3rd International Conference on Mechanical Models in Structural Engineering

CMMoST 2015
24-26 June 2015 Seville SPAIN

Design and calculation of dowel-type joints in timber structures. Behaviour of load against displacement

Manuel Domínguez[1], José G. Fueyo[2] and José A. Cabezas[3]

ABSTRACT

A joint system widely used in the construction of timber structures is based on the use of dowels, which transmit efforts between the timber elements. In these connections, it is attempted to reduce the diameter of the dowel, because large diameters increase the possibility of brittle fracture. In the present work, based on the approach of the European Yield Model that provides the load capacity of the joint, the stress distribution is analyzed in detail and a model is proposed. This model takes into account the slip of the joint and the propagation of the yield areas near the contact surfaces between dowel and timber, as the load increases. An iterative method that links load and slip equations is developed. It also provides information to improve the joint design, especially taking into account its stiffness behaviour. The results obtained from this analytical model have been compared with those from empirical tests of different samples, showing a good agreement.

Keywords: structures, timber, dowel, test, slip.

1. INTRODUCTION

The mechanical basis for designing and calculating joints with dowel-type elements in timber structures is included in the Eurocode 5 [1]. These procedures are also integrated in the Spanish Technical Building Code, and more specifically in the section 8.3 of the Basic Document on Structural Safety for timber structures, CTE DB SE M [2]. The method is based on a theory developed in Europe in 1949 by Johansen [3], and provides the load limit in dowel-type joints with different forms or modes of failure. In North America, it has been adopted as the "European Yield Model", according to Rodd [4].

The calculation must consider the main characteristics of the timber and the connecting elements, in particular the orthotropic behaviour of timber and possible failure modes of plastic type, with development of hinges in the dowel and crushing in certain areas of the timber. In the present work, to optimize the calculation of the joint deepening in its mechanical behavior, tension hypotheses derived of the bending of the dowel are analyzed, assuming no axial stress in the fastener and neglecting the contribution from friction to the load capacity of the joint $F_{v,Rk}$. According to these assumptions, is

[1]*Departamento de Ingeniería Mecánica. Universidad de Salamanca (España). mdominguez1@usal.es (Corresponding author)*
[2]*Departamento de Ingeniería Mecánica. Universidad de Salamanca (España). fueyo@usal.es*
[3]*Departamento de Ingeniería Mecánica. Universidad de Salamanca (España). jacf@usal.es*

possible to obtain the load limit with fairly simple expressions. Each of the expressions is related to a particular failure mode, giving a minimum load capacity per shear plane and per fastener.

Furthermore, the testing techniques of this type of joint are mainly related with two standards that could be considered complementary: UNE-EN 383 [5], which determines the crushing strength and the modulus of crushing for dowel-type joints; and UNE-EN 26891 [6], transposition of ISO 6891, which identifies the strength and slip characteristics of joints build with mechanical fasteners. The first one analyzes the crushing modulus, but only between a piece of timber and a dowel; without taking into account other factors involved in the joint, as the thicknesses of the different pieces of timber or reinforcements such as coupling nuts and washers on the dowel ends . The second standard establishes a test procedure for various metallic fasteners, not just dowels, setting a maximum displacement of 15 mm, regardless of the relative dimensions of the specimens, the size of the context of the joint or the boundary conditions acting on the structure.

2. LOADING BEHAVIOUR OF THE JOINT

As a starting point, it is necessary to specify precisely the characteristics of the joint under study: geometry and mechanical properties of dowel and timber parts, transmitted load and type of support. Although the possibilities of combining the elements of the joint can be large, the usual double shear symmetric distribution has been chosen, as shown in Fig. 1, in order to avoid eccentricities. It should be ensured the use of timber with guarantees of homogeneity, allowing dimensions and strength classes applicable to structural systems. The dowel is made of steel with appropriate specifications for structural applications.

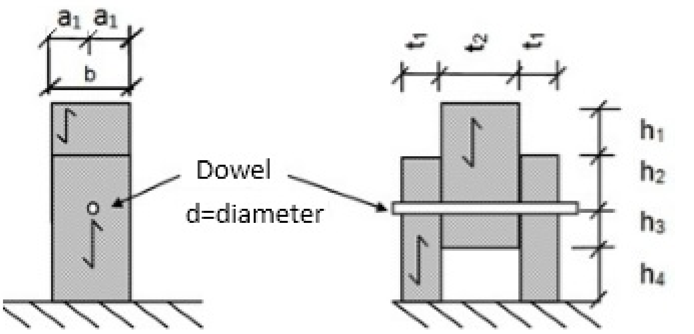


Figure 1. *Dimensions and geometry of the dowel-type connection in double shear.*

