Development of Nailed/Screwed Modules for Stress Laminated Timber Arch Bridges

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Summary

This paper describes the experimental part of a research programme carried out at Napier University in collaboration with the UK's Forestry Civil Engineering, Forestry Commission, to develop a series of new laminated modular systems for timber bridges. It details some of the practical/construction issues relating to their off-site manufacture and on-site assembly. The work follows on from recent research studies by the authors on developing vertically stress laminated timber arches. It is focused on using stress lamination technique to utilise the UK grown small-sections of low-grade timber to form strong low cost sustainable bridges. The main advantages of this form of lamination are the lateral distribution of load, the dispersement of defects in the timbers and the use of timber in compression. The very low cost of early arch bridges was offset by the expensive installation/ erection costs; so ways of reducing these costs have been the focus of current work. For large span bridges, modular construction was considered an effective way of reducing scaffolding costs; whereas, for the short-span ones, complete manufacture of bridges in the workshop was regarded as the best way of reducing site costs. The use of nailing, screwing and gluing was also examined to facilitate the modular construction, to improve stiffness and strength and to reduce cost of stressing.

1. Introduction

Recent research at Napier University, in collaboration with the UK's Forestry Civil Engineering, has concluded that stress lamination of timber in an arch form provides many opportunities to utilise low-grade timber in construction. The construction of long-span bridges has involved major scaffolding costing more than the total for the materials for the bridge. To reduce the cost of a bridge by some 25%, by omitting the use of scaffolding, and to improve on the buildability, a research programme set out to develop a system of modular construction of 'beam units' which are easily lifted and placed side by side and stressed when in place. These units were required to be of low cost, light and robust enough to sustain all construction forces in the temporary mode in order to compete with the alternative construction methods.

2. Stress Lamination of Timber

Stress lamination is different from the known glued lamination which requires strict quality control and results in high quality expensive products. A vertically stress laminated element is formed by drilling holes in the wide face of sawn timbers at centres of between 300mm and 900mm. These timbers are laid side by side on their narrow edge, stressing bars are passed through the holes and then stressed to between 100kN and 200kN tension.

The friction between the faces, induced by mechanical stressing, permits transfer of load from one laminate to the next. This converts the whole into a solid load-bearing orthotropic deck with the ability to transfer load laterally and longitudinally. The natural variability and defects found in timber are responsible for the reduced allowable stresses in whole timber. However, when vertically laminated the defects and natural variability are dispersed and the efficiency of the system is greatly enhanced. This form of construction utilises a low cost sustainable material with the minimum input of quality control and production energy. The resultant life cycle carbon footprint is very low compared with other bridge construction materials.

Fig 1 A 20m span test bridge at Glentress during construction

3. Recent Research

A recent research study by the authors [1, 2] investigated the performance characteristics of stress laminated timber arches in detail. The significant findings include the ability of the structures to sustain large deformations and the redistribution of resulting stresses and also the effectiveness of the arching action which contributed to their stiffness and strength characteristics. The arch shape allowed the timbers to take forces in compression parallel to the grain through the friction between the laminates and end bearing. Unlike a masonry arch, which would fail as a result of a very small shape change, the stress laminated timber arch can sustain large deformations, is very good in bending and recovers on load removal. All load tests to failure over a 3 year period resulted in ductile (slow plastic) failures which would give plenty of warning in a real structure.

(a) Laboratory tests (2.1m to 15m spans)   (b) Field tests (20m span)

Fig 2 Arch structures during testing

The study showed that it is possible to make a good prediction of structural performance using a step-wise elastic linear analysis based on large-deformation concept. Semi-empirical models were also developed to assist engineers with the analysis-design process, taking into account many possible boundary conditions.

Because this type of structure proved successful with span to depth ratios of 1 to 100 and the material is essentially all timber, these structures were extremely material and energy efficient. This has formed the basis for further development of different types of structure using the stress lamination technique.

