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C o n t e n t s

Editorial

In attempting to interpret and understand a building fully it is necessary to consider not only the aesthetic, but also the functional factors that have influenced its creation. While much has been written about architectural style (and there is a growing body of work considering the development of various building types) some types have been largely overlooked. Two such neglected building types are the subject of papers in this issue of the Journal.

Nick Cox draws our attention to the boathouse, a building type now sadly dwindling in number due to neglect. After briefly charting the place of the boathouse in the designed landscape of the country house, he chronicles the rescue of a seriously dilapidated example of historic importance in the park at Belton House, Lincolnshire. In relating how this delightful Swiss/neo-Tudor, Salvin-designed building was saved he focuses on the importance of the historic research, archaeological evidence and technical understanding that guided the complex process of its conservation.

Emily Gee's paper invites us to consider the purpose-built lodging houses or hostels that were erected to cater for the influx of single women attracted to new job opportunities in cities, particularly London, towards the end of the nineteenth century. Many of these jobs arose in the wake of inventions such as the typewriter and telephone, and providing suitable accommodation for the single women who operated them became a pressing social issue. By looking at the building type in its historical context, the paper provides a basis upon which to make informed decisions for the future of such buildings. Those buildings that survive in anything like their original internal form provide an important record in the social history of the working woman, and as such deserve some measure of protection, or should at least be recorded before they are lost to adaptation or redevelopment.

The remaining papers are of a more technical nature and deal with the impact of fire on stone, the repair of marble, and cantilever stone staircases respectively.

Effective fire risk management is essential for the safe occupation of any type of building irrespective of its age or cultural importance. While safety will always be the paramount concern, in the case of a historic building there will be an equally strong desire to protect, as far as possible, the building fabric from the harmful effects of fire and the necessary actions of firefighters to bring fire under control. In the aftermath of a fire a thorough examination of a building's fabric will be necessary to establish the extent of the damage and to formulate a repair strategy. A succinct summary of our current understanding of what happens to the surface of stones subjected to the damaging effects of fire is provided by Miguel Gomez-Heras and his colleagues. Their paper also supports the installation of water misting or fogging fire suppression systems, which minimize the damage to the surface of stones, so commonly encountered when more traditional water-based firefighting methods are employed.

Jonathan Kemp's paper offers an interesting insight into the current practices and materials adopted by specialist conservators for filling voids in marble surfaces. It is the accepted view that because the quality and condition of individual pieces of marble, and the environment in which they are located, can be quite variable there can be no universal 'one size fits all' approach to repair. The views of conservators collected by the author highlight their differences in approach and materials used, indicating that contemporary practice is still evolving and no consensus view yet prevails. Hopefully this paper will stimulate further discussion and debate amongst practitioners and promote the dissemination of knowledge and the establishment of best practice.

Our final paper looks at the elegant cantilever stone stairs that were made popular in the Georgian period by fashionable architects, including William Chambers and Robert Adam, and that have long been a source of interest. Their graceful flights seem to float in the air, defying gravity, causing the observer to ponder on how they work without collapsing. Ian Hume provides a clear non-mathematical explanation to readers unfamiliar with the structural principles involved and, in addition, offers pithy advice about common faults and what to look out for during inspections. For those with doubts about the structural adequacy of these stairs the reported results of load testing will provide comfort and reassurance.

Professor Peter Swallow

Impacts of Fire on Stone-Built Heritage

An Overview

Miguel Gomez-Heras, Stephen McCabe, Bernard J. Smith and Rafael Fort

Abstract

Fire is a major threat to stone-built cultural heritage and this paper is a review of the existing research into fire damage on building stone. From early research based on anecdotal evidence of macroscopic observations, scientists have moved on to develop various techniques for approaching the investigation of fire damage to stone (high-temperature heating in ovens, lasers, real flame tests), different aspects of the damage that fire does have been learned from each, developing understanding of how microscopic changes affect the whole.

This paper seeks to highlight the need for a greater awareness of the threat that fire poses (and the need to take precautionary measures in the form of fire-suppression systems), of the immediate effects, and of the long-term management issues of natural stone structures which have experienced fire.

