Development of Long Span Stress-Laminated Timber Arch Bridges

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Summary

For the last 2 years the authors have been involved in optimisation of the performance of stress-laminated timber (SLT) structures by utilising the strength properties of timber in an arching action for use as vehicle and pedestrian bridges. During that time 9 permanent bridges have been built and 7 have been load tested. The tested bridges were a half-scale of a 12m span bridge (i.e. 6m span) and a full-scale bridge of 15m span. Laboratory tests have also been carried out on a series of third-scale models with 3 different arch profiles and with 2 flat decks to study the interactions of friction and arching profiles with different pre-stressing tensions. It has become clear that the design rules for flat SLT decks do not necessarily apply to arches. Furthermore a study of the structural behaviour of a full-scale long span SLT arch structure (20m span bridge) is being carried out at Napier University, so that static and dynamic responses to vandal loadings are examined and evaluated. Contracts are being let for the construction of 4 new arch bridges of spans between 20m and 26m. The extensive testing programme, augmented by analytical work aims to develop reliable design procedures for arch structures using UK softwood.

Keywords: timber structures; bridges; design methods; load testing.

1. History and Development

Stress-lamination of timber is a method of construction where a group of rectangular sawn timbers is compressed together by high tensile steel or threaded bars. The bars are passed through pre-drilled holes in the wide face of the timber sections and are tightened against external bearing plates. The resulting pressure sets up friction forces between the laminates which make the whole into a solid load-bearing timber plate or deck with the ability to distribute load laterally and longitudinally [1].

The simplest form of stress lamination probably began in the 19th century for building bridge decks by nailing neighbouring timbers together but with use, nails loosened or fatigued or corroded [2]. By way of a repair, about 25 years ago, the timbers were compressed together with stressing bars above and below the deck. This was successful although the stressing bars were vulnerable to damage. The type of structure was seen to have good potential so holes were drilled in new timbers and the bars were threaded through, near to the neutral axis, to form some new decks for trial.

The technique was later picked up in the USA at a time that a national survey showed a need for many small span replacement bridges in rural America. The form of construction seemed ideal as it utilised timber in smaller sections which were readily available, further, the construction did not require very specialist skills. The Timber Bridge Initiative was passed by Congress in 1989. This
emphasised the need for research, new bridge designs and of course brought with it funding. The initiative was to utilise wood and provide rural highway infrastructure to replace or repair the 592,000 bridges across the country which were damaged or worn out. A major programme of research and trials was set up by the USDA Forest Products Laboratory in 1988 [3] to develop the mechanical stress-lamination decks. This eventually lead to a new AASHTO standard [4] on the subject in 1991. From those beginnings the USDA’s National Wood in Transportation Program has funded 322 projects resulting in many more timber bridges throughout the USA.

As development took off in the USA, Michael Ritter visited other research centres in Australia and Europe. He stimulated development in a number of institutions including the Sydney Institute of Technology and the Nordic Timber Council. In 1996 Crews, K.I. [5] published a guide for Australian practice and Kleppe, O. and Aashiem, E. produced some spectacular structures in Norway. Other parts of Europe have also benefited from this form of construction. In the UK the authors have worked to maximise the performance of stress-lamination by utilising the strength properties of timber in an arching action, which contributes significantly to the overall strength and stiffness of the bridges.

All developments in mechanical stress-lamination of timber for bridge decks have used flat decks or beams in bending. They have either been plate decks, built-up decks or cellular decks. The plate decks can only span to about 6m using full highway loading and normal maximum timber sizes, up to around 250mm deep. Because of the restriction on maximum available timber sizes the built-up and cellular decks were developed to span further while supporting the same highway loads. These decks however entrap moist air which can create a rot problem.

Various design rules have been developed by a number of researchers to deal with butt joints and lateral transfer of loads to produce reliable bending and shear resistances for bridge decks for heavy highway wheel loads [5]. However, there remained a number of limitations if this form of construction were to be successfully used in the UK.

