An Overview of the Development of Stress Laminated Cellular Timber Bridge Decks for Short to Medium Span Applications in Australia

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Abstract

Stress laminated timber bridge deck technology has been established in Australia since 1991, resulting in the construction of over 40 prototype bridges. This paper presents an overview of the R&D undertaken to implement this technology, involving laboratory testing and field application of plate decks spanning up to 9m and high capacity cellular decks spanning 12m, with the potential to span up to 30m.

Introduction

Maintenance and rehabilitation of Australia's timber bridges is a national priority. On the East Coast of mainland Australia there are an estimated 10000 timber bridges having spans greater than 6m, with about 85% of these under the control of local councils. Many of these bridges were built during the late 1800's to the early 1930's, using native hardwood timbers, which are strong, durable and were at the time of construction, in relatively abundant supply.

Most of these bridges were designed for 18 tonne loads. Whilst routine maintenance of these bridges has been undertaken, it is often inadequately funded. Many are in a degraded condition and are inadequate to safely carry the 44 tonne and greater design loads now required [*Crews – 1994a*]. Whilst the prevailing attitude amongst engineers towards timber bridges has been one of "patch and replace", the cost of replacement is prohibitive and in the early 1990's Government finally realized that rehabilitation and maintenance strategies were necessary for maintaining and upgrading timber bridges as an essential part of the transportation infrastructure.

Research work undertaken at the University of Technology, Sydney since 1990, has focused on the development of a high capacity replacement deck system which is based upon reliable engineered wood products manufactured from plantation grown timbers, is cost effective, and upgrades bridge load ratings to conform with modern AUSTROADS design requirements.

The focus of this research is the stress laminated timber deck. Originally conceived as a method for rehabilitating deteriorated nail laminated timber bridge decks, stress laminating of timber bridge decks has been developed and found

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widespread application throughout North America and Europe since the mid 1980's and in Japan, Australia and other countries since the early 1990's [*Aasheim – 1999; Duwadi & Ritter – 2001; Taylor et al – 1994; Usuki et al – 1994*].

Types Of Deck Systems

Plate Decks

The basic deck type, which has been most commonly used in practice, is the plate deck, shown in Figure 1. Once the prestress force is applied and maintained at or above the minimum design level, the stressed deck will behave as an orthotropic plate, effectively resisting loads, since these can be distributed laterally across some finite width of the deck (the distribution width) and then transferred longitudinally to the sub-structure. The most critical factor for design and maintenance of stress laminated timber deck systems, is to achieve and maintain adequate prestress force between the laminates so that the orthotropic plate action is maintained.

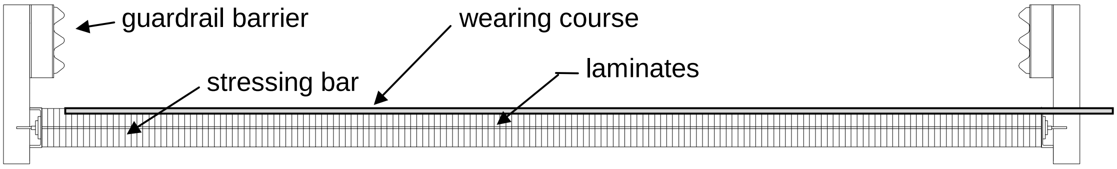


Figure 1. Schematic view of a typical plate deck

"Built-up" Decks

Plate decks constructed from glulam or LVL have been used in spans up to 10 to 12m, although for sawn timber the span limitation is usually between 7.5 and 9m, depending upon both the depth and stiffness of the laminates [*Crews – 1994b*]. In order to span further (up to 25-30m), alternative, more "efficient" structural forms have been developed. These are generally referred to as "built-up" decks; the 3 main forms being "T" beams, "box" beams and "cellular" decks (Figure 2).

