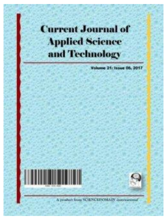


Current Journal of Applied Science and Technology

28(5): 1-6, 2018; Article no.CJAST.42993
ISSN: 2457-1024
(Past name: British Journal of Applied Science & Technology, Past ISSN: 2231-0843, NLM ID: 101664541)

Comparison of Anchorage Strength of Bonded-In Steel Bars with Epoxy Resin, Varying the Superficial Treatments and Moisture after Bonding, Using *Corymbia citriodora* Wood

Julio César Pigozzo[1], Eduardo Chahud[2], Felipe Nascimento Arroyo[3], André Luis Christoforo[4*], Diego Henrique de Almeida[4] and Francisco Antonio Rocco Lahr[5]

[1]Department of Civil Engineering, State University of Maringá, Colombo Avenue, 5790, Maringá (PR), 87020-900, Brazil.
[2]Department of Civil Engineering, Federal University of Minas Gerais, Antônio Carlos Avenue, 6627, Belo Horizonte (MG), 31270-901, Brazil.
[3]Department of Civil Engineering, Integrated Faculty of Cacoal, Dos Esportes Street, 1038, Cacoal (RO), 76965-864, Brazil.
[4]Department of Civil Engineering, Federal University of São Carlos, Washington Luís Highway, SP-310, km-235, São Carlos (SP), 13565-905, Brazil.
[5]Department of Structures, University of São Paulo, Trabalhador São-Carlense Avenue, 400, São Carlos (SP), 13566-590, Brazil.

Author's contribution

This work was carried out in collaboration between all authors. Authors JCP and FARL designed the study, wrote the protocol and managed the analyses of the study. Authors ALC and EC 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.

Article Information

DOI: 10.9734/CJAST/2018/42993
Editor(s):
(1) Dr. Manoj Gupta, Associate Professor, Department of Mechanical Engineering, NUS, 9 Engineering Drive 1, Singapore.
Reviewers:
(1) Nasmi Herlina Sari, University of Mataram, Indonesia.
(2) Yingzi Zhang, Harbin Institute of Technology, China.
Complete Peer review History: http://www.sciencedomain.org/review-history/25748

Original Research Article

Received 19th May 2018
Accepted 25th July 2018
Published 1st August 2018

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

ABSTRACT

The pull out of steel bars bonded-in in structural wood pieces present highly satisfactory performance concerning esthetics, strength and connection stiffness, nevertheless, great concerns arise relating to the bonding quality control, making some authors suggest that the bonding operation must be done in a factory environment with the adequate quality control and by specialized people. Several studies have been published analyzing methods of production control or the effect of common contaminators, present in the bonding area which might affect the global capacity of the connection. In this work, anchorage strength was evaluated under the effects of four superficial treatments on the anchorage area of steel bars and increasing and decreasing moisture variations after bonding. The adhesive used was the epoxy resin Sikadur32 Fluid and the steel bars were perpendicularly fixed to the wood fibers, obtained through a random sample of a lot of sawed *Corymbia citriodora* wood. In 98.70% of rupture, specimen occurred due to loss of resin adhesion on the bar surface, due to chemical and mechanical loss adhesion.

Keywords: Bonded-in bar; structural resins; anchorage strength; superficial treatment.

1. INTRODUCTION

Development and increase of the availability of structural adhesives, allowed advance in timber structures construction. These adhesives became widely used, allowing the construction of large structural members, such as glued laminated wood beams and structural members reinforced with structural polymers [1,2].

Connections with steel bars bonded to wood are widely used in European countries. Such a connection has received attention and recognition, mainly: for the excellent aesthetic appearance and performance; simple and easy to perform; and are sturdy and durable. Its main applications are top connections; connections of structural parts in foundation blocks; reinforcements in zones of maximum curvatures of glued laminated beams; transfer of forces within a structure or part thereof; connecting elements on gantry nodes; and connecting elements of wood pieces in masonry, concrete or steel. Bonded steel bars are predominantly required in the axial direction [3,4].

The development of test methods for evaluating the behavior of adhesives that determines the anchorage strength and the connection durability under different climatic conditions, fatigue effects and production control are the purposes of the recent research with connections formed by bonded bars castings [5,6].

