Fundamental Structural Behaviour of "Built-up" Stress Laminated Timber Bridge Decks

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Abstract

Following the successful implementation of stress laminated timber bridge deck technology for decks spanning up to 9m, a 3 year research initiative was commenced early in 1995 at the University of Technology, Sydney (UTS), to undertake fundamental research and development of cellular bridge decks using stress laminated timber technology.

This work is funded collaboratively by the Australian Research Council and industry, and has involved both full scale serviceability and ultimate load testing (up to 12.2m) as well as an examination and analytical investigation into fundamental behaviour of cellular and "T" beam structural forms constructed from timber elements. Research is currently being undertaken to extend this technology to applications with clear spans of 25 to 30m.

This paper presents the findings of on-going research at UTS and discusses the implications of it for timber bridges. Research undertaken to date indicates that the technology is structurally and economically viable.

Introduction

The research and development program for Stress laminated timber (SLT) bridge decks commenced at the University of Technology, Sydney in early 1990 and has focused on a technology transfer of the current state of the art from overseas into an Australian context. The purpose of this testing program has been to develop an "engineered system" for both new and replacement bridge decks to the AUSTROADS and Standards Australia design codes, for use by both state and local government authorities in maintaining some 10000 timber bridges that are known to be in service on the east coast of mainland Australia.

This program resulted in the first prototype hardwood bridge spanning 9.6 metres, being constructed over the Yarramundi Lagoon on Main Road 570 in December of 1991.

Subsequent laboratory testing[1] and field monitoring of prototype bridges, has now established SLT technology in Australia. Design, construction and maintenance procedures have now been documented,[2] culminating in the recent publication of a limit states design code and commentary.[3]

However, it has been found both in Australia and overseas, that the application of stress laminated orthotropic plate decks are limited to bridges of up to about 9m span (refer to Table 1). Approximately 60% of bridges in New South Wales exceed this span limit and as such, a definite need exists to be able construct spans in the 11m to 15m range, for the rehabilitation and maintenance of the existing timber bridge asset.

Similarly, in North America, the desirability of larger spanning timber bridges has led to an extensive research and development initiative, investigating

Table 1 - Maximum Possible Spans for Plate decks

Type of timber used: (290x35mm laminates)	**Maximum Span: for single span bridge**	**Maximum Span: for double span bridge**	**Maximum Span: for multiple span bridge**
softwood (F8)	6.8 - 7.0m	7.5m	8.5m
hardwood (F17)	7.0 - 7.2m	8.0m	9.0m
hardwood (F27)	8.0 - 8.2m	9.0m	10.0m

NOTES:

1) softwood data based on F8 Radiata pine, using ingrade stiffness of 12200 MPa
2) all spans are assumed to be continuous over the supports
3) multiple span deck based on 5 spans, with the end spans 1m shorter than the 3 middle spans
4) the deflection limits for the above decks are span / 400 for T44LL and span / 350 for T44LL with DLA.
5) using limits of span / 500 and span / 400 respectively for (4) would reduce spans in Table 1 by approx. 300 to 500mm
6) decks have been modelled using AUSTROADS T44 and HLP320 loads

alternative structural forms other than orthotropic plates. An overview of some of these options, which includes steel wood composite decks and prefabricated deck trusses, parallel cord trusses, "T" beams, box beams and cellular decks, has been reported by Taylor and Ritter.[4] The latter three of these options are generally referred to as "built-up" timber sections.

Of these systems, the "T" beam and the cellular bridge have particular interest for application in Australia, as they utilise material which is readily available from the timber industry and for which reasonable quality assurance and reliability of material properties is available,[5] making the material acceptable for use in timber bridge structures.

"Built-Up" Timber Bridge Decks

Built-up Sections

Experimental work investigating behaviour of "T" beams (figure 1) and "box" beams has been undertaken in the United States at the Forest Products Laboratory in Madison, Wisconsin, and at the University of West Virginia.[6] An alternative structural form to the box is the timber cell, which uses thinner, closer spaced webs (usually made from LVL - laminated veneer lumber) with two transversely laminated flanges, typically constructed from sawn material of between 150 and 200mm in nominal depth, as shown in figure 2.

Recent investigations (as a part of study tour by the authors to North America in 1994), have indicated that the "T' beam form of this construction also has considerable potential for application in Australia.

