Eighth International IBPSA Conference
Eindhoven, Netherlands
August 11-14, 2003

A HYGROTHERMAL MONITORING AND MODELING OF A HISTORIC ROOF

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ABSTRACT

Computer based modeling tools were used to examine the hygrothermal environment inside a heavy-masonry historic building experiencing crypto-efflorescence damage to its moisture-laden brick vault. Monitoring was carried out to investigate the damage pattern against changes in the interior environment and to validate simulation models. The models predicted a period of 1,612 annual hours during which the vault was vulnerable to salt damage under the current environmental regime and a potential reduction of this critical period by 98% as a result of a remedial measure. The models also predicted a high rate of moisture release into the interior environment from the drying-out process of the moisture-laden brick vault.

INTRODUCTION

Historic buildings are often constructed with porous building materials and thick walls which exhibit significant moisture interaction with the environment. This behavior contrasts with modern buildings which tend to exclude moisture penetration by the use of impervious material such as vapour barrier and glass. Moisture release and absorption by the building material has a great affect on the indoor environment (Plathner et al., 1998) and consequently when modeling a building of porous material, the model's ability to take into account the moisture flow is critical in accurately predicting the hygrothermal environment (Mendonca et al., 2002; Twinn, 1997). In recent years, great advances have been made in the development of models which simulate the hygrothermal conditions within buildings and the transfer of heat and mass through the building fabric.

This study was conducted in order to understand the hygrothermal environment of two historic chambers whose masonry ceiling has been undergoing substance damage from salt activity. Firstly, environmental monitoring was carried out to establish a typical pattern for the damage, secondly, a building simulation program EnergyPlus was selected to model the chamber environment and its sensitivity to changes in occupancy, air change rate and heating. Lastly, a hygrothermal simulation program WUFI was used to model the moisture condition within the moisture and salt-laden ceiling to predict the future condition of the ceiling salts. The aim of this modeling and monitoring work was to help identify the cause of brick spaling from a historic roof and to identify appropriate measures to reduce this.

CASE STUDY CHAMBERS

General Description

The two case study chambers – east chamber and west chamber – are located in the second storey of the 12th century, main keep building at Dover Castle. Each chamber is rectangular in shape with a floor dimension of 17m x 7m. The average thickness of the chamber exterior wall is about 6m and is constructed out of limestone with a mixture of slate, pebble and chalk for the wall core. There are various smaller chambers, galleries and circular stairwells within the thickness of the wall. The floor is of timber construction. Each chamber is spanned with a 3m to 5m thick brick vault. A typical roof section is shown in figure 2 (English Heritage, 1995). The soffit of the vault is exposed brick, and the chamber walls are finished in lime plaster up to the level of vault springing which starts at 4m height from the floor level. The vault reaches a maximum height of 7m from the floor level.

Figure 1 Typical chamber

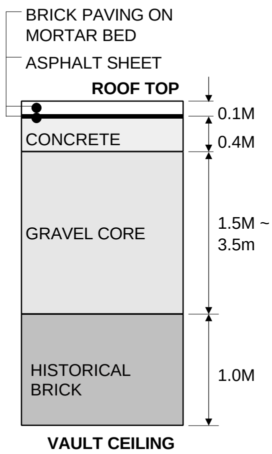

Figure 2 Cross section of the brick vault

There are two 1.5m wide galleries surrounding the chambers at the vault level. These galleries originally functioned as ventilation shafts for the chambers until the ventilation tubes connecting the galleries to the chambers were blocked at the gallery end. Today, the chambers are naturally ventilated by infiltration and by stack ventilation during the building opening period of 10:00 to 18:00 hours when the first floor main entrance and the rooftop staircase doors are kept in open condition.

Space heating in the chambers is provided by two convective heaters which are supplied with water at 75°C to 77°C from old boilers housed in a separate building. Heat is continuously supplied between late September to mid April with no mechanism for temperature control.