Bonded steel bar joints have several recognized technical and economic advantages, and their use is one of the most promising types of high strength joints for the timber structures industrialization [7,8]. They warn, however, that the use of a safe and economical way, depends on the deep knowledge of all the parameters that influence the anchoring behavior and the many different work situations. Currently, the adhesives are individually tested on anchoring specimens for each wood species and surface texture of the steel bars used under the conditions: moisture content and temperature variations.

There are several possible anchorage rupture types and the predominant characterizes the anchorage strength. If in any long-term conditions any external effect changes the connection rupture type, this could prejudice the entire structural system. Aspects, such as the effects of corrosion that could arise on the adhesion surface of weathered steel bars, would deteriorate the glue line and progressively decrease adhesion, thus, the steel bar surface treatment becomes decisively important in the timber structures design [9].

Currently, the systematic studies of steel bars bonded with structural resins present themes related to the behavior of the connection under long-term actions, considering influences such as temperature variations and relative air humidity, as well as the test methods for adhesives and test methods for production control. Structural resin requirements [10,11]: To achieve good adhesion in wood; achieve significant shear strength to maintain integrates the section of the adhesive layer; and to maintain the bars anchoring, by means of the combination of chemical and mechanical adhesions, completely involving the steel bar rough surface. Due to the particularities of the bar surface preparation in the construction environment, the practice of applying textured bars has been standardized to maximize mechanical adhesion. Due to economic reasons, construction processes and the low cost of the material, it is possible to disregard the high levels of preparation of steel bar surfaces to maximize the chemical adhesion, compared to the high performance of the mechanical adhesion.

In this study of steel bar anchoring, using an epoxy resin, the anchoring behavior of high-tack steel bars bonded perpendicular to the *Corymbia citriodora* wood grain, with variations in the steel bar surface treatment and moisture content after bond.

2. MATERIALS AND METHODS

In this experiment was used the Sikadur32 resin (consistency: pasty; type: epoxy; commercial supplier: SIKA S/A) considering that this resin presented an excellent adhesion behavior in the wood for moisture content up to 35%, presenting glassy consistency and high mechanical strength after hardening and cure.

Six *Corymbia citriodora* wood beams (ρ = 1000 kg/m³ at 12% moisture content) were used without preservative treatment, with 6.0 (thickness) x 20.0 (width) x 300.0 cm (in direction to the grain) and were air dried. From each beam four specimens with dimensions of 6.0 x 20.0 x 55.0 cm (in a direction of the grain) were obtained, representing four sets of tests with six replications. In each specimen, four CA-50 steel bars (f_{yd} = 500 MPa); diameter of 6.3 mm, axially requested in two load cycles with monotonic loads, were used, the first cycle is with up to 70% of the ultimate strength. Steel bar adhesion surfaces were evaluated from the average size of the surface fillets, obtaining surface area equal to 2.03 cm^2 for each unit of bar length; anchorage length of 7.5 cm). Steel bars were bonded, perpendicular to the grain, in holes with a diameter of 9.5 cm (Fig. 1) and ordered with two consecutive monotonic loads in the axial direction, with the first loading reaching about 70% of the ultimate strength.

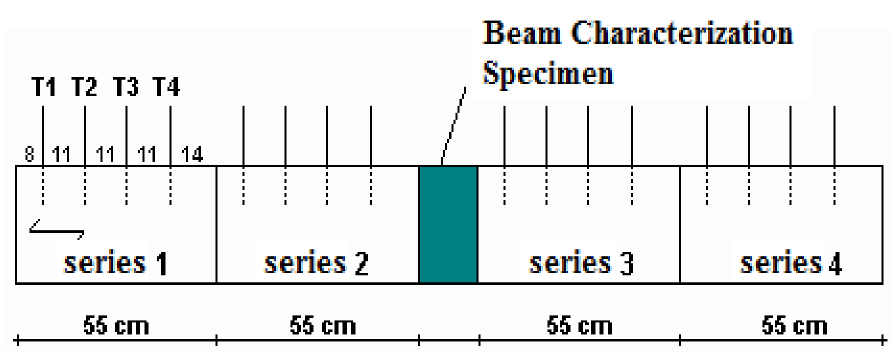
Each steel bar received a different surface treatment in the anchorage region: (Treatment 1: T1): cleaning with a rotating steel brush until it reaches white color, and then cleaning with thinner for residue and oiliness removal; (Treatment 2: T2): oxidized surface without cleaning; (Treatment 3: T3): surface with hot immersion galvanizing; (Treatment 4: T4): oxidized surface and simple cleaning with thinner. Specimens were conditioned, kept immersed in water until reaching the moisture content equals to 15, 20 and 25%, representing four series of tests:

- Series 1 (S1): bonding with average moisture content at 13% (air dry), five days for resin cure and tests with average moisture content at 13%;

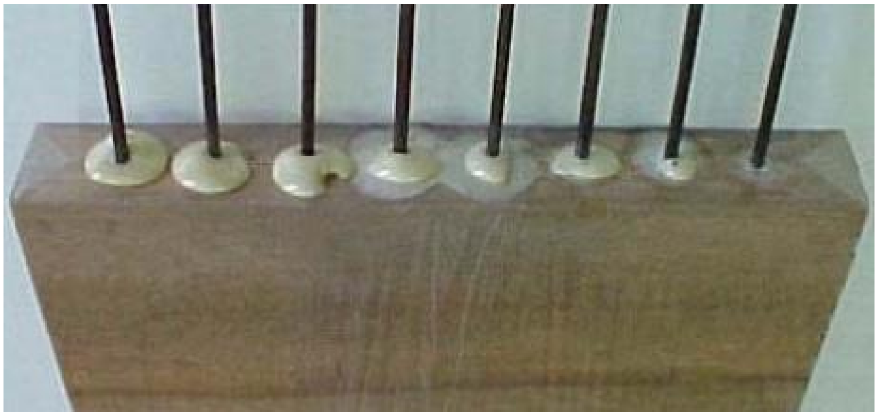
- Series 2 (S2): bonding with average moisture content at 13%, five days for resin cure and tests after 15 days on air-conditioning time, with average moisture content at 15%;

- Series 3A (S3A): bonding with average moisture content at 15%, five days for resin cure and tests after 30 days on air-conditioning time, with average moisture content at 20%;

- Series 3B (S3B): after S3A tests, in the same specimens, other steel bars with the same treatments were bonded with average moisture content at 20%. The tests occurred after the specimens were kept in the shade, in a ventilated place for slow drying for 53 days, until moisture content at 15% (Fig. 2);



(a)



(b)

Fig. 1. Obtaining specimens scheme: (a) series 1 to 4 scheme; (b) *Corymbia citriodora* beam with bonded-in steel bar for four series with polyurethane resin

- Series 4A (S4A): bonding with average moisture content at 15%, five days for resin cure and tests after 68 days on air-conditioning time, with average moisture content at 25%;

- Series 4B (S4B): after S4A tests, in the same specimens, other steel bars with the same treatments were bonded with average moisture content at 25%. The tests occurred after the specimens were kept in the shade, in a ventilated place for slow drying for 80 days, until moisture content at 15% (Fig. 2).

Mechanical tests were carried out in a universal machine tests (AMSLER, capacity 250 kN) according to Eurocode 5 [12] standardized procedures.

For statistical analysis were carried out multiple comparisons of means via F test with H_0 hypothesis that all means are equal, after, Tukey test with a confidence level at 95%, for normal distribution data.

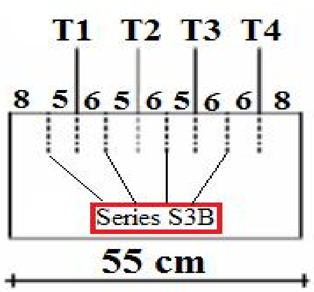


Fig. 2. Obtaining specimens scheme to series S3B and S4B

(Note: numbers between steel bars correspond to the distances in centimeter (cm) to the hole centers)

3. RESULTS AND DISCUSSION

Table 1 shows anchorage strength average values (x_m) and standard deviation (S_d) for each test series and treatments. Table 2 shows Tukey test to anchorage strength average values for each test series.

F tests show that Series 1, 2 and 3A had hypothesis H_0 rejected, therefore, Series 3B, 4A and 4B had hypothesis H_0 accepted. Table 2 shows Tukey test to anchorage strength average values for each test series.

From six series tests with the four specimens and six replications, there were 576 anchorage strength tests. In three times, specimen rupture occurred due to surface adhesion loss of the hole in the wood, and in four other results, the rupture was mixed, with loss of adhesion in the wood and loss of adhesion on the steel bar surface. In 98.70%, rupture model was characterized by loss of adhesion at the steel bar surface, initially with chemical and mechanical adhesion loss.

