CONTACT SHEAR STRESSES IN DOWEL-TYPE JOINTS WITH EXPANSIVE KITS OF TIMBER STRUCTURES

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ABSTRACT
This paper studies the shear stresses appearing in dowel-type joints of timber structures which use expansive kits. To achieve this goal a finite element model has been prepared capable of determine the effect of these kits over the global response of the joint. In its development different procedures have been used to take into account the existence of the expansion process, the presence of surfaces in different parts of the joint which get in contact, the compression pressures provoked by this contact, the consequent shear stresses caused by the friction, and finally the effect of all these previous points over the overall performance of the joint, especially in the relationship between the applied load and its slip. The correct design of the model has been checked using experimental tests. The results obtained show that the use of expansive kits slightly improves the load-carrying capacity of the dowel through the rope effect.

Keywords: Timber structures, fem, dowel-type joints, expansive kits.

INTRODUCTION

Dowel-type joints are one of the most widespread types of connections used in timber structures. The methods proposed in the different national and international codes and standards to calculate these joints are based on the equations proposed by certain scientists more than half a century ago (Johansen, 1949). Since then, many innovations in timber structures have been developed, for example in the materials used, with the introduction of glued laminated timber, laminated veneer lumber or fibreboard; in structural calculation methods, with the introduction of computers that allow the running of programs that consider not only elastic behaviour, but also plastic performance, etc.

One of these barely tested possible innovations is the use of expansive dowels in timber structures (Rodd, 2003). This kind of elements, which is extensively used in other structural materials such as concrete, allows the introduction of contact pressures between the surfaces of the dowels and the timber holes in which they are placed. This provokes frictional forces that improve the mechanical performance of the joint, especially the load-slip relationship of the whole connection. However, the use of these kits implies the appearance of high shear stresses around the contact surface and also hazardous tensile stresses in the direction perpendicular to the fibre. Timber is particularly weak under these two types of stresses.

This paper shows the magnitude of these types of stresses provoked by expansive kits using a specially prepared finite element (FE) model. This model is capable of simulating the performance of the joint using a subroutine, expressly programmed in Fortran, to describe the
elastoplastic anisotropic mechanical behaviour of timber (Kharouf, 2003) taking into account both the tensile and compressive yield strengths. It also includes contact force transmissions between the surfaces of the expanded dowel and the surfaces of the hole in which it is placed and, finally, it is capable of simulating the expansion process inside the dowel. To check that the model works properly, the load vs displacement diagrams provided as a result have been compared with those coming from a battery of experimental tests carried out using realistic materials, geometries and loads.

**DOWEL-TYPE JOINTS WITH EXPANSIVE KITS**

Even though, as mentioned in the introduction, dowel-type joints are one of most widespread types of joints used in timber structures, the use of expansive kits, so common in other structural materials like concrete, has hardly been probed in timber structures, except in certain research studies (Rodd, 2003; Larsen, 2000).

The advantage of using this technology lies in the possibility of introducing pressure in the surroundings of a hole’s surface, which could provoke friction stresses that increase joint capacity through the rope effect (Awaludin, 2008). This effect and its advantages are currently well known and studied. For example, it appears when threaded rods or adhesive are used between dowel and hole surface. Nevertheless, these two possibilities also have certain disadvantages. In the first case, the frictional forces introduced by threaded rods are very irregular and vary with the magnitude of the displacement, which makes it very difficult to calculate them, and even to express them in an equation. The second option, adhesives, entails certain additional expenses arising from the cost of the adhesive itself and, especially, from its handling and application. It also requires the use of holes with greater clearances, since both rod and adhesive must be introduced together. In this dragging process, part of the dowel surface could lose its adhesive, a failure that is almost impossible to notice from the outside, but which proves dangerous because, while considered in the design, the rope effect would not be actually working.