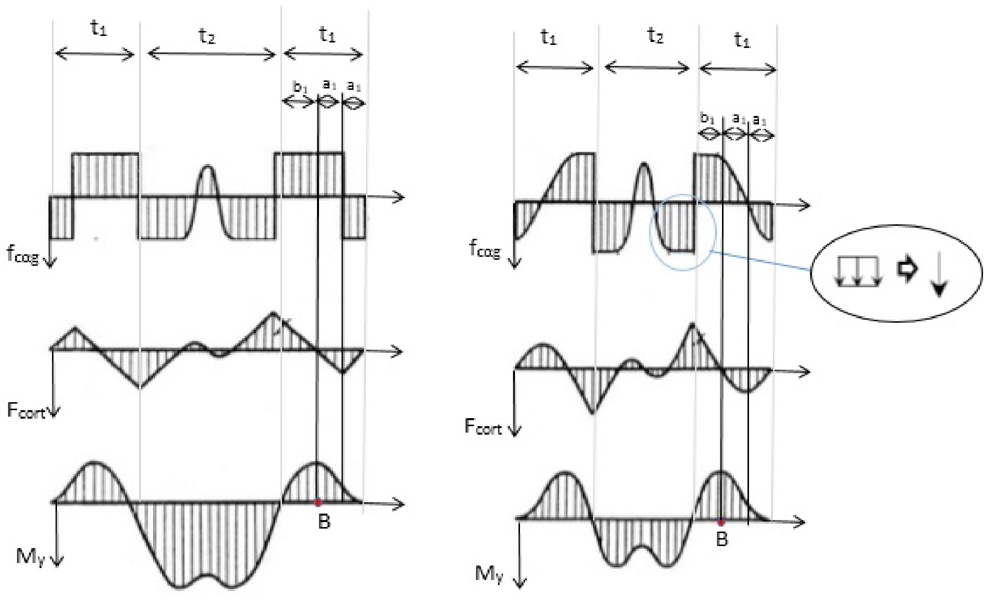
The geometric arrangement of the dowel must prevent undesirable failure modes. It should be placed sufficiently separated from the edges to avoid cracks. Besides this possible type of failure, it must be considered those described specifically for dowel-type joints in the Eurocode 5 [1]: crushing of the external pieces of timber (failure mode 1), crushing of the central piece of timber (failure mode 2), plastic deformation of the dowel with a hinge in its center (failure mode 3) and plastic deformation of the dowel with three hinges, one in its center and the two others in the external pieces of timber (failure mode 4).

The criterion of minimal slip of the joint is usually associated with larger and stiffer dowels, which means that the dowel is subjected to shear forces and the timber is exposed to higher local stresses. This may induce a design against the principles of economy. The calculation of a stiffer dowel leads to failure modes 1 and 2 (with timber crushing in the external and central parts respectively) and also implies a weakening of the net section of the beam (or a design with an increased section to compensate it).

To achieve an improvement in the redistribution of stresses in the dowel and increase the rope effect, it is profitable the formation of the plastic hinges characteristics of the failure modes 3 and 4. The failure mode 4 shown in Fig. 2 is of special interest because it presents more distributed forces on the dowel, increasing the load capacity of the joint. In Fig. 2 it can be seen the rotation angle of the dowel θ related to the plastic hinges and the crushing widths b_1 and b_2 of the external and central pieces respectively. If the slip of the joint u is small, the rotation θ is virtually nonexistent; but it increases with the slip, as shown in the figure on the right. Meanwhile, the size of the zone in the timber which transmits the load is related to the crushing widths b_1 and b_2 of the external and central pieces respectively.

Figure 2. *Geometric parameters that characterize the crush zone.*

The model proposed by Johansen [3] provides the ultimate load of the joint, considering that the failure can be caused by timber crushing or by formation of plastic hinges in the dowel. The load capacity of the fastening elements is deduced assuming that the stress-strain curve of the fastener has a rigid-plastic behaviour and the crushing occurs in a timber slab with thickness equal to the diameter of the dowel d. Fig. 3 shows the stress distributions proposed by Johansen [3] for the failure modes 3 and 4.