History of Vault Ceiling

The chamber roof structure has undergone significant renovation over the past 210 years. In 1790 the two original timber framed roofs were replaced with brick vaults which are currently in place. In 1995 the exposed top of the vault was water-proofed with a new asphalt layer and brick paving with drainage channels to stop a long history of visible water ingress into the chambers. Although visible water ingress has ceased, core samples taken from the vault structure in 1999 indicated a moisture concentration in the range of 0.6% to 4.2% net weight at a depth of 150mm from the ceiling and higher concentration of 4% to 18% net weight at a depth of 260mm, indicating a reservoir of water trapped in the vault fabric (Mason, 2000).

Material analysis also revealed a high concentration of soluble salts within the vault fabric originating from the bricks. Figure 3 shows two types of salt activity presently taking place in the ceiling: Efflorescence and crypto-efflorescence.

Figure 3 Efflorescence and crypto-efflorescence damages on the vault ceiling

The two salt activities differ in the following way: "*Efflorescence occurs when there is a plentiful water supply, but if the water supply is limited, the liquid front retreats inwards, resulting in crypto-efflorescence … Whereas efflorescene is merely unsightly, crypto-efflorescence causes delamination, spaling and cracking of the external brickwork surface as a result of the expansive crystallization of soluble salts within the brick pore structure*" (Harrison, 1998).

Hygroscopic Salt Activity

Salts absorb and release moisture in response to the relative humidity (RH) of the surrounding air. Salts in a solid state will absorb moisture until equilibrium with the surrounding RH is reached. When the RH rises, moisture absorption will resume and when the RH decreases, moisture will be released. During this process, salts can undergo phases change from solid to liquid and vice versa when the RH reaches the saturation level of salt solution expressed as the equilibrium relative humidity (ERH) which is unique to each salt type. When the RH rises above the ERH, salt liquefies and when the RH falls below the ERH, it crystallizes. When a phase change occurs it is accompanied by a volumetric expansion or contraction that exerts a damaging mechanical force against the host masonry pores causing failure in the form cryptoefflorescence.

Salt contaminated masonry will normally hold several types of salt as in the case study vault. The combination of different salt types, each with a unique ERH, will define an ERH range where the host masonry is susceptible to salt damage. Analysis of the vault fabric shows salts mainly consisting of sodium chloride and sulphates of calcium, potassium and sodium (Pickering, 2000) which in combination exhibit an ERH range of 75% to 95% (Pickering, 2000).

This suggests two possible environmental solutions to minimize salt damage to the brick vault: Maintaining the chamber RH above 95% or below 75%. The first solution is a poor choice due to the potential occupancy discomfort, microbial grow and damage to the exhibition items. Maintaining RH below 75% is the preferred option, but it requires a stabilization period before the drying front moves sufficiently into the ceiling fabric and the cohesive force of the host masonry begins to resist the crystallization force. The pre-stabilization period is affected by the salt response rate and the surrounding material property and therefore is difficult to predict (Price, 2000). In one similar study the stabilization period lasted longer than two months (Watt, 2000).

MONITORING

Method

In order to understand the causes of the salt damage at Dover Keep and to test the validity of the environmental models, the air temperature and the RH of a ventilation tube, the galleries, the chambers, and the exterior were monitored over three separate periods – summer 2000 (5 weeks), winter 2000 (5 weeks) and summer 2001 (5 weeks) – using HOBO battery-powered, electronic dataloggers set to monitor RH and air temperature at every 1 hour interval. Figure 4 shows the monitored locations.

The occurrence of flaking was also visually recorded by the building custodians during summer 2001 by noting the deposition of new debris on the chamber floor. The number of visitors to the chamber was also recorded.

