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Mechanical model to approximate the behaviour of dowel-type joints with expansive kits in timber structures

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ABSTRACT

This work presents some advanced 3D mechanical models, developed using the finite element method, for dowel-type joints with and without expansive kits used in timber structures. Some key points in the design of the models are the correct calculation of the design load working on the joint, the approximation of the mechanical behaviour of the different materials which constitute these joints, the accurate description of the contact zone between timber and dowel and finally the mechanism proposed to model the effect of the expansive kit using the tools available in the commercial finite element program used. The results obtained from the models have shown a good agreement with a battery of empirical tests carried out to complete the work, and the comparisons between the results of the models with and without expansive kits show very interesting outcomes.

Keywords: structures, timber, FEM, dowel-joints, expansive-kits

1. INTRODUCTION

In the last decades, in countries like Spain, the use of timber structures has grown due to the environmental and aesthetic advantages of this structural material compared with other materials such as concrete or steel. Just like in any other kind of structures, in timber structures, joints are one of the key points in their designs. The most widely used types of joints are those using dowels and nails, and they can have different shapes and configurations. All of them have in common that the loads are transmitted between the different timber parts through shear stresses in the dowels. Furthermore, they are also subject to moments and compressive stresses. Figure 1 shows some real cases of this type of joints.

Eurocode 5 [1] is the European Standard which provides technicians and builders with the procedures and methodologies to design and calculate timber structures. From this European technical rule come the standards which are used in the different European Countries. The Spanish version of this standard is known as CTE DB-SE-M [2], and is included in a set of structural and construction regulations called Technical Building Code. The section 8.3 of the Spanish standard includes the procedures for a safe design of dowel-type joints. These procedures are based on the mechanical

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models suggested in 1950 by Johansen [3]. Figure 2 shows the four possible failure mechanisms proposed by Johansen for double shear joints. The Standard covers other possibilities, for example, when the joints work under single shear, or when there are materials other than timber.

Figure 1. Examples of some real dowel-type joints

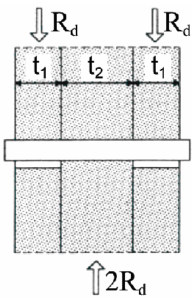
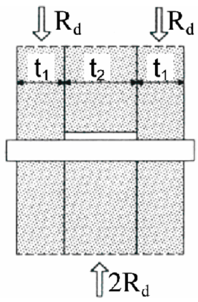
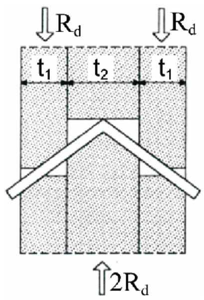
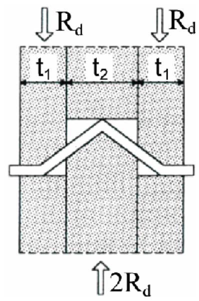
Type a. Failure in the external wood.	Type b. Failure in the internal wood.	Type c. Failure in wood plus 1 plastic hinge in the dowel.	Type d. Failure in wood plus 3 plastic hinges in the dowel.
$R_{d.a} = f_{h,1,d} t_1 d$	$R_{d.b} = 0.5 f_{h,1,d} t_2 d \beta$	$R_{d.c} = \frac{f_{h,1,d} t_1 d}{2+\beta}\left\{\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y,d}}{f_{h,1,d} d t_1^2}}-\beta\right\}$	$R_{d.d} = \sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,d} f_{h,1,d} d}$
			

Figure 2. Failure modes of dowel-type fasteners in double shear

The variables in the equations of Figure 2 are:

- R_d .... Design load-carrying capacity per shear plane and per fastener. Because in this case there are two shear planes, the total capacity will be $2R_d$.
- t_i .... Timber board thickness or penetration depth of each member
- d .... Fastener diameter
- $f_{h,i,d}$ .... Design embedment strength in timber member i
- $\beta = f_{h,2,d} / f_{h,1,d}$ ... Ratio between the embedment strength of the members
- $M_{y,d}$ .... Design fastener yield moment

The so-called expansive kits are widely used in structural materials just like steel and concrete. It allows introducing stresses in the joint which modify its mechanical behaviour [4]. The aim of this work was to determine the advantages and disadvantages of using this technique on dowel-type joints in timber structures. To achieve this goal a mechanical model of the system has been developed and implemented in the commercial finite element program Abaqus. This mechanical model is especially complex due to the presence of nonlinearities associated with the contact between dowel and timber parts, and with the occurrence of elastoplastic behaviour in particular areas of both materials (steel and timber) [5]. These problems, difficult to overcome by themselves, become more complicated because of the particularly complex constitution of timber and its related mechanical behaviour: it is an anisotropic material with different stress-deformation relationships in the different directions. More specifically, the values of the properties in the (longitudinal) fibre direction differ significantly from their values in the transversal plane to the fibre. In this transversal plane these variations are much smaller. Taking into account all these circumstances, timber is consider as a transversely isotropic material. This complex mechanical behaviour required a correct design of the model that has been carefully implemented in Abaqus. The results obtained have been compared with others reached through some empirical tests.

