Climate-Induced Damage of Wood: Numerical Modeling and Direct Tracing

By Roman Kozłowski

Introduction

Uncontrolled variations of relative humidity (RH) in the environment are the principal hazard to the preservation of wood indoors. The climate-induced stress is caused by the hygroscopic nature of wood and its dimensional response to the sorption or desorption of moisture. If moist wood is restrained from natural shrinkage on drying, it will experience tension leading to irreversible stretching and eventual cracking. If a dried wood is restrained from free swelling on return to high-RH regions, it can undergo plastic deformation in compression, with resulting crushing of the internal structure and buckling. The damage is not limited to wood itself but also threatens decorative layers for which wood serves as a substrate. Panel paintings, polychrome wooden sculpture, and lacquer objects are examples of works of art particularly vulnerable to RH variations. The recent extensive analysis of the deformation and response of the 13 mm thick panel of poplar, on which Leonardo's *Mona Lisa* is painted, to the variations of climatic parameters in the painting's environment, is a good illustration of the problem (Perré, Rémond, and Gril 2006). Also, Vici, Mazzanti, and Uzielli reported extensive research on wooden boards, simulating the supports of panel paintings, that were subjected to step variations of RH (Vici, Mazzanti, and Uzielli 2006).

To implement an effective protective strategy for wooden objects, precise cause-effect relationships between the magnitude and rate of the RH variations, on the one hand, and the physical change in the wood, on the other hand, are necessary. Knowledge of such relationships allows identification of critical levels of a specific climatic hazard beyond which objects can suffer irreversible deformation or damage. This knowledge is a vital condition for establishing standards for the environments of historic objects, as well as for establishing guidelines for a range of issues such as heating, ventilation, and air-conditioning in buildings, or the display, packing, handling, and transporting of objects.

The research effort to determine the response of painted wood to RH variations was undertaken first by Mecklenburg, Tumosa, and Erhardt (1998). They quantified mechanical properties and dimensional responses (strain) of materials constituting painted wooden objects, such as wood itself, hide glues, gesso, paints, and varnishes. By relating the independent RH responses of each of these materials, the authors could determine the allowable RH fluctuations a particular composite object may ultimately endure without irreversible deformation or damage. Their analysis of the climate-induced risk of the mechanical damage to the wood itself is worth considering in detail. Strain-stress relationships were determined for several species of wood. The researchers also identified strain levels at which wood begins to deform plastically (yield points) or at which mechanical damage occurs. Then the dimensional responses of the same wood species were determined within a full range of RH, and the critical or threshold changes in RH that induced strain levels corresponding to the yield point or failure were derived. The largest response in the direction tangential to the growth rings was considered, as this represented the worst-case condition. As the dimensional response depends strongly on RH, the allowable RH variations were presented as functions of the starting RH levels.

The described approach, however, could provide only a first approximation of the critical RH variations endangering the wooden objects. The model was valid for pieces of wood cut from positions away from the axis of the tree trunk; it neglected the curvature of the growth rings. Such simplification is not, however, valid for wooden sculptures that can be regarded as carved of a tree trunk with the sculpted surfaces loosely following the tangential planes parallel to the trunk axis. Furthermore, the model provided only maximum values of stress corresponding to the maximum possible restraint of the object, without showing how the stress levels depended on the time periods over which the RH variation occurred.

The Mecklenburg approach was therefore further refined by a project undertaking full numerical modeling of the moisture movement in wooden objects in response to RH variations, as well as assessments of resulting internal stresses and risks of damage (Bratasz, Jakieła, and Kozłowski 2005; Jakieła, Bratasz, and Kozłowski 2008a)

A case of a massive wooden cylinder, simulating a wooden sculpture, was considered, as it constitutes one of the worst cases in terms of risk of climate-induced damage to wooden objects. The stress development in such an object is the result of slow moisture diffusion in response to the change in ambient RH. For example, when RH is reduced, the outer part of the wood will dry more quickly than will the interior. The dry outer part will then be restrained from shrinkage by the still-wet core beneath, a circumstance that will result in mechanical stress: the outer shell will go into tension, and the core will go into compression. A particularly important aim of the study was to determine the allowable thresholds—i.e., the amplitude and rate of RH variations that wooden cylindrical objects can safely endure.

