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Multiyear hygrothermal performance simulation of historic building envelopes

Michele Libralato[1,2], Alessandra De Angelis[1], Paola D'Agaro[1], Giovanni Cortella[1] and Onorio Saro[1]
[1]Polytechnic Department of Engineering and Architecture, University of Udine, Italy
[2]Corresponding author, michele.libralato@uniud.it

Abstract. The objective of this work is to quantify the effects of the short-term climate change with a multiyear (MY) approach on the results of the heat and moisture transfer simulations of an historic building located in Udine (Italy) and to evaluate if a single year simulation could be representative of the results obtained with the MY. The hygrothermal performance and the moisture related risk are evaluated for a brick wall with and without insulation, with a MY of 25 years and with three single years selected form the MY. The software DELPHIN is used for the simulations and the damage indicators are calculated using simplified methods (number of days with unfavourable conditions). Depending on the damage considered, the years have different effects on the studied wall. The simulations that use the MY weather file allow to obtain more accurate results than using one-year simulations, but the effort and time required for the interpretation of the simulation results could be not acceptable. It is then shown that the choice of a representative weather file is crucial to the results of the risk analysis and that considering more than one weather file is necessary to obtain representative results for different damages mechanisms.

Keywords – Weather files, Climate change, Buildings, Moisture, Heat and moisture transfer.

1. Introduction

In the last decades, heat and moisture transfer (HMT) simulations of building envelopes have become more accessible to researchers and practitioners in building physics, and the efforts to obtain more reliable simulation procedures are increased: HMT simulations became crucial for the evaluation of building materials, allowing to perform performance simulations and damage risk assessment of new sustainable materials [1] and the possibility of increasing the energy performance of historic buildings avoiding moisture related damages that could be caused by retrofits [2]. Moreover, the HMT simulation of materials could be used to model the passive control of environmental conditions with hygroscopic materials [3] as a low-tech system to reduce HVAC utilization. These applications are valid instruments that could be used to reach the following UN Sustainable Development Goals:

-Goal 3: Healthy indoor and outdoor environment, Healthy building materials (3.9)
-Goal 7: Energy efficiency in buildings (7.2)
-Goal 13: Climate change mitigation and adaptation in the built environment (13.3)

However, even if validated, HMT simulations are subject to many uncertainties. The sources of these are mainly the material properties, material model simplifications [4], geometry simplifications [5] and boundary conditions.

1.1. Weather files

Boundary conditions for HMT simulations are used to describe the heat and moisture loads from the outdoors and the indoors that affect the building envelopes. Measured weather files are used to calculate these loads. When performing moisture related risk assessments, the choice of the correct weather file depends on the studied phenomenon and it is not trivial. Extreme weather files for a given location should be preferred to simulate the worst conditions for the building materials. Many procedures are provided in literature for the determination of a reference weather file, depending on the damage type and on the studied building materials.

According to EN 15026:2007 the choice of the weather file should be made considering the acceptable failure rate. For the most common applications the acceptable failure rate is once in ten years so that the weather file should represent the 10 % of the worst performing weather years of the weather record. Based on this indication TRY (Test Reference Years) do not provide valid results for risk assessments: being generated as representative years they correspond to the 50 % of the ranking. However, depending on the studied moisture related problem, the worst performing year is not the same: moisture accumulation could occur in cold winters or in warm humid summers, depending on the structure, it could be affected differently, for example, by wind driven rain or by internal conditions. Nevertheless, many attempts to design a “moisture design reference year” (MRY) are reported in literature. The authors of [6] presented a procedure based on a derived weather parameter: the Climatic Index. The parameter is used to rank the weather files and to identify a small group of weather years among the weather record to be used for the simulations and risk assessment procedures. The authors of [7] presented a weather file generation procedure, based on a month selection, aimed at the generation of an extreme weather year for moisture risk calculations. The procedure, if generalised, allows to perform the statistical analysis for different weather variables, generating an extreme year depending on the assessed risk. The reference year approach is used to avoid using the entire weather record, that could be not available and time consuming. Conversely, it has been observed that using not recent weather files, for example TRY from old weather records, could cause results not representative of the close future weather conditions. This is caused mainly by short term climate change which effect on the simulation is reduced by the statistical selection procedures [8, 9]. To overcome this limit the use of future climate modelling for weather files generation is presented in [10, 11].

