

Hygrothermal Simulation of Wood Exposed To the Effect of External Climate

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Abstract. The article is focused on simulation of moisture transfer in wood of norway spruce (*Picea abies* L.). Experimental specimen was exposed to the northern climatic conditions in Lund University, Sweden. The moisture content of wood was measured 10 mm from the surface for nearly three years. The ABAQUS program was used for numerical modelling of moisture transfer simulation in 3D. The surface sorption of wood was simulated using user defined subroutine DFLUX developed by VTT Research Centre of Finland Ltd. for the needs of European Project Durable Timber Bridges. Climate data for the analysis was used from in-situ measurement nearby realized by weather station. The temperature, relative humidity of the air and precipitation data was record each hour. Numerical analysis took into account influence of rain effect on different parts of specimen surface.

1. Introduction

Wood is hygroscopic [1] and anisotropic [2] material. It is natural material which works even when built in a construction. Wood hygroscopicity is manifested through its susceptibility to moisture. Moisture of wood is constant in stabilized conditions according to a relationship (4) [3]. In case ambient air humidity increases, equilibrium between wood and the ambient environment and is reached after a certain time period. Over time wood adsorbs the ambient moisture, thus changing its mechanical and elastic properties. These changes are influenced by wood anisotropy and wood behaves differently in each of the three natural directions, i.e. longitudinal (L), radial (R) and tangential (T) [4]. In general, mechanical and elastic properties of wood decrease with increasing moisture. Once the ambient air humidity decreases, the surplus of moisture becomes released from wood structures and is distributed in the ambient environment. In case the ambient environment is too humid, wood moisture may exceed the point of wood fibre saturation [5]. This may be particularly caused by rain, snow and a longer time period with high air humidity and possible water condensation on the surface of a wood sample. In this condition all capillaries in wood are fully filled with water and the wood structure starts containing free water, not just bound water, as is the case before reaching this point [5].

The experiment was performed with the use of a norway spruce wood (*Picea abies* L.) sample, which was exposed to ambient weather conditions. The measurement was performed on a sample with dimensions of 22 × 95 × 400 mm, which was placed on the roof of Lund University, Sweden, between 2009 and 2011.



The numeric model calibration used climatic data from the nearby meteorological station installed on the university roof, where the experiment was performed. The numeric simulation of the experiment was performed in finite-element calculation software ABAQUS [6]. Moisture transport modelling after wood fibre saturation is demanding, since water occurs in the wood in several different phases and their combined effect on moisture transport has never been sufficiently numerically described. Therefore, a simplified one-phase moisture transport [7] was selected, which was modified, so that it would be possible to describe conditions exceeding the wood fibre saturation point with sufficient accuracy. Some of the simplification features of the numeric model are based on the fact that adsorption and desorption curves are identical. This model was developed and calibrated in VTT Technical Research Centre of Finland [7]. An experiment performed in Lund University, Sweden, within a research project Durable Timber Bridges [8], was selected as the basis for the numeric model calibration. The calibration of boundary conditions for the numeric model and testing of suitability of the selected diffusion curve was performed with the use of a modification of the measured climatic data, so that simultaneous transport of free water, bound water and water vapours were expressed.

2. Methods

The measured sample was made of spruce wood (*Picea abies* L.) with dimensions $22 \times 95 \times 400$ mm, as shown in Figure 1.



Figure 1 – Speciment [8]

A meteorological station recorded air temperature, relative air humidity, wind direction, and precipitation in selected times in one-hour intervals. The experiment was performed from 22 September 2009 to 23 March 2012.

The measuring sensor, which measured and recorded moisture, was placed in the middle of the bottom part of the sample. The measurement was performed in the middle of the sample surface, i.e. in the depth of 11 mm. The location of the measuring sensor is shown in Figure 2.

