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Vibration characteristics of vaulted masonry monuments undergoing differential support settlement

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ABSTRACT

This paper assesses the feasibility of vibration testing to detect structural damage caused by the settlement of buttresses in the Beverley Minster, a Gothic church located in the UK. Over the past eight centuries, the accumulated support settlements of the buttresses of Beverley Minster have pulled the main nave walls outward, causing severe separation along the edges of the masonry vaults. Bays closer to the main crossing tower have remained intact; however, at the west end of the Minster, the crack width between the walls and vaults has reached about 150 mm, leading to approximately 200 mm of sag at the crown of the vaults. Due to uneven settlement of buttresses along the nave of the church, the Minster now has ten nominally identical vaults at different damage states. In this work, two of these vaults representing the two extremes, the most damaged and undamaged structural states, are subjected to vibration testing with impact hammer excitation. From these vibration measurements, damage indicators are extracted in the modal, frequency, and time domains. In the modal domain, the differences between modal parameters are observed to be comparable to measurement uncertainty and hence insufficient to reach conclusions about the presence of vault damage. However, the amplitudes of frequency response functions in the frequency domain are observed to indicate a clear difference between the damaged and undamaged states of the structure. A time domain autoregressive model, support vector machine regression, is also found to be successful at indicating the differences between the two structural states of the vaults. We conclude that vibration measurements offer a practical solution to detect wall–vault separation in historic masonry monuments, provided that multiple damage indicators are evaluated.

1. Introduction

Masonry is a common building material in many historic monuments and has unique intrinsic properties that make it particularly susceptible to differential support settlements. Support settlement is a more frequent problem among masonry buildings because masonry structural systems tend to be significantly heavier than those of reinforced concrete or steel buildings. When the demand for large bearing capacities from supporting foundations are not met due to deteriorating soil conditions, the supports of a masonry building incrementally settle and induce tensile forces in the structure. However, unreinforced masonry buildings are primarily designed to be loaded in compression; as such, they are characterized by stiff units separated by relatively soft mortar joints. As a result, tensile forces induced by differential support settlement easily lead to geometric distortion and structural discontinuity, which alter the mass, stiffness and energy dissipation properties of the structure. Since the vibration response is intimately dependent on these properties, the change in the structural behavior due to damage may be detectable by vibration measurements. This hypothesis is the focal point of this manuscript.

The success of vibration-testing-based structural health monitoring (SHM) depends not only on the structural characteristics of the building and the type and severity of damage, but also on the response *features* used to characterize the vibration properties. In an ideal situation, a measured vibration response feature is directly correlated to the presence and extent of damage. However, in practice the response of a structure is typically measured in terms of time-dependent acceleration. Any attempt to directly correlate these raw time domain acceleration measurements to structural damage is hindered by the sensitivity of the time domain response to many factors, such as environmental conditions and ambient vibrations that are unrelated to the presence or extent of damage. Therefore, data processing and/or coordinate transformation

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Fig. 1. The interior view of the nave of the Beverley Minster displays the limestone piers that support the stone vaulting. The leaning of the columns outwards is visually observable on site.

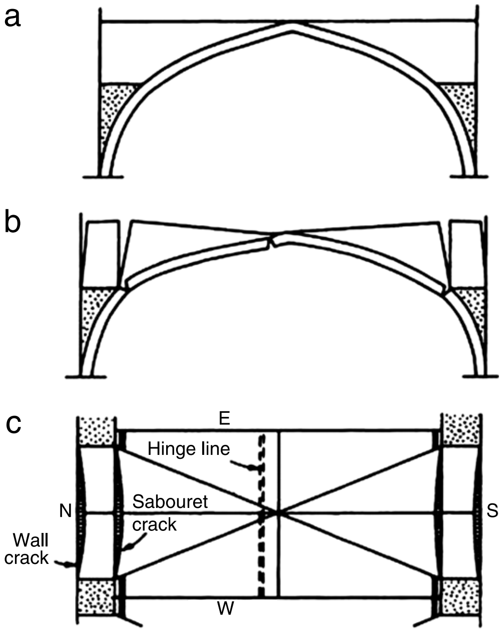

Fig. 2. A schematic of Sabouret Cracks, by Heyman [2] (with permission).

