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UNDERSTANDING THE DECAY OF 14TH CENTURY MAGNESIAN LIMESTONE CARVINGS IN YORKSHIRE, UK

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ABSTRACT

The Chapter House at Howden Minster is a small octagonal 14th century magnesian limestone building. The architectural decoration on the interior walls is among the finest of its period in England. The building has been a ruin since the 18th century, and its elaborate interior stone carving has suffered from ongoing erosion. The deterioration of the stonework is severe and an evaluation of historic photographs reveals the flaking has recently accelerated. To understand the reasons why the stone degradation is so serious, we are examining the decay mechanisms of the stone in the laboratory, subjecting magnesian limestone blocks to environmental changes that typically drive stresses on the stone, i.e. evaporation, moisture transport, and salt crystallisation. On site we are using a microclimatic survey in conjunction with detailed condition recording, to try to establish the specific microclimatic factors and events that trigger the damage.

The internal environment of the Chapter House is monitored at different heights with a telemetric system accessible with a GSM modem for regular remote downloading and management. The parameters being measured within the Chapter House are relative humidity, ambient temperature, surface temperature, and radiant temperature. We are examining changes in the liquid moisture content and profile of the walls through gravimetric measurements of wooden dowels and electronic probes. A weather station is mounted on the roof, which monitors local wind speed and direction, relative humidity, ambient and radiant temperature, and rainfall. The environmental pollution is also being measured with passive diffusion tubes.

The monitoring programme aims to establish correlations between environmental factors and physical damage. Changes in the microclimate at different locations in the building are being evaluated against the varying patterns of deterioration of the stone, which have been recorded during the associated programme of graphic documentation and regular repeated and time-lapse macro-photography. In order to quantify progressive physical loss of stone in depth over time, we are examining stereo-photographs taken in one location over a ten-year period.

By studying patterns of physical deterioration and relating them to localised microclimates we hope to determine the primary causes and rate of deterioration of the stonework so that we can implement changes to mitigate them.

INTRODUCTION

Impetus for the Project

The Chapter House, at Howden Minster in East Riding Yorkshire is made from local magnesian limestone. The stone surfaces in the lower sections of the interior of the building are at risk; areas of stone are entirely eroded or detaching in large flakes. When the rate of flaking was examined from 1999-2001, by ‘surface rationalisation’, i.e. brushing off large flakes from the surface and observing changes in the same location, it was found that within a year the area had formed new flakes of the same proportion. The extent and level of recent degradation is alarming. The patterns of historic deterioration on the ornate carved stone interior provide evidence that the rate of physical attack on the stone has not been continuous or as aggressive throughout the lifetime of the building.

A careful inspection of the building does not provide answers for why the stone is degrading on the interior of the lower walls and not on the exterior. The source of the problems, and the reason the deterioration is currently active, is not simple.

The problems observed at Howden prompted English Heritage and the Getty Conservation Institute to collaborate on a project, which began in 2003, to look closely at the mechanism of decay of magnesian limestone. The project's aim is to evaluate how the stone reacts to individual stresses and to determine the cause of the degradation that is occurring at the site. The investigation has focused on characterising the stone, investigating its physical construction, observing patterns of deterioration on site, collecting photographic evidence**,** monitoring environmental change, and evaluating isolated degradation mechanisms in a laboratory.

History of the Building

The Collegiate Church of Howden Minster was built primarily in the 13th century but completed in the 14th century. The small Chapter House, which is Decorated style in the lower sections to the height of the windows, and Perpendicular style above, was completed in 1388, and is said to have been the last Chapter House of its type built in England (1). The Chapter House is an octagonal building, accessed from the South side of the Chancel, with seven large imposing windows. The interior walls below the windows are surrounded by a canopied stone seat, suitable for an assembly of thirty, composed of elaborate carved arcades with ogee headed arches enclosing quarterfoil panels.

The Minster fell into disrepair and neglect during the Reformation, following the loss of its endowments in 1548 in the dissolution of the Collegiate Churches and Chantries. By the early 17th century, the East end of the church including the Chancel and Chapter House fell into ruin and were cordoned off from the rest of the Church. The Chapter House roof and window glass were destroyed in a fire in 1750. The Minster was split into two parts, one active: the nave and transepts remain in use and are today a parish church, and the other a ruin. In the late 20th century, the ruins were taken into the guardianship of the government's Department of the Environment, and are now managed by its successor body English Heritage.

