ACCOUNTING OF THE THREAD EMBEDMENT IN TIMBER STRUCTURES DOWEL-TYPE JOINTS. LOAD-SLIP RELATIONSHIP

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ABSTRACT
This work is devoted to the development of a design method for dowel-type joints in timber structures that takes into account the increase in load capacity due to the use of threaded dowels. While the method is based on acknowledged criteria of structural standards, it also considers the crushed areas that appear in the timber near the zone of contact with the dowel’s thread. Thereby, it comes closer to the actual mechanical behaviour of the whole joint when it suffers a relative displacement between its different parts under an external load. The equations for defining the load capacity of the joint proposed in this study have been developed considering the timber fibres in embedment by the dowel’s thread. The validation of the new analytical method proposed has been performed through a battery of experimental tests, and the comparison between the analytical and the experimental results is shown.

Keywords: Timber structures, displacement, dowel-type joint, thread embedment.

INTRODUCTION
The design of dowel-type joints in timber structures is based on the theory and equations developed in 1949 by the European scientist Johansen (Johansen, 1949), who considered the work of the internal forces as a result of the appearance of crushed areas in the timber and plastic hinges in the dowel when external loads act. His criteria were adopted by the European standard Eurocode 5 (CEN, 2004) and also in North America, under the name of “European Yield Model” (Rodd, 2003). Johansen’s theory provides designers with equations to calculate the load limits of dowel-type joints for different configurations such as timber-timber and timber-steel, taking into account different failure mechanisms like the combined appearance of plastic hinges in the dowel and crushed areas in the timber, which is considered to behave as an orthotropic elastoplastic material.

Certain studies indicate the possibility of improving the load capacity of the joint by increasing the frictional forces which appear between dowel and timber hole (Rodd, 2003). This increase can be obtained using hidden bindings, shear plate connectors or rougher contact surfaces (Sjödin, 2008), that provoke crushing in the timber fibres and increase the so-called rope effect. This requires the modification of the old equations to take into account this new effect, and also of test procedures (CEN, 2007) and (CEN, 1991), used to verify this type of joints giving load-slip relationships. Therefore, the aim of this work is to propose new equations whose results are verified using experimental tests. As a first step towards this goal, attention is focused on double shear timber-to-timber dowel type joints. The effect of roughness considering dowels with smooth or rough surface, and other reinforcement
elements such as shear plate connectors, washers and nuts at the ends of the dowel or expansive kits, will be dealt with in future works.

DESCRIPTION OF THE CASE STUDY

First of all, an accurate definition of the characteristics of the joint under study is to be provided, including geometry, mechanical properties of the dowel and timber parts, transmitted load and type of support. The usual double shear symmetrical distribution has been chosen, among the possibilities for combining the joint’s elements, as shown in Figure 1. The specific data of the tested joint are also defined in Table 1. Homogeneity of the timber used should be guaranteed according to specification EN 1912 (CEN, 2008).

![Fig.1 - Dimensions and boundary conditions of the case study](image)

Table 1 - Characteristics of the dowel-type joint tested

<table>
<thead>
<tr>
<th>Joint assembly: Symmetric timber-to-timber joint with a dowel in double shear.</th>
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<tbody>
<tr>
<td>Timber</td>
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<tr>
<td>• Characteristic density</td>
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</table>

Geometry. Commercial dimensions:

| o Thickness of the external pieces | \( t_1 = 80 \text{ mm} \) |
| o Thickness of the central piece | \( t_2 = 160 \text{ mm} \) |
| • Safety factor against crushing of timber of the joint | \( \gamma = 1.3 \) |
| • Relative orientation of the timber fibres between external and central pieces | \( \alpha = 0^\circ \) |

Steel dowel: metric screw of strength quality 5.6:

| • Dowel diameter | \( d = 10 \text{ mm} \) |
| • Yield strength of the steel | \( f_y = 300 \text{ N/mm}^2 \) |
| • Ultimate strength of the steel | \( f_u = 500 \text{ N/mm}^2 \) |
| • Safety factor of the dowel | \( \gamma = 1.1 \) |

Load coefficients:

| • Modification factor for service class 1 and medium-term load | \( k_{\text{mod}} = 0.8 \) |

Rope effect of the reinforcement elements:

| • Threaded dowel with washers and nuts on the ends | No |
| • Axial link of the dowel caused by the adhesive | No |
| • Others | Yes, embedment |

