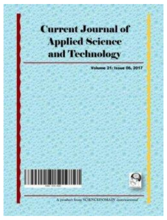

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Design and Execution of Wood-concrete Deck Bridge

Julio César Pigozzo[1], Felipe Nascimento Arroyo[2], André Luis Christoforo[3],
Diego Henrique de Almeida[3*], Carlito Calil Junior[4]
and Francisco Antonio Rocco Lahr[4]

[1]Department of Civil Engineering, State University of Maringá, Colombo Avenue, 5790, Maringá (PR), 87020-900, Brazil.
[2]Department of Civil Engineering, Integrated Faculty of Cacoal, Dos Esportes Street, 1038, Cacoal (RO), 76965-864, Brazil.
[3]Department of Civil Engineering, Federal University of São Carlos, Washington Luís Highway, SP-310, km-235, São Carlos (SP), 13565-905, Brazil.
[4]Department of Structures, University of São Paulo, Trabalhador São-Carlense Avenue, 400, São Carlos (SP), 13566-590, Brazil.

Authors' contributions

This work was carried out in collaboration between all authors. Authors JCP, CCJ and FARL designed the study, wrote the protocol and managed the analyses of the study. Author ALC wrote the protocol and statistical analysis. Authors DHA and FNA managed the analyses of the study, wrote the first draft of the manuscript and managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

In Brazil is growing demand of short and medium span bridges not only in the new agriculture borders but also in the secondary roads in advanced regions. Traditional timber bridge not always meet the requirements of quality, they demand continuing maintenance and adequacy to actual heavy traffic. Mixed wood-concrete deck bridge arises as a viable alternative, because of its low

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**Corresponding author: E-mail: christoforoal@yahoo.com.br;*

construction cost, low maintenance and its high strength and stiffness. This paper presents the studies, design, execution and results from static load tests on wood-concrete deck bridge build with *Corymbia citriodora* wood specie logs, treated with CCA against xylophages organisms, reinforced medium strength concrete and steel bar connection bonde-in wood with epoxy resin, as shear connectors, were all used in construction system. Loaded tests were performed six months after the release of traffic. Results of the load tests indicate that the bridge performance is satisfactory.

Keywords: Orthotropic equivalent plate; Timber Bridge; wood-concrete deck system.

1. INTRODUCTION

Timber bridges in Brazil have been built with little technological knowledge, resulting in structures of low durability and inaccuracy in safety. Such bridges do not always reach fully satisfactory conditions on vicinal or rural roads, still less to compete with metallic bridges and reinforced concrete on highways [1].

Cost of a timber bridge executed with updated techniques is low, being of easy construction and satisfactory durability. The number of these bridges may be so great that the sum of their costs and work to execute them reaches the value and size of the great bridges [2]. Thus, it is very importance specializing the calculation and constructive techniques of timber bridges [3].

In the development of the bridges, one of the fundamental parts is the deck, part of the superstructure that forms the running track and distributes the loads of the wheels of the vehicles to the main beams. During many decades, the decks of sawn wood were the most adopted structural system, according to Fig. 1. However, only in the course of the 20th century was there a gradual renewal of deck design, especially in Europe, North America, Japan and Australia [4].

Fig. 1. Typical deck sawn timber [5]

Pieces used in decks with sawn wood are mostly hardwoods with high resistance to abrasion and rotting. Consecrated species are replaced without criteria and adopted inadequate constructive details, causing pathologies [6,7] (Fig. 2). Alternatives to solve the presented problems appeared with deck asphalt paving of prestressed pieces and decks covered with reinforced concrete [4].

Mixed deck system has been used successfully in bridge constructions, consisting of a concrete slab connected to longitudinal members of wood, in such a way that the parts work together. The level of stress transfer between the concrete slab and the wood can define a monolithic behavior, when there are no relative displacements between them, or semi-rigid behavior, when the stress transfers occur with small relative displacements [4].