Failure mode 3 (a central hinge)　　Failure mode 4 (hinges in the center and sides)

Figure 3. *Stress distribution in the dowel.*

Taking into account the above simplifications and the static equilibrium equations, it is possible to obtain the load capacity per shear plane $F_{v,Rk}$ from the characteristic crushing strength $f_{hi,\alpha k}$, the dowel diameter d, and the following width of crushing

$$b_1 = \sqrt{\frac{2 \cdot M_{y,Rk}}{f_{h1,\alpha,k} \cdot d}} \cdot \sqrt{\frac{2 \cdot \beta}{1 + \beta}} \tag{1}$$

with:

- $M_{y,Rk}$ characteristic plastic moment of the dowel.
- $f_{h1,\alpha,k}$ characteristic crushing strength of the piece with thickness t_1.
- d dowel diameter (assumed to be equal to the hole).
- β crushing ratio of the two members, defined according to

$$\beta = \frac{f_{h1,\alpha,k}}{f_{h2,\alpha,k}} \tag{2}$$

that can also be related to the crushing widths:

$$f_{h1,\alpha,k} \cdot b_1 \cdot d = f_{h2,\alpha,k} \cdot b_2 \cdot d \rightarrow \beta = \frac{b_1}{b_2} \tag{3}$$

The total crushing width can be calculated as a function of the ratio of the two crushing members β and the crushing width of one of the parts b_1 according to

$$b_t = b_1 + b_2 = b_1 + \frac{b_1}{\beta} = b_1 \cdot \frac{\beta + 1}{\beta} \tag{4}$$

The value of coefficient β is particularly relevant when the timber parts are of different strength class or when there are changes in the angle of relative orientation of the timber fibres α, for instance if there are beams that require different directions in the structural composition.

3. TEST PROCEDURE

The behaviour of the joint exposed to loads can be studied from tests, which present a complex problematic for these type of joint because the orthotropy and heterogeneity of the timber and the influence of other environment variables. Overall, the technical regulations have attempted to perform an independent analysis of the failure variables, including timber crushing and dowel bending, as described by authors like Ariza [7]. In Europe, the traditional rules belonged to the so call "approach of the basic stresses" (with samples of small size and generally free of defects), focused on working with homogeneous materials like steel and concrete. However, is necessary a treatment closer to the nature of structural timber.

The development of the tests involves the use of samples with an exhaustive control of variables such as its moisture or density. Testing machines must be calibrated and verified with accuracies according to the standard UNE-EN 26891 [6], which implies that the device measures the slip of the joint under load with an accuracy of ± 1% or more, and for slip below 2 mm with an accuracy of ± 0.02 mm. In this work, a compressive test has planned as shown in Fig. 4, with load durations that guarantee a static behaviour. The loading procedure includes the premises given in the standard UNE-EN 26891 [6], with an estimated load F_{est} initially calculated from the load per shear plane $F_{v,Rk}$.

The load is applied at a constant speed to a value of $0.4 \cdot F_{est}$, and it is maintained for 30 s. Then, it is reduced to $0.1 \cdot F_{est}$ and maintained for another 30 s. Next, it is increased until reaching the final estimated load or a 15 mm displacement. Below $0.7 \cdot F_{est}$ it must be used a constant rate of loading corresponding to 0.2 F_{est} per minute with a tolerance of ± 25%. Above $0.7 \cdot F_{est}$ it is possible to increase this speed until the specimen reaches the final load or a 15 mm slip in an additional time of testing of 3-5 min. The total test time should be between 10 and 15 min. Fig. 4 shows the composition of the sample in the testing machine.

Figure 4. *Composition of the sample in the testing machine.*

The slip and load tests allow observing the different stages of the behaviour of the joint. It is possible to identify the evolution from the initial formation of the contact between the timber and the dowel, until the transition from the elastic zone to a plastic behaviour, which is associated with a reduction of stiffness and a maximum level of load on a plateau, until reaching a final and definitive failure. These phases have been documented by Dorn [8] and are shown in the Fig. 5.

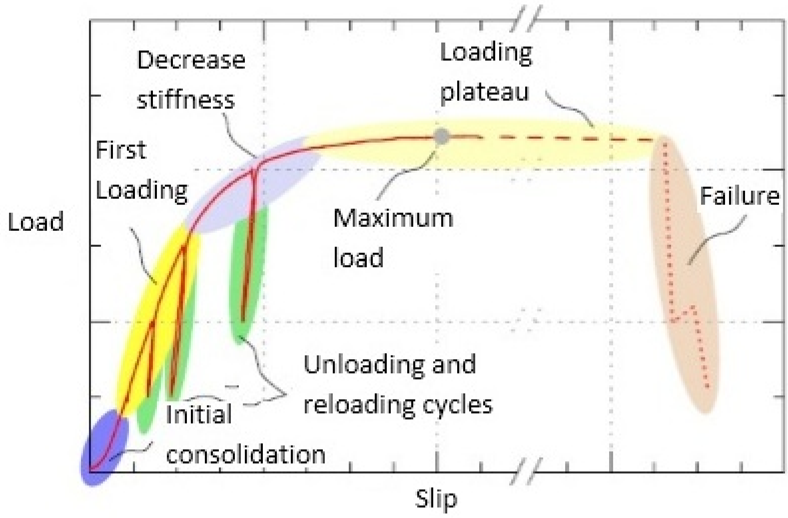


Figure 5. *Individual load phases of a typical dowel-type connection, by Dorn [8].*

