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Behavior of Shear Connectors Formed by Bonded-in "X" Type Steel Bars in Wood-Concrete Specimens

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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, don't have a standard code which rules the shear connector tests for mixed wood-concrete structures. Due to the excellent connector diversification, regarding shape, stiffness, limit strength and the placement in the structural member; and variables as: spaces between connectors, spaces between connectors and the member ends of wood or concrete, dimension

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variation and mechanical properties of the materials involved, besides the rate and reinforced grid disposition in the concrete members, several normative documents suggest that wood-concrete specimens represent the real connection behavior. In this work, were used a push-out type specimen to characterize the connectors formed by bonded-in steel bars in “X” type behaviour, with a 45º between steel bars and wood grain. In this work, were used: *Corymbia citriodora* wood specie, without surface treatment; Threaded surface steel bars (CA-50 steel); and reinforced concrete of medium strength. Steel bars were bonded in the wood with epoxy resin Sikadur32 fluid and anchorage in the concrete by adherence. In each steel bar, in the axial direction and in the shear plan surface, two electric extensometers were fixed in opposed points. Results present the steel bar anchorage behaviour, force distributions in the steel bars, as well as the rupture model and mechanism and the procedures to obtain the connection sliding modulus and limit strength.

Keywords: Connection stiffness; connection strength; limit strength; sliding modulus.

1. INTRODUCTION

Several types of steel connectors are possible for mixed wood-concrete structures [1-3], the main features that allow comparisons between them are: ultimate strength; sliding modulus and final installation cost. Sliding modulus represents the connection stiffness, being obtained by “push-out” test in symmetrical wood-concrete specimens, with dimensions’ compatible with the real problem [4,5].

Sliding modulus is the relation between applied force and the relative displacement between wood-concrete, considering simultaneously wood, concrete and connector deformations [6,7]. In Brazil, there are few published studies on mixed wood-concrete structures. According to Matthiesen [8], the advantages of the “X” arrangement in relation to the perpendicular position are observed. "X" connectors, by the way, load in bars were applied, showed higher stiffness, compared to the perpendicular connectors, depending on connector diameter considered.

Steel bar anchorage with epoxy resins are economical when well designed and executed. The use of steel bars bonded to timber structures began with the need to use connectors in different types of loading (axial, perpendicular or loading combinations) [9]. Such connections are recommended for their excellent performance, facility, economy and aesthetics. Variations in the bonded steel bar positions, showed excellent results [10,11]. Bonded steel bars inclined to the wood members grain are more efficient, they can transmit forces in their directions to the steel bar capacity limit, they transmit efforts to a greater region of wood member allowing a better tension distribution, they are less vulnerable to wood cracking in the bonding area, increase the wood shear strength and exhibit excellent group behavior (all steel bars work simultaneously allowing a bond of high strength and stiffness).

In this work, the behavior and the mechanism of rupture of the connection formed by 45º inclined steel bars, in relation to the wood member grain, with epoxy resin, in the “X” type, were evaluated, to determine the distribution of forces acting on the steel bars, the sliding modulus and the connection ultimate strength.

2. MATERIALS AND METHODS

Experimental procedures were developed in a symmetrical wood-concrete push-out type specimen, to know the behaviour of steel bar connectors bonded in the “X” type; steel bar stress distributions; average sliding modulus determination; steel bar connection ultimate strength; wood-concrete interface cracking behaviour.

The specimen was executed with *Corymbia citriodora* wood specie treated with CCA (Chromated Copper Arsenate) with a mean diameter equal to 17.6 cm and length in direction fibre equal to 47.0 cm (Fig. 1). After acquiring the definitive beam shape, her was protected with a polyethylene film to keep the internal moisture content constant.

Connectors were formed with CA-50 steel bars (Table 1), bonded in the wood with Sikadur 32 fluid resin. In each bar that composed the connector, two electrical extensometers were fixed, so that they remained in the shear plane, aligned with the axial direction of the steel bar. Extensometers were fixed diametrically opposite the steel bar so that they presented tensile and compressive deformations when starting the bending steel bars (Fig. 2). Fig. 3 shows the resulting vertical stresses and deformations recorded on extensometers A and B of steel bar 1.