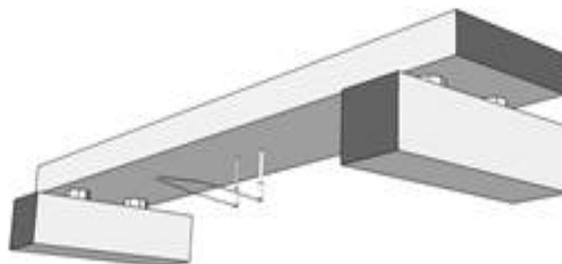
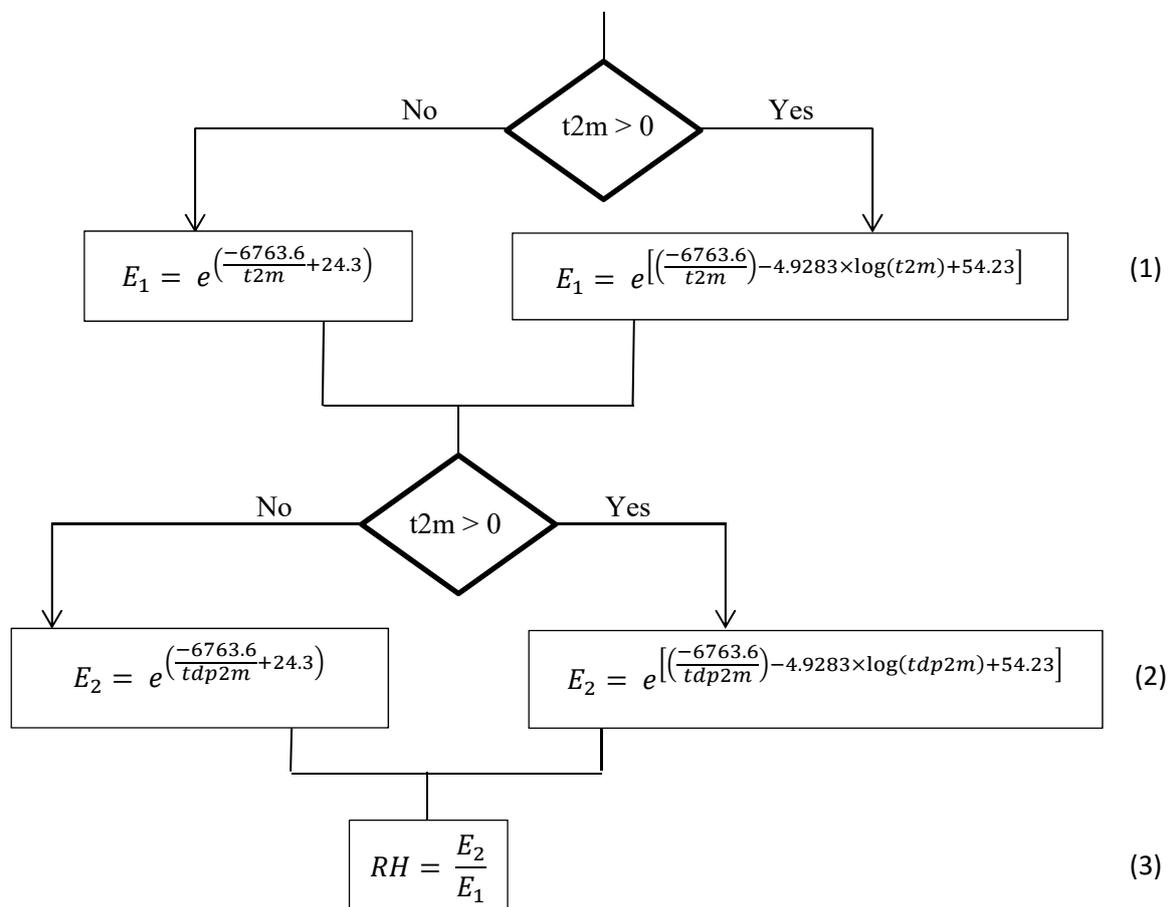


Figure 2 – Sensor location [8]

Air temperature, relative air humidity, and precipitation were selected from the measured meteorological data for the numeric 3D simulation. Figure 3 shows the course of relative humidity, temperature and precipitation. The green curve shows the course of relative humidity in percentages. Temperature is expressed in degrees Celsius and is displayed as an orange curve. The blue curve shows the precipitation in millimetres. The meteorological station did not record data between 16 September 2010 18:00 and 23 September 2010 13:00. The missing data were taken over from ECMWF (European Centre for Medium – Range Weather Forecast), database ERA-INTERIM [9]. The whole September data from the area of the city of Lund were taken over. Temperature data in two metres above ground and dew point temperature were used from the database. These values were used to determine relative humidity with the use of equations (1), (2), (3) [3]. Temperature in (1) to (3) is expressed in Kelvins. The equation (1) is used for dew point temperature. The equation (2) is used for temperature measured 2 metres above ground. The equation (3) is a conversion of these temperatures to relative humidity. The calculated relative humidity was subsequently compared to the measured values, which showed that the values are nearly identical, deviations ranged within decimal points of percentage points.



