FULL-SCALE MODAL TESTING OF VAULTED GOTHIC CHURCHES: LESSONS LEARNED

by S. Atamturktur, A. Pavic, P. Reynolds, and T. Boothby

Gothic-style vaulted churches represent a significant European and North American architectural heritage. Originating in medieval Europe, the Gothic style of construction in unreinforced masonry continued from the 12th through the 16th centuries in Europe and was revived in England and North America in the 19th century. Given their cultural and architectural value, these structures continue to be used for religious services and for tourism even though there is evidence of weakening effects of aging (e.g. creep) and accumulated damage through their life span (e.g. support settlements and prior earthquake damage). As a result of the increasing demand for the condition assessment and rehabilitation of these historic structures, the application of modal testing for condition assessment of large-scale masonry buildings is a growing new area in the field of experimental mechanics.

In current practice, for civil structures, the modal parameters obtained experimentally by modal testing can be used to improve a finite element (FE) model,[1] to assess the vibration serviceability,[2] or to monitor the structural health of the system.[3] Such use of experimental data is based on the assumption that the measurements are accurate representations of the actual system dynamics. This assumption necessitates an intelligent use of proven experimental tools to obtain the dynamic parameters of the structure to an acceptable level of accuracy. Although modal testing of various forms of laboratory specimens and modern "engineered" civil structures has received significant attention in literature, this is not particularly useful for *in situ* testing of vaulted Gothic churches, which has different practical requirements and challenges in the selection of test protocol, equipment, and set-up.

The inherent complexities of masonry systems, in general, call for a degree of tolerance of errors in reconciling experimental and analytical modal data. Due to the distinct structural style and construction technology, masonry buildings behave differently than contemporary reinforced concrete and steel structures. Masonry is more nonlinear and inelastic and the assembly of mortar and masonry units is rather inhomogeneous due to the mortar joints. Thus, masonry structures push the limits of the basic assumptions of linear elastic behavior of structures on which standard modal testing is applied. Moreover, the connectivity of two masonry structural components involves factors depending on the contact pressure, surface friction, and existing cracks as well as the elastic behavior of each stone unit and mortar joint. The interaction of these factors typically yields a rather flexible connection between structural components. This allows local modes to be more pronounced relative to global modes. As a result, the structural component connectivity and load distribution is affected by the amplitude and location of the excitation affects. Additionally, high dissipative forces in a masonry assembly make identification of low amplitude dynamic features difficult.

Aside from the issues specific to masonry structures, the practical issue of testing a complex vaulted system, such as limited access to the site and complicated geometry, are a further challenge for modal testing of such structures. For instance, among the controlled exciters that apply to civil structures, the access limitations of masonry cathedrals often leave impact hammers as the only feasible excitation option. Additionally, the geometry of these buildings includes construction imperfections and the fabric may include accumulated damage due to differential movements and other factors. As a result, the mass and stiffness distribution is never uniform and thus assuming the symmetry conditions may be quite wrong.

The present paper discusses recent tests conducted on several Gothic churches. The tests described herein are conducted with the sole intention of extracting sufficient knowledge to improve FE models of the structures. This discussion is intended to be neither an exhaustive review of all the aspects of modal testing nor it is intended to address all the testing problems associated with masonry structures. The primary goal of this paper is to illustrate the typical modal testing results that can be expected from complex vaulted Gothic churches, indicate typical problems, and suggest their solutions when testing that specific type of large civil engineering structures.

STRUCTURES DISCUSSED

Characteristically composed of stiff units surrounded by relatively soft mortar without much ductility, unreinforced masonry systems are primarily designed to be loaded in compression. The negligible tensile capacity of a historic masonry assembly exposes the structure to tensile failure.

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S. Atamturktur (SEM member, hsa109@psu.edu) is a PhD Candidate in the Civil and Engineering Department and T. Boothby is a Professor of Architectural Engineering in the Architectural Engineering department, The Pennsylvania State University, State College, PA; A. Pavic (SEM member) is a Professor of Vibration Engineering and P. Reynolds (SEM member) is a Senior Lecturer in the Department of Civil & Structural Engineering, University of Sheffield, Sheffield, UK

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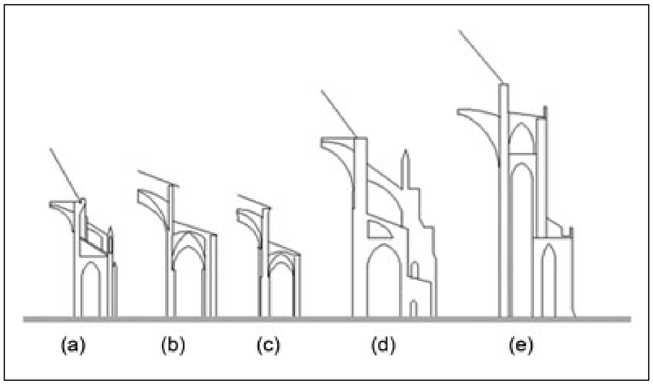

Fig. 1: The case study structures vary in dimension and construction style: the cross sections of (a) Beverley Minster, Beverley, UK; (b) The Basilica of Santa Maria Novella, Florence; Italy; (c) The Cathedral of Santa Maria Assunta, Crema, Italy; (d) Washington National Cathedral, Washington, DC, USA; (e) The Cathedral of Saint John the Divine, New York, NY, USA

Besides commonly known earthquake and wind forces, the differential movement of supports is particularly problematic for masonry structures as it induces severe tensile forces in the system. The structural performance of these buildings depends on their ability to transfer the external loads to the ground while the structural components remain under compression. During the transfer of loads, the complex vaulted sections are the most likely to develop tensions and therefore are prone to structural problems. That is why, in the present study, we primarily focus on the complex vault systems and their supporting structural elements, such as piers, arches, or buttresses.

