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INVESTIGATION OF OSCILLATING CLIMATES FOR WOOD DRYING USING THE FLYING WOOD TEST AND LOADED BEAMS: NEED FOR A NEW MECHANO-SORPTIVE MODEL♣

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ABSTRACT

In this work, the effects of moisture content variations produced by oscillating drying conditions have been studied by means of non-symmetrical drying (flying wood) and loaded drying (3-point bending test). The oscillating conditions are intended to produce a mechano-sorptive creep that is able to reduce drying stresses. However, our experimental data seem to prove that the activation of the mechano-sorptive creep by oscillations of the moisture content is very limited. Besides, the simulations showed that noisy conditions due to the kiln regulation already activate the mechano-sorptive creep, even for non-oscillating conditions, and could confuse the results. Contrary to the experimental observations, the implementation of classical mechano-sorptive models in the drying simulation model is far too optimistic, which means that these models are not suitable when the material is submitted to numerous oscillations.

Keywords: Drying stress, beech, oscillating conditions, mechano-sorptive model, flying wood.

INTRODUCTION

Drying is an essential process in the wood industry. During drying, the stress that develops in the boards can produce several defaults such as deformations and checks. In order to reduce the stress level, the activation of viscoelastic creep by suitable drying conditions (elevated temperature together with elevated EMC) is the strategy adopted for the drying at high temperature of softwoods and has been developed successfully with tropical hardwoods (Aguiar and Perré 2000a). However, this strategy fails with species prone to thermal degradation (collapse, discolouration, etc.).

The use of oscillating drying conditions appears to be an alternative solution to reduce the stress level at low temperature levels, through the activation of the mechano-sorptive creep. Indeed, during oscillating drying, the continuous change in moisture content (MC) at the peripheral zones of the boards under stress should activate the mechano-sorptive creep. However, the best way to apply this concept remains an open question in the scientific community (Terziev *et al.* 2002, Salin 2003, Sackey *et al.* 2004, Milić and Kolin 2008, Herritsch *et al.* 2008).

Theoretical approaches, including a computational simulation model, are therefore of great interest for selecting oscillation amplitudes and frequencies. Some studies relate the effects of oscillating climates to the evolution of the moisture content field within the board (Salin 2003, De La Cruz-Lefevre *et al.* 2010). Yet, few works investigate the impact of oscillating climate on the drying stresses. In the case of oscillating conditions, the choice of the mechano-sorptive model is of utmost importance. Numerous mathematical models have been proposed over the last decades regarding this behaviour. The proposed models aim to fulfill many requirements listed by Grossman (1976). In spite of this, the determination of the model parameters from experimental results remains a serious

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challenge because of the coupled phenomena and the artifacts of the testing protocol (Muszynski *et al.* 2005). This is probably the reason why the simplest mechano-sortive models, such as those of Ranta Maunus (1975), Salin (1992) or Leicester (1971), are usually embedded in drying codes (Figure 1).

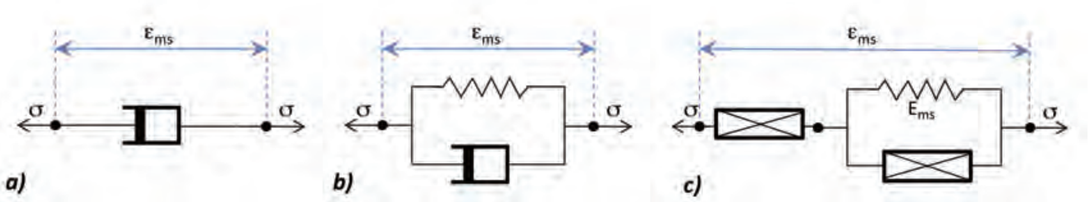

Figure 1. Schematic illustrations of mechano-sorptive model: a) Ranta Maunus (1975), b) Salin (1992), c) Leicester (1971).

This paper proposes two laboratory configurations that were used to investigate the mechanical effects of moisture content variations produced by oscillating conditions: the flying wood test (Brandao and Perré 1996) and the drying of a loaded beam.

