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Original article

Modelling of heat and moisture induced strain to assess the impact of present and historical indoor climate conditions on mechanical degradation of a wooden cabinet

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ABSTRACT

To assess the risk of present and future indoor climate conditions within historic buildings on mechanical degradation of wooden art objects, it is of high importance to know the climate variations that these objects might have been exposed to in the past. Historical indoor climate data can indicate climate variations that may have caused damage to objects. Avoiding these variations in the present and future may prevent new or further degradation. However, historical indoor climate data conditions are often not available and cannot be derived from recent indoor climate data as many historic buildings nowadays have climate control systems. In this study, multi-zone hygrothermal building simulation is applied to reconstruct the historical indoor climate in a 17th-century Dutch castle based on meteorological data, building properties, and user behaviour. Furthermore, a finite element model is created to analyse heat and moisture induced strain of a historic wooden cabinet. This cabinet has been located in the castle since the 18th century and shows damage caused by movement of the wood in response to climate variations. Mechanical degradation of the cabinet could have occurred when the strain exceeded the yield strain for safe, reversible deformation. The results show that combining a hygrothermal building simulation model and a finite element model can generate an adequate prediction of the microclimate around an object; though obtaining accurate data on hygroscopic and mechanical material properties can be difficult. Although the cabinet has experienced considerable tension after a conservation heating system was installed in the castle during a recent major renovation, the predicted strain was within the limits for safe, reversible deformation. This corresponds to the observation that no further damage occurred after the renovation. Damage may not be caused by the regular present or historical indoor climate in the castle, but could be indicated if the long-term average moisture content of the wood significantly deviates from the room conditions or if the vapour concentration in the room increases because of a flooding event.

1. Research aims

The purpose of this study is developing a method to predict the impact of indoor climate variations within a historic building on the mechanical degradation risk to a wooden cabinet. The article discusses the potential and limits of reconstructing the historical indoor climate by a multi-zone hygrothermal building simulation model and coupling the outcome with a finite element model to predict the hygrothermal and mechanical behaviour of a two-dimensional wooden object under different indoor climate scenarios. The results can be used in guidelines for tolerable indoor climate variations in historic buildings to prevent mechanical degradation of wooden art objects.

2. Introduction

Many historic buildings have housed art objects, such as paintings and furniture, for centuries. As a result, the historical collections today have become intrinsic to the monumental value of the building. Conservation strategies, therefore, focus on preservation of both the building and its collection therein; changes to the external appearance of the building are not desired and biological,

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chemical and mechanical degradation of the objects must be prevented. Nowadays, modern climate control systems are regularly implemented in these monumental buildings to maintain a suitable indoor climate for the building and the collection, as well as to generate a comfortable indoor climate for visitors. The guidelines for indoor climate conditions related to museum collections by ASHRAE [1] are generally applied. However, this is much too often primarily directed at reducing the risk of mechanical damage by aiming at an A or even an AA climate class. Maintaining strict indoor climate conditions in monumental buildings lacking thermal insulation could cause damage to the external envelope, such as fungal growth and condensation on cold surfaces, and may require high energy consumption [2]. Moreover, art objects have generally adapted to their particular historical indoor microclimate. If the microclimate is changed, the risk of mechanical damage to the object increases until the artwork has acclimatised to the new conditions [3].

Deterioration of historic wooden objects is commonly attributed to unfavourable variations of ambient temperature and relative humidity (RH). These variations can induce physical damage to the wood due to its hygroscopic nature and related dimensional response to the moisture sorption and desorption [4]. Moisture changes generally have the greatest structural effect at extremely low and high RH levels and the least effect in the central RH regions [5]. The highest dimensional moisture response occurs in the tangential direction; the swelling in this direction is about twice the swelling in the radial direction and eighty times the swelling in the longitudinal direction [6]. Although objects that have been housed in unheated historic buildings for many decades or even centuries may have been exposed to large climate variations in the past, they have often remained in remarkably good condition. Rachwał et al. [7] showed that although RH fluctuations over 20% frequently occur in historic buildings without a climate control system, these fluctuations are not expected to cause damage to the pictorial layers on freely responding wooden panels when the fluctuation duration is less than one day. Additionally, the authors indicated that the critical RH fluctuations significantly increase at low temperatures because the temperature decrease reduces the moisture diffusion coefficients in wood. Moreover, Rachwał et al. [8] indicate that much of the deterioration of painted wooden artefacts in historical interiors is caused by continuous RH cycling instead of infrequent serious damaging events. Wooden cabinets may be particularly vulnerable to climate variations as they often consist of three hygroscopic layers: surface wood veneers, a glue layer and a wood support [9]. A large part of the historical wooden cabinets shows cracks. Although the internal side of the cabinets is much less subjected to climate variations than the external side of the cabinets, the shrinkage percentage of the wood in the internal side is often the same as in the external side and even shelves and drawer-bottoms have shrunk [10].

