The effect of climate change on the future performance of retrofitted historic buildings

A review

L. Hao[1,2], D. Herrera[2] and A. Troi[2]

[1] Dept. Architecture, Built environment, and Construction engineering, Politecnico di Milano, Milano, Italy.

[2] Institute for renewable energy, EURAC research, Bolzano, Italy. Email: Lingjun.hao@eurac.edu

Abstract – Historic buildings account for more than one quarter of Europe's existing building stock and are going to be crucial in the achievement of future energy targets. In order to ensure their endurance, conservation compatible solutions are needed. Nevertheless, some alteration in the climate is already certain and therefore the impact of climate change on retrofitted historic buildings should be considered in terms of occupants' comfort, heritage conservation, and energy performance. Inappropriate interventions might weaken the potential of original passive climate adaptive system, such as thermal mass and night cooling, leading to higher risks of overheating. Similarly, retrofit solutions will change the moisture dynamics of historic envelopes, which might lead to moisture damages when combined with more extreme precipitation events. This paper reviews recent literature that provides evidence of climate change's impact on retrofitted buildings, reveals potential future risks, and thereby throws light on new factors influencing the retrofit decision-making process.

Keywords – historic buildings; energy retrofit; climate change; overheating; wind-driven-rain

1. INTRODUCTION

Climate change is driven by the concentration of greenhouse gases (GHG) in the atmosphere. According to the 2014 IPCC (Intergovernmental Panel on Climate Change) report [2], the increase of global surface temperature by the end of the 21st century is expected to exceed 1° (relative to 1986–2005). Together with this temperature increase, extreme climate events are expected to be more frequent. The length, frequency and intensity of heat waves [1] might increase in large parts of Europe, Asia and Australia. The EEA (European Environment Agency) also confirmed this tendency. The warming risk is particularly strong at high-latitudes. Moreover, both reports predicted a change in the precipitation patterns. It is very likely that "*extreme precipitation events will become more intense and frequent in many regions*" [2]. The increase in precipitation may particularly occur in winter, and in high-latitude regions.

1 Heat waves are excessively hot periods that last for several days or longer, which will cause the overheating of human body. [1]

Dating from 2000, several European projects studied the impact of climate change on historic buildings. For instance, the European project NOAH'S ARK [3] defined the meteorological parameters that are critical to the built heritage and developed a vulnerability atlas and a guideline to prepare structure and materials for future risks. On this basis, the CLIMATE FOR CULTURE project [4] enhanced the risk prediction method with high-resolution climate models and whole building simulation for specific regions. NANOMATCH [5] aimed at producing nano-structured materials for historic materials under the climate change context and PARNASSUS [6] focused on the impact of future flood and wind driven rain on historic buildings due to climate change and the validation of adaptation measures. Meanwhile, researchers from the ADAPT NORTHERN HERITAGE project [7] are currently working on the identification and implementation of adaptation activities for northern European countries. These projects confirmed the relevance of investigating the impact of climate change on historic buildings. The studies looked into the consequences of higher temperatures, shifting precipitation patterns, higher flooding risks, and rising sea levels, which will influence heritage conservation, energy performance and retrofit decisions. However, all these studies considered historic buildings in their original state, that is, prior to energy improvement intervention.

To limit climate change and guarantee energy security, there is an increasing attention to the retrofit of historic buildings. The construction sector contributes with 18.4 percent of total global anthropogenic GHG emissions [8]. Historic buildings constitute a considerable share of building stocks in Europe since more than 14 percent of existing buildings were built before 1919, 12 percent were built between 1919 and 1945 [9], and more than 40 percent were built before 1960 [10]. Most of these historic buildings have not undergone any energy retrofit. As a result, the average energy consumption in historic buildings is considerably higher than in modern buildings [10]. It is estimated that the retrofit of European dwelling stock built before 1945 could save up to 180 Mt of CO_2 within 2050 [9] and improve the thermal comfort of occupants.

At the same time, retrofit interventions might change the historic building state largely, from the indoor climate to the envelope's moisture dynamics [11, 12]. Combined with climate change, inappropriate retrofit solutions might further endanger building conservation and weaken buildings' performance. This paper reviews recent literature that provides evidence of climate change's impact on retrofitted buildings, highlights potential future risks and reveals the research needed.