The implementation of classical mechano-sorptive models in the computational model *TransPore* is discussed in the last part of this work by comparing the theoretical and measured results.

MATERIALS AND METHODS

The Dryer

The drying chamber used in this study was developed in the laboratory of ENGREF (for more details see Perré *et al.* 2000). It is constructed from a stainless steel cylinder, two meters long and one meter in diameter. The relative humidity is controlled through the temperature of a water film that flows at the bottom of the chamber, and electrical resistances heat the air flow at the top of the chamber. Two centrifugal fans and a water pump provide homogeneous conditions within the chamber. The drying parameters are maintained by a double loop PID controller connected to a personal computer.

The Drying Conditions

The samples are dried with a dry bulb temperature at 60°C and a dew point at 48°C for the conventional schedule or with a dew point oscillating between 51°C and 45°C over a period of 3 hours (1.5 hour of linear increase and 1.5 hour of linear decrease), for the oscillating schedule (Figure 2). Both conditions ensure average equilibrium moisture content close to 8%.

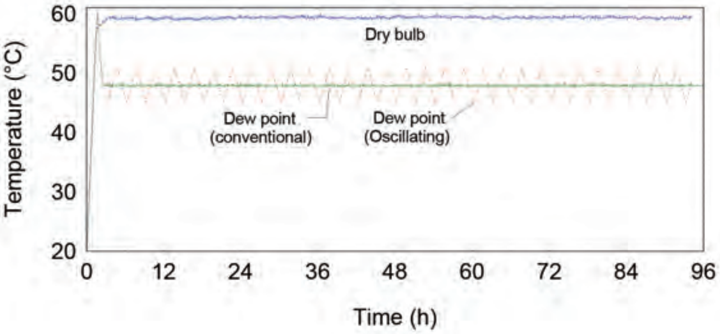

Figure 2. Actual drying conditions obtained in our kiln for the conventional and oscillating tests.

The two sample configurations

In this work, two laboratory configurations were used to assess the drying behaviour of wood regarding the drying kinetics and the stress development: the *flying* wood test and loaded beams.

The *flying wood test* is a dissymmetrical drying of small samples proposed by Brandao and Perré (1996). Five faces of each sample are coated so that the moisture migration occurs in only one direction. This configuration allows one part of the drying stress, which can be assessed only via destructive tests, to be converted into section deformation, which can be measured continuously. The section curvature is measured by an electrical displacement sensor (Figure 3a). The design required different tricks to ensure permanent contact between the sensor head and the sample face without force. This device was developed by Aguiar and Perré (2000b). In order to avoid the effect of temperature on the electrical resistance, the samples' position is determined via a tension divider bridge powered by a DC generator. Additionally, the mass of the samples is measured continuously by a stress gauge glued onto the sample support. In this way, the evolution of the average moisture content can be estimated during the drying test.

Other specimens were loaded using the *3-point bending test* method. The developed setup allows free rotation of the beam at the supports and the loading head, even for a large deflection (Figure 3b). An LVDT (linear variable differential transformer) is used to measure the deflection of the sample at mid-length during the test. The internal spring of the LVDT was removed to ensure that no additional force was applied on the sample. The load is about 10 N.

Four specimens were tested simultaneously in each kiln run (two flying wood and two 3-pt bending tests).

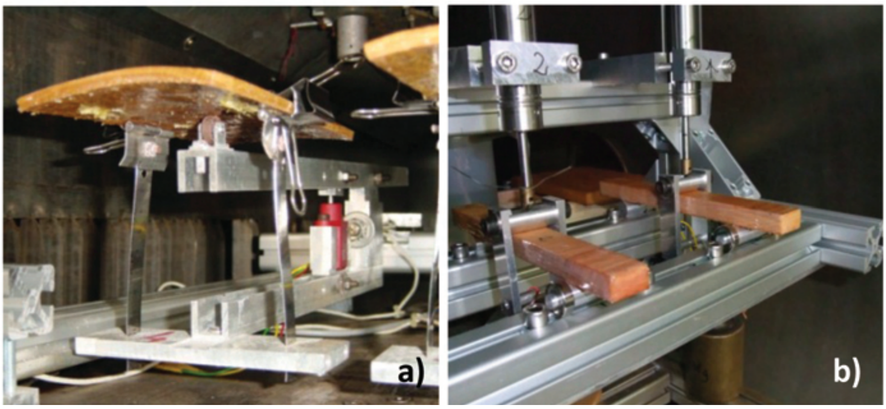

Figure 3. Samples fixed on experimental devices: (a) flying wood device and (b) 3-point bending device.