This contribution reports the results of the simulations of an historic building envelope performed using the entire weather record of 25 years as weather file and then using 3 weather years from the weather record, selected with the Climatic Index criterion presented in [6].

2. Methods

The software tool Delphin 6.0.20 is used for the simulations [12]. The material properties used are taken from the Delphin material database [13]. The simulations are performed for two wall types presented in the next section, one without insulation, representing the original building wall and one with 15 cm of Mineral Wool insulation. The Weather Record is measured at the weather station of Udine Sant’Osvaldo (Italy), is kindly supplied by ARPA FVG (OSMER) and it is obtained from the years 1996 to 2020. The direct solar irradiation to the oriented wall is calculated using the pvlib library [14]. The internal conditions are calculated from the external dry-bulb air temperature using the EN 15026:2007 method for the high moisture load.

2.1. Case study

The considered building is “Palazzina Sommariva” in Udine (Italy) designed by Arch. Ermes Midena [15] and built starting from 1938. The building wall considered is North-East oriented and it does not present relevant shadings. The building envelope is 45 cm thick, in solid brick wall with cement plaster and gravel panels as external cladding and a plaster layer on the internal surface. For simplicity, the wall is modelled as a one-dimensional wall, including a mortar layer in the bricks layer as presented in Table 1. Considering the conductivities of the Delphin material database and the effective thermal resistance for the brick layer given by UNI 10355:1994, the U value of the wall is 1.36 W/(m^{2}K).

A second wall is considered in the study, including a 15 cm layer of Mineral Wool [id:645] between the Solid Bricks and the Internal Plaster, to present a possible retrofit solution that considers the impossibility of adding an external layer of insulation to preserve the characteristic external façade. With this layer, the U value of the retrofitted wall is 0.22 W/(m^{2}K).

Table 2. Building envelope material description

	Material from Delphin DB	Thickness [cm]
Ext. cladding	Lime Cement Mortar [id:143]	5
Solid bricks	Historical brick [id:97]	12
Mortar	Lime Cement Mortar [id:143]	1
Solid bricks	Historical brick [id:97]	25
Int. plaster	Lime Plaster [id:148]	2

2.2. Weather record

The supplied weather data set presented short periods (shorter than two days and of the 10 % of the hours of each month) of missing and invalid values (relative humidity higher than 1 or positive global solar irradiance at night) so that it has been possible to replace the missing data, with different interpolation techniques, depending on the weather variable. An exception is found in the 2018 measurements where the dry-bulb air temperature series was missing from 3 July to 5 October. To perform the simulations the data series has been filled with the data series from [16].

The principal weather variables of the data set will be here presented. Along with the annual values also the 5-years averages are presented to better present the short-term climate change trend. In Figure 1 the temperature values are presented, and a clear trend of increasing temperatures is shown, with an increase of 0.06 K each year, on average. This trend is confirmed by the 5-year mean values.

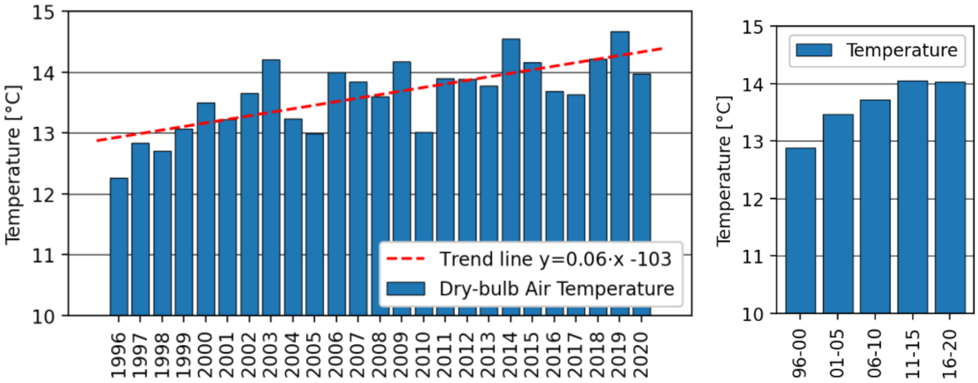

Figure 1. Dry-bulb air temperature annual mean values with trend line and 5-year mean values used in the study.