Brushed steel bars (Treatment 1) show the lowest average anchorage strength value in all six series (except 4A series) compared to other surface treatments. Treatment 4 (oxidized surface steel bar and simple cleaning with thinner) present better average anchorage strength values compared with other treatments.
In series 1, 2, 3A, and 3B, the anchorage strength average values of T2, T3 and T4 treatments can be considered equal to the significance level of 5%. In series 4A and 4B, all treatments (T1, T2, T3 and T4) can be considered statistically equal to the significance level of 5%.

Table 1. Results of anchorage strength (RA) for 4 treatments and six series (values in kN)

Beam	Series 1				Series 2			
	T1	T2	T3	T4	T1	T2	T3	T4
1	13.80	19.30	14.60	17.50	9.70	15.00	13.00	11.00
2	14.30	18.70	18.00	18.00	12.00	18.00	16.00	12.00
3	11.00	20.20	17.10	17.10	8.40	12.00	12.00	11.00
4	10.20	18.40	16.40	17.30	8.20	14.00	12.00	12.00
5	14.90	21.40	17.70	16.80	8.60	16.00	20.00	11.00
6	13.90	21.10	22.50	19.60	12.00	16.00	17.00	12.00
x_m	13.02	20.51	17.70	17.70	9.78	15.00	14.67	11.58
S_d	1.92	2.49	2.65	1.03	1.73	2.12	3.45	0.56
Beam	**Series 3A**				**Series 3B**			
	T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
1	12.50	13.40	12.70	12.40	17.00	18.00	17.00	19.00
2	8.50	12.80	13.20	14.30	15.00	17.00	16.00	18.00
3	8.40	11.90	12.00	10.10	16.00	16.00	16.00	15.00
4	12.30	13.10	9.80	14.20	14.00	16.00	16.00	20.00
5	11.10	11.70	13.20	12.80	17.00	18.00	19.00	18.00
6	8.30	13.00	12.10	12.40	18.00	20.00	17.00	16.00
x_m	10.18	12.65	12.20	12.70	16.17	16.67	16.83	17.62
S_d	2.14	0.69	1.27	1.53	1.40	1.95	1.07	2.04
Beam	**Series 4A**				**Series 4B**			
	T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
1	12.70	11.50	12.90	16.20	21.00	21.00	22.00	19.00
2	13.30	11.50	11.90	13.20	19.00	17.00	21.00	21.00
3	9.30	9.40	7.00	11.20	17.00	18.00	19.00	18.00
4	13.80	9.70	13.60	14.70	19.00	20.00	21.00	21.00
5	11.80	12.50	10.50	11.80	17.00	19.00	22.00	19.00
6	7.20	7.50	7.50	10.90	19.00	20.00	19.00	19.00
x_m	11.35	10.35	10.57	13.00	18.54	19.05	20.48	19.45
Sd	2.58	1.83	2.78	2.11	1.46	1.38	1.51	1.15

Table 2. Tukey test for different treatments steel bar treatments in each series (values in kN)

Series	T1	T2	T3	T4
1	13.02a*	20.51b	17.70b	17.70b
2	9.78a	15.00b	14.67b	11.58b
3A	10.18a	12.65b	12.20b	12.70b
3B	16.17a	16.67a	16.83a	17.62a
4A	11.35a	10.35a	10.57a	13.00a
4B	18.54a	19.05a	20.48a	19.45a

** same letters on the line mean that the average values do not differ significantly at 95% of probability*

In all treatments, after adhesive cure, average anchorage strength decreased with increasing of moisture content and increased with wood drying.

Series 1 with surface steel bar treatment 2 (oxidized surface without cleaning) shows higher average value to anchorage strength equal to 20.51 kN. Series 2 with surface steel bar treatment 1 (cleaning with a rotating steel brush until it reaches white color, and then cleaning with thinner for residue removal and possible oiliness) show lower average value to anchorage strength equal to 9.78 kN

4. CONCLUSIONS

In 98.70% of rupture specimen occurred due to loss of resin adhesion on the bar surface, due to chemical and mechanical loss adhesion.

There were no significant differences between the surface treatments applied to the steel bars, considering moisture content conditions at time test. Mechanical adhesion was little influenced by surface treatments.

Brushed steel bar (Treatment 1) show the lower value to anchorage strength for all series, in other hand, Treatment 4 present better results.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history/25748