Vegetal material

Beech wood, the second most commonly kiln-dried hardwood after oak in France, has been chosen for this study due to its elevated shrinkage coefficient, and hence an elevated risk of drying defaults.

The tree used for sampling comes from a natural stand of a forest from the department of Meurthe et Moselle in France. Its diameter was about 60 cm. Flatsawn and quartersawn boards were cut 1000 mm long, 200 mm wide and 35 mm thick.

For the *flying wood tests*, the samples were 150 mm long, 100 mm wide and 5 mm thick. Five out of the six faces of the wood samples were coated with a polyurethane glue.

For the *3-point bending tests*, the samples were 160 mm long, 18 mm wide and 10 mm thick. The support span was 100 mm. Two out of the six faces of the wood samples were coated with glue so that the water transport occurs through the board thickness (radial or tangential direction according to the sawing pattern).

To draw clear conclusions on the effect of drying conditions, samples dried with constant and oscillating conditions come from the same longitudinal line, which is the best way to limit the effect of wood variability. Tests on quartersawn and a flatsawn boards were carried out simultaneously in each kiln run, so they were dried in exactly the same drying conditions.

Computational model for wood drying

The comprehensive simulation tool *TransPore* (Perré and Dégiovanni 1990), which solves the coupled heat and mass transfer equations within the board, is used in our simulations.

Stresses and deformations develop in the board due to shrinkage. In order to take into account the drying quality in the *TransPore* computational model, a rigorous one-dimensional mechanical formulation was adopted (Rémond *et al.* 2007). This formulation was derived from previous 2-D works (Perré and Passard 1995, 2004; Mauget and Perré 1999).

RESULTS AND DISCUSSIONS

Experimental investigation

Four series of tests were achieved on flatsawn and quartersawn boards with similar sampling sequences. The following results depict representative results gathered from these campaigns.

a) Flying wood tests

Figure 4 depicts the drying rate curve and curvature as a function of the average moisture content of the board dried with constant or oscillating conditions. The heating period is not depicted on these figures and the drying rate is determined from a linear regression over a sliding subset of fifteen points. During the first drying period, at constant drying rate, no shrinkage occurs at the surface: consistently, the specimen remains flat. After this period, bound water is removed near the exchange surface: the drying rate reduces and, due to shrinkage, the curvature becomes positive. The curvature increases to a maximum curvature. Notice that the maximal curvature reached by the flatsawn board is greater than the quartersawn board, which can be easily explained by the higher shrinkage value in the tangential direction. When shrinkage occurs near the impervious face, the sample comes back to a flat shape and finally acquires a negative curvature which is a consequence of the well-known phenomenon of stress reversal due to viscoelastic and mechano-sorptive creeps.

Figure 5 depicts the curvature as a function of time. The maximal curvature, attained at around 6 hours of drying for the two sawing patterns, is similar for constant and oscillating drying conditions.

From these results, it is difficult to tell whether or not oscillating conditions allow the drying stresses to be relaxed, as conclusions drawn from Figure 5a and 5b are in opposition. The other campaigns produced the same unclear conclusion, whatever the sawing pattern.

On the whole, our unclear conclusions about the effects of oscillating conditions are in agreement with the confusing results reported in semi-industrial configurations by different authors (Chadwick and Langrish 1996, Terziev *et al.* 2002, Sackey *et al.* 2004, Welling and Riehl 2004, Herritsch *et al.* 2008, Milić and Kolin 2008, De La Cruz-Lefevre 2012).