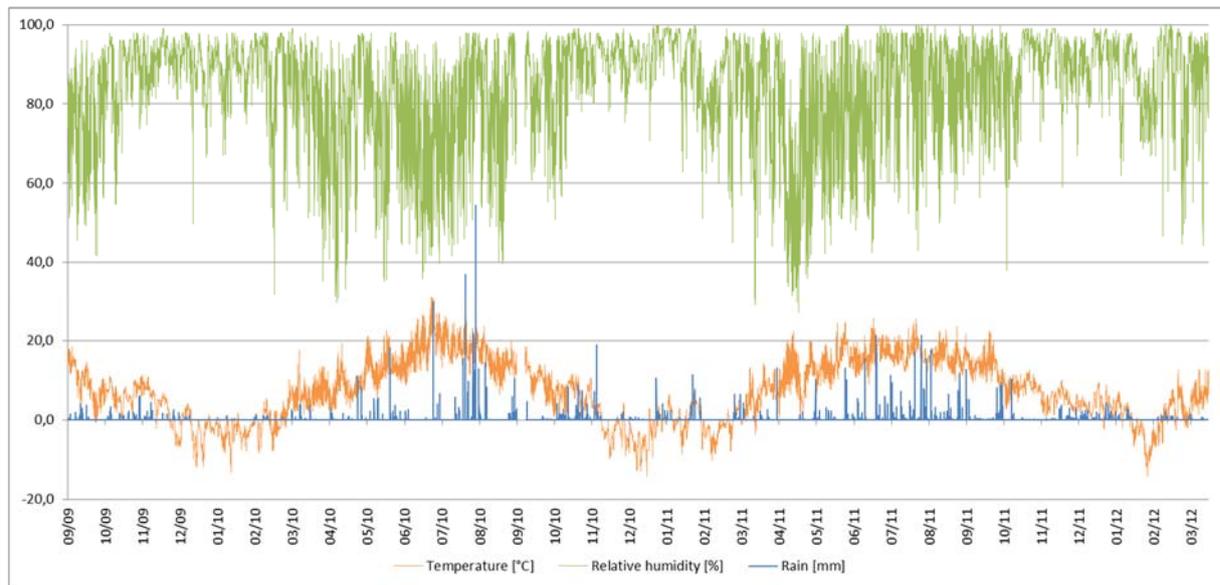


Figure 3 – climatic data

A symmetric sample model was created in software ABAQUS 6.14 [6]. Regarding the demanding nature of the numeric model, symmetric boundary conditions were used in order to reduce the numbers of elements calculation time and capacity. Three different surfaces, upper one, side one, and bottom one, were created on the sample so that it was easier to simulate numerically the real behaviour of the sample. Weather data were simulated on these surfaces. The data included air temperature and relative humidity. One of the questions was how to integrate precipitation in the calculation, when the simulation input data are only prepared for two inputs, i.e. temperature and relative humidity. Therefore, relative humidity was selected and modified so that it was artificially increased to 100 % when rained. After rain, the value of relative humidity was put back to the original measured value. These modifications were used just for two surfaces, the upper one and the side one. The bottom surface was unaffected by rain, since it was hidden from rain at the bottom part of the sample. Two simulations were calculated. One simulation was with a variant without the effects of rain, i.e. even when raining the measured relative humidity did not reach the value of 100 %. The other simulation included the effect of rain, i.e. the value of relative humidity reached 100 % when rain was recorded. Such modified weather conditions were only used for surfaces which could be affected by rain, i.e. upper and side surface

The numeric simulation calculation was performed in a subprogram DFLUX [7], which was modified during research projects in VTT Technical Research Centre of Finland LTD. The calculation is based on moisture equilibrium calculation, which is performed in accordance with the equation (4) [3]. u_{air} is equilibrium moisture, T is temperature in Kelvins and h is relative humidity. Subsequently, the original value is compared with the calculated value, and based on the ambient environment humidity, the direction of moisture transport is determined. This is calculated for every edge of every element. The calculation is extended with other input data, such as surface emissiveness. This coefficient shows the sample surface treatment. Therefore, wood with coating and without coating would have different coefficients. Two values of emission coefficients, which were compared, were used for the calculation. The concerned coefficients are 1.28×10^{-7} according to Torradi [10] and 3.2×10^{-8} according to Hanhijärvi [11]. Another variable which enters the calculation is a diffusion curve. Nilsson & Sandberg [12] was selected as the most suitable diffusion curve, which is defined to up to 80 % moisture of wood. This value was sufficient for the whole calculation.