Other geometric data according to Fig. 1. (EN 1995, 2006)

| \( a_1 = 80 \text{ mm} \) | \( h_1 = 100 \text{ mm} \) | \( b_2 = 115 \text{ mm} \) | \( h_3 = 115 \text{ mm} \) | \( h_4 = 200 \text{ mm} \) | \( h_5 = 120 \text{ mm} \) |
The geometric arrangement of the dowel should ensure the prevention of undesirable failure modes, for instance, it should be placed far enough from the edges to avoid cracks. However, besides this possible type of failure, attention should be paid to those described specifically for dowel-type joints in Eurocode 5 (CEN, 2004): crushing of the external pieces of timber (failure mode 1), crushing of the central piece of timber (failure mode 2), plastic deformation of a dowel with a hinge in its centre (failure mode 3) and plastic deformation of a dowel with three hinges, one in its centre and two in the external pieces of timber (failure mode 4).

The minimal slip of the joint criterion 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 that is in contradiction with the economy principles. The calculation using a stiff dowel leads to failure modes 1 and 2 (with timber crushing in the external and central parts respectively) and also to a weakening of the net section of the beam (or a design with an increased section to compensate it).

EXPERIMENTAL TESTS

Although there are tests to study the mechanical behaviour of joints subjected to loads, the type of joint studied proves particularly complex because of the orthotropic nature and heterogeneity of the timber and the influence of other environmental variables. Technical regulations have generally attempted to perform an independent analysis of the failure variables, including timber crushing and dowel bending, as described by certain standards (CEN, 1991) and (CEN, 2008). In Europe, the traditional rules belong to the so-called "approach of the basic stresses" (with small and usually free of defects samples), focused on working with homogeneous materials such as steel and concrete. However, an approach that is closer to the nature of structural timber is required.

The development of the tests involves the use of samples with an exhaustive control of variables such as moisture or density. Testing machines must be accurately calibrated and verified according to standard EN 26891 (CEN, 1991), 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 been planned, as shown in Fig. 4, with loading durations that guarantee a static behaviour. The loading procedure includes the premises given in standard (CEN, 1991), with an estimated load $F_{est}$ initially calculated from the characteristic load-carrying capacity per shear plane $F_{c,Rk}$.

The load, with a value of $0.4 \cdot F_{est}$, is applied at a constant speed and maintained for 30 s. Then, it is reduced to $0.1 \cdot F_{est}$ and maintained for another 30 s., to be further increased until the final estimated load or a 15 mm displacement is reached (Fig. 2). Below $0.7 \cdot F_{est}$ a constant rate of loading corresponding to $0.2 \cdot F_{est}$ per minute with a tolerance of ±25% must be used. 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 3-5 min of testing. The total test time should be between 10 and 15 min.

The slip and load tests show the different stages of the behaviour of the joint. It is possible to identify the evolution from the initial establishment of contact between timber and dowel, through the transition from the elastic zone to plastic behaviour, which is associated with a reduction of stiffness and a maximum level of load on a plateau, until final and definitive failure is reached. These phases have been documented by Dorn (Dorn, 2013).
The initial consolidation involves contact connections which typically show very low stiffness at the start of the loading process. This low initial stiffness is probably due to imperfect contact between dowel and timber resulting from geometric roughness in the contact area and imperfections on the contact surfaces. Geometric imperfections lead to a lower and irregular stiffness factor through the first loading steps, until it spreads over 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 most tests. It can be approximated by a straight line in dowels with small sections or joints with very stiff behaviour, as is the case when using epoxy adhesive. Perfect linearity cannot be expected, since 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 phases significantly exceeds the maximum stiffness of the first load. Unlike the first load, these show an approximately linear elastic behaviour. The deformations in the contact area between steel and timber remain, and the timber does not regain its original shape. During reloading, the dowel fits perfectly in the timber around it with no consolidation behaviours, in contrast to what occurs 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 its slope and returns to the point where the previous loading ended. This behaviour is identical in dowels with the same stiffness during unloading and reloading and at different stages of the process, regardless of density or thickness of the timber parts.

Afterwards, stiffness decreases until a plateau is reached. Increased loading leads to a dramatic decrease of stiffness and the achievement of the maximum capacity of the joint. This decrease in stiffness is due to the stresses that exceed the yield strength in certain areas, which causes plastic deformation expansion. In dowels with medium and high slenderness, the tendency to form plastic hinges intensifies, which illustrates the failure mode with central and double hinge in the dowel described in the previous section. Maximum load and ductility are significantly dependent on 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 certain specimens (e.g. with very dense timber)
the yield plateau is barely reached. In the case of long yield plateaus, brittle fracture occurs locally in the timber matrix (shear failure), which does not, however, affect overall ductile behaviour.

