ICOM-CC
18th Triennial Conference
2017 Copenhagen

PREVENTIVE CONSERVATION

The development of a methodology to understand climate-induced damage in decorated oak wood panels

S.E. EKELUND*
Rijksmuseum Amsterdam/Eindhoven University of Technology
Amsterdam/Eindhoven, The Netherlands
s.ekelund@rijksmuseum.nl
stinaekelund@hotmail.com

R.A. LUIMES
Eindhoven University of Technology
Eindhoven, The Netherlands
R.A.Luimes@tue.nl

C.A.F. GAUVIN
Eindhoven University of Technology
Eindhoven, The Netherlands
C.A.F.Gauvin@tue.nl

P.H.J.C. VAN DUIN
Rijksmuseum
Amsterdam, The Netherlands
P.van.Duin@rijksmuseum.nl

A.J.M. JORISSEN
Eindhoven University of Technology
Eindhoven, The Netherlands
A.J.M.Jorissen@bwk.tue.nl

H.A. ANKERSMIT
Cultural Heritage Agency of the Netherlands
Amersfoort, The Netherlands
B.Ankersmit@cultureelerfgoed.nl

A.S.J. SUIKER
Eindhoven University of Technology
Eindhoven, The Netherlands
A.S.J.Suiker@tue.nl

R.M. GROVES
Delft University of Technology
Delft, The Netherlands
R.M.Groves@tudelft.nl

H.L. SCHELLEN
Eindhoven University of Technology
Eindhoven, The Netherlands
H.L.Schellen@bwk.tue.nl

*Author for correspondence

KEYWORDS: decorated panels, oak wood, panel paintings, furniture, museum indoor climate, empirical data, numerical simulations

ABSTRACT

Climate-induced damage in decorated oak wood panels is considered to be a high risk for pre-eminent museum collections. To advise museums on the development of sustainable future preservation strategies and rational guidelines for indoor climate specifications, the risk of this type of damage – physical and mechanical

INTRODUCTION

For conservators and other museum professionals, an important task is to minimise the risk of damage, so changes to the condition of the objects, such as out-of-plane deformation, shrinkage, delamination and cracks, should be avoided. However, it is still difficult to predict under which circumstances such changes occur, but, generally, fluctuations in the indoor museum climate are regarded as a high risk for objects. Therefore, in previous research, the focus has been mainly on monitoring the indoor climate instead of monitoring possible changes to the objects; reading climate graphs is more straightforward than monitoring object changes. For this reason, in this research, decorated oak wood panels were analysed to develop preventive conservation strategies and to advise on acceptable microclimate fluctuations for museum objects.

To increase knowledge on the effects of climate fluctuations on actual museum objects, scientific research has been performed since the 1980s. 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 regulating the indoor museum climate. Mechanical and physical properties at a variety of climate conditions were 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 when subject to microclimate 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 have been 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 a gap between the results obtained by laboratory and numerically based research, and the general observations of conservators working with aged museum objects. Accordingly, the conservation community requires 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.

– is analysed in full depth in this research. A comprehensive methodology is required that meets the requests of the conservation community and also helps to bridge the gap between scientists and conservators. Therefore, this research couples an extensive examination of empirical data obtained from naturally aged museum objects, i.e. a collection analysis, with numerical modelling and experimental testing. A multidisciplinary collaboration has been initiated, whereby conservators and scientists are working together to fulfil the common objectives of sustainable and low-risk preservation of valuable museum collections. In this paper, the methodology is outlined and some results are presented.