"T" beam Decks

The first stressed "T" beam was introduced in West Virginia in 1988 following an extensive research end development program, involving laboratory testing at the University of West Virginia. This program resulted in the construction of a 22.3 metre span prototype near Charlestown, West Virginia, which utilises 150mm x 1140mm LVL (laminated veneer lumber) beams and 230mm deep decking.[7]

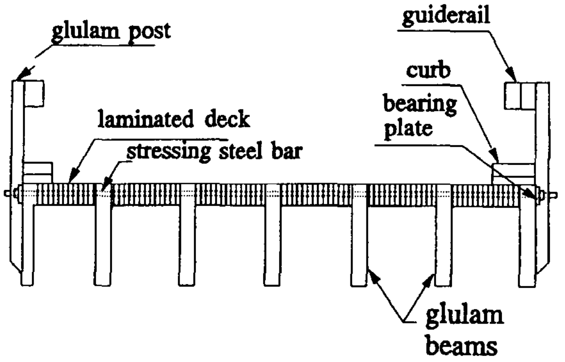

Figure 1 - General details of "T" beam bridge deck

Subsequently, glulam beams were used in lieu of LVL beams. The timber research program at the University of West Virginia, has as one of its primary aims, the promotion of local species hardwoods. Details of the "T" beam deck are shown in figure 1.

Box Beam Bridge Decks

As a part of the Timber Bridge Initiative, the Forest Products Laboratory (Madison) end the University of West Virginia are also developing a low profile box system using widely spaced thick web members with spacings typically at about 1.2 metres. Several prototype bridges have been constructed in the last few years as a part of an extensive construction program, involving some twenty new bridges in West Virginia.

Cellular Timber Bridge Decks

The cellular concept received some preliminary evaluation by the Ontario Ministry for Transportation in 1988, but the results of this preliminary research were not published and the testing program for this particular work did not proceed.

A prototype bridge based on this preliminary research was constructed for the Ministry of Natural Resources over the Chippewa River in 1993. This bridge has a clear span of 25 metres and a single lane width of 5.3 metres and has an overall depth of 1200mm. The deck consists of 38 x 184mm flange laminates of sawn timber with 65 x 1200mm deep LVL webs at approximately 500mm centres. The bridge was essentially designed as a series of plywood web beams which do not take into account the shear and torsional interactions of the cellular form of construction.

Conceptual work on cellular decks as presented in this paper was commenced by the authors in late 1991, as a response to the need to develop longer spanning SLT bridge decks to meet Australian needs for spans up to 12.2m. This work referenced the research then being undertaken in the U.S. to develop a structurally efficient form which could utilise both sawn timber and LVL / glulam beams being produced from softwood plantations in Australia.

The cellular deck, whilst similar in concept to the box beam, essentially differs, in that it uses more closely spaced and thinner web members, with the webs typically being made from LVL in thickness’ from 45 to 63mm and spaced at centres not exceeding 5oomm.

Details of the cellular concept developed by the authors and tested at the University of Technology, Sydney, are shown below in figure 2. The test decks are full scale, single lane bridge decks, spanning up to 12.2m (40ft). These are almost identical to the prototype bridges which have been constructed subsequent to the R & D work.

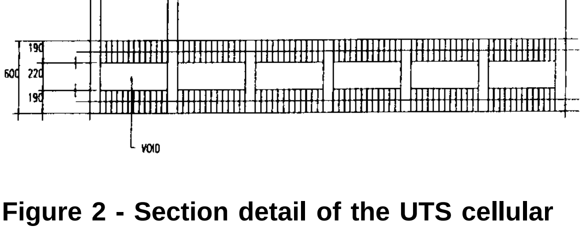

Figure 2 - Section detail of the UTS cellular deck, utilising Radiata pine flanges and pine LVL webs

Research And Development For Cellular Decks

General Considerations

The first major research program into the structural performance of cellular stress laminated timber bridge decks is currently being undertaken by the authors at UTS. Initial research in 1993 by Crews[8] indicated that decks with cellular cross sections have significant structural advantages provided the stiffness of the flanges and webs are such as to enable the balanced utilisation of their respective strength. In cases where the stiffness of the web beams precludes the effective utilisation of the strength of the flanges a “T” beam form may be more appropriate.

To calibrate analytical models and to determine design parameters it is necessary to understand the torsional and orthotropic flexural characteristics of these structural systems. The testing program at UTS has been tiered, to enable implementation of the technology as soon as possible with a series of prototype bridges, which will then be monitored under field and in service conditions. The field testing of prototype bridges will complement the continuing laboratory based research and development work.

Three full size cellular deck configurations and a series of partial deck component cells have been tested at UTS to date. This ‘proof testing’ of full size decks has enabled the validation of the cellular bridge concept and has enabled the construction of several prototype bridges in NSW to proceed.