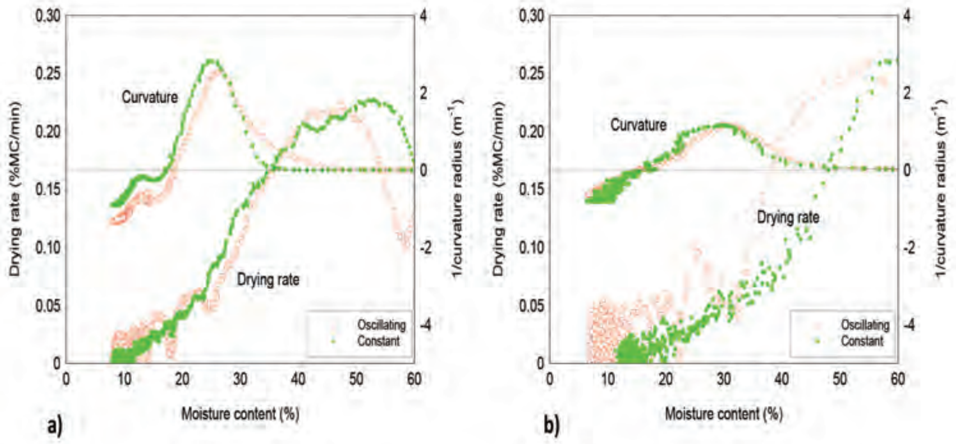

Figure 4. Drying rate curve and curvature obtained for the flying wood test on the flatsawn (a) and quartersawn (b) specimens (*Experimental* results).

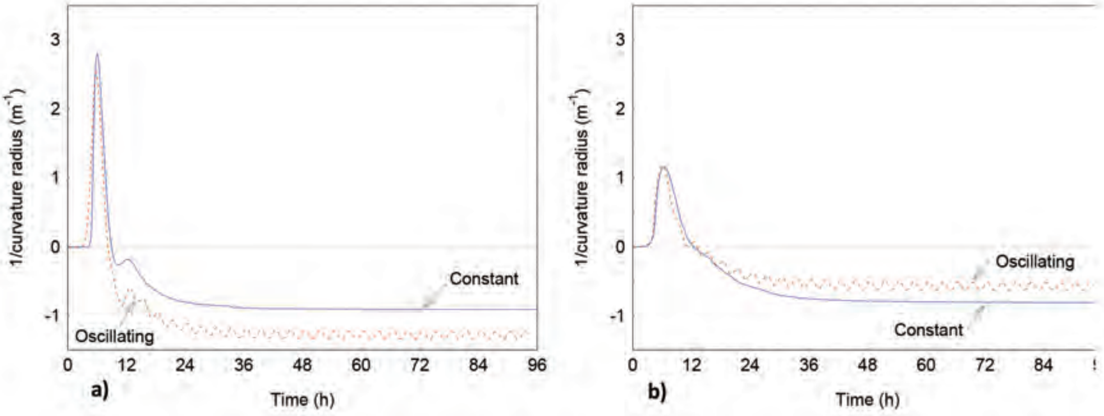

Figure 5. Evolution of the curvature of flatsawn (a) and quartersawn boards (b) dried with constant or oscillating conditions (5 mm thick) (Experimental results).

b) Three-point bending tests

Figure 6 depicts the evolution of the deflection of flatsawn and quartersawn boards loaded in a 3-point bending configuration. During the constant drying rate period, the thermoactivated viscoelastic creep increases the deflection of the sample, which reached a plateau at the end of the heating up period at 1.5 hour. Then, the peripheral part of the specimen enters the hygroscopic range, which activates the mechano-sorptive creep. During this stage, the deflection increases. When the MC tends towards the equilibrium moisture content (EMC) throughout the section, the deflection reaches a plateau. This result is observed whatever the drying conditions, in spite of the continuous mechano-sorptive activation at the peripheral part of the specimen in the case of oscillating conditions. This plateau confirms the concept of mechano-sorptive strain limitation observed in many studies. Considering the small difference between the final deflections observed for the oscillating and constant drying conditions for flatsawn and quartersawn boards, it seems that the activation of the mechano-sorptive creep by oscillations of the moisture content at the board surface is very limited.

