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Diffusion-model-based risk assessment of moisture originated wood deterioration in historic buildings

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ABSTRACT

The paper deals with investigating the response of wood artefacts to relatively fast changes of ambient air humidity and temperature and with estimating the wood stress and strain variations due to the moisture content changes. The moisture content dynamics are described by a specially developed model based on the Fick's second law and further transformed into a state space model. The surface boundary conditions are tied up with a model of equilibrium moisture content. As the final objective of the diffusion model application the moisture induced stress and strain in the wood artefact is assessed. The obtained stress amplitudes are compared with the yield point stress as the boundary of elastic deformations. The model application has particularly confirmed that the concerned transfer phenomena have to do with only a thin surface layer of wood while the deeper layers are not touched by them. For a given set of data provided from unheated historical churches the stress and strain responses are evaluated and compared with their admissible limits in order to estimate the risk of potential moisture originated damage.

1. Introduction

Due to hygroscopic nature the preserved wood artefacts suffer from the variations of ambient air humidity and temperature. The volume changes induced by the variations of moisture content in wood are considerably anisotropic and give rise to internal stress amplitudes. The distinctively anisotropic effect of swelling or shrinkage of the wood volume may result in a damage of wood [8]. As regards relatively fast variations of moisture content it is intuitively apparent that they can touch only a thin surface wood layer. This shallow response, however, results in high values of both moisture content gradient and the consequent stress development [7,12].

In most sites of the cultural heritage some variations of ambient air humidity and temperature arise particularly due to using *historical buildings* to this purpose [24,25]. Primarily the magnitude of the environment variations is dependent on the impact of varying *weather conditions* and of the *visitors' traffic* in the building and the practical measures of preventive conservation have to allow for certain humidity and temperature changes and for their influence on the moisture content [7]. The aim of this study is the following

- By means of a model to predict the moisture sorption variations induced by variable air humidity and temperature.
- From these variations to estimate the stress and strain response of wood and in this way to assess the risk of its damage.

In industrial application the moisture transfer issues are characterized by the coupled heat and moisture transfer [1,9]. For the drying processes this coupled transfer is analysed in Salinas et al. [17] and Sandland [18]. In the problem area of cultural heritage preservation the heat transfer is present always in the slightest degree and will be considered negligible in this study.

The placement and material of the exhibits may be very diversified. As a representative of typical cases a flat wood specimen freely placed in the internal environment is examined in this study. In a testing chamber equipped with air-conditioning control, the

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specimens have been repeatedly exposed to relatively fast and substantial changes of the ambient air humidity φ_A to investigate their response of moisture content u. Both φ_A and u are considered as *dimensionless* variables, namely φ_A as relative humidity (RH) and u as the *mass ratio*, and temperature is considered in $^\circ K$. As a reference state of the moisture sorption an equilibrium moisture content (EMC) is used to assess the potential of moisture exchange. The application of the EMC concept was also applied to a low power air conditioning in historic interior environment as the so-called equal sorption humidity control [29,30].

The rest of the paper is organized as follows. The application of the second Fick's law to dynamic moisture transfer between a flat representative wood specimen and its varying ambient including the appropriate boundary conditions is dealt with in Section 2. With respect to relatively thin surface layers considered this model is conceived as one-dimensional and its state space approximation is introduced in Sections 3 and 3.1. In order to obtain a more handy tool for dynamical considerations transfer functions resulting from the state space model are investigated in Sections 4 and 4.1. The identification of the introduced model based on the experiments in laboratory conditions is dealt with in Section 5 and the moisture induced stress and strain response is analysed in Section 6. The final application of the modelling technique to a risk assessment of moisture originated harmful effects is demonstrated in Section 7 and the discussion on the results and contribution is in Section 8.

