,000, but the final installed cost may be \$ 10,000. 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 (girder). However, there is potential (through correct detailing) to reduce the installed cost of the girder for the asset owner, without significantly reducing the adaptability of the girder. Development of a competitive alternative to hardwood girders will require close collaboration between product developers, asset owners and bridge gangs, particularly with respect to work practices.

2.3 Engineering Approaches to Hardwood Girder Substitutes

When considering hardwood substitute girders, it is useful to first review the behaviour of existing hardwood girders. As part of a joint project between FCDD, RIC and Wagners Composite Fibre Technologies (WCFT), a 300 x 300 F22 timber girder was supplied by RIC for destructive testing. It was tested with a support span of 6600 mm and a loading span of 500 mm, as shown in **Figure 2**. The results of this test provide a useful benchmark for the purpose of comparison with alternative hardwood girders.

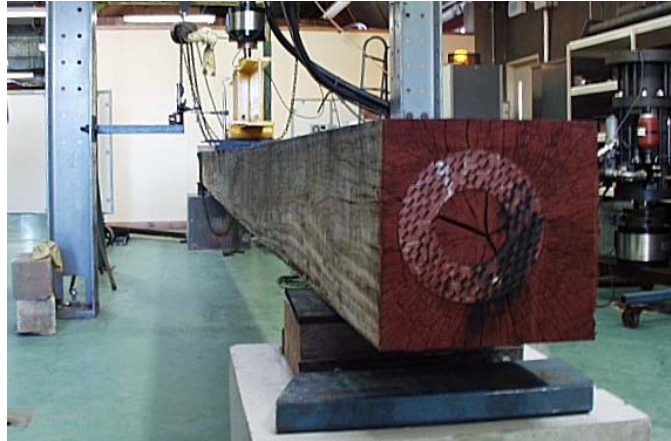


Figure 2 Timber Beam Test Arrangement

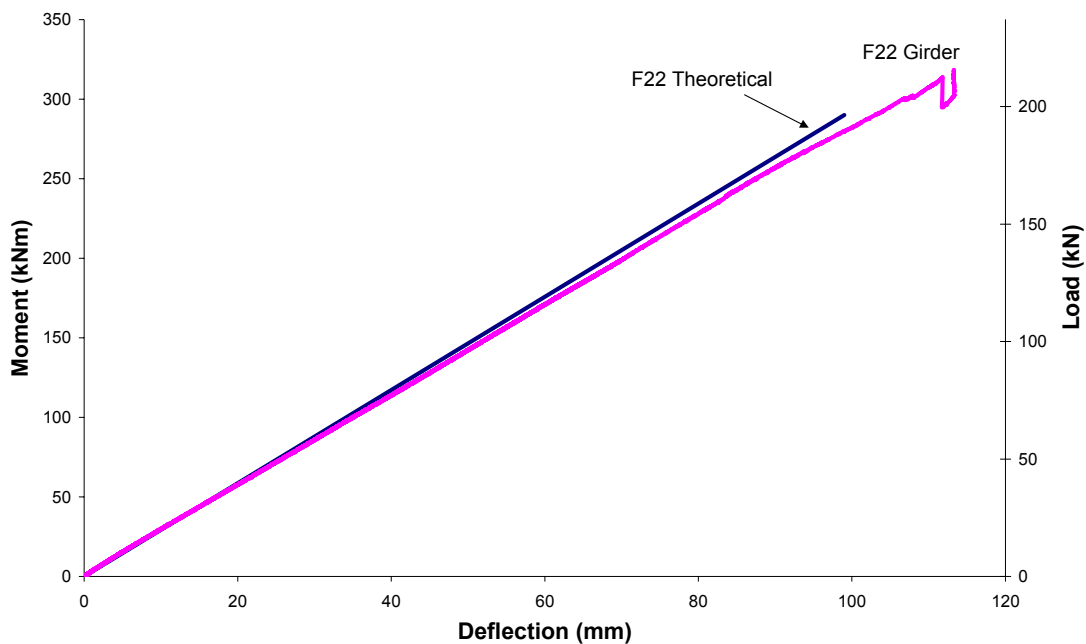


Figure 3 Moment and Load – Deflection Graph of Timber Beam

The behaviour of the beam was linear until cracking of the timber in the tensile region, which occurred at a load of approximately 220kN, as shown in **Figure 3**. 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 on 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 calculated modulus of the timber beam was 10500 MPa, which is marginally lower than the