As an alternative to these two procedures to obtain the rope effect, this work studies how to introduce these frictional forces using expansive kits. Just as the two procedures mentioned, it has advantages and disadvantages. Compared with threaded rods, the expansive kit produces a steadier friction along the entire length of the rod and over the entire displacement interval. Compared with adhesive, it guarantees friction on the entire dowel surface, thus avoiding potential incorrect distribution of the adhesive. However, it also has two major disadvantages. First, the expansive kit pressure on the hole surface can provoke perpendicular to grain stresses in its surroundings. Timber is especially weak under this kind of stresses. The second disadvantage is that, nowadays, there is no cheap, fast and safe industrial procedure to get the expansive kit in place. This would be a task to tackle if the effectiveness of this methodology is proved.

Although there are different possibilities to produce the expansive effect, after having tested some kits, the use of a hollow steel tube which is expanded thanks to steel spheres with greater diameters than the inside diameter of the tube seems to provide the best results. Using this method, a small expansion of the tube can be achieved, after which a solid rod is used to fill the tube. Figure 1 shows the expansion procedure.
FINITE ELEMENT MODEL

A very important goal of this research was to prepare a FE model to simulate the structural behaviour of dowel-type joints with expansive kits in timber structures (Mackerle, 2003). The building of this model is especially complicated because of the multiple difficulties that have to be tackled (Xu, 2009; Resch, 2010). The first is to achieve a correct simulation of the mechanical behaviour of timber, which is anisotropic with different stress-strain relationships in the different directions. This is due to its special microstructure formed by long fibres placed in the longitudinal direction of the trunk and joined together through weak links. This implies different elastic moduli and elastic strengths in the different directions. The usual way to simulate such complex mechanical behaviour is to propose a simplified one, which consists of considering timber as an orthotropic elastoplastic material (Hill, 1948; Guan, 2001) with three main directions: a longitudinal direction that coincides with the direction of the fibre and two perpendicular ones called radial and tangential. These directions are represented inside a section of the trunk in Figure 2.

This approximate mechanical behaviour model is usually found in the commercial FE method programs. Although it normally works fine when applied to composite materials, it certainly fails when it is used to simulate the mechanical behaviour of timber because of its different strengths when working under tensile or under compressive stresses (Xu, 2014; De Borst, 1990). In the direction of the grain, under tensile stress, timber shows an elastoplastic behaviour until fibre fracture occurs; while under compressive stress, the failure is caused because the timber cells buckle and collapse. On the other hand, in the directions...
perpendicular to the grain, under tensile stress, timber fails when the weak links that join the fibres are unable to withstand the stresses (Chen, 2013), and under compressive stress a grain-crushing situation appears. These different mechanical phenomena explain why there are different yield strengths in tension and compression. Depending on the timber class, the ratio between strengths can be up to 20. To be able to simulate these special mechanical behaviours, some of these commercial programs have special tools that can connect with user-defined subroutines in which the mechanical behaviour of the material is programmed, as is the case with this study.

The second goal in preparing the FE model was to correctly design the contact areas. In this case, this is especially difficult because the model consists of three different parts: side, centre and dowel. This involves a wide range of possible movements between them, and also large displacements which can lead to convergence problems. To avoid these problems, as far as possible, the model must include displacement constraints to impede all movement possibilities that are irrelevant for the study. Also, the correct element type and contact algorithms must be selected for this specific case. In the normal direction of contact, the algorithm selected was ‘hard contact’, which prevents slave surface nodes from penetrating facets created with master surface nodes. While this is the most exigent algorithm, it is also the most precise. Others, such as the ‘exponential’, ‘linear’, ‘tabular’ or ‘scale factor’ algorithms can be used if the ‘hard contact’ one causes convergence problems, but they yield less accurate results. In the tangential contact direction there are also several possibilities: ‘frictionless’, ‘penalty’, ‘static-kinetic exponential decay’, ‘rough’, ‘Lagrange multiplier’ and ‘user-defined’. The one selected for this work was the penalty method and, to assess the effect of the frictions caused by the expansive kit, the results were compared with those obtained from the frictionless option.

