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A Structural Wood System for Highway Bridges

Un système porteur en bois pour ponts-routes

Holzbausysteme für Strassenbrücken

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SUMMARY
The Ontario Ministry of Transportation and Communications (MTC) is developing a new family of timber bridges based on the transverse post-tensioning of longitudinally laminated decks. The paper highlights only selected findings. The development program is aimed at rehabilitating wood as a viable and competetive structural material for bridges. The system permits low grade materials, consumes less than 10 percent of the energy required by steel bridges and can be built, by unskilled labour, any time of the year.

RESUME
Le Ministère des Transports et Communications de l'Ontario développe actuellement un nouveau type de ponts en bois, basé sur la précontrainte transversale de madriers. Ce rapport met en valeur les résultats les plus intéressants. Le but de ce programme est de réhabiliter le bois, matériau compétitif et durable, dans la construction de ponts. Le système développé permet l'utilisation de bois de qualité inférieure, il est insensible aux conditions climatiques, nécessite moins de 10% de l'énergie requise par la solution métallique et peut être monté par un personnel non qualifié.

ZUSAMMENFASSUNG
Das Ontario Ministry of Transportation and Communications hat eine neue Art von Holzbrücken entwickelt, die auf dem Prinzip der Quervorspannung von längs angeordneten Bohlen beruht. Das Referat beschreibt nur einige ausgewählte Ergebnisse. Das Programm hat zum Ziel, für Holz als Brückenbaustoff zu werben und die Entwicklungs- und Wettbewerbsfähigkeit des Holzes aufzuzeigen. Das System erlaubt die Verwendung von Holz geringer Qualität, ist witterungsunabhängig, benötigt weniger als 10% der Energie einer entsprechenden Stahllösung und kann durch Hilfskräfte ausgeführt werden.

Summary

The Ontario Ministry of Transportation and Communications (MTC) is developing a new family of timber bridges based on the transverse post-tensioning of longitudinally laminated decks. The paper highlights only selected findings.

The development program is aimed at rehabilitating wood as a viable and competetive structural material for bridges. The system permits low grade materials, consumes less than 10 percent of the energy required by steel bridges and can be built, by unskilled labour, any time of the year.

Traditional Design

This paper deals essentially with the rehabilitation and improvement of bridges constructed using longitudinally laminated, nailed decks supported by timber pile bents. Hundreds of these bridges exist in the province of Ontario, and there are probably several thousand of them throughout Canada.

In present designs the maximum span length is about 6.0 m, however, a multi-span, continuous deck may exceed 100 m in length. Traditionally, a deck is constructed in multiples of three, such that one laminate is butt-jointed over the pier and the other two at alternating third points of the span. There is no physical continuity of the laminates provided at the butt-joints other than two nails by which the ends are connected to the adjacent laminates.

Observed Modes of Failure

The maximum permissible single axle weight in Ontario is 10 000 kg (98.06 kN), but on logging and mining roads where many of these bridges are located, weights of up to 20 000 kg (196.12 kN) have been frequently observed. This observation is reflected in the new Ontario Highway Bridge Design Code which specifies a 200 kN single axle and a 280 kN tandem for the design of bridge decks.

Under such loads these bridge decks often fail. The failure is precipitated by the bending of nails and the crushing of the adjacent wood. In addition, incompressible materials may accumulate between the laminates, being driven down by the tires of heavy commercial vehicles. This allows water to enter between the laminates and to penetrate to their untreated heartwood through the enlarged nail holes. The combined effect of wood decay and decreasing transverse load distribution among the laminates often leads to local deck failures after only a relatively short service life.

Another significant weakness of these decks is the absence of longitudinal continuity of the laminates. A recent test carried out on a two-span, nailed strip consisting of 24 lines of laminates indicated that the lack of continuity caused a total disintegration of the structural system at less than 60 percent of the predicted ultimate load, although the laminations proper showed no signs of flexural failure. Another test, where repeated service level loads were applied, resulted in a similar failure after only 65,000 cycles as opposed to a minimum of 500,000 cycles required by the Ontario Highway Bridge Design Code.

Retrofitting Existing Structures

Normally bridges that displayed local failures in the past were immediately replaced. However, due to the deteriorating economy and the high cost of replacements, MTC directed its continuous bridge testing program towards wood structures in 1973. This program is aimed at determining the behaviour and load carrying capacity of existing bridges. Since that time numerous bridges have been tested including trusses, sawn timber stringers, glue laminated girders, laminated decks with or without concrete overlay and wood piling.

