ANALYSIS OF EUCALYPTUS GLUED-LAMINATED TIMBER PORTICOS STRUCTURAL PERFORMANCE[1]

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ABSTRACT – This study evaluated the structural behavior of porticos made from eucalyptus glued boards, using wood of Eucalyptus sp and resorcinol formaldehyde adhesive. Three units, in real scale, of tri-articulated straight porticos, with a 5 meter porthole and a 26 º inclination, capable to support tiles covering placement were designed, constructed and subjected to load testing, until rupture. The amount of adhesive used in the construction of the porticos was 250 g/m^2 and the bonding pressure of 1.3 MPa. The Hankinson model was employed as an estimator of the glued joints strength, under different angles between the fibers. The average value for the last resistance of the structures was 4.63 times the design load, according to the criteria established by the ABNT, 1997. The structures showed satisfactory mechanical performance and deformations lower than the ones allowed by the standard. It was concluded there is technical feasibility to manufacture porticos fully bonded with small thickness veneers.

Keywords: Timber structures; Connections; Adhesives.

ANÁLISE DO DESEMPENHO ESTRUTURAL DE PÓRTICOS DE MADEIRA LAMINADA COLADA DE EUCALIPTO

RESUMO – Neste trabalho, avaliou-se o comportamento estrutural de pórticos confeccionados a partir de tábuas coladas de eucalipto, utilizando madeira de Eucalyptus sp e adesivo resorcinol formaldeído. Foram projetadas, construídas e submetidas a testes de carga, até a ruptura, três unidades, em escala real, de pórticos retos triarticulados, com vão livre de 5 metros e com inclinação de 26º, aptos ao emprego de cobertura cerâmica. A quantidade de adesivo utilizada na construção dos pórticos foi de 250 g/m^2 e a pressão de colagem de 1,3 MPa. O modelo de Hankinson foi empregado como estimador da resistência de juntas coladas, sob diferentes ângulos entre as fibras. O valor médio obtido para a resistência última das estruturas, foi de 4,63 vezes a carga de projeto, segundo critérios estabelecidos pela norma ABNT, 1997. As estruturas apresentaram desempenho mecânico satisfatório e deformações inferiores às permitidas por norma. Concluiu-se pela viabilidade técnica de se confeccionar pórticos inteiramente colados com lâminas de madeira de pequena espessura.

Palavras-chave:Estruturas de madeira; Ligações; Adesivos.

1. INTRODUCTION

The manufacture of timber structures or parts of timber structures in the industrial environment for later transportation and mounting in construction is not common in Brazil yet. In European and North American countries, for instance, timber, steel and concrete structures has been pre-made since a long ago.

Glued-laminated timber, *Madeira Laminada Colada –MLC*, is the term, in Brazil, for pieces of wood made from wood sheets of relatively reduced dimensions when compared to the final piece dimensions. These wood sheets are attached by gluing in a certain way that the fibers are parallel among themselves.

Traditionally, the resorcinol formaldehyde adhesive is the most used to make pieces of high resistance and wood fail perceptual to its application in ambient temperature and the high stability under varied humidity and temperature. (PIZZI, 1983)

The glued-laminated timber technique enables the use of reforestation species and allows the manufacture of pieces in various dimensions and shapes for structural purposes, making them suitable for any industrial process with a remarkable quality control and material use rationalization (DELLA LUCIA; VITAL, 1980; BONO; INO, 1998; MANTILLA CARRASCO; PAOLIELLO, 1998). There are other technical vantages that can be added when using the available technical resources such as resistance acquisition, rigidity and durability.

The use of the glued-laminated timber is not spread in Brazil yet, most of the experimental researches use wood beams (BONO; INO, 1998; VALLE, 1999). Some of these researches emphasize the mechanical classification of the pieces in order to obtain the maximum resistance of the structural wood beams (CUNHA; MATOS, 2010).

For calculating the glued wood structures and their dimensioning process, it is necessary that the glued joints have predictable behavior and high resistance levels to comply with each project specific regulations and requirements.

A structure resistance, stability and life span depends on, in most of the occurrences, on the joinery resistance, rigidity and durability. These are the most common causes for many structure tests rupture and they demand special attention when dimensioning them.

The study of FINK scissors truss performance indicated rupture loads three times the project load. The structures deformation seemed to be related to the rigidity imposed by each kind of joint. That was concluded while analyzing the difference between the deformation presented in the end of the fifteen years and the truss initial deformation (CARVALHO FILHO, 1984; WILKINSON, 1984).

