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Determination of the Sliding Modulus and Limit Strength of Shear Connectors for Mixed Wood-Concrete Structures

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Abstract Tests with specimens are still the most suitable way in order to get to know the mechanical and elastic behavior of shear connectors, which are used in mixed wood-concrete structures. The most used wood-concrete specimens are the symmetrical push-out type models. About the great diversity of connectors, considering type, stiffness, strength value and their position in the structural member, besides other varieties as: spaces between connectors, dimension variation and mechanical and elastic properties of the materials involved, several normative standards suggest that the wood-concrete specimens shall represent the real connection behavior. In Brazil, due to lacking of normative procedures, plenty of wood-concrete specimen models and criteria have been used for the determination of the limit strength and the slip modulus of these connections. In this paper some wood-concrete specimen models are presented, they were suggested in some normative documents and others presented into the international literature and national research. Some procedures are suggested for obtaining the slip modulus and limit strength, representing the real conditions of the connection.

Keywords Shear connectors, Slip modulus, Connection strength limit, Connection stiffness

1. Introduction

Mixed structural system of wood and reinforced concrete has been used successfully in the construction of "T" section beams, in slabs for urban and rural bridges and floors. This type of structure consists of a concrete slab connected to structural members of wood in such a way that the parts work together [1].

Joint action of wood and concrete in the flexion is developed by the shear connectors and the level of stress transfer between the concrete slab and the wood can be integral or partial, defining a monolithic behavior when there are no relative displacements between these materials or behavior of a composite part when small relative displacements occur. Most connectors transfer stresses in the interface of the materials in a discrete way, although there are also connectors that transfer these efforts in a continuous way, as for example the bonded connections [1].

The efficiency of the structural element with composite section is related to the quality of the connection system, since the behavior of the connectors directly affects the distribution of internal forces as well as the deformations of the structure. Many types of connectors are possible for composite structures of wood and concrete. The main characteristics that allow comparisons between them are: the ultimate strength, the slip modulus and the final cost of installation [2].

Sliding modulus represents the rigidity of the connection, being obtained by means of direct tests in concrete-wood specimens. By knowing the stiffness of the connection, the amount and spacing between the connectors, one can estimate the effective stiffness of the mixed structural element [3, 4].

In Brazil, the lack of standardization for tests of shear connectors for wood-concrete mixed structures has allowed the researchers to adopt different methodologies and formats for the specimens. Although all of these specimens are symmetric push-out type, there are many differences between them. Few studies have been published on mixed wood and concrete structures, and most authors have used nail-type connectors or bolts perpendicular to the interface of the two materials, concentrating predominantly on composite beams with a "T" section.

In this work some models of specimens and some procedures used to obtain the sliding modulus and the

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ultimate strength of the mixed connections, recommended in some normative standards and used in others consulted literature, are presented.

2. Literature Review

Structural elements in bending with composite sections formed with the same or different materials, there are several factors that influence the evaluation of the shear forces that occur at the interface of the connected elements, such as: variations and combinations of the internal stresses along the structural element; variations in the mechanical properties of the materials involved; simplifications imposed by the basic assumptions of calculation; approximations used in the calculation models; and the mechanical and elastic behavior of the connections. Thus, the determination of the sliding modulus of the connection from the direct tests on structural elements does not result in values with good precision [5].

Testing in specimens is still the best procedure to know the behavior of the connectors, however, as the relative displacements progressively increase, changes in the positions of the support reactions and in the eccentricities of the acting forces occur. In this way, it produces undesirable interferences between the connected members and the behavior of the model gradually progresses to differ from the behavior of the actual connection.

The slip modulus is defined as the angular coefficient of the curve obtained from the load versus relative displacement, considering in its value all the elastic and mechanical parameters of the materials involved in the connection, such as: dimensions and stiffness of the connector; stiffness and strength to the inlay of the wood used; if one of the parts is concrete, consider the cracking or crushing strength of the concrete and specimen imperfections [5].

Most of the connectors show the load *versus* relative displacement diagram with nonlinear behavior, and the determination of the secant slip modulus is widely used, simplifying the computational process of the composite structures. The limits of the measurement intervals for determination of the secant slip modulus have been adopted with different criteria, significantly altering the calculated value. Some connectors present large displacements at the beginning of the requests, which then decrease progressively as the connector overcomes the initial gaps in the holes or notches. Other connectors have large displacements, from 40 or 50% of the maximum load that strengths. Considering different behaviors, the procedure definitions for the determination of the secant slip modulus is of fundamental importance. Fig. 1 shows an example of load *versus* relative displacement diagram and curves whose angular coefficient may correspond to the sliding modulus [6].