The intricate coupling that exists between heat and mass transfer and the mechanical behaviour via shrinkage renders the analysis of the results very complex without the help of a simulation tool. In this work, we use the comprehensive computational code TransPore, whose mechanical module includes the viscoelastic and mechano-sorptive formulations.

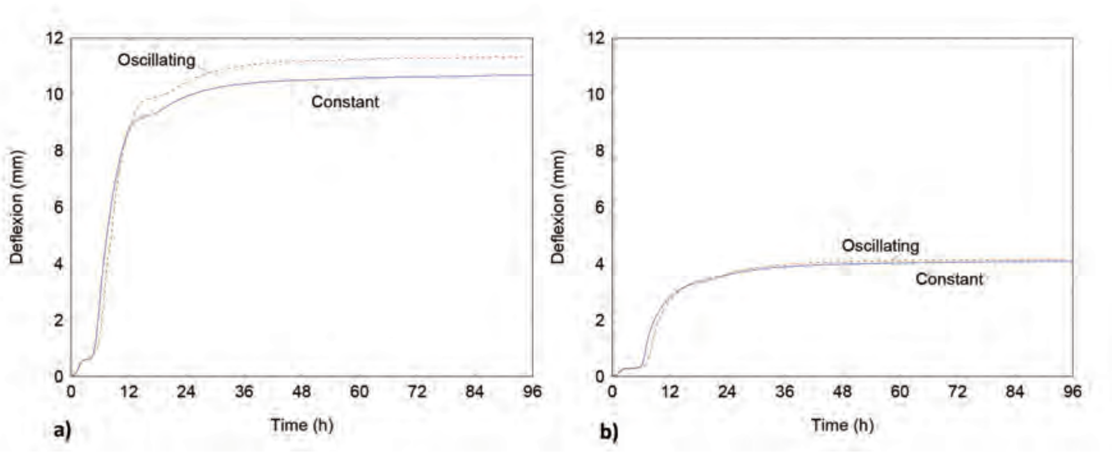

Figure 6. Evolution of the deflexion of flatsawn (a) and quartersawn boards (b) dried with constant or oscillating conditions (10 mm thick) (*Experimental* results).

Numerical investigation

a) Possible effects of noise regulation

In order to explain the unclear conclusions, we can investigate how noisy conditions, due to the non-perfect regulation of a real kiln, may affect the results. In this way, the effect of a noisy EMC is explored with the help of the *TransPore* numerical tool. In the following, the numerical code was tested with “perfect regulation” (we just use the set values as boundary conditions) and a “noisy configuration” (a sine noise added to the dry bulb temperature with 0.8°C of amplitude and 12 minutes of period). This noise induces a variation in EMC of ca. ± 0.2%.

The parameters measured on flatsawn specimens such as thickness, initial moisture content, shrinkage coefficients and Young’s modulus are used in the following simulations. For other transfer and mechanical parameters the average values for the beech are input in the code. The material parameters of Salin’s model were taken at 45 MPa for the mechano-sorptive strain limit in the radial direction and at 135 GPa^{-1} for the mechano-sorptive component.