$$u_{air} = 0.01 \left(\frac{-T \times \ln(1-h)}{0.13 \left(\frac{1-T}{647.1} \right)^{-6.46}} \right)^{\frac{1}{100 \times T^{-0.75}}} \quad (4)$$

The model for calculating a 3D moisture field was created from 8 nodes element DC3D8 [6] in shape of form a linear hexahedron [6]. According [6] this element could be used for diffusion moisture transport. The material model was orthotropic with a cylindrical coordinate system, which takes into account annual rings in wood and thus better describes the real condition. The finite element mesh was created with regard to a reduced number of elements, but with sufficient accuracy at the place where the sensor is located. The finite element network for the sample model was created denser in the middle, where the measurements were made. The finite element network there was formed with cubes of an edge of 5 mm, in other parts the network was formed with blocks of 5 × 5 × 45 mm. The modelled sample with the finite element mesh is shown in Figure 4. Wood density was considered 450 kg/m³.

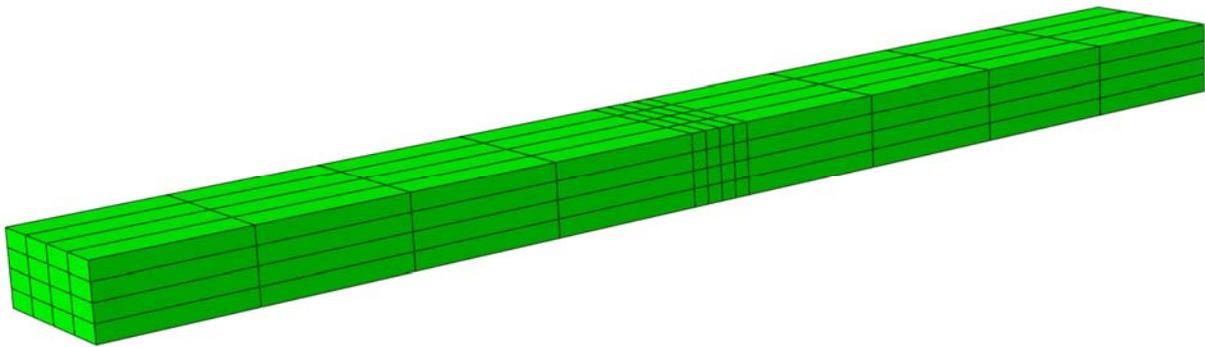


Figure 4 – Finite element mesh in specimen

3. Results and discussions

The input data for simulation calculation that consist of the measured temperatures and moisture were inserted in the calculation with one-hour interval recording. The calculation step in ABAQUS software was set to 6 hours. This time period for calculation step was set in order to reduce the calculation time. Figures 5 and 6 show the measured values as well as the results of numeric simulations with the effect of rain and without the effect of rain. The orange curve in Figures expresses the measured data in the middle of the sample body and in the middle of its depth. The bright blue curve expresses numeric simulation results without the effect of rain. The dark blue curve expresses numeric simulation results with the effect of rain. The horizontal axis shows time in day intervals. The vertical axis shows moisture in percentages. For illustration, Figures 5 and 6 show the results from the summer and winter season. This selection needed to be made, since it was impossible to show all the results

Figure 5 shows results from July 2011. The deviation between the measurement and numeric simulation without the effect of rain is lower than for numeric simulation with the effect of rain. However, numeric simulation calculations with the effect of rain more correlate at places with higher peaks according to the real measurement. The measurement results show that moisture sometimes exceeds the fibre saturation point even in the summer months.

