Non-Destructive Testing of Historic Structures to Establish Vibration Criteria

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Abstract:

Building new structures or adding to existing ones to expand living quarters in urban areas has raised a new problem for construction companies. Using explosives for the foundation excavation of these structures induces ground vibration that can be detrimental to nearby historic buildings. Historic structures reflect the cultural heritage and national history of a nation. Preservation and restoration of these historically and architecturally significant buildings will represent an effort to preserve the cultural heritage of a nation.

Construction technology has evolved; therefore general vibration criteria that protect new residential structures are not applicable to some vulnerable historic buildings. Historic buildings are mainly stone and brick masonry that is sometimes covered by stucco. Gravitational load and adhesion of mortar between individual stones or bricks mainly control the lateral resistance. Interior walls are covered with plaster, which is normally installed in three layers over the brick substrate. These layers are commonly known as scratch coat, brown coat, and white coat.

The visual inspection and analysis of some of these historic structures by the authors has indicated a general deterioration in the ceiling and wall plaster and separation of stucco from exterior walls. Some of the deterioration is so vulnerable to damage that small external force can easily cause failure of a large portion of the plaster or stucco. Investigations have shown that the separation of plaster or stucco from brick substrate is sometime not detectable by naked eye and more detailed analysis is required.

The purpose of this article is to provide a technique to evaluate the structural integrity of a historic structure by nondestructive methods. Based on this evaluation a sensible vibration criteria and monitoring plan can be established to protect these structures during the nearby blast induced ground vibration.

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Non-Destructive Testing of Historic Structures to Establish Vibration Criteria

By:

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Introduction:

Building new structures or adding to existing ones in urban areas has raised a new problem for construction companies. Using explosives to excavate a foundation induces ground vibration that can be detrimental to nearby historic buildings. Historic structures reflect the cultural heritage and history of a place. Taking steps to protect historically and architecturally significant buildings demonstrates a company's respect for the community.

Construction technology has evolved; therefore, general vibration criteria that protect new residential structures are not adequate for some historic buildings. Frequently, vulnerable historic buildings are constructed of stone and brick masonry covered by stucco. Lateral resistance is controlled mainly by gravitational load and mortar adhesion between individual stones or bricks. Interior walls are often covered with plaster installed in three layers over a brick substrate. The layers are commonly known as scratch coat, brown coat, and white coat.

This article presents techniques for evaluating the structural integrity of historic structures by nondestructive methods. Based on careful evaluation, sensible vibration criteria and monitoring plans can be established to protect historic structures during blast-induced ground vibration.

In some historic structures evaluated by the authors, visual inspection and analysis has indicated general deterioration in ceiling and wall plaster and separation of stucco from exterior walls. Some deteriorated sections are so vulnerable that a small external force could easily cause failure of a large area of plaster or stucco. These investigations have shown that the separation of plaster or stucco from the substrate is sometimes undetectable by the naked eye.

Establishing vibration criteria for a structural system requires knowledge about the condition and strength (ultimate shear, tension, and compression strength) of construction material. The material strength affects the amount of dynamic load (vibration) that the structure can withstand before failing. Numerous techniques can determine the stability of plaster, masonry, and other construction assemblies:

- Tactile Assessment
- Scanning Laser Doppler Vibrometry
- Ultra-Sonic Wave
- Impulse Radar
- Thermal Imaging

This article discusses the authors' use of tactile assessment and ultra-sonic wave techniques to evaluate historic structures, identifying the location of potential voids or weak areas beneath stucco, plaster, and mortar.

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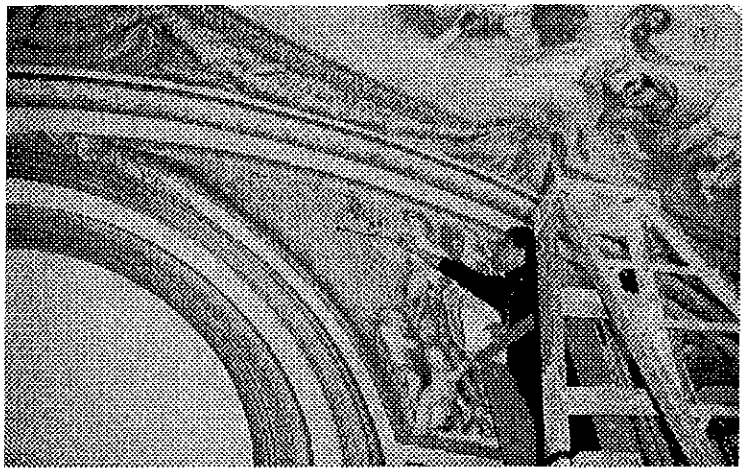
Tactile Assessment:

During tactile assessment, plaster on the walls and ceilings of a historic structure is visually inspected. Any paint failure, open crack, delamination, or visible deformity is recorded. Suspect areas are then tested for movement or separation from the masonry substrate by gently pressing with the palm of the hand using the auscultation technique.