4. Markets and Uses for SLT Structures which are Driving Research

The stress lamination technique was first developed in Canada [3] and has been successfully used for 30 years in the USA where many hundreds of flat deck bridges have been built. The arch form was first developed in the UK in 2000 and has since lead to about 40 commercial bridges being built.

These bridges are mostly arches for pedestrians but there are some flat decks for 44 tonne lorries. This year the first long span arch and flat deck combination will be built for 44 tonne lorries. Commissions have also been received to design a 40m span railway arch and flat deck combination and a 40m span Leonardo double arch footbridge.

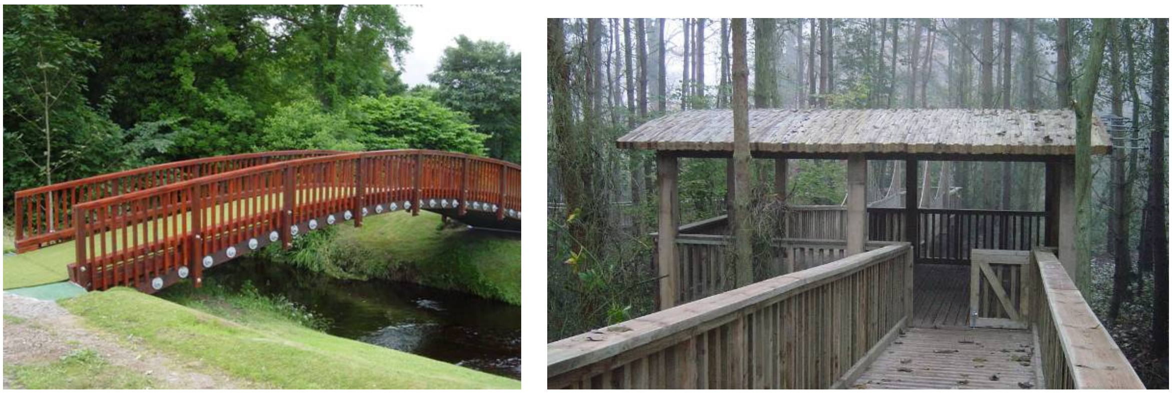


Fig 3 Examples of a stress laminated arch structures built in the UK

Stress laminated arches have been used for roofs, though there is still much development required, and there is great interest in the use of the technique for industrial floors. There are also plans to build tall towers using stress laminated legs and bracing panels stressed between legs to provide the lateral restraint. Also, there is a new market in Forestry for temporary bridges for forwarders and harvesters which are large machines with total weights up to 40 tonnes. Because they have a very high ratio of strength to weight, the forest machine can carry its own bridge without the need for a crane.

However, the biggest market will be for footbridges. In the UK there is a need for at least 2000 replacement bridges in rural areas. Development of these kinds of bridges, made in factories and light enough to be transported to site complete and lifted into place, will be in demand.

5. Construction of Modules

The aim of this project was to determine the viability, dimensional limits and the type of fixings that would be required to produce self-supporting modules to take construction loads. The modules would have to span the full distance from abutment to abutment and be of a weight that could be easily lifted. The aim was to produce modules weighing less than one tonne so that an excavator (often available on site for other purposes) can lift easily. This means that there will be no need to hire a crane, so keeping cost down.

The width of a module was selected to be a multiple of the number of stressing holes in each full-section of the lamina. For example, for a system with laminates of 4 holes per section, the width of a module would be a multiple (n) of four times the thickness of a laminate i.e. $n \times 200$mm for 50mm laminates. It was therefore decided to start with 400mm wide modules which would keep even the longest spans under a tonne in weight.

The laminates were temporarily fixed by nails or screws to one another to form the modules. The modules would then be lifted into position and laid side by side, while being temporarily supported laterally, and stressed together to form the permanent bridge deck.

5.1 Timber species

The stress lamination project in the UK aimed to explore the possibilities of using locally grown species such as Sitka spruce, a low-grade plantation timber, for large structures. However, as Sitka spruce is not durable and is very difficult to treat with preservative, other home-grown species like Scots pine, Larch or Douglas fir are preferred for high value bridges, as they are either more durable or take preservative easily. However, some structures were built using Sitka spruce for demonstration purposes.

