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Moisture dynamics in the masonry fabric of historic buildings subjected to wind-driven rain and flooding

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ABSTRACT

Current climatic projections show clearly that increasingly more extreme weather events are to be expected in the future. Historic buildings are considered to be the most vulnerable to this adverse climatic impact, via moisture induced deterioration and resulting strength decay in their construction materials. Therefore, the identification of these climatic effects is important to be able to develop suitable tools to mitigate them, both for individual buildings and on a regional scale. This paper presents the analysis of a comprehensive environmental monitoring of two historic buildings in Tewkesbury, Gloucestershire, UK, to provide thorough insight on their performances under environmental loading on a comparative basis. Firstly, the effect of wind-driven rain (WDR) and flooding is assessed by correlation with relative humidity (RH) measurements. The WDR measurements are then compared against values calculated using well established semi-empirical models and reasons behind the limited correlation are discussed. The dynamic hygrothermal response of two different historic fabrics is studied in greater detail by monitoring in-wall temperature and RH. The conclusions drawn from the analysis of the monitoring outputs are then further elaborated on by using hygrothermal characterization obtained by dynamic vapour sorption (DVS) testing of material samples extracted from the fabric of these buildings. The study concludes that the current environmental conditions pose a threat on the building envelopes unless routine maintenance is provided, and that monitoring methodology devised is clearly successful in quantifying the exposure of the two historic buildings to environmental conditions, onsetting deterioration phenomena in the envelop materials.

1. Introduction

Projections of current climatic events reveal compelling evidence that the overall precipitation has significantly risen – however this increase is not always accompanied by a comparable increase in the number of wet days, therefore extreme weather events are to be expected more intensely and more frequently in the future, globally and in the UK (e.g. Refs. [1–5]). It is generally assumed that such increase in extreme weather conditions heightens hygrothermal cyclic loading of traditional building fabric made of porous materials, eventually increasing the rate of decay. Current literature is building up evidence of such phenomena, which in turn may manifest in the form of additional losses in load-bearing capacity in building envelopes (e.g. Refs. [6–8]) or further biodegradation due to saturation or cyclic/acyclic variations in the moisture content (e.g. Ref. [9]).

Among the climatic hazards that are most influential on historic buildings, wind-driven rain (WDR) is found to be especially detrimental as it may cause surface erosion and facilitate moisture penetration and biodeterioration (e.g. Refs. [10–13]). The amount of WDR that impact a building envelope can be measured using suitable gauges, estimated by semi-empirical equations or simulated by more sophisticated computational fluid dynamics (CFD) modelling (e.g. Refs. [14–16]). Such studies aims to correlate the WDR impact to surface degradation phenomena, such as erosion, soiling, discoloration etc. (e.g. Refs. [11,16,17]) or its influence on indoor conditions (e.g. Refs. [10,18]). The extent to which in-wall RH conditions are affected by WDR exposure, however, has remained to a large extent anecdotal due to scarcity of in-field observations and experimental work. Robust quantification of deterioration mechanisms and appraisal of potential damage in relation to specific exposure conditions and historic material fabric is essential to

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realistically determine need and cost of mitigation or adaptation measures for architectural heritage. According to [19] UK has the highest potential for decay due to exposure to climatic agents among European countries. Moreover, as one in every five dwellings in the UK was built before 1919 [20], a large proportion of the building stock is potentially vulnerable to long-term and cumulative adverse effects of climatic exposure [4]. The PARNASSUS project (2010–2014) was set up to collect direct data from seven historic buildings at different sites in England, chosen using an innovative methodology developed on the basis of hazard, vulnerability, installation feasibility and exposure criteria [21] and further elaborated its findings by means of a set of laboratory tests and computer modelling.

This paper presents the environmental monitoring system developed for this purpose and discusses the hygrothermal characterization work carried out with respect to two historic buildings in Tewkesbury (Gloucestershire, England) (Fig. 1). Tewkesbury is an early medieval town founded at an elevation of approximately 15 m above sea level at the confluence of the River Avon and River Severn, chosen for its exposure to floods, the earliest recorded incident being in 1484 [22,23]. In the last decade the most intense flood event causing widespread damage in Tewkesbury was recorded in July 2007 [24], with associated costs in the range of £3.2 billion [25]. The May 2012 events caused flooding at the site of interest with estimated costs £600 million nationwide [26], whilst this value is much higher for 2015 floods [27]. [1] report predicts that southwest England will have substantial seasonal changes in precipitation in the next 50 years [1]. Tewkesbury is therefore highly representative of a location with long history of exposure of its building stock to critical events and of future heightened hazards. Of the two buildings reported here, Abbey Mill is a Grade II listed, 4 storey brick masonry building from the late 18th century, built on foundations that are considered to be from the early 12th century. It is located next to the River Avon leat adjacent to a wide flood plain, at the bottom of Mill Street. The second building, 1-Mill Bank is a 16th century 2 storey oak timber frame cottage with brickwork infill, also Grade II listed, located on raised ground on the bank of the River Avon, right across the road from the Abbey Mill. Both buildings whose use is currently residential, are known to have been in use throughout their lives and in a good state of conservation with functioning drainage and roofs and no visible structural distress.

2. Environmental monitoring

On the basis of exposure considerations and installation feasibility, and with the aim of having a clear depiction of how different climatic factors relate to each other and influence the hygrothermal state of walls made of different fabrics, the environmental monitoring system designed and installed on Abbey Mill and 1-Mill Bank in March 2011 is composed of indoor and outdoor temperature (T) and relative humidity (RH) sensors; surface mounted thermocouples shielded against solar radiation, in-wall T and RH probes, anemometer, water level sensor, air pressure sensor, horizontal rain gauge and wind-driven rain (WDR) gauges. The sequence of five T and RH sensors across the wall section are aimed at obtaining an accurate T and RH profile through the wall thickness. The in-wall T and RH probes were chosen among the thinnest commercially available products (approximately 5 mm in diameter) to ensure minimum intrusion on original building fabric. The WDR gauges installed was developed and manufactured as part of this project so as to allow an automatic logging of vertical rain flux with the same cadence of horizontal rainfall and other parameters. Only one outdoor T and RH sensor and horizontal rainfall gauge was used for both buildings, taking advantage of the short distance between them (around 20 m), while all other parameters were monitored separately for each building. All sensors in each building were wired to a datalogger and this was remotely connected to a computer and logging could be controlled and data downloaded through a website interface in real time. Fig. 2 provides a schematic representation of sensor arrangement on buildings' façades and close ups of each sensor. In the 1-Mill Bank cottage the north-western façade was instrumented, while instrumentation was installed on the south-western and the north-western façade of Abbey Mill. Both buildings were monitored for a total of 14 months between March 2011 and May 2012. For both buildings, logging was done every minute for the first 2 months and to 5 min then onwards in line with other high precision monitoring work in the relevant literature. This integrated and comprehensive system of measurement is novel and allows for much deeper understanding of the interaction between envelop and environment [28].

2.1. Horizontal rainfall and wind-driven rain

Wind driven rain (WDR) plays an important role on the

Fig. 1. Aerial view showing the site, and the north-western elevations of Abbey Mill and 1-Mill Bank, respectively.