Specifically, the load carrying capacity and the service life of the longitudinally laminated decks were identified as being a direct function of the "tightness" of the structural system. ("Tightness" is defined as the ability of the structure to withstand relative interface movement and the access of foreign materials between adjoining components). The solution to retrofitting these structures was therefore sought in creating an artificial "tightness" and it was found in transverse post-tensioning the deck.

A small three-span bridge with a total length of 16.78 m (55 ft.) and a longitudinally laminated timber deck, came up for replacement in 1976. Built in 1951, its deck now showed signs of irreversible deterioration along the lines described above. The bridge is located on a logging road where heavily loaded trucks travel at relatively high speeds.

The prestressing system employed consists of pairs of 16 mm (5/8 in.) diameter Dywidag bars at 0.915 m (3.0 ft.) centres anchored in steel plates along the sides of the bridge deck. The bars were protected by enclosing them in grease-filled PVC pipes. The top bars were layed in transverse troughs cut into the asphalt wearing surface, while the bottom bars were attached to the wood deck by brackets and screws.

The prestressing of the pairs of bars was carried out in a sequential manner by using two jacks at a time. This operation had to be repeated several times as the width of the deck shortened by as much as 460 mm (18 in.) before the specified average prestressing stress of 0.69 mPa (100 psi) had been attained. About 82 percent of this shortening was related to straightening the laminates and closing the spaces between them. After prestressing, efforts to insert razor blades between the laminates failed, and during a rainfall it was observed that the deck became practically water tight.

The bridge was load-tested before and after the application of prestressing, using one of the two MTC testing vehicles. The maximum gross weight of these vehicles is 890 kN (200 kips) each and any bridge that is not substandard is expected to support either or both (as the case maybe) of these vehicles without any sign of distress. The deck indicated a local failure at the 795 kN load level prior to prestressing. After prestressing, the bridge sustained the full specified load without any difficulty.

The improvement in behaviour was substantial: measured deflections, hence stresses in the laminates, across the deck had been reduced by a factor of 2.0. The bridge has been monitored on a continuous basis since then, and no further deterioration of the deck has been observed. The prestressing force was found to somewhat fluctuate with changes in temperature and humidity of the ambient and to have stabilized after four years at approximately 55 percent of the original value. This is more than adequate.

During the summer of 1979, two other structures were retrofitted by transverse post-tensioning. One is on a country road in Southern Ontario; the other - a major bridge - is at Prince Rupert, British Columbia. Both operations were successful.

Characteristics of the Prestressed Wood Deck

The MTC wood development program includes a number of individual projects: a few have been completed, some are underway and others have yet to be started. Consequently, in order to describe the characteristics of the prestressed wood deck, certain stipulations are to be made. But from all the evidence so far available, it is certain that it responds to loads as an orthotropic plate that derives its strength at ultimate limit states from a combination of the following:

- by improving the lateral distribution of wheel loads,
- by forcing the system into load sharing action,
- by preventing the development of torsional shear stresses, and
- by longitudinal "bridging" of defects and discontinuities.

The improvement of lateral distribution of wheel loads has been demonstrated by the bridge (Hebert Creek) that had been retrofitted in 1976. The other three items will now be discussed.

Load Sharing at Ultimate Limit States

In the Ontario Highway Bridge Design Code "load sharing" is defined as a construction composed of three or more essentially parallel members so arranged or connected that they mutually support the load; in case of failure of one member, the system retains its capacity to support the load.

In order to create a data base, MTC contracted the Western Forest Products Laboratory (WFPL) of Vancouver, to undertake the testing of a large number of wood specimens both in individual and load sharing modes. Three species were included, namely B.C. hem fir, Ontario red pine and Ontario white pine. All samples were 51 mm x 254 mm rough-sawn boards, 4.88 m (16 ft.) long. They were purchased green and kiln-dryed to an approximate moisture content of 19 percent.

After retaining only that material graded as #2 and better, each sample size was reduced to about 420 specimens. Sixty of each species were tested individually for elasticity and modulus of rapture. The rest were tested for load sharing by combining together either 6, 12 or 18 laminates per specimen by transverse post-tensioning. Each of the three groups contained 10 beam units for each species, totalling 90 post-tensioned wood specimens.

It had been observed that the average values, regardless of the number of specimens in the beam, hardly fluctuate, but there is a dramatic increase in ultimate strength for the load sharing systems. The increase from individual specimens to an 18 - laminates beam is 82.5, 74.9 and 50.8 percent for white pine, red pine and hem fir, respectively. This increase is not associated with transverse distribution as the load was always applied uniformly across the width of the beam.