Numerical Modeling of Moisture Movement in a Wooden Cylinder and a Related Stress Field

Of several elementary strains that add up to the total strain of a specimen, our model considered only elastic strain. The investigations focused on acceptable levels of strain, such that the wood's response would be completely recoverable after removal of the stress. Therefore, the model did not consider plastic deformations. Furthermore, the viscoelastic strain was neglected, as its contribution at normal indoor temperatures is very small in comparison to that of the elastic strain. Also, the thermal strain is insignificant, as thermal expansion is almost isotropic, and the heat diffusivity is rapid when compared with rates of temperature variations in the usual display environments.

The results of the modeling are shown below for limewood (*Tilia* spp.), as this wood was widely used in the past to produce wooden sculptures and decorations, for reasons of availability and ease of processing. The following material properties, required to model moisture transport in wood and the resulting internal stresses due to nonuniform moisture distribution on drying or wetting, were determined in the laboratory:

- equilibrium moisture contents (EMC) at several temperatures (T) and for a full range of RH;
- moisture diffusion coefficients as a function of moisture content in wood;
- mechanical properties: Young's moduli, yield points, and strengths;
- swelling/shrinkage in radial and tangential anatomical directions in response to changes in T and RH.

The modeling aimed to analyze water vapor movement into or out of wood in response to variations of T and RH in its environment, and thus to calculate the evolution of the moisture content gradient across wood. The numerical technique employed sought to change the continuous process of water vapor diffusion into a discrete event in the time and spatial domain. The finite elements method and a cylindrical computational mesh, commensurable with the symmetry of a tree trunk, were used. Moisture transport along the radial direction only was considered, and the calculation was limited to the cross section of the cylinder. In this way, the moisture exchanges and the related stress field were independent of the length of a cylinder. The field of stress for each moisture distribution and the related restrained dimensional change were obtained with the use of the finite elements procedure, using the same cylindrical computational mesh.

The results of the modeling are shown as stress levels induced by RH variations. As mentioned above, they depend not only on the magnitude of that variation but also on the RH range within which the variation occurs. Therefore, maps of the stress values which took into account the starting RH levels had to be produced. Two such maps, calculated for a wooden cylinder of a diameter of 13 cm for two different time scales of the RH variations—instantaneous and diurnal—are shown in figures 1 and 2. Domains of RH variations endangering wood by causing deformation or complete failure are marked, as are tolerable RH variations producing stress within the elastic domain. The map of stress levels induced by the instantaneous RH variations shows that any variation exceeding 10%–15% produces stresses exceeding the elastic limit, in which case wood can undergo damaging plastic deformations. The risk of failure appears for the RH variation of 40% if the change occurs from a high initial RH level of above 95%. The variations centered on 50% RH can be considered the safest—a fact that confirms the established observations of the conservation practice. The reason for that finding is that the least slope of the dependence between RH and moisture content in wood is in the midregion of the water vapor adsorption isotherm.

The map of stress levels induced by slower, diurnal variations (fig. 2) indicates an increase of the domain of RH variations that produce stress levels within the elastic limit safe for the material. RH variations potentially leading to failure have been practically eliminated.

The numerical simulations open up the possibility of considering the climate-induced risk of damage to wooden objects of any size or form, possessing individual mechanical and moisture transport characteristics, and exposed to any real-world display conditions. The calculated outcome is precise and reliable, at least for a comparative evaluation of similar cases. Somewhat arbitrary decisions, however, must be made in the selection of critical levels above which RH variations should be assumed to endanger wooden objects. Analysis of rapid RH variations should be undertaken if the activities of humans—operating heating or air-conditioning systems intermittently or transporting works of art without sufficient care for climate control—are considered as the hazards. In contrast, longer time scales for the RH variations need to be taken into account to describe the effects of natural climatic variations. In the Noah's Ark project on the effects of global climate change on cultural heritage, the diurnal variations of RH were used to describe risk, and a 30% magnitude of the variation was taken as the threshold value—with a considerable damage potential, according to the results of the modeling presented above (for more details, see the project's Web site, www.noahsark.isac.cnr.it).

The numerical simulations, however, and the cause-effect relationships between the RH variations and the physical changes in the wood that they produce cannot be relied upon as a fully adequate tool of risk assessment. The principal problem is that the numerical simulations depend highly on the availability and quality of the wood's parameters, which may not be known a priori. While these can usually be determined for samples of new wood, such assessments may not necessarily reflect the actual material properties of historic wooden objects that have adapted over many decades to a particular indoor environment in which they have been preserved. Such adaptation might have involved an unknown level of permanent change, like deformation or fracturing, which may accommodate stress and shift the yield point of the material. Therefore, numerical simulations using material characteristics typical of new wood can be considered only as general indications of risk. Furthermore, the modeling yields discrete values of the thresholds in the magnitude of the RH variations, whereas failure of wood discernible from the macroscopic perspective is preceded by the progressive evolution of damage at the microlevel. It is generally known that the continuous accumulation of such slight changes—rather than infrequent serious damaging events—accounts for much of the deterioration process observed.