The initial consolidation involves contact connections which typically show very low stiffness at the start of loading process. This low initial stiffness is probably due to the imperfect contact between dowel and timber, resulting from the geometric roughness in the contact area and the imperfections in the contact surfaces. Geometric imperfections lead to a lower and irregular stiffness factor in the first loading steps, until it spreads to the entire length of the dowel.

The first load is identified in the phase that directly follows the consolidation process, and wherein the load-slip curve describes a non-linear path in the most tests. It can be approximated by a straight line in dowels with small sections or joints with very stiff behaviour as the case of using epoxy adhesive. The perfect linearity can not be expected, since the consolidation is still in progress, and the material behaviour of timber begins to be nonlinear (plasticity of compression).

It may present one or more cycles of unloading and reloading. The stiffness in the unloading and reloading significantly exceeds the maximum stiffness of the first load. Unlike the first load, they show an approximately linear elastic behaviour. The deformations in the contact area between the steel and timber remain, and the timber is not restored back to its original shape. During reloading, the dowel fits perfectly in the timber around it, without consolidation behaviours unlike what happens in the first phase. When it is loaded beyond this level, and slips exceed the level achieved prior to unloading, the curve tends to reduce the slope and recover the continuity of the first load. This behaviour is identical to dowels with the same stiffness during unloading and reloading and at different stages of the process, regardless of the density or thickness of the timber parts.

Afterwards, the stiffness decreases and a plateau is presented. With increasing load, stiffness decreases dramatically, and the maximum capacity of the joint is reached. The decrease in stiffness is due to the stresses exceed the yield strength in certain areas, with the growth of plastic deformations. In dowels with medium and high slenderness, the tendency to form plastic hinges intensifies. That is, the failure mode with central and double hinge in the dowel described in the previous section. The maximum load and ductility are significantly dependent on the density, friction behaviour, and the side constraints on the dowel arising from the reinforcements (such as fasteners with washers and nuts on the ends). The slips until failure differ considerably, and in some specimens (eg. with very dense timber) the plateau of yield is hardly reached. In the case of a long yield plateau, brittle fracture occurs locally in the timber matrix (shear failure), which however does not affect the overall ductile behaviour.

The failure is identified in the last stage of the load-slip curve. It occurs spontaneously and leads to a sudden drop in load. The failure mode depends on the same parameters mentioned above in relation to the maximum load, namely density, friction, and the lateral reinforcements of the dowel.

4. CALCULATION MODEL BASED ON THE EVOLUTION OF THE SLIP

As an alternative to obtain the value of the load capacity of the joint as indicated by Johansen [3], this section develops constitutive equations relating load and slip, that allow identify the stiffness behaviour, from the study of the forces and moments involved in the behaviour of the dowel. To define the free-body diagrams, portions of the joint will be taken according to the pictures shown in Fig.6.

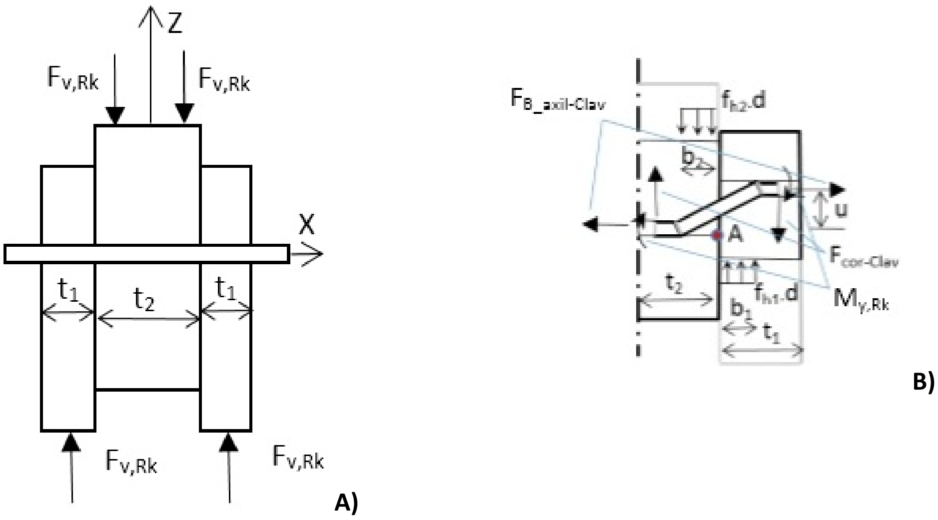


Figure 6. *Scheme of loads on the joint. A) Joint assembly. B) Zone exposed to plastic deformation.*