In the mixed wood-concrete decks, the concrete slab protects the wood against: weather and surface abrasion by abrasion; reduces vibrations caused by dynamic loads with increasing self-weight; increases sound insulation and fire protection; and provides greater rigidity and strength compared to the only wood system. Although concrete and wood have different mechanical and hydrothermal properties, there are no known problems of use due to these causes [8].

There are several types of connectors for composite wood-concrete structures. The main characteristics that allow comparisons between them are: ultimate strength, slip modulus and final installation cost [9]. In the mixed deck presented in this work, connectors were formed using steel bars glued to the wood in the "X" format, where they were already studied and presented high rigidity and low cost [10].

The use of glued steel bars is characterized by the sticking of bars into holes with larger diameter [11]. Denotes an innovative and improved method of connections, being an important technique for connections using adhesives. There are several advantages of bonded steel bar connections, such as: they allow higher levels of stress transfers; they resist great bending moments; the holes used do not weaken the structural members; avoid possible mistakes in construction sites; allows to join large pieces, acquiring bigger free spans; the structural parts become more aesthetic, avoiding apparent connectors; easily protected against fire; potentially cheaper than the finger-joint system; and have less material and lower production costs. Performance requirements and project regulations differ between them [12]. There are currently some recommendations for use in EUROCODE 5:1993 [13].

Mixed and designed bridge, called Florestinha Bridge, is located on vicinal road in Piracicaba, São Paulo, Brazil. Fig. 3 shows the cross-section adopted. This mixed deck is similar to that presented by Yttrup and Nolan [14], where *Corymbia citriodora* beams were treated with CCA (Chromate Copper Arsenate), inserting tips and bases to obtain constant average thicknesses of wood in all the cross-sections.

Table 1 shows the geometric characteristics of Florestinha Bridge. Elastic characteristics of these bridge are: Ec = 2,020 kN/cm²; Gc = 808 kN/cm²; Ew = 2,000 kN/cm²

Fig. 2. Deterioration and shallow deck decay [5]

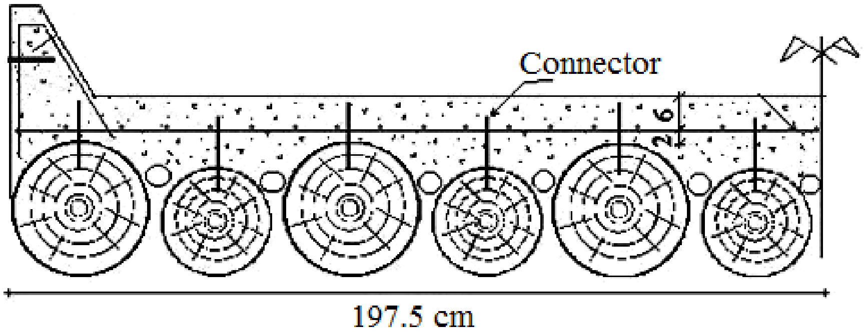

Fig. 3. Transversal section of Florestinha Bridge

Table 1. Geometric characteristics of Florestinha Bridge

Spam = 610 cm
Width = 395 cm
Number of timber beams = 12
Concrete slab thickness = 12 cm
Height of timber beams = 25.2 cm

Width of timber beams = 25.2 cm
Minimum spacing between connectors = 25 cm
Maximum spacing between connectors = 50 cm
Sliding module (section) = 4,560 kN/cm

2. MATERIALS AND METHODS

2.1 Calculation Model

Adopted calculation model comprises two phases for the determination of the internal stresses: the first one corresponds to the determination of the effective stiffness of the mixed beam and the second one the determination of the stresses and displacements, considering the deck an orthotropic slab. The automated calculation for orthotropic slabs was performed with the OTB (*Orthotropic Timber Bridges*) program, adapted by Lindquist et al. [15].