Fig. 2. Schematic position of the sensors installed on the north-western façade of 1-Mill Bank and the south-western and north-western façades of Abbey Mill (WDR: Wind-Drive Rain Gauge, HRF: Horizontal Rain Fall Gauge, WS&WD: Wind Speed and Wind Direction Gauge, ST: Surface Temperature Sensor, WL: Water Level Sensor).

moisture induced psycho-chemical deterioration of building façades [17,29,30]. It might increase the risk of mould formation by inducing further moisture migration within the wall section [31]. Although climate models do not give robust estimates for wind speed and direction [4], the expected increase in rainfall intensity implies that WDR will remain as a governing environmental agent causing decay phenomena on building fabric. Therefore, its correct quantification is of great importance.

In this study the horizontal rainfall was measured on the roof of Abbey Mill using a tipping bucket rain gauge and was found to be around 535 mm for the 14 months monitoring period, compared with a 606 mm annual total for the closest Met Office station at Pershore over the period 1981–2010. WDR measurements, on the other hand, were taken by a bespoke gauge made up of a plexiglass plate of 250 mm^2 which collects and drives the rain in a standard horizontal rain tipping basket (Fig. 3). WDR readings were collected from 5 different locations on 3 facades of both buildings. The results obtained over 14 months show that the total amount of WDR affecting the gauge locations are 84, 52 and 61 mm for Abbey Mill and 11 and 20 mm for 1-Mill Bank. Differences in measurements between the two buildings can be attributed to the greater exposure of Abbey Mill, being the tallest structure within its close vicinity and located right next to a flood plain, while gauge position on the same surface also show to be a critical parameter.

Total precipitation amounts (Fig. 4a) shows that the trends of all gauges are strongly correlated. Maximum amounts of WDR were recorded in September 2011, December 2011 and April 2012. Ultimately the aim is to understand the effect of WDR on in-wall hygrometric conditions. Fig. 4b shows that the effect of a WDR event is a marked reduction in temperature of up to 5 °C and a reduction in the excursion of RH indicating that the wall does not dries-up during the diurnal cycle.

According to [32] for a weather incident to "moisten" the wall, the following should occur concurrently in a "half-day": (i) more than 4 mm of horizontal rainfall, (ii) average wind speed greater than 2 m/s and (iii) average wind direction within ±60° of the perpendicular of the wall. The rainy period between early morning and early evening of 07/05/2011 clearly satisfies the first criterion as shown in Fig. 4b. The wind speed and direction distribution over this period is shown in Fig. 5, therefore the second criterion is also

Fig. 3. WDR gauge designed and manufactured as part of project PARNASSUS on the facades of Abbey Mill and 1-Mill Bank, respectively.

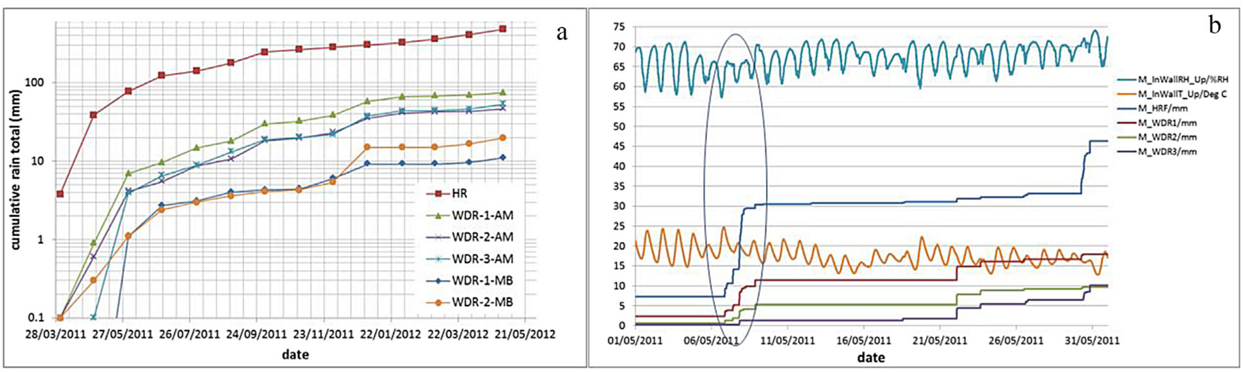

Fig. 4. Monthly cumulative horizontal (HRF) and wind-driven rain (WDR) amounts (a) in logarithmic scale as measured at Abbey Mill (AM) and Mill Bank (MB) and (b) correlation to in-wall temperature (T) and relative humidity (RH) variations in Abbey Mill at the upper floor level.

satisfied. However, the average wind speed for the indicated period is 1.7 m/s although 37% of all wind readings over this period are

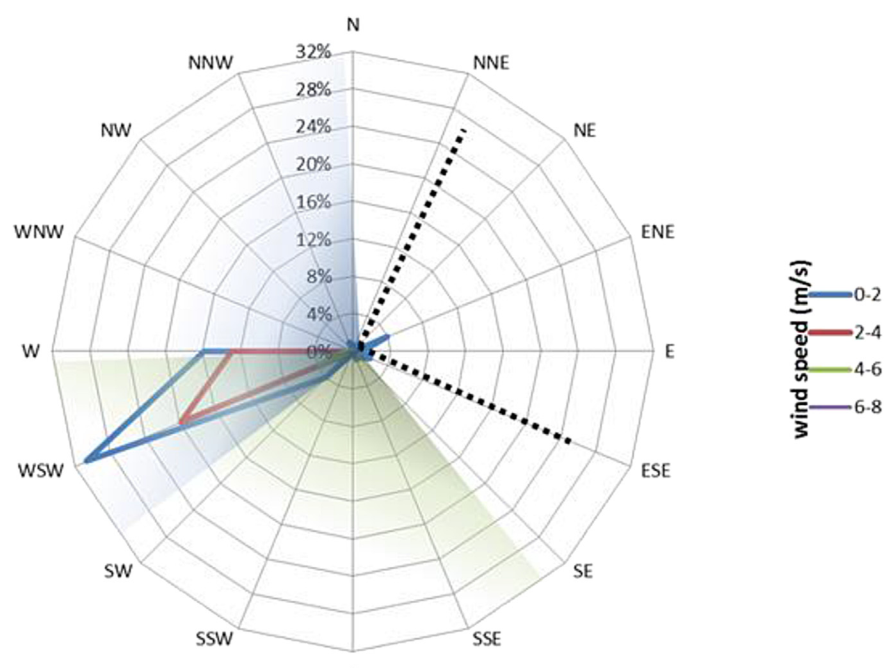

Fig. 5. Distribution of wind speed and direction on the facades of Abbey Mill between for a half day 07/05/2011 (facades are shown with dotted lines and funnels indicate ±60° of the normal of the facades).

above 2 m/s.

A similar effect can be also seen at a T-RH sensor placed at 1.5 m from the street level, in occasion of the disruptive rain event of end of April 2012 which resulted in water rise of up to 4 m in the Avon leat in the immediate vicinity of the Mill, flooding the building to a level of 0.6 m from the street datum. As seen in Fig. 6, the maximum RH measured is up to 90%, this value reducing by up to 7% in the hotter diurnal period. However, during the heavy raining period and water rising event the in-wall RH remains almost constantly at 90%, except for a dry interval on 30/04/2012. It should also be noted that the WDR events are not concurrent with the heavy rain causing flooding. Comparison of the external temperature and in-wall temperature clearly shows the lag caused by the wall thermal inertial and can be also seen that the variation in RH are correlated to the external temperature changes.