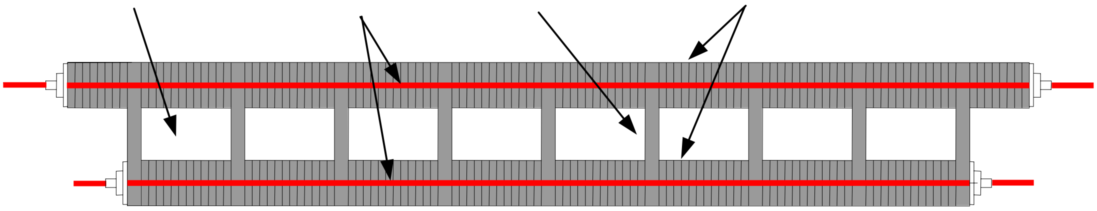


Figure 2. Schematic view of a typical cellular deck

Research and Development

A comprehensive R & D testing program was considered necessary in order to characterize the structural performance of SLT decks using Australian timber species and provides a technical basis for design procedures.

The testing programs for both plate and cellular deck systems have been based on "full scale" laboratory testing, involving application of loads that modeled both the design serviceability and design ultimate conditions. This laboratory-based work has been linked with an extensive program of field monitoring of prototype bridges [*Crews et al – 1994*]. The results have identified the fundamental characteristics of stress laminated deck behavior and have quantified the following with respect to both serviceability and ultimate strength limit states:

- the effects of differing levels of prestress and various butt joint patterns,
- the effects of creep and prestress losses,
- load distribution and strength sharing effects prior to breakdown of composite behavior,
- slip and load redistribution mechanisms, which occur at and beyond the limits of linear composite behavior.

R&D Program for Plate Decks

In an effort to avoid "re-inventing the wheel", the R&D program has, wherever possible, focused on a "technology transfer" of the current state of the art from overseas into an Australian context. The first prototype bridge in Australia was the Eltham Bridge in Victoria, opened November 1991, followed in December 1991 by construction of the first hardwood deck, over Yarramundi Lagoon at Agnes Banks on a rural link road west of Sydney. These bridges have been very successful prototypes and have paved the way for construction of numerous other prototype bridges since [*Crews & Walter – 1996*].

Subsequent full scale laboratory testing validated the stress-laminated timber concept for plate decks spanning up to about 9 meters. Monitoring and load testing of many these bridges has been undertaken as a part of a continuing R & D program. The first limit states design code and commentary for plate decks was published in 1995 [*Crews - 1995*]. Construction and maintenance procedures have also been developed, establishing the general use of this technology in Australia. Details of the first prototype bridges and the associated research and development work have been reported elsewhere [*Crews et al – 1993*].

The Need for Longer Spanning Decks

However, approximately 60% of timber bridges in Australia exceed the effective 9m span limit for plate decks and as such, a definite need exists to construct spans in the 11m to 15m range, for the rehabilitation and maintenance of many existing bridges. Also, in some situations, there are advantages in being able to reduce the number of pier supports by increasing the span of the deck superstructure. In North America, the desirability of larger spanning timber bridges also led to an extensive research and development initiative, investigating alternative structural forms other than orthotropic plates [*Taylor et al – 2000*]. These "built-up" decks utilize both sawn timber and engineered wood products which are readily available from the timber industry, are usually manufactured under a quality assured process, and have reliable material properties; making the materials acceptable for use in modern bridge structures.

R & D Program for "Built-up" Decks

The focus of Australian research for built-up decks has been the cellular deck. This deck form, whilst similar in concept to the box beam, essentially differs in that it uses more closely spaced and thinner web members, with the result that secondary bending effects are greatly reduced and shear lag effects are negligible [*Crews – 2002*]. Additional research into load distribution of "T" beam decks has also been undertaken, but the majority of the research has involved testing cellular decks.

Typically, a cellular deck consists of sawn laminate flanges, with a depth of 150mm to 250mm, with LVL webs 45mm to 65mm thick, spaced at centers not exceeding 500mm. Composite action between the flanges and webs is created by application of a post-tensioned prestress force, applied through the centroid of each flange. For the Australian testing program, two full sized, single lane decks spanning 12.2m were constructed and tested under laboratory conditions, using webs and flanges manufactured from *pinus radiata* to form a 3m wide deck, as indicated in Figure 3.