Consulted standards do not mention the test methods or the test specimen types for determining the ultimate rigidity or connections strength in mixed joints of wood-concrete. They take by analogy the recommendations for the connections between wood/wood or steel/concrete, where most suggest that the tests should realistically represent the behavior of the structure.

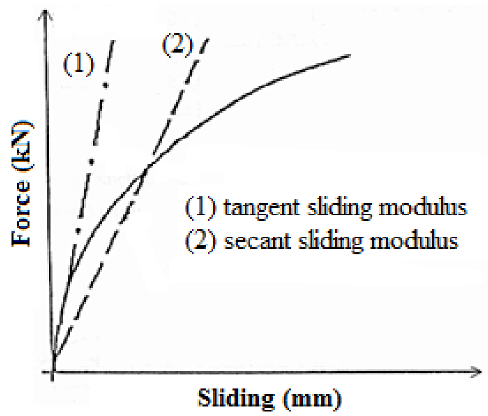

Figure 1. Sliding modulus obtaining through force *versus* relative sliding diagram [6]

ISO 6891:1983 Standard code [7] is clear with respect to the procedure of loading and measuring slides, however, it only recommends that the dimensions and types are equivalent to the actual conditions. This standard was intended for wood structures and not wood and concrete, but its procedures were cited by Ceccotti [2] and applied in mixed structures.

DIN 1052:1988 Standard code (Part 1/Table 8; Part 2/Table 13) [8] presents values for the sliding modulus in composite sections of wood, considering some types of connectors, however there is no reference to the composite parts of wood and concrete.

BS 5400:1979 Standard Code [9] (Fig. 2) presents test specimen detail for the study of connections between steel and concrete, with the connectors perpendicular to the interaction surface, presenting the respective dimensions and reinforcement for concrete parts. It is recommended for special connectors that the test specimens be compatible with the actual situation.

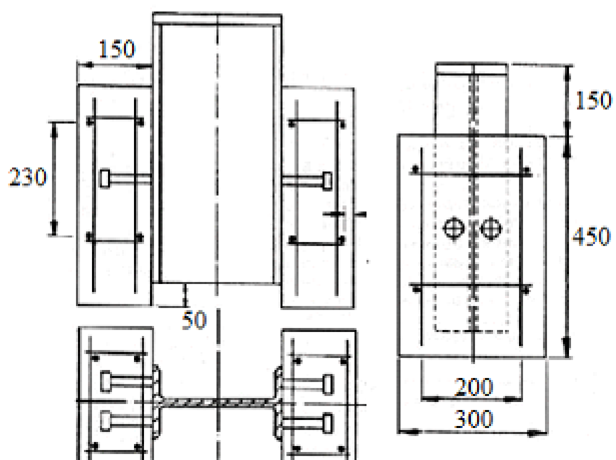

Figure 2. Shear test specimens for steel and concrete (units in mm) by BS 5400:1979 Standard Code [9]

Eurocode 4:1994 Standard Code [10] presents a test specimen model, procedures and test evaluations for connectors used in steel and concrete composite parts, with the following recommendations: if after the test it is noticed that the reinforcement was smaller than that required for sizing, the test shall be repeated with the necessary reinforcement; the longitudinal dimension of each concrete slab must be related to the longitudinal separation of the connectors in the mixed structure; the width "b" of each concrete slab must not be greater than the effective width of the concrete table of section "T"; the specimen must represent the mixed structure studied, when there are ribs or stiffness they should be present in the specimens; and if at the end of three tests on identical test specimens the deviation of any result from the mean value exceeds 10%, at least three additional tests shall be taken and the results shall be statistically evaluated by taking the lower quantile 5% with confidence level 75%.

Eurocode 5:1993 Standard Code [11] presents expressions for determination of the sliding modulus (K_{ser}) for connections of wood parts, using as connectors: nails, bolts, clamps and self-tapping screws positioned perpendicular to the shear plane. It also considers the instantaneous sliding modulus (K_u) in the shear plane, with value: $K_u=(2/3)\cdot K_{ser}$, for projects in the ultimate limit state.

