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ABSTRACT
This paper presents the preliminary findings of research currently being undertaken at the Department of Architecture of the University of Cambridge. The research focuses on heating historic large hall structures and in particular, the heating of historic church buildings, considered a significant type of historic structure safeguarded for its association with cultural heritage, still in regular use and with particular conservation problems raised by the recent application of heating systems within them. Most historic churches were not designed to be heated. Contemporary demand for comfort however, has made the introduction of heating to churches a requirement. The present paper looks at how today’s elevated comfort thresholds threaten the conservation of the historic fabric and artefacts in these buildings. The conclusions of this study should hopefully provide valuable guidance for the adoption of energy-efficient and preservation-friendly heating of churches and other similar types of buildings, where problems are less pronounced.

Keywords: heating, church, energy, conservation, deterioration, thermal comfort

INTRODUCTION
There is a widely accepted need to reduce carbon emissions and energy demands on fossil fuels, especially in buildings. Furthermore, concentrated efforts are being placed upon alleviating the inefficiencies associated with systems, practices and processes related to the existing stock of buildings we inhabit, which by current
Historic church buildings are considered special in this context of historic structures, as they simultaneously embody a much cherished part of cultural heritage to be protected and conserved but also often present acute inefficiencies for the same reasons for which they are conserved i.e. they are large, impressive hall structures which unfortunately also enclose large volumes of damp, cold air; they are often embellished with highly-valued and they provide a much desired link to the past. There is great pleasure associated with inhabiting these old buildings but they were never designed to be as warm as we might want them to be today. Moreover responding to increased thermal comfort demands can seriously damage these buildings if efforts are made to heat without careful consideration being taken of the conservation requirements and the thermal characteristics of buildings’ elements.

This paper introduces two main axes to the subject of energy management of historic structures. The first axis draws attention to the fact that historic church buildings already have an established history of heating regimes related to them both historic and contemporary; The other axis presents compiled data, which associate particular heating systems and strategies with particular effects on the comfort of occupants, the preservation of these buildings and the conservation of their contents. The conclusions that are drawn have associated limitations but are nevertheless useful in highlighting particular problems or preferences that are related to the heating of these historic edifices and no doubt will be of wider interest to the scientific community in possibly offering clues for addressing the broader issue of sustainability environmental, social and economic of cultural heritage in our contemporary times.

BACKGROUND

Heating historic church buildings
A vast majority of historic church buildings in the UK did not receive heating of any sort.[2] A few fireplaces have been identified in a very small number of churches dating from before the 17th century, but most church buildings prior to the nineteenth century in the UK and elsewhere in Europe were entirely unheated.[3] Stoves, braziers, chafers and hot-air systems begin to appear inside church buildings in the first half of the nineteenth century. [4] The early heating systems are of two types: localised systems (fireplaces etc) and central heating systems (see below). In most cases, these systems were appended to an existing building, which had no heating provisions originally. Nevertheless, solutions were found in order to make the additions of these systems as seamless as possible, by carefully concealing ducts or trenches in the fabric of the building and by current standards they are also part of the historic edifices they have serviced for so long.

There are a wide variety of central heating systems. Several types of hot-air hypocaust systems became common in church buildings. An innovative version of a hot air central heating, hypocaust system is described by Reverend Henry Moule in 1870; he suggests a system comprising a hydrocarbon-fired furnace, producing both smoke and steam, circulated in pipes laid in trenches in the church floor down the central aisle and then exhausted at the far end of the building through chimneys or
flues.[5] Hot-water systems were also used, both low pressure (LPHW) and high pressure (HPHW) being employed. LPHW systems, comprising a furnace and boiler with a distribution system of thick pipes placed either over ground or underground in trenches with grates over them were the first to be adopted. [6] Various types of boilers were used for these gravity hot water circulation systems and many of them are still in use to date.[7]

Surprisingly, and more importantly however, church buildings were amongst the first buildings to receive guidance from various authorities so that they might be more holistically considered as environmental systems. Banham, in his influential work, The Architecture of the Well Tempered Environment, mentions that ‘the concept of total involvement of the entire structure, its inhabitants and their activities, in the processes of ventilation and distribution of heat’ became implemented in the nineteenth century [8]. Indeed, Reid’s understanding of heating was fully-integrated with the ventilation system, providing simultaneous ingress of fresh air, much like a contemporary design for natural ventilation today would today.[4] Therefore, it is not only that there is a history of environmental technology becoming adapted to and integrated in architecture in the UK in the nineteenth century, but also a rigorous tradition of pioneering environmental thinking, which appears to have been abandoned with the advent of air-conditioning and artificial lighting in buildings in the twentieth century. This disengaged architectural composition from environmental considerations which regarded natural or heat-aided ventilation as a tool to thermally temper buildings.

