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CLIMATE-INDUCED DAMAGE IN HISTORICAL CABINET DOORS

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ABSTRACT: Climate-induced visual cracks or dimensional changes in historical art objects are aesthetically undesired. A thorough analysis of the failure mechanisms is essential to obtain a better understanding of the causes of damage. Therefore, a numerical model is developed that can accurately simulate climate-induced damage development in oak wood. In the model, the thermal and hygral responses are described by extended versions of Fourier’s law of heat conduction and Fick’s law of moisture diffusion. Discrete fracture is simulated by surrounding the continuum elements in a finite element model with interface elements equipped with an interface damage model. Preliminary numerical results are in good agreement with an analytical solution of a one-dimensional hygral-mechanical coupled problem, and describe the thermal-hygral-mechanical response of oak wood museum objects realistically.

KEYWORDS: Oak wood, Climate-induced damage, Heat conduction, Moisture hysteresis, Discrete fracture

1 INTRODUCTION
The protection and preservation of works of art is important, as these objects constitute a significant part of our cultural heritage. Museums are concerned with the responsible task to safely preserve works of art, while at the same time open their collections to the public. This task is not evident, as indoor climate fluctuations, often caused by the entering public, are regarded as one of the major risks for susceptible art objects. Currently, climate-induced damage is prevented by imposing strict limitations on indoor temperature and relative humidity fluctuations. This results in a low risk preservation of susceptible collections, though at the expense of high energy demands. Nowadays, museums strive for a more sustainable collection management and the challenge is to determine whether the strict limitations can be relaxed without increasing the risk of damage.

2 HISTORICAL CABINETS
In recent years, the Furniture Conservation Department of the Rijksmuseum has carried out several challenging treatments on oak cabinets on stands decorated with marquetry. These cabinets have large flat doors to provide ample space for decorative surface layers, see Figure 1. To analyse the damage observed on these objects in more detail, the Rijksmuseum organised a masterclass during which 17 pairs of Dutch seventeenth century cabinet doors were investigated [1]. It became clear that the doors showed a variety of substrate structures and construction methods. However, all doors showed shrinkage and shrinkage cracks mainly located at failed joints in the wood substrate.

3 CLIMATE-INDUCED DAMAGE
Scientific research focusing on understanding the cause of the observed damage is essential for the development of sustainable preservation strategies. For this purpose, a sequentially coupled numerical model is developed that can accurately simulate climate-induced damage development in oak wood.

3.1 HEAT CONDUCTION AND MOISTURE DIFFUSION
The effects of the ambient climate are described by extended versions of Fourier’s law of heat conduction and Fick’s law of moisture diffusion.

Figure 1: Cabinet with marquetry. The Netherlands, circa 1690-1710. Oak, 221 x 192 x 63 cm. Rijksmuseum, Amsterdam.
Heat conduction in the bulk material is described by:

\[ \hat{c}(h) \rho \frac{\partial T}{\partial t} = \nabla \cdot \mathbf{q}_{th} \quad (1) \]

where \( T \) is the temperature, \( t \) is the time, \( \rho \) is the density, \( c \) is the heat capacity, \( \mathbf{q}_{th} \) is the heat flux vector and \( \nabla \) is the gradient operator. The formation of cracks will have an influence on the energy transport in the material. Due to the cracks, the heat flux will reduce and heat conduction slows down. To account for this effect, the reduction of the heat flux evolves with the amount of damage formed in the material:

\[ \mathbf{q}_{th} = -\hat{\lambda}(h)(1-d)\nabla T \quad (2) \]

where \( \hat{\lambda} \) is the conduction coefficient and \( d \) is the damage parameter, which results from the mechanical response and is bounded as \( 0 \leq d \leq 1 \). Here, \( d = 0 \) corresponds to the initial, undamaged state of the material and \( d = 1 \) to a material for which damage has fully evolved and the heat flux therefore has reduced to zero. Moisture diffusion in the bulk material is described by:

\[ \frac{\partial h}{\partial t} = \nabla \cdot \mathbf{q}_{m} \quad (3) \]

where \( h \) is the relative humidity and \( \mathbf{q}_{m} \) is the moisture flux vector. Similar to the transport of heat, the transport of moisture is affected by the amount of damage as:

\[ \mathbf{q}_{m} = -D(1-d)\nabla h \quad (4) \]

where \( D \) is the diffusion coefficient, which is commonly defined as:

\[ D = \frac{\delta_d \hat{P}_{sat}(T)}{\mu \xi(h)} \quad (5) \]

where \( \delta_d \) is the vapour permeability of stagnant air, \( \hat{P}_{sat} \) is the saturation pressure, \( \mu \) is the vapour resistance factor and \( \xi \) is the moisture capacity. An important phenomenon that significantly affects the moisture content at moderate relative humidity, is moisture hysteresis. This effect is accounted for by implementing the hysteresis model originally developed by Frandsen [2] in the coupled modelling framework.

### 3.2 DISCRETE FRACTURE

The transport of heat and moisture in wood is typically associated with the anisotropic expansion and shrinkage of the material. The dimensional change of the material is accounted for by means of a thermal and hygral expansion coefficient. The total strain tensor is decomposed as:

\[ \varepsilon = \varepsilon^t + \varepsilon^{th} + \varepsilon^m \quad (6) \]

where \( \varepsilon^t \), \( \varepsilon^{th} \) and \( \varepsilon^m \) are the elastic, thermal and hygral strains, respectively. If thermal and hygral strains are prohibited, tensile stresses will develop, which, when exceeding the tensile strength, will induce quasi-brittle fracture in the oak wood object. This fracture behaviour is simulated by surrounding the continuum elements in a finite element model of the object with interface elements equipped with the mixed-mode interface.

**4 RESULTS**

First, the simulation results were validated against an analytical closed-form solution for a one-dimensional steady-state hygral-mechanical coupled problem. Subsequently, the mechanical response of oak wood was analysed by considering the effects of moisture hysteresis. Finally, the simulated climate-induced failure response of an oak door panel was compared against test results obtained from full-scale experiments on mock-ups, see Figure 2.

**5 CONCLUSIONS**

The results of the numerical model show good agreement with the solution of the analytical benchmark problem, and describe the thermal-hygral-mechanical response of oak wood museum objects realistically. In future work, the climate-induced failure response of an oak cabinet door under various climate conditions will be analysed in a combined experimental-numerical study. The obtained results will be used to advise museums on future preservation strategies and sustainable guidelines for indoor climate specifications.

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