Finally, the third special feature in the design of the model was aimed at generating the effect of expansion of the dowel. This part was addressed by using the same procedure that would be used when designing thermal expansion. The difference in this case is that the expansion is not three-dimensionally isotropic. To correctly simulate the mechanical expansion caused by the steel spheres on the tube, a special case of expansion was prepared to generate two-dimensional isotropic expansion in the plane perpendicular to the axis of the dowel and no expansion in its longitudinal direction. Figure 3 shows the predefined field applied on the dowel to simulate the mechanical expansion effect.
MATERIALS, GEOMETRIES AND LOADS

Once prepared, the basic features of the FE model must be applied to a particular case, with specific values for the material properties, the geometries and the loads. These values must be close to those that could be working in an actual timber structure joint. Among all the possible timber classes, one of the most widely used was selected: timber glulam class GL24h. Its strength properties, elastic modulus and density can be seen in Table 1 (CEN, 1999).

Table 1 - Strength properties (N/mm²), Elastic Modulus (N/mm²) and Density (kg/m³) of class GL24h.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending strength</td>
<td>( f_{m,k} )</td>
<td>24</td>
</tr>
<tr>
<td>Tensile strength parallel to grain</td>
<td>( f_{t,0,k} )</td>
<td>16.5</td>
</tr>
<tr>
<td>Tensile strength perpendicular to grain</td>
<td>( f_{t,90,k} )</td>
<td>0.4</td>
</tr>
<tr>
<td>Compressive strength parallel to grain</td>
<td>( f_{c,0,k} )</td>
<td>24</td>
</tr>
<tr>
<td>Compressive strength perpendicular to grain</td>
<td>( f_{c,90,k} )</td>
<td>2.7</td>
</tr>
<tr>
<td>Shear strength parallel to grain</td>
<td>( f_{s,k} )</td>
<td>2.7</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>parallel to grain</td>
<td>( E_{0,\text{mean,average}} )</td>
<td>11600</td>
</tr>
<tr>
<td>perpendicular to grain</td>
<td>( E_{90,\text{mean,average}} )</td>
<td>9400</td>
</tr>
<tr>
<td>Transversal elasticity module</td>
<td>( G_{\text{mean,average}} )</td>
<td>720</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho_k )</td>
<td>380</td>
</tr>
</tbody>
</table>

Figure 4 shows the proposed geometry of the joint, only considering the part of the timber elements necessary to study the behaviour of the joint, rather than their entire length, to minimize the size of the FE model. Also, a block has been added as a complementary part that does not exist in the actual structures, but that has also been used in the experimental test specimens. Its function is to keep the distance between the two lateral timber parts.
Finally, once the timber class and the geometries have been selected, the loads working on the joint can be calculated using the equations proposed in Eurocode 5 (hereinafter EC5) to design dowel type joints (CEN, 2004). According to it, the characteristic load-carrying capacity per shear plane $F_{v,Rk}$ is the minimum value given by the four equations which correspond to the four possible failure mechanisms shown in Figure 5. Since the dowel-type joint proposed works in double shear, this load value corresponds to the force acting on each of the lateral timber parts. To keep equilibrium, the reaction in the central timber part will be $2F_{v,Rk}$. This will be the load applied in the finite element model, but divided by four, since the existence of two perpendicular planes of symmetry allows modelling only a quarter of the joint.

![Figure 5 - Four possible failure mechanisms and their load value as proposed by EC5.](image)

In the failure mechanisms (c) and (d), the term at the end of the equations, $F_{ax,Rk}/4$, is added to considered the contribution to the load capacity of the axial forces which can appear in the dowel in its longitudinal direction when using reinforcements like adhesives to glue the dowel in its hole or washer and nuts situated in the extremes of the dowel. This is called the rope effect. In this term, the value $F_{ax,Rk}$ is the characteristic axial withdrawal capacity of the fastener. This value is calculated using the following equation:

$$F_{ax,Rk} = \pi d_{eq} t_f \cdot f_{v,k}$$

where

$$f_{v,k} = \frac{f_{v,90,k}}{\sin \alpha + 1.5 \cos^2 \alpha}$$
The meaning of the variables in these equations, and those in Figure 5, can be consulted in EC5. Expansive kits, which are a special kind of reinforcement, also generate the rope effect through the friction stresses and forces that they provoke. This study describes how the relationship between these friction stresses and the rope effect force is determined using a specifically designed FE model and checking the matching of the magnitudes obtained from these equations.