Therefore, application of nondestructive methods of direct tracing of physical change in historic materials, like fracturing intensity at the microlevel or delamination of the surface decorative layers, is an important research task. Such methods have been developed for applications in engineering, but they have not been sufficiently adapted to tracing damage in cultural heritage objects. And yet, direct tracing of physical change is the optimal way for indicating risk to objects in museums or risk during their transportation. The ultimate goal should be economical and easily available sensors, warning the staff of increased risk to sensitive objects.

An example of a nondestructive tool for directly tracing the fracturing intensity in wooden cultural objects exposed to RH variations in their environment is the monitoring of acoustic emission. This tool has been popular in wood science and technology but has only recently been successfully applied to diagnosing cultural wooden objects (Jakieła, Bratasz, and Kozłowski 2007, 2008b).

Tracing the Evolution of Damage in Wooden Objects by Acoustic Emission Monitoring

Acoustic emission (AE) is defined as energy released because of microdisplacements in the structure of materials undergoing deformation. The energy, which passes through a material as ultrasound waves, is typically detected through the use of a piezoelectric transducer coupled to the surface. The piezoelectric transducer converts the surface vibration to a voltage signal that is preamplified with the maximum gain in the frequency range of 60–1000 kHz. The schematic of a signal processing system of an AE sensor designed for monitoring damage in works of art is shown in figure 3.

The AE events recorded in wooden objects, both in the laboratory and in historic buildings, could be divided generally into two time-frequency bands: one of low frequency, 5–30 kHz, and long duration, 500–2,000 μs; and the other of high frequency, 80–300 kHz, and short duration, 20–450 μs. The low-frequency events were observed when specimens were subjected to a mechanical impact, when they were subjected to a change of temperature alone, or when two pieces of wood were rubbed one against the other. In contrast, high-frequency events accounted for 90% to 95% of all events recorded when the specimens were subjected to stress leading to the wood's damage. It was therefore evident that a frequency signature existed in the AE waveforms: the short, high-frequency events could be associated with fracturing of the wood structure, whereas the long, low-frequency events could be associated with nondestructive processes like reversible dimensional changes or spurious noises. To extract the high-frequency AE components related to mechanical damage, the signal of the transducer was divided, filtered by both low-pass and high-pass filters, and amplified. Then the events that contained low-frequency components were eliminated by a microprocessor. The AE activity related to damage was recorded in the memory as energy of high-frequency events accumulated per certain time intervals—for example, 15 min. The level of the AE activity could then be displayed, recorded in a datalogger via the analog output, or transmitted into a computer via the digital output.

The accumulated energy of the high-frequency components was found to depend on the magnitude and rate of the RH variations. The AE activity became negligible below the threshold magnitude for the rapid RH variation characteristic of a given object, or when the time interval allowed for the RH variation increased above a critical level, corresponding to a safe adaptation time for the object. Moreover, the AE activity correlated well with the predictions of numerical simulations described above.

The method was also applied on-site to the monitoring of wooden objects in historic churches: sculptures of the altarpiece in the church of Santa Maria Maddalena in Rocca Pietore, Italy, and wooden elements of historic organs of the church of Saint Andrew the Apostle in Olkusz, Poland. The field tests further confirmed the usefulness of the technique in tracing climate-induced stress in wood. Acoustic signals related to church activities, such as the sounds of bells, did not affect the measurements. The burst of AE activity clearly correlated with adverse climatic variations in the indoor climates of the churches, caused mainly by intermittent heating in winter for the church services. The AE monitoring directly followed the ongoing fracturing of the old wood. It showed, as expected, that the threshold in the magnitude of the damaging RH variations was not a discrete value. The increasing energy of burst events was recorded at increased loading as fracturing occurred in locally weakened areas in wood. A failure of wood discernible from the macroscopic perspective was therefore preceded by the progressive evolution of damage at the microlevel. This finding was in contrast to results for the new wood monitored in the laboratory, for which almost no AE activity—and therefore no fracturing—was observed below the threshold.