Contemporary heating regimes are numerous both in terms of heating strategy and in terms of heating method. Historic church buildings are often dealt with inappropriately to provide the elevated comfort thresholds that we have become accustomed to. Inappropriateness is both in terms of the lack of physical integration of the new systems in the architectural context, and also in terms of their environmental behaviour. Ill-designed systems can have adverse effects on the occupants and the fabric of the building. Such effects are draughts, thermal stratification, condensation, deterioration of the sensitive parts of the building and possibly elevated energy consumption.[2] Typical examples of localised systems that are incongruous with the environmental properties or the optimal historical environmental perspective of these buildings are radiant heat emitters, forced and fan convectors, flueless heaters and stoves.[2] All these systems can be used optimally but still must be treated holistically in order to work safely and economically. Central hot-air systems are also known for causing severe stratification and must be more cautiously considered and integrated in order to become economical and safe for the building. [2]

**Conservation problems**

Valuable religious furnishings and artefacts along with historically-valued building elements constitute the internal environment of historic churches. Several different heating methods and strategies have been commonly used in church buildings historically to serve two principal aims:

1. To provide a thermally comfortable environment for the occupants
2. To provide a dry indoor environment in order to protect the fabric from deterioration [2]

Increasing thermal comfort demands have expanded the use of heating in churches, but badly implemented heating strategies often cause preservation problems in the
When a historic building is heated, guidance is required to ensure energy efficient operation and maintenance of the heating system and its components (boilers, pipes, controls etc.) to reduce heat losses (The Carbon Trust suggests that a draught proofing programme should be developed, in order to improve the performance of services in old buildings) and reduce energy consumption. For these reasons, in the UK, the Carbon Trust recommends that the Church of England monitors cathedral and church buildings and starts locating and reporting the annual energy consumption as this can be easily derived from energy bills' [14]. According to a report of CofE (2008) heating-space accounts for the majority of carbon emissions of churches (Figure 1)

The choice of heating system should consider three factors: occupants’ satisfaction, conservation of historic fabric and artefacts. Camuffo D. and della Valle A. (2007) state that heating methods until now were designed to serve only economy and thermal comfort requirements, while conservation issues have been very rarely considered. There are several documents which constitute a discussion of benefits and drawbacks of the available heating systems [15,2,16] Darrio Camuffo has published several papers, which present cases of historic structures in Italy [17, 18,19]. The papers reach similar conclusions which can be summarised under the conclusion that heating historic large hall structures should ensure minimum interruption of microclimate conditions. The worst effects of heating historic structures are due to the consequent heat and humidity imbalances, which cause great stresses to the historic fabric and sensitive artefacts (e.g. painted wood, see below) [10]. It must be mentioned however, that it is ambiguous in Camuffo’s paper as to what type of system is used exactly and with what frequency. Local systems, i.e. systems which do not have a distribution network as do central systems, are of various types, both hot-air and radiant and use a variety of fuels and may be used either intermittently or constantly. This lacuna is critical in hindering the provision of any sort of useful
guidance. Relative Humidity (RH) and Temperature changes may cause dry and wet cycles that are usually responsible for deterioration procedures that often have damaging effects on historic structural elements. [20]

Deterioration procedures
Deterioration of the historic structure can be caused by either physical disruption of building envelope or by disruption of the internal micro-climate. [21] Liquid water (i.e. Rain or ground water) is possible to penetrate the structure through badly-maintained drainage systems, damaged elements of the building envelope, infiltration or capillary action. Water Vapour condensation may occur when temperatures and relative humidity fluctuations are sharp; then water vapour rises on the cold wall, ceiling or window surfaces and condenses, causing deterioration to paintings, internal wall surface and stained glass. Salt Activity may occur due to hygroscopic salts, which are contained in different construction elements and artifacts. Levels of hygroscopic salts are determined by relative humidity, as they have a particular equilibrium and when RH rises above that point the salt dissolves and usually moves into the porous structure of traditional building materials. When RH decreases the salt crystallizes and potentially disrupts the pores of materials, which are normally smaller than the crystals. Bio-deterioration can cause either physical disruption, as the microorganisms colonise an area of the affected element, or chemical disruption, due to the by-products, which are produced by the life-cycle of the microorganism. Finally, Dimensional Changes of different materials are caused by Changes in humidity levels. Especially elements, which consist of different layers of materials, are vulnerable to expand or contract, due to Relative Humidity fluctuations. In the case of painted wood, each material expands by different percentage when humidity rises and is caused across the structure resulting in delamination and flaking of painted surface. [21]