F22 design modulus of 10800 MPa. The failure on **Figure 3** is typical of linear elastic materials, particularly the limited post-failure load carrying capacity.

In most cases, alternative girders will be used as substitute members in existing timber bridges. FCDD has identified three broad (philosophical) approaches to the engineering of such alternative hardwood girders based on discussions with asset owners, namely:

1. Reference to AS 1720.1 - Existing structures have been functioning with girders selected by visual stress grading. Therefore alternative hardwood girders should be pre-engineered to have mechanical characteristics compliant with AS 1720.1. This approach places emphasis on timber characteristics rather than loading models;
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, and as mentioned in Section 2.1, this is often involves SM1600 loading;
3. Capacity of old growth timber - When old growth timbers were plentiful, timber bridges were adequate. Bridges with these timbers still in good condition are still adequate. Therefore alternative hardwood girders should be pre-engineered to have the capacity of these old growth girders [3]. This philosophy is quantified using test results, and makes limited reference to codes.

In practice when developing hybrid girder hardwood alternatives, each of the above approaches amounts to manipulating the cross-section and material usage to produce target stiffness and strength behaviour. These target behaviours vary significantly from each other, yet each has its merits. It is possible that different approaches may be required for different asset management situations. If a hardwood girder alternative concept is to be applicable to all three approaches, then it must be very adaptable. Over time, it is possible that these approaches (target performance) will develop further (and preferably converge) based on detailed collaborative research.

2.4 Summary of Issues Influencing Development of Hardwood Girder Substitutes

Timber bridges are likely to require on-going maintenance and management for the foreseeable future under the contrary community requirements of increasing load and reduced availability of appropriate hardwood timber. This creates a demand for technically and economically viable alternatives. The development of alternatives is influenced by a lack of nationally agreed definition and certainty regarding the target requirements of such alternatives, in particular:

1. Lack of a recognised and representative specification for hardwood girders;
2. Lack of a recognised standard or code for timber bridge design or evaluation;

This is illustrated by different philosophical approaches used as the basis for target performance parameters of hardwood girder substitutes described in Section 2.3. This may result in a proliferation of alternatives. However a collaboratively developed national approach to this problem is likely to produce more cost effective and reliable alternatives for the community.

3 HYBRID ALTERNATIVE HARDWOOD GIRDER

The philosophy of the hybrid beam concept developed by FCDD is based on the optimal use of different materials as shown on **Figure 4**. 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 and some of the bending capacity for the beam, maintain the separation between the reinforcement modules, and provide the functionality associated with timber.

Reinforcement modules used are a combination of materials including steel reinforcing, polymer concrete, carbon and glass fibre reinforcing. Steel reinforcing bars are primarily used to provide additional 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 glass fibre reinforced polymer (GFRP) laminates (modules). This provides an extremely effective barrier against moisture ingress, and subsequent corrosion of the bars (bars are terminated short of the end of the reinforcing module). The GFRP also provides strength after the steel has yielded. As a conceptual illustration, the GFRP typically used has tensile strength equivalent to a Y32 bar, however it contributes comparably little to the stiffness, being equivalent to a Y12 reinforcing bar for stiffness calculations (strength of the glass is only mobilised at high strain values well after the steel has yielded). The GFRP 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.

