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Abstract

Climate induced damage in decorated oak wooden panels is considered to be a high risk for the preeminent museum collections. To advise museums on the development of future sustainable preservation strategies and to define rational guidelines for indoor climate specifications, climate induced physical and mechanical damage has been analysed in a collection study, experimental testing of mock-ups and by finite element modelling. The collection study consisted of the development of a comprehensive methodology to select objects of interest from the collection and analyse their condition using a combination of visual inspection and archival searches. Mock-up samples of wooden panels with representative structural elements were exposed to varying climate conditions in climate controlled rooms and monitored with state-of-the-art experimental mechanics equipment. Further the collection study and experimental testing were used to inform the development of a finite element model of crack growth under 3-point bending. The work was performed within the Cimate4Wood project, a multidisciplinary collaboration between conservators and scientists work. The paper presents the methodology of the museum study and results from the museum study, experimental testing and modelling.

Introduction

For conservators and other museum professionals an important task is to minimize the risk of damage to the condition of the objects, so that changes, such as permanent out-of-plane deformations, irreversible shrinkage, delamination and cracks are avoided. However, it is still difficult to predict under which circumstances these changes will occur in the museum climate. In previous research, the focus has been mainly on monitoring the indoor climate instead of monitoring possible changes to the objects, as reading climate graphs is more straightforward than monitoring object changes.

To increase the knowledge of the effects of climate fluctuations on actual museum objects, scientific research has been performed since the 1980's. One of the first modelling studies performed by Colville et al. (1982) considered the mechanical behaviour of the different layers of a panel painting by using the finite element method. Erhardt et al. (2007) examined the effect on museum objects by regulation of the indoor museum climate. Mechanical and physical properties at a variety of climate conditions have been investigated for individual materials or combinations of materials often applied in decorated panels by Bratasz (2010). Nowadays, different research groups are developing numerical models in order to understand and reproduce the mechanical behaviour of wood to micro-climate fluctuations (Saft 2011). Scientific research has usually been restricted to either experimental work on material samples or in-situ monitoring of single museum objects, although recently experiments were combined with modelling (Konopka 2016). Although this research has contributed to the understanding of climate-induced damage in susceptible museum objects, in general there is still is a gap between the results obtained by laboratory and numerically-based research, and the general observations from conservators working with aged museum objects. Accordingly, the conservation community asks for empirical data from large collections of museum objects (Boersma et al. 2014, Van Duin 2014) to better link the laboratory and numerically-based research to the general condition of susceptible museum objects.

The research has first focussed on , decorated oak wooden panels have been analysed to develop preventive conservation strategies and to advise on acceptable micro-climate fluctuations for museum objects. To meet the requests of the conservation community, the research presented here couples an examination of empirical data obtained from naturally-aged museum objects, i.e. the collection analysis, to numerical modelling and experimental testing. Insight in the general condition of the objects is obtained by large-scale surveys of museum collections, supplemented by laboratory-based research, in-situ measurements of museum objects and numerical simulations. Moreover, the results of the large-scale surveys are used to verify the experimental and numerical results.

Methodology

The aim of the collection analysis, also referred to as the museum study, is to gather and analyse relevant empirical data from a large group of objects, naturally aged in historic houses and museums. To fulfil this aim, a methodology has been developed incorporating a step-by-step procedure to document the objects and their condition, which is followed by a statistical analysis. To gain insight into the characteristics of damage of decorated oak wooden panels, both archival information and visual inspection of objects has been documented. In the archival study, origin, artist and period, location, acquisition date, history of locations and loan history has been accessed in the museum registers. Further documentation includes conservation reports, records of scientific investigations e.g. analysis of paint layers, dendrochronology, historic photographs or infrared, ultraviolet and X-ray photography. By inspecting individual objects, the following information can be obtained or checked: manufacturing techniques, construction, characteristics of decorative layers, detailed measurements and the precise condition of the object. For the purpose of this study, shrinkage, cracks, and signs of previous conservation treatments were carefully recorded. By linking this with the archival information, the relevant aspects that determine the objects' current condition may be understood as a function, provided by statistical analysis, of its exposure to climatic fluctuations during its lifetime and its susceptibility to these fluctuations.

These relevant aspects are used as input for the development of numerical models which are able to simulate the observed damage in decorated oak wooden panels induced by hygro-thermal climate fluctuations. In these models, the hygro-thermal behaviour is coupled to the discrete fracture behaviour, where the results are calibrated and validated based on the relevant aspects obtained from the collection analysis and experimental measurements. This allows for an in-depth analysis of the complex hygro-thermal-mechanical coupled behaviour of oak wood and damage patterns observed in museum objects. The results of the simulations help to explain the observed damage and current condition of the museum objects. Moreover, the effect of future climate fluctuation on susceptible objects can been predicted.

For the calibration and validation of the numerical model, experiments are performed on well-defined material samples, mock-ups and in-situ objects. Wood is a complex anisotropic material and several studies have already dealt with understanding the structure-function relationships of strongly heterogeneous oak wood (Badel and Perré 2007). The hygro-thermal-mechanical properties obtained from these experiments serve as important input parameters for the numerical model. In addition, typical features of real decorated oak wooden panels, such as age, origin, structure, residual stress etc., are deduced and included in the simulation approach.

