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A method for an effective microclimate management in historical buildings combining monitoring and dynamic simulation: the case of "Museo Archeologico di Priverno"

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ABSTRACT

In this work a method is proposed to estimate the effect of indoor microclimate on the risk of degradation of ancient materials stored in historical buildings. The method, which combines microclimate observations and dynamic simulation, has shown to be strategic in preventive conservation of historical buildings. Indeed, once the building model is calibrated, it can be effectively used for evaluating the microclimate control solutions on the conservation reducing general degradation risks. The method has been applied to a historical building close to Rome, where deteriorations in ceilings occurred and visitors complain about thermal discomfort. First, the HVAC system in the model has set in order to guarantee both thermal comfort and adequate condition for the conservation of the material. Then, the crack width of wooden ceiling has been estimated by means of an empirical model based on indoor temperature and relative humidity data and validated with the measurements of the crack width. It was found a reduction of annual variation from 0.4 mm to 0.2 mm, experimented by panels, and an improvement of maximum daily variation, especially in winter and summer (less than 0.01 mm on average).

KEYWORDS
Historical building, microclimate, conservation strategy, dynamic simulation.

INTRODUCTION

In the last years, an increasing attention has been paid to the energy refurbishment of the existing buildings (Mazzarella 2015), both modern and historical buildings, which belong to public institutions (Ascione et al. 2017; Cornaro et al. 2016; Semprini et al. 2016). Even though in Italy the energy retrofit for the historical buildings is not mandatory due to the priority of conservation heritage, several studies about this issue have been conducted by combining experimental data and whole-building dynamic simulation (Bellia et al. 2015; Dalla Mora et al. 2015; Lucchi 2016; Roberti et al. 2017). However, to take advantages of simulations, the calibration of building model is necessary. Currently, most of the calibration methodologies focuses on matching of measured and modelled energy consumptions instead of hourly measured indoor climate data (Paliouras et al. 2015), especially the relative humidity data. Moreover, the optimization of retrofitting solutions (including new control strategies) mainly concerns the energy saving and the conservation of the aesthetic aspect of buildings, while the control of the indoor climate with respect to its interaction with objects is little considered. Among climatic parameters, the relative humidity plays a key role in the degradation and the durability of building components, especially organic and hygroscopic materials. This is very important when valuable artworks and/or building components made of material sensitive to hygrometric variables are within the building.

This paper aims at showing a methodological approach which uses indoor microclimate measurements and simulations for addressing a climate control solution adequate both for the conservation of the valuable wooden ceilings and for the thermal comfort of visitors.

MATERIALS AND METHODS

A flow chart of the methodology proposed in this study is displayed in Figure 1. First, the calibration of the building model is carried out following two steps: a) the Sensitivity Analysis (SA) for the identification of the most affected input parameters on the building model and b) the genetic algorithms, by means of GenOpt® (Genetic Optimization), for the minimization of the discrepancy between measured and simulated data. Then, the calibrated building model can be used to analyse retrofit/control solutions taking also into account the degradation risk of the materials to preserve and the thermal comfort of the visitors. The workflow can be generally applied to other historical buildings that need for refurbishment or novel control strategies and where the conservation of artworks has the priority. It is worth to note that the methodology takes advantages only if a comprehensive knowledge of the indoor climate and its interaction with the objects is reached.

For this study, the building model was calibrated by using hourly measured data of indoor temperature (T) and relative humidity (RH) and surface temperature (T_s). Then, the temporal behaviour of the width cracks (C) in wooden panels was modelled by means of an empirical model based on T_s and RH data to predict the effect of the estimated indoor climate on C.