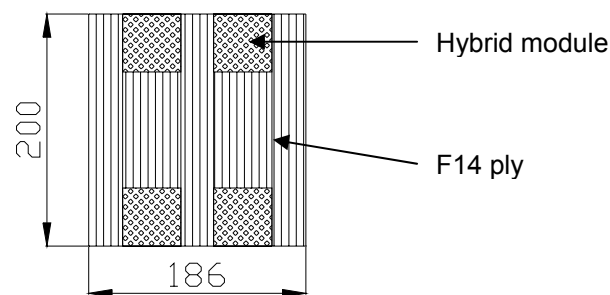


Figure 4 Cross-Section of 3m Test Beam

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 186 mm wide x 200 mm deep were manufactured using Alkaline Copper Quaternary (ACQ) treated plywood timber. The first was made from solid F14 plywood. The second beam was similar but had four composite modules added to it as shown in **Figure 4**. The beams were tested in four-point bending with a support span of 2500mm and a loading span of 500mm.

The first (plywood) beam closely matched the characteristic stiffness of 8×10^{11} Nmm², but had an ultimate strength 40% higher than the characteristic F14 bending strength of 20MPa (f'_b in AS1720.1-1997 Section 5 is 40MPa, with 50% of plies having the grain direction parallel to the span). The results for this test are shown on **Figure 5**. Typical code results for F22 and F34 timber are also given on **Figure 5**. The second (reinforced) 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 composite hybrid beam also had a ductile failure mode (**Figure 5**), providing significant warning of failure through cracking of the ply and the associated large deflections.