The buildings selected for the study are selected to represent a variety of Gothic architectural styles. Case study structures are the following [Fig. 1]:

(a) Beverley Minster, Beverley, UK; main nave vaults of the 13th–15th century English Gothic church.
(b) The Basilica of Santa Maria Novella, Florence, Italy; main nave vaults of the 13th–14th century Italian Gothic church.
(c) The Cathedral of Santa Maria Assunta, Crema, Italy; main nave vaults of the 13th century Lombard style church.
(d) Washington National Cathedral, Washington, DC, USA; the choir vaults of the 20th century English Gothic revival church [Fig. 2].
(e) The Cathedral of Saint John the Divine, New York, NY, USA; the main nave vaults of the 20th century English Gothic revival church.

GATHERING BASIC INFORMATION

Although the testing of historic masonry churches is, at best, difficult, this paper illustrates that, with careful preparation, planning, and execution of the experiment, reasonable quality modal testing can be achieved. For this to occur, it is of crucial importance to complete successful preparatory studies prior to arriving on site, including reconnaissance trips, arrangements of test logistics, preliminary FE modeling, and preliminary in situ tests.

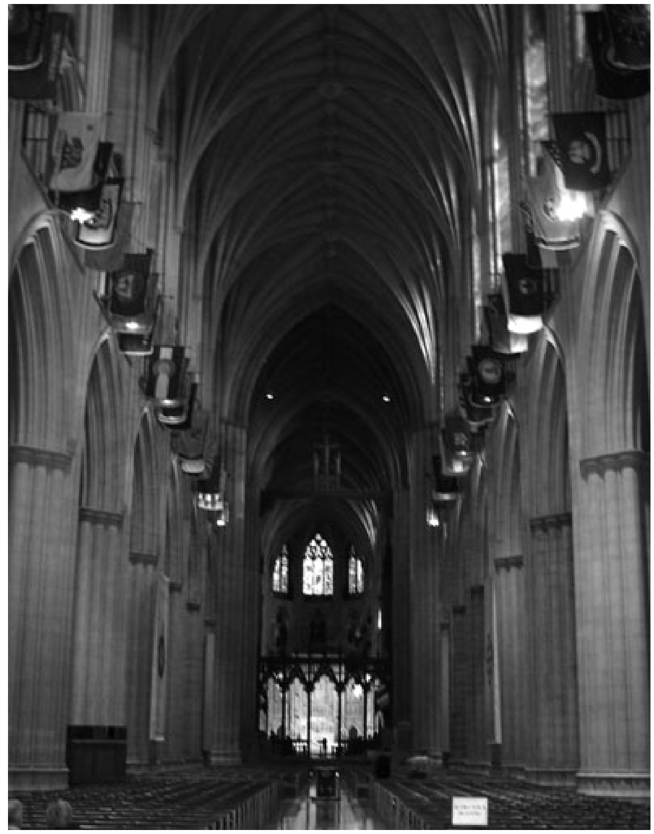

Fig. 2: The interior view of typical ribbed vaults in Washington National Cathedral

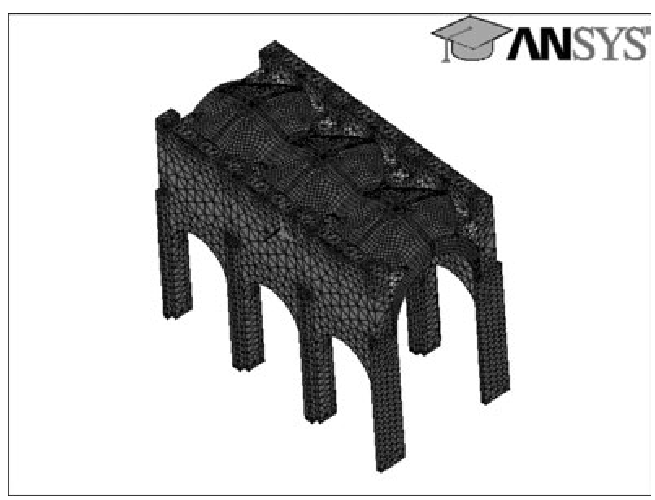

Fig. 3: The finite element model of the Cathedral of Santa Mara Assunta is developed to simulate the modal parameters a priori to the experiment

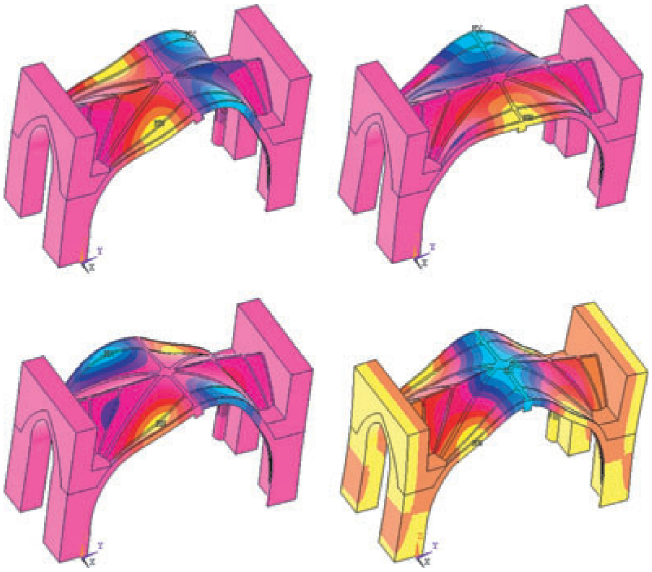

Fig. 4: The primary modes of vertical vibration in complex vaulted systems are composed of symmetric movements of the crown and the longitudinal, transversal, and diagonal ribs