ABNT NBR 7190:1997 Brazilian Standard Code [12] defines the ultimate strength value for connections with steel bolts in wood members, such as the force applied to a standardized specimen that causes a specific residual deformation equal to 0.2%. It presents the dimensions of the specimens and test procedures, but nothing comments on the determination of the sliding modulus or wood-concrete standardized tests.

3. Specimen Models to Sliding Modulus Determination

Several specimen models were used to obtain the ultimate strength and sliding modulus of the connectors. Symmetrical push out shear test specimens are the most commonly used, because they are easy to perform and test.

BS 5400:1979 Standard Code [9] (Fig. 2) presents a test specimen for tests of pin-type with heads steel connectors, positioned using welds perpendicular to the shear surface in steel and concrete members (Fig. 2). They observe the details of the double reinforcement with bars of high strength and adhesion, with diameter of 10 mm.

Eurocode 4:1994 Standard Code [10] presents a specimen model for tests of pin-type with heads steel connectors, positioned using welds perpendicular to the shear surface in steel and concrete pieces (Fig. 3).

Details of the double reinforcement with bars of high strength and adherence with diameter of 10 mm are observed in Fig. 3. Eurocode 4:1994 Standard Code [10] also presents the possibility of special tests using specimen that represent the specific conditions of the mixed beam under study, with the following considerations: specimen longitudinal dimension is related to the spacings of the connectors of the mixed beam; concrete width slab should not be greater than the effective width of the mixed beam; concrete thickness slab should not be less than the mixed beam concrete slab thickness.

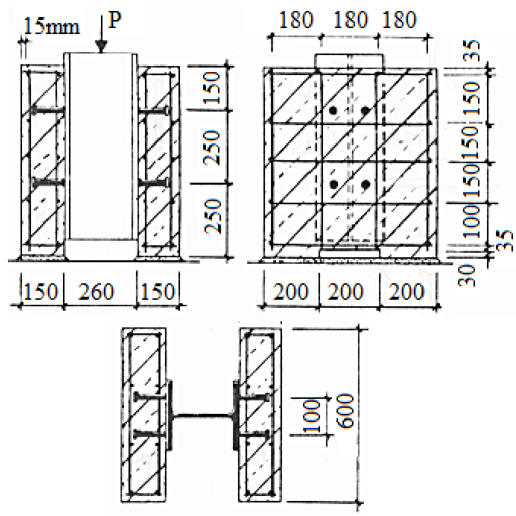

Figure 3. Shear test samples for steel and concrete (units in mm) by Eurocode 4:1994 Standard Code [10]

Richart and Willians [13] and Nicolas [14], carried out tests on wood and concrete specimens using self-tapping screw type connectors with three slopes in relation to wood grain, (Fig. 4). For execution facilities, the concrete was kept in the internal part of the specimen.

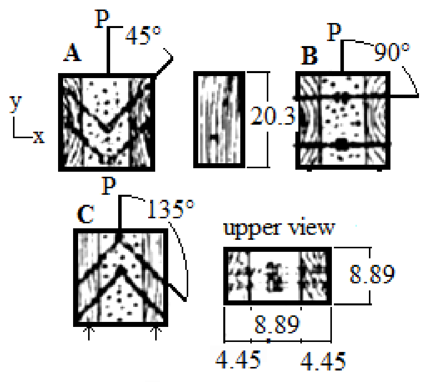

Figure 4. Specimen by Richart and Willians [13] (units in cm)

Ceccotti [2] suggests a possible specimen for determination of the load *versus* displacement diagram of the shear connectors (Fig. 5). Suggests the use of two connectors regardless of the connection system. This unconventional specimen, despite the test difficulties, better represents the actual condition of the connectors being applied.

Souza [15] tested push-out shear wood-concrete specimens using several connectors types: steel pins, nailed angles and wooden pegs, with circular and rectangular sections, perpendicular to the shear plane and two dimensions for the width of the concrete pieces (Fig. 6).

