EXPERIMENTAL CAMPAIGN AND ANALYSIS ON DOUBLE-SHEAR WOODEN CONNECTIONS

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Abstract: The presence of water in wooden elements is very important because it represents the key in the determination of the resistances of a wooden sample. The influences of the environmental conditions like temperature, relative humidity, wind, rain are constantly changing wood properties. The paper presents the different types of water that are found in a wooden piece together with experimental results on the displacement of double-shear wooden connections with wooden dowels that have been modified in two pre-established environments. The moisture content has been changed from 12% natural moisture of wood in normal building conditions to 8% and 16% for wood that is found in different climatic conditions. The experimental results are then compared with numerical calculations from the international standard Eurocode 5.

Keywords: moisture content, displacement, dowel-type joints, wooden dowels, monotonic tests

1. Introduction

Because wood is a natural element, it has different properties and characterizations that have to be taken into account when it is calculated for being used in structures. Although it is not necessary to know all details of the composition and structure of the freshly cut piece of wood up to the element prepared for use, some parts are important to be taken into account: like wood structure (if it has knots, cracks or torsion of fibres) and moisture content that is based on the amount of water that a wooden piece has. It is well-known that fresh timber has a big amount of water but as the wooden piece is cut, the wood still has water inside it and it can always retain or disperse moisture from and to the surrounding environment. It is considered to be as a sponge that can be influenced by humid or dry climates.

This is the reason why after being cut from the tree, the wooden piece has to be put through a multitude of processes so that it arrives at equilibrium moisture content with the place where the building will be made. Moisture content of the wooden piece is closely linked to the relative humidity and temperature of the surrounding environment. In this case, if the wooden piece is subjected for a certain period of time to an environment in which temperature and humidity are constant, then, the moisture content will also have a constant value. Moreover, following the same process, if the wooden piece is placed freely in open air, the humidity will grow together with the environment. [1]

This process is an important factor in the evolution of wooden materials in time because it can affect their resistance properties and rigidity and it is also taken into consideration in calculating the structures for mechanical resistance and limit states (as it is mentioned in the international standard Eurocode 5). This is the reason why the effects of moisture content and the changes that can be made influenced by it have to be analysed and taken into consideration. [2]

The moisture content can be identified in three forms: bound water or hygroscopic that is found in the wall cells; green water or capillary water that is found in the cavity cells and as water vapours that are found in the cavity cells or in other chambers in the wood structure.

Fig. *Error! No text of specified style in document.* - Representation of the moisture content and the types of water that are found in the wooden piece (source: [3])

The properties of moisture content of a wooden piece used are found in a hygroscopic interval of humidity that is formed before the fibre saturation point that represents the point where there is no more free water in the lumen and the cell wall is saturated with bound water. Water gets into the wood structure and makes the molecules be bound to the cell walls. After the fibre saturation point is achieved (the walls are full with water that can take to the swelling of the wood), the cell cavities receive water (process that does not influence the volume of wood). The wooden piece can arrive at equilibrium moisture content when the transfer of humidity from the inside to the exterior is not achieved anymore and this depends on climatic factors like temperature and relative humidity but also on the defects that appear on wood from natural causes.

The variations that appear in the moisture content of wood can produce cracks because of the constant changes in volume and they can also create a good environment for the development of moulds and insects that influence the resistance capacity of the wooden material. This is why, in the calculation these changes in the structure of wood have to be taken into account.

If the conditions in which the wooden material is kept are characterised by a dry environment, then the moisture content of wood is 0; and if the air humidity is around 100% then the moisture content of wood is 28% (that means that in the cell cavity water is not present anymore and the water from the wall cells has a maximum value). The transport of the moisture content takes place parallel to the fibres and it is a slow process that takes into account the temperature, the moisture content, the density and wood anisotropy. [8]

The research made by Ranta-Maunus (2003) mentions that when the wooden piece is dried in correct conditions, wood resistance does not decrease and its maximum resistance is seen at a moisture content of 10%. The moisture of wood is influenced by the orientation of the rings, by the knots, by the marks left by the steel dowels, by the cracks that can create a non-uniform water movement because of the deformations that appear on the surface of the wooden piece when it is subject to drying or humid conditions. [9]

The study conducted by [12] is also based on the modification of wood by changing the environment conditions, this can make wood stronger or it can damage it permanently because of the decomposition of hemicellulose. When temperatures are higher, wooden components are less stable; however, if the temperature is lower, wooden resistance in compression is growing. The phenomenon is called thermal modification of wood and is used in order to improve its mechanical and chemical composition to make it stronger in different climatic conditions.