Introduction

Stone is an essential component of practically every historic building. Stone is, however, far from being an immutable material, as it can undergo severe disruption due to various decay agents. This clearly generates a cost in terms of the maintenance repair of buildings. There are several estimations of stone conservation costs. In the UK context, for example, the recently completed project 'Safeguarding Glasgow's Stone-Build Heritage', calculates that the cost of repairing damaged stone buildings in this city will be around £585 million in the next 20 years with a calculated 395,000 tonnes of stone required to carry out the necessary repairs in this time span.[1]

Fire stands out among decay agents because it generates irreversible decay of stone, with long-lasting effects, in a very short period of time. Studying the impact of fire on stone is therefore of great importance – fire can cause a significant decline in the strength of stone, lead to loss of surface material and may compromise the structural integrity of a building. Furthermore, surface changes may lead to the loss of the aesthetic values of the stone – particularly important when stone is used as an ornamental dressing in a monument or sculpture. This importance has been recognized at a supranational level with a recently completed research report (COST Action C17 – Built Heritage: Fire Loss to Historic Buildings) in which one of the aims was to quantify the scale of loss to historic buildings due to fire. In the UK alone, an average of seven heritage buildings per month are damaged by or lost through fire.[2]

The cracking of stone at high temperatures, coating by soot and colour change in stones containing iron are the most obvious effects generated by fire (Figures 1 and 2). Possibly because of this, most early research was almost anecdotal in nature, and focused on macroscopic observations of bulk changes to stone caused by fire.[3]

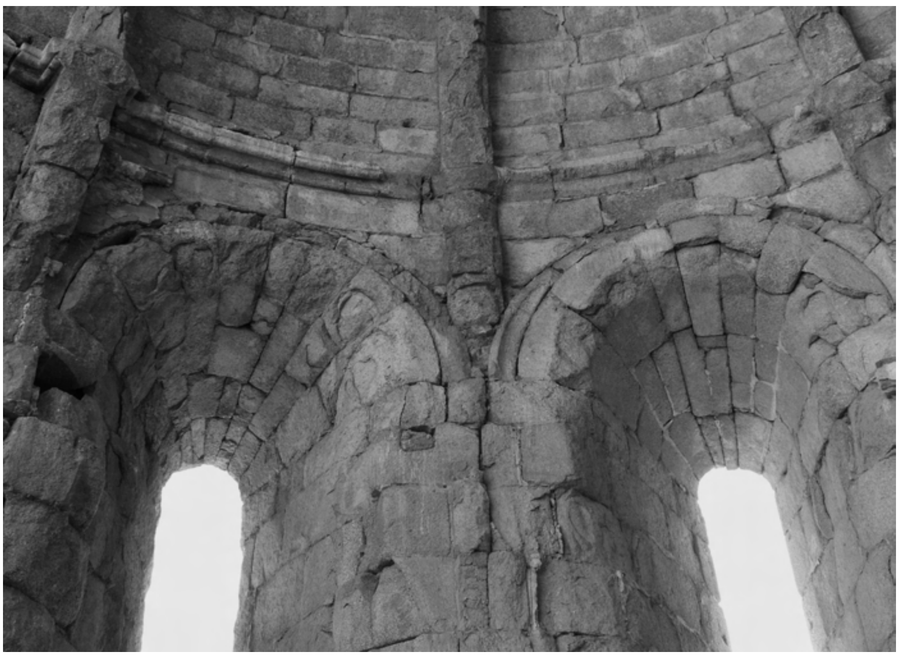

Figure 1 Severely spalled granite as a consequence of an historical fire. The concentrically 'onion-skin' structure of the spalling is especially noticeable in the window arches, through which flames may have moved to the exterior of the building.

Figure 2 Sandstone after a localized fire at Dungiven Priory, Northern Ireland – note the discolouration (reddening) of stone in the 'clean' area where the flames burned, the soot-coated stone above, and the fracturing which caused severe loss of material.