Prior to mid 2002 there had been no known examples of stress-laminated timber bridge structures in the UK. Initial investigation was prompted by a need for low cost forestry and rural public road bridges which had originally been built as stone arches and traditionally replaced by steel and concrete. Home-grown timber is now plentiful in the UK, although the quality and sizes are limited. Mechanical stress lamination techniques similar to those used in the USA and Australia looked to be of interest.

The span limitation was immediately a problem compounded by the size limitations of UK grown timber. Built-up and cellular decks were considered but neither has an immediate future in the UK because there is no established glue-lamination industry to produce beams for built-up decks and the climate rules against cellular decks. The UK is much wetter than other locations where these structures have been developed and as a result rot would become a problem through poor drying and ventilation. This led the authors to investigate implementation of stronger engineering properties of timber (compression and end bearing) in an arching action which would avoid and surpass the limitations of decks in bending.

2. Development of Stress Laminated Timber Arches in the UK

A search of international work revealed no guidance on this type of structure so the design rules for flat slab decks were viewed as the starting guide for SLT arch bridges. In order to determine the structural behaviour and performance of this new design (stress-laminated timber arch bridge) as it would be the first bridge of this kind to be constructed, a half-scale model with 6m span, 1m wide and 0.5m rise was built using 50mm×100mm deep timbers. After testing of this half scale bridge, an opportunity arose to build a 15m span bridge near Manchester. This bridge was designed as an arch with a 1.2m rise and 2m width with timber sections of 50mm×250mm deep. It was decided to build this at the university, under controlled conditions, then load test it before transporting it to its final destination in Manchester.

The bridges were designed for a uniformly distributed load of 3.2kN/m² using grade C24, FSC certified, timber; although the ultimate goal is to use C16 or C18 as these are the grades readily available from home-grown produce.
Grade D50 hardwood was used for the outer leaves of the 15m span bridge to resist the very high bearing stresses from the tensioning bars. The timber for the 6m demonstration arch was all softwood and consequently the outer leaves were subjected to bearing deformations.

### 2.1 6m span arch bridge

The design specified 100mm deep timber sections. The stressing bars were specified as 15mm diameter Dywidag steel high tensile ribbed shuttering ties. The rise was set at 0.5m to give a shape which could operate as a deck for pedestrians. It was set in a steel frame to provide effective rigid lateral support. After several pre-loadings, the bridge was subjected to a four-point loading of up to 50kN as illustrated in Fig. 1.

![Diagram of 6m span arch bridge](image)

**Fig. 1** Details of the 6m span arch bridge.

The bridge was then subjected to a series of point (line) loads at 0.75m from a support, then at 1.5m, 2.25 and finally at 3.0m positions. In each loading position, loads were increased up to a maximum of 15kN and the deflections were recorded. Finally the bridge was subjected to a point (line) loading at 2m from a support and was increased until failure occurred at 29.6kN, due to upwards bulging of the arch on the unloaded side. The performance of the bridge throughout the testing and in particular the magnitude of the failure load clearly indicated the considerable reserve of strength provided by the arching action in the bridge. In Fig. 2 the exaggerated deflected profiles of the bridge at various load levels up to 15kN are shown [6].

![Graph showing vertical deformation profile](image)

**Fig. 2** Vertical deformation profile of the 6m arched bridge under point (line) loading at 2m from a support. (Deflections are exaggerated by a factor of 4 for illustration.)
2.2 15m span arch bridge

The results from the 6m span tests gave confidence to design and build a permanent structure at 15m span. The design specified 250mm deep C24 timber sections and the bridge was constructed in a car park outside the laboratory and was loaded by up to 10 sand bags of 1 tonne (10kN) each, totalling 100kN, evenly distributed over the middle third of the span, using a mobile crane. The supports were tied horizontally to provide the lateral thrust and these ties were fitted with strain gauges so that the thrust could be measured. Displacement transducers were used to measure the vertical movement. The instrumentation and the bridge during loading is shown in Fig. 3. In Fig. 4 the load deflection/relaxation of the bridge at various positions along the length of the arch are shown. The applied loading represented approximately twice the design bending moment and the structure showed no sign of any distress.