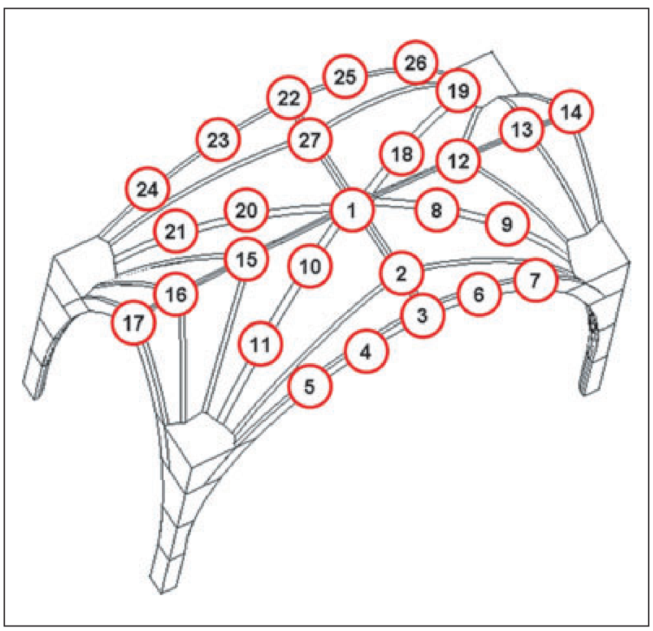

Fig. 5: Test grid adapted during the tests on Washington National Cathedral included measurements of vertical acceleration at 27 points. Excitations are placed at four different locations: Points 1, 3, 12, and 18

Preliminary Finite Element Models

As for other engineering disciplines making use of modal testing, preliminary FE models assist in the decisions related to the test setup, including the selection of the test equipment. The preliminary FE model of gothic churches is often built with limited knowledge about the structure. At this stage of the analysis, the material properties can be obtained by consulting references and boundary conditions can be applied according to previous experience on masonry churches. General overview of the material properties is given by, for brick masonry, McNary and Abrams,[4] and for stone masonry, Robertson.[5] Discussion of the boundary conditions of vaults is presented by Boothby et al.,[6] and of domes by Atamturktur and Boothby.[7] For all the structures discussed in this article, FE models of the vaulted section were developed prior to the development of the test plan. In Fig. 3, the FE model of the Cathedral of Santa Maria Assunta is presented to illustrate the level of detail included in the initial FE models.

In the case of Washington National Cathedral, the preliminary FE model predicted the modes to be primarily composed of axisymmetric and bending modes. The axisymmetric modes primarily constitute vertical movements of the crown, while the bending modes primarily constitute symmetric movements of diagonal and orthogonal axes [Fig. 4]. Based on this observation, a total of 27 measurement points are located at every one-third length on the main axes of the quadripartite vaults [Fig. 5]. Also, the excitation is at the points where the highest response is predicted. Accordingly, the frequency range of interest is determined based on these modal predictions to be between 3 Hz and 50 Hz. The use of

Fig. 6: Due to the limitations on the access to the back of the vaults, the equipment was carried by a lift crane to the top of the vaults at Beverley Minster

initial FE predictions in the planning phase will be discussed later.

Reconnaissance Trips and Preliminary Tests

Reconnaissance trips assist in determining the limitations of the physical access to the structure as well as the necessary logistics. Figure 6 shows how equipment was carried to the back of the vaults by the lift system during the tests on Beverley Minster. A simplified modal test with a limited number of measurement points, either during the reconnaissance trip or immediately before the main experiment, is a convenient way of confirming the suitability of the structure for a more detailed modal testing campaign. These preliminary tests are also of great value to assess the likely quality of the test data and to make necessary adjustments for the main experiment.

Similar to the main modal testing, the preliminary modal testing should also be planned with the aid of the FE model. Once the preliminary tests are successfully executed on site, the findings can then be used to refine the preliminary FE model, through which improved estimates of higher modes may be obtained.

Based on the authors' experience from these tests, questions that require answering prior to performing modal testing of historic masonry churches are as follows:

- What is the accessibility of top of the vaults?
- What are the possible ways to transport the equipment?
- Is there power source available? If so, how long must the power cables be?
- Is there a lighting source available? If not, what can be arranged? What are the relevant fire safety regulations?
- What is a suitable location for the data acquisition and signal processing equipment?
- How long must the transducer cables be?
- What is the condition of the vibration surface? Does it need cleaning before transducer mounting?
- Is it necessary to mount the transducers on curved surfaces? How can the transducers be mounted on the curved surfaces?
- Can all the proposed points on the test grid be reached?
- What kind of material is permitted to mark the measurement points?
- What is the most suitable excitation source for the structure? Are there other alternative excitation sources, for instance carillon bells, peal bells, etc.?
- Are there any issues that may risk the health and safety of the test crew?

PLANNING THE MAIN EXPERIMENT

In the planning phase, the test objectives and the specifics of the structure dictate the equipment selection, test layout, and data acquisition parameters. The key objective of the tests described in this paper is an identification of the first 10–15 modes of the vaults. In the following paragraphs, the testing issues, such as the selection of the response transducer, excitation source, data acquisition, and signal processing system, are discussed.