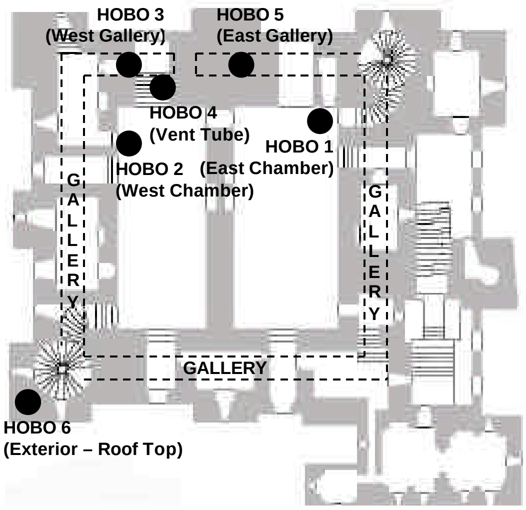

Figure 4 First floor plan with datalogger locations indicated

Results

The average monitored air temperature and RH are shown in tables 1 and 2.

Table 1 Average monitored air temperature (ºC)

LOCATION	SUMMER 2000	WINTER 2000	SUMMER 2001
Exterior	16.2	6.4	16.7
Vent Tube	17.2	-	17.0
West Gallery	17.1	-	17.6
East Gallery	-	-	17.6
West Chamber	17.9	17.6	17.8
East Chamber	-	-	17.6

Table 2 Average monitored RH (%)

LOCATION	SUMMER 2000	WINTER 2000	SUMMER 2001
Exterior	63	87	77
Vent Tube	100	-	100
West Gallery	96	-	93
East Gallery	-	-	96
West Chamber	76	52	72
East Chamber	-	-	73

Monitoring inside a ventilation tube was carried out to confirm moisture release from the water logged brick vault through which the ventilation tube penetrated. The RH level in the ventilation tube was almost a steady 100% indicating saturated brickwork surrounding the tube.

The average summer RH of the galleries which are located within the thickness of the exterior wall was higher than the average exterior RH despite the higher internal air temperature by 1°C suggesting higher moisture level in the galleries than the outside. Greater fluctuation in the gallery RH compared to the ventilation tube indicated greater air movement. Although the RH fluctuated along the upper ERH range, flaking activity in the upper galleries was never observed confirming salt contamination limited to the brick vault above the chambers.

The lower average RH in both chambers compared to the galleries is the result of greater air movement experienced in the chambers. The winter air temperature was similar to the summer due to indoor heating and accordingly the winter chamber RH level was well below the ERH range despite the high winter exterior RH (87%).

Figures 5 and 6 show the monitored RH and air temperature during summer 2001 for the west and east chambers. Both figures show increased frequency of flaking with RH in the ERH range as indicated in grey arrows. The monitoring of the flaking activity was carried out only in summer 2001.

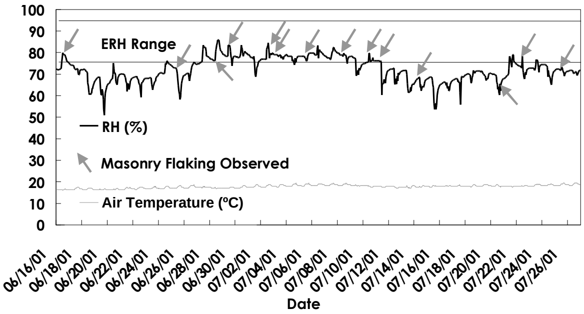

Figure 5 West chamber air temperature, RH and observed incidences of flaking activity

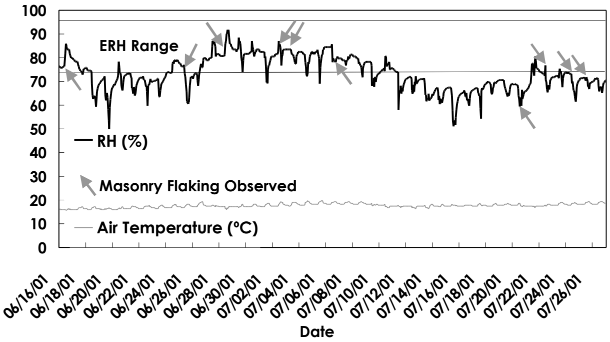

Figure 6 East Chamber air temperature, RH and observed incidences of flaking activity

Absolute Humidity - The average absolute humidity of the two summers and winter are compared in figure 7. The higher absolute humidity level observed in all monitored locations in comparison to the exterior indicates moisture source from within the building.