The first cellular bridge deck tested in the laboratory consisted of a 12.2 metre clear span with 140 x 35 hardwood laminates and 63 x 450 deep LVL webs. Whilst preliminary analysis had indicated that the design depth for this particular span should be 600mm, a depth of 450mm was adopted in order to maximise the induced curvatures in the deck. The underlying purpose of this was to quantify the extreme performance characteristics of this particular structural form.

The second series of laboratory tests involved testing 600 deep decks which were constructed of 63 x 600 LVL webs at 485mm spacings, with 190 x 35 treated Radiata Pine flanges (as shown in figure 2). This particular deck configuration was tested for serviceability loading conditions with a span of 9.8 metres and for serviceability and ultimate limit strength state loading conditions on a 12.2 metre span.

Objectives of the Research Program

The primary objectives of this research and development program are to study the behaviour of cellular stress laminated timber bridge decks and to develop appropriate analytical models which represent this behaviour within the service design load range.

The program includes experimental work, analytical modelling and interpretation of the data, and calibration of the analytical models, concluding with the formulation of appropriate design methodologies for the application of this new technology.

The essential components of the project include the following:

- Experimental investigation of serviceability and ultimate limit states for the cellular stress laminated timber deck system. These tests have been completed for 3 full scale decks tested to destruction under laboratory conditions, establishing specific structural behavioural patterns for this technology.

- Identifying the various limit states for the components, e.g. longitudinal shear, interlaminate slip and identification of the limit states for the particular structural systems.

- Deflection serviceability limits for structural components such as the flange laminates, webs and stressing bars.

- Stability and strength limits for the component cells and then for the structural system as a whole.

Scope

The global issues being addressed within the scope of this project include:

- Characterizing material properties.

- Experimental investigation of single cell behaviour such as shear lag effects and strain distributions within a cell and relationship to multi-cell behaviour, based on full scale testing.

- Characterizing the structural behaviour of individual cells up to service load limit stage.

- Theoretical and analytical investigations into the effect of geometric parameters such as centre to centre spacing of webs, aspect ratio of the cell i.e. breadth to depth ratio, based on the characteristics ofa ‘typical cell’.

- Analytical investigation of the influence of geometric parameters on the structural behaviour of cells.

- The effects of changing prestress levels.

- Descriptive reporting of web behaviour within a cell, e.g. load distribution width for cells, effects of load distribution before and after web failure.

- Identification of load transfer mechanisms and contributions of the web to structural response of the cell before and after web failure occurs.

- Dynamic responses and long-term cyclic load effects i.e. the effects of sustained and repeated loads on serviceability and the effect of duration of load on strength, taking account of discontinuities and “shakedown” effects.

Results of Full Scale Tests

At the time of writing, the tests completed or currently underway for the cellular stress decks are:

- Full scale tests (both serviceability and ultimate limit state destructive) on 2 single lane cellular decks spanning 12.2m, with depths of 450mm and 600mm.
- Full scale tests (both serviceability and ultimate limit state non-destructive) on 1 single lane cellular deck spanning 9.8m, with a depth of 600mm.
- Serviceability and ultimate limit state non-destructive tests on single component cells, spanning 9.8m with depths of 600mm, 900mm and 1200mm.
- Cyclic T44 serviceability loading of single component cells, spanning 9.8m with a depth of 600mm.
- Testing of deck segments to quantify slip behaviour at web to flange interfaces, between flange laminates and around / at butt joints.

The full scale flexural tests and the proof load shear tests give an indication as to overall structural response of this cellular system in an empirical sense, but do not in themselves permit a clear understanding of the fundamental behaviour.

In order to quantify the latter, component testing of individual cell and various deck segments commenced in May 1995 and is due for completion in August 1996.

