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Concerning timber-concrete panels and T-beams for rural bridges

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Abstract

A study of the state-of-the-art of timber-concrete structures reveals a great potential of this technique for structural applications in both urban and rural environments. In addition to the efficient structural performance, it provides an excellent architectural effect due to the contrast between timber and concrete elements used in the wall panels, roof and floor slabs for various types of new construction and/or repair and renovation. The mechanical performance of a composite structure largely depends on the efficiency of the connection system, which can be of the rigid or semi-rigid type. This system must assure the interaction between concrete and timber to transmit shear stress efforts along the interface and to impede the vertical movement between the elements. To promote the use of timber-concrete structures, this study evaluates the mechanical performance of timber-concrete panels and T-beams with emphasis on semi-rigid steel connectors such as nails and screws. The analysis of these composite structures is based on the principle of equilibrium of forces and compatibility of displacements, verified by means of differential equations of fourth order and by the finite element method through the use of the Sap2000 software. Presented are examples of verification and design of structures to meet requirements of the ultimate and serviceability limit states. In the light of the theoretical and experimental results obtained, it can be concluded that timber-concrete composite structures have favorable horizon for application in civil construction and it is important that the development of this constructive technique is continued by the technical and scientific community.

Keywords: concrete-timber structures, beams, panels, rural bridges, experimental analysis, finite element method, connections, slip modulus.

Introduction

In general, composite structures consisting of concrete and timber can be placed as an alternative solution to the structures of current use in the civil construction, especially the crossing-bridge superstructures and bridges of rural roads.

In fact, through the constructive technique of the composite structures it is possible to use timber and concrete in a more rational form, exploring the elasticity and the strength properties of these materials. These composite materials applied to bridges result in a structure with greater durability, having both a durable running surface and a protection for the timber against humidity.

As also presented by Ceccotti (1995), a concrete-timber composite structure presents both a lesser dead load and a lesser use of formwork and scaffolding in relation to the structures of reinforced concrete. On the other hand, when comparing timber structures with concrete-timber composite structures, it is noticed that the last ones provide a greater loading capacity.

The mechanical analysis of composite structures is based on the principle of equilibrium of forces, compatibility of displacements, and the performance of these structures largely depend on the efficiency of the connection system, which can be of the rigid or semi-rigid type. This system of connection provides the transference of the horizontal shear efforts, as well as hindering the vertical unfastening of these materials. In case of semi-rigid connections, the effect of the slip of the flexible connection system must also be considered.

In this context,this paper presents a theoretical and experimental analysis of prototypes of bridges, also verifying: the efficiency of connection systems, which is composed by nails or screws; the agreement between the experimental result curves and the theoretical ones based on numerical computer programs.

Modeling The Composite Structures

Generally, in a composite structure with rigid connection system, the internal efforts and displacements can be evaluated only considering a transformed section method.In addition, in the composite structures where the connection system is of semi-rigid type, the structural behavior is influenced by correspondent rigidity of this system, which requires consideration on the effect of slip in the contact surface between the two materials.

Using fourth-order differential equations, Stevanovic (1996) presented methods for the determination of the internal efforts in steel-concrete and concrete-timber composite structures, respectively. Ceccotti (1995) presented, with some adaptations, the method of the European code for designing of timber structures, Eurocode 5 (2004).

In these procedures, the equations are developed from the equilibrium of forces and the compatibility of displacement, considering also the rigidity of the connection system through the corresponding slip modulus. In the modeling through the Finite Element Method using the software Sap2000 (1998), the floor and web are represented by mesh of elements and the connection system is considered of discrete form in the structure through frame elements.

Generally speaking, it is assumed some simplifications when panels are designed. In this case, a T-beam is considered, in which a part of the slab will constitute an effective flange of the transversal section, according to the Brazilian reinforced concrete structure code NBR6118 (1982), represented in Figure 1. In the legend of Figure 1, *l* is the span of the structure.

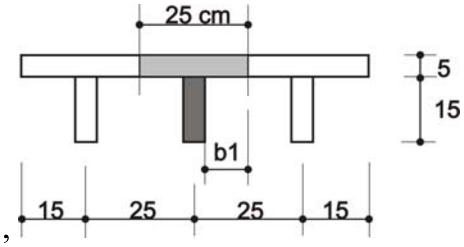

Figure 1. Effective width of flange.