2. MODEL

The development of a mechanical model capable of approximating the actual behaviour of this type of joint is a very complicated process which can be divided in several steps. The first step is to determine the loads which will work on the joint. Secondly, a geometric model must be defined, which must represent, as closely as possible, the real case with its dimensions and boundary conditions. Then, the mechanical behaviour of the different materials which compose the joint must be proposed. In this case there are three different materials: timber, steel in the dowel, and the material of the expansive kit. After that, a very important point is the accurate definition of the contact zone. Finally, it is necessary to correctly approximate the effect of the expansive kit. The following sections expose one by one how each of these steps have been developed in the proposed model.

2.1. Loads

Figure 3 shows a model of the joint. The load coming from the structure through the beam is transmitted to the pillar thanks to the dowel. The whole joint system must be reduced and simplified around this position.

The proposed model is loaded with a vertical force whose value, $2.R_d$, is the smallest of the values obtained with the Johansen equations shown in Figure 2 for the four possible failure modes. These equations involve different variables: design embedment strengths, embedment strengths ratio, thickness of the timber elements, design yield moment and diameter of the dowel. Figure 4 shows the variation of the design load-carrying capacity R_d with respect to the diameter of the dowel for the four possible failures modes.

2.2. Finite element model

There are different possibilities to model the dowel-type joints. One option is to propose a model very close to that suggested by Johansen. In this model the actual 3D joint is simplified to a plane 2D model whose thickness is equal to the diameter of the dowel. The advantages of this model are two. First, the 2D approximation allows studying the case with 2D finite elements which imply less computing power. The second advantage is that this model follows the Johansen approximation, and therefore it gives results closer to those obtained by applying the analytical equations proposed by this scholar. On the other hand, its disadvantage is that it replaces the real 3D system by other which is 2D, which implies differences in material distribution and geometries. This means a different stress redistribution respect to the 3D real case. Figure 5 shows the 2D model that was used during the early stages of the study.

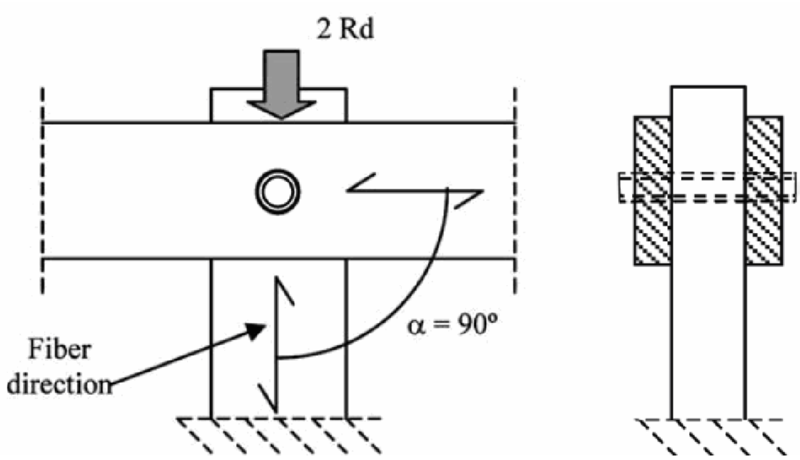


Figure 3. Simplified model of the joint with the design load

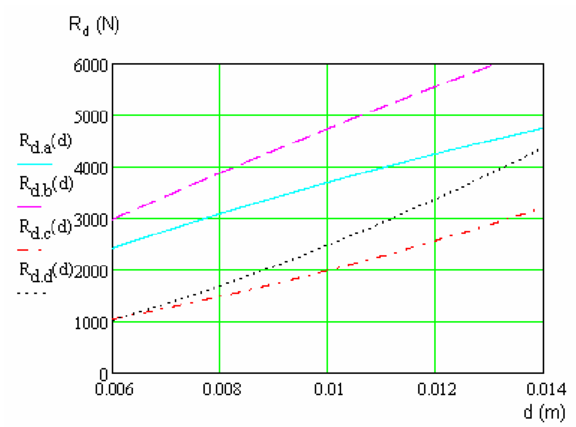


Figure 4. R_d values vs. dowel diameter for the four possible failure mechanisms

In order to improve the results and get closer to the real 3D case, the latest versions of the model were also 3D. They imply the drawback of employing a much larger number of elements, which requires the use of more powerful computers and longer time to perform the calculus. Therefore, because of the complexity of these models, it is necessary to employ methodologies that reduce the number of mathematical operations. Because the case studied was the joint in double shear, it was possible to apply double symmetry conditions, which reduce the model to its quarter, thereby reducing the number of finite element needed. Figure 6 shows the lines representing the whole model, and in solid colour the quarter obtained by applying the symmetry conditions. A second possibility to reduce the number of elements is to use a general coarse mesh but applying a fine mesh to particularly interesting areas. In this case, the most interesting areas are those of the timber and dowel close to the contact zone between them. The way in which this option was implemented will be specified later, when the implementation of the contact zone is discussed in detail.