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, with numerical modelling and experimental testing. Insight into 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 a collection analysis, also referred to as a 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 is developed incorporating a step-by-step procedure to document the objects and their condition, which is followed by a statistical analysis (Ekelund 2017). To gain insight into the characteristics of damage to decorated oak wood panels, both archival information and visual inspection of objects is documented. In the archival study, the origin, artist and period, location, acquisition date, history of locations and loan history is accessed in the museum registers. Further documentation includes conservation reports, records of scientific investigations, e.g. analysis of paint layers, dendrochronology, historic photographs and infrared, ultraviolet and x-ray photography. By inspecting individual objects, the following information is obtained: 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 determining an object's 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 were used as inputs for the development of numerical models which were able to simulate the observed damage in decorated oak wood panels induced by hygrothermal climate fluctuations. In these models, the hygrothermal behaviour was coupled with discrete fracture behaviour, where the results were calibrated and validated based on the relevant aspects obtained from the collection analysis and experimental measurements. This allowed for an in-depth analysis of the complex hygrothermal-mechanical-coupled behaviour of oak wood and damage patterns observed in museum objects. The results of the simulations helped to explain the observed damage and current condition of the museum objects. Moreover, the effect of future climate fluctuation on susceptible objects can be predicted.

For the calibration and validation of the numerical model, experiments were performed on well-defined material samples and mock-ups, as well as measurements on 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 hygrothermal-mechanical properties obtained from these experiments served as important input parameters for the numerical model. In addition, typical features of real decorated oak wood panels, such as age, origin, construction, residual stress, etc., were deduced and included in the simulation approach.

The collection analysis and the numerical and experimental studies were inter-related 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 was analysed and the results from these real objects (ROs) were integrated into a database. This database aimed to systematically record the condition of the real objects based on relevant features. The first data set was subjected to a statistical analysis in order to relate relevant features to the observed damage. The statistical characteristics were validated using a second data set, which had a similar variance, and trends and representative objects (in terms of construction, material parameters, etc.) were defined. The representative objects were 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 was experimentally tested to obtain relevant material behaviour that could be used as input for the RVO. Moreover, the results of the RVO helped to design the experiments on the RRO. The RVO was then integrated into the statistical analysis built from the ROs. A calibration process fitted the RVO to the RO. Once the RVO was properly validated, it was considered representative of the RO, and extended numerical simulations could be performed to better understand the climate-induced damage of the decorated panels.

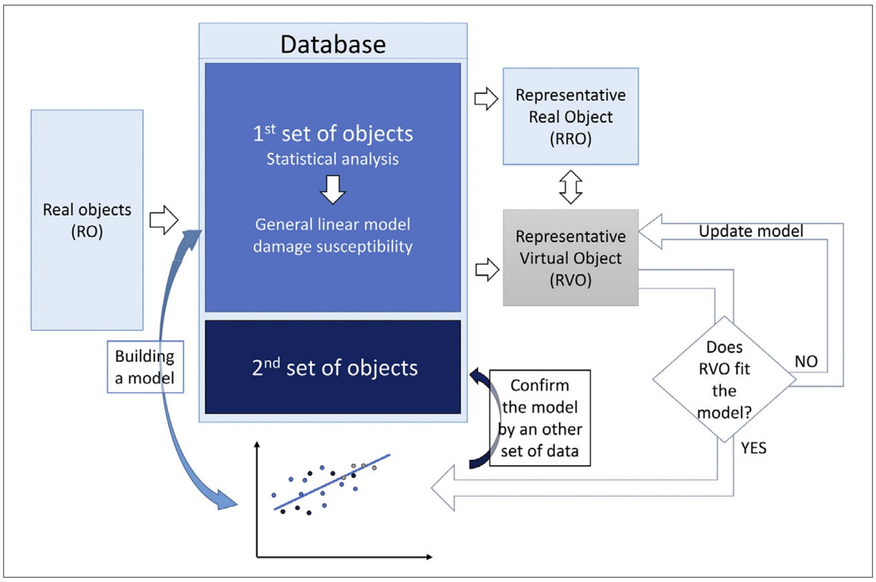

Figure 1. Cognitive scheme for the interaction between the collection analysis, numerical modelling and experimental testing

RESULTS

From the museum study carried out at the Rijksmuseum in Amsterdam, the Netherlands, involving more than 370 aged panels, empirical data was collected and a number of parameters related to construction, material, history and condition were analysed statistically. The results from the museum study showed that shrinkage cracks and failing joints were the most common types of damage registered on decorated oak wood panels.