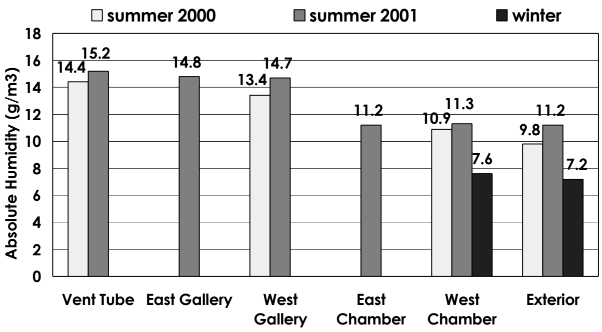

Figure 7 Comparison of average absolute humidity levels of all monitored locations

The steady decrease in the absolute humidity level from the ventilation tube to the chambers also reflects the relative degree of ventilation experienced in these areas with the ventilation tube experiencing the least, the chambers the most and the galleries somewhere in between.

The steady decrease in the absolute humidity level difference between the interior and the exterior from summer 2000 to summer 2001 – vent tube: 4.6g/m^3 to 4.0g/m^3; west gallery: 3.6g/m^3 to 3.5g/m^3; west chamber: 1.1g/m^3 to 0.1g/m^3 – suggests drying of the building fabric over a single year.

MODELING THE CHAMBER ENVIRONMENT

Method

Monitoring indicated that the flaking activity of the brick vault could be as a result of the trapped moisture in the vault structure resulting in the vault experiencing an RH in the ERH range. In order to assess the potential for different remedial measures that could be implemented, a hygrothermal simulation model was created.

Significant moisture transfer can take place between a moisture generating environment and the surrounding building material. At periods of excess vapour pressure, moisture is absorbed into the building fabric and at periods of low vapour pressure, released back into the environment resulting in a time-delayed response of vapour pressure against changes in moisture generation rate.

The porous nature of the brick and its saturated condition in the case study vault require a simulation model that is capable of modeling the moisture transfer behaviour between the building fabric and the chamber environment. EnergyPlus (EP) was selected for hygrothermal modeling because of its Effective Mean Penetration Depth (EMPD) algorithm which describes both thermal and mass transfer as well as moisture storage and release from building materials (EnergyPlus, 2002).

Simulation Condition

No hourly based weather data was available for Dover. The standard 2001 weather data file for Langdon Bay, which is located 4.7 km north-east of Dover, was updated with the monitored local external air temperature and RH (Met Office, 2000-2001). The updated weather file was used to simulate what-if scenarios using the EP model which is calibrated against the monitored chamber data of summer 2001 and winter.

The physical property of the west chamber was selected for modeling due to the availabity of winter and summer monitored data. The material property of the vault construction material was based on the material data provided in EP and WUFI material library.

To simulate the current space heating, a baseboard heater was specified and its output condition varied until a close approximation to the winter monitored condition was achieved. As in the actual case, the heating system was scheduled to operate 24 hours a day from October until mid-April.

The monitored average daily number of 470 visitors was used as the occupancy rate. The average metabolic rate and heat emission data were based on CIBSE Guide A (CIBSE Guide A, 1999). The occupancy period was based on the building visiting hours.