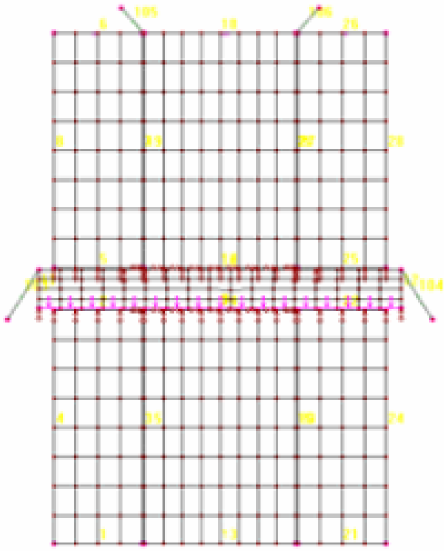


Figure 5. 2D model used in the early stages of the study

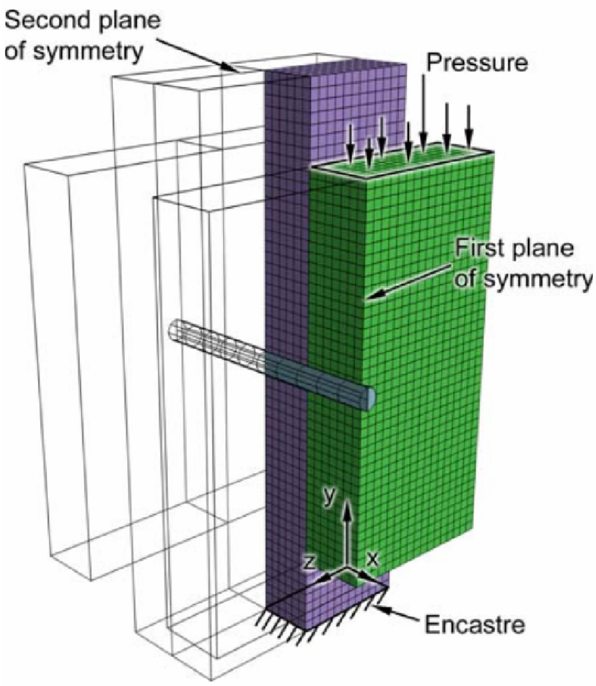


Figura 6. 3D advanced model with double symmetry boundary constraints

The type of element used to build the model was C3D8R. This kind of element was used for all the parts of the joint: wood, dowel and expansive kit. This is a continuum solid 3D element with eight nodes and reduced integration. More specific characteristics of this type of element can be found in the Abaqus user's manual [6].

2.3. Material approximations

The wood strength class selected was C18, as defined in UNE EN 338 [7]. This corresponds to a softwood timber whose strength values and other mechanical characteristics are shown in Table1.

Table 1. Strength properties (N/mm^2), elastic modulus (N/mm^2) and density (kg/m^3) of class C18

Bending strength	$f_{m,k}$	18
Tensile strength parallel to grain	$f_{t,0,k}$	11
Tensile strength perpendicular to grain	$f_{t,90,k}$	0.5
Compressive strength parallel to grain	$f_{c,0,k}$	18
Compressive strength perpendicular to grain	$f_{c,90,k}$	2.2
Shear strength parallel to grain	$f_{v,k}$	2.0
Modulus of Elasticity		
parallel to grain	$E_{0,mean,average}$	9000
	$E_{0,k}$	6000
perpendicular to grain	$E_{90,mean,average}$	300
Transversal elasticity module	$G_{mean,average}$	560
Density	ρ_k	320