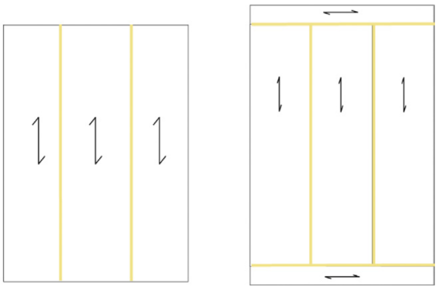

Figure 2. Principal panel structures: a) non-restrained three-board panel; b) restrained three-board panel with cleated ends. The black arrows indicate the wood grain direction and the yellow lines indicate animal glue lines

Shrinkage was recorded on non-restrained (Figure 2a) as well as restrained panels (Figure 2b), even though the consequences of shrinkage were more pronounced on restrained panels. As shown in Table 1, glue-joint failure was identified on 72% of the restrained doors and 73.3% of the restrained panel paintings. For non-restrained panels, the scenario was different: only 18% of the non-restrained doors and 20.2% of the non-restrained panel paintings showed 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 was the most determinant characteristic for assessing risks of mechanical damage on decorated wooden panels. Movements in the core construction also influenced the condition of overlaying layers, as open glue joints or cracks in wood in many cases resulted 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 being investigated.

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

Core construction	Dutch cabinet doors (n = 128)				Dutch 17th-c. panel paintings (n = 249)			
	restrained		non-restrained		restrained		non-restrained	
	n	percentage	n	percentage	n	percentage	n	percentage
Glue joint failure	68	72.0 %	50	18.0 %	71	73.2 %	178	20.2 %
Crack in wood	68	53.3 %	60	8.8 %	71	18.3 %	178	15.7 %

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

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

The experiments on the mock-ups (RROs) are underway. The experimental set-up can be seen in Figure 3 and the preliminary results for the restrained mock-up 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 was measured by means of temperature and relative humidity sensors, strain gauges, linear variable displacement transducers (LVDTs) and moisture content (MC) sensors. Figures 4 and 5 show the measured relative humidity and strain. It can be seen that the mock-up responded immediately when a step change in relative humidity was applied. Furthermore, the measured negative strain (shrinkage) increased

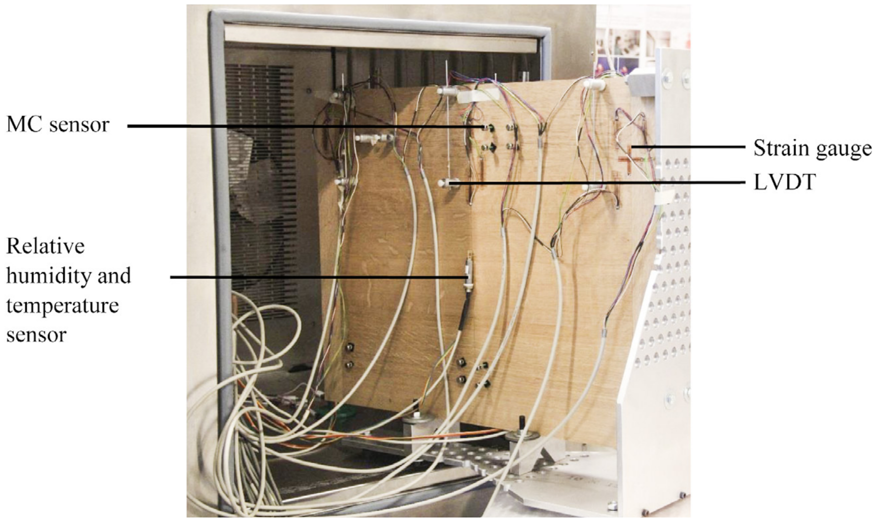

Figure 3. Experimental set-up. Climate chamber with restrained mock-up onto which measurement devices are applied