Couri Petrauski (1999) by dimensioning glued joints that were sheared by compression, by torsion, by traction, by cutting or by these forces combination, built and tested trussed structures on glued-laminated timber of *Eucalyptus citriodora* and of *Eucalyptus grandis*. As a result, an average quotient of 7,3 was obtained. The displacements observed were totally satisfactory. The author attested the viability of applying this methodology to the glued joints dimensioning.

Petrauski (2000) built and tested roof scissors truss made of glued-laminated timber of *Eucalyptus grandis* and each joint was made using, exclusively, adhesive.

These joints analysis and dimensioning model was proposed using the Hankinson valid model. According to ABNT, 1997 criteria, the joints last resistances were, in average, 4,26 times the project load. The displacements that occurred to the project load lever were 1/5 of those allowed by ABNT, 1997.

In use conditions, the development of glued wood joints is able to be influenced by various factors, either quantitative or qualitative. According to Custódio et al. (2009), adhesive joints have an essential role in improving repair techniques and wood structures rehabilitation, substituting the mechanical joints. They distribute the applied load in a uniform manner over all adhesion area, adding a light with to the structure and they have a higher resistance to fatigue related to other kinds of joints.

When it comes to laminated wood, the present rule stares that the sheets gluing has to be done putting the fibers in a parallel position among the sheets. There is no accordance among the researches about the specific rule and then, the need of the different resistance levels of glued-laminated timber structures under different fiber angles has emerged.

Therefore, this paper had the aim to project, build, test loads and evaluate the development of glued-laminated timber porticos structures made of *Eucalyptus* that were able to be used in small or medium buildings that demanded angles gluing between the wood sheets.

2. MATERIALAND METHODS

The used wood was the Eucalyptus sp., of unknown age and origin. It is commercially denominated as Lyptus and it was supplied by Aracruz Produtos de Madeira in boards format. These boards were primarily submeted to visual inspection, apparent density and mechanical classification. The mechanical classification was to determine the longitudinal elasticity modulus in a non-destructive manner.

After that the wood was characterized following the ABNT, 1997 criteria. The following mechanical elasticity modulus were conducted: fibers parallel compression, elasticity modulus under fibers parallel compression; parallel shearing and fibers normal traction. These tests aimed to obtain mechanical resistance and wood rigidity parameters to be used in the project of the structure developed during the research.

The projected structure was a straight tri-articulated portico to be used in the sustenance of commercial, industrial, rural or even residential buildings. This research differential included the fact that the structure timber and porticos joints were all glued.

The adhesive used was the resorcinol formaldehyde that is known for its use in structural making. A previous study established the adhesive quantity to be used and the gluing pressure. As a consequence, a 250 g/m² of adhesive and a gluing pressure of 1,3 MPa was used (COURI PETRAUSKI, 2012). The adhesive was made of a resin and hardener powder mix in a ratio of 5 to 1.

2.1. Geometric configuration and structure verification

The glued-laminated timber structure projected during this research is schematically illustrated in Figure 1. The knots A, C and E are articulations and the knots B and D are rigid, that is, they must resist to the efforts Md, Nd and Qd. They are, respectively, bending moment calculation, normal force calculation and shear force calculation that act simultaneously on these joints proportionally to the project load. The use an articulation in knot C, considering an industrial project, aims to facilitate the structure pieces transportation to the erection place. During the mounting process, the joint in the knot C was made with a metal spherical bearing specially made for its purpose.

The portico was dimensioned to be used with permanent vertical loads, equivalent to the loads used in ceramics roof tile covering and with a 26° inclination for the water run-off and a spacing of 2,5 meters between the porticos. The covering was considered to be made of purlin cleats rafters and lath. Five purlin cleats were used and evenly distributed to transfer the covering loads to the superior stringer of the portico.

The accidental loads lifting due to the wind, was made in accordance to the ABNT, 1988 criteria, considering an industrial building in the region of Viçosa-MG, in an open areas with few obstructions. In wind conditions, besides its effects on the covering, a hypothetical lateral wind was also considered, that could act on the portico vertical bars. Considering possible overloads, a distributed load of 150 N/m² and a concentrated load of 1000 N, applied to the ridge, were considered according to the ABNT, 1988 criteria.