Since during the evolution of the loading process yield effects are identified in the dowel (and these are related to the propagation of crushing in the contact areas), the free-body diagrams should initially consider several forces and moments. An equilibrium equation of moments about point A (shown in Fig. 6B) is proposed. The values of shear force represent a contribution to the work of the dowel, but they make difficult the calculation of the efforts as a whole. In order to avoid the introduction of shear stresses in the equilibrium equation of moments, a section of dowel is analyzed until the maximum bending stress point, and therefore zero shear, which would occur at point B, as indicated in Fig. 3. The contribution from the rope effect related to the axial force acting on the dowel $F_{B\_axil\text{-}Clav}$ is neglected. The development of this equation of static equilibrium of moments leads to

$$\sum M_z{}^A = 0 \rightarrow 2 \cdot M_{y,Rk} + F_{B\_axil-Clav} \cdot u = f_{h1,\alpha,k} \cdot d \cdot b_1 \cdot \frac{b_1}{2} + f_{h2,\alpha,k} \cdot d \cdot b_2 \cdot \frac{b_2}{2} \qquad (5)$$

from where the width of crushing b_1 is obtained:

$$b_1 = \sqrt{\frac{2 \cdot M_{y,Rk} + F_{Baxil-Clav} \cdot u}{f_{h1,\alpha,k} \cdot d \cdot \left(\frac{\beta + 1}{2 \cdot \beta}\right)}} \tag{6}$$

This expression generalizes the Eq. (1) of Johansen's work [3], integrating the components of the rope effect. Assuming the simplification of stress transmission in a flat slab, as it is discussed in the Eurocode 5 [1] and the theory of Johansen [3], the next equation is reached:

$$F_{vR,k} = f_{h1,\alpha,k} \cdot d \cdot b_1 \cdot \frac{\beta^2 + 1}{\beta} \tag{7}$$

4.1. Plastic moment of the dowel

The development leads to the need to identify the plastic moment that produces the complete yielding of the dowel. It can be treated similarly to the case of nails, whose moment is defined by the test described in the standard UNE-EN 409 [9]. In this form is included in the Eurocode 5 [1], which also proposes to calculate it analytically as a function of the steel ultimate strength $f_{u,k}$. However, although the dowel can present yielding, does not reach its final breaking point. The ultimate strength would be reached in advanced deformation situations of the dowel, which could not work in the early stages. On the other hand, the yielded areas present stresses that increase from the yield strength to the ultimate strength while the bending of the dowel progresses. Using the value of the steel ultimate strength as a variable in the structural calculations could be counterproductive, since it leads to improving the carrying capacity of the joint, increasing, for example, its hardening capabilities, which could open the possibility of using brittle materials. The safety criteria tend to use a ductile behaviour, which "alert" from a possible failure with a long period of yield to adsorb energy.

The above considerations make it advisable to calculate the plastic moment of the dowel as a function of its characteristic yield strength $f_{y,b}$ and the angle of rotation θ, because stress increases with the deformation of the dowel. By introducing variables as the angle (or crushing widths) initially unknown, it is difficult to obtain an equation related to the strength of the plastic hinges in the dowel. Authors like Awaludin [10] give indications to calculate the plastic moment as a function of the yield stress and the dowel rotation according to

$$M_{y,Rk} = \frac{\xi \cdot f_{yb} \cdot d^3}{6} \tag{8}$$

where:

- $f_{y,b}$ characteristic yield strength of the dowel element
- ξ plasticity index of the dowel

The plasticity index of the dowel is a function of the angle at the hinge θ. By the geometrical considerations shown in Fig. 2, the slip u can be related with the total width of crushing b_1+b_2 and with the rotation angle in the dowel θ

$$tag(\theta) = \frac{u}{b_1 + b_2} \tag{9}$$

Eq. (8) is based on works of Blass [11], which establish the plasticity index ξ as

$$\xi = min\begin{cases}(0{,}866 + 0{,}00295 \cdot \theta) \cdot \left(1 - e^{\left(\frac{-0248 \cdot \theta}{0{,}866}\right)}\right) \\ 1\end{cases} \tag{10}$$

that it is shown in Fig. 7. When the plastic hinge of the dowel develops an angle of 45°, with large slip, a limit value of plasticity index is taken, ξ = 1.0, leaving a safety margin.