Table 1 shows the relatively low strength of the timber in tension perpendicular to grain compared with tension parallel to grain. The difference is also significant between bending and axial strengths, and it does not exist in other common structural materials like steel. Following the Eurocode 5 [1], from the characteristic strengths shown in Table1, it is possible to obtain the design strengths by the equation:

$$X_d = k_{\text{mod}} \frac{X_k}{\gamma_M} \quad (1)$$

where X_k is the characteristic strength and γ_m is the material partial safety factor for limit states design. In fundamental combinations, γ_m equals 1.3. K_{mod} is the modification factor, which takes into account the effect of moisture and load duration on strength. In this study it was assumed that the service class was 1 or 2, and the loads were a combination of a permanent one and another with medium duration. With both hypotheses, we have a medium term load case, so that the K_{mod} coefficient is 0.8. With the above assumptions, the design strengths were calculated. Other important parameter for calculating a dowelled connection is the characteristic density ρ_k indicated in kg/m^3. From this parameter, using the EC-5 European Standard [1], it is possible to obtain the characteristic embedment strength value using the following equations:

$$f_{h,0,k} = 0.082\ (1 - 0.01\ d)\ \rho_k \text{ in N/mm}^2 \quad (2)$$

$$f_{h,\alpha,k} = \frac{f_{h,0,k}}{k_{90} \sin^2 \alpha + \cos^2 \alpha} \quad (3)$$

where α is the angle between the force direction and the grain for each part of the connection. For softwoods,

$$k_{90} = 1.35 + 0.015\ d \tag{4}$$

Considering a dowel diameter d = 10mm, k_{90} = 1.5 is obtained and the characteristic embedment strengths at 0º and 90º are 23.6 and 15.7 N/mm^2. As a result, using equation 1, the corresponding design embedment strengths are 14.5 and 9.7 N/mm^2.

The second material in the joint is the steel that constitutes the dowel. From its characteristic tensile strength $f_{u,k}$ in N/mm^2 it is possible to obtain the characteristic value of the yield moment. For cylindrical steel dowels, following the European standard, the next equation must be used:

$$M_{y,k} = 0.3 f_{u,k} d^{2.6} \tag{5}$$

From it, the design yield moment can be obtained by

$$M_{y,d} = \frac{M_{y,k}}{\gamma_M} \tag{6}$$

being γ_M the material partial safety factor for steel. In the studied case, the steel selected has a characteristic tensile strength $f_{u,k}$ = 240 N/mm^2 and, as usual, 210,000 N/mm^2 of Elastic modulus. For a dowel diameter d = 10mm, the characteristic yield moment results $M_{y,k}$ = 28,664 N·mm and, with a safety factor γ_M=1.1, the corresponding design yield moment is $M_{y,d}$ = 28,058 N·mm.

Isotropic elasto-plastic constitutive behaviour has been used to model the steel dowel, while orthotropic elasto-plastic behaviour has been considered to model the performance of timber in compression [8]. Tensile behaviour of the timber, parallel and perpendicular to the grain, was modelled using orthotropic elasticity [4]. Figure 7 shows the material model representations.

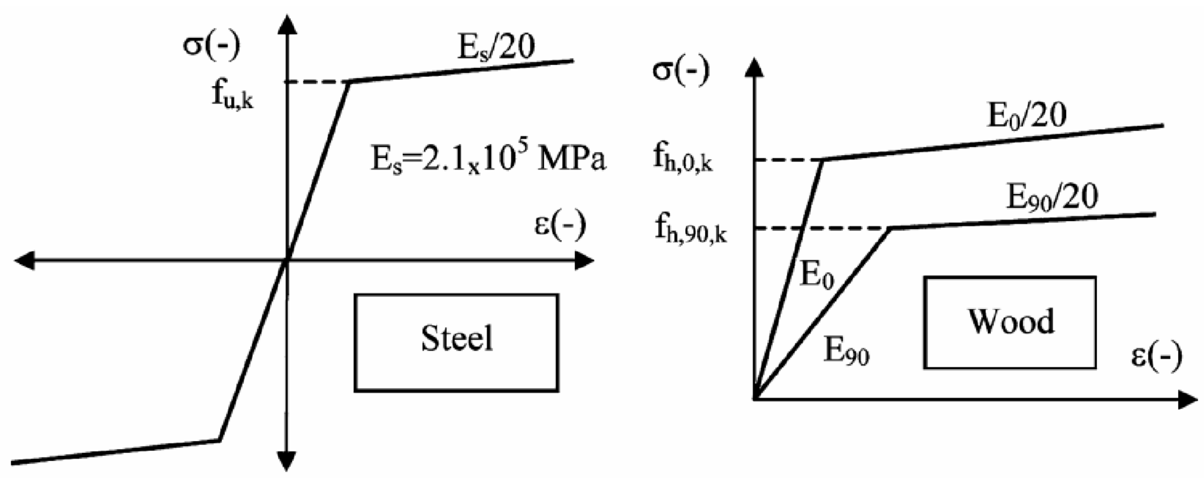


Figure 7. Material approximations used in the model

2.4. Expansive kit model

A suitable modelling of the expansive kit is one of the key points for the success of the whole model. The procedure followed in this case was to design the dowel with a diameter slightly smaller than the real one and also smaller than the diameter of the hole in the timber members. Then, the dowel is carefully placed in its position in the assembly and an expansion process is applied on it. This expansion process is imposed during an auxiliary step previous to the load steps. The expansion is obtained using the same tools that Abaqus has to impose thermal expansions and contractions in any other model. The process implies to apply a predefined field of temperature to the dowel, which has a thermal expansion coefficient previously assigned. The thermal expansion obtained has been calculated to equal the mechanical expansion obtained using the expansive kit. Figure 8 shows the dowel in red, positioned in the assembly, and the yellow squares indicate the presence of a predefined field of thermal increments.