For the first phase of the calculation, the model suggested in Annex B of EUROCODE 5:1993 [13] was adopted, considering the mixed board as a "T" section composite beam. Round timber beams were interpreted as beams of equivalent square sections, considering the average diameters beam in the span center (Fig. 4).

Tests performed on concrete and wood specimens with real dimensions obtained, for each CA-50 steel connector with a diameter of 8.0 mm, average strength in the final limit state of 30 kN and mean slip modulus k = 38 kN/mm.

The effective stiffness (*Elef*) in the longitudinal direction obtained in the first phase results in the following value:

Elef = EcIc + ycEcAcac² + EwIw + ywEwAwaw²

Elef = 1,904,797,440 kN.cm² (1)

In the second phase of the calculation, the deck is considered as an equivalent orthotropic slab with the thickness of the concrete slab. Bending stiffness (Dx and Dy) and torsional stiffness (Dxy) are determined. These rigidity values are used to calculate the elastic properties (E_L)eq, (E_T)eq and (G_{LT})eq of the equivalent plate.

$$(E_L)_{eq} = 12\frac{D_x}{t_{eq}^3}(1-\nu_{xy}\nu_{yx})$$

$$(G_{LT})_{eq} = 6\frac{D_{xy}}{t_{eq}^3}$$

$$(E_T) = 12\frac{D_y}{t_{eq}^3}(1-\nu_{xy}\nu_{yx}) \qquad (2)$$

Where, t_{eq} is the equivalent plate thickness.

With the values of the elastic properties equivalent (E_L)eq, (E_T)eq and (G_{LT})eq, the internal stresses are calculated according to Cusens and Pama [16]. The Poisson coefficients can be attributed null because they represent a small influence on the behavior of the plates when bi supported. The flexural stiffness of the bridge in the "x" direction is expressed by the product "Elef" divided by the bridge width, and the flexural rigidity in the "y" direction is expressed by the "EI" of the concrete slab divided by the bridge length.

$$D_x = \frac{EI_{ef}}{b}\,;\quad D_y = \frac{E_c.I_c}{L} \text{ or } \qquad (3)$$

$$D_y = \frac{1}{L}\left(E_c.\frac{L.h_c^3}{12}\right)$$

The value of the torsional stiffness is given by:

$$D_{xy} = B_{xy} + \frac{G_c.t^3}{6} \,, \qquad (4)$$

$$B_{xy} = 0,06.\frac{E_w.n_v.h_w.b_w}{12.\left(h_w^2+b_w^2\right)}$$

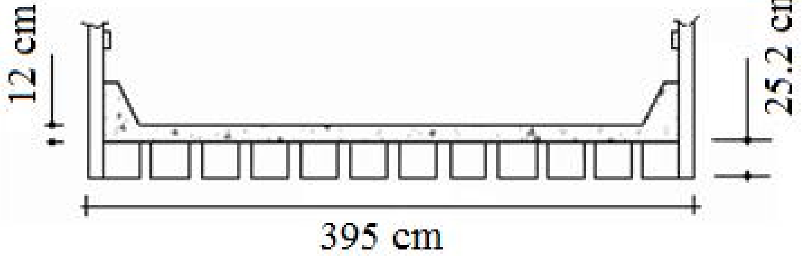

Fig. 4. Transversal section of calculation

"Dxy" value is the torsional rigidity of the beams plus the torsional stiffness of the concrete slab. With this data, the elastic properties of the equivalent plate are as follows:

$$EL: 33{,}488\ kN/cm^2;\ ET: 2{,}020\ kN/cm^2;\ \text{and}\ GLT: 852.8\ kN/cm^2. \quad (5)$$