The Method of calculation by differential equations

The fourth-order differential equations for the case of a concrete-timber structure under concentrated load in the middle-span are developed from the equilibrium of forces and the compatibility of displacement of the structural element. The rigidity of the connection system is considered through the slip modulus for unit of spacing of the connectors, which is obtained experimentally from the shear test specimen. These equations can be solved by the Mathematica program (1997) with appropriate boundary conditions.

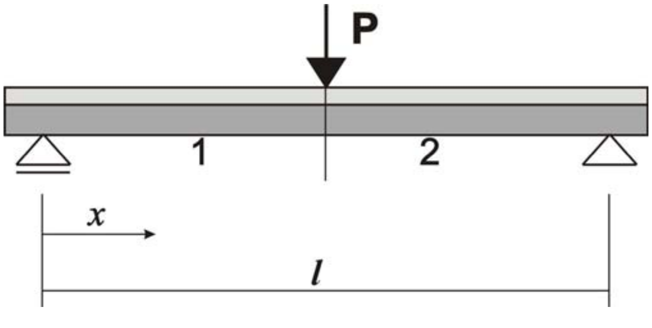

Figure 2. Simply supported beam.

For $0 \le x < \ell/2$: $w_1^{iv} - \alpha^2 w_1^{ii} = \frac{\alpha^2}{EII}\left(\frac{Px}{2}\right)$ and for $\ell/2 < x \le \ell$: $w_2^{iv} - \alpha^2 w_2^{ii} = \frac{\alpha^2}{EII}\left(\frac{P(-x+1)}{2}\right)$,

where: $\alpha = \sqrt{\overline{K}\left(\frac{1}{E_w A_w} + \frac{1}{E_c A_c} + \frac{r^2}{EI0}\right)}$; $EI0 = E_c I_c + E_w I_w$; and $EII = \frac{EI0\alpha^2}{\left(\alpha^2 - \frac{\overline{K}r}{EI0}\right)}$.

The subscripts c and w indicate concrete and timber, and the other symbols are : A = cross-section; E = modulus of elasticity; I = moment of inertia; EI0 = stiffness without connection between the concrete and the timber; EII = stiffness assuming the infinitely rigid connection; r = distance between the centers of gravity of the timber and concrete.

The Method of calculation adopted from the Eurocode 5

The Eurocode 5 (2004) presents expressions that direct the design of structures, composed by material with different mechanical properties and with flexible connections. By means of this code, Ceccotti (1995) suggests adaptations for its use in concrete-timber composite structures.

Equation (1) presents the effective rigidity, $(EI)_{ef}$, in which it is considered both the influence of the elastic modulus of each element and the influence of the slip of the connections of composite beams through the slip modulus for unit of spacing of the connectors:

$$(EI)_{ef} = E_c \cdot I_c + y_c \cdot E_c \cdot A_c \cdot a_c^2 + E_w \cdot I_w + y_w \cdot E_w \cdot A_w \cdot a_w^2 \qquad (1)$$

In which: E_c, I_c, E_w, I_w, are the modulus of elasticity and the moment of inertia of concrete and timber, respectively. In addition, as follows the other parameters to be pointed out in (1):

$$y_c = \left[1 + \frac{\pi^2 \cdot E_c \cdot A_c \cdot s}{\overline{K} \cdot l^2}\right]^{-1}; y_w = 1{,}0; a_w = \frac{y_c \cdot E_c \cdot A_c \cdot (h_c + h_w)}{2[y_c \cdot E_c \cdot A_c + y_w \cdot E_w \cdot A_w]}; a_c = \frac{(h_c + h_w)}{2} - a_w \text{, where:}$$

s is the spacing of connectors; l is the span; K is the slip modulus of connection; A_c is the area of concrete; A_w is the area of timber; h_c, h_w, a_c and a_w are showed in Figure 3.

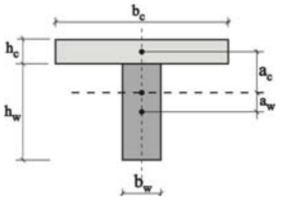

Figure 3. Representation of "T" beam cross section.