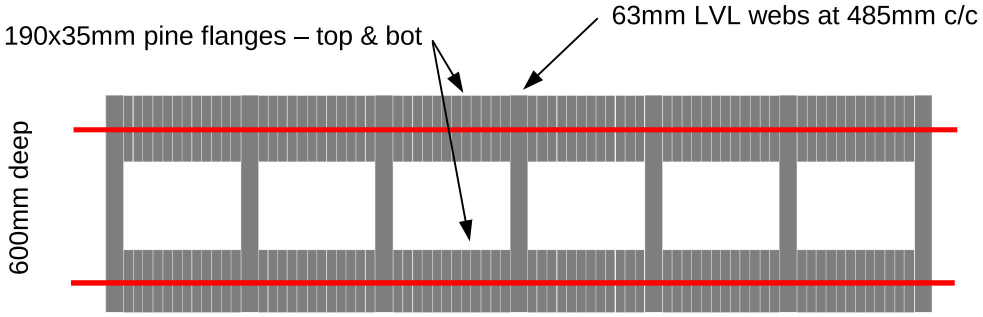


Figure 3. Section detail of a single lane 12.2m span cellular deck

Instrumentation and Loading of Decks

The general specification for instrumentation and loading the full-scale decks was based upon the following considerations:

- Installation of up to 50 vertical deflection (with a measurement range of 150mm), 10 horizontal measurement devices and 10 strain gauges.
- 30 of the deflection-measuring devices were installed at mid span across the deck (15 on the top and 15 on the bottom), 5 were installed at quarter points and 3 located over each support
- Load cells of 200 kN capacity were installed at all loading points in order to electronically record the test loadings.
- Pad load forces were applied to the deck through 400mm x 200mm x 20mm thick mild steel loading plates located at points "A" and "C" in Figure 4. Wider pads (1500mm x 200mm) were located at "B" to model the heavy load platform.
- The loading system required force applications four jacks of up to 200 kN (for service loads) and two jacks with capacity up to 600 kN (for ultimate loads).
- Load were applied on the top surface of each deck through 25mm diameter high tensile steel rods which transferred the axial loads to a reaction floor.

Four types of loading event were defined for testing to simulate moment envelopes for AUSTROADS design loads, by varying the location where forces were applied to the deck. These locations are described in Table 1 and indicated in Figure 4.

Table 1. Loading Positions for Deck Tests

Load Position	Location of jacks	Description
LP 1	C	Eccentric load, one wheel path on edge of deck 2 jacks loaded simultaneously
LP 2	A & C	Symmetric T44 load, two wheel paths 4 jacks loaded simultaneously
LP 3	B	Symmetric HLP load, one wheel path 2 jacks loaded simultaneously
LP 4	B (with spreader beam)	Symmetric Line Load 2 jacks loaded simultaneously