Fig. 1 Exterior of the Chapter House viewed from the East.

In 1984, a roof was put over the exposed octagonal Chapter House structure, and proposals were made to glaze the open windows. In the last twenty years, English Heritage has tested a number of conservation treatments at the site including consolidants and desalination, all of which have been unsuccessful. The current testing programme will inform any future treatment at the site.

STONE CHARACTERISATION

Samples of the stone were examined by analyzing stone flakes and standard thin sections with polarized light microscopy as well as textural and elemental analysis using an environmental scanning electron microscope (ESEM). The results reveal hollow spheres composed of dolomite crystals, $CaMg(CO_3)_2$, in the size range of 50 μm. These are interpreted as partially dolomitized oolites based on their texture and diagenetic history.

The texture and pore size distribution of weathered stone from Howden is similar to freshly quarried samples from the nearby Cadeby magnesian limestone quarry. Cadeby is a sedimentary stone composed of dolomite oolites with calcite and iron oxide inclusions.

Salt Analysis and Location

Powder samples from a series of vertical and depth profiles analyzed with ion chromatography and ESEM show a mixture of magnesium sulfate, calcium sulfate, sodium chloride and potassium nitrate salts. Salts are concentrated in specific areas within the wall; the location is dependent on the porosity of the stone and on the type of salt and its solubility. Magnesium sulfate is present in very high concentrations in the first centimetre in depth from the interior surface. Samples from this location were found to have a sulfate concentration of 77 mg/g and magnesium concentration of 19 mg/g. The magnesium concentration inside the wall beyond 2 cm in depth is much lower than the surface concentration: below 0.6 mg/g.

Magnesium sulfate, sodium chloride and potassium nitrate are located predominantly in the centre of the wall height whereas calcium sulfate is found principally under the window height.

STRUCTURAL EVALUATION

The walls below the windows, constructed of large masonry blocks, are 450 mm in thickness at the top and 580 mm at the base.

The structure was examined in 2005 with non-destructive survey techniques: impulse radar and dynamic impedance to evaluate how water might enter the core of the wall (2). The resulting interpretation of the interior wall structure was that the outer and inner faces were linked by a course of bonding stones, which extend the full span of the wall at 2.5m from the ground. Such a stone course could collect water, entering the wall through the cill of the window above or from rising damp below. It was conjectured that such a through stone course might be responsible for the significant deterioration at the central portion of the wall face.
To gain a better understanding of the structure and the route of moisture ingress, an invasive excavation was carried out in 2007. A wide joint was removed from both sides of a wall at this course level enabling a good view of the internal composition of the wall, and stones were removed from the lower and upper parts of the wall. It was found that some stones do run through the wall at this level, but other adjacent stones do not.

VISUAL EVALUATION OF THE SURFACE

Photographic Record

Photographs, prior to the reroofing in 1984, show that extensive damage to the surface topography has occurred in the last twenty-four years. Photographs from 1980 reveal that the surface has undergone significant damage following this intervention. (See Figs. 2-3.)