Historic buildings are defined in this paper according to the scope of EN 16883 [13]. That is, a historic building does not necessarily have to be formally "listed" or protected. Historic building therefore refers to any building that is worth preserving. At the same time, retrofit refers to the modification of the existing structure aiming at improving a building's conditions to an acceptable level while minimising energy consumption.

2. IMPLICATIONS ON INDOOR CLIMATE

2.1 HISTORIC INDOOR CLIMATE

Indoor climate is the result of a complex interaction of several factors, e.g. the building geometry and envelope, the HVAC system, occupants, and external climate. Despite of the complexity, the direct correlation between internal and external climate has been investigated and verified. For instance, Coley et al. [14] explored the relationship between internal temperatures and changing external temperature. The building simulation included the dynamic representations of occupancy densities, solar gains, air densities, air flow and heating systems. Despite of those complex heat flows, the relationship responds to a linear regression with different constants of proportionality (that is, of steepness) depending on the building types. This could be used to estimate the buildings' resilience to climate change. The linear relationship between internal and external temperature has the potential to predict future indoor climate. In the study of the relationship between indoor and outdoor humidity, indoor absolute humidity has a strong correlation with outdoor absolute humidity year round [15]. In the case of historic buildings, Krame et al. [16] established an indoor climate prediction model for historic buildings. This is a simplified model developed with lumped model structure and optimised by genetic algorithms. In this model, indoor temperature is an output of outdoor temperature and solar irradiation and then indoor relative humidity is calculated by outdoor pressure and modelled indoor temperature. According to this research, indoor climate of historic buildings is strongly related to outdoor climate.

Retrofit solutions also play an important role in the configuration of the indoor climate. Pretelli and Fabbri [17] introduced several concepts to describe indoor microclimate of historic buildings at different use phases,[2] which emphasised the changes of indoor climate due to the retrofit interventions. At the same time the change of indoor climate is usually one of the main goals of retrofit actions to fulfil the requirement of thermal comfort. But research on indoor climate of historic building focused more on conservation rather than thermal comfort to protect historic characteristics. For instance, norms and studies usually aim at preserving building fabric and artefacts, or assess indoor climate non-invasively. [18–20] With the increase in the adoption of retrofit solutions in residential historic buildings, occupants' thermal comfort should also be assessed carefully.

2.2 THERMAL MASS, NATURAL VENTILATION AND OVERHEATING RISK

A building's envelope is the interface between the indoor and outdoor climates. Two main interactive processes controlled by this interface that influence the indoor climate are thermal inertia and ventilation. Temperature in "free running" buildings is closely related to outside temperature because of their depen-

2 Original Indoor Microclimate (OIM), Subsequential Indoor Microclimate (SIM) and Actual Indoor Microclimate (AIM)

dence on passive strategies [21, 22]. Thermal mass[3] is a typical passive climate regulation strategy in historic buildings. A large body of literature has verified the thermal inertia effect of thermal mass which is beneficiary to internal thermal comfort [24, 25]. Passive cooling effect combining thermal mass and natural ventilation, especially night ventilation, could remove waste heat to maintain a comfortable temperature during summer. Many investigations showed the principle and effect of night cooling to reduce surface and indoor temperature [26–29]. However, this cooling system depends on building thermal mass, outdoor temperature swing [29], solar radiation, and ultimately user behaviour, as it has to be properly managed. For example, Gagliano et al. [30] suggested a time lag of 12 to 14 hours for the east walls of a historic massive building (Catania, Italy). Values above that time lag cut down the night cooling length, and values below that weakened the thermal inertia effect.

Internal insulation is a common solution for the energy retrofit of historic buildings [31–33]. However, the addition of insulation internally may minimise the benefits of thermal mass and ventilation. Combined with an outdoor temperature increase, overheating risk might increase in retrofitted buildings [34]. Studies of climate change impact on overheating are abundant [35, 36], but research on overheating risks in retrofitted historic building is still very limited.