The research has led to the development of an economical AE sensor, which can be mounted on a wooden object or on a wooden dummy imitating an object, to monitor the risk of mechanical damage in a given environment. The calibration procedure showed that the smallest damage the sensor was able to trace corresponded to a fractured area of only 5 μm^2—thus the sensor fulfilled the requirement for damage detection at the microlevel. The allowable amount of accumulated energy can be decided on case-by-case basis. If this level is exceeded, an increased risk of mechanical damage to the object is documented. An alarm can then be activated to warn the staff of the increased risk of mechanical damage to sensitive objects.

Author Biography

Roman Kozłowski graduated in chemistry in 1970 (MSc), received his PhD in 1974, and received his DSc in 1989 from the Jagiellonian University in Krakow, Poland. Since 1986 he has been head of research related to conservation science and to the protection of cultural heritage at the Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences (ICSC PAS), Krakow. He was principal investigator for several research projects within the Fourth, Fifth, and Sixth Framework Programmes of the European Commission. His research focuses on microclimatic monitoring, response of materials to changes in environmental parameters, composition and porous structures of historic materials, and their interaction with moisture.

Figures

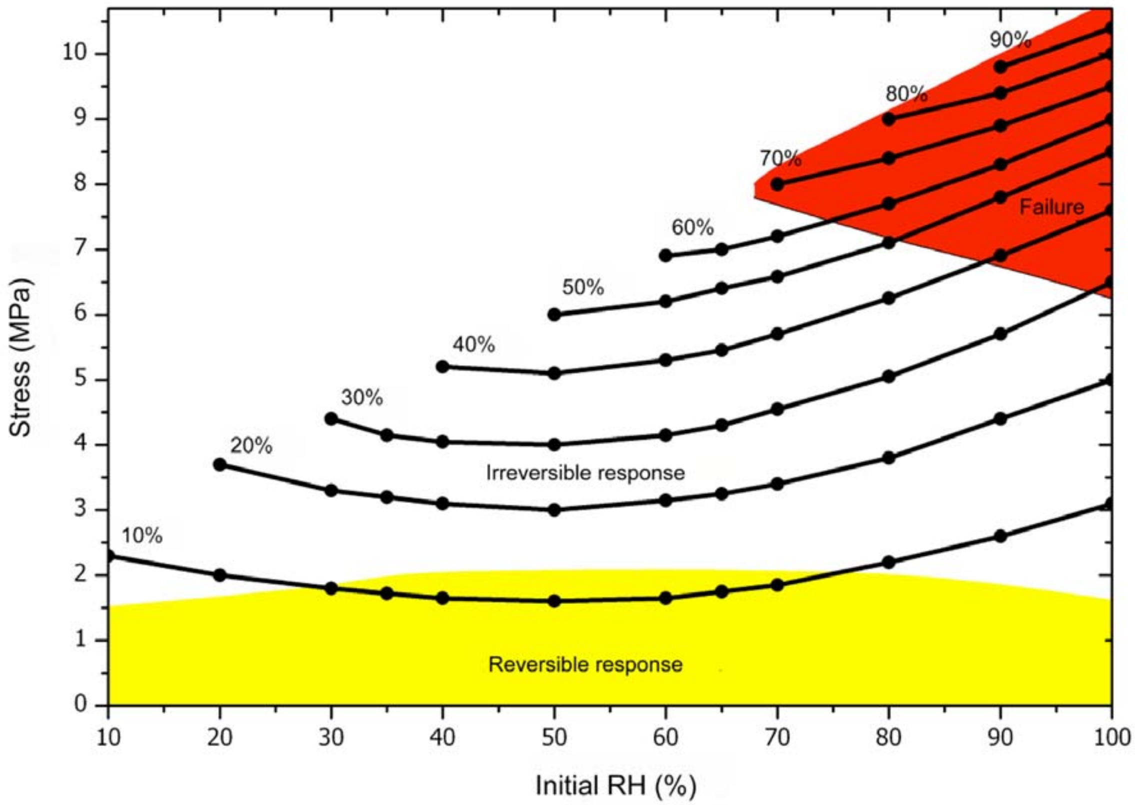

Figure 1

Stress induced by step RH variations between 10% and 90%, plotted as a function of the initial RH level from which the variation starts. Domains of RH variations endangering the wood by irreversible response (deformation) or complete failure are marked, as is the domain of tolerable variations that produce safe, reversible response of the wood.

