Damage risk analysis of a Timurid heritage located in Iran exposed to outdoor climate change (Ghiassieh school)

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Abstract. The first step to preserving the historical heritage against global warming effects is finding how this phenomenon affects building material degradation. Due to the vulnerability of Iranian heritage to climate change and lack of proper literature, research on climate change's impact on Timurid heritage buildings in Iran has been determined as the primary research goal. The study is performed by analysing weather data, HAM simulations, and different damage criteria. This paper aims to find an appropriate method to study climate change's impact on historical buildings. A Timurid historical school is chosen as a case study to better understand the current climate change effects on building components. The analysis shows that the significantly rising air temperature and wind speed, along with reduced rainfall and humidity, causes a notable decrease in building envelope moisture content in addition to an increase in hydrated salt crystallisation cycles during the studied period. These fluctuations may have played a crucial role in the pathologies that can be observed on site, and their continuation and expansion in the future, as the models have predicted, may lead to irreparable damages to the building.

1. Introduction

Figure 1. Map of the predicted changes in average temperature and precipitation (left). 1980-2100 [1]. Ghiassieh school, Timurid era (right).

Hosting one of the oldest civilisations, the Iranian plateau's rich cultural heritage is reflected in part by its 22 UNESCO world heritage sites. Based on the Germanwatch Global Climate Risk Index (CRI), an analysis based on one of the most reliable data sets available on extreme weather events' impacts [2], Iran is ranked as the 18th country considering climate change effects. Acquiring more knowledge of building material behaviour and risk damage criteria subjected to climate change is the first step toward assessing adaptive approaches to preserve historical buildings against this phenomenon.

Ghiassieh School (dates back to the 9th century in the Timurid era) located in northeastern Iran, was chosen as the case study. The location area has been selected based on previous analysis [3], which shows a significant change in climate over the region.

Due to the region's vastness and scattering of heritage over the area, studying pathologies for all the historical buildings is time-consuming. Furthermore, due to a lack of data recorded for some parameters...
essential for the simulations, particularly for the radiation, doing HAM simulation over a long period is not straightforward. To study the impact of climate change beyond the natural climate variability, analysis of a long period of at least 50 years is required. So first, the climatic parameters and degradation criteria independently from the construction are analysed. Temperature is a fundamental parameter for heritage since it has a significant impact on material durability. Higher temperatures cause a reduction in material stiffness and strength. Wind parameter significantly impacts the wind-driven rain and erosion. The materials’ hygrothermal performance is directly affected by relative humidity and precipitation; mould growth, corrosion and salt crystallisation are critical for building durability. Salt weathering is a critical criterion of degradation in historical heritage [4]. Next, as the building envelope is constantly exposed to swelling and shrinkage effects due to moisture content fluctuations, the moisture index and wind-driven rain (dependent on the building) are calculated. The Moisture Index can be considered to be a moisture budget and comprises a wetting and drying function. The wetting function describes the availability of water or the source part of the water budget. Annual precipitation or wind-driven rain can be used as wetting function value. The drying function explains the sink part of the water budget. The drying function includes terms that describe evaporation, soil retention, and run-of rain.

Wind-driven rain (WDR) is one of the most critical moisture sources that negatively affect facades [5]. The building geometry and points in facades exposed to the WDR are considered in our calculations, so this parameter is a type of building-based analysis. Knowledge of the quantity of driving rain that reaches building facades is also an essential requirement as a boundary condition for heat, air-moisture (HAM) transfer analysis [6].

The weather-based analysis does not account for the dynamic response of the wall, the material properties and material-dependent damage criteria. HAM simulations provide an interesting approach to acquire more detailed knowledge about the degradation process of building components.

Timurid heritage had been built using brickwork, gypsum mortar and decorative tiles. Due to the extent of the damages, a restoration operation for the Ghiasieh school started in 1990. Analysis before and after restoration indicates that salt crystallisation, stresses induced by moisture load in material components, cracks due to land subsidence, wind erosion and thermal stress (Figure 2) are the leading causes of material deterioration.

![Figure 2](image-url) A: Northeastern (main) façade. B: Migration of Calcium Sulphate from gypsum mortar. C: Southeastern porch. 1980.