Some investigations have analysed the drawbacks caused by internal insulation. For example, Gagliano et al. [37] verified that thermal mass and ventilation in historic buildings could reduce cooling demand by 30 percent in moderate climate, but additional insulation might cause drawbacks. In the simulation by Cirami et al. [38], the operative temperatures of six retrofit solutions are higher than the un-retrofitted historic wall on the hottest day, but night cooling could counterbalance the negative effect. An office building with thermal mass could effectively limit the change of indoor temperature. Yet, with the external temperature increase, daily average temperatures tend to be unacceptable, showing that thermal mass alone cannot ensure a comfortable thermal condition any longer [21]. Similarly, in Lee et al.'s [22] dwelling case study, overheating will occur in four constructions (including masonry) caused by additional insulation under future climates. Without natural ventilation or solar protection, thermal mass cannot remedy the situation. However, the implementation of new solar protection features on historic façades is in most cases not feasible due to the need of preservation of original historic style and features. In summary, previous research has already identified the potential risk of overheating in future retrofitted historic building, however there is still a need for further research to quantify the effect of climate change and to identify alternative retrofit solutions that prevent overheating and achieve thermal comfort both in present and future scenarios.

3 "Thermal mass" refers to construction mass that could store heat. It is usually featured with high heat capacity such as poured concrete, bricks and tiles. [23] C.A.Balaras, "The role of thermal mass on the cooling load of buildings. An overview of computational methods," Energy and Buildings, vol. 24(1), pp. 1–10, 1996.

3. IMPLICATIONS OF FUTURE CLIMATE ON CONSERVATION

3.1 THE ROLE OF WIND DRIVEN RAIN AND INTERNAL INSULATION

The hygroscopic characterization of historic building material should be surveyed before retrofit actions. D'Ayala et al. [39] monitored temperature and relative humidity of two historic fabric inside the wall, concluded that historic material has different moisture absorption, and desorption features. Some solid masonry walls have a relatively high surface water absorption, the moisture content inside is more depending on exterior climate factors such as wind driven rain, solar radiation and wind [40].

Changes in climate factors (e.g. temperature, relative humidity, wind, precipitation) would accelerate the erosion of detailing and construction, or undermine binder and coating [41, 42]. Among all climate factors, Wind Driven Rain (WDR) is particularly important. It can cause both surface erosion and weaken the construction. Several research studies have shown that WDR directly affects the moisture content of historic envelopes. Abuku et al. [43] compared the mould growth risk with and without WDR in a moderately cold and humid climate (Essen, Germany) on the internal side of a historic brick wall (with no insulation). The results showed a serious risk on mould growth in summer and winter when WDR loads are considered, while there is a little risk without WDR loads. In a laboratory study by Johansson et al. [44], a 250 mm wall was built to represent the real historic wall situation and it was exposed to normal rain loads from Gothenburg (Sweden) and Bergen (Norway). The study revealed that WDR is the dominant factor determining the moisture movement in the wall. Furthermore, D'Ayala and Aktas [39] not only verified the adverse impact of WDR, but also inferred that more frequent rain could be more dangerous for historic envelopes. Nik et al. [45] simulated future moisture loads in a wooden wall and found that higher amounts of moisture will accumulate in walls in the future.

Implementation of internal insulation usually changes the moisture dynamics in historic walls. In some cases, internal insulation brings extra vapour diffusion resistance, which will impede the inward drying of the wall. This is especially important in the case of vapour tight insulation systems. Additionally, the temperature gradient across the original wall is reduced with the addition of insulation. In some cases the drying capacity of a historic wall will be reduced with interior insulation, leaving higher moisture content inside historic walls [44]. For instance, Odgaard et al. [46] monitored the hygrothermal performance of a historic masonry wall (with and without diffusion open insulation) for more than two years and found that the relative humidity of the insulated wall was 20–30 percent higher than the untreated wall. In the simulation of Kehl et al. [47], moisture content of the wooden beam end is always increased when coupled with interior insulation with or without convection, so that the increase could be assumed as an block impact of internal insulation.