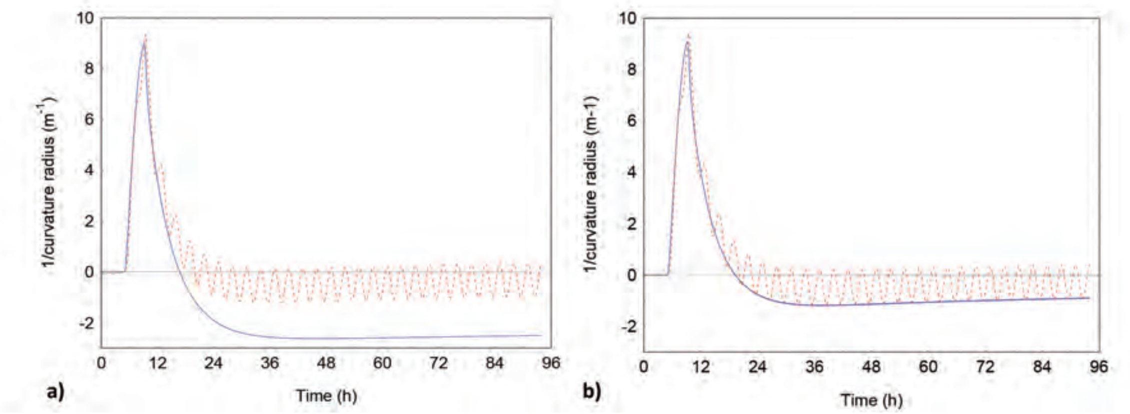

Figure 7. Evolution of the curvature of flatsawn board in the flying wood test with constant drying conditions and oscillating conditions (dashed line: amplitude 5°C on the dew point and 3h of period) (a) perfect kiln (b) noisy kiln (Simulated results).

There is a clear difference between the final curvatures in the constant and oscillating conditions for the perfect kiln (Figure 7a), but this difference almost disappears for the noisy kiln (Figure 7b). In this case, the noisy EMC at the board surface activates continuously the mechano-sorption. As the stress level at the exchange surface also affects the stress level throughout the section, the mechano-sorptive creep acts on the whole section and reduces the curvature, in exactly the same way as for oscillating conditions!

Similar trends were observed with the 3-point bending test: a difference in the final deflection exists in the case of a noisy kiln, but is significantly reduced compared to the simulation obtained in perfect conditions.

These results are of utmost importance, as, for industrial kilns, constant drying conditions are obtained by PID controllers tuned (more or less successfully) to compensate the effects of thermal losses, air renewal, humidification systems, thermal inertia, heating power, drying rates and so on.

A new question arises from these simulations: is the computed mechano-sorptive creep triggered by fluctuations in drying conditions realistic or not? In other words, we need full confidence in the mechano-sorptive model, even when applied to oscillating conditions, to advance our understanding.

b) Need for a new mechano-sorptive model?

In oscillating drying conditions, the moisture content cycles at the exchange surface activate the mechano-sorptive creep, which reduces the residual drying stress. The predicted final curvature of the specimen tends to zero, which is not in agreement with the experiment (Figure 5). Some irrecoverable deformations seem to occur at the beginning of drying. Therefore, Salin's model is not realistic in the case of oscillating drying conditions and a new model is required.

Figures 8 to 11 depict the predicted curvature or deflection of the quartersawn board presented in figure 5b and 6b for different mechano-sorptive models and parameters. The measured climatic conditions in the kiln chamber are used as input parameters in the model.

The simpler model, Ranta Maunus' model (Figure 1a), is not realistic for oscillating drying conditions as it does not depict a creep limit with cyclic moisture content variations applied to a loaded specimen. Again, this unlimited deflection is in contradiction with the 3-pt bending experiment (Figure 9b with Ems_R=0). We saw previously that

Salin's model (Figure 1b) is not valid either for this configuration. Leicester's model (Figure 1c) is capable of predicting that the creep rate decreases as a function of mechano-sorptive creep already attained (the concept of strain limitation) and additionally assumes that some irrecoverable strain can occur during the test (Figures 10 and 11). However, the use of a dashpot in series with the mechano-sorptive Kelvin elements, as proposed by Svensson and Toratti in 2002, is not able to respect the strain limitation observed in 3-pt bending (Figure 11b).

In conclusion, the models available in literature for mechano-sorption are not able to explain the experimental data observed with oscillating drying conditions. Therefore, a new mechano-sorptive model should be devised in the case of oscillating drying conditions. This task needs experimental data collected with the aid of a specific experimental device. We intend to perform a study to fulfill this need, in the same spirit as the work done to assess the viscoelastic behaviour of wood at high temperature (Placet *et al.* 2008a, Placet *et al.* 2008b).

