Ultrasonic Investigation for the Characterization and Evaluation of Guastavino Tile Vaults: A Pilot Study

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Introduction

In response to aging infrastructure in the United States, nondestructive evaluation (NDE) is increasingly used as a monitoring tool, a method of investigation and in a quality control capacity. The adaptation of existing NDE techniques to the evaluation of historic architectural and structural materials provides great potential for increasing the information available to professionals evaluating historic structures.

The process of addressing the significant public safety concerns of aging tile assemblies, such as Guastavino tile vaults, can be complicated by the difficulty of access – the undersides of the tiles often soar over heavily-used public spaces commonly filled with pews and other structures which make temporary scaffolding problematic. The proposed sounding method examines the feasibility of evaluating Guastavino tile vaults from the top, which would allow architects and engineers to evaluate the vaults from the often easily-accessible attic spaces, thereby reducing the need for expensive and disruptive scaffolding systems for evaluation. This could also facilitate more frequent periodic inspections.

Engineers evaluating the structural condition of existing tile vaults often need to determine construction details, including combined wythe and mortar bed thicknesses, in order to model vaults. Hammer sounding is frequently employed to qualitatively evaluate the condition of the soffit layer of Guastavino tile. The ultimate goal of this research path and the basis of this pilot study on the ultrasonic investigation of Guastavino tile vaults was the removal of the aural subjectivity inherent in hammer sounding by the quantification of this same phenomenon: the differing acoustic quality of delaminated and bonded tiles. By capturing and quantifying the impact response of steel hammer taps with an ultrasonic transducer and data acquisition system, the raw signals can be analyzed in the frequency domain using modern computational methods in an effort to characterize vault construction and condition.

Previous Pilot Study Results

In a previous pilot study undertaken to measure pulse velocity and frequency responses and determine the feasibility of the proposed method, data was acquired from Guastavino vaults in New York City's St. Thomas Church and Battery Maritime Building.

The frequency response of these signals was compared to human ear observations and, as anticipated, the attenuation of the signal was greatest at those locations that were noted as sounding delaminated. Figures 1 and 2 compare the frequency content in a sound versus delaminated sample in the Guastavino vault at St. Thomas Church. The frequency content between 15 – 20 kHz is shaded in each plot to illustrate the large attenuation in the delaminated sample.

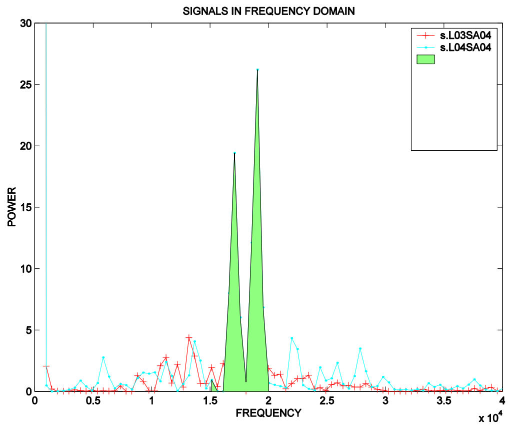

Figure 1*: The frequency plot of the sound sample (s.L03SA04) shows a definite spike in content in the 15 – 20 kHz range*

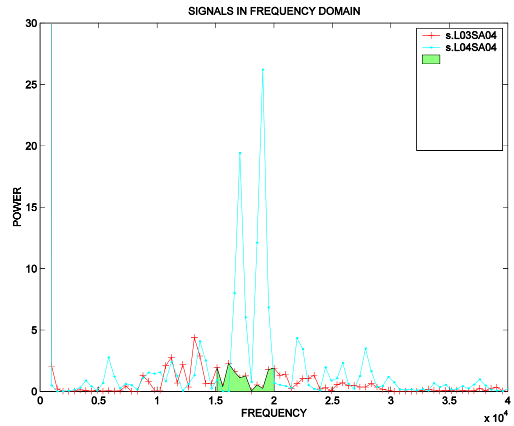

Figure 2*: The frequency plot of the delaminated-sounding sample (s.L04SA04) shows little content in the same 15 – 20 kHz range*

The second approach is to characterize the construction of the vault itself by analyzing its modal response. In the pilot study, the frequency content of the signal was found to vary depending on construction type (number of wythes, thickness of mortar, etc) of the samples (See figures 3 – 6). Both construction characterization and condition characterization are very promising avenues for further research.