Additional stiffening (EI_{add}) was considered due to the presence of the wheel guards. This increase in the influence range of the first longitudinal wood beam is calculated using the Equation 1. The value found was:

$$EIadd = 524{,}905{,}727\ kN.cm^2 \quad (6)$$

2.2 Implementation of the Bridge

Mixed bridge executed has the following dimensions: width 3.95 m, length 7.00 m and theoretical free span of 6.10 m. Twelve *Corymbia citriodora* plank beams were treated with CCA, with a length of 7.0 m and a average diameter at the center of the span of 28.5 cm. Medium-strength concrete (f_{ck} = 15 MPa) was molded "*in loco*" with dimensioned reinforcement, which fits perfectly on the natural irregularities of the timber beams. To fill the natural openings between the round beams, treated and brittle struts with compatible dimensions sufficient to prevent the flow of the concrete were used. It was adopted as a design criterion the execution of these bridges without shoring.

Concrete slab has a minimum thickness of 8.0 cm in the crest of the round pieces and a mean thickness of 12.0 cm, considering the total volume of concrete used to fill the depressions between the beams.

After the definitive positioning of the beams, they were clamped transversely in the center of the deck using steel cables, forming alternating double plots according to Fig. 5. The placement of these steel cables is relatively easy, but their behavior is not efficient enough for the distributions of vertical loads between the beams, being only efficient to prevent the relative spacing of the beams horizontally. These frames allowed a vehicle to travel over the timber beams without any difficulties or safety risks during the load test, and can be considered as secondary elements (without structural function) after the concrete slab is executed.

Connectors used were of high strength CA-50 steel (f_{yk} = 500 MPa) with threaded surface and positioned in each beam (Fig. 6), with smaller distances between connectors closer to the end of the tray for better compaction.

Fig. 5. Launch of timber beams

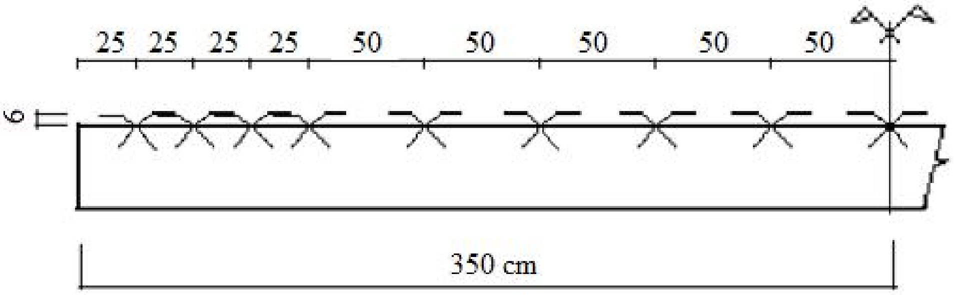

Fig. 6. Position the connectors "X" on each timber beam

Connectors were glued with Sikadur-32 fluid epoxy resin, manufactured by SIKA S/A., into holes with larger diameter and maintaining the thickness of 1.25 mm for the glue line (Fig. 7).

Special care was taken in bonding the steel bars to avoid: positioning defects in the gluing angle, air bubbles in the glue line or hole filling faults.

Among the various injection systems possible, a disposable and low cost solution was sought, avoiding cleaning processes with strong solvents. Considering that the Sikadur-32 fluid epoxy resin allows little time for application (about ten minutes after mixing the resin begins to acquire increasing viscosities that make it difficult to inject in the holes), it was decided to take to the construction site transparent plastic bags containing the total of 250 g of components A and B separated within each bag. At the time of bonding, these components were mixed manually and, with the resin ready, injected into the bores quickly using a small disposable tube with the same diameter as the steel bar, tied with elastic at the end of the plastic bag. The resin was injected from the inner end of the bore and when it came out, the exact volume was obtained for the anchoring of the bar. The bars were introduced with small rotations, facilitating the exit of the air contained and avoiding the formation of bubbles in the glue line (Fig. 8).

Batchelar and Mcintosh [17], reviewing connection breaking experiments due to improper blends and/or misapplications of *in situ* epoxy adhesives, concluded that all bonding operations should be done in the factory environment with adequate quality control and by specialized people.