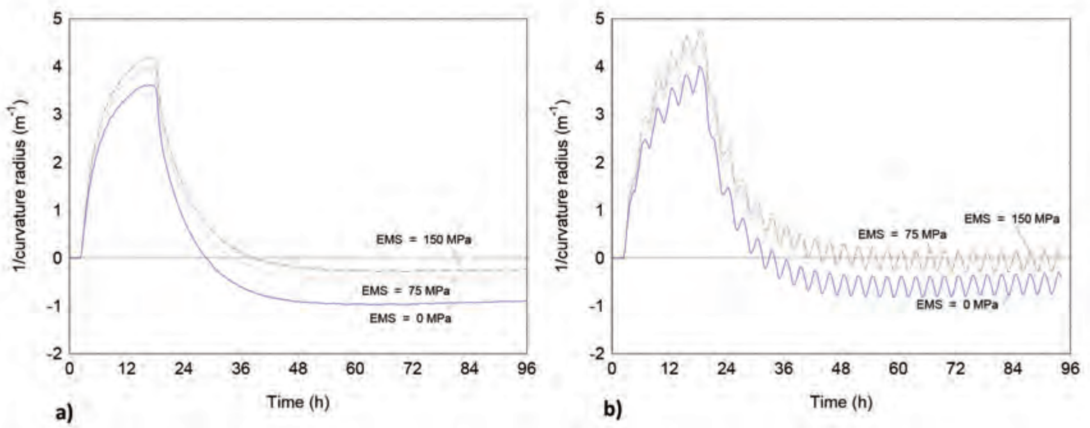

Figure 8. Evolution of the curvature of quartersawn board in the flying wood test with constant drying conditions (a) and oscillating conditions (b). The Salin mechano-sorptive model was adopted: msR= 78 GPa-1, with different value of EmsR(*Simulated* results).

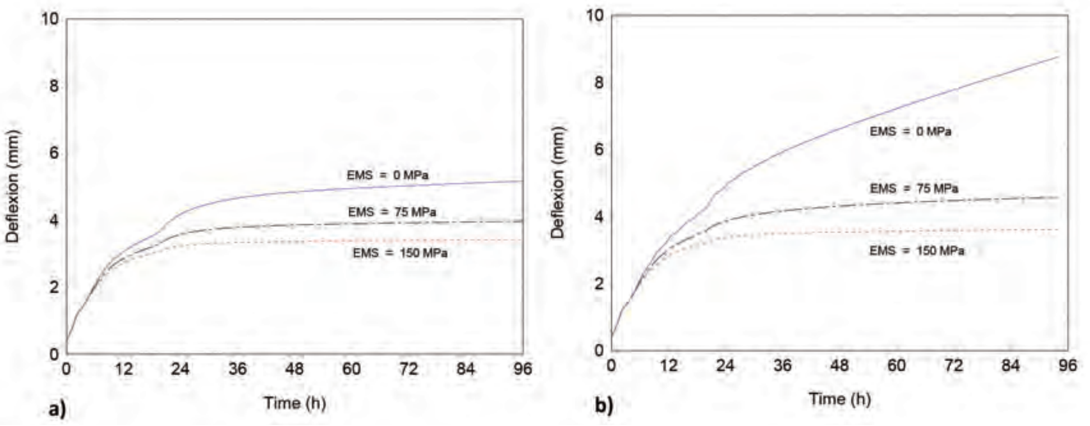

Figure 9. Evolution of the curvature of quartersawn board in 3-point bending test with constant drying conditions (a) and oscillating conditions (b). The Salin mechano-sorptive model was adopted: msR= 78 GPa-1, with different value of EmsR (Simulated results).