The Finite Element Method

Using the Sap 2000 program (1998), the panels were modeled, of concrete and timber, represented by shell elements. In this program it is considered a mesh of finite elements that represents the flange in concrete of each structure and it is defined in the horizontal plan contained in the half thickness of the flange. The thickness attributed to each finite element indicates the real thickness of the flange, h_c, see Figure 3. Analogously, each timber part is represented by a mesh of elements defined in the plan contained in the vertical and longitudinal directions of the structure, of which thickness is the same of the section of the timber, b_w, see Figure 3.

The nails and screws that constitute the connection systems are represented by frame elements that link a node of the upper edge of the timber to another node of the mesh that models the flange in concrete. Each frame element is placed observing the spacing used in the prototypes. The vertical hindering of the flange and web of the composite structures is assured by imposing that two nodes of an only bar have to present the equal displacement in vertical direction.

The Stiffness Of The Connection System

The stiffness of a connection system is estimated by its slip modulus, which quantifies the resistance offered against the displacement in the surface of contact between two materials.

As presented in Ceccotti (1995), a procedure for the determination of the slip modulus consists in establishing the instantaneous slip modulus for the serviceability limit state, K_{ser}, and the instantaneous slip modulus for the ultimate limit state, K_u. The first one that corresponds to the initial loading levels is obtained by the inclination of the straight line to the beginning of the load-slip curve and to the corresponding point to 40% of the force of rupture with its respective slip. Already, for the ultimate limit state is considered that $K_u = (2/3)\ K_{ser}$.

Detailing Of Tested Structures And Material Properties

The mechanical performance of structures with connection systems by means of screws and nails was verified experimentally through test of prototypes of panels destined to the use in floors of constructions, crossing-bridges and small bridges of rural roads. Three panels presented in Figure 4 were constructed, in which nails or screws were used.

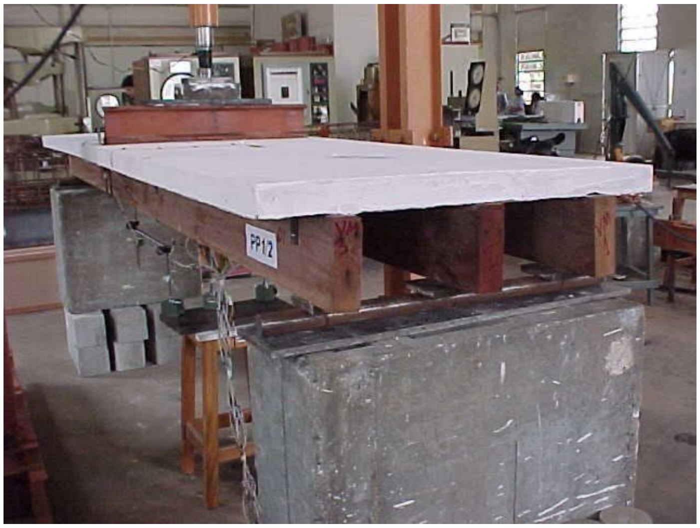

Figure 4. Details of panels.

To identify the connection systems for nails and screws of 9.525 mm and 12.700 mm diameter (3/8 inch and 1/2 inch), it was made denominations such as PPR, PP3/8 and PP1/2, respectively. In Table 1, the connection system features are presented, as well as the effective area of these connections that were placed in each unit of length of timber part.

Table 1. Characteristic of the connectors.

Connector	Diameter	Tensile strength	Spacing	Area by connector	Effective area
	mm	MPa	mm	cm^2	cm^2/m
Nails 24x60	6.580	600	50	0.340	6.80
Screws 3/8	9.525	240	75	0.713	9.51
Screws 1/2	12.700	240	75	1.267	16.89

The Brazilian wood species *Goupia glabra* was used for the construction of the prototypes. The mechanical properties: longitudinal elastic modulus, 14700 MPa, and compressive strength, 60.57 MPa, were characterized using the code NBR7190(1997). The Moisture Content was 11.46 %. The flange of the panels was constructed with mixed concrete, with a compressive strength 22.05 MPa and the elastic modulus 19297 MPa.