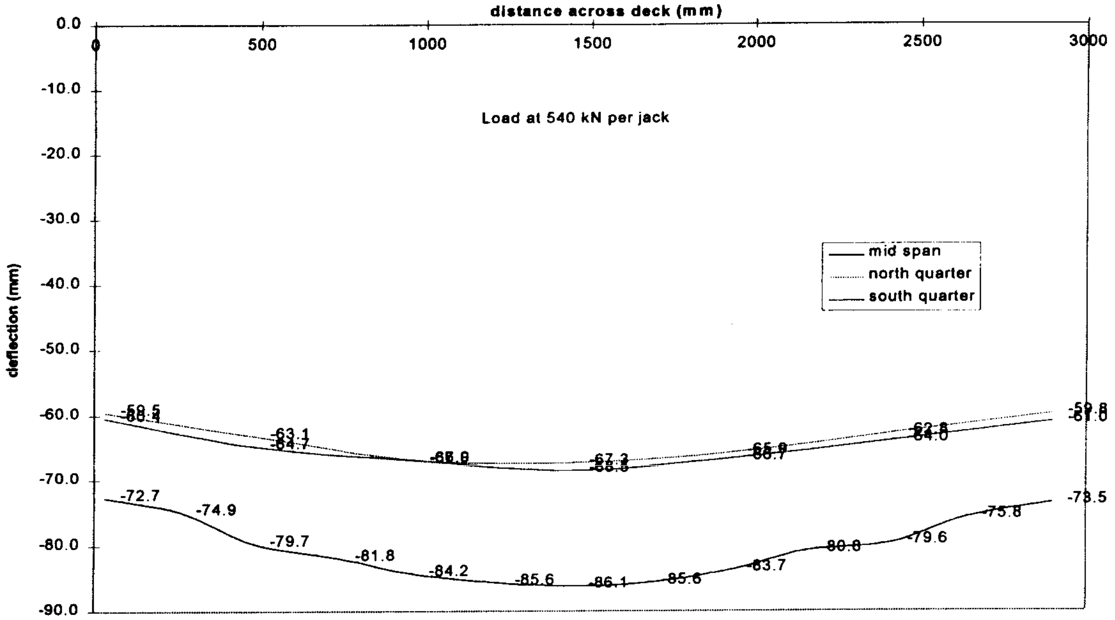

Figure 3 - Cross section deflection profiles - 12.2m span deck with 2 point loads of 540 kN, 1200mm apart and symmetrical about midspan

Basic Load Response

Whilst there was a need to undertake tests of lateral and torsional stiffness on the plate decks, the tests undertaken on the full scale single lane cellular bridge decks constructed at UTS, indicate that load eccentricity does not form a major problem for the structural deck system.

The load response behaviour of a cellular deck in the linear elastic range (and even into the non-linear range) is much more akin to that of a wide beam, rather than the orthotropic plate behaviour of the plate decks. This is illustrated in figure 3 below.

In applying the various loading conditions on the cellular decks at UTS, a number of loading scenarios have been modelled including both two point and four point loading in order to effectively model the bending moment envelopes induced by T44 and HLP320 vehicles for both the serviceability limit states and the ultimate limit states, as defined in the AUSTROADS Bridge Design Code 1992.

Serviceability load testing was undertaken at a variety of prestress levels, (1000, 700, and 550 kPa) whilst testing to failure loads was undertaken with a prestress of 700 kPa. For the 600mm deep decks, the design ultimate limit state loading (HLP320) was satisfied at a load level well below the actual “failure” load capacity of the deck.

Additional testing has also been undertaken on short span segments of the cellular decks to quantify punching shear responses and to apply ULS proof shear loads, to ensure that shear capacity of the decks are adequate to meet the AUSTROADS design standards.

Ultimate Load Capacity - Flexure

As indicated above, the first hardwood deck tested in the laboratory, had intentionally used a very small depth to span ratio to induce significant curvature and facilitate the development of clearly defined limit states and to enable the determination of the ultimate load carrying capacity. Because such testing had not been previously undertaken, the failure mechanism and ultimate load carrying capacity were not readily predictable.

The shakedown failure modes were also unknown. The normal design depth for this 12.2 metre span would have been 600mm rather than the 450mm as tested. One interesting phenomenon, which was noted during the tests was the fact that even when all the LVL webs had fractured in flexure, the deck still retained significant load carrying capacity (still carrying 580 kN per wheel path), albeit with very large deflections.

Only one of the hardwood flange laminates exhibited any signs of failure, although interlaminate slip was noticeable at some butt joints, at the higher load levels.