2.2. Wind-driven rain calculations by semi-empirical equations

Semi-empirical equations have been proposed in literature to compute the amount of wind driven rain (WDR) incident on a wall and are commonly used to calibrate/validate parameters for CFD analysis (e.g. Refs. [15,33–35]). In this study, the amount of WDR for a selected rainy period was calculated using the most common semi-empirical approaches, the ISO model [32] and Straube and Burnett (SB) model [36,37], to then compare it against the monitoring results. The WDR spell used for the computations is the one already in Figs. 4b and 5, chosen on the basis of the criteria outlined by Ref. [38].

Both semi empirical models are based on the physical correlation of WDR, wind speed and horizontal rain. According to the ISO model [32]:

$$R_{wdr} = \alpha \cdot U_{10} \cdot R_h^{0.88} \cdot \cos\theta \qquad (1)$$

where α is the WDR coefficient, U_{10} is the wind speed measured 10 m above ground (m/s), R_h is the horizontal rainfall intensity (mm) and θ is the angle between the wind direction and the normal to the building façade. In the ISO model the coefficient, α, is computed as:

$$\alpha = 0.222 \cdot C_R \cdot C_T \cdot O \cdot W \qquad (2)$$

where C_R and C_T are the roughness and topography coefficients, respectively, while O is the obstruction factor and W is the wall factor. C_R is calculated on the basis of height above the ground (z) and the minimum height (z_{min}) parameters. The buildings under investigation are located next to a big flood plain; therefore terrain category II, defined as "farm land with boundary hedges, occasional small farm structures, houses or trees", was the most suitable to use [32]. z_{min} corresponding to this category is equal to 4 m. Because the readings were taken from higher than 4 m above the ground for both structures, hence $z > z_{min}$, C_R will be calculated using the equation (3):

$$C_R(z) = K_R \cdot ln\left(\frac{z}{z_0}\right) \qquad (3)$$

where K_R is the terrain factor and z_0 is the aerodynamic roughness length, which are equal to 0.19 and 0.05, respectively for terrain category II.

The topography coefficient, C_T, deals with the increase in the wind speed over escarpments or isolated hills, and it is taken as 1.0 in this study. Obstruction factor, O, is defined by Ref. [32] on the basis of distance of obstruction from the elevation. The building examined is located right next to a wide plain and the instrumented façades both face this plain with different orientations and without any interposed structure nearby. Hence the O factor was taken equal to 1.0. W factors were taken as 0.4, 0.3 and 0.3 for Abbey Mill gauges, WDR1, WDR2 and WDR3, respectively, according to their location on the façade.

In the Straube and Burnett (SB) model, the WDR coefficient, α, is calculated using equation (4) [36,37]:

$$\alpha = DRF \cdot RAF \cdot \left(\frac{z}{10}\right)^{\beta} \cdot R_h^{0.12} \qquad (4)$$

where RAF is the rain admittance factor and varies between 0.20 and 1.0. Here, as per the diagrams provided by Ref. [37]; it was

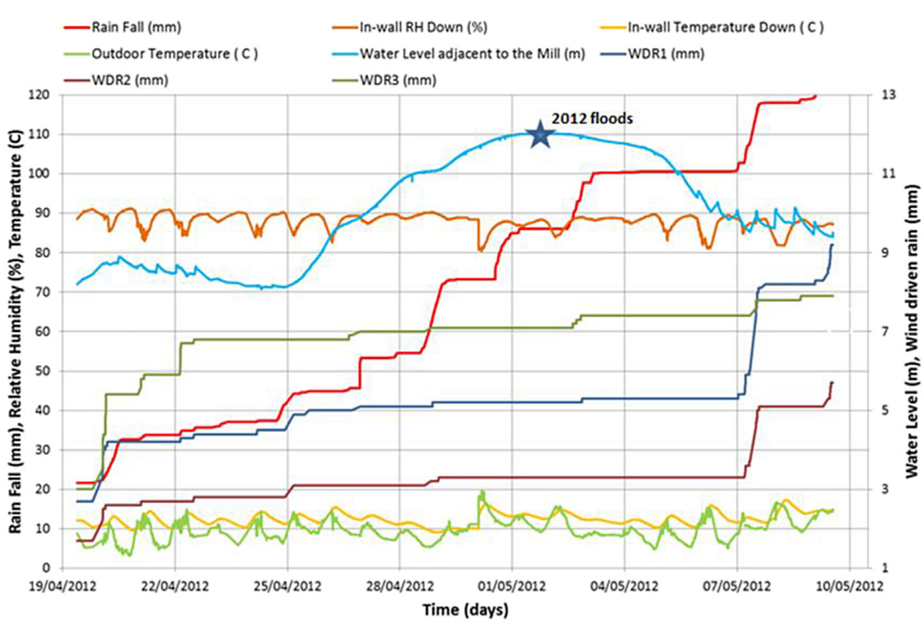

Fig. 6. Graph showing the correlation between water level rising in the leat, in-wall RH and T at a level of 1.5 m from the ground and rainfall and wind-driven rain (WDR), for the flooding event of May 2012.

taken as 0.4 for the gauges on the south-western façade of Abbey Mill, and 1 for the one on the north-western façade. The coefficient β is the power-law exponent of the mean wind speed profile that corresponds to the terrain roughness, and lastly, z is the height above the ground (m). For exposure level A defined as "open country: level terrain or open with few obstructions and only scattered buildings, trees or other obstructions", β is equal to 0.25. DRF is the driving rain function and change between 0.5 for drizzle and 0.15 for intense cloudbursts. It is equal to the inverse of $V_t(d)$, the terminal velocity of water droplet fall, which is calculated as [39]:

$$DRF = \frac{1}{V_t(d)} = 1\Big/\Big(-0.166033 + 4.91844d - 0.888016d^2 + 0.054888d^3\Big) \quad (5)$$

where d is the raindrop diameter, the median of which is suggested to be calculated by Ref. [37] as:

$$\overline{d} = 1.105 \cdot R_h^{0.232} \quad (6)$$

The ISO model has been applied to the case study using horizontal rain R_h, wind speed and wind direction monitored locally every 5 min, corresponding to the interval of monitoring of the WDR gauges. Cumulative WDR was also computed by using both models with the locally measured horizontal rain, while hourly wind speed values at 10 m above ground obtained from the Centre for Environmental Data Archival (CEDA) website for Pershore, the active weather station closest to Tewkesbury, were used for this evaluation (Fig. 7). When using the wind speed and direction from Pershore, both semi empirical models, while in agreement, substantially underestimate the readings at the most exposed gauge AM_WDR1; the SB model provides a reasonable estimate of the readings at AM_WDR2; but the estimate for AM_WDR3, which has exposure at 90° to the previous two gauges, is very poor. When ISO model calculations are made using the wind values monitored on site, there is a significantly higher correlation between the calculated WDR values and those measured on site.