Table 2 gives the average values of the slip modulus, which divided for the spacing of the connectors, either 5 cm for the nails or 7.5 cm for the screws, resulted the slip modulus by unit of size, $\overline{K}_{ser}$ and $\overline{K}_u$, respectively.

Table 2. Slip modulus.

Connection type	Limit state			
	Serviceability		Ultimate	
	K_{ser}	$\overline{K}_{ser}$	K_u	$\overline{K}_u$
	N/mm	N/(mm.cm)	N/mm	N/(mm.cm)
Nails 24 x 60	14427	2885.4	9617	1923.6
Screws 3/8	11471	1529.4	7647	1019.6
Screws 1/2	15464	2061.9	10309	1374.6

Each shear test-specimen, see Figure 5, was molded with the same materials of the prototypes, containing a pair of connectors for each timber prism, with equal spacing to those used in the structures. In the assembly of these specimens bars of steel of diameter of 5 mm were placed in each face to avoid the fissures of the concrete.

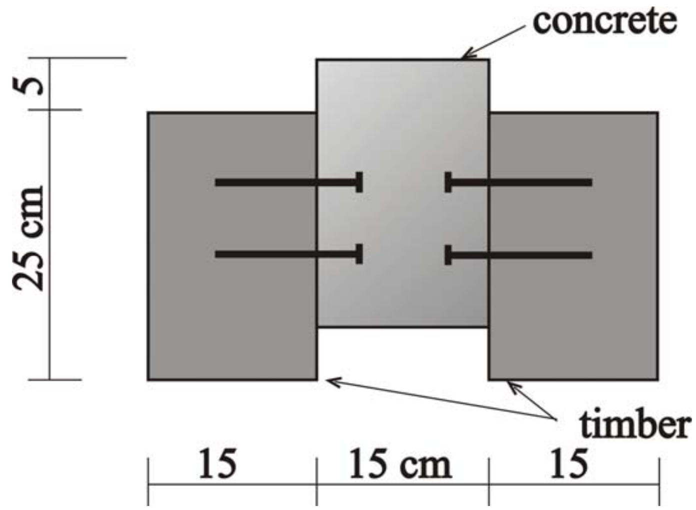

Figure 5. Shear test-specimen.

Verification Of The Vertical Displacement Through The Theoretical Models

The three curves plotted in Figure 6 show the experimental displacements of the PPR, PP3/8 and PP1/2 panels. It is pointed out that panel PPR, of which connection system is constituted by nails, practically presented behavior of rigidity of equal efficiency of PP3/8 panel, in which it was used screws of 9.525 mm of diameter.

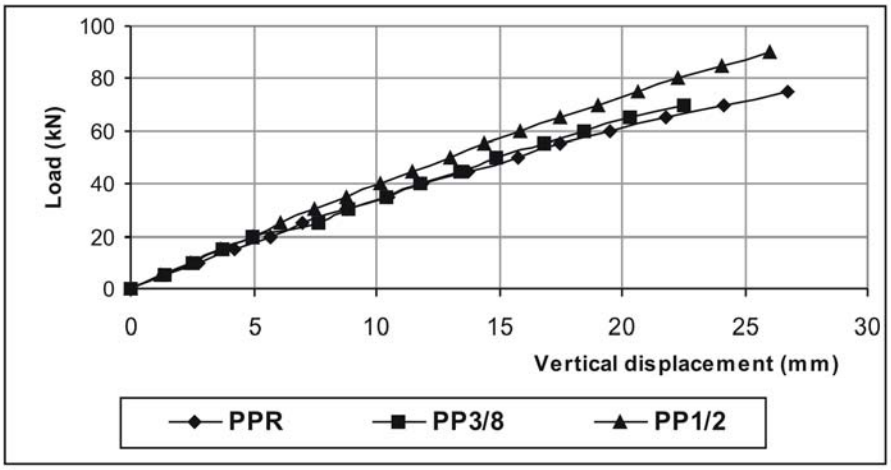

Figure 6. Experimental load-deflection curves.