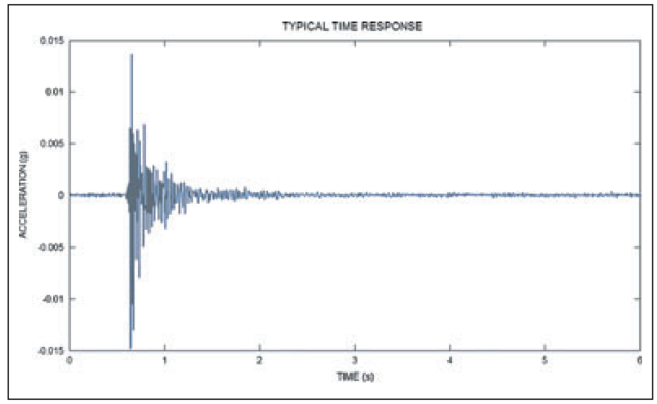

Fig. 7: A typical time domain response of the vaults of the Cathedral of Saint John the Divine has a peak of 1.5 g. The response is reduced to the ambient vibration level in less than a second

Response Transducer

The usual response to a typical impact blow is limited to 1.5–3.0%g and decays rapidly to 0.02–0.05%g, which is the level of typical ambient vibration. Figure 7 shows the driving point time domain vertical response of the crown of St. John the Divine. The maximum response is approximately 1.5%g. The first 10 modes are observed to fall between, for Washington National Cathedral, 5–25 Hz; for St. John the

Fig. 8: Aligning the axis of the sensors vertical on curved surfaces is a difficult task. In our studies, we exploited candles, modeling clay, plaster platforms, and adjustable mounting cases

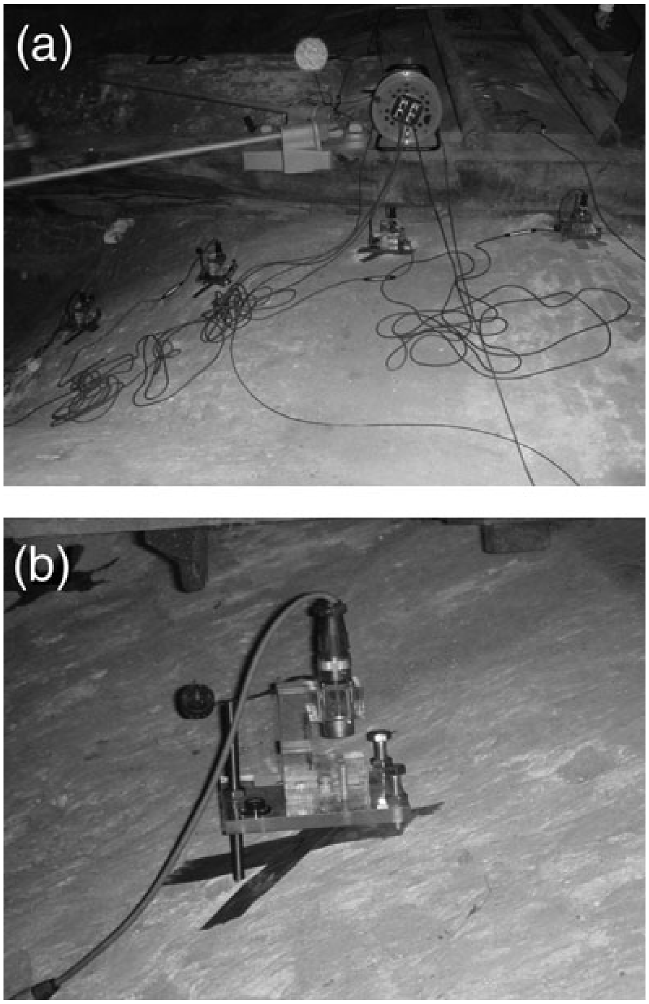

Fig. 9: (a) When testing on vaults, mounting the accelerometer on curved surfaces is almost always necessary. (b) Adjustable screws of mounting cases enabled vertical positioning the accelerometers

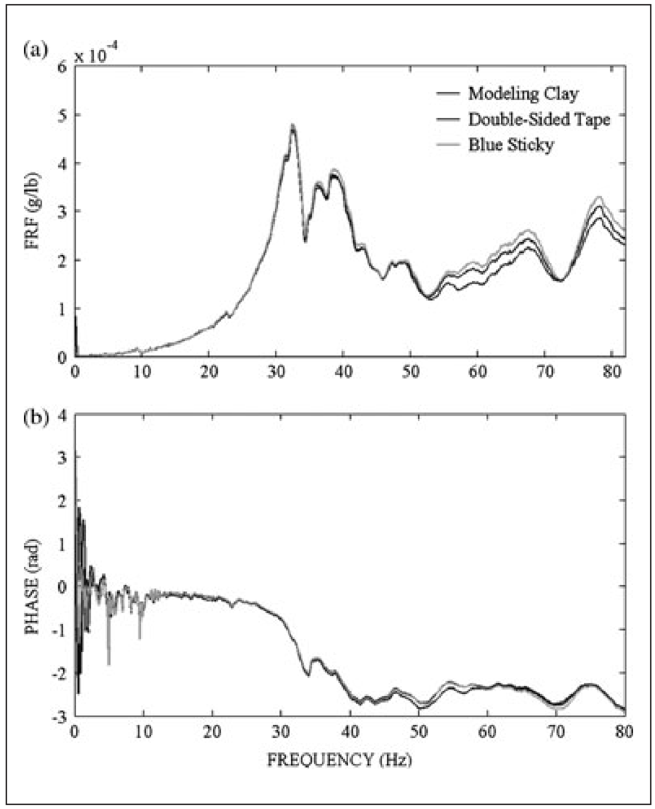

Fig. 10: Mounting the sensors on the vibration surface during the tests on Washington National Cathedral with modeling clay, double-sided tape, and sticky tack yields almost identical driving point FRF, (a) magnitude, (b) phase

Divine, 10–20 Hz; for Santa Maria Novella, 9–30 Hz; and for Beverly Minster, 3.5–20 Hz. Thus, when testing these structures, the selected accelerometer needs to be capable of detecting frequencies as low as 2–3 Hz. An accelerometer sensitivity of 1 V/g or greater is desirable.