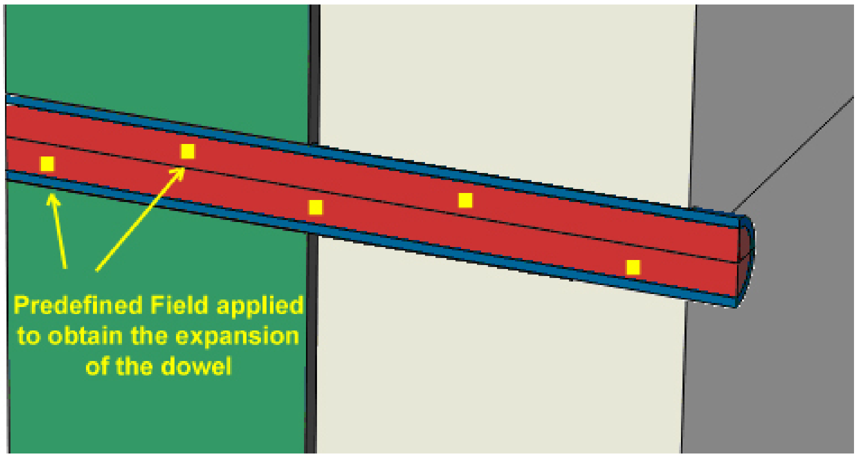


Figure 8. Predefined field applied on the dowel to simulate the mechanical expansive effect

After the thermal expansion, the diameter of the dowel plus the kit does not reach the dimension that it would have under a free expansion, because the expansion is constrained by the timber material which surrounds it. Equilibrium must be reached between the expansion of the dowel plus the kit and the contraction of the timber which contacts with it. This situation provokes the appearance of compressive stresses in all the parts in contact. The level of these stresses will be a function of the interference (difference between the diameter that the expanded dowel plus the expansive kit would have if they could expand freely and the initial diameter of the empty hole in the timber members). These compressive stresses are precisely the key point to study in these new advanced dowel joint designs, trying to determine their positive and negative effects.

2.5. Contact zone design

Finally, Figure 9 shows the area of contact between the expansive kit and the wood. This contact area will transmit the forces coming through the dowel from one timber member to another. The dowel works under shear stresses in the border area between the two timber elements.