**EXPERIMENTAL TESTS**

To check the correct design of the FE model and its results, a battery of experimental tests was made with the same geometries, constraints, materials and loads proposed in the model. The tests were made following the indications of the European standard EN26891 (CEN, 1991). The first step of this procedure consists in estimating the maximum load $F_{est}$ for the class timber and dimensions of each joint to be tested. The loading speed must be calculated, so the final load is achieved in about six minutes. The moisture and density of the specimens are checked before and after the tests. The testing machine used was a Codein MCO-30 which can apply loads of up to 30 ton. This machine can perform tests at constant displacement speed, it uses an electro-mechanic transmission system and includes digital measure equipment to record load vs displacement diagrams. The testing machine must be calibrated so the device measures the displacements with an accuracy of ±1%. Special gadgets and rigid plates were used to apply the load. The software of the machine does not include the load vs time procedure of the EN26891 test, so it requires manual control. A specimen in the testing machine can be seen in Figure 6.

![Fig. 6 - Specimen in the testing machine.](image)
RESULTS AND DISCUSSIONS

The first step was to check the correct performance of the FE model by comparing its results with those obtained from a battery of experimental tests. Figure 7 shows the load vs displacement curves obtained using both methodologies. The load is applied on the upper surface of the central timber part (Figure 4), and the displacement refers to the centre of such surface. The comparison is shown for two different sizes of dowel diameter: 11 mm and 13 mm. When the expansive kits were used, the initial diameters of the dowel were 10 mm, which grew to 11 mm after the expansion process; and 12 mm, which grew to 13 mm. The other properties remain unchanged: timber class, geometries and constraints. The tests were also performed on more specimens with other diameter values, but these two cases can be taken as a good representation of all of them.

Because of the great variability of timber properties, the test was repeated with three specimens for each set of specifications. The experimental results shown in Figure 7 are the mean of the values from these repetitions. With regard to the FE results, three different cases are shown: dowel without expansive kit and neglecting friction (named NEK_FC0 in Figure 7), dowel without expansive kit and taking friction into account (NEK_FC3) and, finally, dowel with expansive kit and friction (EK_FC3). The coefficient of friction used was 0.3, a value obtained from the bibliography (Gorst, 2003; Sjödin, 2008). As expected, friction increases the value of the load required to achieve a given displacement, shifting the curve upwards, as shown in Figure 7. That is, the friction increases the load capacity of the joint. The curve corresponding to the use of the expansion kit is located above the latter, so it is concluded that its use further increases the load capacity.

The scale of the displacement axis reaches 15 mm, which corresponds to the maximum displacement considered in standard EN26891. EC5 uses a stricter criterion, considering the load capacity $F_{v,Rk}$, which is calculated as indicated in previous sections. For the specific dimensions and materials studied in these two cases, this load equals to $F_{v,Rk}=7115$ N for the 11 mm dowel and to 9502 N for the 13 mm one. These load values correspond to vertical displacements of the upper surface of the central timber part around 0.6 mm and 0.65 mm, respectively, both of them far below the 15 mm of the EN26891 criterion, which does not take into account the dimensions of joint elements or the timber class.
The increase in load capacity is due to the rope effect, which increases with the frictional forces between the timber hole and the external dowel surfaces. In EC5, this effect takes value $F_{ax,Rk}/4$, which appears in the equations for failure modes (c) and (d). These two kinds of failure present plastic crushing in the timber and also plastic hinges in the dowel. The expansive kits increase the contact shear stresses and therefore the rope effect. Figure 8 shows the contact shear stresses for $F_{v,Rk}$ in the expansive kit case.