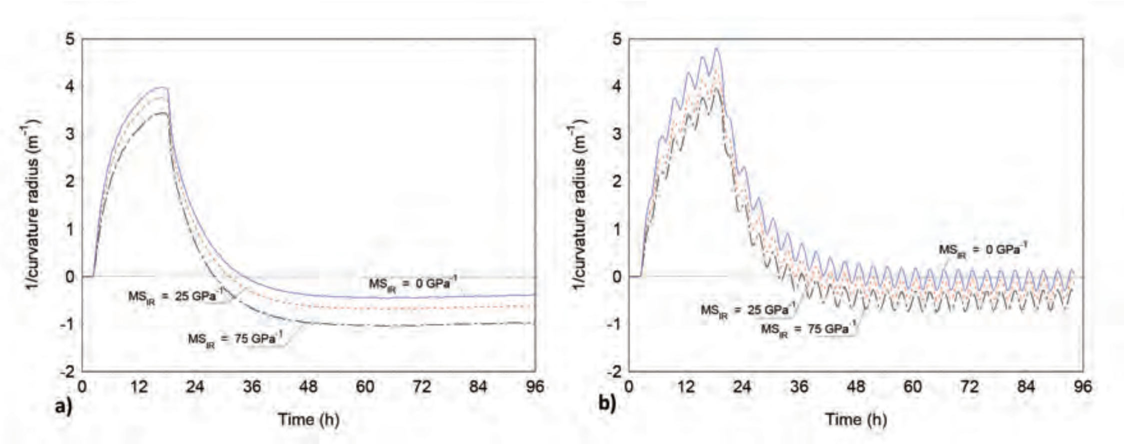

Figure 10. Evolution of the curvature of quartersawn board in the flying wood test with constant drying conditions (a) and oscillating conditions (b). The Leicester mechano-sorptive model was adopted: (ms$_{iR}$= 78 GPa^{-}1, Em$_{sR}$= 75 MPa) with different value of ms$_{iR}$ (*Simulated* results).

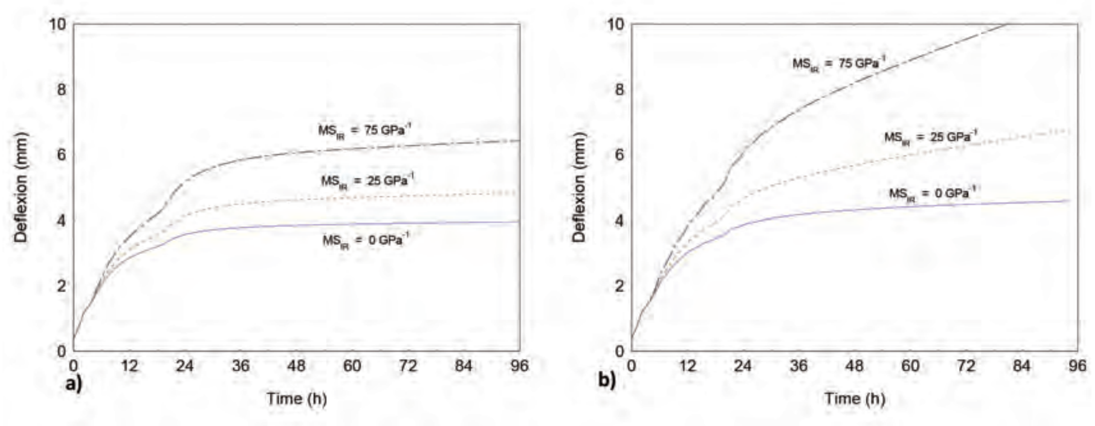

Figure 11. Evolution of the curvature of quartersawn board in 3-point bending test with constant drying conditions (a) and oscillating conditions (b). The Leicester mechano-sorptive model was adopted: (ms$_{iR}$= 78 GPa^{-}1, Em$_{sR}$= 75 MPa) with different value of ms$_{iR}$ (*Simulated* results).

CONCLUSIONS

In the present work, the effects of oscillating drying conditions were studied by experimental and computational investigations. Our set of experimental data obtained with the flying wood test and the loaded beam test showed that the activation of the mechano-sorptive creep by moisture content cycles at the board surface is of limited impact. However, the simulations showed that noisy conditions, due to the regulation of the kiln, enhance the mechano-sorptive creep in exactly the same way as for oscillating conditions. On the whole, the confusing results and unclear effects of oscillating conditions could be partly explained by the difficulty of achieving constant drying conditions. Indeed, the ability of oscillating conditions to reduce the drying stresses remains an open question.

Additionally, the simulations showed that the classical mechano-sorptive models are not adapted to oscillating drying conditions. A new mechano-sorptive model should be devised for these specific drying conditions in order to select adapted oscillation amplitudes and frequencies.

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