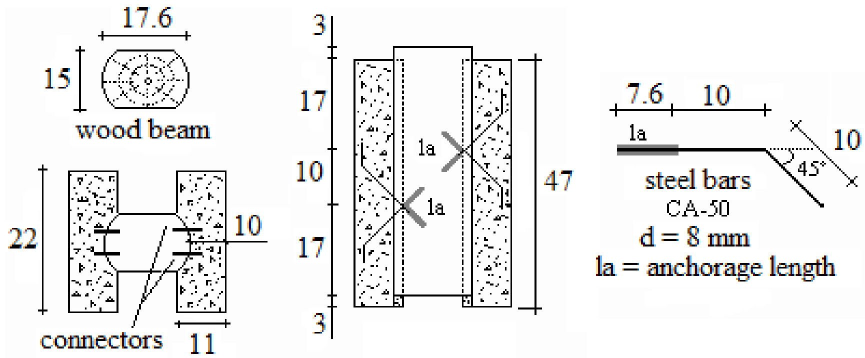

Fig. 1. Wood-concrete specimen details and bonded steel bars (units in cm)

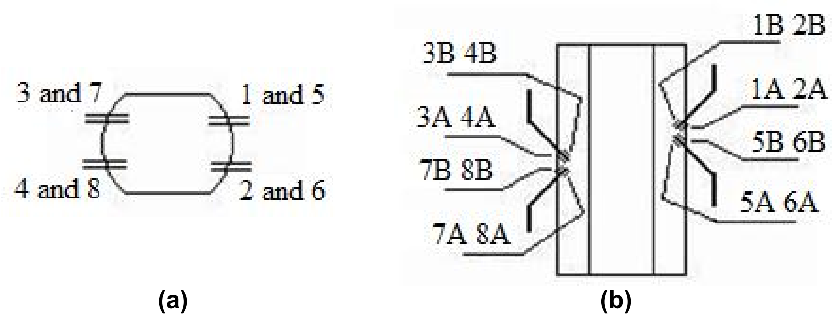

Fig. 2. Electric extensometer positions: (a) in bars 1 to 8; (b) side A (stressed tensile) and side B (compressed)

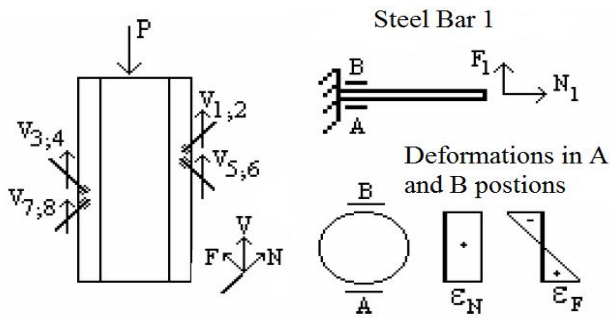

Fig. 3. Resulting vertical forces (V) in the steel bars, their components N and F and the tensile and compression deformations recorded in extensometers A and B, respectively

Table 1. Steel bar diameter (d), hole diameter (D), anchorage length (la), anchorage surface (Aa) and glue line thickness (e)

d (mm)	D (mm)	la (cm)	Aa (cm²)	e (mm)
8.0	10.5	7.6	20.0	1.25

Vertical stresses $V_{1;2}$; $V_{3;4}$; $V_{5;6}$ and $V_{7;8}$ initially act on the wood-concrete interface, on the traversed (steel bars 1 to 4) and compressed bars (steel bars 5 to 8). With the deformations recorded in the extensometers A and B, the axial (ε_a) and bending (ε_f) deformations can be obtained in each bar.

All steel bars received a surface treatment by applying a rotating steel brush at the anchorage length until the white colour was reached, then thinner (general purpose cleaning) was applied as a solvent to remove oily residues.

Concrete was prepared with formulation 1:2.90:3.24 (in weight), with water-cement ratio (w/c = 0.65). Expected strength, at 28 days of age, was 26.0 MPa. *Portland* cement (CPII-F32 type) was used; medium sand and brittle 5/8 and 1" in equal proportions.