In the 25 years period also relative humidity of air (Figure 2) is increasing, with 0.2 % RH increase on average every year. The 5-year averages shows that the linear correlation is not representative of the trend. Figure 3 shows the total annual vertical rainfall, in this case the trend line has a small slope, and it is not representative of the trend. This is confirmed by the 5-year averages: the periods 2016-2020 and 2001-2005 have the lowest average rainfall values.

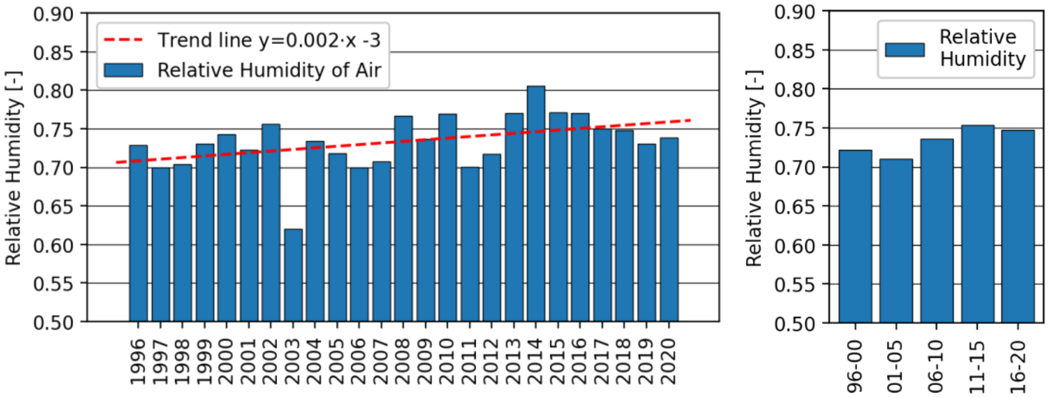

Figure 2. Relative humidity annual mean values with trend line and 5-year mean values used in the study.

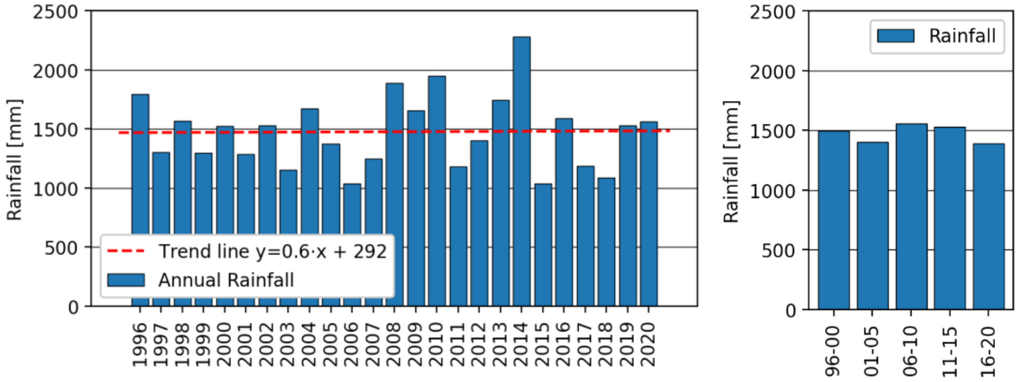

Figure 3. Vertical rainfall annual mean values with trend line and 5-year mean values used in the study.

Figures 4 and 5 describe the annual Heating Degree Days (HDD) and the Cooling Degree Days (CDD). The degree days are useful to understand the heating and cooling loads that could affect a building in each location. In this case the degree days are calculated using the simplified procedure presented in [8]. In this case the average trend is showing a decrease of the HDD that is commonly correlated with a lower heating demand, and an increase of the CDD, correlated with a higher cooling demand. The year 2019, reported as the 3rd hottest year in the last 100 years, presents about 5 times the CDD than the average of the previous years.