![Fig. 8 - Contact shear stresses for $F_{v,Rk}$](image)

The commercial FE program ABAQUS provides different variables to study contact stresses and displacements (Abaqus, 2013). It uses the variable CPRESS to indicate normal pressures between the surface of the hole in the timber, considered as the slave surface, and the dowel surface, selected as the master surface. The variable COPEN is used to indicate whether there is separation between these two surfaces and, if so, its magnitude. The variables CSLIP1 and CSLIP2 control relative displacement between both surfaces. And finally, CSHEAR1 and CSHEAR2 are the contact shear stresses. Numbers 1 and 2 refer to any two mutually perpendicular directions on the tangent plane at each point. In this specific model, direction 1 coincides with the circumferential direction of the hole surface, while direction 2 coincides with its longitudinal direction. Because the rope effect involves forces working in the longitudinal direction of the dowel, Figure 8 shows CSHEAR2, which corresponds to the stresses acting in that direction.

To study the forces due to these stresses, the three sets of nodes indicated in Figure 9 were created in the model. Figure 9(b) shows the set of nodes used to calculate the tangential contact force due to CSHEAR2 acting on the central timber part, whereas Figure 9(d) shows the set corresponding to the lateral timber part. The tangential contact force that the shear stresses provoke on one part does not compensate the force on the other because of the fact that the block at the bottom of the model transmits part of the force acting in this direction. A third node set was prepared in the section of the dowel by the plane separating the two timber pieces, in order to calculate the axial force on this section of the dowel from normal stresses $S_{22}$. This set can be observed in Figure 9(c), and its aim was to help to determine the relationship between the tangential contact force and the axial force.
According to equations (1) to (3) from EC5, the above mentioned stresses depend on several variables: dowel diameter, timber class through its density and friction coefficient. The FE model has been used to study the effect of these variables, contrasting the results with those from the EC5 equations. From the reference case described in the previous sections (GL24h glulam timber class, dowel diameter of 10 mm expanded to 11 mm and friction coefficient of 0.3), a battery of parametric studies was conducted, varying the magnitude of one of these variables in each case:

1. Dowel diameters of 8, 10, 12 and 14 mm, which grew to 9, 11, 13 and 15 mm respectively after expansion, were considered. According to EC5, load capacities $F_{v,Rk}$ for each of these four diameters would be 5013, 7115, 9502 and 12152 N respectively.

2. The second variable studied was friction coefficient, using 0.0, 0.2, 0.3, 0.4 and 0.6. The first value corresponds to a frictionless situation, which cannot exist in reality but is interesting to introduce as a reference to observe the effect of friction when considering the other non-zero values. The friction coefficient does not appear in the EC5 equations and therefore does not modify $F_{v,Rk}$.
3. Finally, the influence of timber class was studied, considering glulam GL24h, GL28h, GL32h and GL36h with densities of 380, 410, 430 and 450 kg/m$^3$ respectively. The EC5 equations yielded load capacities $F_{v, Rk}$ of 7115, 7390, 7568 and 7742 N respectively.

The results of all these parametric studies are shown in Figure 10, varying one of the variables considered in each case: diameter (Figure 10(a)), friction coefficient (Figure 10(b)) and timber class (Figure 10(c)). The variation of the axial force on the dowel calculated according to EC5 equations (1) to (3) is shown under code $Fax, Rk/4_EC5$. The other curves come from the execution of the FE model, the cases being labelled under EK or NEK, which stand for with and without expansive kit respectively. They show the variation of the tangential contact forces due to CSHEAR2 stresses acting on the central and lateral timber parts (labelled $tg\_Ctrl$ and $tg\_Ltrl$ respectively), and the axial forces on the dowel due to S22 normal stresses (code $ax\_Dwl$).

The results indicate that the use of the expansive kit improves the rope effect in all the cases. Moreover, they show that the axial force never reaches the $F_{ax, Rk/4}$ values proposed by the EC5 equations. As mentioned above, these equations are intended for other kinds of reinforcement mechanisms, such as adhesives or washers and nuts, with much more effective transmission mechanisms leading to higher levels of rope effect.

