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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.