After making a pre-dimensioning, the use of five wood sheets was chosen to build each structure bar with 2,8 cm of thickness each one. As a result, each bar had a final thickness of 14 cm. It was also decided to do the verifications considering that the superior stringer bars had 17 cm high and the two pillars had 21 cm.

After creating the different hypothetical loads and following the ABNT, 1997 precepts, the calculation requirements were obtained. These are briefly presented

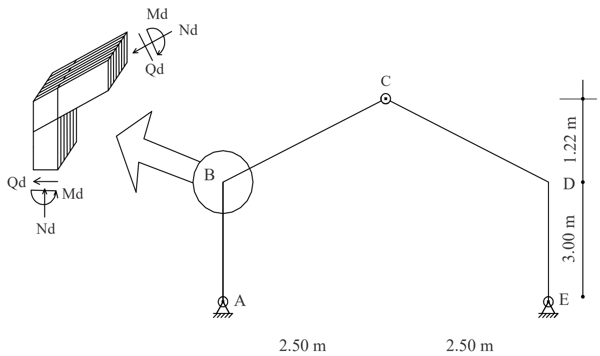

Figure 1 – Geometric configuration of the structure with detail of the B shaped rigid knot.
***Figura 1** – Configuração geométrica da estrutura com detalhe do nó rígido em B.*

in Table 1. The most unfavorable hypothesis for the wind considered action of lateral load, perpendicular to the wall and evenly distributed. In the covering overall hypothesis, the action of a concentrated load of 1kN on the ridge predominated. The project vertical load was equal to a total load of 14,81 kN.

In Table 1, the nomenclature used was:

· Md = Pending moment calculation

· Nd = Normal force calculation

· Qd = Shear force calculation

· Mg, d = Bending moment calculation due to permanent load

· Ng, d = Normal force calculation due to permanent load

· Ng, k = Normal characteristic force due to permanent load

· Nq, k = Normal characteristic force due to accidental loads

The procedures for the final verification of the structure were conducted according to the Brazilian regulation criteria. The structure bars were verified by the use of flexo-compression and flexo-traction according to each case and to the active shear forces.

For not having a standard method for the glued-laminated timber verification, the adopted criteria were the ones proposed by Couri Petrauski (1999) and Petrauski (2000). According to method, the analysis of the glued area that involves the verification of the glued area receives the tensions from the required forces. And also it is necessary the transversal tension verification of the wood sheets of the joints at the moments of the imposed actions. The verification of the transversal section has to be done according to the ABNT, 1997 criteria.

The point C articulation verification was also accomplished, In this case, the finding results were used to make a metal spherical bearing that was used during the experiment.

The main project parameters adopted in the different verifications were the following:

· $f_{c0,k}$= 57,50 MPa , characteristic resistance in parallel compression of the fibers;

· $f_{v0,k}$ = 9,7 Mpa, characteristic resistance in parallel shearing of the fibers;

· $f_{v0,k}$= 13,72 Mpa, characteristic resistance in shearing of the joints glued in a parallel position related to the fibers;

· $f_{v90,k}$= 5,65 MPa, characteristic resistance in shearing of the joints normally glued to the fibers;

· $f_{tor90,k}$= 10,06 MPa, characteristic resistance in torsion of normally glued joints between themselves.

Besides that, the following features were adopted:

· Number of surfaces glued on rigid joints of the knots B and C equals 4;

· Number of wood sheets in the joints of the knots B and C, deriving from the pillar, equals 2;

· Number of wood sheets in the joints of the knots B and C, deriving from the superior stringer, equals 3;

· Thickness of the wood sheets equals 2,8 cm;

· Angle between the direction of the wood piece fibers, in the joint,

· Height of the pillar pieces equals 21 cm; and

· Height of the superior stringer equals 17 cm.

After having all the verifications done, it was concluded that the initial pre-dimensioning could be kept and that the structure behavior limit situations were associated to the solution for the joints rigid knots in B and in C.