Next, an acoustic examination is conducted using a small, lightweight percussion mallet. Figure 1 illustrates the acoustic examination.

Figure 1 - Identification of Under Surface Defects by Percussion and Auscultation



The percussion and auscultation process is implemented in approximately 1 foot by 1 foot increments. Fully adhered and internally well-bonded plaster and stucco sounds different from weakened and loose material.

Once the structure's condition is established, the ultra-sonic wave equipment is used to determine wave propagation within the construction material.

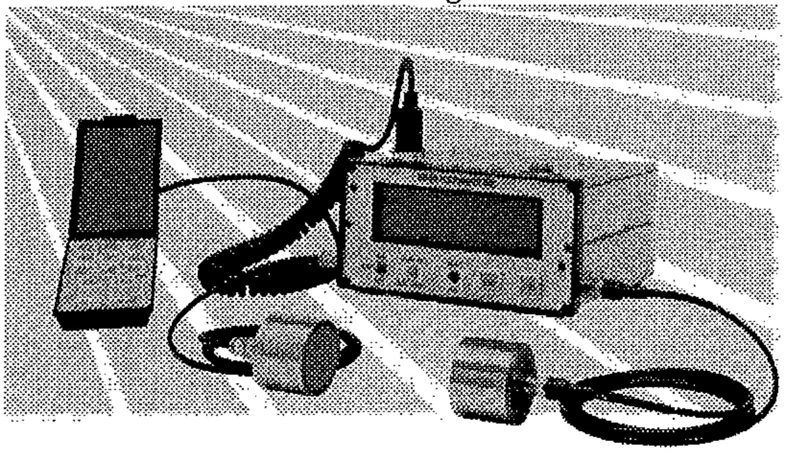
Ultra-Sonic Wave:

The ultra-sonic wave test method uses wave propagation to identify basic characteristics of the structural material. The testing equipment shown in Figure 2 includes a source sensor, instrument, and a receiver sensor.

The source and receiver sensors are placed on the structure at a known distance. The source induces an ultra-sonic wave that travels through the building material and is recorded by the receiver. The instrument determines the travel time through the building material. Using the distance and travel time, the propagation velocity within the building material can be calculated. Either shear propagation velocity or compression propagation velocity can be measured by selecting the appropriate sensor.

Denser building materials have a higher propagation velocity. Delaminated, separated, or damaged plaster or stucco has much lower propagation velocity than if it is well-bonded.

Figure 2 - Ultra-Sonic Wave Instrumentation



Next, by using wave propagation theory, the allowable dynamic stress induced by construction activity can be calculated. The allowable dynamic stress is compared with the yield strength to ensure no damage to the structure.

Wave Propagation in Elastic Medium:

Material strain is a property of wave propagation in elastic media; it is calculated using the following equation:

$$\varepsilon = \frac{2 * PPV}{V} \qquad \text{Eq. 1}$$

Where:

ε = Strain in the mortar, plaster, or stucco (in/in)
PPV= Peak Particle Velocity (in/s)
V= Propagation Velocity (in/s)

It is important to distinguish clearly between wave propagation velocity *(V)* and the velocity of the particle in the stressed zone *(PPV)*. Equation 1 states that the strain level of a vibrating medium correlates directly to the particle velocity and propagation velocity of the medium.

Equation 1 can be used to determine allowable peak particle velocity *(PPV)*, based on the allowable strain of the material.