2. Methodology

2.1. Climate-based analysis

The historical records for the temperature, relative humidity and wind velocity with a 3-hourly and precipitation with 6-hourly temporal resolution from 1951-2017 are analysed. In addition, the annual average plots for the temperature, wind velocity, and relative humidity with annual total precipitation are discussed during the current paper.

Next, the moisture index (MI) is calculated for the studied location. The moisture index simply can be computed as the ratio of WI to DI using Equation 3.

\[
MI = \frac{WI}{DI}
\]

The MI is moisture index, WI is the Wetting index, and DI is the Drying index. This index can be calculated independently from the construction. Also, deviation from the mean of wetting and drying index is computed (for detailed information, see [7] ). Furthermore, the number of freeze-thaw cycles
has been studied. Based on daily $T_{\text{mean}}$, a cycle is counted each time the temperature drops below 0°C, given that the previous day was a non-freezing day [8].

The number of phase transitions was used as a method for estimating potential salt damage [9]. In the sodium chloride (Halite) case, this was assessed by counting the number of times the average daily relative humidity crossed the critical deliquescence point of 75.3 % for sodium chloride.

In the case of the hydrated salts, the thenardite–mirabilite transitions \( \text{Na}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} \) only accumulated on the consecutive days when thenardite would convert to mirabilite (through thenardite dissolution followed by mirabilite crystallisation) and exert a crystallisation pressure higher than 10 MPa. If the temperature is less than 22.5 °C, the Correns Equation suggests a crystallisation pressure of mirabilite greater than 10 Mpa [10]. So 22.5°C acts as a boundary for crystallisation.

2.2. Construction-based analysis

2.2.1. Wind-driven rain. Here, the ISO semi-empirical method is used, which is calculated based on wind velocity, wind direction and horizontal rainfall. WDR can be calculated for a specific orientation using Equation [11].

\[
\text{WDR} = \frac{2}{9} \cdot \text{V}(10) \cdot \cos(\Theta) \cdot [(r_h)_{\text{h}}]^{0.88}
\]

Where WDR is the free field wind-driven rain, V(10) is the wind speed (m/s) at 10 (m) height, $\Theta$ is the angle between a line normal to the wall of interest and the wind direction, $r_h$ is the rainfall on a horizontal surface (mm/h). It should be noted that the low temporal rain resolution (6-hourly) may lead to an underestimation of the WDR loads.

2.2.2. HAM simulation. Two data types are essential for accurate and reliable numerical simulations: climate data with high temporal and spatial resolution and accurate information on the wall assembly materials. Given that recordings of the radiation data only started in 1980, HAM simulations were performed for the period 1980-2018. Recorded weather data for 1980-2018 are used as the exterior climate conditions in HAM simulations. The climate dataset contains 3-hourly data for the air temperature, relative humidity, wind velocity and direction, cloud coverage, and direct and diffuse solar radiation. In addition, horizontal rainfall is available at a 6-hourly resolution. To select the indoor climate class, temperature and RH sensors have been installed in various building spaces and monitored the indoor climate. Based on a preliminary analysis and EN 13788, indoor humidity and temperature class 1 is picked. The wall assembly is simulated by adopting the 1-D simulation approach consists of 440 mm historical brick and 10 mm of Gypsum on the interior side. Due to lack of access to decorative tiles, this paper only addresses the walls that do not comprise tiles, as future work will focus on the tiles' material characterisation.

So far, no laboratory test results have been reported to assess Timurid's brick hygrothermal performance and physical properties, which is essential for a proper numerical simulation. For the first time, 600 years old clay-made Timurid bricks (25*25*10 cm) from the case study have been analysed to determine their physical properties and moisture transport functions. Due to the high cultural value of the building, only a few brick samples from the southeastern façade that is exposed to the dominant wind have been picked. All the tests have been performed by using European standard methods: EN 15148 for the absorption coefficient, EN 1936 for the material's density and open porosity, EN 12572 wet and dry cup method for water vapour transmission properties, and EN 16322 for the moisture saturation point, knick point and critical moisture content. In addition, the Mercury intrusion test has been performed to determine the pore size distribution of the samples. The bricks were classified into three categories with different physical characteristics. The third type, which is almost waterproof due to its proximity to the centre of the oven, has been baked at a very high temperature and was used only for the flooring, so not considered for the simulations. The appropriate moisture retention curve (Figure 3) has been fitted to the brick categories based on the experiment results. Table 1 provides an overview of the test results, compared with a historical brick selected from the Delphin material library (Old brick Dresden), picked as our reference brick due to similar properties to the brick samples. Outputs for the
moisture content, field, core and surface temperature and relative humidity of the wall assembly, and freeze-thaw cycles at 5mm depth of the wall surface have been defined and post-processed. Based on rank of the year for the moisture index [7], simulation results for the wet year of the first and last decade, 1982 and 2009, are compared to see if climate change affected the hygrothermal performance of building components.