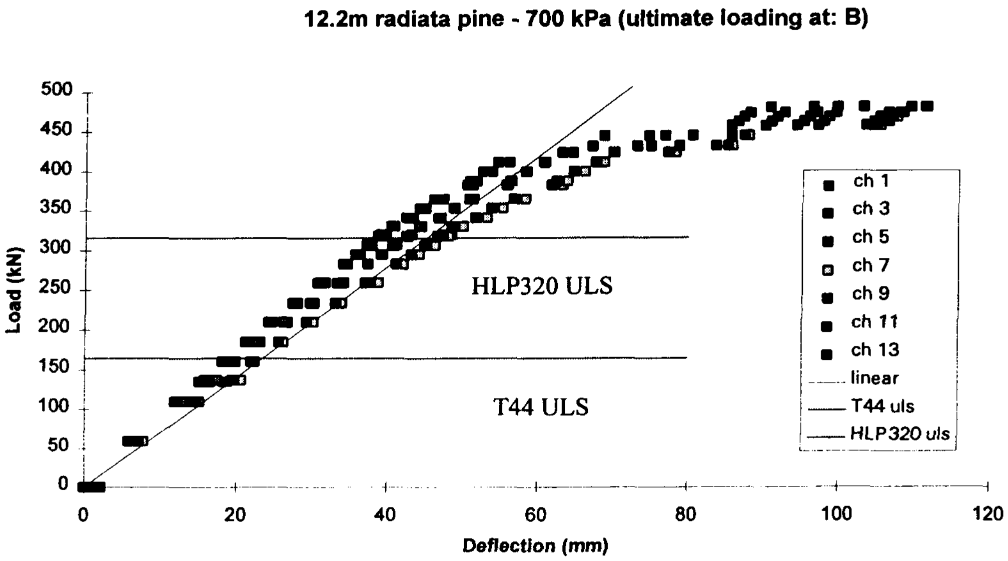

Figure 4 - Load vs. Deflection plots for a 12.2m span Cellular deck (pine flanges, 600mm deep)

Even at this reduced depth, the hardwood cellular deck had an ultimate bending moment capacity of 1622 kNm, which was considerably greater than the 1000 kNm required to meet the T44 ULS for a single wheel path. However, it fell slightly short of the HLP320 wheel path loading, which required a ULS moment capacity of 1740 kNm. The hardwood deck had no problems meeting the AUSTROADS shear load requirements for both T44 and HLP loading.

The tests on the Radiata Pine decks were commenced some six months after completion of the hardwood tests. This enabled certain refinements to be made and the authors had more specific expectations as to the likely performance of the cellular system. Summary results for the 9.8 metre span and 12.2 metre span pine decks are presented in Table 2.

Table 2 - Summary of ULS Tests on Cellular Decks (under flexure)

Deck Type:	actual ultimate BM (kNm)	Design T44 ULS BM (kNm)	Design HLP320 ULS BM (kNm)
12.2m hardwood (450mm)	1622	1000	1740
12.2m softwood (600mm)	3000	1000	1740

Two points of importance should be noted. Firstly, at the "design depth" of 600mm the essential load deflection response is linear up to the HLP320 ULS requirement, as is seen in figure 4. Secondly, the ultimate load capacity of these decks was significantly in excess of (70% above) the design requirement for the HLP320 ULS.

Observed Failure Mechanisms

The failure mechanisms on these particular decks are quite interesting. From the tests and from readings taken at butt joints using highly sensitive LVDT's, it appears that the load distribution mechanism which occurs, is one of horizontal slip of the laminates, particularly at the interface with the LVL webs.

The observed responses show that the theoretical outer fibre stresses in the flange material were well in excess of the fifth percentile MORs for the pine laminates. Interestingly no failures were observed to occur in any of the laminates, both during and then after the test in a post mortem of the deck.

The failures which did occur were essentially localised tensile failures in the lower tensile region of the two LVL webs which failed. The load sharing mechanism is fascinating. It appears that the cellular system continues to take increasing load until such point as the horizontal shear overcomes the frictional resistance induced by the prestressing forces between the flanges and the web elements. When this occurs microslipping appears to occur resulting in significant load redistribution, and a settling in of the flanges with the webs.

Ultimately however, the "distribution width" converges, resulting in extreme stress concentrations in the outer fibres of the central (under load application points) LVL webs, which in turn ultimately led to minor compression and then tensile bending failures in the lower tensile region of the LVL webs.

Post Critical Behaviour

As can be clearly seen from figure 4, the system behaviour of a stress laminated timber cellular deck is non linear in the lead up to ultimate flexural capacity and over the entire loading range exhibits marked ductility. When failure finally occurred the extent of wood damage was highly localised at midspan in the LVL webs, immediately under the load application points.

However, despite the fact that the principle elements had failed and discontinuity existed at midspan, significant load carrying capacity still existed in the deck well in excess of the design ULS requirements, specified by the AUSTROADS Bridge Design Code.

This was verified by post failure testing of the deck, which was observed to produce essentially the same linear load response up to the AUSTROADS design ULS loads despite the fact that web failure had occurred. This highlights the extraordinary load sharing characteristics of this particular structural system whilst providing excellent serviceability stiffness characteristics to minimise deflections.

Current Status Of R & D

Component Testing

Research being undertaken at the time of writing involves testing on individual component cells as shown in figure 5, with depths of 600mm, 900mm and 1200mm and prestress levels of 1200, 1000, 700, and 500 kPa. Additional load tests have been undertaken on the 600mm deck for prestress levels of 300 kPa (static loads) and 500 kPa cyclic load tests. These series of tests not only characterise the material and component system behaviour for bending, shear, and torsion, but also focus on quantifying the slip interaction mechanism between web and flange laminates.