Lenth and Kamke (1999) have conducted experiments on a young and mature wood exposed to pre-established conditions in a chamber with a controlled environment. The tests have been relevant for an analysis of the moisture content on wood behaviour. The data for the equilibrium moisture content have resulted from weighing the wooden samples. For them, wood degradation is determined each time the differences appear on wooden samples. When specimens arrive at a

constant mass after they have been submitted to new conditions (95% and 25°C), the climatic chamber is depressurised and the weight of wood is recorded before being put in an oven at 103°C, dried and then weighed again. The results of the study have shown differences between young wood and mature one; an important point in the experiments is the fact that degradation appears with mass loss and that it grows function of the level of humidity. [10]

In the study made by (Pinto, n.d.) it has been shown that the degradation of the wooden material affects its physical properties (its density ρ) and rigidity properties (the elasticity module E and the G). The changes have an evolution in time and in the end they arrive at a mass loss of the wooden piece seen as a reduction of the cross section. All aspects grow the complexity of the realisation of a real numerical model of a structure that will be re-calculated in order to receive a rehabilitation solution. [11]

The current paper presents two experimental programs that are linked together: change of moisture content of wooden elements in a climatic chamber, monotonic tests and double-shear tests on wooden connections. Three essences of wood have been used for the experiments, two for the elements of the connection: chestnut and spruce that are linked together by a wooden dowel of massaranduba. In the climatic chamber the moisture content of the wooden elements is changed from 12% to 8% and 16%. From the double-shear tests for both types of wood and both moisture contents data on the slip-modulus are analysed and compared with the results from the calculations following the international standard.

2. Materials and methods

The experimental campaign has been conducted in the Civil Engineering Laboratory in the University of Minho, Portugal and it is made on two types of wood: Chestnut (*Castanea sativa*) and Spruce (*Picea abies*) for multiple connections made of wooden pieces and linked with wooden dowels of Massaranduba (*Manilkara spp*). The representation of the connection can be seen in the figure below (Fig.2) and it is formed by a central piece that is bigger and two smaller exterior pieces; the dowel has a diameter of 12 mm.

Fig. 2 - Representation of the wooden connection used for the study of double shear tests, together with the dimensions of the pieces and the application of the force

The process is divided in three steps. In the first one, the wooden pieces are put in a climatic chamber in a controlled environment with values of temperature and relative humidity in order to change the moisture content in the wooden pieces from 12% values usually found in structural wood to 8% and 16%. The controlled environmental conditions are $T=20^{\circ}\text{C}$ and $RH=29\%$ for moisture content $m_c=8\%$

and $T=20^{\circ}\text{C}$ and $\text{RH}=80\%$ for moisture content $m_c=16\%$. The values are read from hygroscopic curves of equilibrium of wooden materials found in the national standard [13].

For the determination of the moisture content the wooden piece has to be weighed in order to know its mass, after that it has to be dried in an oven for 48 days until a moisture content of 0% is reached so that the quantity of water from inside it is no longer present and finally a new weighing is made. The formulas used for the determination of the moisture content are taken from the standard (ISO/DIS 13061-1) [4]:

$$m_c = \frac{m_1 - m_2}{m_2} * 100 \quad (1)$$

where:

m_c - the moisture content in %;

m_1 - the initial mass of the wooden piece before being dried in an oven in g;

m_2 - the mass loss of the wooden piece dried in the oven in g.

After the wooden elements have arrived to the moisture content desired, the pieces are assembled and the connections are made, linked with the wooden dowels. Then, the second step of the experimental campaign is conducted following the standard EN 26891:1991 [5]. The connection is installed on a system where it is subjected to a force until the breaking of the dowel or when a displacement of 15 mm is reached. A monotonic test has to be conducted in order to see what the maximum force that the connection can bare is. From this test the value of the estimated force is taken. F_{est} is then used for the next experiments as a value of reference.

Fig. 3 - The steps of the experimental campaign following the standard for the determination of the displacement

The figure above (Fig.3) shows the different steps that are taken in order to make the experimental campaign following the standard. It can be seen that the force in kN referred to time in seconds is the estimated force used in monotonic tests that show the value that is for reference in the double-shear tests. The tests start with a charge until $0,4 F_{est}$, then it rests for 30 seconds, then it descends until $0,1 F_{est}$ with another rest of 30 seconds, followed by a controlled force of $0,7 F_{est}$ and then a free charging until the wooden dowel breaks or a displacement of 15 mm is reached. The steps are presented detailed in the standard.