On the other hand, the ISO model, used with local reading of wind speed and direction, although does not represent a perfect match, of each single event, provides a very good estimate of cumulative values. The observed differences can be ascribed to the sampling interval for wind speed and direction, these being the instantaneous values recorded every 5 min, rather than an average, time lag between the readings of the various gauges within the acquisition system, and local turbulence at the wind gauge which can affect the wind direction readings. The SB model's estimates do not improve using the local wind speed and direction measures. These comparisons prove that the WDR gauges were properly designed and provided a reliable measure of the WDR impacting the façades. The difference in recorded rain at the three gauges proves that exposure and location on the façade, and particularly height are critical, and affect both the quantity of rain per event and the number of events, within the same time interval. The comparison with the semi empirical models shows that these are oversensitive to exposure and not enough to height, but most importantly shows the importance of using local measures of both wind speed and direction and horizontal rain.

2.3. Temperature and relative humidity

A main objective of this project is to provide a better characterization of the dynamic hygrothermal response of historic fabric. Abbey Mill walls are made of solid brickwork in English bond 350 mm thick, while the infill brick masonry of Mill Bank cottage is just 150 mm thick including the plastering, without insulation. In order to build a profile of the temperature gradient across the thickness of the two walls structures, T values were monitored on five different locations: indoors, inner surface, in-wall, outer surface and outdoors, while the RH readings were taken at three locations: indoors, in-wall and outdoors. The median T and RH values and the range of variation obtained for both buildings are shown in Fig. 8. The records show clearly the influence of exposure, position and fabric. The average profile is relatively similar for the three locations as far as temperature is concerned. However the range show substantial differences, not just on the external surfaces but also within the wall, highlighting a clear risk of freeze-thawing for the lower location in Abbey Mill. This location also show the lowest value of average internal temperature and the highest and narrower range of RH, confirming that the moisture in the wall is close

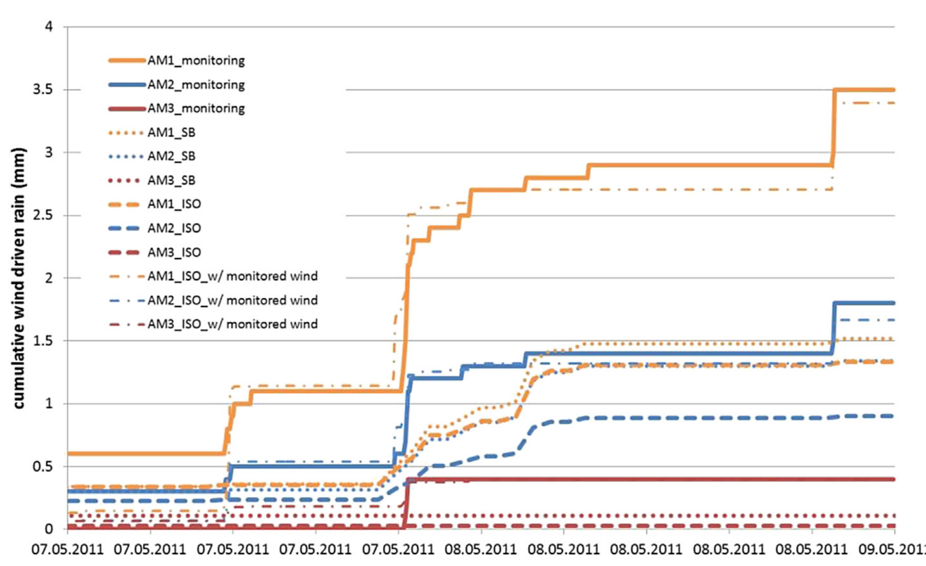

Fig. 7. Cumulative WDR values obtained by means of on-site monitoring and ISO and SB models for the indicated period.

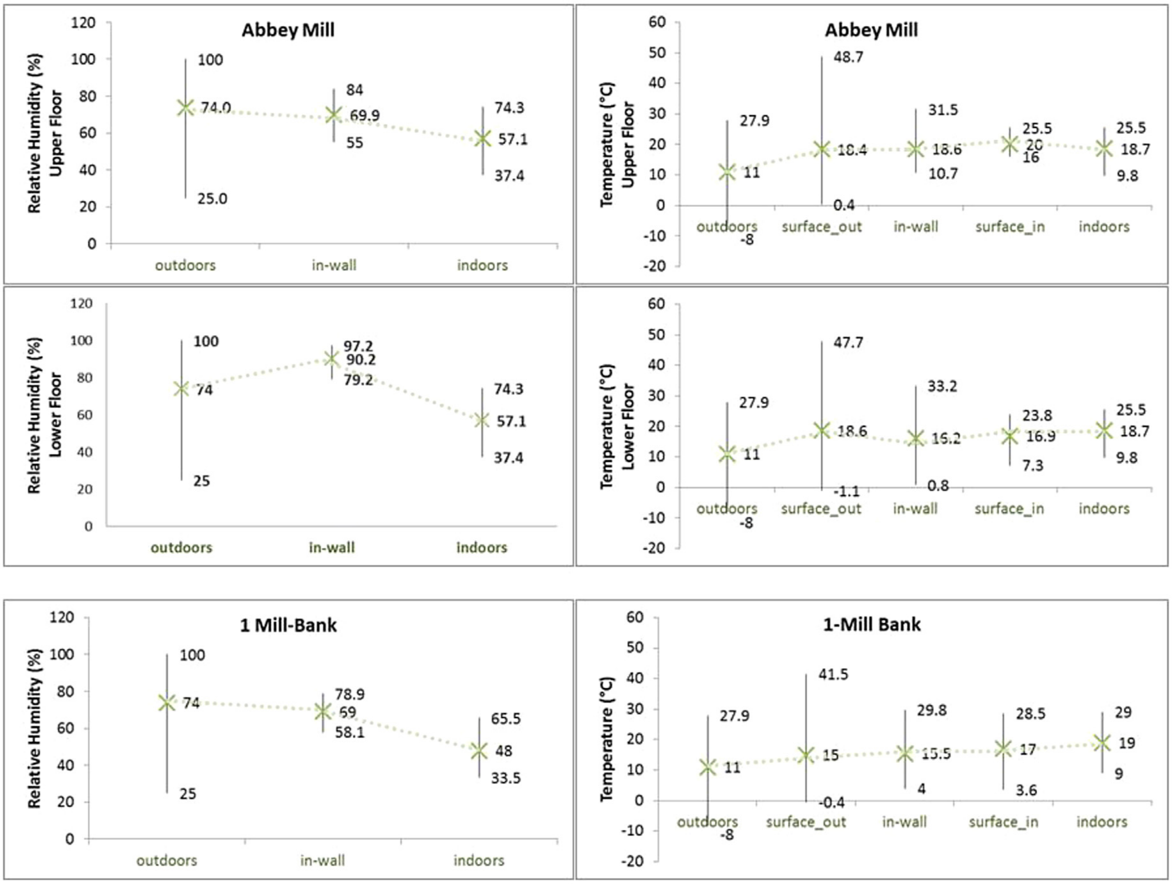

Fig. 8. Range and average RH and T values obtained for Abbey Mill and 1-Mill Bank over 14 months' monitoring period.

to saturation for a large portion of the year. It should also be noted that the in-wall values are higher than the external (except when there is precipitation) showing that the moisture in this wall is most likely due to a contribution of environmental humidity and raising damp. The profile also show that while for relatively thin walls like the Millbank one (1 brick thick) there is modest difference between indoor air temperature, indoor surface temperature and in-wall temperature this is not the case for thicker walls, where the assumption of either the indoor temperature or inner or outer surface temperature as a proxy for the in-wall temperature would lead to erroneous assumptions as to the hygrometric conditions inside the wall.