The collection analysis and the numerical and experimental studies are interrelated in this research as shown in the scheme in Figure 1. In the collection analysis, a set of decorated wooden panels from the Rijksmuseum collection is analysed and the results on these real objects (RO's) are integrated into a database. This database aims to systematically record the condition of the real objects based on relevant features. The first data set is subjected to a statistical analysis in order to relate relevant features to the observed damage. The statistical characteristics are validated using a second data set, which has a similar variance, and trends and representative objects (in terms of construction, material parameters etc.) are defined. The representative objects are translated into a mock-up, i.e. a representative real object (RRO) and a numerical model, i.e. a representative virtual object (RVO). The RRO is experimentally tested to obtain relevant material behaviour that can be used as input for the RVO. Moreover, the results of the RVO help to design the experiments on the RRO. Then, the RVO is integrated in the statistical analysis built from the RO's. A calibration process fits the RVO to the RO. Once the RVO is properly validated, the RVO is considered representative of the RO, and extended numerical simulations can be performed to better understand the climate-induced damage of decorated panels.

Results

From the museum study carried out at the Rijksmuseum in Amsterdam, the Netherlands, involving more than 370 aged panels, empirical data has been collected, and a number of parameters related to construction, material, history and condition are analysed statistically. The results from the museum study show that shrinkage cracks and failing joints are the most common types of damage registered on decorated oak wooden panels. Shrinkage is recorded on non-restrained (Figure 2.a) as well as restrained panels (Figure 2.b), even though the consequences of shrinkage are more pronounced on restrained panels. As shown in Table 1, glue joint failure is identified on 72.0% of the restrained doors and 73.3% of the restrained panel paintings. For non-restrained panels the scenario is different: only 18.0% of the non-restrained doors and 20.2% of the non-restrained panel paintings show glue joint failure. The comparably high amount of glue joint failure identified on the non-restrained panel paintings can probably be explained by a restrained (historic) mounting in the frame. The core construction of the panel is the most determining characteristic to assess the risks of mechanical damage of decorated wooden panels. Movements in the core construction also influence the condition of overlaying layers, as open glue joints or cracks in wood in many cases result in losses or lifting of the decorative layers. The correlation between restraint, i.e., the restriction of a board to deform freely, and damage is one of the relevant features that is currently investigated.

As a result of the selection criteria, all panels in the museum study are made of an oak wood substrate, of which a great majority of the panels is made of radial-cut boards. This explains the relatively large amount of shrinkage in the radial direction and the low frequency of out of plane deformation, such as cupping or warping. Since the weakest points of the objects are the glue joints between the different members of the panel, the number of boards in a structure is highly significant for the current state of the object. It can be concluded from the museum study that the complexity of the structure of the object is of importance for understanding the type of damage observed.

To further analyse the relation between the structure and the type of damage identified on decorated oak wooden panels and to assess if the observed damage is induced by climate fluctuations, a representative real object (i.e. a mock-up) and a representative virtual object (i.e. a numerical model) are selected by the methodology outlined in the methodology section. Both representative objects are based on the following relevant features: panel structure, dimensions, number of boards, presence of cleated ends and veneer layers, and type of joints. Two types of panel structures are analysed, namely non-restrained and restrained panels, as these structures correspond to the least and most severe types of damage observed, respectively. The maximum width, height and thickness of the objects are equal to 547mm, 732mm and 15mm respectively. The non-restrained objects are composed of three boards joined by a butt joint and animal glue while the restrained objects are composed of three boards, also joined by a butt joint and animal glue, and two cleated ends joined by a tongue and groove joint and animal glue (Figure 2). The effects of veneer layers are analysed as well, as non-restrained and restrained objects are both provided with veneer layers. The objects are exposed to two different climate profiles: i) a step-wise climate profile for which the relative humidity decreases from 60% to 35% in steps of 5% every 5 days, whereby the temperature is fixed at 20°C and ii) a variable climate for which the relative humidity fluctuations are representative for the climate measured in Amerongen Castle, the Netherlands, during the period 18 January to 19 February 2012, whereby the temperature is constant and equal to 20°C.

The experiments on the mock-ups (RRO's) are in progress. The experimental set-up can be seen in Figure 3, and preliminary results of the restrained mock-up that is exposed to climate profile i) are presented in Figures 4 and 5. As can be observed from Figure 3, the applied climate profile and the response of the mock-up is measured by means of temperature and relative humidity sensors, strain gauges, linear variable displacement transducers (LVDT's) and moisture content (MC) sensors. Figures 4 and 5 show the measured relative humidity and strain. It can be seen that the mock-up responds immediately when a step change in relative humidity is applied. Besides, the measured negative strain (shrinkage) is increasing for a decreasing relative humidity. Note that the amount of shrinkage is different for different measurement locations. The strain gauges indicated by numbers 04 and 16 show less strain compared to the strain gauges indicated by the numbers 01, 08, 13 and 20, as these locations are more constrained due to the close presence of the cleated ends.