For FE model updating, it is most convenient to measure vibrations in the axis system employed in the FE model. For instance, if the analytical model is created in global Cartesian coordinates, directly acquiring the vertical or horizontal response eliminates the inaccuracies introduced in the decomposition of the response into three coordinates. Although this choice facilitates the comparison of experimental and analytical results, it often makes mounting the transducer more difficult. Given the customary double curvature of the vault surface, vertical or horizontal mounting of transducers require casting a mounting base [Fig. 8]. Alternatively, accelerometer cases with adjustable screws, as seen in Fig. 9, are very convenient for mounting. In addition, they also offer a solution for the difficulties with direct surface mounting because of the accumulation of dust, dirt, or bird droppings on surface of the vaults.

When adjustable bases are not available, mounting the sensors directly on the surface with modeling clay, sticky tack, or double-sided carpet tape yields satisfactory results for the frequency ranges of interest. A comparison of results obtained with these mounting media is shown in Fig. 10. When testing on top of the vaults, where the attics lack heating or cooling systems, care must be given to the temperature ranges of the equipment and supplies. For instance, during the tests conducted in Crema in summer 2005, temperatures in the attic were above 40°C. Under these extreme conditions, it was observed that the modeling clay softened and artificially amplified the measured responses.

Typically, in standard modal testing, avoiding spatial aliasing and obtaining satisfactory spatial definition of the mode shapes need to be considered when deciding the density of the test grid. The points that define the geometric features best may not necessarily be the most informative measurement locations. The test grid used on Washington National Cathedral is presented in Fig. 5 to provide a general indication of the resolution and distribution of the measurement points. The points are distributed in a symmetric manner mostly for visualization purposes.

Excitation Source

In the modal testing exercises presented in this paper a range of excitation techniques were tried based on both measured and unmeasured excitation. The former are the instrumented impact hammer, electrodynamic shaker, and heel-drop on instrumented force plate excitations. The latter can include carillon bells, peal bells, orchestra, organ, or ambient vibration (wind, traffic, etc.) excitations. It is the experience of the authors that the measured excitation tends to yield better quality results on gothic churches. The focus herein is therefore confined to modal testing with the use of measured excitation yielding frequency response functions (FRFs).

Although shaker and instrumented heel-drop excitations are known to produce higher-quality FRF data when compared to impact tests,[8,9] the difficulties in transporting a shaker or force plate to the top of the vaults combined with the difficulties in positioning it on the curved vault surfaces make the use of the shaker or force plate infeasible. Impact hammers have proven to be more flexible, are deemed more fit for the purpose, and are preferred over shakers or heel-drop tests.

Moreover, the excitation amplitude of an impact has to comply with several criteria: exciting the structure in a repetitive manner while keeping the system behavior in the linear range and keeping the response amplitudes in the measurable range of the equipment. Providing a repetitive excitation is difficult because the inherent damping in masonry structures tends to absorb the localized energy introduced by the impact force before it propagates to distant accelerometer locations. The energy level must be adjusted for each test point to excite all measurement locations without exceeding the voltage limits of the data acquisition system or inducing nonlinearity in the structural system. The more cracks and separations the structure has, the more it will be prone to problems due to nonlinearity. To achieve reliable and coherent results, the selected impact hammer must also be capable of exciting the structure sufficiently above the ambient noise level, such that the response signal-to-noise ratio remains greater than 40 dB over the first few oscillations of the response.[9] Often, there is little an experimentalist can do about the ambient vibration present in the structure or electronic noise floor of the equipment (apart from selecting a better-quality equipment which may not be an option), and thus the signal-to-noise ratio can be improved only by the higher impact force magnitude. As such, the range of ideal excitation force level varies from one structure to the other depending on the mass of the excited structure, ambient vibration levels, as well as the existing damage in the system. For instance, for the Cathedral of Santa Maria Assunta, excitation impulse peaking at approximately 2.8 kN was used, while for the Cathedral of St. John the Divine, approximately 4.3 kN impulse peak was necessary. Depending on the required force level, both the PCB model 086D20 hammer (3-lb head; PCB Piezotronics, Inc., Depew, NY) and the PCB model 086D50 sledge hammer (12-lb head) have been utilized.

Exciting frequencies above the upper limit of the frequency bandwidth tends to fill the measurement data with undesired information. The impact hammers offer a partial control of

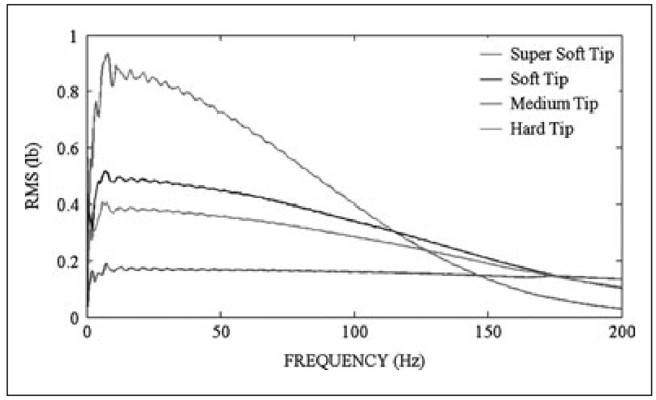

Fig. 11: The frequency content of various hammer tips when impacted on the brick masonry vaults of the Basilica of Santa Maria Novella reveal that the softest tip is capable of exciting the frequency range of interest

the excitable frequency range by alternative tip hardness. The softest tip, which offers the lowest frequency range, must be used. When applied to the brick masonry vaults of Santa Maria Novella, for instance, the nylon tip adequately excited frequencies up to 100 Hz with only a 5-dB root-mean-square drop in the energy content across this frequency range (Fig. 11).