Figs. 9 and 10, for Abbey Mill and 1-Mill Bank respectively, show the dynamic behaviour of the walls over a week. Different periods of the year have been chosen to show the behaviour through the seasons. The first observation relates to the smoother and almost periodical curves obtained for the in-wall RH as opposed to internal and external records which show typical randomness of air RH. For Abbey Mill the uptake and release of humidity in the wall has a similar gradient in summer, but uptake is slower than release in autumn, inversely to the in-wall temperature quicker rise and slower decay. Peaks and troughs of in-wall RH are broadly synchronous to the peak external RH, while the internal RH is uncorrelated, substantially constant even though tracking the external RH extremal, coinciding with higher temperatures (see Fig. 9). For Millbank instead the in wall RH shows a 12 h lag to the external one and seems to be more related to the internal RH (see Fig. 10). Uptake is faster than release but both phenomena are linear.

As far as temperature is concerned, it can be seen that indoor air and surface temperature are very stable around 20 °C for Abbey Mill (fluctuation of up to 1 °C daily) and almost coincident, while in 1-Mill Bank the indoor air temperature shows a very clear daily cycle with a total excursion of about up to 2 °C daily, the surface temperature is 3 °C cooler with a fluctuation of about 4 °C and almost coincident with the in-wall temperature. This clearly proves the greater power of insulation of the solid wall of Abbey Mill in comparison with the single brick wall of Mill Bank (450 mm and 150 mm thick, respectively). This notwithstanding, both walls exhibit the comparable time lag of 3–4 h between outer air peak and in-wall peak temperature, reducing to two hours in summer due to the substantial increase in outer surface peak temperature. However, the change in in-wall peak temperature in all cases is directly related to the change in peak external air temperature rather than the external surface value. The weaker insulation capacity of Mill Bank is also confirmed by the much smaller decrement between internal and external surface temperature experienced by Mill Bank about 5 °C in respect to Abbey Mill, 13 °C (for decrement factor see also [40]). The larger decrement factor shown by Abbey Mill walls indicate a very good level of internal comfort [41], without need of further thermal insulation, while Mill Bank would require some retrofitting to increase the decrement and decoupling of external and internal temperature. When the entire monitoring period is examined, it is seen that the maximum decrement factor obtained for Abbey Mill is still larger than 1-Mill Bank (31 and 16 °C, respectively).

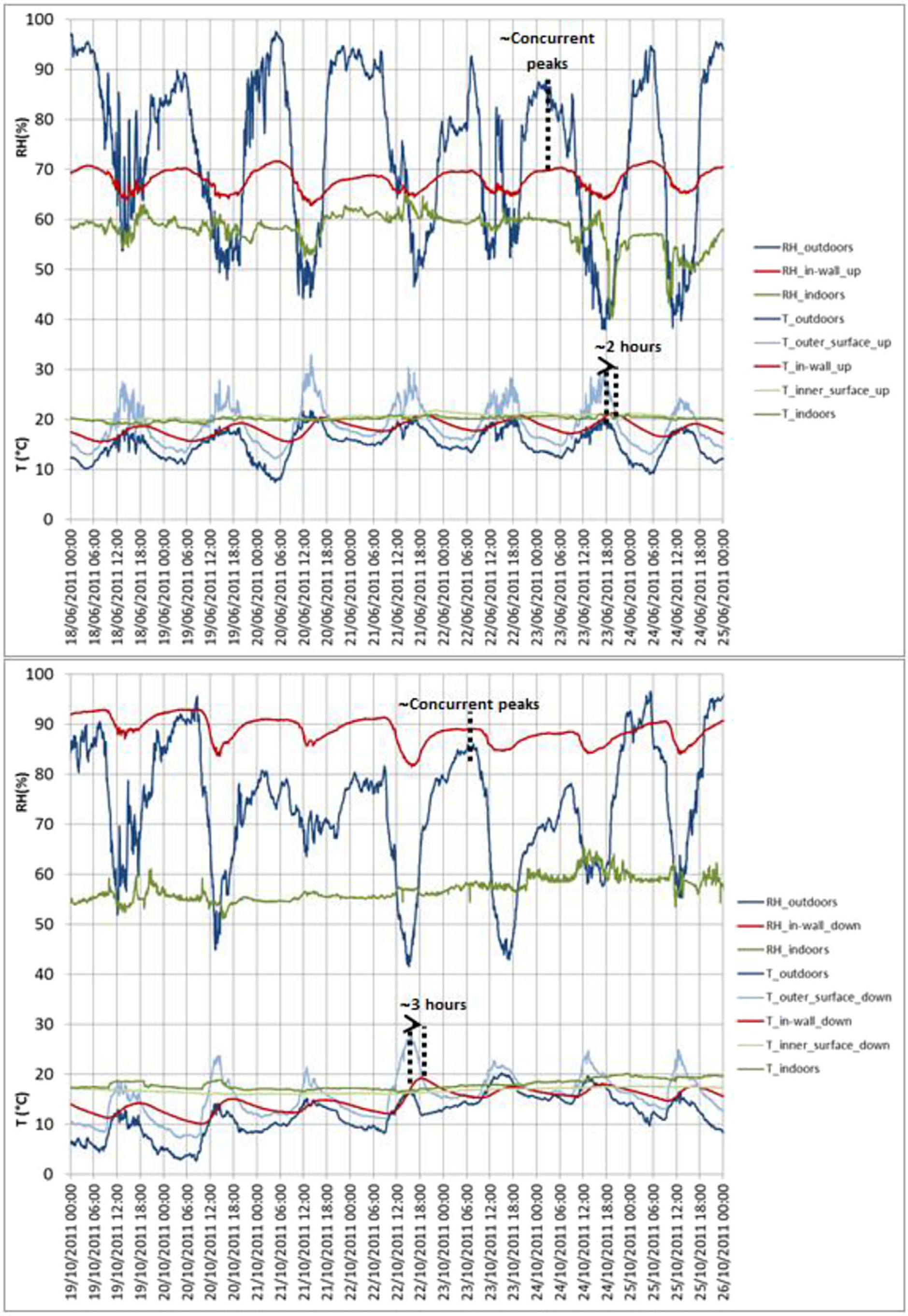

Fig. 9. Examples to T and RH values obtained from Abbey Mill upper and lower storey, respectively, over a week.