The numerical model (RVO) is under development; the first results are presented in Luimes et al. (2016), which considers the analysis of the mechanically-induced fracture behaviour of historic oak wood. The fracture behaviour of samples with three different dates of origin is characterized in terms of failure response, fracture energy, fracture path and failure mechanisms at the microscale. The discrete fracture behaviour is simulated with an interface damage model and the numerical results showed to be in good agreement with experimental results (Figure 6). Currently, the discrete fracture model is combined with a hygro-thermal model in order to simulate climate-induced damage of museum objects.

To further analyse in-situ objects in their current indoor climate, two representative objects were selected: the 17th century cabinets by cabinetmaker Jan Van Mekeren (1658-1733) from the collections of the Rijksmuseum (Figure 7.a) and Amerongen Castle (Figure 7.b) in the Netherlands. In the grand hall of Amerongen Castle two cabinets decorated with floral marquetry can be found. The cabinets have many cracks, mostly hairline cracks in the veneers, but also larger cracks in the construction; these cabinets have hardly received any conservation treatment. A cabinet very similar to the cabinets in Amerongen Castle is on display in the Rijksmuseum. The Van Mekeren cabinet in the Rijksmuseum was in similar condition as the Van Mekeren cabinets in Amerongen Castle before it received conservation treatment in 1995 (Breebaart 2012, Van Duin 2012). Today, there are great differences in the climate surrounding the cabinets in Amerongen Castle and in the Rijksmuseum, respectively. At Amerongen Castle the relative humidity of the room varied between 35% and 75% relative humidity and the temperature varied between 9°C and 25°C based on measurements in the year 2011 (Huijbregts et al., 2015) while in the Rijksmuseum the relative humidity varies between 45 and 60 % and the temperature varies between 19°C to 23°C. By monitoring the two cabinets during a period of one year - by several out-of-plane deformation sensors placed on the same spots in both cabinets -, substantial information is gained about the long-term effects of the surrounding micro-climate on the mechanical response of the objects, as comparative measurements. The results of the measurements on the Van Mekeren cabinets are used to build the statistical models and the measured mechanical response of aged decorated oak wooden panels serves as input for the numerical model. The combined experimental-numerical case study helps scientists to better understand damage formation.

Challenges and relevance for conservation practice

The primary challenging task of this project is to deliver practical information and tools that can be successfully used in the decision making process for acceptable climate fluctuations. What is needed in this respect, is information on large sets of objects coming from different locations. Additionally, insight is provided into what conditions can be expected in relation to construction, material and historical parameters.

The challenge for the experimental and numerical work is to develop a robust way of accessing the visual changes and observed damage and to link the experimental and simulated response to the observed response of the actual museum objects. The methodology applied in this research is essential for overcoming this challenge. For example, an innovative process to characterize the unrestrained mechanical response of a wooden panel is developed for which a step-by-step experiment on a mock-up is designed that can be directly integrated in the modelling study. The representativeness of the mock-up is an important issue to consider in detail, since the museum objects generally exhibit aged material behaviour while the mock-up is made of new material. This matter is obviated by performing additional experiments on small material samples of different age, where the results are used as direct input in the numerical simulations, as is done for the analysis of the fracture behaviour of historic oak wood outlined in the results section.

Summary and Conclusions

A multidisciplinary methodology for the analysis of damage processes in decorated oak wooden panels has been presented. This involves the collaboration of a wide variety of specialists: conservators, scientists and engineers. The research contributes to the understanding of material properties, panel construction types, influence of aging, damage processes and subsequently to the development of sustainable future preservation strategies.

Ultimately, predictions may be made for the susceptibility of the objects to future climate fluctuations, helping museums throughout the world to further develop rational guidelines for sustainable climate specifications.

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Table titles and Figure captions

Table 1. Results of the museum study at Rijksmuseum. Damage of the core construction of restrained and non-restrained panels, respectively

Figure 1. Cognitive scheme of the interaction between the collection analysis, numerical modelling and experimental testing

Figure 2. Principal panel structures. (a) Non-restrained three board panel. (b) Restrained three board panel with cleated ends. The black arrows indicate the wood grain direction and the yellow lines indicate animal glue lines

Figure 3. Experimental set-up. Climate chamber with restrained mock-up onto which measurement devices are applied

Figure 4. (a) Front view of the restrained mock-up. The location of the relative humidity sensor is indicated by the black box. (b) Experimental relative humidity-time curve (continuous black line) for a restrained mock-up. The climate chamber set point is indicated by the dashed black line

Figure 5. (a) Front view of the restrained mock-up. The locations of the strain gauges are indicated by the black boxes and numbers. (b) Experimental strain-time curves for a restrained mock-up

Figure 6. Simulated (upper) and observed (lower) fracture path of oak wood dated 1300 A.D. a) Elastic response. b) Crack initiation. c) Crack propagation. d) Ultimate failure

Figure 7. Cabinets made by Jan Van Mekeren. (a) Rijksmuseum. (b) Amerongen Castle