Armor used in the longitudinal direction was minimum reinforcement established by ABNT NBR 6118:2003 [18] Brazilian Standard Code, enough to avoid cracks in the concrete, being composed of CA-60 bar wires of 4.2 mm to every 10 cm and in the transverse direction composed of wires of CA-60 bar of 4.2 mm every 10 cm, added to bars of steel CA-50 with 8.0 mm every 20 cm. The reinforcements corresponded to 34.3 kg/m³ of concrete or 4.1 kg/m² of slab (Fig. 9).

Load tests were carried out in three phases, being: only with timber beams; after curing the concrete; and six months after the release of traffic, as shown in Fig. 10. The standard vehicle used was a truck with two rear axles and 120 kN loads per axle. Displacements in the center of the span were read with an optical level with sensitivity of 1 mm, by means of millimeter rulers attached to each longitudinal beam (Fig. 11).

Fig. 7. Collage detail of connectors

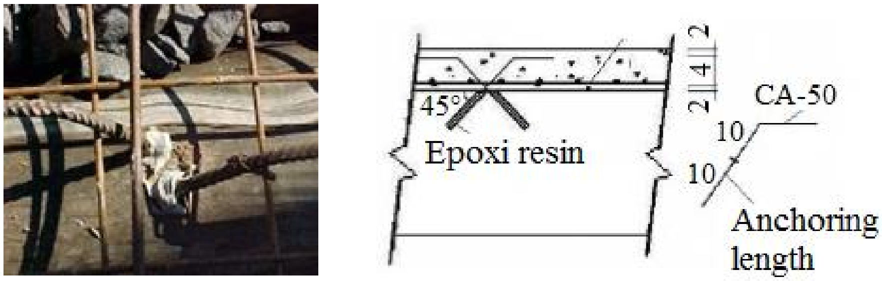

Fig. 8. Details of glued bars and dimensions of connectors

Fig. 9. Details of final armor and beginning of concreting

Fig. 10. Load test on the timber beams and the completed bridge

Fig. 11. Positioning of rules for reading vertical displacements at center line of the bridge

3. RESULTS AND DISCUSSION

Comparison of the vertical displacements for loading 1 in the timber beams and in the mixed deck after curing the concrete are presented in Fig. 12, considering the request of 60 kN in each wheel.

Considering that the steel cable used for transverse locking of the timber beams was not efficient in the transversal distribution of stress, it is still possible to compare the vertical displacements and to perceive the great rigidity of the mixed structure.

Fig. 13 shows the third test of loads six months after the release of traffic. The actual vertical displacements for loads 1 and 2 and the equivalent theoretical displacements obtained through the OTB program are shown in Figs. 14 and 15, respectively, also considering a request of 60 kN on each rear wheel.