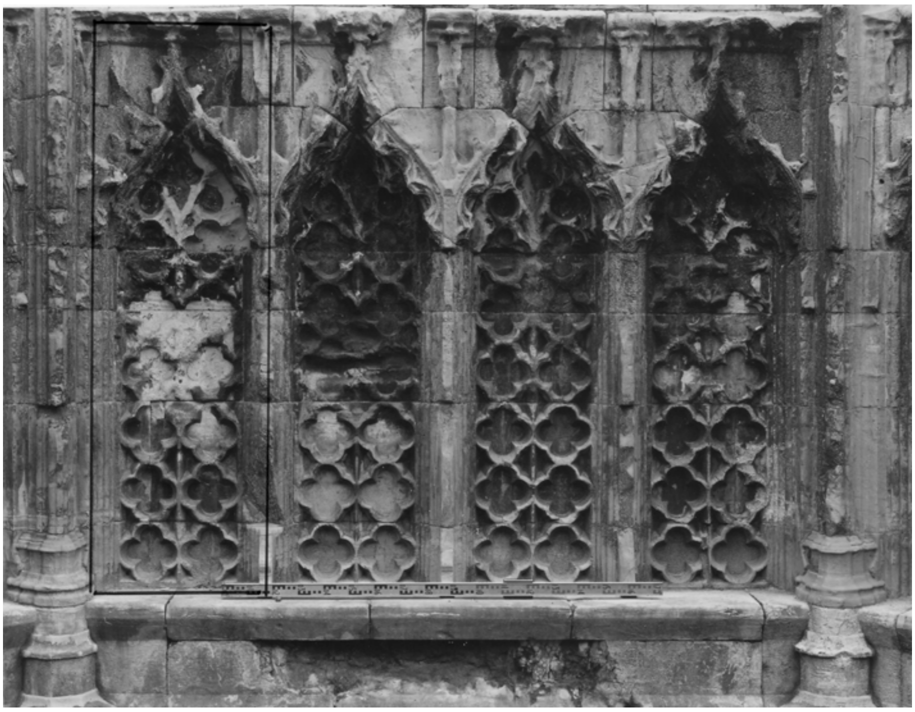

Fig. 2 Photograph of the Chapter House Northwest wall taken in June 1980.

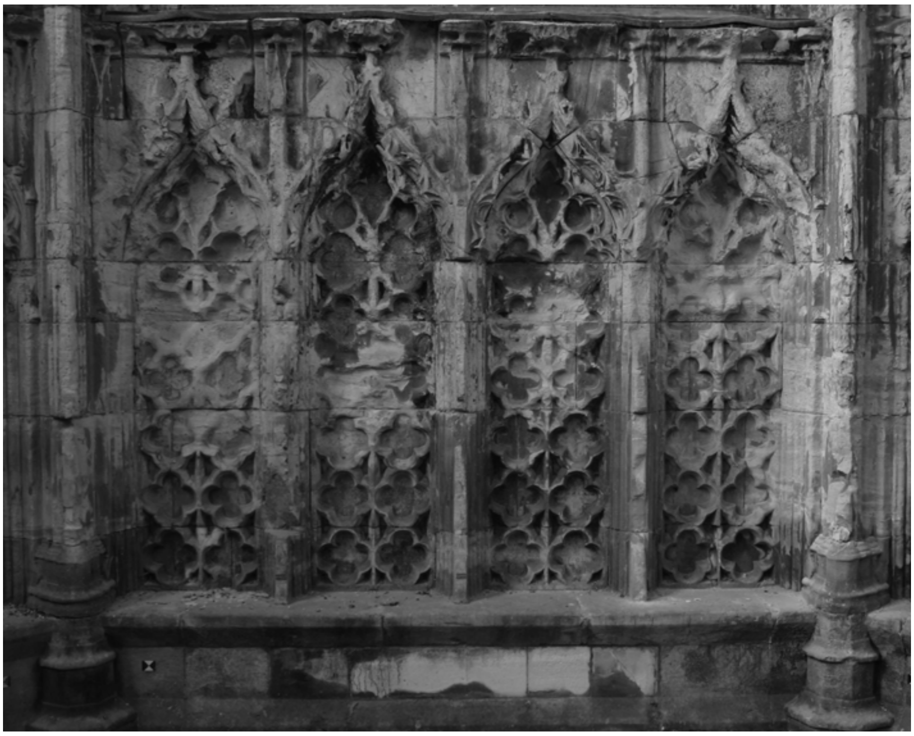

Fig. 3 Photograph of the Chapter House Northwest wall, taken in June 2007, revealing significant recent damage to the stone.

Stereo-Photographic Record
Stereo-photographs taken with a metric camera over a ten-year period allow the incremental loss of surface material over this time to be measured; however, the loss of stone is irregular, and extensive in places, so that the section examined is unrepresentative of overall loss of surface material.

Time-Lapse Photographic Record
Macro-photographs of the flaking in areas are taken at regular intervals, approximately every six months. This helps to establish when new flakes occur.

Field time-lapse photography assists in evaluating stone loss on a daily basis and can be better correlated with environmental data. A custom compact digital camera system was deployed with specialized battery and time-lapse circuitry that allows for full resolution images to be acquired at three-hour intervals over a period of three months. The images are compiled into a high definition movie format, which simplifies the detection of minute changes in the moving images.

Condition Patterns Mapped
The condition of the stones on each of the interior walls has been recorded, and the patterns of deterioration such as flaking, lack of cohesion, and microbiological growth are mapped throughout the interior.