For these tests a relatively dense Douglas fir from the Scottish Borders was used. This resulted in some difficulty with nailing but provided useful comparisons with the timber used for other tests in similar projects.

5.2 Fixings

The module fixings are temporary fixings and as such they need to be low cost provided that the required stiffness and strength are achieved.


Fig 4 Assembly of a 12m span test bridge module in the laboratory.

The first trial was to make a roof for a Royal Highland Show exhibit. The laminates were nailed using 3mm diameter × 90mm long ridged nails fired from a gas powered gun. These modules were 4m span and they held together but it soon became clear that greater rigidity would be required for larger modules and some method was required to align the holes.

It was therefore decided to use plastic tubes through the holes to align them and use the same nailing specification to make the modules for testing. This technique worked well but the very dense Douglas fir was resistant to the gas powered nail gun. Shot firing the nails using cartridges would have driven them to the full depth. This was considered too expensive and would render the module approach non viable. However it was judged that future modules would use less dense timber so the nails which did not drive fully into the laminates were hammered home. Nails were driven in approximately 50mm from each side of every hole which amounted to 8 nails per laminate.

5.3 Module types and sizes

The experimental work was designed to examine a range of different sizes of modules and spans to determine the viability and dimensional limits of modules that could be made. A recent PhD study [5] on stress laminated arch bridges concentrated mostly on span to rise ratios of 12:1 and 6:1 so it was decided to maintain these ratios so that test results could be compared to previous experimental work and provide some valuable cross-referencing.

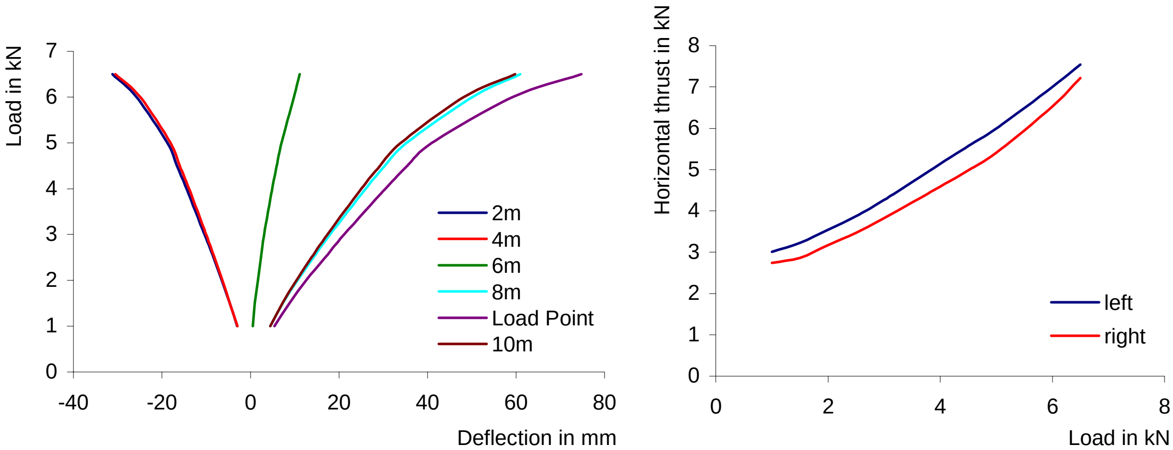
As design had shown that a 100mm deck depth is strong enough to withstand pedestrian loading over a span of 6m, 150mm over a span of 12m and 200mm over a span of 18m, it was decided to construct and test two replicate modules of each of these three spans with two different rises. The rises of these arches were 0.5m and 1m for the 6m span, 1m and 2m for the 12m span and 1.5m and 3m for the 18m span.