A more complete approach to the question of fire-damaged stones should, however, also involve the understanding of *micro-decay* features caused by a specific event of fire and those changes that are, in effect, hidden within the fabric of the stone. These micro-scale mineralogical and textural changes must not be neglected as they often provide a key for understanding the subsequent processes that act at a greater scale, [4] for example, the fracture mechanisms and patterns within the stone that control future chemical and physical decay. To some extent, this has been recognized in recent studies on fire decay that have focused on the relevance of micro-scale changes and processes leading to changes in porosity, mineralogy and micro-cracking. [5]

This change of scale in the study of the effects of fire has also encompassed a change in the timescale over which fire effects are assessed, and recent research has stressed the possible long-term influences of fire when combined with other decay agents. In this way, fire has been identified as leaving a stress legacy that may be exploited by other, less extreme decay processes for many years. [6]

Ways of investigating fire

There have been a number of methodological approaches to the replication of damage generated by fire, the main aim usually being to understand the processes experienced by building stone during fires.

In existing literature, three principal methods can be identified for the 'laboratory' investigation of fire effects. The most common method is to model the effects of the increased temperatures generated during fires within ovens. [7] More recently, however, there has been some exploration of the use of real fires and laser-based techniques to replicate both temperature effects and associated chemical reactions.

The use of ovens to simulate the heating generated by fire has the advantage of their availability and automatic function, as well as the high degree of standardization and replication that can be obtained in such tests. In addition, the wealth of results in the literature obtained with this technique guarantee a database for comparison of new results. Nevertheless, air circulation ovens do not fully reflect the processes that take place during natural fire. [8] The physics of heating in an oven is different to that in a real fire, as stone heating is attained through convection mechanisms in an oven while the main mechanism of stone heating during real fires is through radiation. Nor does oven testing replicate the combustion by-products found in real fires, such as the complex particulates present in equally complex fumes.

Heating with real flames[9] is obviously the most realistic approach to fire testing, as the physical burning replicates reality and the influence of fumes from fuels can be assessed. Unfortunately, tests carried out with these techniques invariably lack any form of environmental control and are therefore unrepeatable in nature. These tests are therefore unrepeatable in nature and pseudo-random. That said, in the context of actual fires, random events are what actually happen, and something new may be learned with each experiment. To maximize this advantage it would arguably be most appropriate to carry out such tests on either large samples or numerous samples so that this variability can be assessed. The use of large blocks in groups of samples also has the advantage over oven-based heating of small samples in that it replicates the dimension – and stresses – associated with the scale of blocks used in construction. This method could be appropriate for carrying out bulk tests on the stone performance, but it might be difficult to establish accurate observations of effects at the micro-scale.

In contrast, laser burning of stone accurately replicates the heating physics during a fire, as it heats stones by radiation.[10] It also allows a high level of repeatability and makes possible the inclusion of combustion products in the damage assessment. Laser testing concentrates a highly energetic beam of radiation onto a small area and consequently allows precise experimentation in very small areas. This makes it a technique that is suitable for small samples and, therefore, convenient for the assessment of micro-scale decay features on, for example, ornately carved surfaces. It is not, however, suitable for big samples and thus for the assessment of bulk changes of the stone. One of the handicaps of laser technology is also that it is expensive and not readily available outside research institutions.

Immediate effects of fire on building stones

The most obvious effect that fire has on many stones is discolouration due to both soot cover and the thermal oxidation of iron-bearing minerals. Thermal oxidation can begin to take place at temperatures as low as 250–300ºC. Different minerals produce different colour changes: for example, hematite and iron hydroxides produce an intense reddening of stone while glauconite becomes brownish and chlorite becomes yellowish at first.[11] These changes may not compromise the structural stability of the material, but can generate extreme aesthetic damage.

In terms of the structural stability of the stone, *in situ* observations of stone buildings that have undergone fires identify a rough distinction of the stone types on the basis of their behaviour after a fire:

- Porous, matrix-rich materials, in which fire may not generate severe bulk disruption of the stone *during* the fire (post-fire performance dealt with below).
- Low porosity, dense materials where breakdown of stone due to fire is evident.