It was noted through the development of the three curves of Figure 6 that the use of a very high effective area of connection (see Table 1) produces a little effect in the loading of these panels, mainly until the levels that define the serviceability limit state, that is, for a displacement of 15 mm. In general, the vertical displacements of these structures are limited to the conditions established by the serviceability limit state of timber codes, since the timber parts represent most of effective inertia of the section of the composite structure section. In a usual construction, according to Eurocode 5 (2004) and NBR7190(1997), the displacement must be limited to the ℓ/200 until ℓ/350 of span of simply supported structure. It was verified through the adaptation of the Eurocode 5 method, that the results obtained for the vertical displacement resulted very close to those by means of the modeling by the differential equations.

From the ultimate limit state, the rupture load of the panel with screws of 12.700 mm was superior in only 16.20% of the load reached for PPR panel, which was of 91.64 kN. This rupture load was above to the value supported for screws of 9.525 in 10.60 %.

In Figures 7 and 8, the experimental and theoretical displacements are presented assuming a perfectly rigid connection system (th-EII curves) what implies in assuming a connection system that does not permit the longitudinal slip between the concrete and the timber. The benefit resulting from the presence of the connection system can also be visualized when the experimental curves are compared with results considering that in the contact surface concrete-timber the slip is not hindered, as represented by the curves (th-EI0).

The modeling of the panels by differential equations is represented by the (th-MATH) curve, with results of Mathematica software. In this case the connection system is considered continuous and represented by the slip modulus per unit of spacing of connector. The vertical displacements estimated by the Sap2000 program are represented by the (th-SAP) curve. In this simulation, each of the three groups of connector system is defined by a discrete form as in the tested structures.

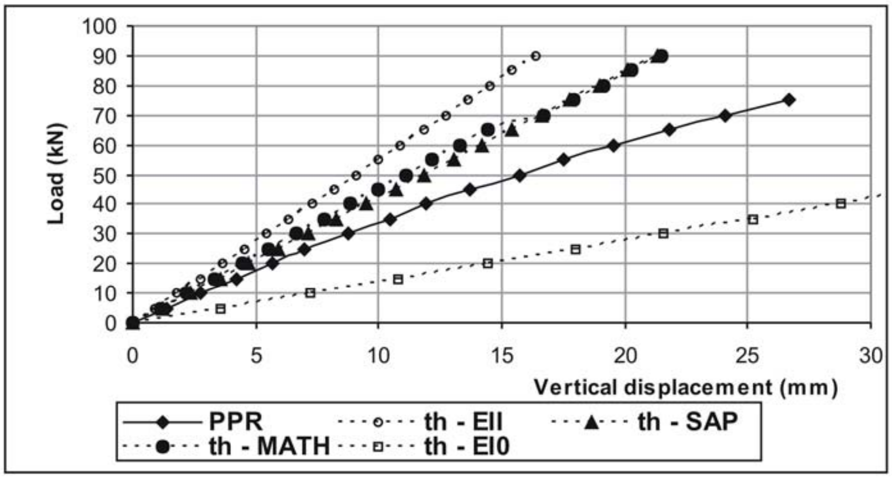

Figure 7. Load-deflection curves –PPR panel.

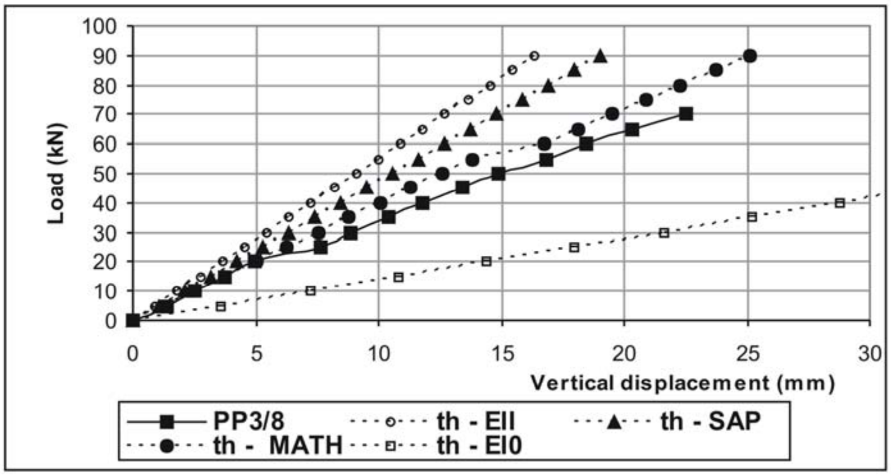

Figure 8. Load-deflection curves -PP3/8 panel.