The placement of the exciter is tied to the expected mode shapes and thus to the corresponding nodal lines. In general, the complex geometry of the vaults yields clustered modes which, near the point of excitation, are excited in phase and amplify the motion while they tend to neutralize each other at other points. By analyzing multiple datasets due to excitations at different locations, it may be possible to isolate these repeated or closely spaced modes. Moreover, some particular modes, hidden when the excitation point coincides with the nodal lines, may be acquired when the impact force is applied elsewhere. Experience gained through field tests conducted on masonry vaults revealed four optimum excitation locations for acquiring comprehensive definition of the vaulted system even when the number of available transducers is limited. The first point, the crown, primarily excites the modes, which constitute symmetric vertical motion. The rest are on the diagonal, transverse, and longitudinal ribs, which excite the bending modes (Fig. 4). Also, system identification from the FRFs obtained by exciting these locations are easier as each impact location activates only a select few of the modes.

Each of these excitation locations will excite intrinsic local modes as well as the global modes. Because local modes have very low modal mass, they manifest themselves with very high magnitudes in FRFs. Although local modes tend to occur above 30 Hz, they are so strongly pronounced that they also dominate the response in the lower frequency ranges where the natural frequencies of the global modes are. Later in the paper, in Fig. 18, the global modes, which are not obvious in the FRFs at first glance, are magnified to make them more visible. In general, striking the ribs instead of the webbing reduces the dominating effects of local modes.

The main problem associated with hammer excitation is the inability to maintain a constant excitation force level and

Fig. 12: The hammer operator hits the predefined excitation points with the sledge hammer while trying to maintain balance on the vaults

direction during averages. The complex geometry of masonry vaults further challenge the hammer operator to perform this task. The primary modes of the complex vaults, as illustrated in Fig. 4, are rather easy to detect. However, the higher order modes become much more complicated. Even insignificant deviations in the excitation location or angle may stimulate different modes and degrade the quality of the mode shapes. It is recommended to mark the excitation points and to pay close attention to hit the same point every time with a similar if not the same angle (which is impossible in manual operation of the hammer; (Fig. 12). The additional mass of the operator and the reaction forces due to swinging action become an inextricable part of the system dynamics and have a degrading effect on the quality of the measurements. However, the observations of the authors are that this effect is not as pronounced as the effects of varying excitation levels or locations. The surcharge, filling the volume between the vault ribs and walls, is a rather stiff portion of the structure, and it can be exploited as a standing point for the hammer operator.

Data Acquisition

The upper limit of the frequency bandwidth of interest is provided by the number of modes desired to be identified and their frequency range. For exercises intending to extract up to the first 10-15 modes of vaulted sections of Gothic structures, a 50-Hz usable frequency bandwidth is sufficient.

Masonry systems tend to have high damping caused by the friction forces between the stone units and opening and closing of the cracks. Hence, the structural response is damped rather rapidly. It may be tempting to acquire the measurements in a short time window. However, the clustered modes of the vaults necessitate a reasonably fine frequency resolution, which in turn necessitates a relatively long data capture time. This is a well-known conflicting requirement when performing hammer testing. Exponential window functions, commonly used to avoid leakage problems or to eliminate the environmental noise, have been found undesirable for modal testing of masonry structures since they introduce artificial damping to the measurements and potentially cause global modes to be dominated by local modes.

QUALITY CHECKS

Reynolds and Pavic[10] suggest a series of quality checks to be completed on the immediate findings of the modal test. This phase is referred to as the exploratory phase.

Immediate Repeatability Check

By comparing the discrepancies between two nominally identical tests performed one immediately after the other, the effects of the ambient vibration on the FRF measurements can be diagnosed. If the discrepancies are excessive, the problem can be remedied by increasing the input level or by increasing the number of averages. However, due to the massiveness of these structures, the traffic- or wind-induced vertical vibrations are found to be insignificant. For instance, the tests conducted on the Cathedral of Saint John the Divine, located on a busy avenue in uptown Manhattan, NY, USA, reveals tolerable deviation between repeated FRFs after five averages [Fig. 13]. Also, when the FRFs obtained on the main nave vaults of the Basilica of Santa Maria Novella, Florence, Italy, through 2 and 32 averages are compared, only a slight improvement in the FRF function is seen [Fig. 14].

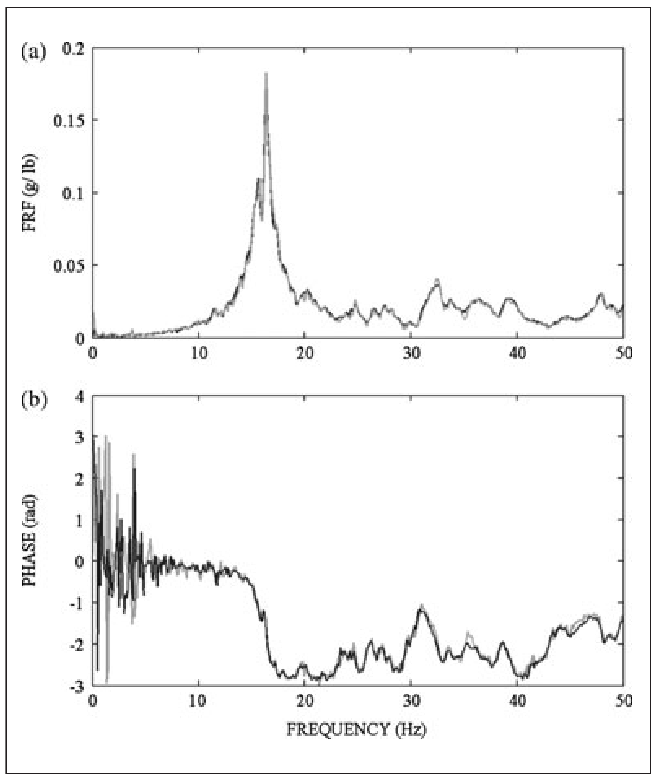

Fig. 13: The repeatability check on the FRF measurements acquired from the Cathedral of Saint John the Divine (a) magnitude, (b) phase

