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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.

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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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