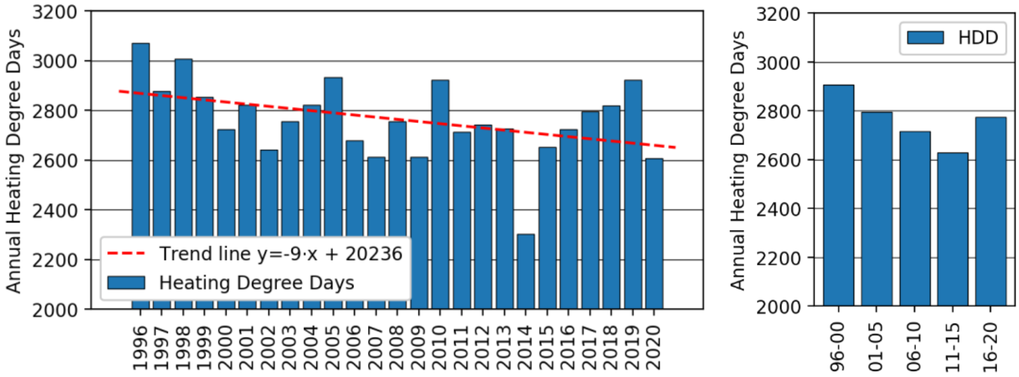

Figure 4. Heating degree days with trend line and 5-year mean values used in the study.

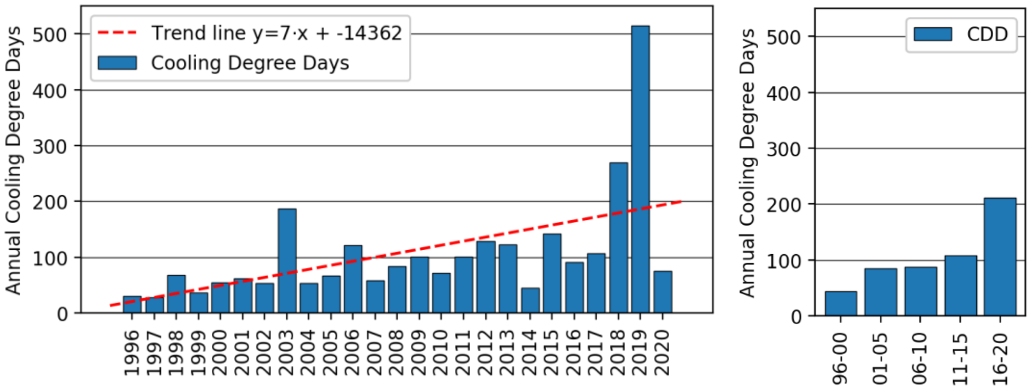

Figure 5. Cooling degree days with trend line and 5-year mean values used in the study.

Among the years of the weather record, using the Climatic Index, 2014, 2008 and 1996 are selected as extreme years of the record for the moisture related risk assessments. These three years have the higher annual rainfall values and the lower solar irradiations.

2.3. Simulations

The simulations using the weather record are performed considering the 25 years in succession with the initial conditions set to 80 % RH and 20 °C. While the single years simulations are performed cycling 10 times the year, with the same initial conditions until dynamic equilibrium is reached, then the last year is used as a result. Only the 1996 simulation of the retrofitted wall did not reach dynamic equilibrium after 10 years. The calculations showed that the point of brick beside the insulation layer accumulated large moisture quantities, while the brick is at relative humidity values close to 99 % RH. Simplified evaluation methods are used to calculate the hygrothermal performance of the wall. For the mould growth risk, the risk is the fraction of hours in which the internal surface of the wall reaches 80 % RH. For the interstitial moisture accumulation, the risk is the fraction of hours in which the internal surface of the brick layer reaches 98 % RH. In the retrofitted wall the brick layer is in contact with the insulation layer, while, for the base case, the brick layer is in contact with the internal plaster. This point is the one with the highest RH values when adding the insulation layer. The high moisture content values could cause reduction of the thermal performance of the wall, decay of the insulation layer and damages on wooden beams inserted in walls.

3. Results

To summarize the behaviour of the walls three simplified indicators have been calculated. The first is the percentage of days with conditions favourable to mould growth on the interior surface. This value is calculated counting the days with values of relative humidity over 80 % RH on the internal surface of the wall. The second indicator is the percentage of days with the interstitial moisture accumulation condition, with the relative humidity above 98 % RH at the internal side of the brick layer. Moreover, the freeze-thaw risk has been evaluated, but the results will not be presented in this contribution. The risk has been found to be acceptable, lower than 10 % for the single year simulations and for the multiyear.