Reinforcement used on both sides of the specimen represented minimal reinforcement in relation to the concrete volume, according to ABNT NBR 6118:2003 Brazilian Standard Code [12], and were adopted to reduce concrete crack. These armors were positioned apart, two centimetres from the wood face (Fig. 4).

Fig. 4. Reinforcement details for the wood-concrete specimen

Six different monotonic loads were applied in the specimen, with progressive maximum limits, thus allowing, loading centralization, observations in the symmetry displacements, accommodation and stabilization of the initial displacements, set of data acquisition calibration and balance, in each test.

Applied loads reached the following limits: 33, 33, 66, 66 and 80 kN. The last load was carried out with three load cycles, according to the ABNT NBR 7190:1997 Brazilian Standard Code [13]. In the third load cycle, ultimate strength was obtained, in the point corresponding to the intersection between the line passing through the residual specific strain (ε = 2‰) and the curve of load *versus* specific deformation diagram.

Loads were controlled by a load cell with a capacity of 200 kN. Vertical displacements were measured by two displacement transducers, electrical and mechanical, with a sensitivity of 0.01 mm and a maximum stroke of 50 mm, positioned on specimen opposite faces. Data acquisition system used was the *Linx system*.

A reaction gantry developed request system with a hydraulic cylinder of capacity up to 150 kN, actuated by a manual control actuator. Fig. 5 shows details on the specimen, instruments and the data acquisition system.

Table 2 shows the properties of concrete, wood and steel bar used in this research. All properties were determined by Standard Codes.

Fig. 5. Instrumented specimen details and data acquisition system

Table 2. Concrete, wood and steel bar strength and elasticity properties

Properties	**Concrete**	**Wood specie**	**Steel bar**
Strength (MPa)	f_c = 29.22	f_{c0} = 44.68	f_{yk} = 500
Modulus of Elasticity (MPa)	E_c = 27,434	E_{c0} = 20,000	E_s = 200,000
Experimental Conditions	Day of age = 28	MC = 12% ρ = 1,010 kg/m³	CA-50 type d = 8.0 mm

Where: f_c = compression strength of concrete; E_c = compression elasticity of concrete; f_{c0} = compression parallel to the grain strength of wood; E_{c0} = compression parallel to the grain elasticity of wood; MC = moisture content; ρ = apparent density of wood; f_{yk} = steel bar ultimate strength; E_s = steel bar elasticity; d = steel bar diameter

3. RESULTS AND DISCUSSION

3.1 Connection Sliding Modulus

Fig. 6 shows the relationship between the force applied (F) and the relative displacements between wood and concrete on the specimen with four connectors. Sliding modulus for four connectors corresponds to the angular coefficient of the secant that passes through the diagram at points $0.1{\cdot}F_{rup}$ and $0.4{\cdot}F_{rup}$. Sliding modulus with four connectors (K_{4conec}) was equal to 122.67 kN/mm. F_{rup} being the maximum connection strength.

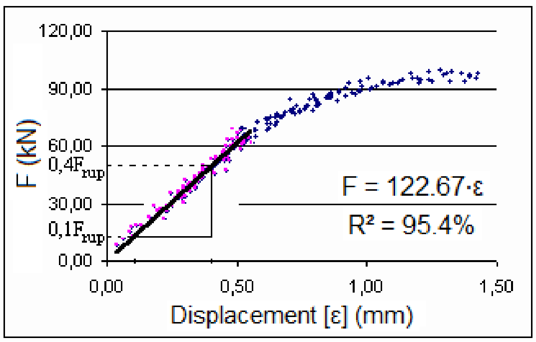

Fig. 6. Force *versus* displacement diagram for specimen wood-concrete with four connectors

Average sliding values (K), of an "X" connector, formed by CA-50 steel bars, 8.0 mm in diameter, bonded with Sikadur32 fluid epoxy resin, in *Corymbia citriodora* wood specie, corresponds to a quarter of the calculated value, where: K = 30.65 kN/mm.

Fig. 7 shows the specimen ultimate strength, obtained in a similar experimental procedure to the proposal of ABNT NBR 7190:1997 Brazilian Standard Code [13].