Comparing the experimental curves and the (th-EI0) curves, in Figures 7 and 8, the increase of the load capacity of each panel is estimated due to the presence of these connectors. For example, for a deflection of 15 mm, the simple presence of these systems allowed increasing the loads of 125%, 150% and 175% for PPR, PP3/8 and PP1/2 panels, respectively.

The agreement of the results obtained with (th-MATH) e (th-SAP) curves, noticed in PPR panel, probably is related to the fact of the slip between the two materials to be, predominantly, due to the effect of bending of the connector. Nevertheless, differently from that it was noted in the curves of the panels of screws, the modeling for the method of the finite elements through the Sap2000 program presented a more rigid structure in relation to those obtained from the differential equations.

In the two last panels, a better approach of the experimental results by means of the modeling through the differential equations is clearly verified. The divergence, which is present in the results of modeling through the Sap2000 program (1998), observed in the panels with connectors of greater diameter, can be certainly attributed to the hypothesis of occurrence of a small crushing of the walls in holes of the timber. This effect, not represented for the used finite elements, not only causes a horizontal slip between the parts but also implies consequently in an upgrade in the displacement. On the other hand, the behavior represented for the suggested modeling, in which the connections were nails, showed good results due to the fact of the slip occurred with predominance of bending effect of the pin.

Thus, the use of differential equations presented advantages, once independent in the mode of rupture of the connection. The mechanical behavior of the connections will be characterized directly by the slip modulus and certainly, with more real results than those observed for the structure. Obviously, the use of two values of the slip modulus, the serviceability limit and the ultimate limit states, allowed the smoothing of the model implemented in the Mathematica (1997) for the consideration of the effect of non-linearity of the material.

Conclusions

This article consisted of a theoretical and an experimental analysis of the structural behavior of concrete-timber panels of bridges of rural roads and crossing-bridges. Considering the obtained results in the tests, the most important conclusions can be summarized as follows:

- the models of design developed from the equilibrium of the forces and the compatibility of displacements presented result close to the experimental ones. This is due to the representation of the behavior of the connection system through the slip modulus;

- from the experimental results of the three panels for load levels that correspond to the serviceability limit state values, the increase of the effective connection area had little relevance for the reduction of the vertical displacements;

- the connection of nails revealed a satisfactory efficiency, providing to greater easiness for its installation in the timber parts, and commercial cost for unit of approximately the 3 to 4 times lesser that the hexagonal screws of 9.525 mm and 12.700 mm diameters.

Considering not only these conclusions but also the development of this research we can verify that the application of concrete-timber composite structures has a favorable perspective, especially for construction of bridges in Brazil.

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References

Associação Brasileira de Normas Técnicas.1982. NBR6118: Projeto e execução de obras de concreto armado, Associação Brasileira de Normas Técnicas, Rio de Janeiro. (In portuguese)

Associação Brasileira de Normas Técnicas. 1997. NBR7190: Projeto de estruturas de madeira, Associação Brasileira de Normas Técnicas, Rio de Janeiro. (In portuguese)

Ceccotti, A. 1995. Timber-concrete composite structures, Timber Engineering-Step/Eurofortech, Almere: Centrum Hout, E13. 2:1-12.

European Committee for Standardization (CEN).2004. European Prestandard ENV 2004. Eurocode 5: Design of timber structures. European Committee for Standardization, Brussels.

Mathematica.1997. Ver. 3.0, Champaign, Il: Wolfram Research, Inc.

Sap2000. 1998. Ver. 7.0, Berkeley, California: Computers and Structures, Inc.

Stevanovic, B. 1996. Elastically coupled timber-concrete beams. In: Proceedings of the International Wood Engineering Conference, 1996 October. New Orleans. 3: 425-430.