Fig. 4 - Comparison between the graphics for the monotonic tests made on the connection with moisture content $m_c = 8\%$ and $m_c = 16\%$

It can be seen that the chestnut sample has a maximum value for the moisture content $m_c = 8\%$ but it drops suddenly from 15 kN to 10 kN and then to 7 kN in a short time. For the moisture content $m_c = 16\%$ the values of the force go in a constant matter compared with the displacement. The maximum force of each experiment for the two essences of wood and the two types of moisture content $m_c = 8\%$ and $m_c = 16\%$ are considered as estimated forces and are further on used for the double-shear tests.

The last step follows the same standard but it is made with reference to the estimated force resulted from the monotonic tests. The analysis is made on the displacement of each connection (the wooden piece in the centre is moving and breaking the dowel inside). The curves load-displacement that result from the tests offer a value for the maximum load for which the connections can resist and information on the ductility and the rigidity of the connection.

The values for the force-displacement curves are recorded by 3 LVDT's planted on the wooden pieces that follow the displacement of the central wooden piece and the dowel. They are put on small metal plates glued to the timber pieces from where they record the mechanical slip and send the results to a computer through a program that can read the values of the displacement, the forces and the time in which the experiment is made.

Fig. 5 - The evolution in time for chestnut and spruce for the moisture content of 8% following the standard

The figures show that the maximum force reached for the essence of chestnut for the wooden connections with moisture content $m_c = 8\%$ is relatively higher than the one for spruce in the same conditions. This is because the resistance for chestnut is higher than the one for spruce. And compared with the displacement, between the two types of wood the evolution is the same in time.

Fig. 6 - The evolution in time for chestnut and spruce for the moisture content of 16% following the standard

The figures show that the maximum force reached for the essence of chestnut for the wooden connections with moisture content $m_c = 16\%$ is higher than the one for spruce in the same conditions. This is because the resistance for the chestnut is higher than the one for spruce. And compared with the displacement, between the two types of wood the evolution is the same in time.

3. Analysis of results

The equilibrium moisture content of wood (emc) represents the moisture content at which wooden pieces arrive when there is no more water absorption or desorption in all the cells that are part of the sample. [50]

$$EMC (\%) = \frac{1800}{W} \left[\frac{Kh}{1 - Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2} \right] \quad (2)$$

Where h represents the relative humidity (in decimal state) and the other parameters depend of the temperature measured in °C:

$$\begin{aligned} W &= 349 + 1,29T + 0,0135T^2 \\ K &= 0,805 + 0,000736T - 0,00000273T^2 \\ K_1 &= 6,27 - 0,00938T - 0,000303T^2 \\ K_2 &= 1,91 + 0,0407T - 0,000293T^2 \end{aligned}$$

Table 1

Results of the equilibrium moisture content		
T=20°C	RH=29%	$EMC_{8\%} = 6,029$
T=20°C	RH=80%	$EMC_{16\%} = 16,769$

The table presents the results of the equilibrium moisture content for the values of temperature and relative humidity that are required in the study for a change in the moisture content of wood. And so for a temperature $T=20^\circ\text{C}$ and a relative humidity $RH=29\%$, the value for the equilibrium moisture content results $EMC=6\%$ and the moisture content of the experiments is $m_c=8\%$ and for a temperature $T=20^\circ\text{C}$ and a relative humidity $RH=80\%$, the value for the equilibrium moisture content results almost $EMC=17\%$ and the moisture content of the second experiments is $m_c=16\%$.

In order to analyse the displacement of the wooden piece, the stiffness of the joint can be calculated following the standard used for the realisation of the experiments EN 26891:1991 [5]. Then, the value is compared with the values from the European standard Eurocode 5.

Fig. 7 - Graphic representation of force-displacement that follows the mechanical behaviour of connections with dowels (source: [7])

The graphic shows the pattern that a fastener has when a force is applied on it. It starts in the elastic deformation domain until a brittle failure. This happens in the case of an ideal fastener but also for an optimal fastener. Then the plastic deformation domain is reached until the ultimate load that takes the fastener to a ductile failure that can go up to the moment in which the dowel breaks completely.

$$k_s = \frac{0,4 F_{est}}{4/3(v_{04}-v_{01})} \quad (3)$$

where:

F_{est} - is the estimated force from the monotonic tests

k_s - is the stiffness of the joint in N/mm determined from the analysis of the load-displacement curve until 40% of F_{est}

v_{01} – represents the displacement measured when 10% of the estimated force is applied on the connection

v_{04} - represents the displacement measured when 40% of the estimated force is applied on the connection

The international standard Eurocode 5 calculates the slip modulus k_{ser} of the dowel influenced by the action charge. It is calculated depending on the type of the connection between the elements and for dowels it has the following formula:

$$k_{ser} = \rho_m^{1,5} d/23 \quad (4)$$

where:

ρ_m - represents the average density in kg/m³;

d - represents the diameter of the dowel in m.