HISTORIC CHURCHES IN CAMBRIDGE, UK

The case-studies
The current research being conducted in Cambridge involves in-depth surveys of four representative churches with different types of heating strategies, which present the most common types of modern heating strategies in church buildings:

1. Gt St Mary’s church, Cambridge: Constant Central (Under-floor) heating
2. St Botolph’s church, Cambridge: Intermittent Local (Electric Panels embedded on Pews) heating
3. All Saints church, Cambridge: Constant Central heating, Thermostatically controlled to keep the church at conservation temperatures (11.5°C -12°C)
4. Queens’ College Chapel: Central heating with water pipes on windows level, used to block the incoming cold draughts during services. (Figure 2)

Figure 2. From Left to right: Gt St Mary’s, St Botolph’s, Queens’ college chapel, All Saints’ church, Cambridge, UK
Methods Employed

The results of the study that are presented here include monitoring and site measurements that took place in Autumn 2010. Temperature (ºC) and Relative Humidity (%) measurements with data-logging devices have provided a comprehensive image of the thermal conditions occurring on several vertical levels inside each case. Energy meter readings have assisted in estimating the typical annual energy consumption of each case-study. On–site surveys were conducted to investigate each building in terms of construction elements and deterioration problems being faced to date.

In this paper only summary of results is analysed statistically to evaluate the energy efficiency of historic ecclesiastical structures and the potential for both providing preservation of fabric and thermal comfort. The data emerging from energy meter readings, regarding the energy consumption within the church have been combined with established carbon emission factors for electricity and gas in order to estimate the CO2 emissions per case-study. In addition the total carbon emissions have been divided by the total area, to which energy is spent (either electricity for lighting, heating etc., or gas for heating), which allows comparison of contribution of case-studies to total emissions.

Modelling is also intended to be included in the final project, using advanced simulation software to test possible alternative strategies for improving the indoor conditions. A similar method has been successfully employed by Geva (1998) [22] to produce systematic analysis of the energy performance of a historic Catholic church.

Results and Analysis

Camuffo (2007) states that there are two heating strategies used in English Churches: central heating (constantly heating the interior) and local intermittent heating (in operation only during services). [9] The case studies surveyed within this project represent the most common cases of constantly and intermittently heated large spaces. The collected data allows for evaluation of the indoor conditions in terms of thermal comfort and conservation requirements.

Occupant’s comfort and conservation. Background research shows that church buildings in the UK use some energy for lighting but most for space heating. Heating a church often serves two principal aims: (1) To provide thermal comfort and/or (2) to provide dry indoor conditions in order to protect the historic fabric, artefacts and organs from deterioration. [9] Therefore the energy efficiency of historic church buildings is highly dependent on the resulting internal conditions both in terms of the comfort and the conservation levels achieved. Thermal comfort is affected by several factors that can be organized under two main categories: (1) personal variables (Activity, Age, Clothing, Sex, etc.) and (2) physical variables (air temperature, humidity, surface temperatures, air movement). Data accumulated from monitoring temperature and RH% over a day of a church’s typical operation; i.e. Sunday, have been plotted to a psychrometric chart (Figure 3). The thermal comfort envelope shown in yellow frame defines comfort standards according to CIBSE. [12] The intermittent local heating system (St Botolph’s church), obviously fails to provide thermal comfort conditions, while the central-heating systems (Gt St Mary’s and Queens’ college chapel) produce the mostly satisfactory temperatures. It is also interesting to notice that although the All Saints system was initially set to heat the
church to low temperatures for conservation reasons, it obviously achieves a high percentage of temperatures which provide satisfactory thermal conditions. (Figure 3) Therefore heating the whole hall volume in either low or high temperatures, seems to be an effective way of achieving comfort conditions.

![Psychrometric chart showing the occurring conditions in case-studies](image)

Research evidence suggests that low comfort temperatures of 20°C and relative humidity 40% - 70% are likely to provide pleasant conditions. In terms of conservation, RH should be within the range of 30% – 60% [13], to ensure that conditions are neither too humid nor too dry. If Temperature is regressed against Relative Humidity, a clear view of condition patterns in case-studies occurs.(Figure 4) The intermittent local heating in St Botolph’s church produces dispersed results due to large fluctuations of Temperature (°C) and RH(%), which fact increases the risk of deterioration [9]. Apart from All Saints church, Central heating systems produce less scattered data and seem to offer reasonable conservation and comfort conditions.