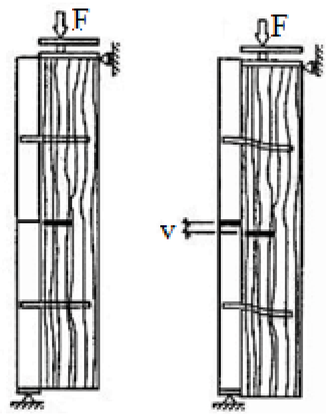

Figure 5. Specimen suggested by Ceccotti [2]

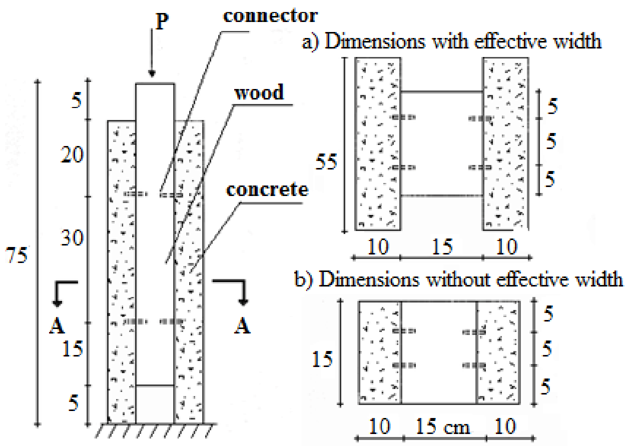

Figure 6. Shear specimen for timber and concrete (units in cm) [15]

Nicolar [14] performed three sets of tests with nail-type connectors positioned perpendicular to the shear plane, and used wood-concrete specimens (Fig. 7). In the first test, the double reinforcement was used with galvanized CA-60 steel bars with a diameter of 3.0 mm, forming two welded meshes of 150 x 50 mm, one on each side of the concrete piece. In the second and third tests the armatures had identical shapes, but were executed with a diameter of 5.0 mm.

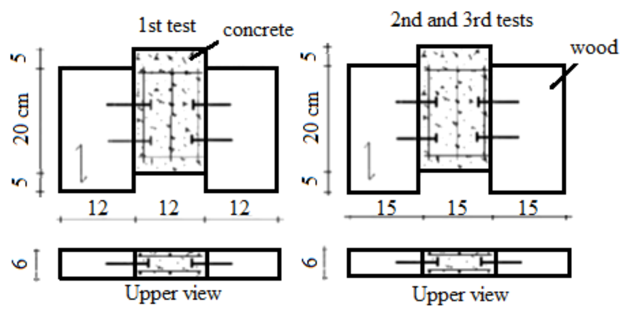

Figure 7. Specimen by Nicolas [14] (units in cm)

Soriano [17] tested two specimen's series with the reinforced concrete part and connectors positioned perpendicular to the shear plane (Fig. 8). In the first series, was used nails and adopted reinforcement in the central plane of the concrete slab with CA-60 steel bars with diameter 3.0 mm, forming welded meshes of 150 x 50 mm. In the second series he used nails with larger diameters and self-tapping screws, adopting the same form of reinforcement, executed with a diameter of 5.0 mm.

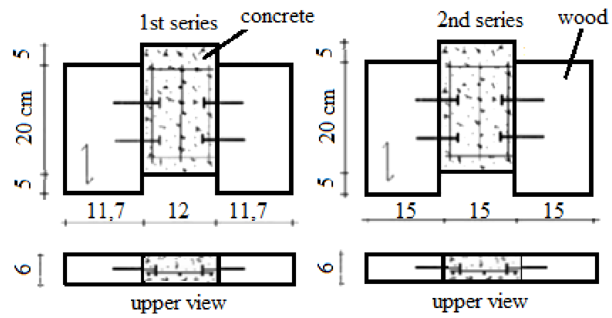

Figure 8. Specimen by Soriano [17] (units in cm)

Matthiesen [18] used three models of shear test specimens to study connectors in wood-concrete. In preliminary tests (Fig. 9), it used the test specimen model with the following types of connectors: grooves in the wood; grooves and self-tapping screws perpendicular to the shear plane; only self-tapping screws perpendicular to the shear plane; and self-tapping screws inclined with respect to the shear plane. The wood used was Cupiúba wood specie (*Goupia glabra*) with dimensions of 10 x 10 x 42 cm, but nothing comments on the armors used.

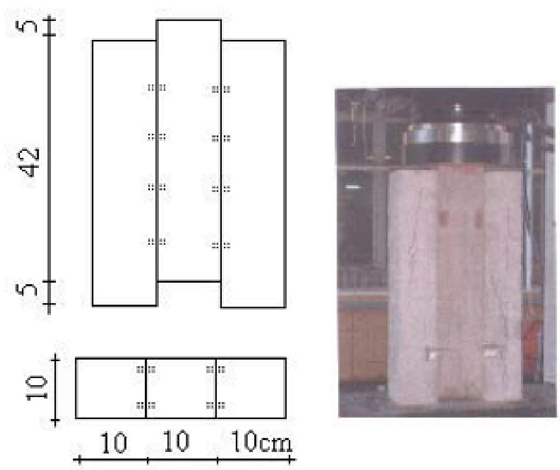

Figure 9. Specimen by Matthiesen [18] (units in cm)