When stone is heated during a fire, a steep temperature gradient is generated from the surface to the inner parts of the stone. Therefore, while the surface of the stone may experience very high temperatures, these fall drastically over a shallow depth. Thus, the most obvious effects of the fire decay are constrained to the first few centimetres of stone. Similarly, if this ‘thermal shock’ is going to generate immediate failure, it is most likely that on a flat surface this breakdown will take the form of the sealing and flaking of the outer layer. Where there is a surface topography to the stonework – corners as well as carving – the complex pattern of convergence of internal heating/stress gradients is likely to produce equally complex, and possibly accentuated, patterns of fracturing.

The main effects that fire has in porous materials with an intergranular matrix (mainly sandstones) are related to chemical changes within the matrix. Clay minerals are especially sensitive to temperature increase and, therefore, in sandstones with a siliceous matrix, structural changes of clay minerals are the predominant effect generated by fire. Minerals, such as palygorskite, smectite, kaolinite or chlorite undergo structural changes at different temperatures that may lead to a collapse of their mineral structure, reducing stone strength. This process leads to a slight increase in porosity and, depending on the minerals, may begin to take place at temperatures from 250ºC to above 600ºC. In sandstones with a calcareous matrix, the calcinations of calcite from 800ºC may constitute the main effect generated by fire, as both the transformation from calcite to calcium hydroxide and the subsequent hydration of calcium hydroxide involve important volume changes that may alter the internal structure of the stone. These materials generally do not spall severely because the grains sit in a matrix and the stone can to an extent 'absorb' the stress produced by fire.

Dense materials, such as granites or marble, experience physical breakdown due to the micro-cracking generated by the thermal expansion of minerals. The absence of a matrix, which in more porous materials absorbs the stresses generated by the expansion of mineral grains, increases the likelihood of mechanical breakdown. The very low porosity also favours this kind of disintegration due to the denser packing of minerals with different thermal and structural properties in the stone. It has been observed that, independently of the stone type, the lower the initial porosity the greater the porosity increase generated during fire – changes up to thirteen times the initial porosity have been reported in building stones with low porosity.[12] In addition to this, calcareous stones undergo severe processes of physical destruction in zones affected by fire above 800°C due to the calcination of calcite.

The porosity and pore-size distribution of stone is of crucial importance in stone decay as they determine the ingress and circulation of water within the stone. The behaviour and dynamic properties of solutions have a major influence upon stone decay agents such as, for example, salt crystallization. These changes have to be taken into account in addition to the damage generated by the fire itself.

As well as the effects produced by temperature increase, the combustion residues produced during a fire could feasibly generate effects on, and within, stone that may have long-term consequences. The smoke, oils and fumes can soil surfaces and, in so doing, add further discolouration to that already generated by iron reddening. [13] Fumes and ashes also introduce new elements to the stone, such as carbon, sulphur, nitrogen and phosphorus and organic compounds, such as oil and waxes, that can coat the stone surface and fill near-surface pores. The combination of these elements with other products from the alteration of the stone may generate salts, such as sulphates, nitrates or phosphates. This may have severe consequences for the future decay of stones (Figure 3).

Longer-term effects of fire in building stones

As discussed above, fire can have immediate 'shock' effects, fracturing the stone and causing spalling and catastrophic loss of material. However, an area of equal importance, which has perhaps been neglected until now is the potential for a single fire event to shape the subsequent performance of a stone façade for many years. Patterns of decay may be influenced by a combination of weaknesses inherited from the fire with background environmental factors like salt-weathering/temperature cycling.

Figure 3 Salt efflorescences related to a soot cover generated by fire (picture courtesy of Mr P. Rohlen)

The behaviour of a natural stone façade in a 'post-fire' environment will depend on whether the fire was experienced recently or in the distant past. If a fire has occurred recently then blackening of stone is the most blatant 'memory' effect. While studies simulating fire with furnace-heating have rightly highlighted the reddening of sandstone,[14] the fire experiment reported by McCabe et al.[15] makes it clear that the blackening of stone from soot is an important by-product of fire, and the most obvious immediate surface effect. This soot cover brings with it the likelihood of reduced permeability and hydrophobic tendencies, influencing subsequent exploitative decay processes that rely on moisture ingress. In the short term, this hydrophobicity may be associated with the severe dehydration of the stone surface, but in the longer term it may be influenced by the deposition and coating by, for example, waxes and other hydrocarbons. The patchy nature of any surface soot cover might also promote other surface/subsurface heterogeneities and can result in detachment of the artificial surface crust in the form of flaking, when salts concentrate and crystallize behind the soot (Figure 4).