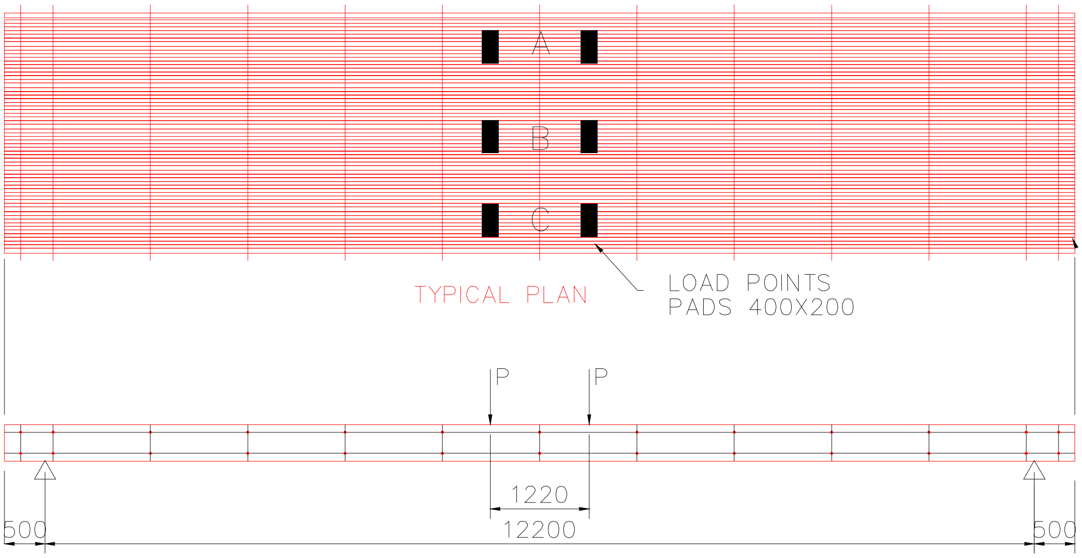


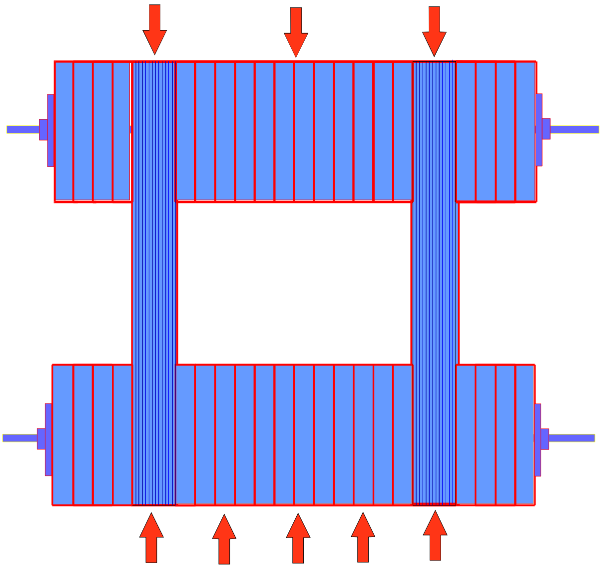
Figure 4. Plan of loading positions

Characterizing Fundamental Cellular Behavior

A further testing program, focusing on developing an understanding of fundamental behavior of individual component cells was commenced in 1996. Typical section geometry for these test specimens is shown in Figure 5.

Component cells were fabricated with depths of 600mm, 900mm and 1200mm and (static) load tested at prestress levels of 1200, 1000, 700, and 500 kPa, with additional tests on the 600mm deck at a prestress of 300 kPa. Cyclic loading was also undertaken on the 600mm cell at prestress levels of 700 and 500 kPa.

The main set of component test cells (as shown in Figure 5) were manufactured using flange laminates which had been finger jointed to avoid the inclusion of butt joints, (which were included in the full scale, single lane deck tests). This form of construction was 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. In addition to the non butt jointed cells, three additional 600mm deep cells incorporating butt joints at patterns of 1 in 4, 1 in 3 and 1 in 2 were tested to quantify the effects of butt joints on deck stiffness and the slip mechanism.



Notes:

- Arrows indicate relative positions where vertical deflection measurements were taken at midspan, loading points and quarter span.
- Flange outstands were used to ensure uniform prestress at the internal web to flange interface
- Four point loading over a 9.8m span was used to simulate design load bending moment envelopes

Figure 5. Typical section of cell component beam

The general specification for instrumentation of the component cells was based upon the following considerations:

- The instrumentation installed included: 24 rotary pots for vertical deflection, 22 LVDT's for horizontal measurements and 26 strain gauges.
- The LVDT's were located at the web to flange interfaces
- Strain gauges were installed at midspan on all webs and selected flanges, to quantify relative strain distribution in the maximum moment regions.
- Load cells of 400 kN capacity were installed at all loading points in order to electronically record the test loadings.

Summary Discussion of Experimental Results

An extensive program of material testing was undertaken to confirm the following characteristic properties for timber used in the decks and component cells:

- Average MoE values of 13000 to 13900 MPa for the LVL webs and 11000 to13000 MPa for the flange laminates
- 5th percentile MoR values of 45 to 50 MPa for the LVL webs and 25 to 29 MPa for the flange laminates
- Average co-efficient of friction values of approximately 0.4 between webs and flanges, with a co-efficient of variation of 12% to 15%.

Deck Tests

The full-scale deck tests "proved" that the cellular concept was viable and provided the design basis for 4 prototype bridges. The results confirmed that provided the prestress level is maintained at a minimum level of 500 kPa (a requirement for all Australian designs), the load response for both serviceability and strength design limit states as defined by AUSTROADS, is linear elastic.

Breakdown in "fully" composite behavior did not commence until the design loads were significantly exceeded, as illustrated in Figure 6, where the ULS design load requirement for a Heavy Load Platform was 1585 kNm. Whilst slip and a consequent breakdown in composite behavior began to occur at about 1800 kNm, web failures did not occur until the bending moment exceeded 2300 kNm. At the ultimate bending moment of 2550 kNm all 7 webs had suffered midspan flexural failures, but no failures were observed in any of the flanges.