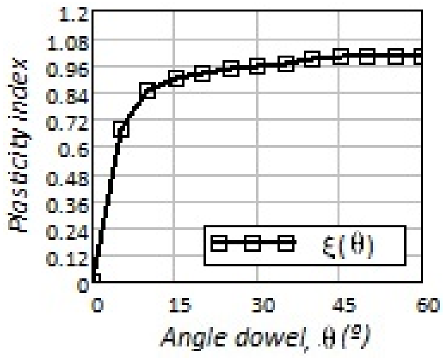


Figure 7. *Evolution of plasticity index.*

4.2. Calculation technique

The above expressions lead to an iterative algorithm. Beginning with a start value b_1 according to Johansen expressions (Eq. (1)), the Eq. (9) with a slip u = 15 mm (as indicated in standard of tests UNE-EN 26891 [6]) is used to obtain the angle of the hinge θ, and the plasticity index ξ applying Eq. (10). These values are introduced in Eq. (8) to calculate the yield moment of the dowel $M_{y, Rk}$, which allows calculating a new value of b_1 according to Eq. (6) that corrects the initial value. With this, the iteration cycle is closed, starting the process again. The results converge quickly to a stable solution, which provides information about the slip and the crushing width. When the error is small enough, the iteration loop is ended and the Eq. (7) applied. A summary of the calculation process can be seen in the flowchart shown in Fig. 8.