![Temperature vs RH%](image)

The estimated Energy usage. In terms of energy use, the efficiency of church buildings strongly depends on the frequency of operation in each case. The physical state of building envelope, the heating system, the heating operation strategy and the primary goal that each heating technique serves also affect the consumption patterns of fuel. The results show that most of typically heated church buildings consume bigger amounts of energy than the limits suggested by the Carbon Management Programme. [14] The constant operation of heating systems at high temperatures is mostly responsible for carbon emissions emitted from each case. Boilers set to comfort temperatures result in a high percentage of carbon emissions compared to the emissions of central heating systems set to conservation temperatures.
Moreover, the church with an electric local heating system (St Botolph’s church) proves to be the most energy efficient one. Although electricity is used both for lighting and heating the space throughout the year, the church manages to emit the least amount of carbon dioxide compared to the rest of the cases, which use electricity only for lighting and other electrical applications. (Figure 5) Nonetheless, localised heating with instantaneous operation does not offer satisfactory conditions for occupants and the church interior as it causes sharp fluctuations to humidity and temperature levels.

Figure 5: Carbon emissions contribution per case-study

DISCUSSION AND CONCLUSIONS

At the moment the majority of surveys within the UK and across Europe look particularly into conservation issues and suggest that environmental control systems should have the least possible impact on the micro-climate and serve occupants’ needs as locally as possible.

In contrast to what previous research appears to be contending, i.e. that local heating systems are more able to provide thermal comfort, the monitoring data here present shows that localised heating, which is of the electric pew heating type and which is intermittently operated, offers inadequate thermal comfort indicators and also produces conservation problems due to fluctuations in the RH. In addition, reusing, or retrofitting existing historical, under-floor, trench heating systems, such as that of St Botolph’s, employing a hot water distribution network and constantly operated produces acceptable comfort indicators. Constant heating also helps to maintain more stable indoor conditions, which limits any deterioration risk arising from rapid changes in the micro-climatic conditions commonly the case with the intermittent heating strategy.

In terms of energy consumption, the analysis of results shows that general space-heating is responsible for the majority of carbon emissions of the surveyed church buildings. Carbon dioxide emissions from churches mainly result from energy used when heating and lighting a church, but at larger sites, other activities like hot water generation, kitchen and catering activities and office energy use, also contribute. However, energy savings can be achieved if particular actions regarding maintenance of mechanical services and operation of space take place.

Suggestions

_Heating and mechanical services._ Heating in historic churches should ensure minimum interruption to the microclimatic conditions. Until now, modern heating techniques were installed to old churches with the aim of satisfying thermal comfort requirements, with little consideration given to conservation of structure. Keeping the
building warm constantly, no doubt makes it more welcoming. However, the case-study survey has shown that low, constant temperatures help to dispel damp and reduce the risk of condensation, keep the internal conditions within acceptable levels of thermal comfort, while achieving considerable energy savings, compared to cases which attempt to heat the total volume of large hall structure up to established comfort temperatures. Therefore, a heating strategy, which combines ambient warm conditions in low temperatures (12°C-15°C) and with a localised heating system acting as an additional source of low energy heating introduced in the occupancy area only (pews, choir, chancel) should be developed to ensure both conservation and good quality of indoor conditions. In addition, and especially in connection with under-floor heating, the use of renewable energy sources such as ground heat source in combination with photovoltaics, can reduce or potentially eliminate carbon emissions. Nevertheless, any interventions to historic buildings should always be performed with the utmost care and consideration for the conservation of cultural heritage. At the same time indoor air movement should be adequately controlled by allowing acceptable levels of natural ventilation (occurring either by the loose fitting of windows; i.e. infiltration, or opening windows when necessary) together with mechanical controls to regulate the air rates, movement patterns and speed and most of all the moisture content of the incoming air, thus achieving conservation.

Building Use. Occupancy patterns are another very important parameter to be regulated, which influences the microclimate in historic churches. In frequently occupied spaces it is difficult to control the incoming air through continuously opening doors. Moreover, people carry moisture inside the church from the exterior, while contributing to the increase of vapors, because of breathing and perspiration. Studies have shown that a single person can be expected to produce approximately 50g of water per hour. However, given the volume of air in even an average size church, this only becomes relevant when very large, wet congregations are present. Managing bookings can be an effective solution to reduce energy use.

Limitation of study. As a final remark, there are some limitations of the study, which are acknowledged. The pilot study is based fundamentally on environmental data gathered through data-loggers installed in the building, measuring temperature and RH at regular intervals and the conclusions on environmental performance are based on analysis of this data. Only a small period of monitoring and measurement was feasible for any one building and therefore any estimate for annual fuel consumption, was based on the assumption that the heating period in the UK is normally nine months.

References
7. Heritage Group (Website) for the Chartered Institution of Building Services Engineers (CIBSE)