As a result of the individual specimen tests, the stiffness versus strength relationships were plotted separately for the three different species, and straight line, best-fit analyses were carried out. It was observed during the WFPL tests in Vancouver, (and in similar tests carried out at the University of Toronto and at MTC's own laboratory in Downsview) that the ultimate load carrying capacity is attained usually after about 25 percent of the laminates are broken. The availability of the stiffness v. strength functions permitted the construction of a statistical model, by which the average failure sequence of transversely post-tensioned laminates can be described.

Calculations were carried out for beams with 24 laminates, a number that provides for the width of a bridge deck within which deformations are uniformly distributed. It is interesting to note that for all three species, maximum strength was obtained after six laminates failed, a phenonenon that was confirmed by several laboratory tests carried out on full-size laminates. The calculated strength increase due to load sharing were 58.0, 59.6 and 43.7 percent for white pine, red pine and hem fir, respectively. These leave, in comparison with the WFPL test results, 24.5, 15.3 and 7.1 percent actual increases yet to be explained.

Shear Stresses and Internal Bridging

In preparation of the Ontario Bridge Code, MTC contracted the University of British Columbia to carry out in-grade testing of large sawn-timber beams. The part of the project that is of interest here, included 452 individual specimens of 152 mm width, of which 48 were broken. Sections with three different heights were included, namely 203 mm, 305 mm and 406 mm. All wood was rough-sawn B.C. fir, graded #1 and better, with moisture content between 21 and 44 percent.

It appears that ultimate flexural strength is decreasing with the width-to-height ratio of the cross section. The total reduction from 203 mm to 406 mm is an astonishing 40.4 percent. At the time of this writing, there is no readily available explanation for this phenomenon and it is not certain that all species and cross sectional sizes would exhibit the same trend. It can be speculated, however, that the answer to this question should perhaps be sought in the macro-structure of the wood proper.

When a close-to-square section is formed, it likely includes the whole log, cut to eliminate the circumferential material. This leaves the macro-structure symmetrical, both ways, to the centre of gravity of the section. When two or more sections are cut from a log, say 51 mm x 305 mm material used in laminated decks, the chances are that none or only one section will end up with a symmetrical macro-structure. This lack of symmetry causes the shear centre of the section to move away from the centre of gravity, resulting in torsional moments under vertical loading.

It has been observed that when a single plank (laminate) is being tested for flexure in the cantilever mode, the end of the plank tends to rotate around its longitudinal axis. On the other hand, the transversely post-tensioned decks internally eliminate torsional moments due to the random orientation of the individual macro-structures and do not permit the development of torsional stresses due to close to absolute confinement.

It appears evident that the strength of individual specimens is determined by internal discontinuities (knots) and by interrupted and misaligned grains. The reduction in comparison with parallel grained clear specimens is, on the average, 40 to 60 percent, depending on whether the failure is compression or in tension. It is also statistically obvious that discontinuities and faults are randomly distributed in a laminated deck, i.e. they do not constitute a line of weakness in the orthotropic continuum created by post-tensioning. The transverse post-tensioning mobilizes longitudinal friction of considerable magnitude among the laminates by which longitudinal flexural stresses can by-pass the discontinuities.

This "bridging", along with the elimination of torsional stresses, is believed to be responsible for the part of apparent strength increase, not explainable by the statistical process described. These aspects will be investigated by MTC in the near future.

Longitudinal Continuity of Laminates

The third point butt joints, mentioned earlier, have proved to be lines of considerable weakness, since laminates tend to move independently under loads. The test at the University of Toronto indicated a disastrous effect: the nails split the ends of the laminates resulting in a piano-key type of failure.

In order to eliminate this weakness, a variety of methods of correction were considered. The one that was found to be most feasible involves the "nail-plate" or "gang-nail", a commercially available fastener being used in prefabricated wood trusses for residential construction. The gang-nail is manufactured from galvanized sheet metal by punching out the teeth with a machine die. These plates are then pressed into the wood applying hydraulic jacks and are used to connect two components together. The sheet comes in various thicknesses and is made of mild steel with an ultimate tensile strength of 320 mPa.

From pilot tests it appears that a 14 gauge (1.90 mm) plate would match the flexural strength of a 51 mm (2 in.) thick red pine laminate at their mutual 5th percentile level. However, since the strength coefficient of variation of steel is only 8 percent while that for red pine is 36 percent, it is assured that, in a load sharing system, the plates would rupture first. Thus, the use of plates on these decks introduces ductility, a highly desirable structural features, that wood when failing in tension does not possess.