This slip mechanism is believed to be the critical limiting factor for effective serviceability structural performance and the cause non-linearity at high load levels for cellular sections. The same slip mechanism is believed to be the governing factor for the “T” beam bridges currently in use in North America and a series of “T” beam tests is also planned as a part of the current R&D program at UTS.

The component test cells (as shown in figure 5) have been manufactured using flange laminates which have been finger jointed to avoid the inclusion of butt joints, which were included in the full scale, single lane deck tests.

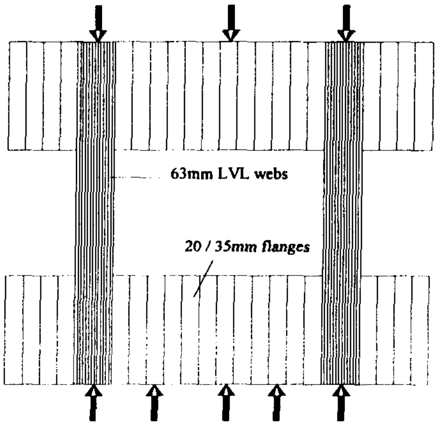

Figure 5 - Typical Section of cell component beam used in Component Tests. Arrows indicate positions of vertical deflection measurements

This form of construction has been incorporated to deliberately remove the discontinuity effects of the butt joints and to directly relate slippage to the release of strain energy in the deck.

Discussion of Preliminary Results

Analysis of the results will continue until at least the end of 1996. Initial results from the 600mm deep deck indicate that a strong correlation exists between web to flange (horizontal) slip, the commencement of non-linear load deflection behaviour and the onset of any permanent deflection in the deck (vertical slip) after removal of the loads. This is illustrated for a 600mm deck at 700 kPa in figures 6 & 7.

The prestress level has a marked effect on the “stiffness” of the deck and the commencement of the slip mechanisms discussed above. On the basis of the preliminary analysis of data obtained from the component tests, it is strongly recommended that the prestress pressure in cellular decks should not be allowed to fall below 700 kPa, with an absolute lower bound level of 500 kPa. Below 500 kPa the structural behaviour of the deck changes markedly, both in terms of stiffness and ultimate strength.

A linear elastic finite element model has been developed as the major part of a student research project supervised by and with significant input from the authors. This model is being calibrated with test data from the full scale laboratory tests and forms the first stage of development of a more comprehensive analytical model (incorporating the slip mechanism) which will be undertaken as the component testing is completed.

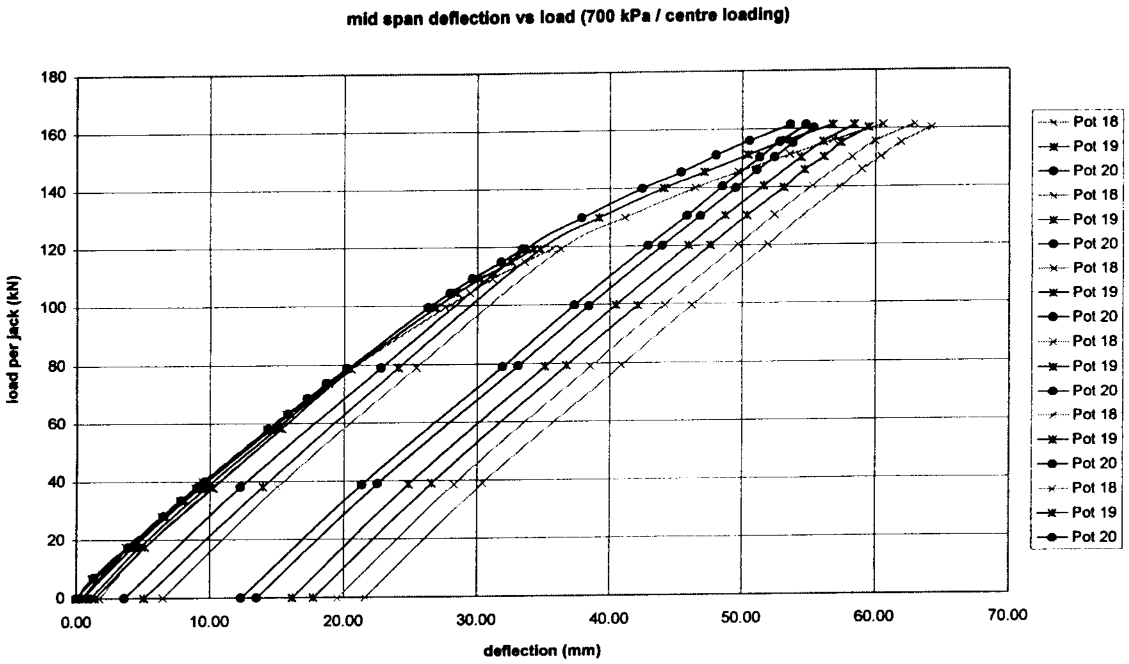

Figure 6 - load vs. deflection at midspan for 6 load cycles ranging from 40 kN / jack to 160 kN/ jack