Failure occurs spontaneously in the last stage of the load-slip curve, leading 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.

The formation of the plastic hinges characteristic of failure modes 3 and 4 is useful to improve the redistribution of stresses in the dowel and increase the rope effect. The failure mode 4 shown in Fig. 3 is of special interest because the forces on the dowel are more widely distributed, thus increasing the load capacity of the joint. Fig. 3 shows the rotation angle of the dowel $\theta$ related to the plastic hinges and crushing widths $b_1$ and $b_2$ of the external and central pieces respectively. If the slip of the joint $u$ is small, rotation $\theta$ is virtually nonexistent; although it increases with the slip, as shown in the figure on the right. Meanwhile, the size of the timber zone that transmits the load is related to crushing widths $b_1$ and $b_2$ of the external and central pieces respectively.

![Fig. 3 - Rotation angle $\theta$ and crushing widths $b_1$ and $b_2$ for two different slips $u$](image)

**CALCULATION MODEL BASED ON THE EVOLUTION OF THE SLIP**

As an alternative to Johansen’s indications to obtain the load capacity of the joint, this section develops the constitutive equations relating load and slip, which allow identification of the stiffness behaviour of the joint, from the study of the forces and moments acting on the dowel. Because of the yield effects identified in the dowel, which are related to the propagation of crushing in the contact areas, the following forces and moments, shown in the free-body diagrams in Fig. 4, should be initially considered:

- $F_{v,Rk}$ characteristic load-carrying capacity per shear plane.
- $F_{B,ax}$ axial force acting on section B of the dowel, related to the rope effect.
- $F_{tr}$ transversal force acting on the dowel.
- $M_{y,Rk}$ characteristic plastic moment of the dowel for each rotation angle $\theta$ according to the plasticity index (Blass, 2000).
- $f_{h1,k}$ characteristic embedment strength of the piece with thickness $t_1$. 
An equilibrium equation of moments is proposed. Shear forces $F_{tr}$ represent a contribution to the work of the dowel, but they make the calculation difficult. To prevent their introduction in the equilibrium equation of moments, the portion of the dowel between the sections of maximum bending, and therefore zero shear forces, is analyzed. It corresponds to the portion between the points where the bending moment is at its maximum and the transversal force $F_{tr}$ is null. The development of the equation of static equilibrium of moments about point A leads to

$$
\sum M^y = 0 \Rightarrow 2 \cdot M_{y,Rk} + F_{B,ax} \cdot (u - u_{cl}) = f_{h1,k} \cdot d \cdot b_1 \cdot \frac{b_1}{2} + f_{h2,k} \cdot d \cdot b_2 \cdot \frac{b_2}{2}
$$

where $d$ is the dowel diameter and $u_{cl}$ the clearance of the dowel in the hole.

The width of crushing $b_1$ is obtained from equation (1):

$$
b_1 = \frac{2 \cdot M_{y,Rk} + F_{B,ax} \cdot (u - u_{cl})}{f_{h1,k} \cdot d \cdot \left(\frac{\beta + 1}{2 \cdot \beta}\right)}
$$

where $\beta$ is the crushing ratio of the two members, defined according to

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

which can also be related to the crushing widths:

$$
f_{h1,k} \cdot b_1 \cdot d = f_{h2,k} \cdot b_2 \cdot d = f_{h1,k} \cdot \beta \cdot b_2 \cdot d \Rightarrow \beta = \frac{b_1}{b_2}
$$

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

$$
b_1 = b_1 + b_2 = b_1 \left(\frac{1 + \beta}{\beta}\right)
$$
The value of coefficient $\beta$ is particularly relevant when the timber-strength classes are different, or when there are changes in angle $\alpha$ of relative orientation of the timber fibres with respect to the load direction, since $f_{h1,k}$ and $f_{h2,k}$ depend on $\alpha$.

Expression (2) generalizes previous research works (Johansen, 1949), integrating axial force $F_{ax}$, which produces the rope effect. Assuming the simplification of stress transmission in a flat slab, as discussed in Eurocode 5 (CEN, 2004), the characteristic load-carrying capacity per shear plane of the joint is the result of

$$F_{v,Rk} = f_{h1,k} \cdot d \cdot b_1 \quad (6)$$

Slip $u$ provokes the bending of the dowel, which becomes embedded into the timber, and causes the appearance of axial force $F_{ax}$. This force increases the load capacity of the joint through the rope effect that depends on slip $u$, as indicated by equations (2) and (6).