A line passing through the residual specific deformation 2‰ (Fig. 7) has direction parallel to the secant that cuts the diagram at points $0.1{\cdot}F_{rup}$ and $0.4{\cdot}F_{rup}$. Length of the base of displacement readings was adopted L_0 = 33 cm. Specimen ultimate strength, with four "X" connectors, corresponds to $F_{2‰}$ = 95.13 kN and for each connector, F_u = 23.78 kN.

A characteristic of the connectors formed by bonded steel bars is the homogeneous group behaviour, all the bars transmit forces simultaneously, considering that there are no clearances between the diameters of the holes and the steel bars. This makes the load *versus* relative displacement diagram continuously upward and with the same slope, without large initial shifts.

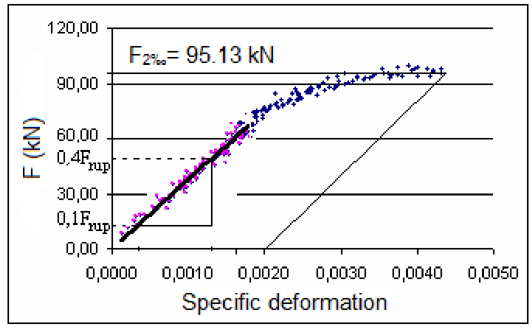

Fig. 7. Specimen ultimate strength determination

3.2 Relationships between Applied Forces on the Specimen and Measured Forces in Steel Bars

Table 3 presents the following results: applied forces on the specimen and axial forces in each steel bar, considering the obtained modulus of elasticity and the steel bar nominal area.

Connector on the specimen eccentricity generates an indeterminate system of equations for the static equilibrium (Fig. 3), but it is observed that the forces acting on the left side of the specimen would necessarily be larger than the forces of the right side. This result was confirmed by the experiment and presented in Fig. 8, which relates the average forces in the stressed tensile and compressed steel bars, with the forces applied on the specimen, for request up to 75 kN.

Fig. 9 shows the position of the resulting forces on the specimen and its respective vertical components (F_v), considering inclinations of 45° between the steel bars and the wood grain.

Table 4 shows the relationships between axial forces in the steel bars and their respective vertical components for a load on the specimen (P, Fig. 9). Vertical components results represent 97.78% of the applied force on the specimen, indicating the existence of other vertical forces acting on the static equilibrium, possibly frictional forces between the pieces that form specimen wood-concrete.

Table 3. Applied forces on the specimen and axial forces in each steel bar

Force on the specimen (kN)	Stressed tensile steel bar		Compressed steel bar	
	$F_{1;2}$ (kN)	$F_{3;4}$ (kN)	$F_{5;6}$ (kN)	$F_{7;8}$ (kN)
2.03	0.37	0.41	-0.88	-0.90
11.70	1.26	1.51	-2.78	-3.06
17.80	5.13	6.99	-6.81	-9.08
27.97	7.79	10.57	-8.87	-11.61
35.60	9.23	12.50	-10.82	-14.11
39.67	10.94	14.76	-11.89	-15.57
42.72	12.51	16.84	-12.78	-16.68
48.32	14.04	18.83	-13.79	-17.99
51.88	15.41	20.65	-14.96	-19.52
60.02	16.44	22.14	-16.45	-21.65
61.54	18.02	24.25	-17.33	-22.94
64.08	19.66	26.31	-18.07	-24.13
67.14	20.54	27.38	-19.65	-26.99
73.24	21.87	28.89	-20.94	-29.70
75.27	22.98	29.96	-22.59	-32.79

Where: $F_{1;2}$ = average value to forces in steel bars 1 and 2; $F_{3;4}$ = average value to forces in steel bars 3 and 4; $F_{5;6}$ = average value to forces in steel bars 5 and 6; $F_{7;8}$ = average value to forces in steel bars 7 and 8