The ventilation rate consists of both air infiltration and controllable ventilation. The building simulation program A-TAS (Tas, 2000) was used to estimate the current infiltration rate of the chamber because of its ability to model natural air flow through building apertures based on temperature and wind data. As in the actual chamber, a hole sized 1m x 1m was modeled in the wall as the main source of infiltration when all the doors in the building are kept closed. A-TAS showed an average of 0.3kg/sec of air movement through the aperture which represents about 1.0 ach based on 1.19kg/m^3 air density and the west chamber volume of 830m^3.

Based on the background infiltration rate at 1.0ach, EP was used to predict the current controllable ventilation rate – ventilation through the building during the building opening hours. The controllable ventilation rate was varied as an input boundary condition until a minimum standard deviation was reached between the monitored and the modeled air temperature, absolute humidity, and ERH hours. Minimum standard deviation was achieved at a controllable ventilation rate of 1.5 ach.

Results

Tables 3 and 4 compare the EP modeled average air temperature, absolute humidity, RH and hours within the ERH band against the monitored data for summer 2001 and winter 2000. Figures 8 and 9 compare the monitored and modeled RH for summer 2001 and winter 2000.

Table 3 Comparison of monitored vs. EnergyPlus model prediction for summer 2001

SUMMER 2001	MONITORED	EP
Average Temperature	18°C	18°C
Average Abs. Humidity	11.0g/m^3	11.1g/m^3
Average RH	72%	73%
ERH Hours	360 hours	370 hours

Table 4 Comparison of monitored vs. EnergyPlus model prediction for winter 2000-2001

WINTER	MONITORED	EP
Average Temperature	17.6°C	16.6°C
Average Abs. Humidity	7.2g/m^3	7.2g/m^3
Average RH	52%	51%
ERH Hours	1	0

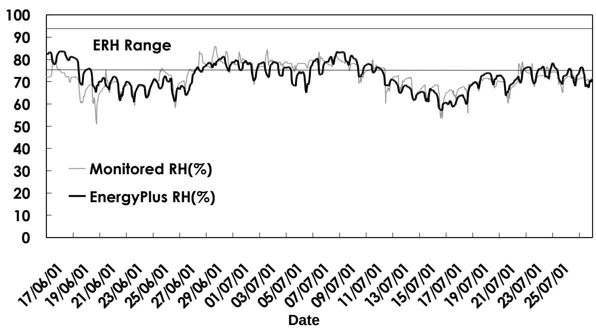

Figure 8 Monitored vs. EnergyPlus RH prediction for summer 2001

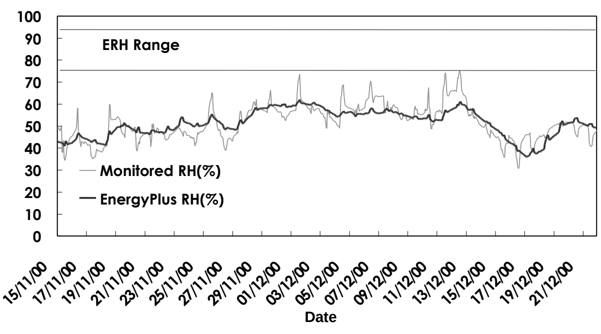

Figure 9 Monitored vs. EnergyPlus RH prediction for winter 2000

As a further test of the EP model, particularly the effectiveness of using its EMPD algorithm in simulating a moisture pervious environment, a comparison was made with A-TAS model which ignores moisture transfer characteristic. The suitability of EP model for the case study chamber is evident in figure 10 by its ability to simulate time-delayed RH response and in table 5 by its close prediction against the monitored data.