Fig. 5 provides a flowchart summarizing the steps for determining the load-carrying capacity of the joint following the procedure based on the equations above.
AXIAL FORCE DUE TO THREAD EMBEDMENT

When dowels with thread along their entire length are used, the timber fibres close to the contact surfaces are crushed against the thread under forces acting in the direction initially perpendicular to the dowel axis, which changes when the slip of the joint increases. Meanwhile, those fibres that are far from the contact are dragged by the dowel movement and its rotation (Fig. 6A).

Once the slip exceeds values around the thread pitch, the timber fibres surrounding the thread become interlocked, opposing the longitudinal displacement of the dowel and causing a rope effect. In the tests carried out, the dowel was removed after the specimen was transversely cut, and the trace of the thread in the timber was found to appear in a 180° arc, in accordance with the semicircle of the dowel section that advances causing crushing (as shown in the diagram in Fig. 6B). This is an expected outcome, since the dowel has to advance through the timber fibres as deformation progresses. This leads to the introduction of an embedment coefficient \( k_{emb} \) reflecting the part of the cross-sectional area exposed to embedding. If the dowel is fully threaded, \( k_{emb} = 0.5 \) is taken. The embedment coefficient is also applicable to other systems, especially those with mechanisms such as opening tabs or lugs that dig into the timber.

\[ F_{ax,emb} = k_{emb} \cdot [K_{ser,e,m-a,\alpha} \cdot \Delta L_{0,emb} + K_{ser,p,m-a,\alpha} \cdot (\Delta L - \Delta L_{0,emb})] \]
\[ = k_{emb} \cdot [A_{emb} \cdot f_{emb} + K_{ser,p,m-a,\alpha} \cdot (\Delta L - \Delta L_{0,emb})] \]

where

- \( F_{ax,emb} \) axial force on the dowel at point B, due to the embedding of the thread into the timber, in N.
- \( k_{emb} \) embedding coefficient.
- \( A_{emb} \) cross-sectional area exposed to embedding, in mm\(^2\).
- \( f_{emb} \) embedding strength of the timber, in N/mm\(^2\).
- \( K_{ser,e,m-a,\alpha} \) slope in the elastic zone, in N/mm.

Figure 6 shows that embedding is conditional on whether there is enough slip \( u \) in the joint for the fibres to interlock, and it is considered zero when slip \( u \) is smaller than thread pitch \( p \) plus clearance \( u_{cl} \). The latter could lead to further study of a particular situation but, considering that this condition is overcome in the early stages of plasticization, it is more important to focus on the stage where the fibres have already become adjusted to the thread. Thus, the axial force would already located in the plastic branch of Fig. 7A that, corrected by the coefficient \( k_{emb} \), is defined by equation
• $K_{ser,p,m,a,α}$ slope in the plastic zone, in N / mm.
• $ΔL$ change in length of the dowel, in mm.
• $ΔL_{0,emb}$ change in length of the dowel in the beginning of the plasticization of the timber fibres, in mm.

Both the change in length of the dowel while it moves along the hole, which is a function of joint slip $u$ and the deformation of the dowel, as the process of embedding of the fibres into the thread of the dowel, are complex. Fig. 8 shows the process of embedding the timber fibres in the threads of the dowel:

• In the early stages of loading, contact occurs only at the crest of the thread, taking place on a smaller surface than in the case of smooth dowels, so that there is a greater settlement phase (Fig. 8A).

• While the dowel has no displacement along its axis or rotation $θ$ by plasticization, the timber slides down along the flanks of the thread, and its fibres present bending and compression areas conditioned by the flank angle (Fig. 8B).

• For higher slip of the joint, Fig. 8C shows that the axial displacement of the dowel causes one side of the timber inside the thread to be subjected to high crushing against a flank of the thread, while the other side may even lose contact. If the displacement of the dowel along its axis continues, even more complex situations, such as a sawing effect, may occur.
The shear modulus in the embedding planes has specific qualities, since it varies depending on the position of the fibres due to the variable stresses which occur in a crushing process that also varies the geometry of the embedded material.

The following has been taken to accurately adapt Equation 8 to the study of embedding of the threaded dowel in the direction perpendicular to its axis:

- The cross-sectional area exposed to embedding as similar to a circular crown with the outer and inner diameters (d and d\text{int}) of the thread multiplied by the number of turns of the thread (n\text{thre}):

\[
A_{\text{emb}} = n_{\text{thre}} \cdot \pi \cdot \frac{(d^2 - d_{\text{int}}^2)}{4} \quad (9)
\]

- The embedding strength of the timber is taken as its compression strength perpendicular to the fibre (f_{\text{emb}} \approx f_{c,90,k})

- The behaviour represented in Fig. 7A has been simplified by considering a rigid-plastic evolution as shown in Fig. 7B, similar to that proposed in the “European Yield Model” (Johansen, 1949). Therefore, the plastic slope is K_{\text{ser,p,m-a,b}} \approx 0.