In the future, the indoor environment in monumental buildings could be critically affected by climate change as climate scenarios predict an increasing indoor temperature and RH [11]. To preserve historic buildings and their collections for future generations, sustainable methods for preventive conservation of cultural heritage have to be developed. This requires more insight into the indoor climate conditions in monumental buildings, their effect on the microclimate conditions around objects, and the response and susceptibility of typical cultural heritage materials and objects to climate variations. The European standard EN 15757 “Conservation of cultural property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials” recommends that objects should be preserved without departing from the historical climate if their condition has been found satisfactory [12]. This means that only improvements that reduce fluctuations in the climatic conditions are acceptable. A recently developed new methodology to assess the impact of past, present and future indoor climate conditions on a wooden cabinet is described in [13]. In this methodology, the past indoor climate conditions are reconstructed based on historical records of indoor and outdoor climate data. Recent studies that were carried out to predict the indoor climate in historic buildings as a result of the outdoor climate derived a linear transfer function between the indoor and outdoor climate [14,15] for each month during the research period. However, these transfer functions may not consider variable internal heat loads due to visitors and irregular use of shading devices, and do not accurately take into account the effects of climate control systems.

The present study focuses on a representative wooden cabinet that has been located in a historic building for several centuries and has large vertical cracks. The historic building of interest is currently heated and internal heat loads during opening hours are significant due to visitors and lighting, while in the past, the building was mainly unheated and closed during winter months. With hygrothermal building simulation, it is possible to predict the indoor climate conditions in a room accurately based on the outdoor climate, building properties, climate control system, and user behaviour. It is therefore possible to validate the model for the present, heated situation and project the indoor climate for the historical, unheated situation. The objective of this study is to determine which indoor climate scenarios may have caused mechanical degradation of the cabinet, based on a reconstruction of the historical indoor climate within the building. The study investigates whether degradation could occur in the present, heated situation and the historical, unheated situation, whether the long-term average moisture content (MC) level of the wood is of influence, and whether damage could occur after a flooding event in the building. A multi-zone hygrothermal building simulation model is used to simulate the current indoor climate in the room where the cabinet is located. This simulation model is validated with on-site measurements. By varying the outdoor climate and set points of the climate control system, a reconstruction of the historical indoor climate in the room is generated. Furthermore, the simulation model is combined with a heat and moisture transfer model to calculate the microclimate conditions around the cabinet because of the surrounding indoor climate and a structural mechanics model is used to calculate climate-induced strain in the cabinet doors. In this way, the study assesses the damage risk of various plausible indoor climate scenarios. Section 3 describes the building, cabinet, on-site measurements, computational models and model validation, Section 4 presents the results of various indoor climate scenarios, Section 5 contains a discussion and Section 6 gives the conclusions.

3. Methodology

3.1. Case study

3.1.1. Building

The selected case study concerns Amerongen Castle, a 17th century castle that is considered an important heritage site in the Netherlands. The building currently functions as a museum and provides room to a collection of valuable furniture and paintings. However, the building had to cope with high internal moisture sources in the past, caused by flooding of the basement due to high water levels in the surrounding moat. These events may have caused fungal growth and mechanical degradation of wooden art objects. The building is characterised by masonry walls with a thickness varying between 0.7 and 1.5 m, providing a high thermal mass, and single glazed windows. The castle underwent major renovation from 2002 until 2011. During this renovation, a conservation heating system (a hygrostatically controlled floor heating system with a

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