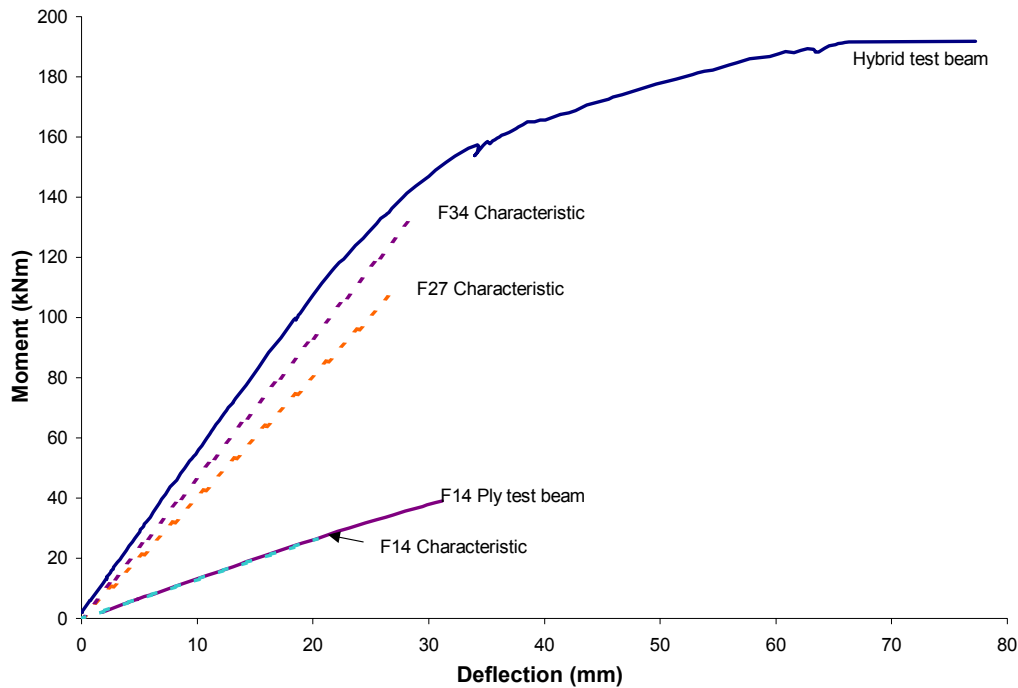


Figure 5 *Moment-Deflection Graph of Results from 3m Beam Tests*

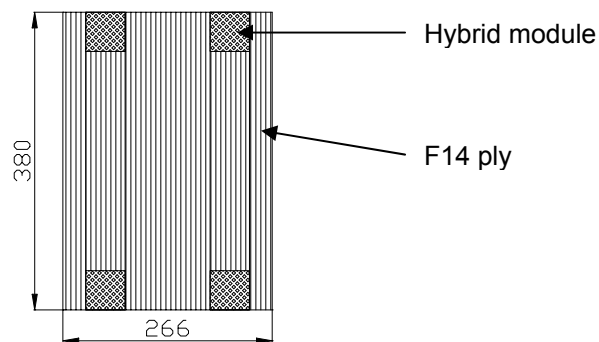


Figure 6 *Cross Section of 6m Test Beam*

Following successful testing of the 3 m beams shown in **Figure 5**, a 6 m test beam was constructed that had a constant cross section of 266 wide x 380 deep (**Figure 6**). This beam again consisted of ACQ treated plywood with four composite modules. The beam was tested in four-point bending with a support span of 5600, and a loading span of 1500. Results for this test are given on **Figure 7**. The 6 m test beam was slightly stiffer than an equivalent F27 beam and had a marginally higher strength than the characteristic strength of an equivalent F27 beam. The failure mode of this beam exhibited some ductility as the steel yielded, however ultimate failure of the beam was initiated by tensile failure of the ply, which caused an inter-laminar shear failure of the interface between the composite module (laminate) and the ply. Consequently, this beam exhibited less “ductility” than the previously tested 3 m beam.

The test results represented on **Figure 5** and **Figure 7** utilised plywood cores. FCDD has also been developing this concept using LVL cores, and results from these investigations have also proved promising. It is likely that products will be developed that utilise both ply and LVL

cores to meet specific alternative hardwood requirements. This is the subject of on-going investigations.

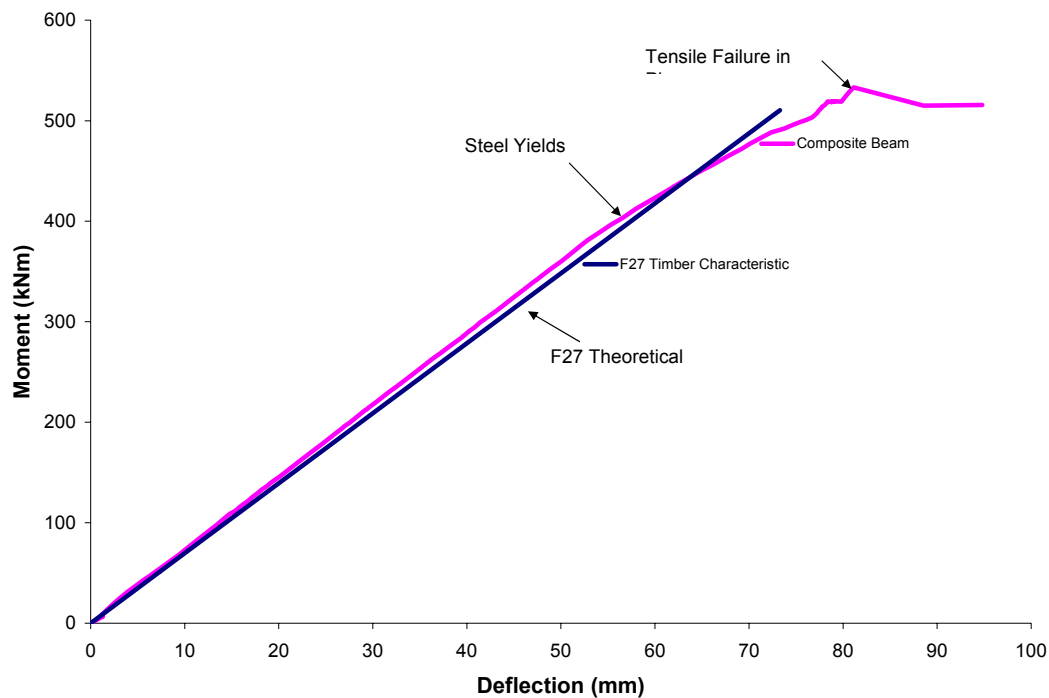


Figure 7 Moment-Deflection Graph of 6m Beam

A review of **Figure 5** and **Figure 7** reveals that there is potential to engineer “pseudo-ductile” behaviour into hybrid beams. That is initial rupture of the timber can correspond to a “plastic” response (**Figure 5**) rather than a sudden loss of capacity (**Figure 3**). 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?