The stone displays different patterns of degradation. Deep sections of stone have been cut back from the surface plane and extensive interlocking cracks are noticeable on some stones. Other stone blocks exhibit spalling and flaking released in layers from the surface (See Fig. 4). Other surfaces lack cohesion and are powdering and features of the decoration have been softly eroded. A thick black crust, which clearly covered much of the surface at one time, now exists in protected, less vulnerable areas. There are clearly multiple factors counteracting to produce this extent and variation in damage.

Fig. 4 Detail of the flaking on the Northwest wall.

The condition survey revealed that the surface condition of the stone relates closely with the individual characteristics of the block as well as its position within the structure.

3D Model from Laser Scan

In 2006 a laser scan of the interior and exterior surfaces of the building produced a 3-dimensional model. The model is a baseline for comparison with future surface scans and will allow the visualisation of air and solar movement.

ENVIRONMENTAL MONITORING

The aim of the monitoring is to establish to what extent microclimatic factors are contributing to the deterioration of the stone. In July 2007, relative humidity and ambient temperature sensors, surface temperature sensors, radiant thermistors were installed on in different heights on the interior of the building; a weather station was installed on the roof. The weather station is powered by a durable solar panel. It monitors wind speed and direction, rainfall, relative humidity, temperature, radiant temperature. The monitoring system is radio telemetric with a GSM modem for remote access to data.

Buffering

The data shows that the building structure offers a level of buffering between internal and external conditions. Although both values follow the same trends, the external diurnal fluctuations are more extreme than the internal values.

Differential Heating

Radiant temperature sensors show significant fluctuations in areas exposed to sunlight. This affects the stone at different heights on each wall at different times of day, depending on the season. The light migrates around the building in a pattern; in the morning it hits the West arcade, and by the afternoon it reaches the East arcade. The light is blocked in certain positions by the bars in the windows. As the stone is heated, the salts inside the pores may crystallise. The differential heating throughout the Chapter House will have an effect on the condition of the stone.

Condensation

The preliminary data demonstrates that the stone is undergoing severe phases of wetting and drying. Comparing the surface temperature of the internal walls with the dewpoint temperature of the air reveals that condensation occurs frequently. Indeed because of the hygroscopic nature of salts in the stone there is more condensation on the stone than the data indicates. In addition it is likely that condensation is occurring more regularly within the pores rather than on the surface. In the summer, condensation occurs approximately every ten days, while in winter it occurs on a daily basis. Because of the regularity of winter condensation there are periods when the stone will remain wet for many days, due to the inability of the liquid condensate to evaporate between condensation cycles. In addition, temperatures indicate that the water may be freezing during these periods causing expansion and stress to the surface of the stone.

Liquid Water Movement, Placement, and Concentration

The monitoring programme also includes evaluating moisture levels within the walls with different methods in the same location. Wooden dowels are inserted into purpose-drilled holes at various heights in the wall, to a depth of 30cm. The dowels are periodically removed and replaced. The wet dowels are cut into three sections and subjected to gravimetric analysis to establish moisture content at varying depths. The results indicated that the walls are wet at the bottom (20% moisture content) and dry at the top (2% moisture content), as is confirmed on site by using calcium carbide moisture measurements. Within the wall, the wettest section is in the middle of the wall and the driest is at the surface. Variations in moisture content are also monitored using probes, attached to the main telemetric monitoring system, which measure the electrical capacitance variation in the wall at incremental depths.

Pollutants

Howden is located in close proximity to the Drax coal-powered power station which may have an impact on the exposure of the stone to pollutants. Passive diffusion tubes are used to record the levels of air-borne nitrogen dioxide, sulphur dioxide, and ozone. Recorded nitrogen dioxide and sulphur dioxide values are lower than those normally considered clean, whereas ozone values are higher than expected.

Air Movement

Though air movement is not recorded inside the Chapter House, extensive degradation of the stairwell—which is in a scarcely lit, covered location, far from ground water exposure—provides evidence that the movement of air is clearly a significant factor driving decay.