The values for the first indicator are presented in Figure 6 for the last year of simulation (dynamic equilibrium) of the single year simulation and for the Multiyear simulation, considering the whole 25-year period. The simulations of the insulated cases obtained 0 days over 80 % RH showing that the retrofit measure improved internal conditions. On the other hand, the cases without insulation resulted in low values of risk, that could be accepted during the service life of the building.

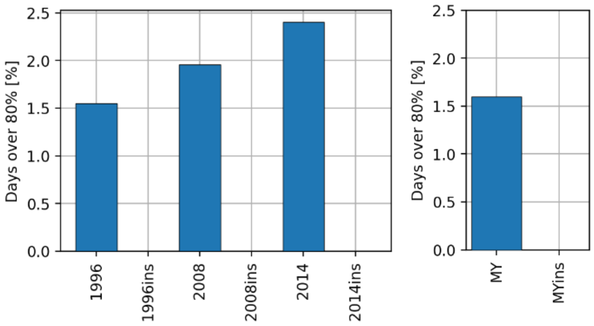

Figure 6. Percentage of days with conditions favourable to mould growth (over 80 % RH) on the interior surface for single year simulations and for the multiyear simulation.

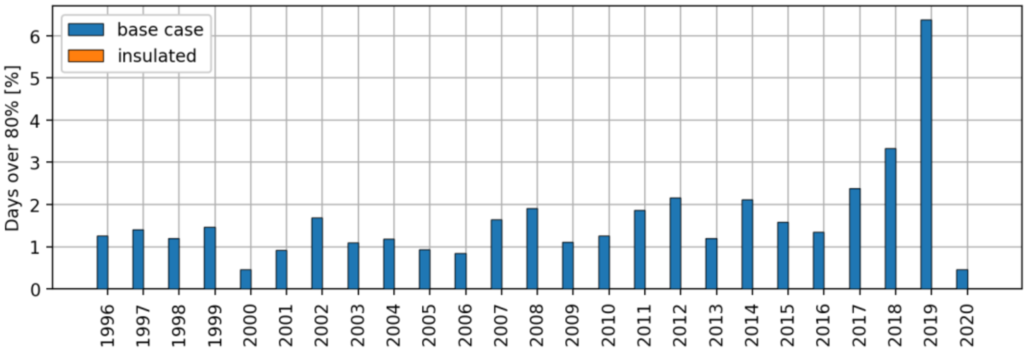

Figure 7. Percentage of days with conditions favourable to mould growth (over 80 % RH) on the interior surface for each year of the multiyear simulation.

Figure 7 shows the annual values of mould growth risk obtained from the multiyear simulation, divided by year. It is interesting to observe that the selected years are not the ones with the highest risk indicator. The insulated wall has 0 % risk each year. Moreover, the values of the risk of the selected years are not the same than the ones of the single year simulation, because the single year simulation risk is calculated after the dynamic equilibrium is reached. The risks obtained for three recent years (2017, 2018, 2019) are higher than the ones calculated in the previous years.

After the mould growth risk, the interstitial moisture accumulation risk is assessed. The relative humidity at the internal interface of the brick layer is considered. Risk is not found for the original wall, while for the insulated case high values of risk (100 %) are found for the simulations based on the years 1996 and 2014 (Figure 8).

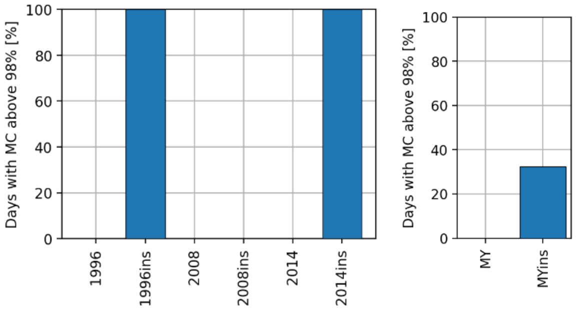

Figure 8. Percentage of days with relative humidity above 98 % RH on the surface of the brick layer facing the insulation for single year simulations and for the multiyear simulation.