3. Hygroscopic characterization via dynamic vapour sorption (DVS) testing

Hygroscopic characterization mainly consists of determination of moisture that a material has under certain ambient RH level. In addition to the gravimetric and volumetric methods outlined in Refs. [42]; sorption isotherms, showing mass of porous materials isothermally in equilibrium with the surrounding environment [43] can be used to convert the RH values into equilibrium moisture content of a building material [44]. Dynamic Vapour Sorption (DVS) method was used in this study for this purpose, as it allows to identify the hygroscopic features of historic building materials efficiently using very small samples (e.g. Refs. [6,45]). The DVS testing of timber, brick and mortar specimens collected from the buildings was carried out by Sorption Measurements Systems Ltd. using a DVS Advantage dynamic vapour sorption system at 25 °C, with sample size ranging from 27 to 65 mg for each analysis. The size should be big enough to accommodate for the heterogeneous constitution of the materials while allowing equilibrium at each RH level to be obtained within a reasonable time frame. The samples were initially oven dried for 300 min under a continuous flow of air to establish the dry mass. The samples were then exposed to a cycle of partial pressure profile corresponding to increments and decrements and of ambient RH of 10% between 0% and 100%. For each

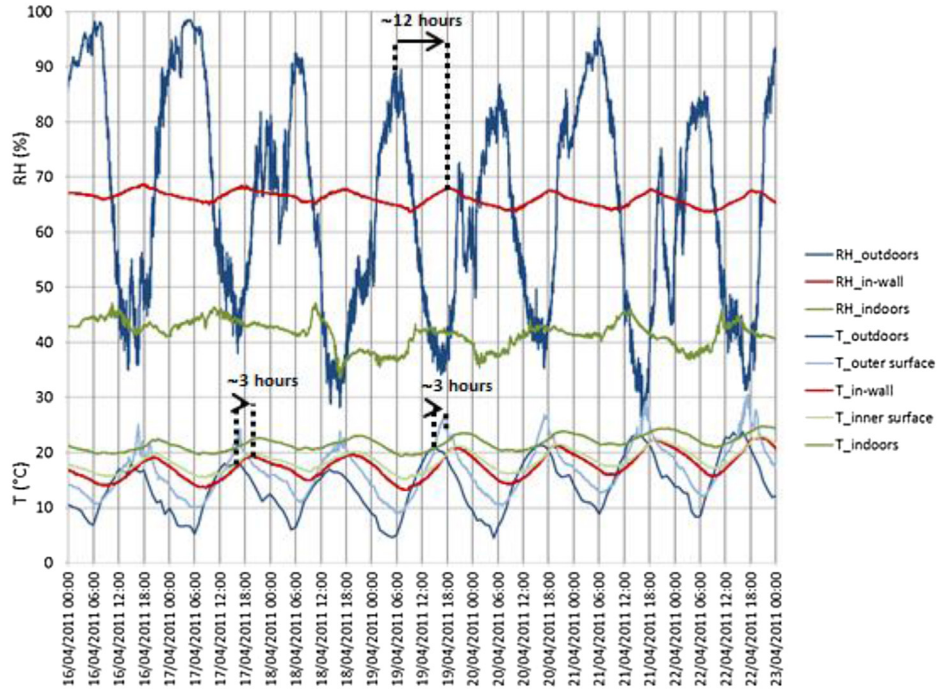

Fig. 10. Examples to T and RH values obtained from 1-Mill Bank over a week.

RH step, the DVS instrument was run in mass variation over time variation mode (dm/dt). A fixed dm/dt value of 0.002% min^{-1} was selected as the criterion to establish equilibrium between the ambient and the sample and hence complete a RH step.

It is evident from the isotherms shown in Fig. 11 that the historic lime mortar are as expected up to one order of magnitude more absorptive than the bricks. This difference is particularly evident for Mill Banks materials, where even at lower RH (40%) the rate of change in mass is about 10 times greater for the mortar when compared to the brick. It can also be noted that the mortar at Mill Bank has a more significant hysteresis than any of the other materials. This can be one of the causes of the greater time lag in RH evidenced by the monitoring (Fig. 10). The difference between moisture intake in old (12th century) and new bricks (18th century) used in Abbey Mill is also noticeable. This amounts to more than 40% at 95% ambient RH, but much more substantial at lower level of ambient RH, the older brick showing higher inertia. Also, there is a more distinctive hysteresis in the sorption and desorption of the new bricks, which is especially critical for shorter drying cycles or variation in RH. However, the modest moisture intake and the small hysteresis of all Abbey Mill materials are reflected in the much smaller inertia exhibited by the change of in wall RH to changes in ambient RH in the graphs of Fig. 10 for this building, when compared to the Mill bank conditions. This substantial difference can be ascribed principally to the diverse hygroscopic characteristics of the two mortars from Abbey Mill and 1-Mill Bank, with change in mass due to moisture intake of mortar samples from 1-Mill Bank around 3.3 times greater than that of Abbey Mill mortar under almost saturated conditions (95% RH). These observed differences reveal clearly the need for hygroscopic characterization of each building material, when considering mitigation measures for historic buildings.

Laboratory tests carried out to determine the physical properties of the samples taken from both buildings showed that the bulk density values of Abbey Mill mortar and new brick are 1460 and 1710 kg/m^3 respectively. These values are respectively 1260 and

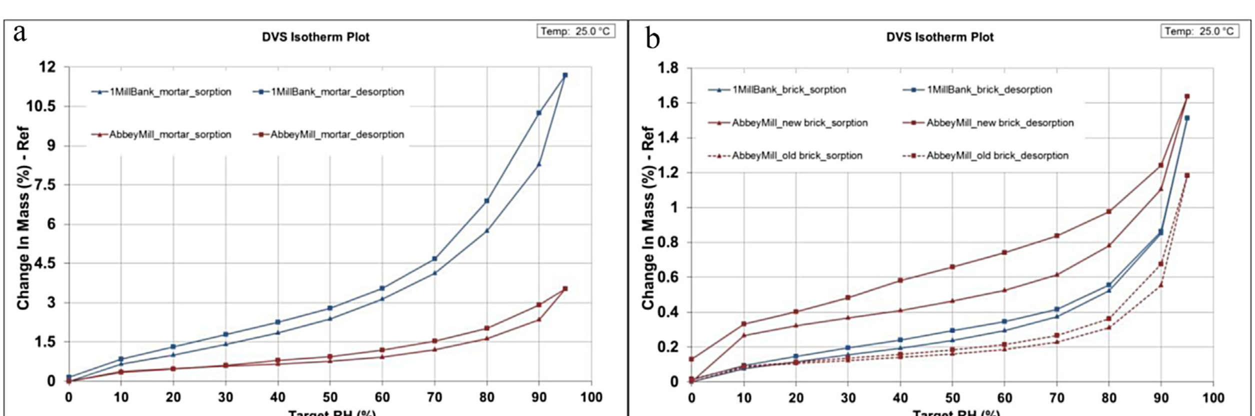

Fig. 11. Sorption and desorption isotherms obtained for Abbey Mill and 1-Mill Bank a) mortars, b) bricks.

1630 kg/m^3 for 1-Mill Bank. This means that when the moisture contents are calculated for each material examined here on the basis of the sorption isotherms given in Fig. 11, Abbey Mill mortar and 18th century brick can respectively absorb 5.1% and 2.7% moisture at quasi saturated conditions (95% RH). These values for 1-Mill Bank mortar and brick, on the other hand, are 14.8% and 2.4% respectively. This shows that the new brick and mortar used in Abbey Mill are more compatible to each other in terms of hygroscopic behaviour, while in the Mill Bank, where the two materials exhibit markedly different hygroscopic characteristics, moisture migration from bricks to mortar should be expected.