There are some design situations when the flexibility of the joint is also influenced by the internal forces of the structure and another slip modulus is used, for the ultimate limit state:

$$K_u = \frac{2}{3} K_{ser} \quad (5)$$

where:

K_{ser} - slip-modulus of serviceability limit state [N/mm]

K_u - slip-modulus for ultimate limit state [N/mm] [7]

Values of the experimental campaign and the results from the calculations for moisture content $mc=8\%$

Wood sample	Fmax [kN]	Fest [kN]	Displ max [mm]	Displ mean [mm]	Ks [N/mm] exp	Kser [N/mm] EC5	Ku [N/mm] exp
Chestnut	13,348	14,5	14,754	5,763	5832,48	5850,718	3900,479
Spruce	10,801	9,5	14,291	5,152	3531,105	4584,813	3056,542

Table 3

Values of the experimental campaign and the results from the calculations for moisture content $mc=16\%$

Wood sample	Fmax [kN]	Fest [kN]	Displ max [mm]	Displ mean [mm]	Ks [N/mm] exp	Kser [N/mm] EC5	Ku [N/mm] exp
Chestnut	13,348	15,0174	12,2	15,445	6,014	6344,002	6503,891
Spruce	10,801	10,6802	11,2	14,046	5,481	3554,318	4932,633

The two tables above present the results of the experimental campaign for the two types of connections of different essences: chestnut and spruce with the two moisture contents considered in the study $mc=8\%$ and $mc=16\%$. It can clearly be seen that for the essence of chestnut the force has a maximum value compared with the one from the spruce essence. This can be the result of the internal composition of the essence, because chestnut is a heavier material with less natural defects (knots, cracks and fibre torsions) than spruce and has a more compact configuration. The same can be said for the displacement that has a higher value for the chestnut connection.

When analysing the stiffness of the joint in N/mm, the connection made with the chestnut sample has higher values than for the spruce one. This can be seen for both moisture contents which show that the essence of the wooden connection with its properties and characterisations are an essential factor in the structural design.

Fig. 8 - Comparisons between the slip modulus following the results from the experimental campaign and the Eurocode 5 standard

From the graphic above it can be seen the difference between the values of the slip modulus after the experiments conducted and after the international standard Eurocode 5. The results depend on the density and the wood species. In this manner, it can be seen that spruce being lighter and with a smaller density in both cases of modified moisture content has the values from the experiments smaller than the ones after EC5 used for the calculations. Regarding chestnut, the values from the experiments and the ones following EC5 are almost the same.

Fig. 9 - The representation of the breaking patterns of the dowels in the connection after the application of the force for a moisture content $m_c=8\%$

The figures above present the different types of dowel breaking of the connection in double-shear for a moisture content of 8%. It can be seen that the dowels completely break after the application of the force and also the mark that the element leaves on the wooden piece.

Fig. 10 - The representation of the breaking patterns of the dowels in the connection after the application of the force for a moisture content $m_c=16\%$

The figures above present the different types of dowel breaking of the connection in double-shear for a moisture content of 16%. It can be seen that the dowels can break completely after the application of the force but as it can be seen in figure a). the dowel can also deform itself but still be unbreakable which means that the connection can still be used until its final failure; also the mark that the element leaves on the wooden piece can be seen.

4. Conclusions

The aim of the study was to investigate the behaviour of double-shear connections with wooden dowels that were subjected to a force until the breaking of the dowel. The wooden elements have been subjected to changes in their internal configuration because they have been introduced in controlled environments (with certain values of temperature and relative humidity) where the presence of moisture has changed the moisture content of the pieces. This can also have an influence on the mechanical resistance of the connection depending on the wood essence.

In this current study, the displacement of the connection has been analysed in order to see the slip capacity of the dowel in the double-shear connection before the breaking of the dowel. The slip modulus resulted from the experiment has been further on compared with numerical calculations from the Eurocode 5 standard, the results are similar and they can suggest that a good concordance between the two: experiments and calculation is made.

Also, from the results it can be seen that the essence of the wooden material is important in the resistance of the connection and that the moisture content influences the behaviour of wood: chestnut is more resistant for a moisture content $m_c=16\%$ compared to $m_c=8\%$ whereas spruce is more resistant for a moisture content $m_c=8\%$ compared with $m_c=16\%$ in terms of displacement and force. The results of the experiments are completed with the images showing the breaking of the dowels inside the connection for both moisture contents considered and the marks that are left on the lateral pieces of wood.

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