The T44 SLS occurs at 40 kN per jack, whilst the HLP320 ULS occurs at 95kN per jack

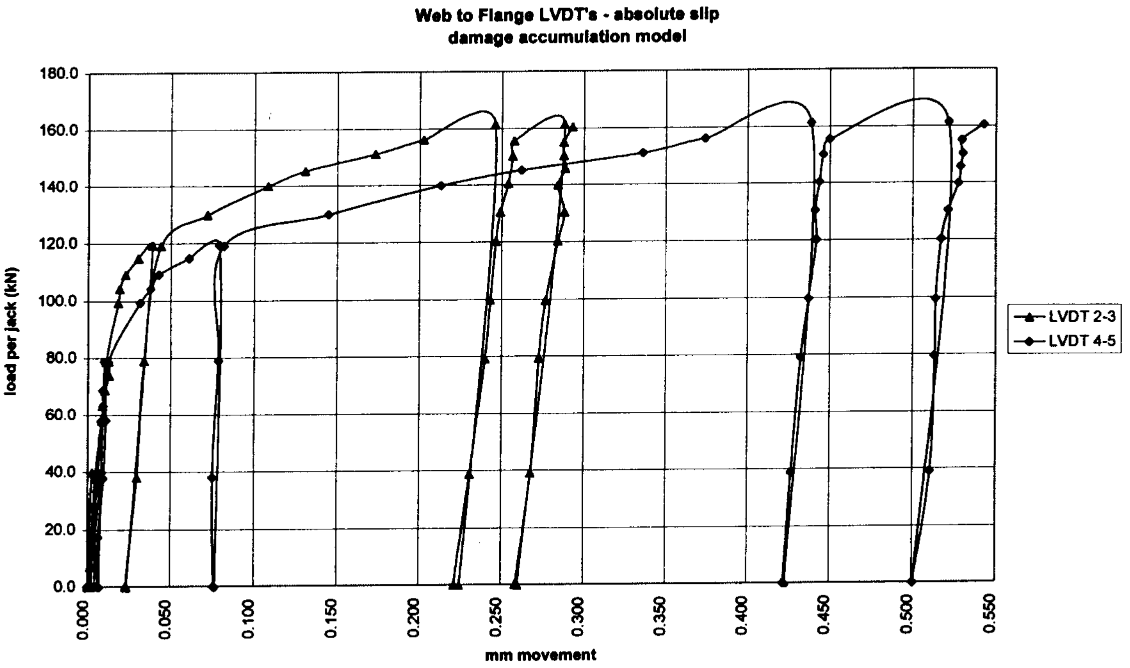

Figure 7 - load vs. Horizontal slip for 6 load cycles ranging from 40 kN / jack to 160 kN/ jack