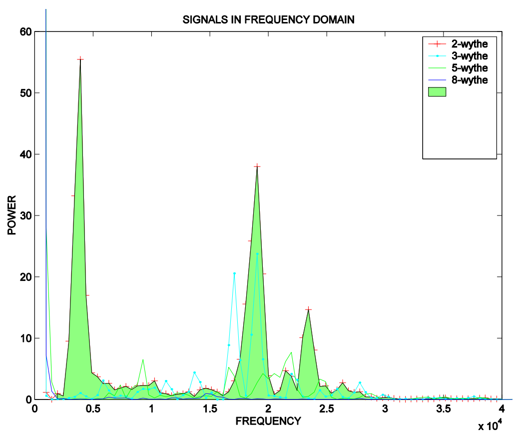

Figure 3*:Frequency plot of the sound 2-wythe sample*

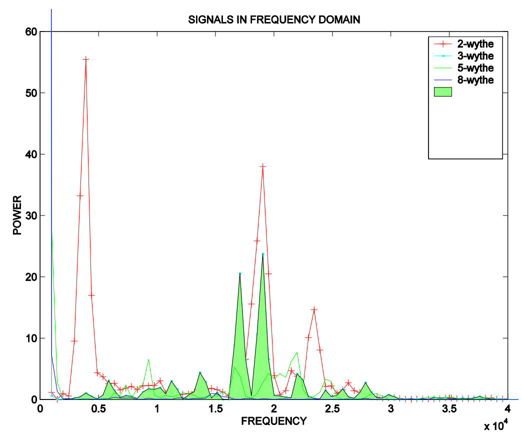

Figure 4*: Frequency plot of sound 3-wythe sample*

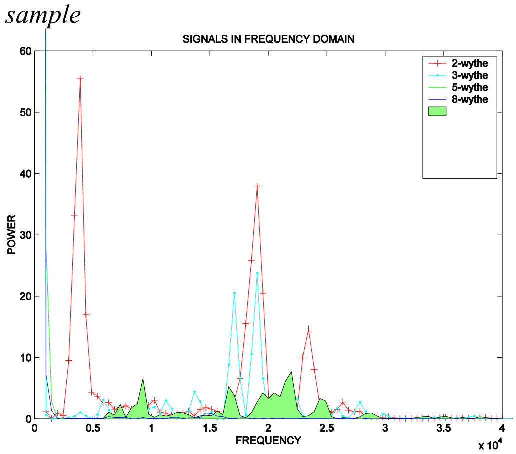

Figure 5*: Frequency plot of sound 5-wythe sample*

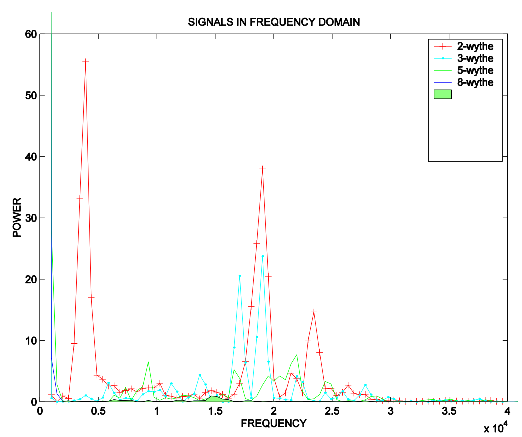

Figure 6*: Frequency plot of sound 8-wythe sample*

Another pilot study was completed at the Federal Reserve Bank of New York, where access was limited to the underside of the vault. This work was accomplished from a lift accessing the finish side of the Guastavino tile system and was completed before and after consolidation by grout injection. The analysis of the spectral distribution showed that the "after-injection" readings taken from the originally debonded tiles very closely resemble the readings of the original sound tiles.

Guastavino Vault Mockup at MIT

Dr. John Ochsendorf of Massachusetts Institute of Technology is responsible for the traveling exhibit, titled "Palaces for the People," which opened at the Boston Public Library in October 2012. In advance of the Guastavino vault that was built for the BPL exhibit, a practice vault was constructed this past summer at MIT. Vertical Access collaborated with John Ochsendorf to help with the construction of this mockup vault, placing simulated faults, such as voids and delaminations, into the vault as it was being constructed.

In one area, a tile-sized piece of rigid foam insulation was laid between the vault wythes instead of a ceramic tile. In another area, a continuous delamination was simulated by placing a thin plastic sheet at a tile/mortar interface. This allowed us to investigate the different ultrasonic frequency responses to an impact at different areas of the vault.