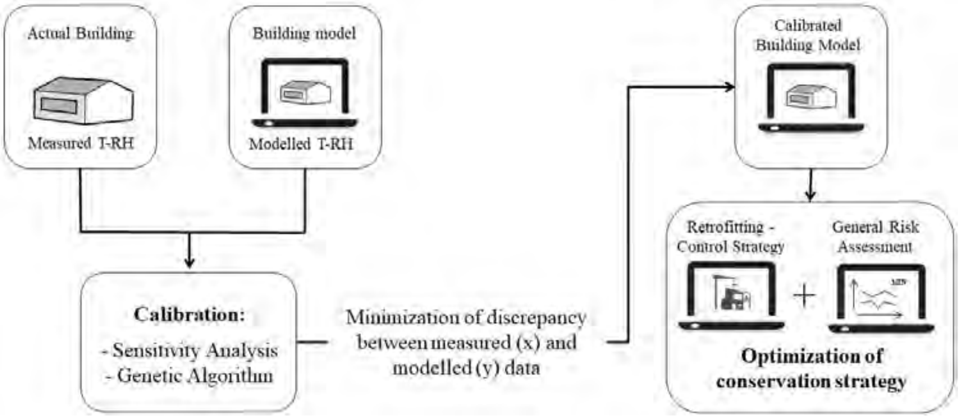
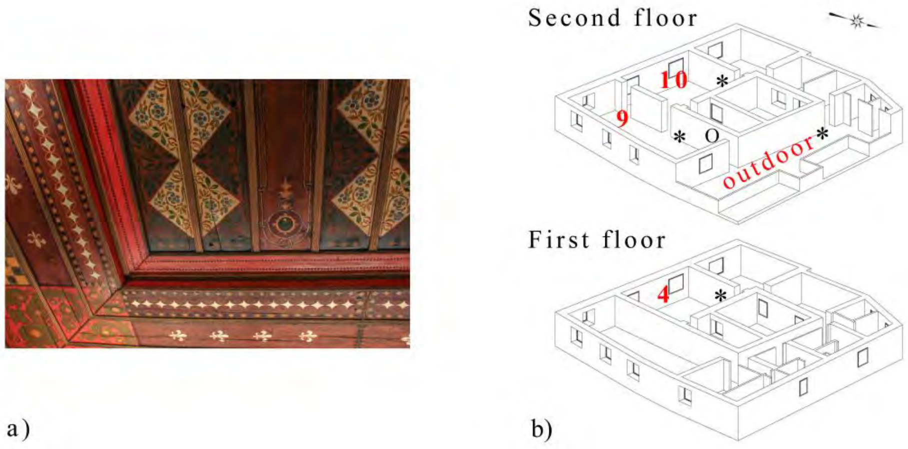


Figure 1 Schematic workflow of methodology.

The building under study and the field campaign

The “Museo Archeologico di Priverno” is housed in the Palazzo Valeriani-Guarini-Antonelli, in the central Italy at about 70 km SE far away from Rome (Lat. 41.5 and Long. 13.2). It is a three-storey building, built between 13th and 16th century and restored in 1924-1926. The HVAC is switched on during opening hours both in winter and summer and consists in one or more convection heating/cooling systems with only temperature control in each room. The study is focused on the conservation of wooden ceilings Liberty decorated by Pietro Campeggi (Figure 2a), that suffer from cracks and deformations especially in summer, when high temperatures are experienced in the room. Visitors complain about thermal discomfort due to rigid temperatures in winter and unpleasant warm in summer.

Sensors to measure indoor and outdoor temperature (T_{in} and T_{out}) and relative humidity (RH_{in} and RH_{out}) were installed as shown in Figure 2a and indicated as ‘*’. Moreover, a sensor for surface temperature (T_s) and a crack width meter (C) were installed on a wooden panel in room 9, indicated as ‘o’ in Figure 2b. These measurements have allowed to monitor the stress/strain behaviour of panel (mechanical degradation). For this study the acquisition time was set to 30 min and the monitoring campaign lasted from August 2016 till November 2017.



a)

b)

Figure 2 a) An example of wooden panels with cracks and deformations at the second floor. b) The axonometric cross section of first and second floor of the Museum. Numbers individuate the rooms where sensors were installed: '*' for T and RH and 'o' for T_s and C.

Building dynamic simulation model

Dynamic building simulation for indoor climate analysis was performed using the IDA Indoor Climate and Energy (IDA ICE) 4.8 developed and distributed by EQUA simulation AB.

The geometry of the building model of the Museum was created starting from the architectural survey provided by Arch. Lucia Di Noto and using the hygrothermal properties reported in *MASEA Datenbank* for opaque components. The wall stratigraphy was gathered from literature referred to construction techniques in lower Latium in the Middle Age and was assumed to be unchanged over time except for ceilings. The building model consisted in sixteen zones, but only the zones with sensors were calibrated.

The climate file used to run the model was determined from T_{out} and RH_{out} measurements. Wind variables and solar radiation, measured at Maenza station (Lat. 41.5°, Long. 13.2°) belonging to the ARSIAL (Agenzia Regionale per lo Sviluppo e l'Innovazione dell'Agricoltura del Lazio), were also included in the climate file.