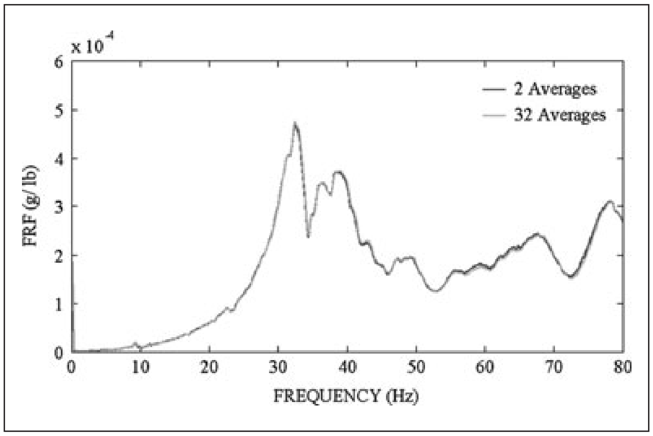

Fig. 14: The effect of increased numbers of averages on the measurements is limited as seen in the driving point FRF at crown collected from the Basilica of Santa Marie Novella

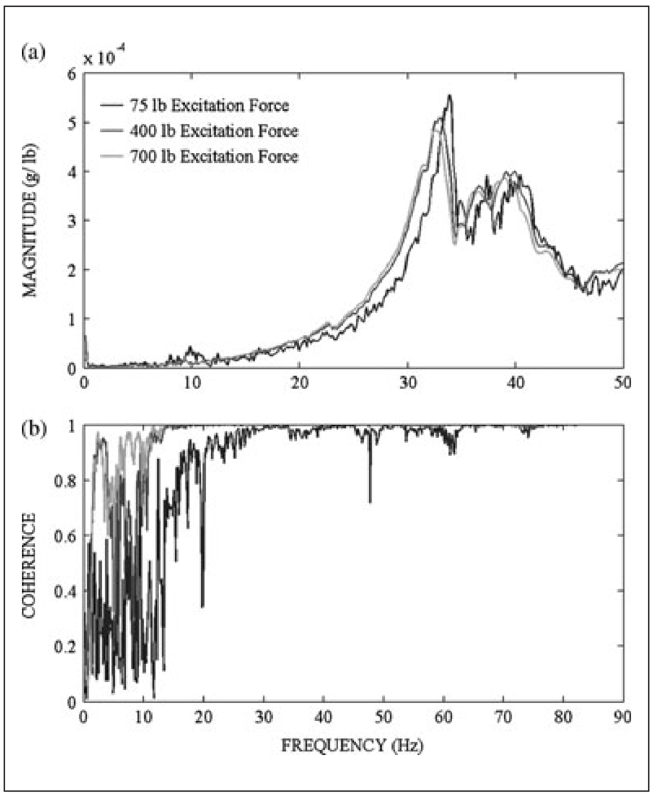

Fig. 15: The linearity check on the measurements acquired from Washington National Cathedral: (a) FRF, (b) coherence function, shows the dependence of the measurements to the excitation level

Linearity Check

Impact-based methods tend to excite the structure at high levels of response, which decay to very low levels within the data capture window.[11] When the structures are linear, this does not cause any problem. However, in the presence of even slight nonlinearities the various states of the structure excited during the impact force may impair the measurements. Throughout the tests on Washington National Cathedral, the excitation force was varying between 500 and 700 lb. The effects of this variation on the FRF are observed to be acceptable. Thus, the structure maintains linearity for the force levels applied during the tests (Fig. 15). However, when the impact excitation is varied between 70 and 700 lb with approximately 100-lb intervals, the changes in the vibration response become noticeable. It is seen that excitation forces higher than 400 lb yield very good results and tend to have high coherence functions. However, excitation forces lower than 400 lb yield noisy data and varying frequency and amplitude. As the excitation force is increased, the natural frequencies tend to be reduced and FRF amplitudes become lower. One possible explanation can be that the friction forces produce more pronounced damping at higher excitation forces. Also, with the increased impact force, the coherence is improved at frequencies lower than 30 Hz.