Nondestructive evaluation method

The NDE method employed was a variation of the impact echo method. In this method, a stress wave is introduced into the material by a hammer tap and the resulting signal (or "echo") of that signal as it travels through the specimen and back to the receiving transducer is recorded in the time domain. Then a Fourier Transform is employed to translate the time-domain signal into the frequency domain as shown in Figures 7 and 8, below.

***Figure** 7:Impact Echo field testing*

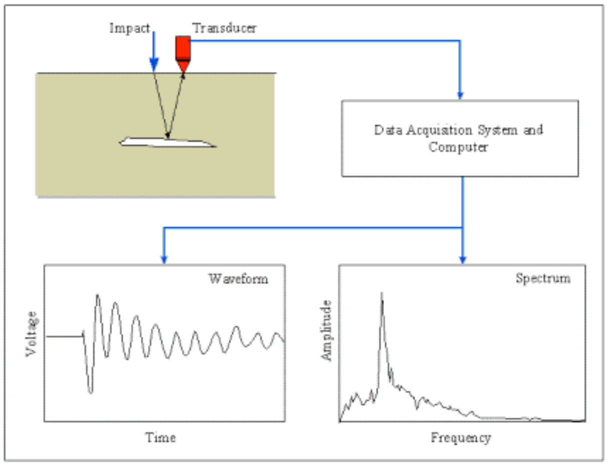

Figure 8:*Impact Echo process diagram*

The frequency content of the frequency domain signal is analyzed to make conclusions about the various boundaries and delaminations in the specimen. In the case of the Guastavino mockup vault, we compared the frequency content of the 5-wythe signals with that of the 4-wythe, 3-wythe and 2-wythe signals, as shown in Figure 9.


Figure 9:*Guastavino vault with 1-, 2 - and 3- wythe construction*

We also compared the sound 5-wythe signals with the signals obtained from testing the various delaminated areas, to see how the signals would differ based on a known fault, as shown in Figure 10, where a piece of insulation was replaced for a tile.

Figure10*:Guastavino mockup vault under construction, showing blue insulation tile which was later covered by more tile*

Results
We found a very clear pattern in the frequency response plot of the sound 5-wythe samples, as shown in Figure 11. We could easily see the different frequency reflections from the wythe boundaries and from the back of the vault.