After the soot layer has detached, or has perhaps been removed by cleaning, care must be taken with the newly-exposed stone surface. This can exhibit rapid granular disaggregation due to the alteration of, for example, a sandstone matrix by the extreme heat of the fire. The exposed surface can be expected to have a much higher permeability caused by a combination of the fire event itself and the mechanisms of salt weathering. These alterations can weaken the stone and may facilitate further the ingress of moisture. The previously mentioned cracking caused by thermal shock and differential expansion of adjoining materials (for example, soft sandstone/rigid mortar) can also be considered as a ‘memory effect’. With the subsequent exploitation of weaknesses inherited from a fire event by background environmental factors, it may be expected that detachment/spalling of block corners would be exhibited on façades.

Fire suppression strategies in building stone

This paper has emphasized the fact that stone is far from being a neutral material that is either immune, or uniform in its response, to fire. The recognition of this fact means that there is increasing acceptance of the essential importance of taking stone behaviour into account when implementing fire suppression systems in historic stone buildings and structures. As stated by the recommendations of COST Action C17, these systems must be appropriate to the specific risk of these structures and up-to-date in relation to legislation, as well as being minimally invasive, sensitively integrated and reversible.[16]

Early extinction of fire and the use of extinguishing methods with low concentrations of chemicals (porous stone may be sensitive to the inclusion

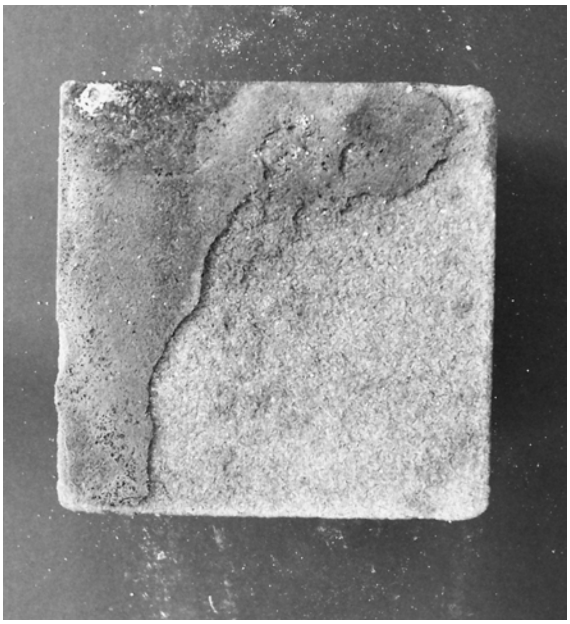

Figure 4 A block of sandstone subjected to real fire and salt weathering simulations in the laboratory. The less permeable soot crust has detached as a result of salts concentrating and crystallizing behind it, exposing more permeable, fire-damaged, sandstone beneath. The exposed stone exhibits rapid granular disaggregation as a result of exploitation by salt weathering.

of chemical substances in pores, perhaps reacting in unforeseen ways) are best practice in the extinguishing of burning structures where stone is present. There may also be a mindset that extinguishing fire with great amounts of water will achieve the quickest and best result, from the point of view of the durability of the stonework, but this is not the case. Large amounts of cold water will increase the likelihood of shock to the stone, and may lead to spalling. Pure water-based extinguishing methods should be used, but if possible, the methods should avoid causing excessive dampness to the stone (e.g. by use of water misting or fogging systems).

The impact of fire suppression and the wetting of stone by water, for example, depends upon the duration of the fire, its temperature and the degree to which a steep internal temperature gradient has been generated, plus the depth to which it has penetrated into the stone. As long as the stone has not had time to be heated by fire, it will not be especially sensitive to sudden large amounts of cold water during extinguishing. Experiments carried out on friable stones, such as sandstones, show that the initial content of water in the stone, prior to the fire, delays the thermal changes by slowing down the heating process that occurs as a result of fire.[17] In contrast, if the stone is allowed to heat up significantly as a result of the fire (as would be the case in delayed extinguishing), the abrupt cooling generated by water can produce spalling of the stone due to a rapid reversal of the initial thermal shock. This is especially noticeable in dense stones, such as granites, marbles and some kinds of limestone.