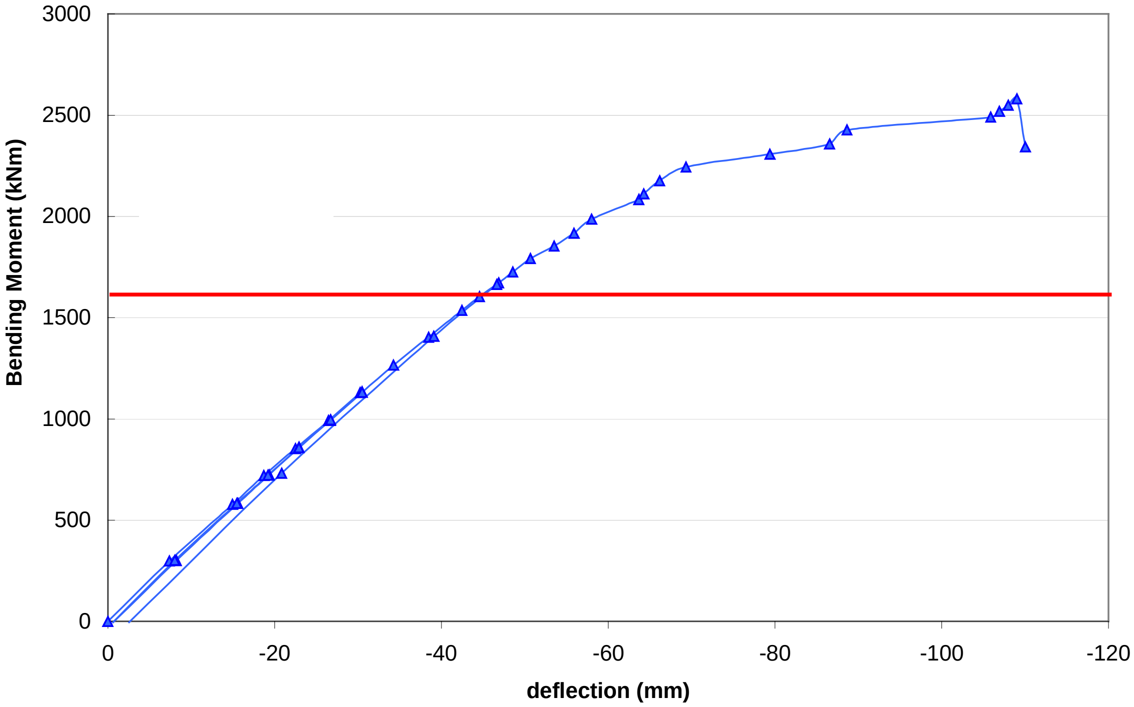


Figure 6. Load vs. midspan deflection for 600mm cellular deck

It was also noted that despite the fact that most commercial timber exhibits brittle failure modes, the "system" behavior of the cellular deck is essentially ductile up to the ultimate capacity, which was determined by flexural failure of the webs. Furthermore, subsequent re-loading of the "failed" deck was undertaken up to a moment of 1800 kNm and despite significant deflection, the deck was able to resist the load without further failures occurring.

The deck tests were also used to quantify the relationship between stiffness and level of prestress, and to derive load distribution factors (LDF's) for determining the relative proportion of load being taken by a single cell.

Figure 7, illustrates the distribution of load to each cell at midspan, for the load positions LP 2, LP 3 and LP 4 described in Table 1. The cellular deck was observed to behave in similar manner to a "wide beam" and continued to do so well into the range of loading beyond which slip occurs. The load distribution factors were found to be independent of prestress, although it should be noted that eccentric loads and torsional rigidity were sensitive to prestress levels below 500 kPa.