In the second series of tests (Fig. 10), Matthiesen [18], specimens were formed by a central element of wood with dimensions of 10 x 10 x 42 cm and two plates of reinforced concrete with dimensions of 10 x 30 x 42 cm. The connectors used were self-tapping steel screws with diameters 9.8 and 12.7 mm and length 120 mm. Screws were positioned with a 50° inclination with respect to the shear plane, in the "X" format. Were used *Pinus oocarpa* Shiede, *Corymbia citriodora* and *Goupia glabra* wood species. It used, in the concrete, double reinforcement formed by welded CA-50 steel bars, with a diameter of 8.0 mm. The author [18] comments that specimen rupture model occurred by embedment connector the wood member.

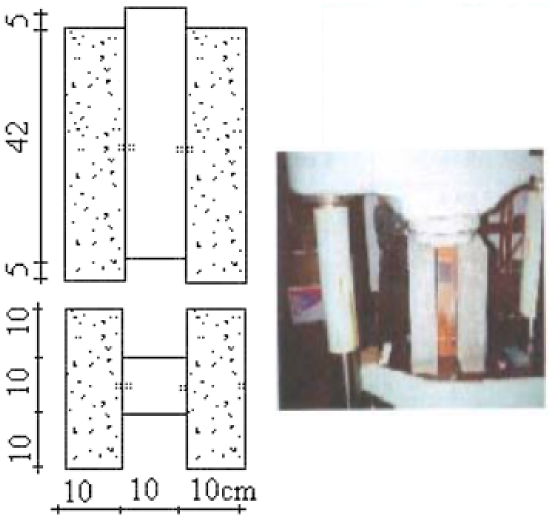

Figure 10. Specimen details at the second series of tests [18] (units in cm)

In the third series of tests used the specimens shown in Fig. 11, formed by a central element of wood with dimensions of 10 x 10 x 25 cm and two plates of reinforced concrete with dimensions of 10 x 10 x 25 cm. Connectors used were: nails with a diameter of 7.0 and a length of 163.0 mm; self-tapping steel screws with diameters of 9.8 and 12.7 mm and length of 128 mm; and steel bar type CA-50 with a diameter of 12.5 and lengths of 128.0 and 150.0 mm. Connectors were positioned perpendicularly and with inclinations of 50º in the "X" format in relation to the shear plane. In the concrete was used double reinforcement formed by CA-50 steel bars with a diameter of 6.3 mm and two steel stirrups CA-60 with a diameter of 4.2 mm. Author [18] comments that, in all specimens where nails or screws of 9.8 mm diameter were used, the rupture occurred by embedment in the wood. For steel screws and bolts with a diameter of 12.7 mm, there was embedment in the wood and localized crushing of the concrete for loading close to rupture.

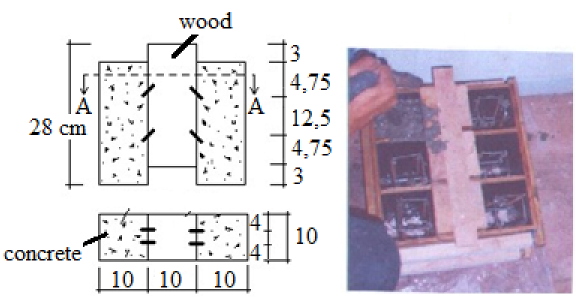

Figure 11. Specimen details at the third series of tests [18] (units in cm)

Pigozzo [6] studied connectors formed by inclined steel bars of 45º glued in the format "X", using epoxy resin. It tested specimens with *Corymbia citriodora* wood specie treated with CCA (Chromate Copper Arsenate) with a diameter of 17.6 cm and plates of reinforced concrete (Fig. 12).

Longitudinal and transversal reinforcements, represented minimum values in relation to the volume of concrete used, according to the ABNT NBR 6118:2003 Brazilian Standar Code [19]. These reinforcements were positioned with spacings two centimeters from the face of the wood.