According to the MSJC Code, type N mortar has the weakest strength. Type N mortar is currently used in building interiors. It is assumed mortar and plaster in older structures has similar properties to type N mortar. The engineering characteristics of type N mortar are as follows:

- Modulus of Elasticity = 800,000.0 psi
- Compressive Strength = 350.0 psi
- Shear Modulus of Elasticity = 320,000 psi
- Shear Strength= 23.0 psi
- Tensile Strength = 9.0 psi

Ground vibration induced by construction activities generates shear, tension, and compression stresses within a structure. By using Hooke's law and the engineering properties of the construction material, one can calculate allowable strains. The following calculations illustrate the results:

$$Allowable\ Shear\ Strain\ (\varepsilon_S) = \frac{Allowable\ Shear\ Stress}{Shear Modulus\ of\ Elasticity} \qquad \text{Eq. 2}$$

$$Allowable\ Tension\ (\varepsilon_T) = \frac{Allowable\ Tension\ Stress}{Modulus\ of\ Elasticity} \qquad \text{Eq. 3}$$

$$Allowable\ Compression\ Strain\ (\varepsilon_C) = \frac{Allowable\ Compression\ Stress}{Modulus\ of\ Elasticity} \qquad \text{Eq. 4}$$

Equations 2-4 calculate the allowable strain level for construction material. Then, by using the collected propagation wave (see Equation 1), the allowable peak particle velocity *(PPV)* can be calculated.

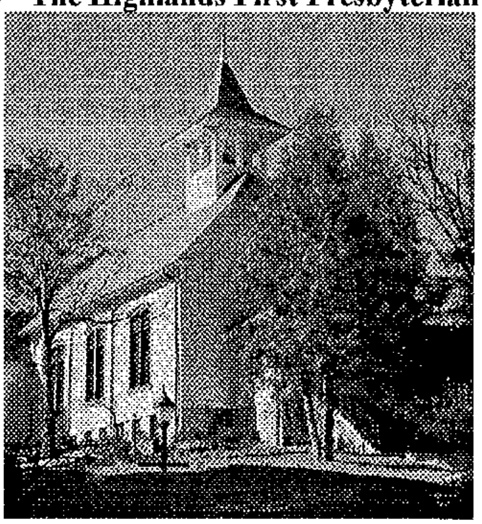
Tactile assessment and ultra-sonic wave techniques were used on the following project to establish allowable ground vibration induced by nearby rock blasting:

Expansion of the Old Edwards Inn, Highlands, NC:

Old Edwards Inn is a five-star resort in the heart of Highlands, North Carolina. They have expanded their facilities toward the east of their existing buildings. The expansion required excavation of rock by blasting techniques or mechanical equipment. Blasting and mechanical equipment such as hydraulic hammers will induce ground vibration.

The Highlands First Presbyterian Church structure is located within approximately 50 feet of the excavation area. The church was constructed in the late 1800s. Figure 3 shows an overview of the church. Excessive ground vibration induced by blasting or hydraulic hammers could have induced stress within the structural elements of the church.

Figure 3 - The Highlands First Presbyterian Church



Due to the hardness and quantity of the rock, controlled blasting techniques were selected. Different parts of the church were visually inspected for paint failure, open cracks, delamination, and any visible deformity. The tactile assessment and ultra-sonic wave techniques were used to identify the condition of the subsurface of the stucco and the mortar between masonry units. In this study no voids were located. The following graph shows one of the ultra-sonic wave test areas on the foundation wall.

Figure 4 - Ultra-Sonic Test Location of Foundation Wall

The blast-induced ground vibration would generate mainly shear stress within the foundation wall of the church; therefore, the allowable shear strain was used to calculate the allowable peak particle velocity *(PPV)*.

To achieve the objectives of this project, the shear wave velocity at different parts of the foundation wall was calculated. The calculated minimum, average, and maximum shear wave velocities were 713 ft/s, 1,478 ft/s, and 2,259 ft/s, respectively. The allowable shear stress was 23 psi. Therefore, the allowable shear strain was:

$$\varepsilon_S = \frac{23}{320{,}000} = 72\,\mu in/in$$

$$PPV = \frac{(Shear\ Wave\ Velocity)\ X\ (Allowable\ Shear\ Strain)}{2}$$

$$PPV = \frac{(713\,X\,12)(72\,X\,10^{-6})}{2} = 0.31\,in/s$$

The maximum blast-induced ground vibration recorded in this project was 0.375 in/s, which was slightly higher than the recommended criteria. The minimum shear wave propagation velocity was used in the calculation producing the most conservative recommendation; therefore the slightly higher vibration level did not affect the structural integrity of the church.

Conclusion:

The public's perception of blasting operations is often less than favorable. Unwarranted claims of damage and lawsuits are becoming more and more common. Fear of blasting is aggravated when historic structures and buildings with cultural significance are affected.

Controlled blasting techniques and a methodical approach for determining site-specific vibration limits can diminish some of the public's concerns. The authors' experience has shown that when steps are taken to provide the best protection available, claims of damage and lawsuits are reduced.