Table 1. The material properties of brick samples comparing with Old brick Dresden.1980-2017

| parameters          | Bulk density kg/m³ | Open porosity m³/m³ | Effective saturation m³/m³ | Water uptake coefficient Kg/m²s⁰⁵ | Water vapour diffusion resistance factor |
|---------------------|-------------------|---------------------|---------------------------|----------------------------------|-----------------------------------------|
| Old brick Dresden   | 1736              | 0.34                | 0.320                     | 0.034                            | 21.3                                    |
| Category A          | 1778              | 0.45                | 0.273                     | 0.45                             | 15.3                                    |
| Category B          | 1767              | 0.42                | 0.247                     | 0.34                             | 18.7                                    |
| Category C          | 2124              | 0.06                | 0.128                     | 0.017                            | 21.3                                    |

Figure 3. The moisture retention curve for the specimens comparing with Old brick Dresden.

3. RESULTS

3.1. Climate-based analysis

3.1.1 Meteorological parameters analysis. Figure 4 shows the annual time series for different climatic parameters. These parameters are the main meteorological factors, and as can be observed, their change rate is significant. Previous research [2] showed that the change rate for all of the main climatic parameters over this area compared with the other parts of the Iran plateau is considerably high and might threaten the historical heritage with desertification, dryness and moisture balance disturbance in contrast with Europe, where the change rate is clearly smoother. A 0.05 °C / year increase in average temperature which means 3.5 °C increase from 1950 up to now(higher than 1 °C increase in worldwide temperature), 0.25 mm/year decrease in annual rainfall, 0.17 % / year drop in humidity combined with a 0.1 m/year rise in wind speed in 67 years may significantly affect the historical heritage located in the area. These significant climate changes also accelerate the building erosion and ageing process of building materials that are directly exposed to solar radiation and the outdoor environment due to more prolonged periods of higher temperature and exposure to higher levels of UV-B radiation, plus considerable exposure to wind erosion.

3.1.2 Freeze-thaw cycles. The annual number of freeze-thaw cycles is calculated using the climate-based criteria (Figure 5-Left). As is shown, the damage risk has decreased by 0.6 % / year.
3.1.3 Salt crystallisation. The annual number of salt transitions has been calculated for Halit (NaCl) and Thenardite-Mirabilite over the studied region to evaluate whether we can expect an increase or decrease of salt pathologies due to climate change (Figure 5-Right). As can be observed, the calculations show that the annual number of Halit transitions has been slowed down. In contrast, the annual number of transitions for thenardite-mirabilite has clearly increased by 0.7% / year. Gypsum was used as the mortar layer in the case study, and Sulphate can be migrated to the bricks by moisture transport. Our lab tests by salinity test strips confirm it and indicate that the bricks surface layer has a considerable sulphate and Calcium. In the long-term period, migrated salts crystallisation can cause cracks in brick masonry walls and decorative tiles.

3.1.4 Moisture Index. The calculated annual moisture index as a construction-independent factor is shown in Figure 6 (left). -5.3% /year drop in the moisture index during the studied period can be observed, where the sharp increase in temperature and wind velocity along with the reduced annual rainfall are reflected. A moisture index reduction typically leads to a reduction in moisture-related risks, such as freeze-thaw, mould, wood decay, bio-colonisation, but on the other hand, it must be studied to what extent there may be negative effects associated with the reduction in moisture content like the ageing of materials. Wet and dry years during the studied period are shown in Figure 6 (Right). 1982 and 2009 are selected as the wet years for the first and last studied decade to compare the HAM simulation results subjected to climate change.
3.2 Construction-based analysis

3.2.1. Wind-driven rain load. The significant increase in wind velocity compensates the decremental rainfall trend, resulting in a status quo in terms of wind-driven rain load (Figure 7). Figure 7 shows a comparison between the facade normal to the dominant wind direction and the facade on the other side before restoration and clearly shows more damage caused by wind erosion and WDR to the main façade, which is exposed to the dominant wind.