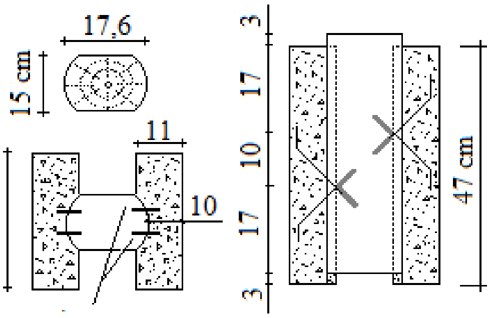

Figure 12. Wood-concrete specimen steel bar connectors glued in the form "X" [6] (units in cm)

4. Methods for Sliding Modulus Determination

There are several proposals in the literature review presenting numerical models, to estimate the sliding modulus values, for connections formed by perpendicular to the shear plane connector in timber connections. Nails, due to their uniformity and low cost, were the most studied connectors in special connectors.

For wood-concrete mixed connections, there are no numerical models, considering the variables involved as: the strength and stiffness of the wood; the strength and stiffness of the concrete; and the strength and rigidity of the connector. Specific design conditions, must also be considered, such as: distance between connectors; distance between the connector and the outer edge of the wood or concrete; effects of grouping the connectors; dimensions and formats of special connectors; and the rate and positioning of the reinforcement on the concrete part.

Soriano *et al.* [20] considered in the tests performed the sliding modulus obtained by tangent at the origin of a curve adjusted to the responses of the applied forces *versus* relative displacements.

In order to obtain the sliding modulus of the connection, Matthiesen [18] used a criteria similar to that recommended by the ABNT NBR 7190:1997 Brazilian Standard Code [12], where, through the load *versus* deformation diagram, it obtained the secant in points 10% and 50% of the maximum strength in each specimen.

Matthiesen [18] commented that the force corresponding to 50% of the maximum strength of the connection for some connectors corresponds to a very large relative displacement, significantly reducing the value of the sliding modulus. It suggests the secant passing the limit of 40% of the maximum request.

Pigozzo [6] obtained the sliding modulus of the connection using a criteria similar to that recommended by the ABNT NBR 7190:1997 Brazilian Standard Code [12], (C.5 Annex), where, through the load *versus* deformation diagram, the secant was obtained at points corresponding to 10% and 40% of the maximum strength of the specimen. It obtained the last strength in a similar way to the recommendations given by the same Brazilian Standard Code [12] (Annex C.5; Fig, 13), that is, by secant at points 10% and 40% of the maximum strength and from a parallel line to this secant obtained the limit strength corresponding to the loading that causes the residual deformation of 0.2%. In Fig. 13: $L_0 = 2\cdot(7\cdot d)+a$; d = steel connector diameter; a = recommended minimum spacing between connectors; a_1 = connector anchorage length on the concrete part; t_1 = wood part thickness; t_2 = concrete part thickness.

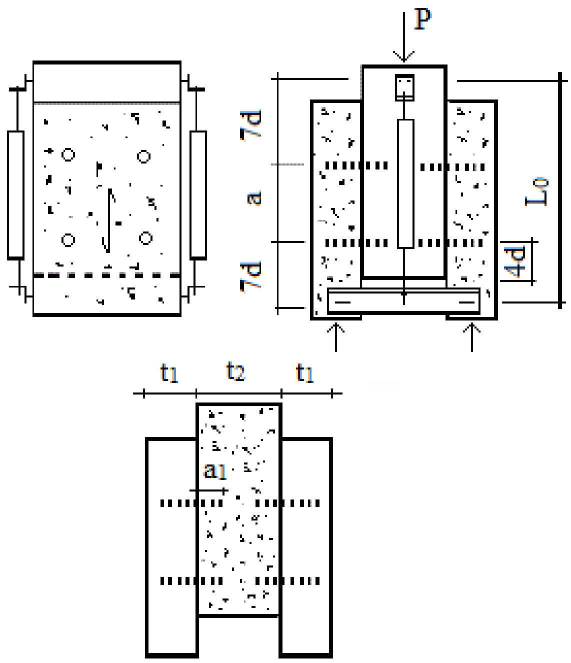

Figure 13. Base measures L_0 or type steel pin connectors [12]

5. Conclusions

For mixed wood-concrete composite calculations, the sliding modulus can be assumed as a linear relationship between the applied load and the relative displacement of the connection.

Average and characteristic values of the limiting strength and sliding modulus of a connection must be obtained experimentally by specimen that represent the real working conditions of this connection.

Specimen must be symmetrical and represent the mixed structure studied. When there are ribs or stiffness, they should be present in the specimens. Dimensions of the parts that make up the specimen must be equivalent to the dimensions of the structure studied.

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