The plateau on **Figure 7** is less pronounced than that on **Figure 5**. Understanding this difference in behaviour is important in the context of the above questions, and this can be explained in terms of material failure strain. On **Figure 5**, the cause of the initial loss of stiffness in the hybrid beam was yielding of the steel within the reinforcing module, and this occurred (as expected) at a bar strain of approximately 0.25%. While the steel continues to carry load, its load carrying capacity no longer increases with increasing strain (hence the reduction in stiffness). The beam continued to deform until the failure strain of the timber was reached at approximately 0.4%. This produced the second major change in stiffness, and subsequent deflection occurred for very little increase in load. By this stage the glass reinforcement was carrying much of the tensile load at the critical cross-section (failure strain of a glass laminate is approximately 1.8%).

The first failure mechanism is relatively benign (steel continues to carry load). The second failure mode (rupture of the timber) is quite violent. If the beam is to continue to carry load after this point (**Figure 5**), then the glass reinforcing system must be able to accept this

sudden transfer of load into it. If there is insufficient glass to “catch” this shock loading then rupture of the glass system may occur, even though there is sufficient capacity in the glass to carry the additional “static” moment at the critical cross section. This produced the result shown on **Figure 7**.

Consequently, ensuring the full plateau is available may require additional glass above that required for static moment capacity. More energy will be released in the case of beams with LVL cores, compared with ply cores due to the difference in cross-section stiffness. Additional glass will be relatively expensive, and will increase the cost of the alternative girder. Consequently the fourth question on the above list should be “is the guarantee of achieving the plateau worth the additional expense?”

4. DEVELOPMENT OF PRODUCTS

Sections 2 and 3 (above) show that many issues are yet to be resolved with respect to alternative hardwood timber girders. FCDD continues to work with road authorities to resolve these issues, and in the process, develop products that meet the needs of these authorities. Currently agreements are in place to develop and supply demonstrator girders to the RTA (NSW), RIC (NSW), and the Department of Main Roads, Queensland. 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 cross-section was shown on **Figure 6**, and will be used as a cross girder in the bridge shown in Figure 1. Other examples of typical hybrid girder demonstrator projects are discussed in Sections 4.1 and 4.2 below.

4.1 Short Span (7 metre) Girders for RIC

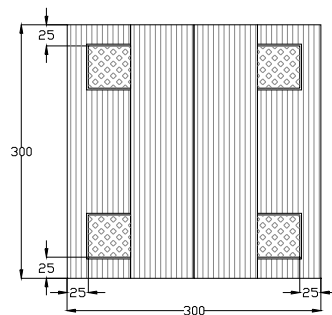


Figure 8 Cross-section of short span RIC beam

The standard timber overbridge beam used by RIC is an F22 hardwood girder with a cross-section of approximately 300mm x 300 mm, and approximately 7 m long. FCDD has developed an alternative beam to match the AS1720.1 requirements (**Figure 8**). 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 1.3×10^{13} Nmm² (an equivalent Modulus of Elasticity of 18,900 MPa), and a design strength of 300kNm (giving an equivalent bending strength of 67 MPa).