2. Diffusion interpretation of moisture transfer model in wood

The diffusion concept of moisture transfer model based on the second Fick's law has been introduced by Skaar [23]. The moisture transport inside the specimen can be considered as a form of diffusion and can be described in the terms of the second *Fick's law*, Shi [20], Saft and Kaliske [16]. The use of this diffusion model in modelling the moisture transfer in wood is not a simple issue due to structural complexity of this phenomenon. The model is based on the assumption of homogeneous and isotropic material properties which is not the case of the wood material. Consequently in comparing Fick's law based simulations with experimental data certain slight discrepancies may be observed. Due to these discrepancies the real sorption properties of wood are also referred to as non-Fickian behaviour [16]. In fact the moisture transfer involves a combination of two phenomena, namely the vapour diffusion through the void structure and the bound water diffusion through the cell walls [20]. Just the latter phenomenon leads to the distinctively anisotropic effect of swelling or shrinkage resulting in the moisture originated stress and even in wood cracks. Nevertheless for common technological purposes the model inaccuracy having originated from this approach is negligible if the moisture content is sufficiently below the so called *fibre saturation point*.

In general the diffusion is a three dimensional process and in case of wood, moreover, it is strongly influenced by its already mentioned anisotropic character. Basic models of this moisture transfer have been dealt with by Backman and Lindberg [3] and Baronas et al. [4]. The wood properties differ considerably in three anatomy axes, namely tangential, radial and longitudinal. The model coordinates of the wood specimen correspond with these axes, namely, x – tangential, y – radial and z – longitudinal. For instance, it is well known that in wood the moisture induced dimensional changes in x direction are the biggest, less than a half they are along the radial axis y and along z these changes are practically negligible. The 3D and 2D moisture induced tension in wood was investigated by Jakiela et al. [12] and Saft and Kaliske [16]. Our aim is to investigate the moisture content changes in wooden artefacts induced by the daylong or longer cycles of ambient air humidity and temperature. It is known that these cycles may bring about some significant responses in moisture content and the consequent strain and stress response in the wooden artefacts.

Suppose a flat wood specimen as a small board where the thickness coordinate coincides with the radial wood axis y, Fig. 1. The specimen *thickness* L is substantially smaller than the other specimen dimensions so that practically the whole moisture transfer takes place in the direction *perpendicular* to the x, z plane and the impact of the specimen edges may be neglected in this respect. Due to this the moisture content inside the specimen is distributed uniformly along the x, z coordinates and the moisture diffusion can then be approximately described by one-dimensional model where the only relevant coordinate remains the radial, y. The applicability of one-dimensional description of moisture diffusion in wood surface is studied in Baronas et al. [5]. The sorption considered as a *moisture flux* q through the specimen takes place in the y direction and then it is proportional to the moisture content *gradient*. On the assumption of the above conditions the dynamics of moisture transfer in the direction perpendicular to the specimen surface (along the y-axis) can satisfactorily be described by the partial differential equation

$$\frac{\partial u(y,t)}{\partial t} = D\frac{\partial^2 u(y,t)}{\partial y^2} \tag{1}$$

where D (dimension $m^2\,s^{-1}$) is the *diffusion coefficient* of the second Fick's law. For modelling the moisture transfer the *moisture flux* q inside the specimen in the y direction (dimension $m^2\,s^{-1}$) is useful to apply. It is negatively proportional to the moisture content *gradient*

$$q(y,t) = -k_1\frac{\partial u(y,t)}{\partial y} \tag{2}$$

where k_1 is a material specific coefficient of *moisture conductivity* with the dimension $m^{-1}\,s^{-1}$. The moisture sorption dynamics is further dependent on the sorption capacity of the hygroscopic material so that the speed of moisture transfer is negatively proportional to the moisture flux *gradient*

$$k_2\frac{\partial u(y,t)}{\partial t} = -\frac{\partial q(y,t)}{\partial y} \tag{3}$$

where k_2 is a material specific coefficient of *sorption capacity* with the dimension m^{-3}. The obtained set of partial differential

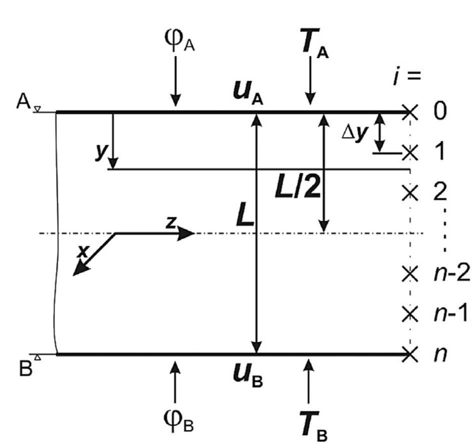

Fig. 1. 1D consideration of the specimen.