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Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials

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ABSTRACT

Building surface erosion is a common phenomenon observed on historic building façades due to wind-driven rain (WDR) impact. Recently, studies on climate change and the effect this might have on increased extreme rainfall events has renewed the scientific interest on determining the risk of accelerated erosive effects. Given the fact that WDR loads on building façades is proportional to rainfall and represents the main moisture source and erosive physical impact for building façades, an assessment method that quantifies the severity of erosion is the first step towards recommending remedial measures. The paper discusses the major factors escalating the gradual loss of surface material, considering value, hazard, vulnerability and exposure in order to examine the WDR drop impact on the aesthetic significance and the structural integrity of heritage buildings, within a parametric framework. The study investigates the effects of different size water drops, with different impact speeds on a range of masonry materials with different surface asperities and varying moisture absorption features, at various impact angles. For the relative quantification of the long-term surface erosion, straightforward and globally adaptable experiments are proposed based on site-specific climatic data and materials. Finally, strength decline of exposed sample units proves the strength-degrading effect of erosive WDR.

1. Introduction: objectives, state-of-the-art and methodology

Widespread major weather events all over the world have focussed attention on the influential effects of climate change. In June 2007, in excess of 150 mm of rain fell over much of Wales, the Midlands, Northern England, Northern Ireland and parts of Scotland and South-west England [1]. Other notable examples include the floods in central Europe in 2002, the New Orleans flood in 2005 and numerous floods in South Asia in 2007 and 2009 [2]. Heavy rainfall, flooding and strong winds or storms have had severe impact on the social, economic and cultural spheres of the country life. Although the consequences of these extreme weather events have been investigated in various sectors (i.e. agriculture, industry, energy, transport), damaging effects on the cultural heritage have insufficiently been addressed [3]. The changing magnitude of extreme weather events has emphasised the need to review the damaging factors in surface deterioration (Fig. 1) and eventually loss of integrity of heritage buildings to identify, quantify, and control the climatic effects for evaluation of remedial strategies.

The study presents novel objectives: (i) Firstly, to define a robust risk assessment framework within which the major factors escalating the loss of surface erosion are documented and classified according to value, hazard, vulnerability and exposure. (ii) Secondly, the dominant factors and their implication on the aesthetic significance and structural integrity of heritage buildings are identified. (iii) Thirdly, a straightforward and adaptable testing regime to quantify the surface erosion due to long-term WDR impact is proposed, relating the drop impact size and duration to the local rainfall characteristics. (iv) Lastly, the study aims to measure the strength decline of exposed sample units after erosive WDR effect using a modestly destructive technique that can be used on site. Impact behaviour examination of varying size water drops with varying speeds and impacting angles forms the parametric framework, wherein a range of masonry materials with different surface asperities and moisture absorption features, are being comparatively tested.

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Fig. 1. Various locations on SE and SW façades of the southern transept of Tewkesbury Abbey.

2. Evidence of wind-driven rain erosion on historic masonry building façades

Several researchers emphasised the adverse effects of WDR on various building materials. For instance, rain has been noted to be an important contributory factor to the extent of stone erosion [4]. Importantly, clean rain is considered the cause for surface erosion of building façades [5]. The effect of WDR on surface stone erosion has been investigated at the Cathedral of Learning, a tall limestone building in Pittsburgh, Pennsylvania [6,7]. Numerical modelling and field measurements of WDR loads on the façades showed that white, eroded areas on the building's walls corresponded to sections receiving high amounts of WDR fluxes. For the same building, Etyemezian et al. [8] also reported that the calculated rain fluxes on the façade of the building were reasonably consistent with the erosion patterns. Monumental brick masonry is also susceptible to WDR erosion as reported for St Hubertus, in the Netherlands, where climatic conditions are similar to the UK. Numerical simulation and on-site WDR measurements were performed to determine the amount of WDR on the most damaged south-west façade [9]. Surface deterioration of granite buildings in Aberdeen, Scotland, is also noteworthy. On the highly exposed façades of some of the buildings, WDR caused mortar erosion and dampness problems and re-pointing was performed as a remedial measure for the façade [10]. Dramatically, for earth-wall buildings, the impact becomes more critical. Heathcote [11] reported that the release of the kinetic energy associated with raindrops impacting on the building façade is the main cause for the removal of material from the surfaces. Furthermore, abrasive action of raindrops on cement-stabilised rammed earth-wall surfaces is also evident and stabilising the soil with a chemical agent such as cement was noted to eliminate, to some extent, this drawback [12]. Similarly, in a study performed with compressed and cement-stabilised building blocks by Kerali, the conclusion was surface erosion due to WDR varies according to the elevation of the block within the wall, orientation of the façade, and the age of the building (period of exposure) [13].

3. Factors affecting façade erosion due to raindrop impact

Rain with a horizontal velocity component given by the wind is called wind-driven rain (WDR) [14], which is one of the main factors being responsible for surface erosion. Erosion here means the detachment of material from a masonry building façade due to the physical impingement of WDR. Detachment occurs through long-term, continuous, repetitive and synergetic action of WDR. The loss of surface material can be quantified by a probabilistic approach to enable variation and uncertainty, and defined as a probability function of value, hazard, vulnerability and exposure. This can be applied to a single feature on a façade (an ornament), a complete façade, a whole building or the historic building stock in a historic centre. The major contributing factors can be expressed with regard to the respective components:

$$P_{\text{Surface Erosion}}(\text{Loss}) = P(\text{Value})\cdot P(\text{Hazard})\cdot P(\text{Vulnerability})\cdot P(\text{Exposure}) \quad (1)$$

Equation (1) provides a probabilistic-based qualitative understanding of the predominant and independent variables determining surface erosion. A similar approach has also been used to evaluate other natural disastrous effects [15]. This formulation can be best understood by examining different locations on the façades of the southern transept of Tewkesbury Abbey (Fig.1). For instance, very heavy rainfalls (high hazard) on the south-east façade (high exposure) causes high physical loss (as the material is vulnerable, see loosening of the masonry) but modest overall loss as there is no ornament (low value) (Fig.1a). Similarly, heavy rainfalls (high hazard) will not cause loss to a well-protected (shielded) façade (low exposure) although the material might be just as vulnerable and has greater value (Fig.1b). However, even moderate rain events (medium hazard) will result in relatively more erosion to the moulded unprotected façade (high exposure, high value, and high vulnerability) (Fig.1c). Besides material type (vulnerability) and façade orientation with respect to prevailing wind direction (directional exposure) (Fig. 1a and c), an important factor is also the duration of any event determining the time exposure. Each variable will now be discussed indetail.

3.1. Value

By value, it is intended as the appreciation (cultural, social, historical) of the fabric of a historic building due to its authenticity and the added value of human interaction with the material (Fig. 1). When there is no substance to erode, there is neither risk nor loss. However, most cultural heritage presents delicate ornamentation and exquisite craftsmanship having historical and evidential importance. Protection of artistic features from the threat of accelerating climatic events becomes necessary. The protection of Sueno's Stone, a sculptured sandstone monument dating from the end of the first millennium AD on the north-easterly edge of Forres, Scotland well clarifies the concept [16]. The monument was