The calibration of the envelope of the building model was carried out using hourly T-RH data collecting in two different periods (May and September 2017), when the HVAC was off and no visits occurred. The calibration consisted in two steps through a semi-automatic procedure, as shown in the scheme in Figure 1. The agreement between measured and modelled data was evaluated by using the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE) and the Coefficient of Variation of RMSE (CV-RMSE) (Fabrizio and Monetti 2015).

Optimization of conservation strategy

Wood panels can be damaged if directly exposed to fast fluctuations of indoor RH and T (Bratasz et al. 2007), which are responsible of changes in the moisture content (MC) of hygroscopic materials. This might cause stresses in terms of shrinkage and/or swelling of fibres with a following deformation up to a definitive fracture if the strain is not elastic. The relationship between the measured crack width (C) and indoor T-RH data has been assessed by using Spearman's rank-order correlation (ρ). It was found that C and T_s are well positive correlated ($\rho = 0.67$), whereas C and RH are highly anti-correlated ($\rho = -0.81$).

From the above outcomes, we have defined an empirical relationship (eq. 1) between crack width (C_{sim}) in wooden panel and T_s – RH data:

$$C_{sim} = a \cdot RH^b \cdot T_s^c \tag{1}$$

The coefficients *a*, *b*, and *c* were computed by a non-linear multiple regression over the whole period of measurements. They are 6.4343, -0.0575 and 0.0057, respectively. The agreement between *C* and C_{sim} is less than instrumental accuracy. In this study, the eq. 1 is used with modelled indoor variables, as a predictive conservation target, i.e. C_{sim} will allow knowing in advance if the novel control strategy is addressed in such a way the mechanical degradation risk of wooden panel is minimized.

The optimization of control strategy of indoor climate was addressed to update the set-point controller of the existing HVAC system without any modification of the plant. The HVAC was designed in the simulation environment as simple fan coils. The new control strategy of the indoor climate was tested using a dynamic set-point for T and RH (Kramer et al. 2017). First, T was set according to the Adaptive Temperature Limits (ATL) for thermal comfort requirements (Nicol and Humphreys 2002) leaving RH in free-floating. Then, for assessing conservation risks, these T limits were compared with T limits computed from the class of control *As,* as recommended in ASHRAE (2011), updating the T dynamic set-point and leaving RH in free-floating. Finally, the modelled RH values were compared with limits recommended in the guidelines to check if the system also guarantees the RH control. The class of control *As* provides a seasonal adjustment for T set point of +5/-10 K and ±10% for RH with respect to the annual mean and short-term fluctuations of ±2 K and ±5%, respectively. For each step, the estimated indoor variables were replaced in the eq. 1 to analyse the effect of the new control strategy on the crack width with respect to no control strategy, i.e. the free-floating indoor climate. For the novel control strategies in the rooms with wooden ceiling, the peak demand is 8.7 kW in heating hours and 1.5 kW in cooling hours, whereas the annual energy consumption is 21026 kWh and 917 kWh, respectively.

RESULTS

The results from the Sensitivity Analysis (SA), carried out by means of 18 general input parameters, have demonstrated that the indoor RH of building model is strongly affected by the rate of infiltration, whereas the indoor T by the thermal bridges. Starting from these outcomes, the building model was calibrated with the most affecting input parameters by using a genetic algorithm. The MAE is, on average, 0.3°C for T, 1.6% for RH and 0.2°C for T_s. The RMSE is, on average, 0.4 for T, 2.1% for RH and 0.2 for Ts. Finally, the CV-RMSE is less than 2.0% for T, less than 1.0% for T_s and less than 5.0% for RH.

Figure 3 shows the histogram plot with the percentage of occurrences (%) of C when the indoor climate is free-floating (red bars) and is controlled (blue bars). In free-floating indoor climate, about 40% of data corresponds to the bin limits 5.00-5.05 mm, i.e. when, in cold period, T is low (T<14°C) and RH is high (RH>85%); about 16% of data is in the bin limits 5.25-5.30 mm, i.e. when, in warm period, T is up to 31°C and RH is down to 35%. In both cases, the thermal comfort requirement of people is not reached. No significant difference has been detected among the three climate controls described in the previous paragraph. However, the control of the indoor climate allows a minor annual variation between minimum and maximum width of wooden cracks: 0.20 mm instead of 0.40 mm in free floating. This means that, when thermal comfort needs and the assessment of material risks according to ASHRAE (2011) are met, wooden panels would test less stresses and, consequently, strains.