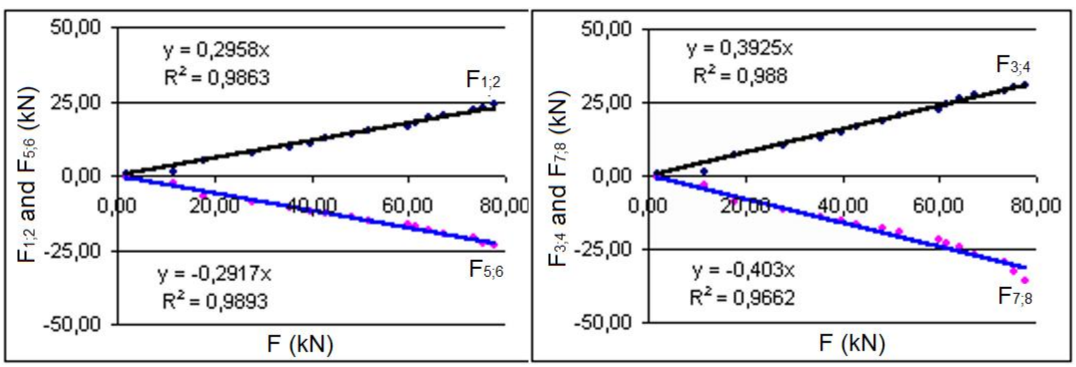

Fig. 8. Relations between the average forces in the stressed tensile and compressed steel bars, right and left sides, with the applied forces in the specimen

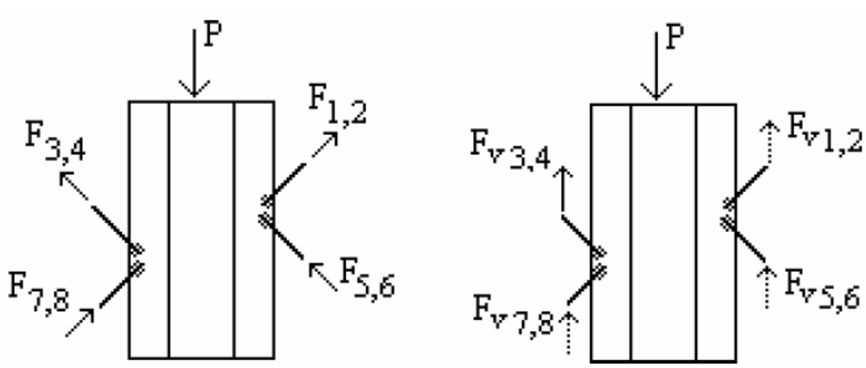

Fig. 9. Resulting forces on the steel bar representation: axial forces (F) and vertical components (F_v)

Table 4. Relations between the load on the specimen and their respective axial and vertical components

Axial forces	Vertical components
$F_{1;2} = 0.2958 \cdot P$	$F_{v1;2} = 0.2091 \cdot P$
$F_{5;6} = -0.2917 \cdot P$	$F_{v5;6} = 0.2062 \cdot P$
$F_{3;4} = 0.3925 \cdot P$	$F_{v3;4} = 0.2776 \cdot P$
$F_{7;8} = -0.4030 \cdot P$	$F_{v7;8} = 0.2849 \cdot P$

3.3 Specimen Rupture Model

Compressed steel bars reach their ultimate strength limit with the appearance of two plastic hinges, one close to the wood piece face and the other close to the concrete face, thus limiting the compressive force. The stressed tensile steel bars cause embedment on the wood and crushing on the concrete surface.

4. CONCLUSIONS

Average sliding modulus of each “X” connector, in *Corymbia citriodora* wood specie, with CA-50 steel bars with a diameter of 8.0 mm, has the value equal to 30.65 kN/mm; Ultimate strength for each connector corresponds to 23.78 kN.

Vertical components results represent 97.78% of the applied force on the specimen, indicating the existence of other vertical forces acting on the static equilibrium, possibly frictional forces between the members that form specimen wood-concrete.

Analyzing the specimen rupture mechanism, it is concluded that F component perpendicular to the steel bar, in the shear plane, provide the plastification moments in the compressed steel bars and embedment on wood at 45º in the stressed tensile steel bars.

Ultimate strength value closely approximates the maximum load capacity of the specimen. Bonded steel bars present homogeneous group behaviour, all bars transmit forces simultaneously even for the initial loadings.

High stiffness and strength were observed in connection with bonded steel bars in the "X" type, compared to the responses of these steel bars in the position perpendicular to the shear plane.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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