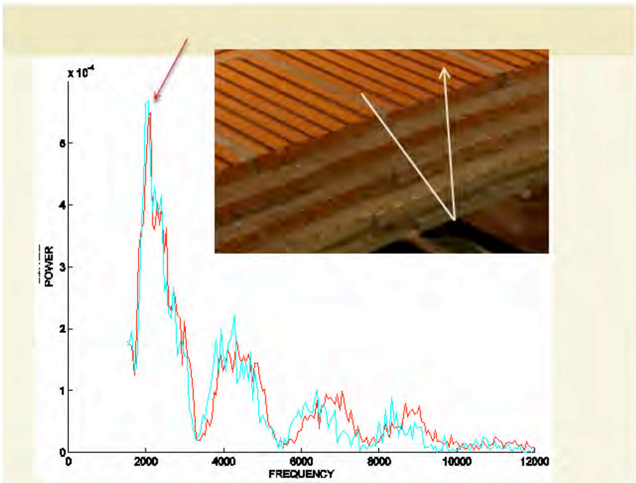

Figure 11a

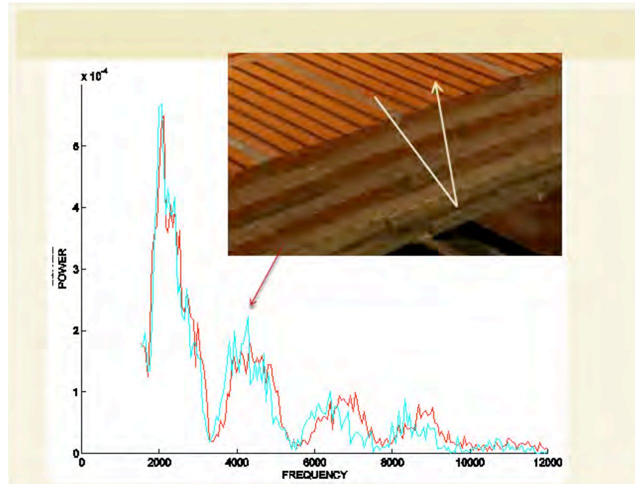

Figure 11b

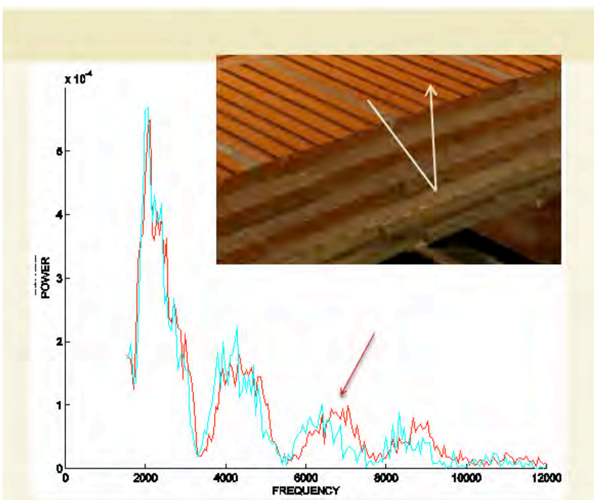

Figure 11c

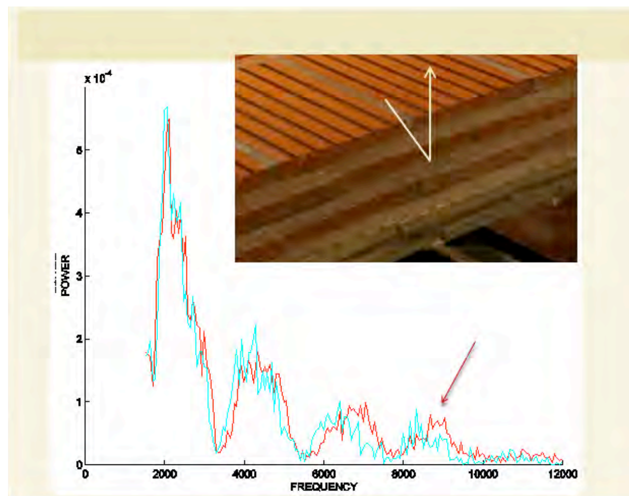

Figure 11d

Figure 11: the impact-echo frequency plots showing the frequency content reflections from a) the back of the vault, b) the fourth wythe, c)the third wythe and d) the second wythe

We also compared the difference between the 5-wythe sound sample, as shown in Figure 12 as the red and cyan plots and the 5-wythe sample, as shown in the blue plot, with the foam insulation embedment. The low frequency energy reflection content is split into two smaller frequency spikes with the foam embedment, instead of one strong low frequency spike as we see in the frequency plot for the sound 5-wythe sample.

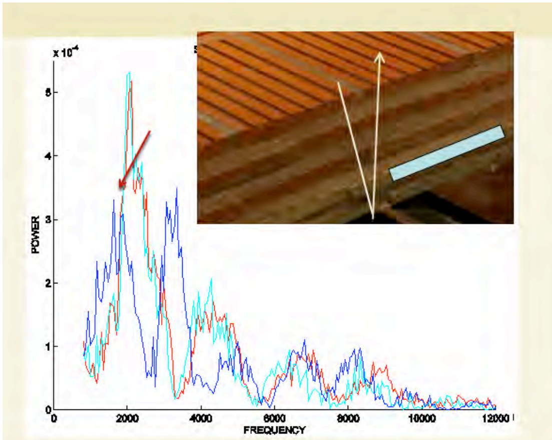

Figure 12a

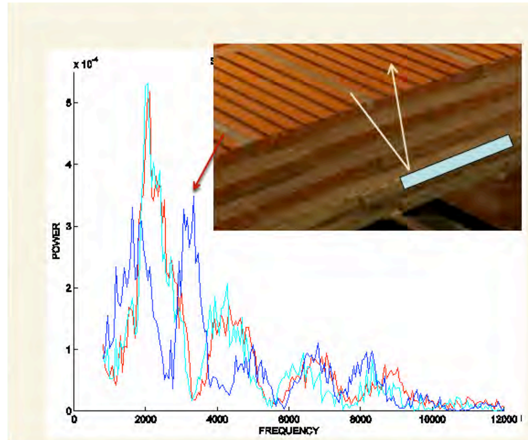

Figure 12b

Figure 12: the impact-echo frequency plots showing the frequency content reflections from a) the back of the vault, b) the foam insulation, as compared with a sound vault of the same construction

Conclusions

The application of an impact-echo method for the construction characterization and the condition characterization of Guastavino vaults is a promising research topic. Future projects should concentrate on the determination of an automated mathematical approach for evaluating the relative magnitudes of the frequency content for different constructions.

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