Excessive water used in extinguishing may also influence the impact of fumes and ashes. These by-products of fire contain chemical elements that may contribute to the generation of salts when wetted during the extinguishing of a fire. Their effects can be especially exaggerated if the stone becomes saturated with water. This allows salts to be transported throughout a block, and can cause damage when the stone dries. Salts remaining in the pores of stone can have dire consequences for future performance.

Conclusions

Research into fire damage in historic buildings is often biased towards obviously sensitive materials, such as wood and textiles. However, stone is not immune to fire damage and can experience severe decay during, and as a consequence of, fire. This damage can range from immediate and conspicuous discolouration and loss of mechanical strength to micro-decay features whose presence may affect the stone performance even in the very long term.

In recent years, research on fire decay and building stone has moved towards understanding these different spatial and temporal scales. For example, the impact of micro-scale mineralogical and textural changes during fires has begun to be recognized as a key for understanding larger scale processes and the behaviour of a natural stone structure in a 'post-fire' environment. Fire decay investigation has started to take into account the fact that this decay process does not just involve a sudden increase of temperature but also the combustion of by-products generated and now considers their long-term impact. However, to date little is known of how fire exploits weaknesses and by-products generated by other decay mechanisms, and how the sensitivity of a given stone to fire evolves with time, one reason being that previous studies, especially those based on oven heating, have used only samples of fresh rock.

This paper set out to review the general issues surrounding research into the fire-damage of stone, provide a basis for understanding the problems involved and suggest some implications for practitioners. Only from the understanding gained in targeted scientific investigations is a better awareness made possible of the importance of careful integral management of stone historical buildings in relation to fire damage. Appropriate management strategies should cover not only the prevention of fires and their suppression (i.e. preparing for such events by the installation or availability of water misting/fogging systems), but also a long-term management plan. Such a plan would take into account the possible influence of fire damage to a stone structure on the future behaviour of the stone in combination with other less extreme environmental factors of decay. Post-fire management will include decision-making on structural stability (related to stress fracturing), soiling (cleaning may be possible, depending on how far the smoke damage has penetrated into the stone), chemical changes (often leading to discolouration/aesthetic problems) and replacement of stone. Each of these issues (taking into account different stone types and the random/unpredictable nature of fire) present different, and extremely complex challenges. Consequently, there are no hard-and-fast rules on how to deal with stone-built heritage after fire. In reality, post-fire management should not be based on generalities. The case of each individual structure must be assessed since every structure, and perhaps even every stone block within a structure, has a unique stress history;[18] conservation should therefore be informed by targeted research and regular monitoring.

Biographies

Miguel Gomez-Heras BSc (Hons), EurPhD, FGS

Miguel Gomez-Heras' research focuses mainly on the impacts of fire and thermal behaviour on stone decay. He participated in the Working Group 2 of *COST Action C17 – Built Heritage: Fire Loss to Historic Buildings*. He is research fellow in the Weathering Research Group in the School of Geography, Archaeology and Palaeoecology, Queen's University Belfast.

Stephen McCabe BSc (Hons), PhD
Stephen McCabe is a post-doctoral research fellow in the Weathering Research Group, School of Geography, Archaeology and Palaeoecology, Queen's University Belfast. His research focuses on the impact of complex stress histories on the decay of historic stone-built heritage.

Bernard J. Smith BSc (Hons), PhD, CGeog
Bernard Smith is a professor in Geomorphology and leads the Weathering Research Group, Queen's University Belfast. His main research interests are in stone decay processes in natural and urban environments, especially salt decay and thermal controls investigated through exposure trials and laboratory simulations.

Rafael Fort BSc (Hons), PhD
Rafael Fort is senior researcher and director of the Spanish Instituto de Geologia Economica (CSIC-UCM). His main research interest is in petrological and petrophysical studies of building stone. He also leads the Petrology Applied to Heritage Conservation Research Group at this institute.

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