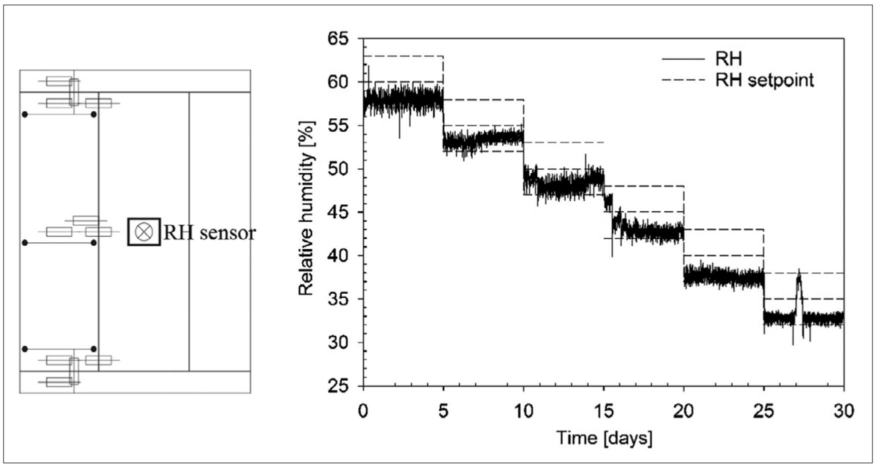

Figure 4. a) Front view of the restrained mock-up. The location of the relative humidity sensor is indicated by the black box. b) Experimental relative-humidity time curve (continuous black line) for a restrained mock-up. The climate chamber set point is indicated by the dashed black line

with decreasing relative humidity. Note that the amount of shrinkage was different for different measurement locations. The strain gauges indicated by numbers 04 and 16 showed less strain compared to the strain gauges indicated by the numbers 01, 08, 13 and 20, as these locations were more constrained due to the close presence of the cleated ends.

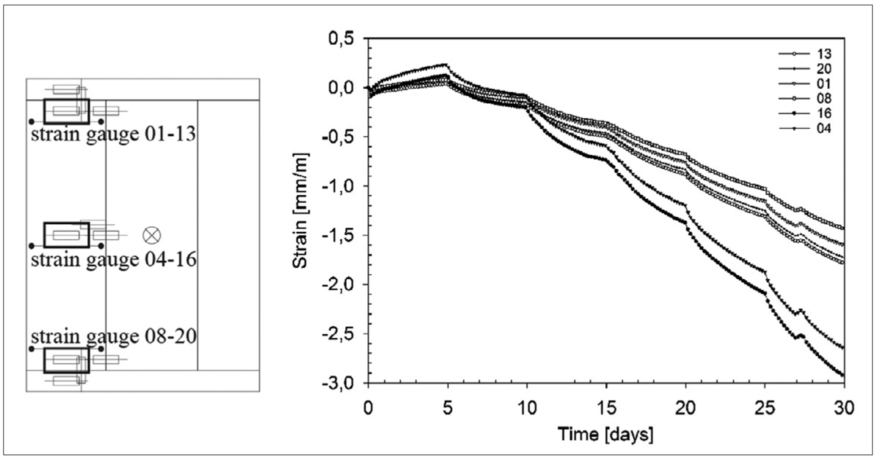

Figure 5. a) Front view of the restrained mock-up. The locations of the strain gauges are indicated by the black boxes and numbers. b) Experimental strain-time curves for a restrained mock-up

The numerical model (RVO) is under development; the first results were 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 was characterised in terms of failure response, fracture energy, fracture path and failure mechanisms at microscale. The discrete fracture behaviour was simulated with an interface damage model and the numerical results were closely aligned with the experimental results (Figure 6). Currently, the discrete fracture model is combined with a hygrothermal model in order to simulate climate-induced damage to museum objects.