Table 5 Comparison of monitored data against EnergyPlus and A-TAS model for summer 2001

SUMMER 2001	MONITORED	EP	A-TAS
ERH Hours	360	370	262
Average RH	72%	73%	68%

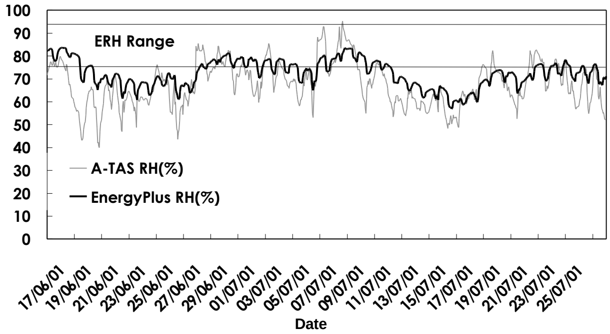

Figure 10 EnergyPlus vs. A-TAS RH prediction for summer 2001

Prediction of Annual ERH Hours

Based on the EP model, the current RH condition of the west chamber was simulated for one year in figure 11. The RH during the winter heating season is below the ERH range and considerably lower than the summer RH. The unheated months posed the greatest risk to the brick damage with a total of 1,612 per annum in the ERH range.

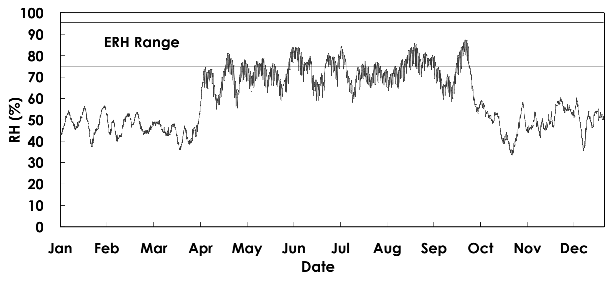

Figure 11 Annual variation in predicted RH

Occupancy rate, infiltration rate, controllable ventilation rate and heating schedule were independently varied from the current chamber condition to investigate its impact on the number of hours per annum the RH was in the ERH range. A theoretically achievable maximum and minimum value for each of these parameters was input into the EP model and its impact on the hours within the ERH range was recorded. This information is useful when investigating the most appropriate environmental strategy to minimize vault flaking.

Figure 12 shows that controlling the occupancy rate from zero to 900 visitors per day affects the annual ERH range by only 130 hours. Varying the ventilation rate from 0.5 ach to 3.0 ach also results in a small change in the ERH range of 180 hours. Varying the infiltration rate from 0 ach to 1.5 ach results in a larger range of 700 hours. Finally, the heating strategy provides the greatest potential in reducing the ERH hours close to zero by supplementing the current heating strategy with non-visiting hour summer heating at half the current winter level.

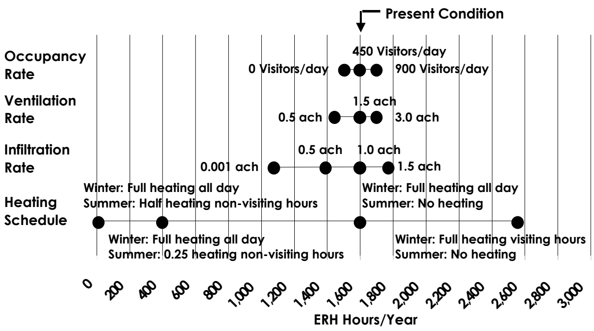

Figure 12 ERH sensitivity under varying internal condition

The sensitivity study indicates that an increase in the ventilation rate increases the ERH hours by increasing the chamber RH. This is surprising since the exterior always exhibited a lower absolute humidity than the chamber (summer 2001: exterior 11.2g/m^3 vs. west chamber 11.3g/m^3; winter: exterior 7.2g/m^3 vs. west chamber 7.6g/m^3). On the other hand, a comparison of the average air temperature shows that the exterior air temperature was always lower than the chamber and in winter lower by about 11°C (summer 2001: exterior 16.7°C vs. west chamber 17.8°C; winter exterior 6.4°C vs. west chamber 17.6°C). It is the effect of the lower external temperature that causes the chamber RH to rise with increased ventilation and infiltration rates. The infiltration rate has a greater impact on the ERH hours because of the entry of the cooler night-time air.