Looking at the histograms of daily span (difference between the maximum and the minimum value) of C (Figure 4), the free-floating strategy might provoke additional daily stresses and consequently strains to the wooden fibres over the year. If a control of indoor climate is considered, the daily span is in about 80% of the occurrences less than 0.010 mm.

It is worth to notice that the T control, so as designed, guarantees the control of RH as recommended in ASHRAE (2011). This means that the current system can be used, as it is, just updating the set-point controller.

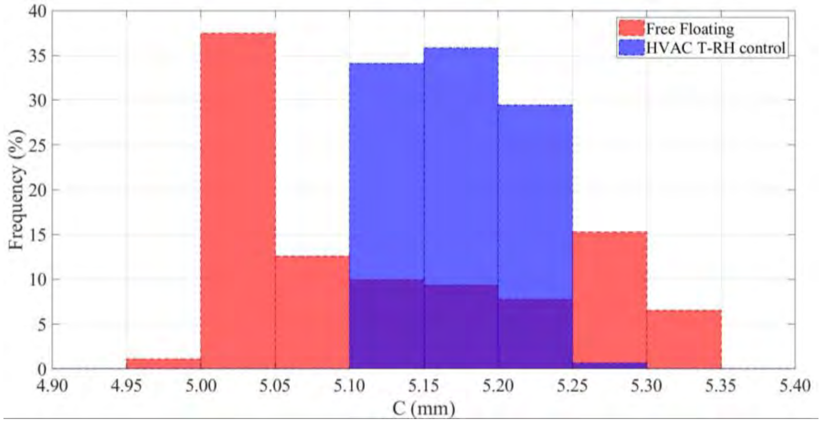


Figure 3 Histogram plot with the percentage of occurrences (%) of crack width when the indoor climate is free-floating (red bars) and is controlled by a dynamic T and RH set-points (blue bars).

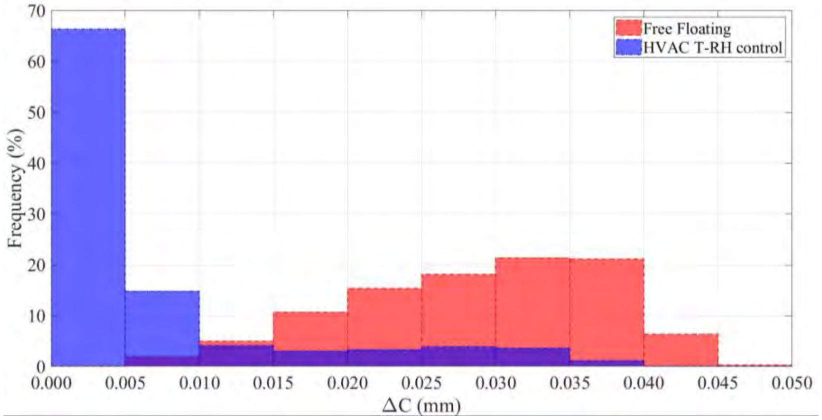


Figure 4 Daily span (ΔC) of crack width when the indoor climate is free-floating (red bars) and is controlled by a dynamic T and RH set-points (blue bars).

CONCLUSIONS AND DISCUSSIONS

The management of historical buildings in Italy is strongly related to the priority of preservation of architectural components. So, the control of the indoor climate should mainly concern the optimization of the current system with respect to the degradation phenomena. This study has revealed that the semi-automatization of calibration methods using hourly measurements of climate variables might be very useful to design a building model as representative as possible of the indoor climate of the actual case. Moreover, it has demonstrated that long-term indoor climate monitoring campaign coupled with the monitoring of crack width of wood might be essential in addressing the optimization of indoor climate control with respect to mechanical degradation of valuable wooden ceilings. Indeed, the indoor climate control, designed so at ensuring both the thermal comfort and the minimization of general degradation risks for objects, seems beneficial also for the peculiar case of the mechanical degradation of wooden panels.

Further simulations will be addressed to investigate the heat and moisture transport inside the wooden panels for modeling the evolution of degradation in the internal layers.

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