Table 1 – Summary of efforts found for the structure calculation.
Tabela 1 *– Resumo dos esforços de cálculo encontrados para a estrutura.*

Barra	Ponto	M_d(kN.m)	N_d(kN)	Q_d(kN)	$M_{g,d}$(kN.m)	$N_{g,d}$(kN)	$N_{g,k}$(kN)	$N_{q,k}$(kN)
AB e DE	A = E	0	-9,77	1,26	0	-8,29	-5,92	-1,36
	B = D	9,58	-9,77	1,26	5,86	-8,29	-5,92	-1,36
BC e CD	B = D	9,58	-4,66	5,08	5,86	-4	-2,86	-0,76
	C	0	-4,66	5,08	0	-4	-2,86	-0,76

2.2. Execution and test of the structures

After the project phase, it was concluded that the Laboratory conditions would not allow the test of the structure in the dimensions presented in Figure 1. It was decided to shorten the portico pillars length keeping the span and the inclination initially predicted. This action would not affect the interest of analysis, since that during the tests, the applied loading would reproduce the forces, being a performance limiting factor. The final configuration used to build the tested units was the one presented in Figure 2. Three experimental units were executed and tested: R1, R2 and R3.

Each portico was made by two symmetrical parts being each part or side separately made After being processed in the planer thicknesser, the wood sheets were sheared in one of their ends in a pre-established angle. The wood sheets were processed and glued in the same day. The structures were glued using a template that was specially built for this purpose using *Jatoba* wood *(Hymanea sp.)*.

Before the mounting, the quantity of adhesive was predicted for each one of the four glue lines to be applied. A brush was used to apply the adhesive mixture. The closed-assembly time was at most of 20 minutes and the open assembly time was null.

After the deposition of all the layers and wood sheets on the granite, the structure received a pre-established pression of 1,3 MPa. This pressure was caused by the tightening screws that were specially installed on the granite for this purpose.

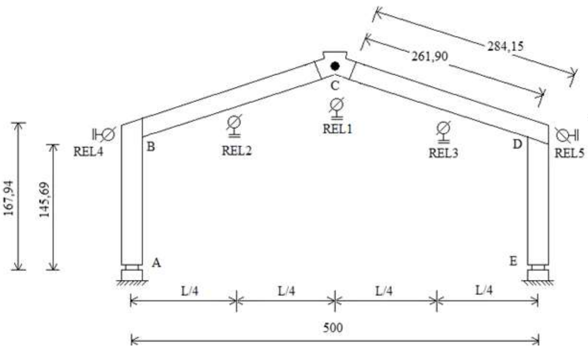

Figure 2 – Geometric configuration of the structure and dial indicators installation position, dimensions in cm.

Figura 2 – *Configuração geométrica da estrutura e posição de instalação dos relógios comparadores, dimensões em cm.*

The structure was under pressure for at least twelve hours. Later on, it was stored for the minimum of ten days before being used in the tests.

The structures were tested observing possible reactions. Vertical and horizontal loads were applied to them. The horizontal load simulated the wind action on one of the pillars. The structure sustenance and the structure joinery systems were made aiming to simulate the project theoretical upwinds and to allow the free displacement to the load direction avoiding, though, consirable displacements out of the structure surface and also avoid accidents when having rupture.

Five dial indicators were installed in pre-established points so they could make the reading of the structure displacement under load applying. They were installed in support reaction load cells to follow and register the applied loads.

Initially a loading up to the project load was applied including the lateral load due to the wind action. The displacements presented on the dial indicators were properly registered. After relieving this load, all the dial indicators were set back to zero. Then, a load 2,5 times the project load was applied. In this phase, intervals, proportional to the predicted total for each level, were established. The displacements observed were registered. Once more, all the loading was relieved and all the dial indicators were taken off, except the one installed in the ridge. And from this moment on, the load was lifted until the rupture of the tested unit.

3. RESULTS

The three structures, denominated R1, R2 and R3 all ruptured as expected, in the rigid joints. The rupture loads were 69,40 kN, 83,18kN and 53,12 kN, respectively to the structures R1, R2 and R3. Considering the project load 14,81 kN the quotient between the rupture and the project loads was 4,68 for structure R1, 5,62 for structure R2 and 3,59 for R3, the average value was 4,63.

All the ruptures occurred in an area around the joinery.

It was already expected, since that according to the verifications made, for instance, the radius necessary of the circular area to combat the torsion moment represented 93 % of the available raius. Although the ruptures occurred around the connections, none of them can be attributed to the joint failure itself. They seem to be related to the resistance capacity of the wood sheets around the connection.

All the structures tested presented typical fractures of perpendicular traction on wood fibers and shearing of the glued plan fibers due to parallel torsion also occurred. The portico R3 also presented compression fracture with a visible fibers crush.