3.2.2. HAM simulation results. The wall setup's hygrothermal behaviour during 1980-2018 is simulated, and outputs are rendered. Based on the studied year's ranking by deviation from the mean of wetting and drying index (Figure 6), 1982 and 2009, the wet years of the first and last studied decade are picked to represent the impact of climate change on simulated wall assembly during the analysed period. Analysing the moisture content of the wall set up -reflecting the climate-based analysis- indicates that the wall moisture content has clearly decreased during the studied period (Figure 8-right) and representative years due to higher temperature and less precipitation. The most average (~11kg/m³) decrease can be observed for brick type A with more porosity and a higher degree of saturation.
Figure 8. The average moisture content during the studied period (Left). The cumulative distribution of the average moisture content for the representative wet years (Right).

Figure 9. The annual simulated number of salt crystallisation for the thenardite-mirabilite (Left-top) and Halite (Right-top). The field plots during representative years show the period/depth with a relative humidity close to the RH equilibrium point.

Figure 9 shows the annual number of salt transitions employing HAM simulation at 5mm depth from the wall surface exposed to the environment. As can be observed, simulations confirm the results of the climate base criteria. A smooth increase in the number of thenardite-mirabilite transitions and a notable decrease in the annual number of halite transitions can be observed. The field plots for the simulated wall assembly during the selected wet years, with a relative humidity close to the RH equilibrium point and colder than 22.5 °C (close to zero and marked in orange), is an ideal environment for the sulphate salt crystallisation, show that during 2009 compared with 1982, there are more areas coloured in the range of the zero on both sides of the wall set up. As a result, the possibility of sulphate salt crystallisation is more in 2009 than in 1982. The mould index (VTT-model) [11] for the wall surface exposed to the environment has been simulated. Given that the case study is located in a semi-arid area, the mould growth index always stays below 1, showing no damage caused by mould growth.
4. Conclusions

This research aims to find a comprehensive method to study the impact of climate change on historical buildings. It is necessary to analyse the climatic parameters over an adequately long period to see this phenomenon's real impact on climatic parameters beyond the climate variability. This was performed by analysing climatic parameters from 1951 until 2018. During this part of the analysis, significant changes were found, indicating a sharp increase in temperature and wind speed, along with a sharp decrease in humidity. These fluctuations can play a severe role in material ageing and erosion of building facades. Based on climate-based indices, building-related criteria, and HAM simulations, a large impact of this phenomenon on the heritage located in the studied area was observed. Moisture index, the number of FTCs, annual number of Halit transitions and wind-driven rain intensity slowed down, whereas the increase in the number of mirabilite transitions was considered as a threatening factor for the region's heritage. On the other hand, it must be studied to what extent there may be negative effects associated with the reduction in moisture content, i.e., an increase in wall temperature fluctuation following by a decrease in wall humidity can lead to spalling in materials and, considering the difference in material expansion coefficient, cause cracks in wall construction. This research showed that the study of possible threatening factors based on climatic parameters and indexes independent from the building can save time and get an insight into the climatic parameters critical to the heritage over the region.

To perform a comprehensive method for studying the climate change effects on heritage, initially, an analysis of the climate parameters should be run. Next to that, both the climate-based and construction-based parameters should be analysed regardless of the case study. These analysis steps do not account for the dynamic response of the wall, the material properties and material-dependent damage criteria. HAM simulations provide an exciting approach to acquire more detailed knowledge about the degradation process of the building elements for the heritage spread over the region. Moreover, HAM simulations allow determining which climatic parameters play a more critical role in the degradation criterion and hygrothermal performance of the elements and should hence be studied with more detail in analysing climate data in future.

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