4.2 Long Span (18+ metre) Girders for RIC

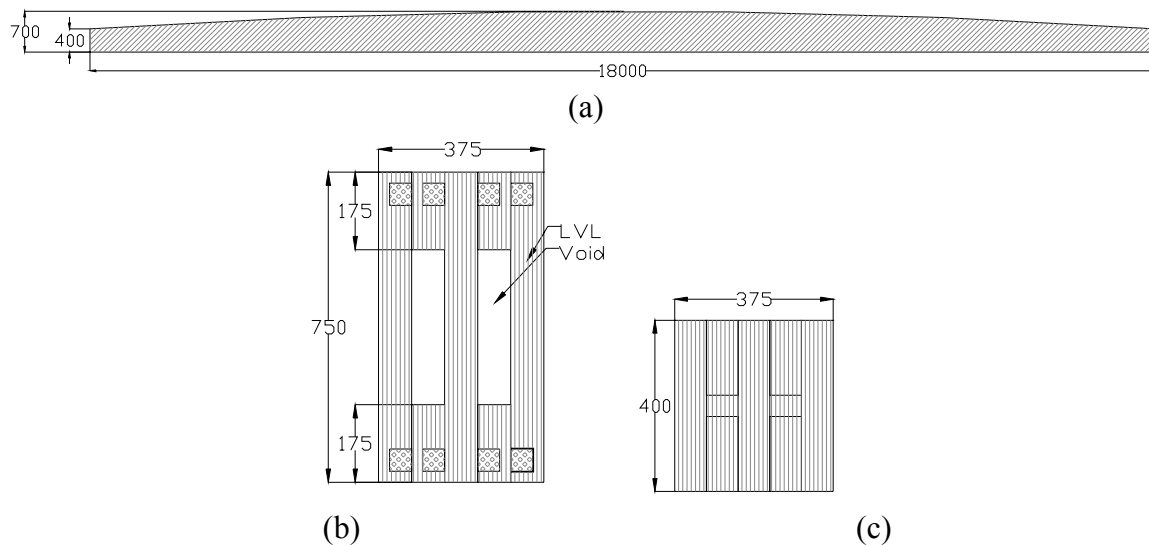


Figure 9 Proposed long-span beam-
(a) Elevation (b) Mid-span Section (c) End of Beam

The RIC also has a number of sites where long spans are required, and site conditions are unfavourable. In some cases, site requirements mean that relatively shallow girders are required to minimise earthworks and retain minimum track clearances, yet sufficient depth is required in order to produce girders with satisfactory stiffness and cost. Consequently these girders will have flat soffits, but the top surface will be curved in the form of the arc of a circle, with a typical rise over the length of the girder of 350 mm (**Figure 9**). This provides reasonable depth of girder at mid span while minimising abutment depth, and is made possible by the relatively low speeds over the bridge caused by tight horizontal alignment of adjacent roads. This form of solution also means that no pre-cambering of the girders will be required. Again, the reinforcement modules are stopped 500 mm from the end of the beam to better protect the bond line from moisture ingress. In the high shear areas at the abutments, the void is filled for the end 1500mm with LVL to create a solid beam.

5 SUMMARY AND CONCLUSION

The engineering and assessment of timber bridges is not particularly well dealt with in contemporary codified documents, and there is a corresponding variation in approach to this problem nationally. This situation is exacerbated when new structural alternatives are to be developed, because there is not a consistent basis to begin with. This can be viewed as a problem or an opportunity depending upon one's perspective. Through collaboration, it is possible that new and improved alternatives can be proposed that more comprehensively address some of the underlying issues with timber bridge engineering. Simply the use of pre-engineered products (rather than highly variable natural products) may assist in developing a more cohesive approach to the problem. This is likely to have the effect of providing greater assurance, regardless of whether it improves the quality of timber bridges.

In addition to the above, 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 philosophical

approach that should be used, particularly with the introduction of the new SM1600 bridge load model. Current alternatives can be broadly summarised as:

1. Use the known geometry and characteristic values from 1720.1 to determine the target structural behaviour of alternatives;
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 that are no longer available.

Other alternatives other than (1) to (3) may also exist. Currently products are being developed by FCDD 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. Progress is being made, and it is likely that new issues and options will arise as these issues are dealt with.

Alternative girders 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. The need for alternative girders is likely to increase as fewer hardwood logs are available to asset owners. There is much to be gained 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

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