4. Possible adverse effects of moisture and temperature variations within walls

One of the most common ways how moisture induced deterioration manifests itself is mould germination, both in historic and modern buildings. It affects the air quality and it is considered to have health implications when certain types are inhaled systematically. There are different methods used to identify the minimum RH value which encourages mould germination in different building materials, as suggested also by the relevant codes (for a succinct compilation of these see Ref. [46]). Some of the factors influential on the determination of climatic control thresholds include type of substrate, duration of incubation and testing method [46], as well as the surface type and how clean it is [47]. Despite the lack of standard testing methods, there are still a number of general rules that are applicable to evaluate the susceptibility of a construction material to mould growth.

As argued also by the Sustainable Traditional Building Alliance [30], although [48] suggests calculation methods for critical surface humidity values to assess risks posed by excessive moisture, these do not take into account a number of factors that are quite influential on moisture migration within the building envelope, such as hygroscopic moisture capacity of materials, capillary suction and moisture transfer. It is generally suggested that a minimum RH value that might result in fungal activity can be taken as low as around 75% for building materials in general, if no other information is available (e.g. Refs. [9,46]) with clear increase in fungal activity likelihood when RH exceeds 80% (e.g. Refs. [49,50]). BS 5250 (2011) suggests that RH values higher than 80% for a sufficiently long time (i.e. a few hours) can result in an onset of mould growth, and once the germination starts taking place, the process can continue under lower RH values. T values reportedly needed for an onset of mould formation can be quite low for very high RH values (i.e. over 90%), however for relatively moderate humidity levels the reported optimum temperature value for most species varies between 20 °C and 30 °C (cf. [49,51,52]).

In order to quantify the threat of mould germination for Abbey Mill and 1-Mill Bank, daily simple average T & RH records were plotted for the two buildings' in-wall and for the outdoor conditions against generalised isopleths taken from Ref. [31]. Fig. 12a shows that mould growth can be expected in the lower floor walls in Abbey Mill, where most of the winter and autumn values are bound between the 1 and 2 days isopleths. These conditions however might be caused more by capillary rise than by WDR. Abbey Mill upper floor (Fig. 12b) on the other hand is not as risky. Mill Bank (Fig. 12c) mould germination risk is similarly not as critical, notwithstanding sustained RH values above 75% for 2 winter months, due to its smaller thickness and hence lower hygrothermal inertia. This also explains the clear correlation between T & RH values and its strictly seasonal pattern. This is less evident for the Abbey Mill records, although these are incomplete due to some malfunctioning of the sensors.

The outdoor T&RH external surface conditions show a much more chaotic pattern, with a wide range of variation for both parameters (Fig. 12d). Fig. 13 shows the distribution of the time elapsed between each successive cycle equivalent to RH fluctuations between 70% and 95%. The 70% threshold is chosen by inspection of the sorption isotherms obtained for building materials, noting that it corresponds to a slope change in the curve and more pronounced hysteresis. It can be assumed as the limit for the material to shift between dry and wet, so the cycles of sustained RH above 70% can be assessed as wetting cycles. During the monitoring period around 140 such cycles were counted, most of them occurring in spring and autumn (Fig. 13a). Fig. 13b shows that fluctuations are mostly a daily and two-daily phenomenon. This may lead to cyclic expansion and contraction of bricks and mortars, hence weakening in the long term [53]. The cyclic wetting-drying impact has been shown to result in higher expansion in bricks than continuous soaking [54]. This action results in changes in pore structure [55] and strain values that are beyond reversible limits and create damage via creep and fatigue as shown for many construction materials [55–57].

Differential expansion and shrinkage in different materials forming the building envelope can also be induced by temperature oscillation and temperature gradients [58]. Daily T gradients are particularly harmful as they can induce strain accumulations in the materials. If the thermal expansion coefficient of masonry is assumed to be 7xe-6/°C [59] and the bond cracking strain is taken equal to 1xe-4 [60], then one can conclude that any T variation above around 14 °C will induce cracking. The maximum daily T variation obtained for Abbey Mill and 1-Mill Bank over 14 months of monitoring is shown in Fig. 14. Here the values shown in yellow indicate the maximum daily T variations occurring at the outer surface, mid-wall and inner surfaces of the wall section, while the values shown in red indicate the daily maximums of the difference between outdoor and in-wall, and indoor and in-wall T values. According to this, crack formation due to excessive thermal strain is expected at the outer sections of the walls in both structures. This microcracking can change the permeability of the outer surface to WDR and other sources of moisture.

5. Conclusions

Current climatic trends indicate that more and more extreme weather events are to be expected. The historic buildings are known to be especially vulnerable to these actions and formulating correct measures able to counteract the adverse effect of climate on historic building envelopes requires a thorough understanding and an accurate quantification of the existing threat. The environmental monitoring system developed and installed as part of this study has been proven effective to capture the variations in the environmental parameters influential on historic building envelopes and give a clear insight about the relationship between critical parameters. The study also showed that the environmental monitoring is still one of the most effective tools to assess the building performance under climatic impact; however the monitoring of in-wall and surface values is a must to produce accurate T and RH profiles across the wall. The WDR gauges developed as part of this study have also been shown to be useful and are easy to replicate for the aim of monitoring vertical rain flux in similar studies. It has been shown that meteorological station data cannot be used as a robust proxy, when the emphasis is on determining the conditions to which the envelopes of specific buildings are exposed to. This study also clearly shows that the semi-empirical models should be further fine-tuned to reproduce the WDR affecting a building façade accurately under given wind and precipitation conditions. When ISO model calculations are made using the wind values monitored on site (instead of wind data obtained from 10 m from