This results in the axial force due to the thread embedment given by Equation 8 being

\[
F_{ax,\text{emb}} = k_{\text{emb}} \cdot n_{\text{thre}} \cdot \pi \cdot \frac{(d^2 - d_{\text{int}}^2)}{4} \cdot f_{c,90,k} \quad (10)
\]

In any case, it should be remembered that there may be different ways of achieving compression between timber and dowel, for example with expansive kits, so each case should be studied separately.

Fig. 9 shows the process for calculating the axial force due to the thread embedment, contemplating the possibility of introducing other effects, such as friction between dowel and timber, or other expansion systems.

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**Axial loading on the dowel**

Axial forces on the dowel for the contribution of different reinforcement

- friction dowel-timber

- thread embedment

\[ u \leq u_{\text{emb}} - u_{\text{emb}} \] Yes

No

Previous capacity to incrustation

Rope load effect

Embedding load

(For fixed displacement)

- expansion

Total effort axial dowel

\[ F_{B,ax} = F_{ax,fric,loads} + F_{ax,emb} + F_{ax,exp} \]

In any case, it should be remembered that there may be different ways of achieving compression between timber and dowel, for example with expansive kits, so each case should be studied separately.

Fig. 9 shows the process for calculating the axial force due to the thread embedment, contemplating the possibility of introducing other effects, such as friction between dowel and timber, or other expansion systems.

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Fig. 9 - Main flowchart for the determination of axial loads on the dowel, taking the slip into account
The number of turns of the thread exposed to embedding can increase with crushing width \( b_1 \), so that it is recommended to adjust its value in an iterative process linked to determining \( b_1 \). On the other hand, the axial forces on the dowel can increase through other causes such as friction between dowel and timber or expansive processes in the dowel different from those described in this work.

**COMPARISON OF RESULTS**

To validate the analytical calculation procedure, the results obtained for the case study considered, defined by the values in Table 1, were contrasted with those of the experimental test of three equal specimens (numbered as P58, P63 and P64 in the tests). This was performed using the load-slip curves, which ensures that the whole load process is considered. Fig. 10, where all the curves appear together, shows that they follow the same trend, although the analytical method yields lower values than those obtained from the tests. Thus, the use of the calculation procedure proposed to determine the load-carrying capacity of the joint as a function of the slip provides values with a safety margin.

![Comparison of analytical and experimental results.](image)

The load-slip curves obtained allow observing the different stages of the behaviour of the joint, so that it is possible to identify the evolution from the initial formation of the contact between the timber and the dowel to the transition from elastic to plastic behaviour. In the area of plastic behaviour, the slope increases due to the embedding effect, improving the load capacity of the joint, which differs from the plateau-type evolution described by other authors (Dorn, 2013) when there are no axial components on the dowel. This effect can be identified in both tests, and analytical calculations (Fig 10A). With small slips, analytical models do not provide information about the carrying capacity, while the tests show an initial consolidation involving contact connections which typically show very low stiffness at the beginning of the loading process (Fig 10B). This low initial stiffness is probably due to imperfect contact between dowel and timber, resulting from geometric roughness in the contact area and imperfections on the contact surfaces. The geometric imperfections lead to an irregular and lower stiffness factor in the first loading steps, until contact spreads over the entire length of the dowel.

**CONCLUSIONS**

This work proposes a method for calculating the load-carrying capacity of dowel-type joints based on equations that take into account the slip in them. The equations proposed include the effect of the timber fibres in embedment by the dowel’s thread, and the ensuing rope effect.
The development of the equations has been described in detail, and the results they provide along the entire loading process have been compared with those of three experimental tests. Evidence shows that the load-slip curves follow the same trend, and that the proposed procedure gives values with a safety margin.

Therefore, this procedure makes it possible to determine the evolution of the rotation angle of dowel $\theta$, which can be used as a dimensionless factor to measure the stiffness of the joint and to limit deformations, as an alternative to the constant 15 mm displacement established in technical regulations, regardless of the size of the joint elements.

This approach opens up the possibility of incorporating the axial forces produced by friction between dowel and timber or other elements that can be added to the joint, such as expansive kits, nuts and washers at the ends of the dowel, etc., to increase the rope effect, so that crushing widths $b_1$ and $b_2$ and the slope in the plateau region may be determined with the same set of constitutive equations relating load to slip.

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