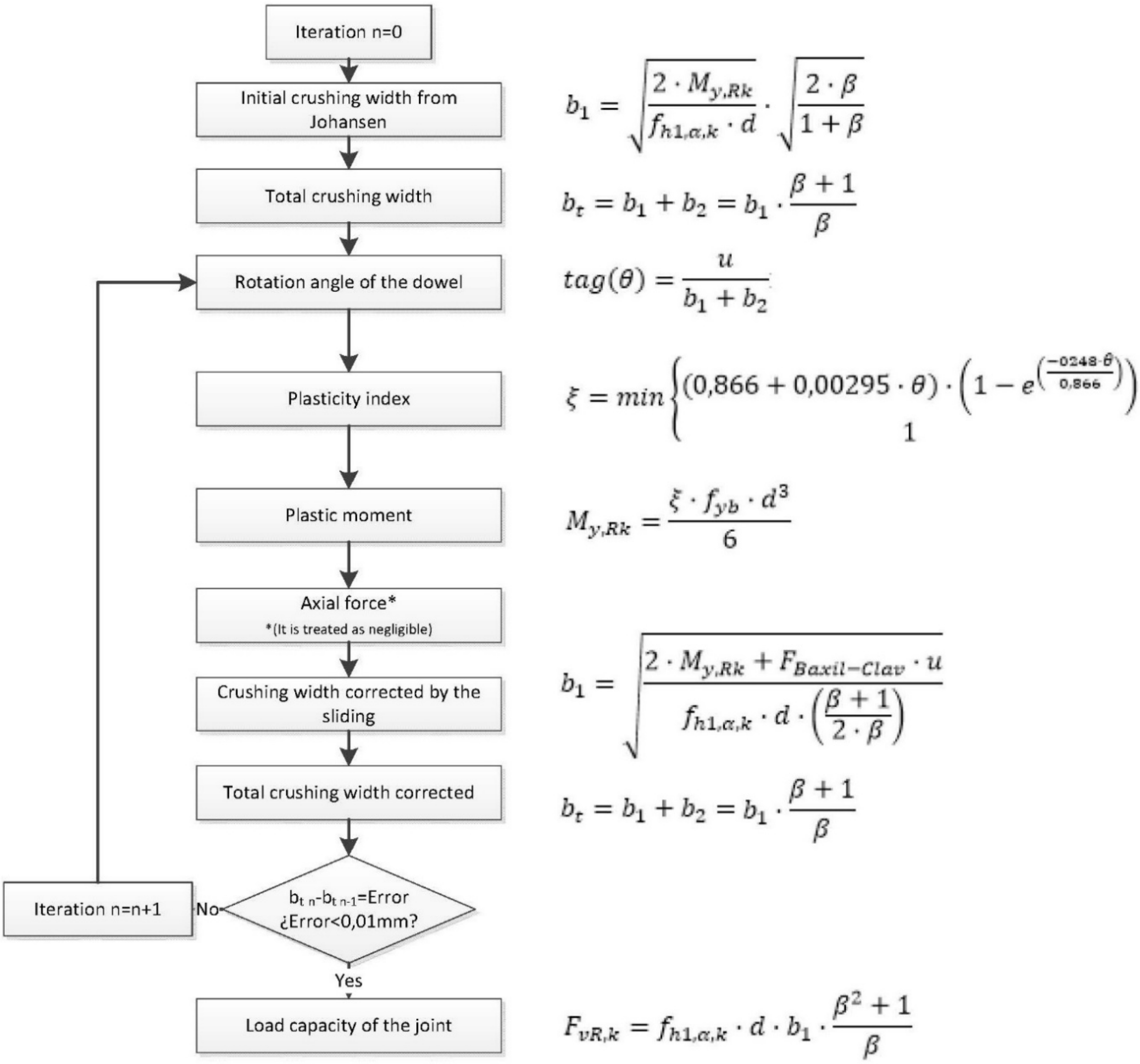


Figure 8. *Summary flowchart for determining the load on the joint from the slip.*

5. VALIDATION OF RESULTS

5.1. Materials and geometry of the models

As an example of application of the model using the calculation technique described in the preceding paragraph, the parameters of the joint have been set according to Table 1. This table also contains the parameters needed to calculate others variables, such as the crushing strength of the timber $f_{h1,\alpha,k}$, whose expression is described in Eurocode 5 [1].

Table 1. Mechanical characteristics of the joint.

Joint assembly: Symmetric timber-timber joint, with a dowel in double shear.	
Timber	GL24 h softwood
• Characteristic density	$\rho_{g,k}$ = 380 kg/m^3
Geometry. Commercial dimensions:	
o Thickness of the external pieces	t_1 = 80 mm
o Thickness of the central piece	t_2 = 160 mm
• Safety factor against crushing of timber of the joint	ϒ =1.3
• Relative orientation of the timber fibres between external and central pieces	α = 0º
Steel dowel with quality 5.6:	
• Dowel diameter	d = 10 mm
• Yield strenght of the steel	f_y = 300 N/mm^2
• Ultimate strenght of steel	f_u = 500 N/mm^2
• Safety factor of the dowel	ϒ=1.1
Load coeficients:	
• Modification factor for service class 1 and medium-term load	k_{mod} = 0.8
Rope effect of reinforcement elements:	
• Threaded dowel with washers and nuts on the ends	No
• Axial grip of the dowel caused by the adhesive	No
Friction in contact zones:	
• Axial grip caused by the friction timber-dowel	μ = 0
• Reinforcements of the interfaces with nail plates, connectors or a similar	No
• Friction beween timber interfaces	μ = 0

The results obtained from the analytical model based on the equations described above have been compared with those from the tests of different samples, which have been built according to the arrangement of Fig. 1. The samples have a depth a_1+a_1 equal to the width t_2, that is, 160 mm; with the dowel centred at the lateral faces, and equidistant 115 mm from the upper face of the central timber element and the supports ($h_1 + h_2 = h_3+h_4$ = 115mm).

5.2. Comparison between analytical and experimental results

The proposed calculation, unlike the Standard (which sets a unique value of the load capacity), allows a comparison of the load with the slip. Therefore, the model can be validated by contrasting its results with those of the tests. Fig. 9 shows the load-slip curve obtained from the proposed analytical model, compared with those from the tests of three specimens with a smooth dowel. All of them correspond to analogous conditions and show the same trend. The evolution of the model leads to a load-slip curve consistent with the development of the test (a first load with decreased stiffness and a plateau region) taking into account that the equation must be corrected with parameters such as the initial clearance. Moreover, the dowels may present special features for large slip, as the contribution of the rope effect that should be an improvement of the proposed method. In the tests, the displacement of 15 mm was overtaken to study a broader segment of the yielded zone. The limitation of the dowel length causes that it was embedded into the hole (with displacement over 40 mm), whereby the contact surfaces were modified, entering the load capacity in negative slopes. It should be noted that, in the theoretical model, it has not yet been considered axial components of rope effect or friction, which would also modify the plateau region.