The 32 % of the days of the multiyear simulation are above 98 % RH, with sensible differences between the single years. Figure 9 shows the percentage of days with damage conditions for each year of the multiyear. It is observed that the highest percentages are not always found in the extreme years (1996 and 2008). This effect could be explained considering that the percentages calculated for the years 1996 and 2014 are obtained after 10 years of simulation, describing a condition of dynamic equilibrium. In this case the year 2014 presents high risk also during the multiyear simulation. The wall has high moisture contents until 2018, when the drying process is relevant, corresponding to higher CDD values. The overall risk value is not acceptable (higher than 10 %) and the risk assessment is not passed.

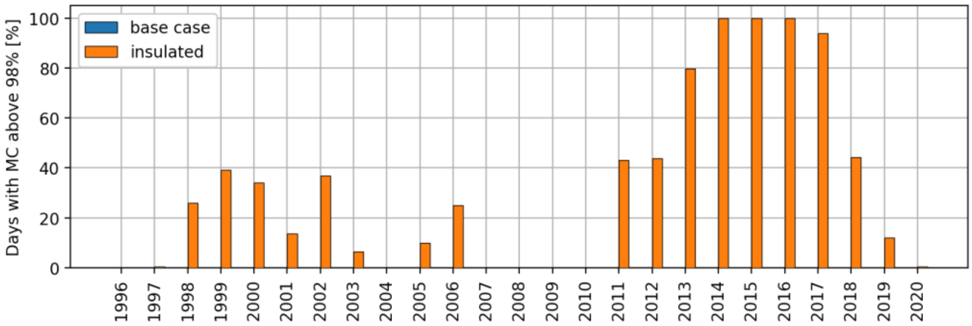

Figure 9. Percentage of days with relative humidity above 98 % RH on the surface of the brick layer facing the insulation for multiyear simulation divided by year.

4. Discussion

The risk assessments performed on the study case produced acceptable risk rates (lower than the 10 %) for the mould growth and freeze-thaw risk, while the interstitial moisture accumulation risk calculated for the insulated wall are unacceptable. Among the three single-year simulations, performed with the three years with the highest Climatic Index, the 2014 showed higher risk for the both the mould growth risk and the interstitial accumulation risk. Mould growth risk assessment is passed, and it should not be considered for the evaluation of the reference years. On the other hand, the risks of interstitial accumulation are relevant and show that 2014 is well selected as one of the extreme years of the record. In contrast, the years 1996 and 2008 in the multiyear have 0 % of risk. This effect, for the year 1996, is mainly caused by the initial conditions set to 80 % RH resulting an extreme year only if cycled. Other effects of the multiyear record could be observed, for example the influence of hot years (with high CDD, showed in Figure 6): during 2003, 2018 and 2019 a reduction of the moisture content is observed from the previous years. Similarly, the moisture accumulated during the 2014 is not dried during the following 3 years. These results are of interest to understand the behaviour of the wall, and they could be useful to evaluate the probability of the wall to dry after an extreme year. It should be also considered that extreme years could be excluded from the reference year selection based on the 10 % level criterion [6] or it could be identified as an outlier. If the wall is not in condition to dry the moisture load of an extreme year (as in years from 2015 to 2017) then it is possible to have more than one year of failure, exceeding the 10 % level (one year of failure over a period of 10 years).

5. Conclusion

The simulation of HMT in building materials is characterised by strong non linearities and uncertainties, thus the choice of the weather file for moisture related risk assessments is not trivial. The studied building envelopes presented low risk conditions for mould growth and freeze-thaw damages, while high risk for interstitial moisture accumulation. This allowed to draw a comparison between the used weather files. Unfortunately, measurements of the damages are not available, and an experimental validation has not been performed to confirm the results. Despite this, the results confirmed that the use of a selected single year cycled to reach the dynamic equilibrium could provide results that are valid for risk assessments and similar to the ones of a multiyear simulation. Nevertheless, the multiyear simulation also showed effects that could not be represented with a single year. Future work will include in the analysis the effects of initial conditions, moisture fluxes and heat fluxes, a comparison with generated weather files (representative and extreme) and the use of more advanced damage criteria (VTT mould growth model, etc.).

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