note the “accumulated damage” after each loading / unloading cycle

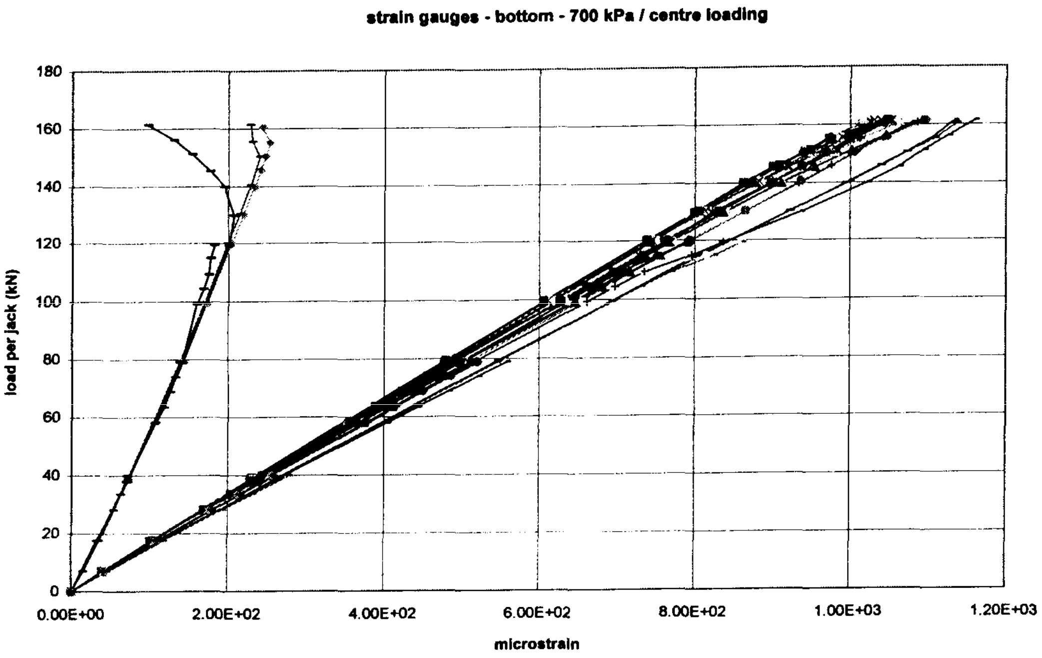

Figure 8 - Strain vs. Load charts for laminates and webs in the critical moment zone.

The system behaviour of a cellular deck in the post design ULS loading range is essentially non-linear as a result of interlaminate slip, despite the fact that at these load levels the material behaviour is still essentially linear elastic (certainly up to the design ULS load level). This latter phenomenon is confined by strain gauging of laminates in the critical moment zones of the deck, results of which are presented in figure 8.

Implementation Of The Technology

To date four prototype bridges utilising the cellular timber technology have been constructed in Australia since 1994, details of which have been presented elsewhere.[9] The most recent of these structures has been shown to be very cost effective, despite the fact that the cellular technology is being currently used at the lower end of its potential span capacity. Two of these bridges (designed by Crews) have won Engineering Excellence awards from the Institute of Municipal Engineers in 1995 and 1996. In all cases, the decks span up to 12m and are based on the 600mm deep prototype decks developed and subjected to full scale laboratory testing at UTS.

In two cases cellular decks have been used to rehabilitate existing reinforced concrete bridge decks (at Lansdowne and Ashlea on the mid north coast of NSW) which had deteriorated to the extent that bridge replacement was required. Both sites had decks of almost identical design and age, except the one at Lansdowne had only 4 spans (each about 11.5m), whilst the Ashlea bridge has seven spans, with an overall length of 85 metres. A schematic cross section of the rehabilitation solution is shown below in figure 9.

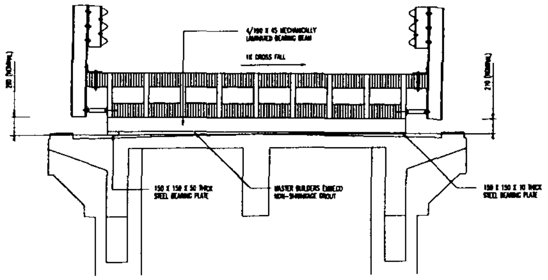

Figure 9 - Typical Cross Section - Cellular Deck overlay over existing concrete decks.

The cellular deck overlay used to upgrade the Ashlea bridge is almost identical to the one at Lansdowne, except that with hindsight on the first bridge some minor design refinements have been included and the decks bear on composite timber beams rather than poured insitu concrete. The cellular decks were prefabricated in a council depot about 25 km from the bridge and transported to site The total road closure time was 3.5 weeks and final cost of the total deck rehabilitation is expected to be about $450,000 or about 20% of the cost of the replacement structure.

Conclusions

Stress laminated cellular bridge decks constructed from Australian hardwoods and plantation grown softwoods have been shown to respond linearly to short-term static loading within the serviceability and strength limit state load ranges specified by the AUSTROADS Bridge Design Code 1992.

The transverse flexural-torsional stiffness of the cellular decks provided effective distribution of internal actions. All the decks tested exhibited considerable ductility when subjected to a range of loads substantially greater than the design service loads.

After extensive web failures at ultimate loads all three decks tested retained the capacity to carry the design service loads with only slightly increased deflections.

Component testing of cellular beams has identified various mechanisms and it is expected that analysis of the results from these tests will quantify critical design and limit states performance parameters. It is believed that these results will have application for "T" beam SLT decks and a program of full scale testing of a partial "T" beam deck will be used to validate the applicability of the slip models. This will also be linked with the results from deck segment tests (smaller specimens) aimed at quantifying shear flow around butt joint discontinuities.

Funding which has been recently made available through an Australian Research Council Grant and industry sources, will further extend this technology through the component testing, currently being undertaken at the University of Technology, Sydney. It is anticipated that the major testing program will be completed by the end of 1996, with results available by the end of 1997.

It is anticipated that the results of this testing will quantify the shear flow and slip mechanisms in "Built-Up" decks and permit the development of rational design procedures for cellular and "T" beam stress laminated timber bridge decks spanning up to 30m.

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