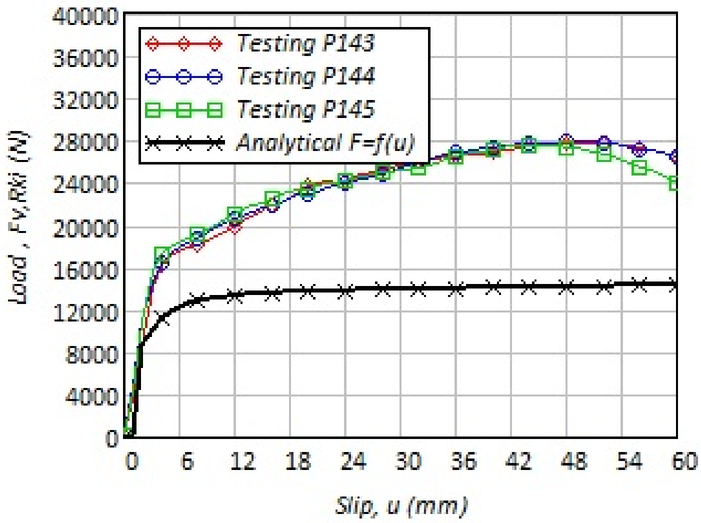


Figure 9. *Individual load phases of a typical dowel connection.*

5.3. Comparison of the results with the Standard values

The equations of the plastic moment, defined in Eurocode 5 [1], are not a function of the joint slip. Therefore, it can not be established a direct relationship between load and slip over the entire range of slip. But the plastic moment and the crushing width must ratify the results with the asymptotic trend of the plasticity index shown in Fig. 7. In Fig. 10, it can be identified how the analytical equations describing the evolution of the rotation angle of the dowel, the plastic moment and the crushing width evolve to approach the limits established in Eurocode 5 [1] leaving a margin of safety.

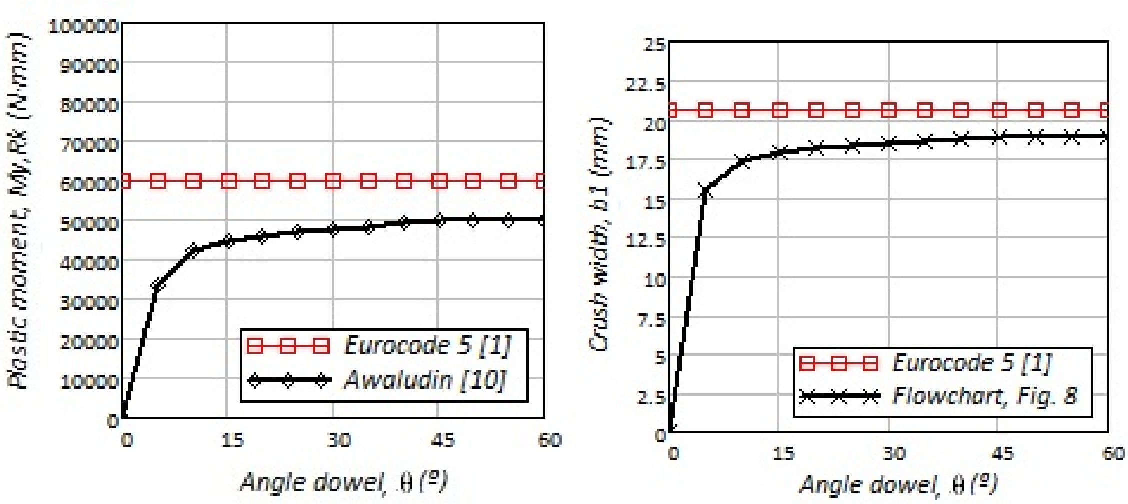


Figure 10. Evolution of the plastic moment and the crushing width.

6. CONCLUSIONS

A model based on iterative calculation has been developed, which expand the design and calculation of structural dowel-type joints, establishing a relationship between slip and load. It was possible to compare the results of this analytical model with the evolution of tests carried out, and calculate parameters characterizing the behaviour of the joint, such as the width of crushing and the angle formed in the plastic hinge for an applied load. The use of the proposed model allows to know how the joint works, avoiding to perform expensive destructive test.

The use of this technique has significant advantages, because it identifies the evolution of the crushing width b_1+b_2 and the maximum bending moment $M_{y,Rk}$ as a function of the slip. Furthermore, the calculation uses the characteristic yield strength of the dowel f_{yd} instead of the ultimate strength f_{uk}.

It can be determined the evolution of the rotation angle of the dowel θ, which can be used as a dimensionless factor to limit deformations and stiffness, as an alternative to the constant displacement of 15 mm (independent of the piece size) established in the technical regulations.

Moreover, this approach opens the possibility of incorporating the axial force that can be applied to dowel, to evaluate the crushing width b_1+b_2 and the slope in the plateau region, in the same set of constitutive equations relating load with slip.

ACKNOWLEDGEMENTS

This work has been developed thanks to the research project BIA2012-36766, funded by Ministry of Economy and Finance, under the VI National Plan for Scientific Research, Development and Technological Innovation. The authors also thank the collaboration of the Institute of Materials and Construction of Zamora (INZAMAC), for facilitate the use of their testing machines to perform the experimental part of this work; and the company REARASA SL, for the manufacture of the specimens used for testing.

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