Reciprocity Check

Reciprocity check is another convenient way to check whether the linear elasticity assumption holds. It was observed that the vaults of Beverley Minster obey the rules of reciprocity as an acceptable agreement between measurements. Figure 16 illustrates the comparison between test points 12 and 20 with an average deviation of 3%. The location of these points in the test grid can be seen in Fig. 17. For Washington National Cathedral, the reciprocity check also yields good correlation between points 12 and 20 (Fig. 18). The excitation points

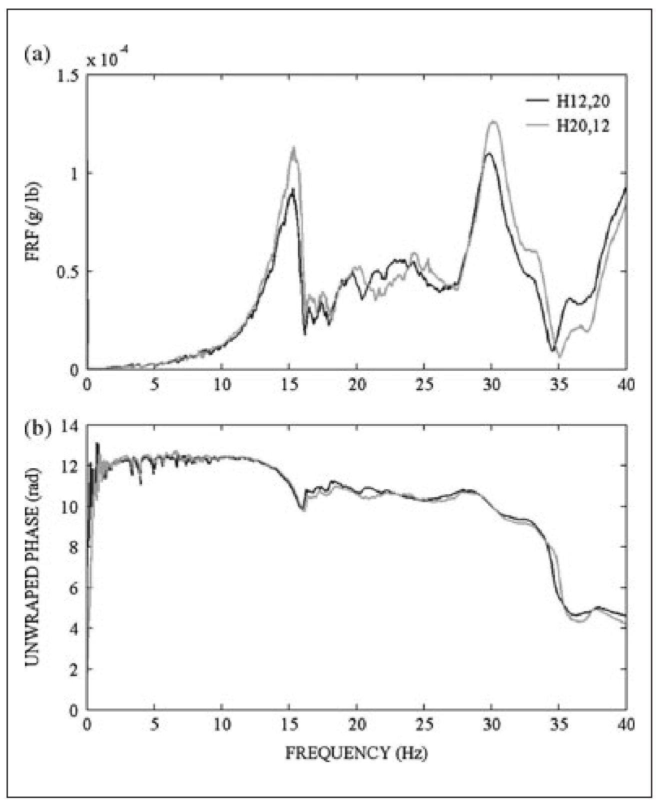

Fig. 16: The reciprocity check on the measurements acquired from Beverley Minster: FRF (a) magnitude, (b) phase

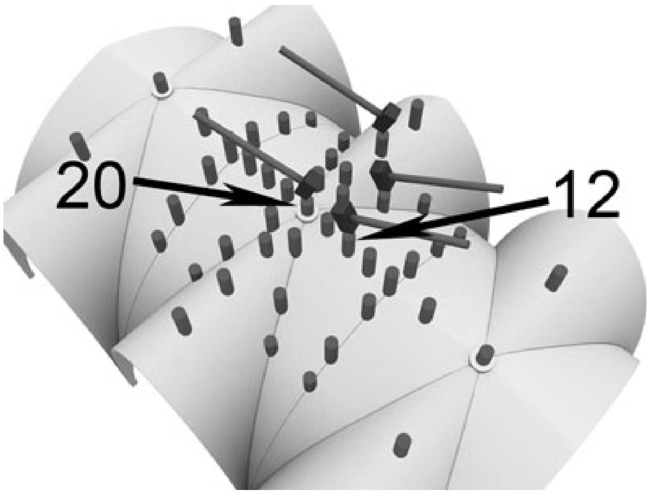

Fig. 17: The location of the points 12 and 20 on the test grid used on Beverley Minster

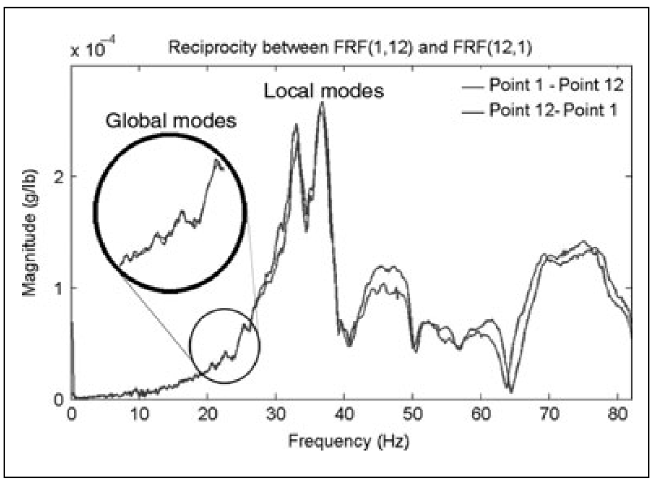

Fig. 18: The reciprocity check on the FRF measurements acquired from Washington National Cathedral

can be seen in Fig. 5. Washington National Cathedral is constructed in the 20th century with medieval construction techniques, but with better control of the material and workmanship. For instance, while the surcharge of Beverley Minster is earth and rubble, the surcharge of Washington National Cathedral is concrete. Also, due to its young age, Washington National Cathedral has less accumulated damage. This is why it is the opinion of the authors that the reciprocity checks of Washington National Cathedral typically yield better agreement compared to its medieval counterparts in Europe.

CONCLUSIONS

The present study discussed test data collected on various Gothic churches at different scales. Modal testing on a Gothic church is more time consuming and physically demanding than testing on many other civil structures. However, it is the experience of the authors that obtaining satisfactory data is possible when test setup and data acquisition parameters are carefully considered and adjusted. Typically, hammer impact excitation can yield satisfactory results when the excitation force is above 400 lb. The linearly elastic behavior assumption holds true for these structures as long as the excitation force is kept consistent throughout the test. Adjustable mounting bases provide sufficient coupling of the transducers with the vibration surface. The vertical response of the vaults is observed to be somewhat immune from the effects of extraneous traffic or wind excitation. Multiple excitation points should be selected to excite a select few of the modes. This approach enables acquiring a vast majority of the lower modes and also eases the system identification process. Exciting the ribs, as opposed to webbing, reduces the difficulties in system identification due to the dominant local modes, which occur when the webbing is excited.

Each heritage building, by definition, is unique not only because of its architectural design, but also because of the variations in quarried stone, construction technology, workmanship, and maintenance. Although no two Gothic churches are alike, from a modal testing standpoint, there are aspects that apply to many. The lessons learned from the testing program presented in this paper will aid future applications of large-scale modal testing on vaulted masonry structures for analytical model calibration.

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