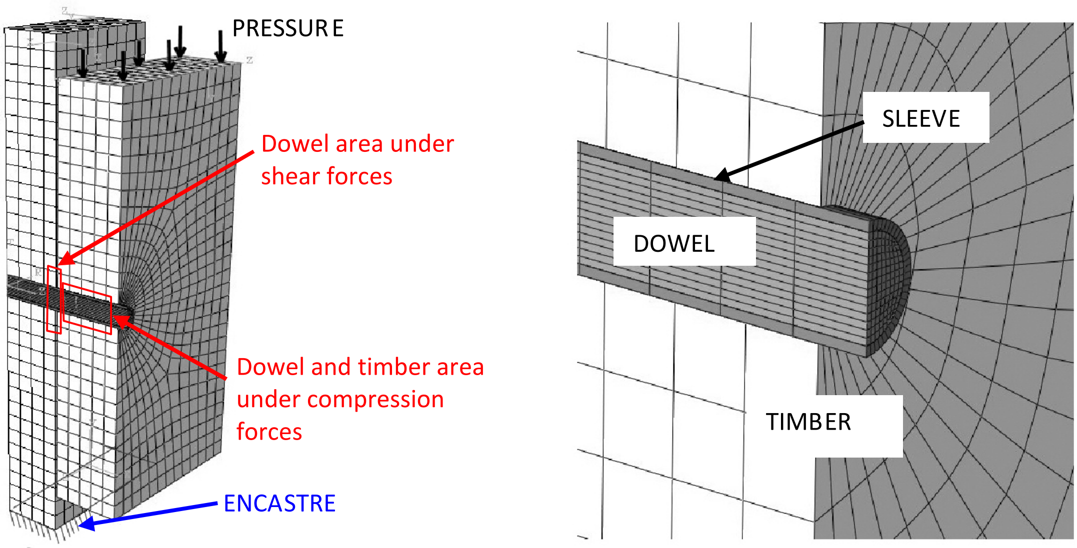


Figure 9. Contact zone design

A correct design of the contact area is paramount to obtain a model that adequately describes the mechanical behaviour of the joint. Also the mesh around this zone should be optimized, trying to make it as dense as possible, but without excessively increasing the time to calculate the whole model. It must be remembered that owing to the presence of nonlinearities in the problem (because of the elastoplastic mechanical behaviour of the materials and the presence of the contact zone) it is required that the model must be recalculated several times in an incremental procedure. This means that the model must be kept as simple as possible, in order to avoid long time calculations. For this purpose, different meshes were investigated using the Abaqus partition tool, which allows dividing the whole model into sections to be meshed with different criteria and sizes. Not all the parts of the model require the same level of accuracy in their calculations. For example, the contact area between the wood and the expansive kit, is the most sensitive and interesting zone. In this area the mesh should be as fine as possible. Meanwhile, in other zones, far from the contact area, the number of elements per volume can be significantly reduced without affecting the accuracy of the results. Figure 9 shows how the different parts of the model have different meshes following these criteria and using the Abaqus meshing tools [6].

3. RESULTS

It is not the main purpose of this article to describe in detail the results obtained from the application of this mechanical model, but to explain how it was made and how it has been applied to this structural case. If the reader wants to see these results in detail, their comparison with the experimental tests performed or how much they match the Johansen equations, he can consult previous works of the authors [9, 10]. Anyway, to complete this paper, a brief summary of some results and comparisons are going to be shown, so that the accuracy and good agreement of the model can be checked. First, in Figure 10, it can be seen some of the stress results comparing the model without and with expansive kit.