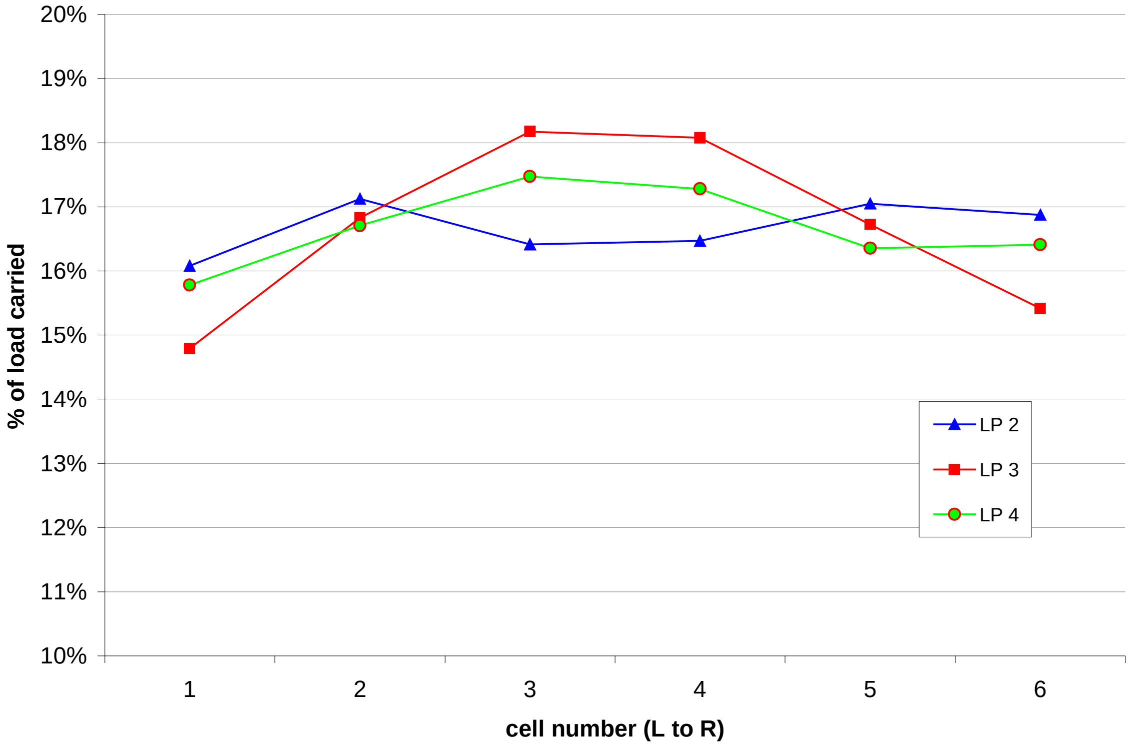


Figure 7. Load Distribution Factors from deck tests

Component Cell Tests

These series of tests not only characterized the component cell system behavior for bending, shear, and torsion, but also focused on developing a fundamental understanding of the slip interaction mechanism between web and flange laminates. The interactive effects of butt joints and prestress levels upon load responses and the onset of slip for individual cells were also quantified, resulting in a series of empirical equations for generalized modeling of deck behavior being derived from the experimental data.

The slip mechanism was found to be the cause of non-linearity at high load levels and has proven to be the critical limiting factor for both serviceability performance and ultimate strength for cellular sections. Essentially, the slip represents a "breakdown" in composite behavior, whereby strain is progressively transferred to the webs, ultimately resulting in flexural failure of the LVL webs at midspan.

The results of testing a 600mm deep component cell, with a normal 1 in 4 butt joint pattern are summarized in Figure 8. The “slip” point is seen to occur in the range 440 to 520 kNm, with an apparent loss of stiffness as load increases. At 800 kNm the first LVL web failed, followed by the second web at 900 kNm - both flexural failures at midspan. The heavy load platform design load (strength limit state) requirement for this configuration is 285 kNm.