6. Experimental Work

6.1 Structural load tests

Prior to static load tests, each module was raised up and then lowered by a crane. This was to allow the module to hang down (sag) from a crane sling as well as being subjected to a small impact under its own weight and allowed for its ends to slide apart. This was repeated a number of times aiming to simulate a range of possible stress conditions that might occur during lifting and assembly on site. Then, each module was placed under the laboratory loading machine, supported at each end by a steel channel, held together and prevented from spreading apart by two 20mm diameter treaded rods, in series with load cells which recorded the horizontal thrust at the springing points of the arch. The modules, after a regime of bedding-down loads, were first subjected to four-point loading of up-to half their service design load (to avoid damage), then by a line load at mid-span before being loaded at a quarter span position to failure. The load was applied through a bed of sand to exert uniform pressure across the laminates. Deformation of the arch was recorded at various positions along the span using displacement transducers. Sample results are shown in Fig 6.

Fig 5 A 12m span nailed bridge module during lifting and under quarter-point load test.



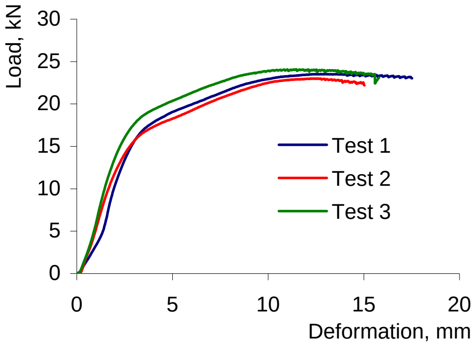
(a) Vertical deformation (b) Horizontal thrust

Fig 6 Load-deflection behaviour of 12m span 1.0m rise nailed module.

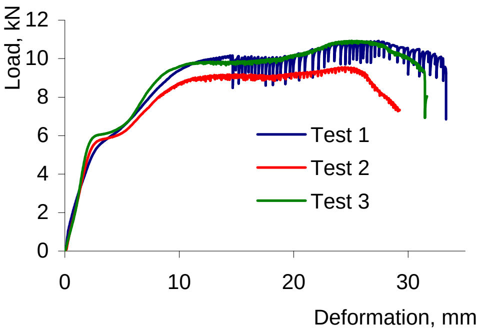
6.2 Fixings tests

To determine the shear strength of the fixings joining the laminates, a series of tests was carried out to evaluate the strength characteristics of three member timber joints incorporating nails in single shear and the plastic tubes in double shear. Three separate tests were carried out: 1) joints connected with both nails and tubes, 2) joints with the tubes only and 3) joints with the nails only, Fig 7.

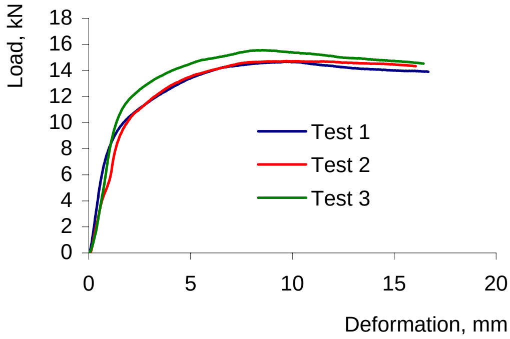
(a) Typical samples



(b) Joints with 2 tubes + 10 nails



(c) Joints with 2 tubes only



(d) Joints with 10 nails only

Fig 7 Load-deflection behaviour of fixings.

The shear capacity of one tube per shear plane equated to 1.73 nails and the capacity of the nails was very close to that permitted by Eurocode 5, almost 3kN at failure. The shear capacity of the connector systems used for the 6m and 12m span modules was adequate to take all the required loadings.

7. Factory Production

The production of a number of demonstration and commercial bridges had shown that factory production of whole, small span, bridges was in most cases a more efficient production method than making modules and assembling them on site. The method would require a small crane and provided that access was possible the cost saving of total factory production would be substantial. As an example, the building of Arran Golf Course bridge, shown in Fig 8, demonstrated that factory production of a 12.6m bridge, built traditionally using stressing bars, would lead to total installed cost of £20k for 30m^2 of bridge which is very competitive.

Fig 8 Arran Golf Course bridge during installation – the completed bridge is shown in Fig 3 (left).