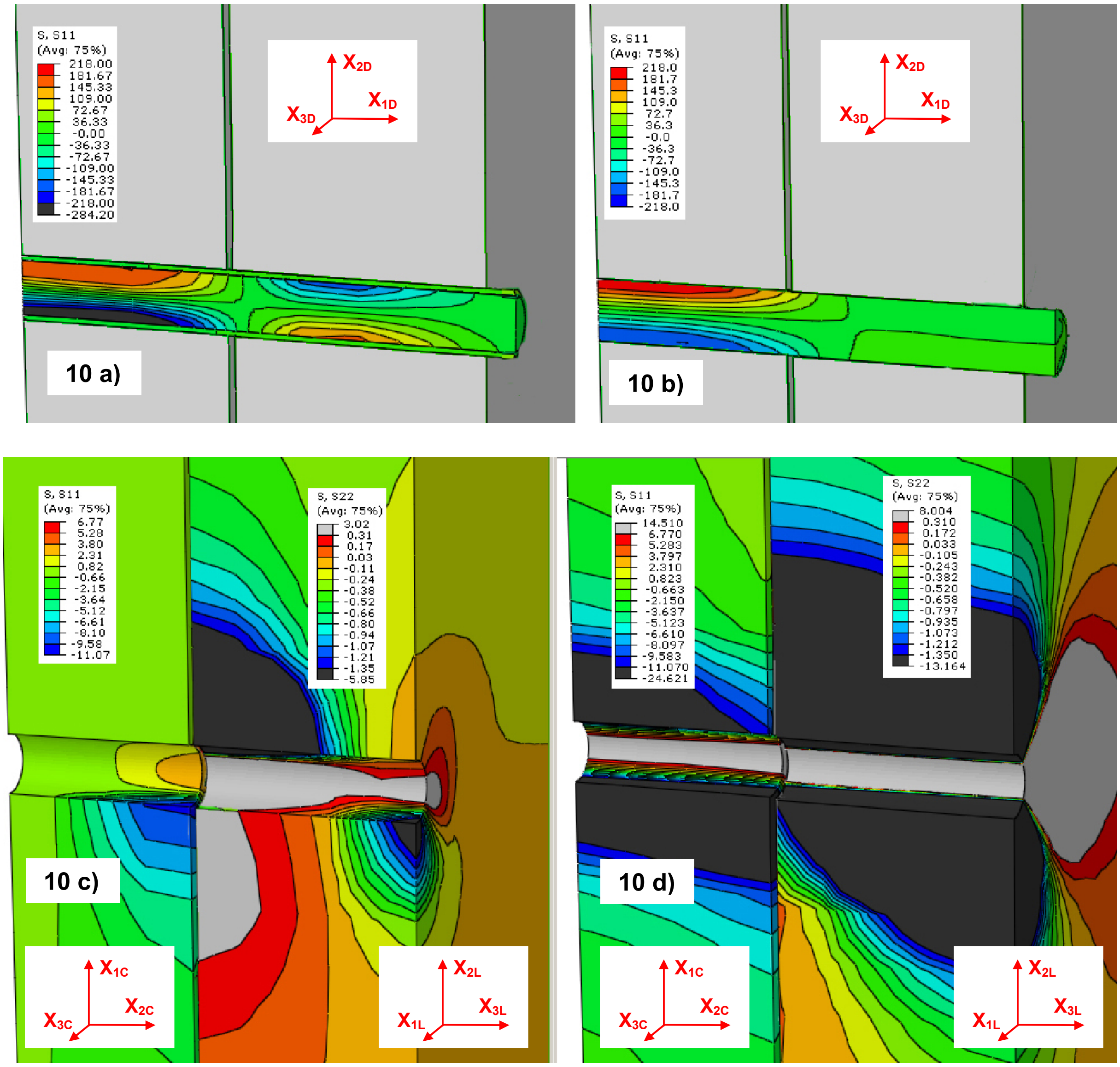


Figure 10. Abaqus results using or not the expansive kit

Figure 10 a) shows the stresses in the steel dowel in its longitudinal direction without using the expansive kit. The stress distribution and magnitudes match the Navier bending law. Comparing with the design strength of the steel, it can be seen that, in the most external fibres of the dowel, they are very close to the yield point. Figure 10 b) presents the same stresses for the case with expansive kit, allowing appreciate a clear variation in the stresses between the two cases.

Regarding the timber, Figures 10 c) and d) display the same comparison of the stresses in the direction of the transmitted force R_d, in both timber elements, between the models with and without expansive kits. The stresses of Figure 10 c) correspond to these considered in the Johansen equations approach (Figure 2).

As it can be seen in the Figure 3, the directions of the timber fibre in the beam and the pillar are rotated 90º relative to each other. Consequently, the direction of the fibre are different in both parts, and two different coordinate systems must be used, one in each timber member. In figures 10 c) and d) the symbols X_{1C} and X_{2C} respectively indicate the axes 1 and 2 of the central timber part, and similarly X_{1L} and X_{2L} for the lateral part. Number 1 denotes the direction of the fibre in each timber part. A third coordinate system is used for the dowel, which is represented by the subscript "D" in figures 10 a) and b).

In the central timber part, the direction of the transmitted load coincides with the direction of the grain. Because of this, the scale shown on the left side of Figures 10 c) and d) has its maximum and minimum limits in relation to the strengths in direction parallel to the grain of the timber class used. These limits are $f_{t,0,d}$ = 6.77 N/mm^2 for tensile stresses and $f_{c,0,d}$ = 11.07 N/mm^2 for compressive stresses. Meanwhile, in the lateral timber element other range is used, because in this part the stresses provoked by the transmission of the load work in direction perpendicular to the grain. Therefore, the scale limits are the strengths perpendicular to the grain: $f_{t,90,d}$ = 0.31 N/mm^2 under tensions and $f_{c,90,d}$ = 1.35 N/mm^2 under compressions. Again, the difference between the stresses with and without expansive kit is remarkable. More detail explanations about these differences can be found in previous works of the authors [9].

The results obtained with the Abaqus mechanical model were also compared with a battery of experimental tests specifically performed to reproduce this type of joints. The tests were carried out following the European standard EN 26891 [11], which specifies the procedure to be follow in this type of tests and the parameters that must be considered, just like the variation of the load vs. time and the load vs. displacement. The load must be a percentage of the maximum value that is supposed the joint resists, and therefore must be approximately calculated in advance. Meanwhile, the displacement, which determines the end of the test, is always a constant value of 15mm. Once this value is reached, it is assumed that the maximum value which the joint can resist under safety conditions has been reached. Anyway, during the tests, this displacement value has been exceeded, in order to see if there is some remaining strength capacity in the joint, and also to obtain a more deformed tested joint showing more clearly the failure mechanism that has been taken place among those proposed by Johansen.

As an example of the comparisons performed in previous works of the authors [10], Figure 11 shows the load-displacement curves obtained with and without expansive kits. It can be seen that there is some improvement when using the expansive kit, especially in the early stages of the tests. Also, after reaching the displacement of 15mm, there is almost no remaining strength capacity in the joint. The results of the mechanical model prepared in Abaqus show a good agreement with those obtained from the experimental tests.

This agreement can also be appreciated in the comparison of Figure 12, which shows the similarity between the deformed shapes obtained after the empirical test and those coming from the finite element model. In both representations it can be seen that the failure mechanism reached was the type d from those indicated in Figure 1. This failure mechanism involved the appearance of four plastic hinges in the dowel and yielded areas in the corners of the timber members. The analytical study using the Johansen equations also indicated the same failure mechanism. These verifications confirm that the model development in this work approximately matches the mechanical behaviour observed in the empirical tests.