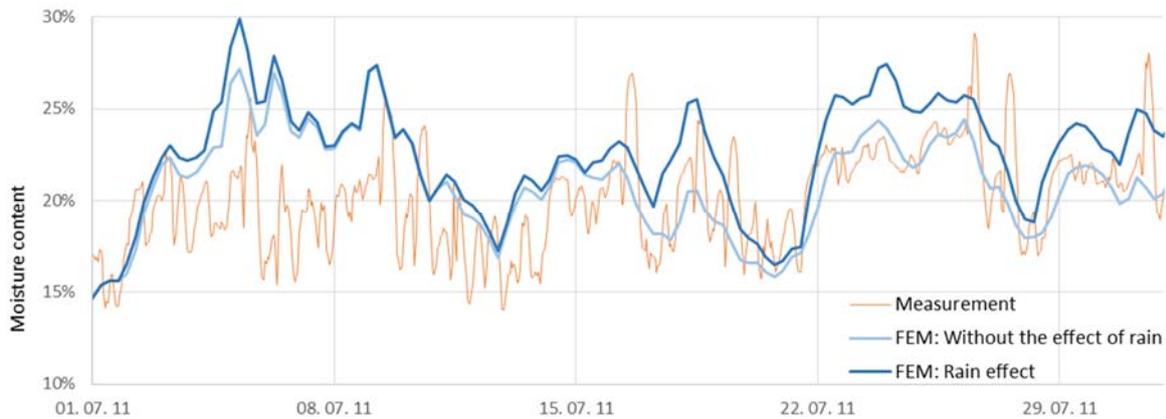


Figure 5 – Results for summer month

Figure 6 that in January 2012 higher moisture in sample was measured than both numeric simulations. In this period numeric simulation with the effect of rain is closer to the real measurement, since it has more accurate results and better follows the shape of measurement than numeric simulation results without the effect of rain. The fact that both numeric simulations are lower than the measured data is probably caused by water being in the form of snow on the sample in this period. With higher temperature the snow started melting and soaked the wood surface while no precipitation were recorded by the meteorological station. A new coefficient needs to be prepared for winter. The coefficient determines that in case of temperatures below $0\text{ }^{\circ}\text{C}$ and recorded precipitation, moisture will stay on the surface for a longer time, i.e. the effect of drying needs to be introduced. This would lead to drawing the numeric simulation closer to the values of the real measurement and to reality as well. In addition, the measured data make it obvious that the wood exceeds the fibre saturation point for the substantial part of the month. It is desirable to integrate a drying effect coefficient in the calculation. That would guarantee higher moisture staying on the sample surface that gets gradually dry. This effect would only be applied to surfaces where water can stay after rain. This effect could also bring higher correlation with measured results.

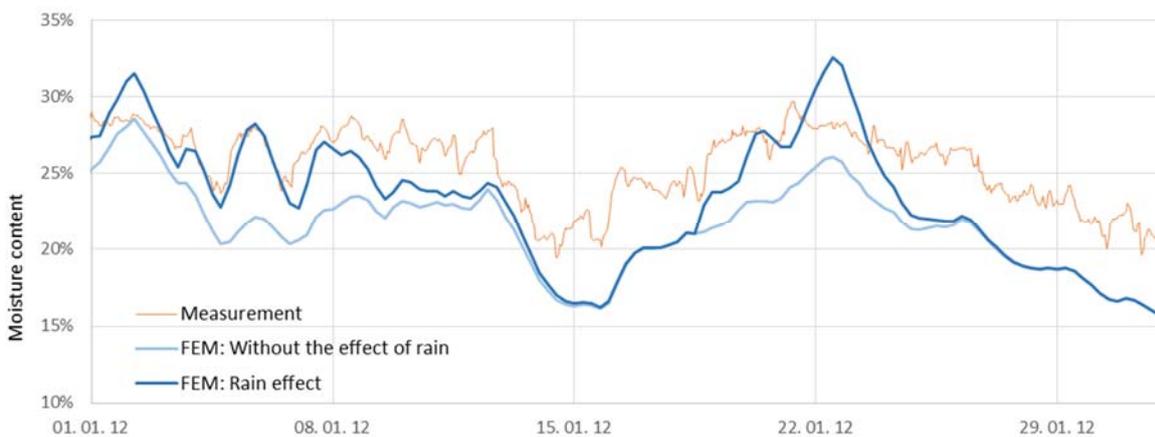


Figure 6 – Results for winter month

4. Conclusions

The calculation step of numeric simulations was set to 6 hours, i.e. 6 hours was the maximum step between which ABAQUS calculated its own iterations. The solution algorithm proceeds according to the iteration method and gradually reduces time steps. Therefore, the input data which were recorded in the interval of one hour were skipped in some parts and thus some values may not have been

included in the calculation, e.g. one-hour rain. This may be the reason for a discrepancy between the measured data results and numeric simulation results. Further discrepancy is caused by an error of the measuring sensor, which measures with its own accuracy and error rate.

These results show that the numeric model with a subprogram DFLUX correlates very close to the measured data.

Acknowledgments

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