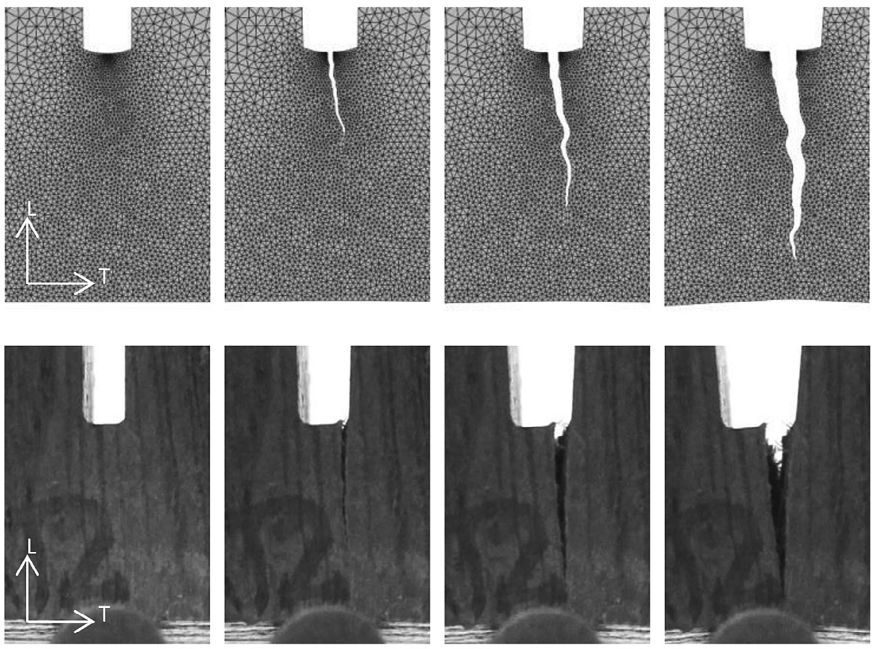

Figure 6. Simulated (upper) and observed (lower) fracture path of oak wood dated 1300 AD: (a) elastic response; (b) crack initiation; (c) crack propagation; (d) ultimate failure

To further analyse in-situ objects in their current indoor climate, two representative objects were selected: the late 17th-century cabinets by cabinetmaker Jan Van Mekeren (1658–1733) from the collections at the Rijksmuseum (Figure 7a) and Amerongen Castle (Figure 7b) 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 to 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 varies between 35% and 75% and the temperature between 9°C and 25°C based on measurements taken in 2011 (Huijbregts et al. 2015), while at the Rijksmuseum the relative humidity varies between 45% and 60% and the temperature between 19°C and 23°C. By monitoring the two cabinets for a period of one year – via several out-of-plane deformation sensors placed on the same spots in both cabinets – substantial information was gained about the long-term effects of the surrounding microclimate on the mechanical response of the objects, as comparative measurements. The results of the measurements on the Van Mekeren cabinets were used to build the statistical models and the measured mechanical response of the aged decorated oak wood panels served as an input for the numerical model. The combined experimental-numerical case study helped scientists to better understand damage formation.

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

CHALLENGES AND RELEVANCE FOR CONSERVATION PRACTICE

The primary challenge of this project was 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 characterise the unrestrained mechanical response of a wooden panel has been 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 wood panels was presented. This involves the collaboration of a wide variety of specialists: conservators, scientists and engineers. The research has contributed to the understanding of material properties, panel construction types, the influence of ageing and 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.

ACKNOWLEDGEMENTS

This work is part of the research programme Science4Arts, which is financed by the Netherlands Organisation for Scientific Research (NWO SFA-11-01). The authors would like to thank Carola Klinzmann, furniture conservator at Museumslandschaft Hessen Kassel, the Rijksmuseum paintings and furniture conservation departments, and the director and staff of Castle Amerongen for their assistance in carrying out the research.

REFERENCES

BADEL, E. and P. PERRÉ. 2007. The shrinkage of oak predicted from its anatomical pattern: Validation of a cognitive model. *Trees* 21: 111–20.