![Fig. 3 15m span arch bridge during testing [6].](image)

![Fig. 4 Vertical deformation of the 15m span arch bridge.](image)

The support frame used for this bridge for testing purposes, was not very effective in preventing its ends from spreading apart. A total of 28.4mm horizontal movement was recorded during loading, which in turn caused undue increase in vertical deformation and also reduction in horizontal thrust. Analytical results showed that such a horizontal settlement would increase the mid span deformation of this bridge by over 13 folds. At the load of 100kN the maximum deflection of the bridge at its mid span reached only 0.008 times its length.

The structure was unloaded and reloaded to 40 kN at its ¼ point. Again the design load was well exceeded demonstrating an adequate reserve of strength. The complete bridge deck was then transported on a lorry with extendible trailer to its final destination near Manchester and lifted into its permanent home and completed in situ. The bridge on site, after completion, is shown in Fig. 5.
This test confirmed the structural design method to be adequate and that the thrusts and movements were within predictions. The structural performance of the tested bridges clearly demonstrated a considerable reserve of strength and highlighted the possibilities for an even more efficient use of materials. But to achieve this, further tests on both scaled and prototype size bridges were required to further understand the influence of arching profile, stressing levels and dynamic responses. Also to ensure that as the arch bridges become more slender their natural frequencies do not reduce to a critical value.

2.3 2.1m span arch bridges

In order to investigate the effects of stressing levels (tension in stressing bars) on the structural behaviour and performance of arched and flat bridges, a series of loading tests, similar to those above, were carried out on 3 different arch profiles and 2 flat decks using 4 different lateral tensions under each loading condition. These were carried out on a 1/3 scale model of a proposed highway vehicle bridge. An important difference between a flat stress-laminated construction and an arched one was considered to be the level of the lateral tension. Arches work in compression and without much lateral tension should still operate whereas flat bridges would collapse. A typical load deflection behaviour of an arch bridge subjected to various stressing levels is shown in Fig. 6.

The results further confirmed findings from earlier tests but extended the understanding of the level of lateral tension and the safety factors involved. Lateral tension can vary with moisture content and humidity and the range of variation needs to be catered for within acceptable safety factors. These parameters are now understood and design rules are being derived.

Because of the consistency of the results from different arch shapes there is now a confidence that very strong structures can result from all arch rises. Further it is now confirmed that allowing the structure to shake down and settle before tensioning is a very important factor as was displayed in the 15m span test.

![Fig. 6 Load-deflection of a 2.1m arched bridge subjected to 4-point loading under various stressing (tensioning) levels.](image)
2.4 20m span arch bridge

A 20m span arch bridge has been designed and is planned to be built in the university car park adjacent to the laboratory in April 2004. Static design has shown that 200mm, C16 timber will meet strength requirements. This provides span to depth ratio of 1 to 100 while the 15m span was 1 to 60. A simplified finite element analysis has estimated a natural frequency value of under 4 Hz which is low but the danger zone is probably nearer 1.5 Hz which is the same as a group of vandals jumping in sequence.

The 20m bridge will be subjected to a series of static and dynamic loadings in addition to extreme pedestrian and vandal marching and the response of the bridge will be measured at various positions along its length. This will be carried out without and then with handrails for comparison.

3. Summary and Conclusions

Nine permanent SLT bridges of varying spans have been built in the UK by the authors. All of the bridges are in some way part of a research and development programme being carried out jointly between Forestry Civil Engineering and a PhD research study at Napier University. The aims have been to develop a design guidance for bridges for vehicle and pedestrian use; in particular for use in rural areas that are low cost and have low environmental impact. It was also aimed to develop a structural market for available and growing UK timber resource.

The development so far has been encouraging although most efforts have gone into footbridges which take livestock and light vehicles. This has been a deliberate policy because there is a need and a healthy market for such bridges while it provided an opportunity to build confidence for design and construction of long span structures.

The research has aimed to increase the spans to the limit of the materials. Thereafter the focus will move towards arches supporting flat stress laminated decks to achieve 10m span for full highway loading. Such designs will suit the weather conditions in the UK because all of the structure will be exposed to wind drying.

In time the stress lamination of timber, particularly arches, will find many markets in the UK. There are many applications for low cost, medium life, high strength structures in a modern society which strives to reduce pollution and create visual harmony.

4. References