The displacements presented on the structures when they were under load action were followed by dial indicators that were installed in specific points of the portico, as it is illustrated in Figure 2. The values observed in the central dial indicators of the span of the superior stringers, REL2 and REL 3, were interpreted based on their average.

Applying lateral load to the pillar created a rotation tendency of the structure. Due to this, it was chosen to start the loading by applying a fraction of vertical loads and, then, all the horizontal load. Lastly, the left fraction of the vertical load was applied, what totalized the project load.

Related to the deformations all the tested structures showed the same behavior tendency. The horizontal load application caused an inversion of the bending moment in knot B. This inversion interfered in the displacements reading.

The loading of the initial fraction of the vertical loads conducted to the vertical displacements observations, from up to down, followed by the dial indicators REL 1 and REL 3, and the observation of the horizontal displacements, from in to outside the structure, followed by dial indicators REL 1 and REL 2, indicated displacements higher than the ones observed before what indicates that the wind load caused displacements from up to down in those points of the structure. An inverse phenomenon occurred in the readings of the REL 3, what indicates that the action of the wind load caused, in that point a displacement from down to up. The readings of the dial indicators REL 4 and REL 5 showed the action of the lateral wind load caused horizontal displacements from out to inside the structure in knot B and from in to outside, in knot D. The application totalized the project load conducted to vertical displacements, from up to down, in the points that were followed by dial indicator REL 1, REL 2 and REL 3. And also horizontal displacements, from in to outside the structure, in the points that were followed by the dial indicators REL 4 and REL 5. The Table 2 presents the final displacements of each tested structure. The Figure 3, illustrates the "deformation" of the structures tested in the conditions exposed above.

After applying the project load, including the lateral wind action, all the portico loading was taken off and a new phase of the test started while applying vertical loads until the structure rupture. The obtained results during this last phase, indicated a linear behavior in the diagram Force x Deformation, even for the highest levels of load.

According to the ABNT, 1997, in case of this kind of constructions, the security must be verified related to the limit state of excessive deformations that can affect the normal use of the construction or its aesthetical

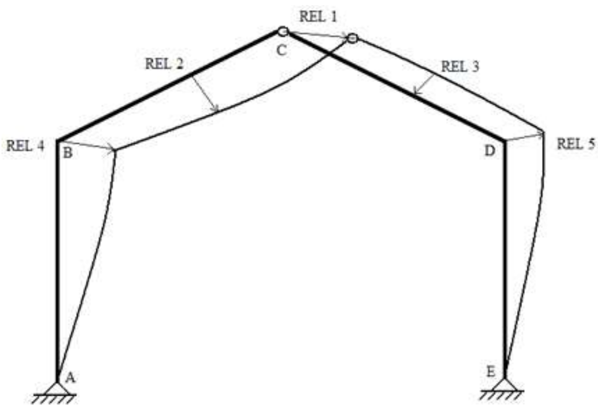

Figure 3 – Appearance of the structure deformity, considered the action of the design load, with load of crosswind application.
Figura 3 – *Aspecto da deformada da estrutura, considerada a ação da carga de projeto, com a aplicação da carga de vento lateral.*

Table 2 – Displacements after the design load application, including crosswind.
Tabela 2 – *Deslocamentos após a aplicação da carga de projeto, incluindo vento lateral.*

Estrutura	REL1(mm)	REL2(mm)	REL3(mm)	REL4(mm)	REL5(mm)
Resorcinol 1 (R1)	0,91	5,15	0,05	13,18	10,99
Resorcinol 2 (R2)	4,42	5,79	0,25	12,91	11,13
Resorcinol 3 (R3)	1,21	4,87	0,61	9,39	8,72

aspect Considering the action combinations, the project level of load related to the structure displacement verification was 9,45 kN.

The Brazilian rule establishes some criteria for the limitation of the structure deformations. For the studied structures, it represents a maximum vertical displacement allowed of 25 millimeters in the ridge, that is, in the central knot C. The values associated to the dial indicator REL 1 were used to conduct the analysis of the maximum displacement.

The effective rise or the calculated one was 8,25 millimeters. Considering the project load, the experimental values obtained to the maximum displacements that occurred in the ridge of the structures denominated R1, R2 and R3, respectively were 10,37mm, 7,26 mm and 6,03 mm. Therefore, the overall displacement in the ridge was 7,89 mm.