BOERSMA, F., K. DARDES, and J. DRUZIK. 2014. Precaution, proof and pragmatism – Evolving perspective on the museum environment. *Collection Environments, Conservation Perspectives. The GCI Newsletter* 29(2): 5–9.

BRATASZ, L. 2010. Acceptable and non-acceptable microclimate variability: The case of wood. In *Basic environmental mechanisms affecting cultural heritage. Understanding deterioration mechanisms for conservation purposes. COST Action D42 chemical interactions between cultural artefacts and indoor environment,* eds. D. Camuffo, V. Fassina, and J. Havermans, 49–58. Florence: Nardini Editore.

BREEBAART, I. 2010. A structural approach to a complex conservation of two late 17th-century cabinets-on-stand in the collection of the Rijksmuseum in Amsterdam. In *Restoring Joints, Conserving Structures. Proceedings of the Tenth International Symposium on Wood and Furniture*, ed. M. Vasques Dias, 82–93. Amsterdam: Stichting Ebenist.

COLVILLE, J., W. KILPATRICK, and M.F. MECKLENBURG. 1982. A finite element analysis of multi-layered orthotropic membrane with applications to oil paintings on fabric. In *Science and Technology in the Service of Conservation. Preprints of the Washington Congress*, eds. N.S. Brommelle and G. Thomson, 150–56. London: International Institute for the Conservation of Artistic and Historic Works (IIC).

EKELUND, S., P.H.J.C. VAN DUIN, A.J.M. JORISSEN, B. ANKERSMIT, and R.M. GROVES. 2017. A method for studying climate-related changes in the condition of decorated wooden panels. *Studies in Conservation* (DOI:10.1080/00393630.2017.1325553).

ERHARDT, D., C.S. TUMOSA, and M.F. MECKLENBURG. 2007. Applying science to the question of museum climate. In *Museum Microclimates*, eds. T. Padfield and K. Borchersen, 11–18. Copenhagen: National Museum of Denmark.

HUIJBREGTS, Z., H.L. SCHELLEN, A.W.M. VAN SCHIJNDEL, and H.A. ANKERSMIT. 2015. 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. *Journal of Cultural Heritage* 16(4): 419–27.

KONOPKA, D. 2016. Hygro-mechanical structural analysis of keyboard instruments. In *Symposium of Analysis and Characterisation of Wooden Cultural Heritage by Scientific Engineering Methods*, Halle, Germany.

LUIMES, R.A., A.S.J. SUIKER, H.L. SCHELLEN, and A.J.M. JORISSEN. 2016. Fracture behaviour of historic oak wood. In *Proceedings of the WCTE 2016 World Conference on Timber Engineering*, 107, 1–9, Vienna.

SAFT, S. and M. KALISKE. 2011. Numerical simulation of the ductile failure of mechanically and moisture loaded wooden structures. *Computers and Structures* 89(2011): 2460–70.

VAN DUIN, P. 2012. The construction of flat decorated doors of Dutch seventeenth-century cabinets. Report of a master class. In *Restoring Joints, Conserving Structures. Proceedings of the Tenth International Symposium on Wood and Furniture*, ed. M. Vasques Dias, 121–43. Amsterdam: Stichting Ebenist.

VAN DUIN, P. 2014. Climate effects on museum objects – The need for monitoring and analysis. *Conservation Perspectives. The GCI Newsletter* 29(2): 13–15.

How to cite this article:

Ekelund, S.E., R.A. Luimes, C.A.F. Gauvin, P.H.J.C. Van Duin, A.J.M. Jorissen, H.A. Ankersmit, A.S.J. Suiker, R.M. Groves, H.L. Schellen. 2017. The development of a methodology to understand climate-induced damage in decorated oak wood panels. In *ICOM-CC 18th Triennial Conference Preprints, Copenhagen, 4–8 September 2017,* ed. J. Bridgland, art. 1507. Paris: International Council of Museums.