8. Further Developments

The sagging shape of the arches, when lifted at their centre point by crane, was taken as the empirical test of handling capacity. The 6m spans were very robust but it became clear when lifting the 12m spans that the nail jointing was at near capacity and that an 18m span would require connectors with larger diameter and length penetrating two or more laminates and this was out of the range of the gas powered nail gun.

In a parallel research, the efficiency of using a combination of glued and nailed/screwed lamination for flat decks and arches and their effects on enhancing structural performance were examined. The findings of this research and possible applications are encouraging and are likely to lead to the use of such techniques for production of long span arch modules. The results of this study are currently being processed for publication in due course.

A possible application of the use of glued and screw method is for the standard steel beam and timber plank road bridges built by Forestry Civil Engineering which have been suffering premature failure of the decks while new health and safety laws are making them difficult to build. To explore this, factory-produced glued and screwed vertically laminated timber slab modules supported on steel beams were tested for wheel patch loads and line loads.

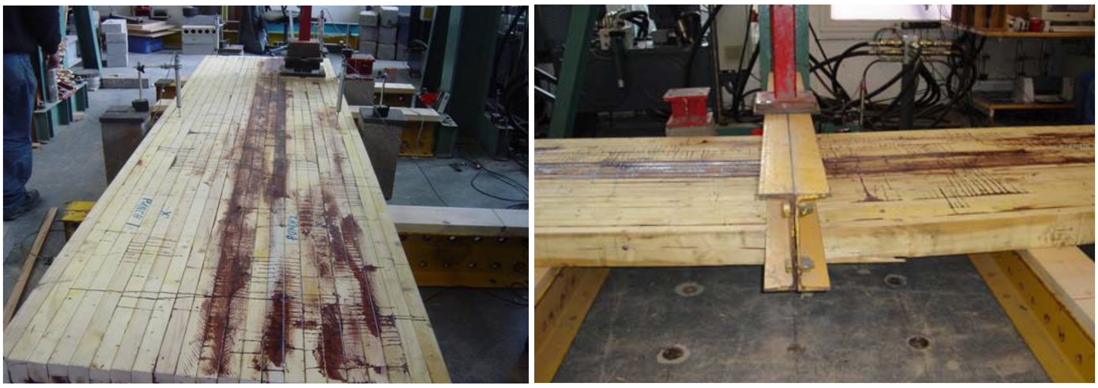


Fig 9 Load testing of glued and screw laminated flat deck.

The modules were glued and screwed with two different types of screw and at two different centres. All screws were 130mm long thus passing through 3 modules. All screws had a 50mm unthreaded shank so that as they were tightened they pulled the last module into the two adjacent ones. Coach screws, requiring pre-drilling, were used on half the deck while the other half was pulled together using narrow gauge screws without pre-drilling. The two different spacings for each screw type were 300mm and 600mm centres.

The load tests consisted of 200kN on a 300mm square patch, at different locations, to simulate a wheel on 4 different locations. Finally a line load was applied at mid-span and increased until failure occurred in bending. The success of the tests lead to the first 18m span road bridge being built using these modules with glue and narrow gauge screws at 450mm centres. These modules have no holes for stressing bars which makes the preservative treatment easier.

9. Summary

The project began by making and testing modular units with a view to reducing the site costs of building SLTA bridges. The tests on the 400mm modules of up to 12m span showed that they were strong enough for all temporary and construction loads. The shear tests on the laminate interface showed that 8 nails of 3mm diameter 90mm long per laminate were adequate for load transfer when used with plastic tubes. The use of plastic tubes to facilitate the insertion of stressing rods also contributed to the shear capacity of the connection medium.

It was shown that this modular approach with nails was limited to 12m span. Larger nails for longer span modules would need to be shot fired which could be too costly, so screws and glue were considered as alternatives. The use of screws and glue for manufacture of smaller bridges without the need for stressing bars was also examined and it was found that they can be viable construction systems as they exhibit adequate structural performance as well as being factory manufactured at low cost.

10. References

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