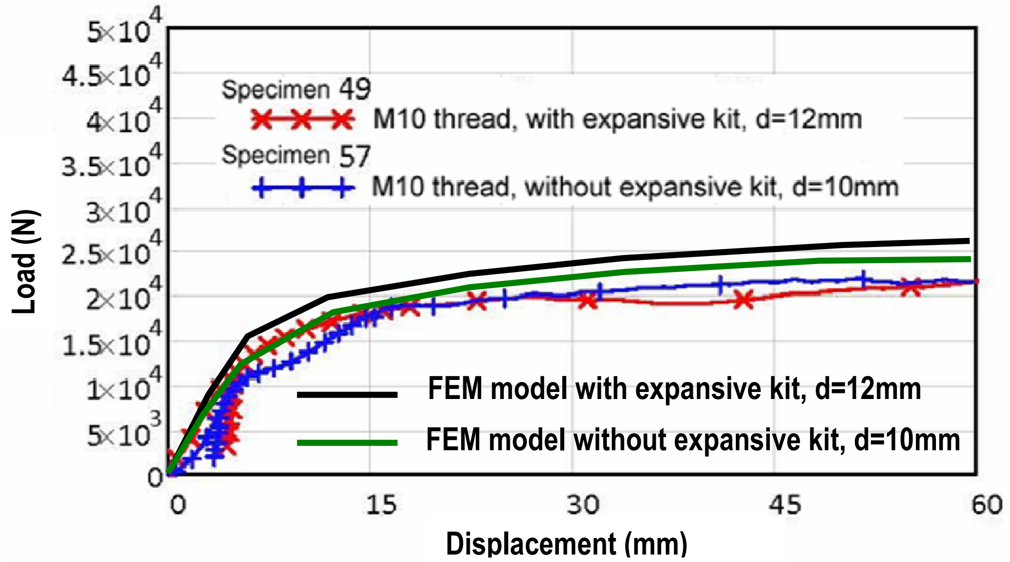


Figure 11. Comparative results when using specimens with and without expansive kit

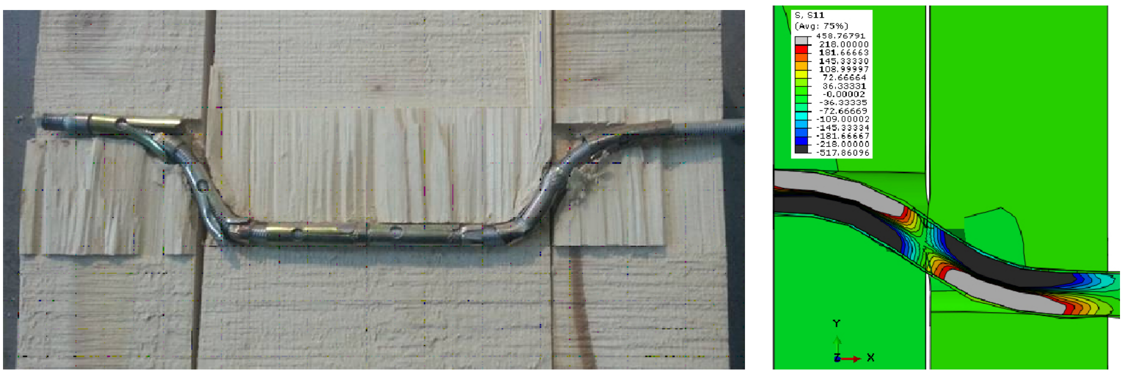


Figure 12. Comparison of results from the experimental test and the Abaqus mechanical model

4. CONCLUSIONS

The procedures used to calculate and design dowel-type joints following the Spanish CTE DB-SE-M and the European Eurocode 5 standards are based on the mechanical models suggested by K.W. Johansen in 1950 [3]. These models, although useful, are very simple and do not take advantage of all the powerful tools that can be used nowadays, just like the finite element method. The present work has used this technique to model the case of dowel–type joints using expansive kits.

To adequately model these complicated joints, several key points must be taken into account. Timber is an anisotropic material with a very complex mechanical behaviour which must be carefully approximated by the material models available in Abaqus. The contact zone involves nonlinearities which can cause difficulties, even abort the calculation process. Especially important is to design a good mesh, which gives very accurate results, but without slowing down the calculation process. Finally, the expansive kit must be simulated using the dilatation techniques available in Abaqus.

The results of the proposed mechanical model, developed and implemented in Abaqus, have shown a good agreement with a battery of empirical tests carried out to complete the work. Once this point has been checked, the results from the models with and without expansive kit could be compared. Discussion from these comparisons of the results can be found in previous publications of the authors [10, 11].

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