Environmental Solution

To maintain the RH level below the ERH range, a combination of building air-tightness measures to decrease the background infiltration rate and an increase in the length of indoor heating hours should be considered. The effect of the heating strategy alone is shown in figure 13 where the annual ERH hours is reduced to 38 hours.

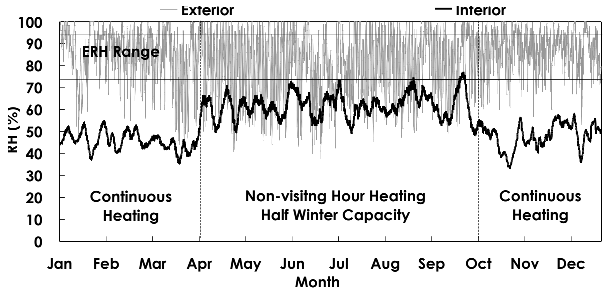

Figure 13 38 predicted annual ERH hours under full winter and partial summer heating

Figure 14 shows that with the introduction of partial summer heating, the internal air temperature rises above 21°C for 977 hours per year (40 days per year) with 23°C being the maximum air temperature in the month of October.

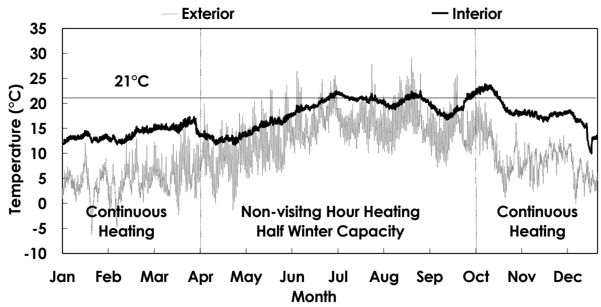

Figure 14 977 predicted annual hours above 21ºC under full winter and partial summer heating

MODELING THE VAULT FABRIC

In order to study the drying out period of the ceiling, a hygrothermal simulation program WUFI (WUFI, 1999) was used to investigate the moisture behaviour within the fabric of the brick vault and its interaction with the chamber environment. WUFI was selected because it is a program specifically designed to model heat and moisture transport within a building envelope.

Method

The layers of the construction elements making up the brick vault were modeled as follows beginning from the roof top: 50mm brick paving , 20mm asphalt, 400mm concrete, 1500mm gravel and 1000mm historical brick.

The annual chamber environmental data obtained from the EP model and the updated annual weather file were used as the surrounding environmental boundary condition.

The initial moisture content of the historical brick was set to 200kg/m^3 based on the average level of moisture content (11% net weight) found at a 260mm depth of the brick vault in the 1999 investigation. The initial moisture content for the gravel layer was set to

490kg/m^3 based on the porosity ratio between the brick and the gravel layers (brick: 0.31m^3/m^3; gravel: 0.76m^3/m^3). No initial moisture concentration was defined for the concrete layer due to its low porosity of 0.18m^3/m^3 and the roof top brick layer because of the intervening impermeable asphalt layer.

Results

Three different chamber conditions – Dry Condition, Current Condition and Wet Condition – were modeled in EP and their effect on the hygrothermal behaviour within the brick vault investigated by WUFI.

The Dry Condition is defined by a low infiltration rate of 0.1 ach, low ventilation rate of 0.5 ach, no visitors and continuous heating during winter and during non-visiting hours in summer. The Current Condition is based on an infiltration rate of 1.0ach, a ventilation rate of 1.5 ach, 470 daily visitors and continuous heating only in winter. The Wet Condition assumes a high infiltration rate of 1.5ach, high ventilation rate of 3.0ach, 900 daily visitors and winter visiting hour heating only.

WUFI modeling was performed over six consecutive years beginning with the 1999 moisture level and substituting the modeled year-end moisture condition as the initial moisture level for the subsequent year. The drying rate of the brick vault under the three environmental conditions is compared in figure 15.