With moisture accumulation in historic envelopes, the duration of materials and thermal efficiency of the building may be endangered. To ameliorate the situation, some historic retrofit projects adopted capillary active systems that minimise the moisture content to acceptable levels [48, 49]. However, the results of some investigations still show scepticism about capillary active systems. Vereecken et al. [50] compared hygric performance of different internal insulation systems in the laboratory: vapour open, non-capillary active systems, capillary active systems, and vapour tight systems. Their results pointed out that, in the steady-state winter conditions, moisture captured by capillary active systems is higher than traditional vapour tight systems. An X-ray projection analysis showed that the moisture was accumulated between the glue mortar and the insulation. Klõšeiko et al. [51] also confirmed the high humidity levels in capillary active systems (calcium silicate, aerated concrete and polyurethane board with capillary active channels) which present the mould growth risk.

3.2 MOISTURE RISKS

When the high moisture condition persists, moisture induced damage may happen, such as mould growth, wood decay and frost damage. Envelopes with low surface temperature are the most vulnerable regions for mould due to the increase in relative humidity. These low temperatures are especially found in places such as thermal bridges, corner regions, cold attics, etc. [52]. Wood is very sensitive to mould growth, and timber is generally used in historic residential buildings. For example, wooden beams were often chosen to carrying the loads of the intermediate floor to the masonry walls. Under certain conditions of relative humidity and temperature, the decay will start with mould growth and follow with the development of wood-rotting fungi. Moreover, with high moisture state in winter, frost damage is prone to occur.

Mould growth affects negatively the environmental quality of the internal climate and the durability of the envelope. In order to prevent mould growth, different mould risk management approaches have been developed in different retro-fitted building components. Climate change will impose new challenges to mould prevention. In the last 20 years, mould growth has been observed more frequently than before in ventilated attics of Sweden [53]. In their research, temperature and relative humidity levels will increase in cold attics in future climate scenarios, and the risk of mould growth will increase with these changes. Moreover, it is found that the addition of insulation could decrease the condensation on roofs but cannot decrease the risk of mould growth. In the case of wood structures, the durability depends on the moisture and temperature conditions and the exposure time to it. The decay of the wooden beams is usually caused by damaged downpipes, leaking roofs and WDR [47]. With more events of extreme rain in future, there will be more overflow in draining facilities. Meanwhile, the high relative humidity in walls caused by retrofit and extreme rain may also increase the risk.

Frost damage is a mechanical weathering process caused by water freeze-thaw cycle. Due to the changes that retrofit interventions impose on the existing structure (e.g. lower temperature on the outer surface due to the application on internal insulation), frost damage is more likely to occur. Zhou et al. [54] proposed the number of actual ice growth and melt cycles as an indicator for freeze-thaw cycles. After simulations of uninsulated and internally retrofitted masonry walls, an increase of freeze-thaw cycles was found in Switzerland after internal retrofitting. Biseniece et al. [55]studied the thermal behaviour of retrofitted historic buildings with two insulation materials, and revealed a possibility of frost damage. As mentioned above, the frequency and intensity of precipitation in winter may increase in many regions of Europe, which has the implication of enhancing the risk of frost damage.

4. CONCLUSION

Climate change might have a significant impact on retrofitted historic buildings in terms of energy consumption, thermal comfort and heritage conservation. Through the review, the combined impact of changes in climate and retrofit is summarised: increased temperature, changed rain pattern and retrofit solutions will change the indoor climate and moisture dynamic in historic buildings. According to the review, overheating will be an increasing concern in the future. The combined effect of internal insulation and increased outdoor temperature may increase overheating risks; at the same time, moisture risks will increase since there will be more extreme precipitation and the drying capacity could be reduced by retrofit interventions.

However, in reviewed literature, direct proofs of these risks are limited. There is a need to carry out research to understand the capability of thermal mass and natural ventilation in future scenarios, as well as the function loss caused by different retrofit solutions. On the other hand, the relationship between moisture state of historic building, rain pattern changes and retrofit solutions should be evaluated on a regional basis. More importantly, retrofit solutions should be defined based on aforementioned knowledge and a clear awareness of future risks to maximise the occupancy's thermal comfort and building conservation.

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