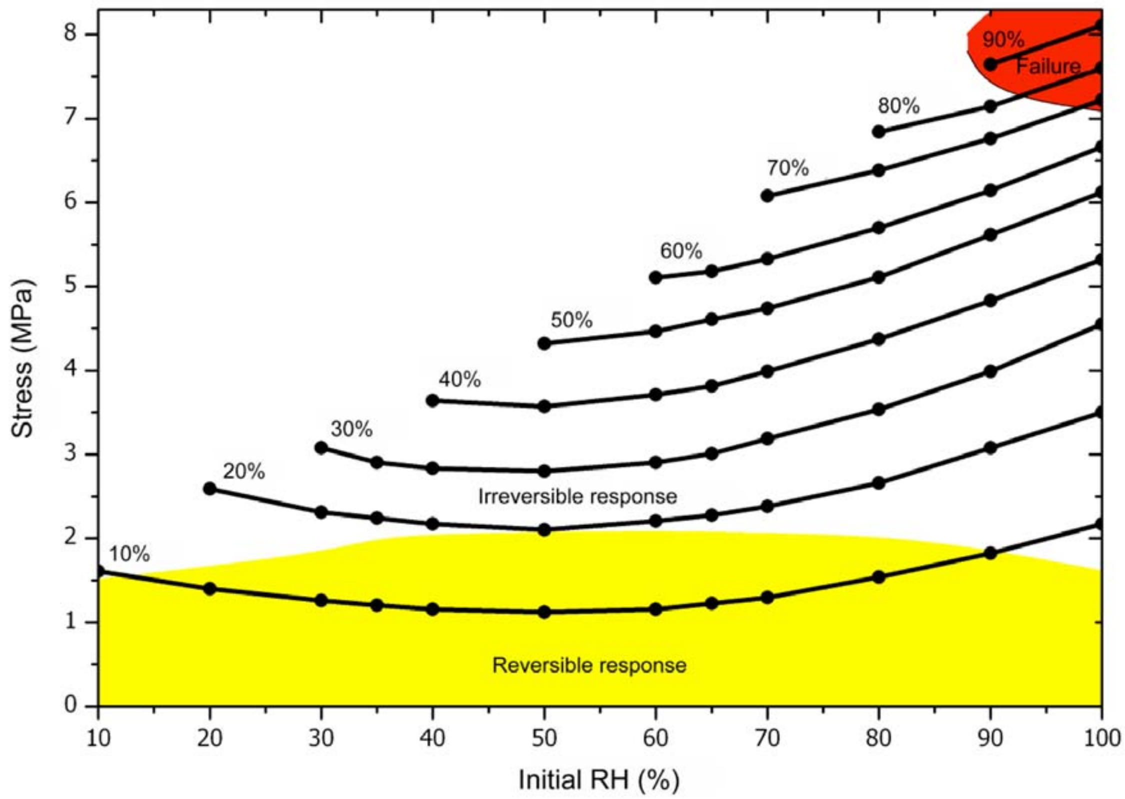

Figure 2

Stress induced by RH variations between 10% and 90% occurring over a time period of 24 h., plotted as a function of the initial RH level from which the variation starts. Domains of RH variations endangering the wood by irreversible response (deformation) or complete failure are marked, as is the domain of tolerable variations that produce safe, reversible response of the wood.