DEGRADATION MECHANISM, BEHAVIOUR, STRESSES

Salt Studies

Magnesium sulfate salts are prevalent in the stone at Howden Minster and appear to be largely responsible for the damage observed there. The source of the magnesium ions in the magnesium sulfate likely comes from the magnesian limestone itself (dolomite), whereas sulfate ions come from deposits formed by sulphur dioxide of historic air pollution. Magnesium sulfate is a very soluble salt, frequently able to convert the ambient moisture into liquid water (3). It is about 300 times more soluble than calcium sulfate, which makes it more mobile and capable of penetrating deeper into the stone leading to more aggressive damage (4).

Damage Caused by Humidity Fluctuations

In a climate chamber in the Getty Conservation Institute laboratory, a possible mechanism of the deterioration at Howden was simulated. In this test, solely changing relative humidity levels provoked the rapid deterioration of the stone that occurs on site.

Blocks of newly quarried Cadeby stone and sampled cores taken on site at Howden were immersed in a mixture of magnesium sulfate, calcium sulfate, and sodium chloride, which replicated the salt mixture analysed in stones that show rapid damage. Other blocks were tested with a solution of pure magnesium sulfate. Cycling the humidity levels in the chamber induced the damaging effects of salt crystallization. At room temperature, the humidity in the chamber was maintained at 30% RH for 24 hours then changed to 95% RH for 24 hours; these conditions were continuously fluctuated causing the salts in the samples to repeatedly crystallize and deliquesce. This stress resulted in expansion and contraction of the stone, which was measured with a linear variable displacement transducer (LVDT)—a metal probe mounted vertically on the stone that measures micron-scale fluctuations in the stone dimension by calibrated changes in voltage based on the movement of the pin through a magnetic field. In these tests, the Cadeby stone started to flake after 1½ months, and showed significant surface flaking after 3 months. The salt mixture that was tested on the stone led to more decay than the pure magnesium sulfate.

Similar laboratory tests will be carried out simulating the conditions that are recorded on site. These include regular instances of condensation on the surface of the stone.

INTEGRATING INVESTIGATIONS

The project aims to integrate investigations to form a more comprehensive idea of the changes that are occurring on site and what these mean.

Time-Lapse Documentation and Environmental Monitoring Data

The field time-lapse camera records damage as it is occurring. Both the creation of new flakes and the loss of existing flakes are recorded. The damage over the time-interval studied thus far only occurs in specific areas of the surface and is episodic rather than perpetual. Recorded stone loss events and the creation of new flakes appear to correlate with environmental changes that are being recorded such as high winds or freezing temperatures.

Mapping Sunlight Migration and Air Movement

The 3-dimensional model will assist in the evaluation of sunlight exposure data. The model will also be used to hypothesize about the direction of air moving within the structure based on external wind speed and direction, handheld anemometer readings, and makeshift field trials such as filming smoke pellet movement.

Mapping Condition and Environmental Monitoring Data

The patterns of the damage relate to the environmental conditions and moisture levels monitored within the structure.

CONCLUSIONS

The environmental data shows that the conditions on the inside of the building differ from those on the outside, a disparity that is reflected in the stone condition. Photographs of the interior of the building reveal that the stone walls have degraded considerably over a twenty-five year period. This period is marked by a significant intervention—the addition of a roof to the structure. It is to be expected that any major change in a structure will affect its equilibrium, resulting in deleterious effects to the materials for a length of time, but stabilizing eventually. However, in the case of the Chapter House at Howden, the damage is not slowing down. It is possible that putting a roof on the building activated latent problems, such as increasing the accumulation of soluble salts and the frequency of crystallization cycles. Examination of magnesian limestone structures reveal that deterioration occurs more frequently and extensively in sheltered areas (4). Roofing the structure may have created new environmental conditions that promote the rapid flaking observed in the Chapter House stonework.

We are investigating the mechanisms and reasons for the severity of the effects of magnesian limestone decay, in the hopes of modifying the conditions that are causing the damage on site at Howden. From these investigations it is clear that magnesian sulfate crystallisation and movement, the stone's porosity, and persistent condensation are all contributing factors in the decay. By monitoring environmental changes it is possible to see how and when certain conditions have an adverse effect on the stone and to predict further damage cycles. By recognising the specific conditions which are detrimental to the building, such as condensation, we carry out building works that will lessen the propensity of these deleterious occurrences. Having established a means for assessing the visual and environmental data, we can now make an informed intervention, or series of interventions, and monitor their effect.

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