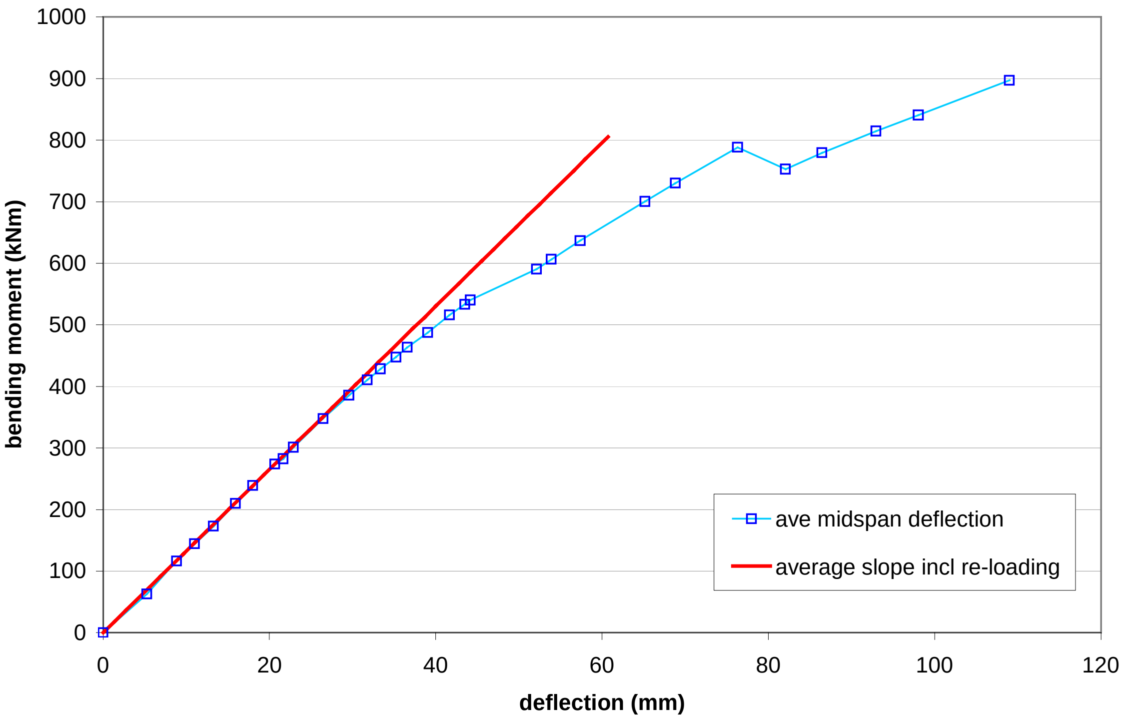


Figure 8. Bending moment vs. deflection for 600mm deep component cell

Modeling Cellular Behavior

Slip occurs when the shear flow at the web to flange interface exceeds the frictional force induced by the prestress. As such, it is a function of the co-efficient of friction between the webs and flanges and the level of prestress. However, the butt joint pattern was also found to affect the point at which slip commences and the interaction of all these variables meant that the onset of slip behavior couldn't be simply modeled using classical friction theory.

The ultimate load capacity of the cellular deck system was also found to be directly related to the "slip point", due to the increase in acquisition of strain that occurs in the webs as loading continues into the post slip region. Prior to slip, the relative strain was observed to remain constant, whereas after slip, the rate of strain acquisition by the webs increased significantly compared to that in the flanges, ultimately resulting in web failure. A number of different approaches were used to develop a predictive model for quantifying the commencement of slip. The most reliable method was found to be based upon analysis of the relative strain distribution between the flanges and webs.

A design methodology, which considers the influence of prestress, butt joints, material properties and surface finishes, has been developed and validated for use in cellular deck systems up to 1200mm deep, which represents an effective design span of about 25m [*Crews – 2002*]. Details of both the test results and derivation of the design methodology are being prepared for future publication.

Conclusions

The R&D undertaken over the past decade has provided a substantive technical basis for the implementation of stress laminated timber deck technology in Australia, both as plate decks and longer spanning bridge decks which utilize cellular forms, capable of spanning 25 to 30m. Over 40 bridges have now been successfully completed and field performance has generally exceeded expectations.

Field performance of four prototype bridges utilizing the cellular deck system has demonstrated both its structural efficiency and cost effectiveness, despite the fact that the cellular technology is being currently used at the lower end of its potential span capacity.

Research continues to be undertaken, and current projects include investigating the effects of nailing the laminations together during assembly and developing prefabricated component systems and associated jointing hardware for use in repairing existing girder bridges and for new modular "kit" bridges. Australian experience has demonstrated that SLT decks produce high performance bridges that are structurally efficient, durable and cost competitive - particularly for rehabilitation of existing timber bridges.

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