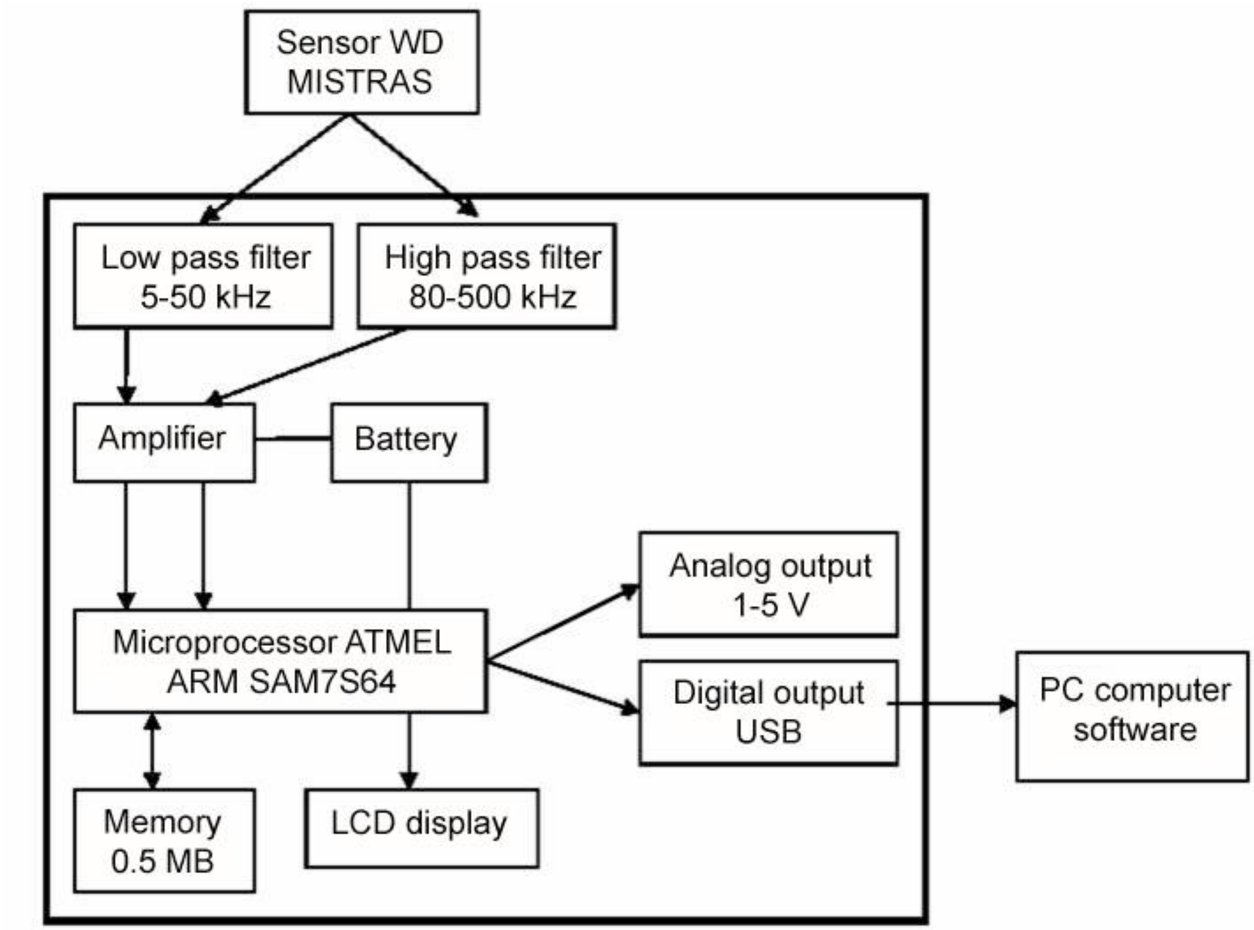

Figure 3

Schematic representation of a simple acoustic emission (AE) sensor for monitoring damage in works of art.

References

Bratasz, Łukasz, Sławomir Jakieła, and Roman Kozłowski. 2005. Allowable thresholds in dynamic changes of microclimate for wooden cultural objects: Monitoring in situ and modelling. In *ICOM Committee for Conservation: 14th Triennial Meeting, The Hague, 12–16 September 2005: Preprints* , ed. Isabelle Sourbès-Verger, 582–89. London: James & and James: Earthscan.

Jakieła, S., Ł. Bratasz, and R. Kozłowski. 2007. Acoustic emission for tracing the evolution of damage in wooden objects. *Studies in Conservation* 52, no. 2: 101–9.

Jakieła, S., Ł. Bratasz, and R. Kozłowski. 2008a. Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions. *Wood Science and Technology* 42, no. 1: 21–37.

Jakieła, S., Ł. Bratasz, and R. Kozłowski. 2008b. Acoustic emission for tracing fracture intensity in lime wood due to climatic variations. *Wood Science and Technology* 42, no. 4: 269-279.

Mecklenburg, Marion F., and Charles S. Tumosa. , and David Erhardt. 1998. Structural response of painted wood surfaces to changes in ambient relative humidity. In *Painted Wood: History and Conservation,* ed. Valerie Dorge, and F. Carey Howlett, 464–83. Los Angeles, California: The Getty Conservation Institute.

Perré, Patrick, Romain Rémond, and Joseph Gril. 2006. Simulation of the effects of ambient variations. In *Mona Lisa: Inside the Painting,* 54–55. New York: Abrams.

Vici, P. D., P. Mazzanti, and L. Uzielli. 2006. Mechanical response of wooden boards subjected to humidity step variations: Climatic chamber measurements and fitted mathematical models. *Journal of Cultural Heritage* 7, no. 1: 37–48.