The results also show that in all the combinations of the studied variables the tangential contact forces caused by the friction shear stresses are always higher on the lateral timber part than on the central part. In the case without expansive kit, the tangential contact force on the central part is almost zero, whereas the use of the expansive kit increases it slightly. Nonetheless, in both cases it is well below the level of the tangential force that appears on the lateral timber part, where the use of the expansive kit seems to have no effect on such force.

A comparison of the graphics of the three parametric studies as presented in Figure 10 shows that dowel diameter is the highest impact factor, while the different friction coefficients and timber classes have none or little effect. Since the diameter is directly related to the amount of surface which transmits the shear contact stresses provoked by friction, its effect on the tangential forces is to be expected. From equations (1) to (3) of EC5 it follows that the relationship between the rope effect force and the diameter $d$ goes as $d^{0.8}$, which corresponds to curve $Fax, Rk/4\_EC5$ in Figure 10(a). Curve EK,$ax\_Dwl$, also in Figure 10(a) and obtained from the FE model, follows the same trend and has a similar slope from 11 mm diameter upwards.
The friction coefficient is not considered in EC5 because, as mentioned above, the equations of this standard are intended for reinforcements that do not work with friction forces. Therefore, curve Fax,Rk/4_EC5 in Figure 10(b) is horizontal. With regard to the results obtained from the FE model, it can be observed that the curve of axial force with expansive kit EK_ax_Dwl in Figure 10(b) does not depend on the friction coefficient and that the other curves only vary when the coefficient changes from 0.0 to 0.2. The frictionless case, as mentioned above, is an unreal situation included as a reference to see the effect of the friction. Since the friction coefficient is actually greater than 0.2, it can be concluded that axial and tangential forces hardly depend on it.

Finally, the influence of timber class on the rope effect is studied, both using EC5, and the finite element model. On the one hand, the EC5 equations depend on it through the value of density, which is different for each class. The biggest difference between the densities of the four glulam classes studied is 18%, from 380 kg/m$^3$ of GL24h to 450 kg/m$^3$ of GL36h. As this variable appears to the power of 1.5 in the EC5 equation (3), it would mean a 29% increase in the load-carrying capacity. On the other hand, curve EK_ax_Dwl in Figure 10(c), which comes from the finite element model, indicates a more moderate increment of barely beyond 6% in the axial forces on the dowel.

CONCLUSIONS

This study shows how the use of expansive systems in dowel-type joints, thanks to the increase of the contact shear stresses that they generate, slightly improves the load-displacement response of the joint through the rope effect. The improvement achieved is well below that obtained using other kinds of reinforcements, such as adhesive to glue the dowel in its hole or washers and nuts situated at the ends. Nevertheless, it is another alternative which could be useful to avoid the difficulties that arise in procedures involving adhesives, or the aesthetic disadvantages of washers and nuts.

Among the variables which EC5 considers that can affect the value of the rope effect, only dowel diameter seems to have a major effect. Neither the timber class, nor the friction coefficient seems to significantly modify the tangential forces or the dowel axial forces. The use of stronger timber classes does increase these forces, but well below the values calculated using the EC5 equations. Meanwhile, the different friction coefficients show almost no impact on the rope effect forces. This parameter is not considered in the EC5 equations, since these are intended for reinforcements such as adhesive or washers and nuts at the ends of the dowels, methods that do not use friction to generate the rope effect.

To perform this study, a very complex FE model was prepared. It includes contact between the surfaces of the different elements of the joint, expansion procedures to simulate the effect of the expansive kit and a Fortran subroutine expressly developed to simulate the anisotropic mechanical behaviour of the timber. None of the orthotropic elastoplastic mechanical models included in the library of materials of the commercial FE programs takes into account the different response of timber under tension and under compression. For this reason, it was paramount to prepare a tailor-made material model to obtain correct and accurate results. The adequate performance of such model was checked through a battery of experimental tests.
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