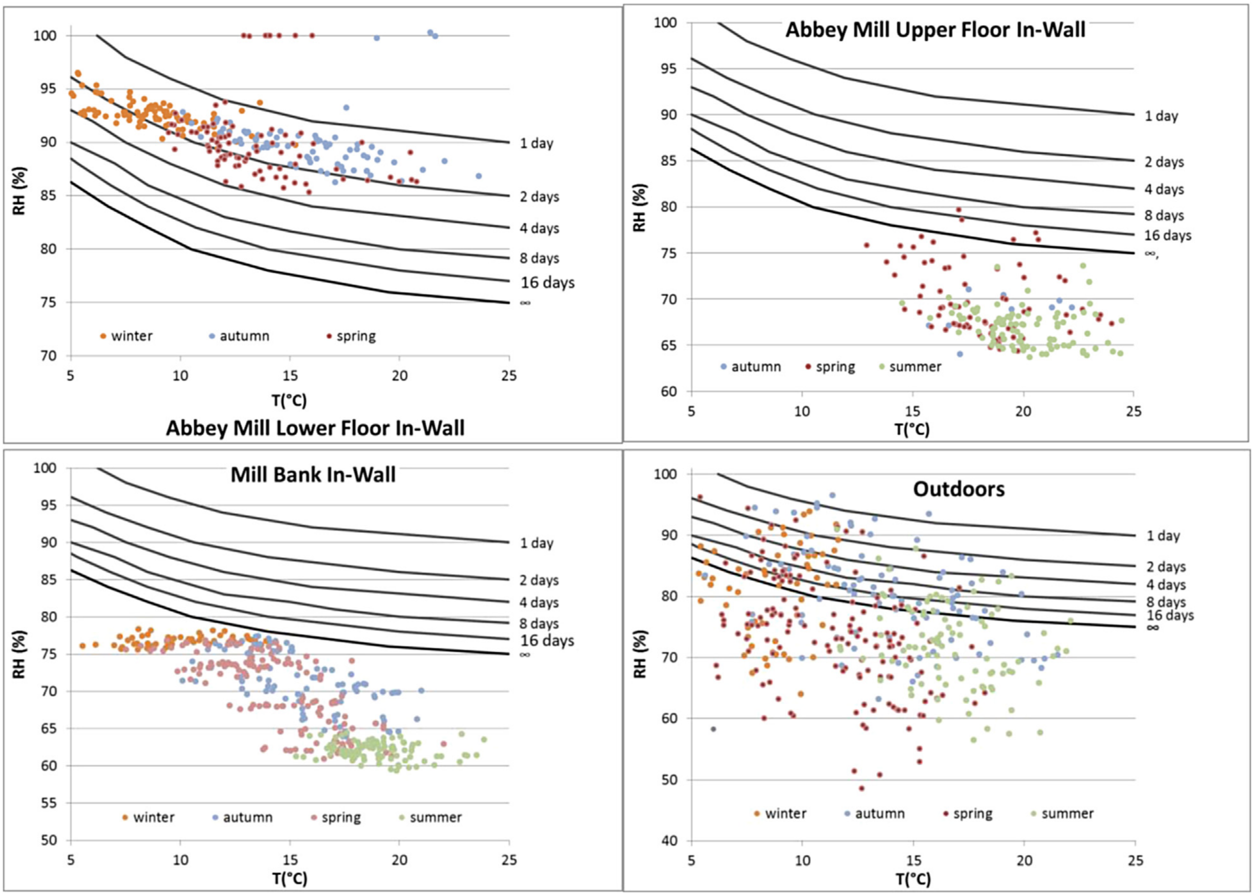

Fig. 12. Monitored T& RH daily averages and generalised isopleths of spore germination time.

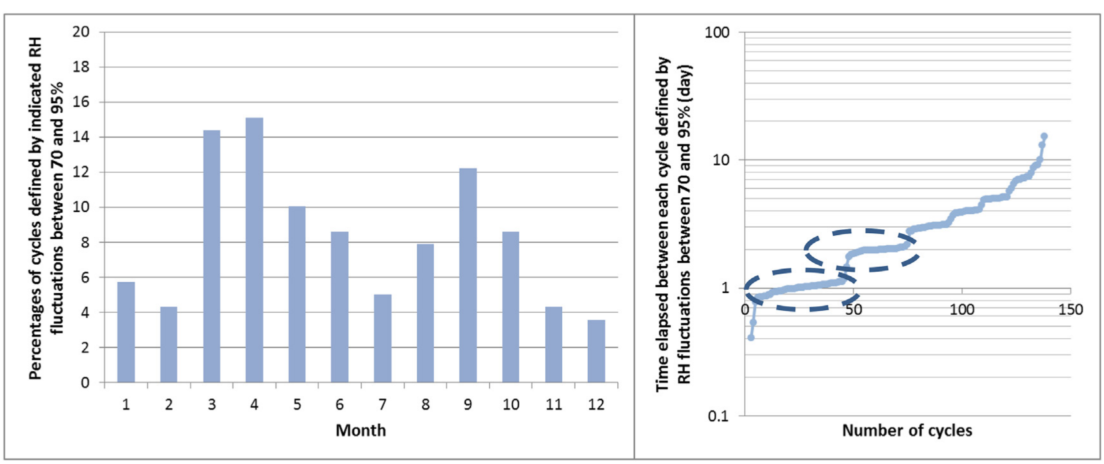

Fig. 13. Distribution of time elapsed between successive RH fluctuations in the outdoors between 70% and 95%.

the ground level), there is a significantly higher correlation between the calculated WDR values and those measured on site.

In order to best exploit investments in on-site monitoring, this should always be supported by a thorough hygrothermal characterization of the materials as the amount of moisture that the building embodies can be accurately quantified only then. This study clearly shows that there might be substantial differences in the moisture absorption and desorption features of bricks and mortars, even within the same building, therefore generic values should be avoided.

The monitoring has shown that deteriorating phenomena due to hygrothermal conditions can pose a real threat for both these historic building typologies, either due to biological activity or to microcracking associated to temperature and moisture fluctuations. Their effects can become damaging when sustained number of cycles occur, if maintenance and repair actions are not routinely taken. The current prediction of more intense more frequent rain and increase in temperatures, can only create more adverse

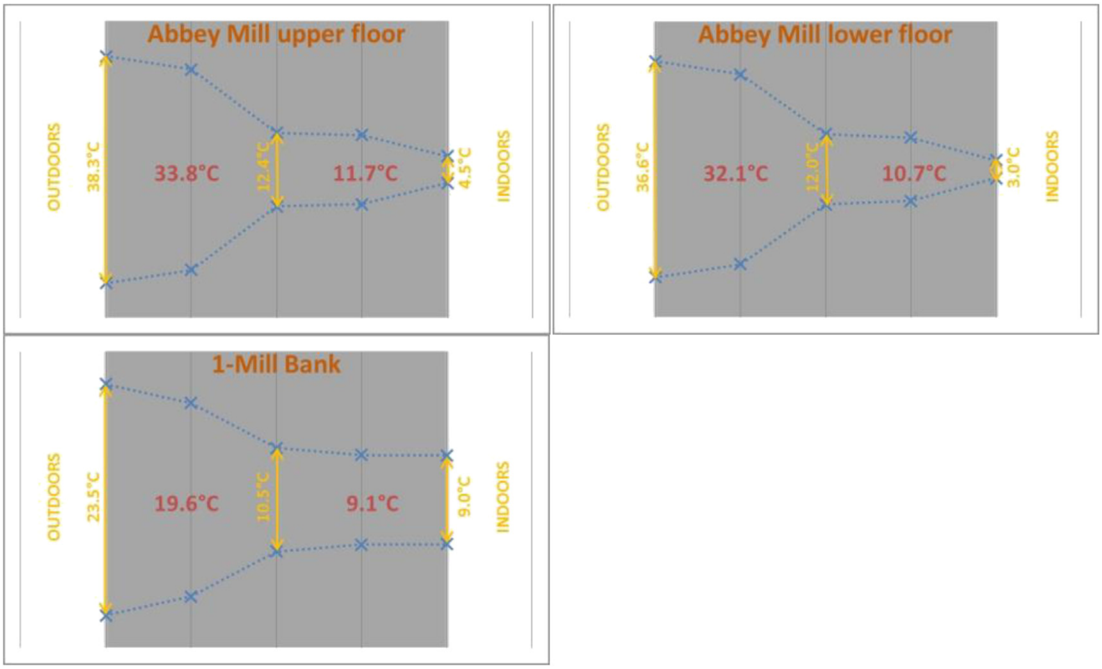

Fig. 14. Maximum daily temperature variation across the wall sections of Abbey Mill upper and lower floor and 1-Mill Bank, respectively.

environmental conditions than presently monitored.

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