4. DISCUSSION

Couri Petrauski (1999) and Petrauski (2000), evidenced that lettice porticos could be built with good performance if all the joints were made of glued-laminated timber. These structures present small values in the joinery in the active bending moment. In the structure tested during this research, it is the opposite, the bending moments acting in rigid joints are of high values and these joints behavior is of fundamental importance to the resistant behavior, stability and rigidity of the porticos. The fact that the glued joints were a limiting factor of the structures dimensioning advantaged their performance. In fact, the pillar bars and the superior stringers could have their section reduced and so allow a more economical displacement. The goal was to evaluate the joinery behavior of the glued joint made the joints that made convenient the fact that the bars (pillars and stringers) were under lower forces than their resistance capacity. When under load testing, the structure would get to its resistance limit when forcing the glued joinery before getting to the resistance of the transversal section of the pillars or the superior stringers. That happened. All the structures broke down by rupturing in the area around the rigid joints, that is, the knots B or D.

The quotients between the rupture load and the project load indicate the security of the structures. The average value obtained during this research was 4,63. This quotient can be considered very satisfactory when compared, for instance, to results obtained in similar structures tests (CARVALHO FILHO, 1984; WILKINSON,1984,; BARACHO JUNIOR, 1990; PETRAUSKI, 1991; COURI PETRAUSKI, 1999; PETRAUSKI, 2000).

The failure of compression that happened in the region around the joint, observed in portico R3, was according to the direction indicated to the bending moments. The verification of the flexo-compression, considering the two or three wood sheets around the joinery , had demonstrated to be a dimensioning limit situation. It was expected that the resistance capacity of the wood sheets would wear off when dealing with loads that were much higher than the project load. And it also happened according to the Brazilian regulamentation for wood structures. Applying these criteria, it is expected that the rupture occur with loads that are form 3,5 to 4,5 times higher.

The way the connections rupture occurred, demonstrated that around the area all the requirements were transmitted by shearing tensions acting on the glued surfaces. The bending moment acted as a torsion moment on the joinery region. The theorical considerations of the method used for the glued joints verification seem to be compatible to the connection behavior, while it is in good conditions of use.

The ruptures do not present fragile character as it was expected, since they are entirely glued. On the other hand, the fractures occurred in a gradative way with a gradative energy liberation, except in the end of the process. Similar observations were made by Couri Petrauski (1999) and Petrauski (2000), in both of them the rupture way was evaluated with roof scissors truss that was made of glued-laminated truss.

The linear behavior of the structures entirely glued deformation had been observed by Couri Petrauski (1999) and Petrauski (2000). This, for sure, is a positive characteristic of this type of structure.

Considering the deformation limit of the structure, the proximity between the value of the theoretical displacement and the experimental average of displacement indicated a good accuracy of theoretical verification. A probable explanation for this accuracy can be the fact that when using the resorcinol formaldehyde adhesive, the glued joint behavior has, in good conditions of use, the rigidity considered at the theoretical deformation calculus.

Related to a long duration loads, Wilkinson (1984) and Carvalho Filho (1984), attest that, the final displacement of a structure can be up the limit of three times the initial displacement due to the type of joinery. To achieve the maximum displacement allowed of 25 mm, it would be necessary a load level applying of 3,16 times the project load and doing so, the structures deformations would be satisfactory.

The porticos built with Eucalyptus sp., entirely glued, using resorcinol formaldehyde adhesive presented an excellent performance in terms of resistance and rigidity. The theoretical consideration of the glued joinery rigidity conducted to results that were compatible to the ones presented by the structures, this fact is an indicator of the conducted analysis adequacy.

5. CONCLUSION

The proposed methodology for the glued joints verification turned out to be adequate, based on the observed performance of the structures projected and tested during this research.

Considering the resistance criteria, the porticos performance was satisfactory.

At the project load levels, the deformations did not reach the limits established by the Brazilian regulamentation. Even when predicting a final displacement of three times the initial one to reproduce an action of a long duration loading. The estimates for the theoretical displacements were compatible to the observed ones, including when they were related to the deformation configuration.

The proposed technique for the manufacture of the structures was fully viable. It also happened, when it came to the proposed solutions for the verification and execution of the clued joinery with a very satisfactory performance. When considering the obtained results to the rigidity and resistance criteria.

6. ACKNOWLEDGMENTS

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