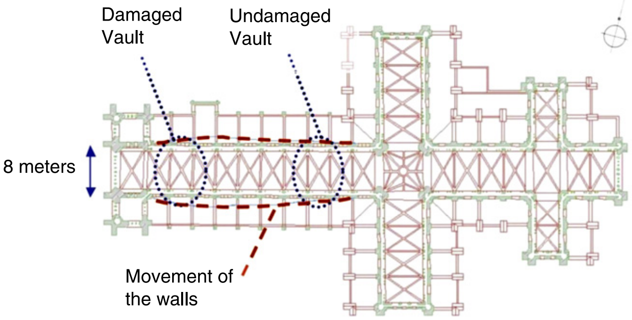

Fig. 3. The movement of the walls is not uniform along the length of the nave; as such the Minster now has ten vaults with varying damage states. Two vaults representing the most damaged and undamaged states are selected for the study.

become necessary to extract low-dimensional diagnostic features from the raw time domain measurements. The clear requirement for these features is that they must be sensitive to damage and insensitive to noise factors, such as changes in environmental conditions and ambient vibrations. This requirement makes feature selection challenging since both the damage-sensitivity and noise-sensitivity of vibration features are application-specific. Therefore, the most suitable feature for a structure with a particular type of damage may be unsuitable for another structure or even for a different type of damage within the same structure. As a result, the damage-sensitivity of vibration features for a given structural system must be individually evaluated for a given damage scenario. In this manuscript, we evaluate the damage-sensitivity of various vibration response features to the separation between walls and vaults, a common structural problem in Gothic churches.

This evaluation can be performed most effectively by separately testing damaged and undamaged states of the same structure. However, one can hardly imagine damaging an existing historic structure for such evaluations. In fact, engineers involved in SHM applications rarely have the opportunity to test an existing structure in its damaged and undamaged states. Considering this difficulty, Beverley Minster presents a unique opportunity by allowing the investigation of ten masonry vaults, which are substantially similar in their geometry, boundary conditions, construction materials, erection technique and workmanship, varying only in the extent of structural damage they have endured (Fig. 1). Structural damage in Beverley Minster's vaults manifests itself primarily as Sabouret cracks [1] and has been primarily caused by settlement of nave buttress foundations (Fig. 2). Section 3 discusses the details of the damage in Beverley Minster's vaults and briefly overviews the history of the structure.

In the present study, two vaults, one which exhibits the most severe wall–vault separation and the other visually no wall–vault separation, are selected and subjected to vibration testing. Hereafter, these two vaults are referred to as the damaged and undamaged vault prototypes (Fig. 3). These two prototypes provide the opportunity to obtain vibration measurements from two different structural states of otherwise similar vaults of Beverley Minster. With this statement comes a caveat; these two prototypes are assumed to be different only in their damage states, while their initial geometry, boundary conditions, construction materials, erection techniques and workmanship are accepted to be sufficiently similar. Actions taken to justify this assumption include (1) performing full-size geometrical surveys to determine geometric variability, (2) conducting local non-destructive tests to estimate material variability and finally (3) simulating the effect that estimated geometric and material variability have on the vibration response of the structure through finite element models. Section 4 discusses the actions taken to quantify the vault-to-vault variability and Section 5 discusses the finite element model simulations. The finite element model simulations illustrate that the vault-to-vault variations have an insignificant effect relative to the effect of the structural damage on the vibration response.

Section 6 overviews the adopted testing campaign, namely, vibration testing with an impact hammer. The following sections discuss the evaluation of the collected vibration measurements. In Section 7, this evaluation is completed in the modal domain. Section 7 includes the finding that certain modal features, such as natural frequencies and mode shapes of the first three modes, fail to indicate the differences in the structural states of the two prototype vaults. Further evaluations are completed in the frequency and time domains in Sections 8 and 9, respectively. In the frequency domain, the amplitudes of frequency response functions (FRF) acquired from the damaged vault are noticeably