The model shows that the moisture decay rate within the fabric is greater with increased dryness in the chamber environment. However, the difference in the rate diminishes after several years and tapers off to a moisture level of about 420kg/m^3 (60% of original moisture level) at the end of the sixth year.

Over the two year period between 1999, (the year when moisture content was measured) and 2001 (case study year) the model suggests a moisture release of 230kg/m^3 of masonry into the chamber.

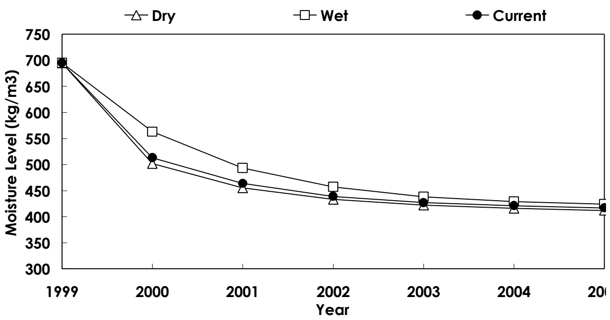

Figure 15 Vault interstitial moisture level over a period of six years of drying period

Figure 16 compares the year-end RH values at four different depths of the brick vault over a six year period assuming the internal environmental condition remains unchanged. The following depths were selected for investigation: Brick vault surface over the chamber, 12mm depth, 22mm depth and 154mm depth. For 2001, the year that flaking was monitored, the model indicates flaking taking place at a depth between 12mm to 22mm. The model also indicates that the interstitial RH will eventually enter the ERH range at progressive depths as the drying front moves into the vault fabric predicting the potential of continued vault flaking until stabilization is reached.

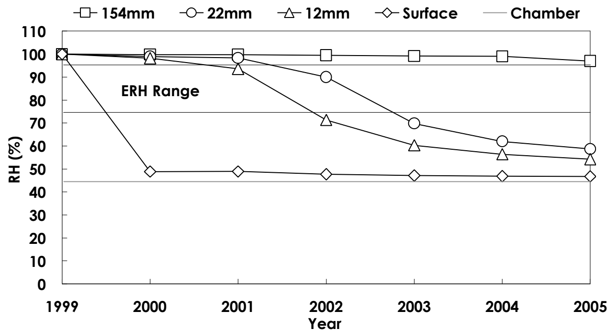

Figure 16 Interstitial RH at four vault depths

CONCLUSION

The use of monitoring and simulation have proved to be useful in investigating the hygrothermal environment within a historic building. Monitoring has confirmed that the ceiling flaking is induced by the hygrothermal environment inside the chamber and that a chamber RH below the ERH range will not immediately cease the flaking activity. Good agreement has been achieved between the EP predictions and the monitored data in a hygroscopically heavy weight building such as Dover Keep. The WUFI model has been useful at predicting the movement of water throughout a heavy construction and predicting the potential for salt damage with time. No follow up investigation of the actual brick vault condition was carried out to validate the WUFI prediction of the drying out period. The use of these tools has allowed strategies to minimize salt damage to be evaluated.

The authors note that in the future it would be interesting to apply newly developed heat and moisture models such as DELPHIN4 (Funk and Grünewald, 2001) which considers both salt movement and the effect of salt on moisture transfer in the study of the building.

In this case study two simulation tools were used: EnergyPlus to investigate the effect of the hygroscopic fabric on the RH within the building and WUFI to examine moisture movement within the building fabric, the former model providing the boundary conditions for the latter. A simulation tool that allows both the RH in the air domain and the moisture profiles in the fabric domain to be simultaneously calculated would be of great use. The development of modular and zonal models as proposed by Mendonca et al. and Schijndel et al. would be useful to those investigating problems in historic buildings.

ACKNOWLEDGEMENTS

The authors express gratitude to English Heritage and the staff at Dover Castle for allowing access to the building and for the permission to publish the results.

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