Cyclic tests carried out by others in the past showed that the fatigue life of these plates is disappointingly low. The mode of failure is either the fracture of the nails at the neck or their gradual slipping out of the wood. MTC's own tests indicate that the presence of compressive stresses between the laminates due to prestressing tends to inhibit both failure modes and assures sufficiently high fatigue life at service load levels. The same tests also seem to prove that in the post-tensioned deck moment transfer by the plates is of secondary significance: the primary requirement is shear transfer by which "piano-key" type of failures are prevented.

The Stressed Wood System

Considering improved transverse load distribution and strength enhancement by load sharing, the improvement due to transverse post-tensioning is 272, 256 and 207 percent for white pine, red pine and hem fir, respectively. In accordance with the provisions of the Ontario Bridge Code, these would permit maximum simply supported spans of 6.0 m, 8.7 m and 11.8 m for the species in the same order. Unfortunately, deflections associated with these spans for red pine and hem fir are unacceptable and it appears, therefore, that on account of the dramatic enhancement in load-carrying capacity due to transverse post-tensioning, only those tree species that have strength characteristics close to white pine can be used economically. In order to make appropriate use of the available strengths of the tensioned decks, they must be combined with other structural systems.

a. Decks for Existing Truss Bridges

Many existing truss bridges, steel or wood, have problems of deterioration of their decks, either concrete or wood. The transversely post-tensioned, longitudinally laminated wood deck is an eminently suitable replacement for these decks due to its light weight, improved load distribution among cross beams and contribution to the strength of the bottom tension chords of the trusses.

b. Composite with Concrete Overlay

Under development is a wood/concrete composite at present. The shear connector is a continuous concrete key, 125 m wide and 38 mm deep, cut into the top of the laminated deck by a gang-saw. The key is reinforced at its tension side by a

250 mm long ARDOX nail, driven into every third laminate, at an appropriate angle. The second role of the nail is one of holding the concrete overlay down. The key provides for fully composite action such that the 305 mm wood deck with a 102 mm concrete overlay is estimated to be able to span close 15 m (50 ft.). The concrete overlay can be used as a wearing surface without further protection.

c. Longitudinal Web Splice
The structural height of the laminated deck can be increased by splicing two planks together along their edges by using strips of the gang-nail. Depending on span and load requirements, the spliced element can be combined with a number of ordinary deck laminates in a repeated fashion. They are all held together by transverse post-tensioning applied at the centre of the deck. A version of this idea is where the spliced element is combined with ordinary deck elements at both top and bottom, each having its own prestressing, thus creating a multicell structure.

d. Integrated Deck Trusses
If larger span requirements are to be satisfied, the structural height provided by the spliced elements may not be adequate. They can be replaced by trusses whose elements are held together by gang-nails of appropriate size and configuration. In some cases, struts or stayed legs can replace the trusses. Again, the post-tensioning system, applied at both top and bottom (with spacer blocks) chords, is the integrating agent.

e. Stiffening by Tie Bars and Kingposts
Many of the existing wood truss bridges have their cross beams stiffened and strengthened by the addition of tie bars. The system has an excellent record in Canada. Longitudinal bars can be used to stiffen the transversely post-tensioned laminated decks. A system with two king posts would give a maximum span of 22.7 m (74.4 ft.) in white pine.

f. Steel/Wood Composites
The longitudinally laminated wood deck can be made composite with longitudinal steel girders by the way of continuous steel angle shear connectors bolted to the top flange. The angles protrude into slots cut in the bottom of the laminates and contribute to the lateral distribution of wheel loads. Excellent for both new construction and retrofitting.

Cost, Energy and other Considerations

From the three bridges that have been rehabilitated by transverse post-tensioning it appears that the cost (in Canadian Dollars) of a new bridge would not exceed $325/m^2$ ($30/sq.foot) of deck area, while the rehabilitation including new bulkheads and the stripping of existing wearing surface and subsequent resurfacing, is about $95/m^2$ ($9/sq.foot). The construction of these bridges is entirely mechanical and therefore could be done any time of the year. Since the bridges are built up from relatively small elements, in most cases the presence of a crane may not be required.

Observation of these shows them to be extremely tight and waterproof. In addition, the prestressing forces do not permit the development of cracks when heated, and therefore resist the escape of flammable gases. The epoxy coating is guaranteed to protect the Dywidag bars for approximately 35 years. The system permits the removal of the bars, one at a time, without loss of strength and interruption of vehicular traffic, for examination and replacement if so required.

Wood is a renewable structural material and it has been shown consistently throughout this paper that the enhancement by transverse post-tensioning makes feasible the application of the lowest grade species for bridge construction. The system requires an extremely low amount of energy, an aspect that will have major consequences in the years to come.

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