Fig. 12. Results comparison of load test 1 and 2 with cargo 1

Fig. 13. Third test load, cargo 1 and 2

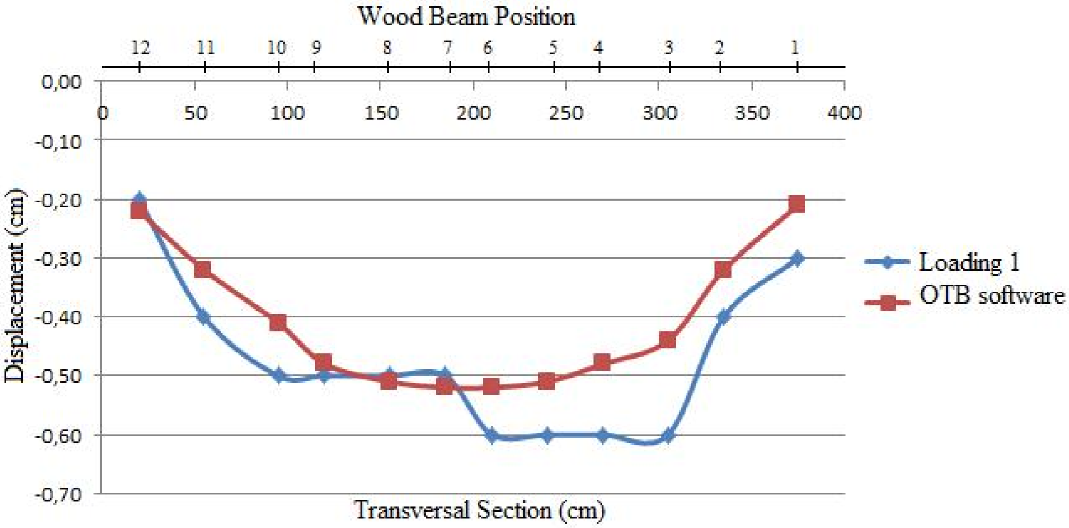

Fig. 14. Comparison of vertical displacement in the porthole center with loading 1

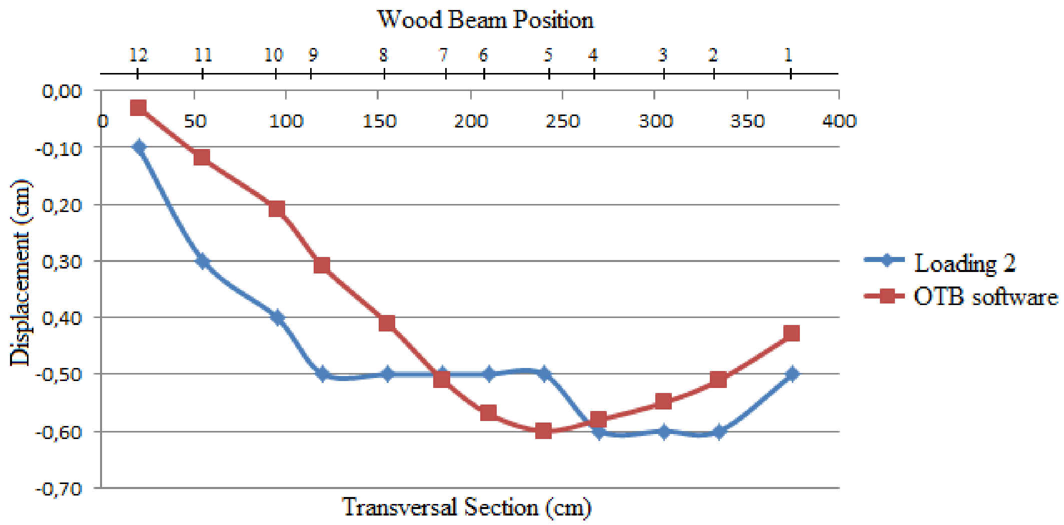

Fig. 15. Comparison of vertical displacement in the porthole center with loading 2

4. CONCLUSIONS

Results show the theoretical and experimental behavior of the analyzed bridge. The mixed deck acts as an orthotropic slab and the timber beams form a statically redundant structural system, thus allowing the redistribution of stresses through the concrete slab when a load is positioned on a more flexible beam.

Sensitivity of the equipment used to obtain the experimental displacements prevented a more precise comparison. However, the order of magnitude of the results reveals that, with the elastic parameters obtained with the equivalent plate, a satisfactory prediction of the real behavior of the mixed bridge was obtained.

Wood beams interlaced with the steel cables, showed maximum vertical displacements of the order of 4.5 cm under the region of application of the loads for loading 1, while the mixed deck presented displacements in the same region of the order of 0.5 cm, showing the high rigidity of the mixed system.

Experimental results show the possibility of improving the height of the deck, taking the internal stresses and displacements closer to the boundary states. Low cost, ease execution and social interests highlight the mixed system for small bridges on back roads.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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