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DETECTION AND DELINEATION OF VOIDS IN REINFORCED AND NON-REINFORCED MASONRY

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ABSTRACT

Reinforced and non-reinforced masonry walls rely upon grout to provide axial, shear and bending load resistance. Grout must be well consolidated to sufficiently bond to horizontal and vertical reinforcing steel to transfer stresses between the grout and the reinforcement. If voids are present, adequate bond may not be provided. In addition to affecting structural integrity, missing grout and voids will allow water to collect around reinforcement leading to corrosion and, potentially, leakage to the interior. Unlike reinforced concrete which can be inspected after form removal, masonry voids go undetected because the masonry units remain in place concealing the grout and voids.

Destructive and non-destructive methods for determining the presence of voids, their locations and delineation of the size of voids in masonry walls are discussed. These methods include infrared thermography, impact-echo, impulse radar, test borings, human range audible soundings and random demolition. The non-destructive methods may be employed during construction for quality assurance or in the investigation of existing structures for rehabilitation.

INTRODUCTION

Masonry bearing wall construction has proven to be a popular and effective material for use in a numerous and wide variety of mid- to low-rise buildings and in some high-rise structure applications throughout the United States. The design of these types of structures may be performed using masonry as either the primary structural elements or as components of a building's main structural system. Building wall systems using either reinforced or non-reinforced elements are designed to provide resistance to forces created by wind, earth pressure, impact, blast or earthquake loadings as well as normal dead and live loadings. Structural elements rely upon the grout surrounding the reinforcement in the cores of masonry units to transfer stresses to provide resistance to the loads. The presence of voids in grout may severely impede the transfer of stresses to the reinforcement and may greatly reduce the capacity of the structural element. In addition to structural integrity, voids in the grout provide areas where water can collect around the reinforcement leading to corrosion of the bars and loss of section. The water and corrosion products can leak from the void pocket into the building interior causing damage and staining. Also, the expansive forces of corrosion products may lead to additional cracking, spalling, and diminished integrity.

These construction defects can result from poor construction practices by an inexperienced labor force or an improper design which creates grouting difficulties. Installing an excessively stiff grout (low slump) or failing to properly consolidate or vibrate the grout can lead to voids. Construction debris in the masonry cells or congestion in areas of reinforcement laps may cause a blockage of the flow of grout resulting in large sections of reinforcement with little or no grout surrounding the bars. This may be complicated by installing the masonry in high lifts which reduces the amount of consolidation in the lowest areas of the cells. These types of defects have been observed in many projects across the east coast of the United States where many designers and contractors have little or no experience with reinforced and grouted masonry construction.

Unlike reinforced concrete where defects are often observed upon removal of the form work, masonry voids can go undetected. The defects can sometimes manifest themselves as persistent leakage and staining from efflorescence or corrosion products or by blistering of paint on the cells where water has become trapped in the walls. In other cases, the voids may not be detected until the walls are loaded and fail structurally.

DETECTION METHODS

Many methods exist for determining the presence of voids, their locations and delineating the void size. These methods may be classified as either destructive or non-destructive techniques. Some of these methods include:

- Random Demolition
- Test Borings
- Sounding
- Impulse Radar
- Impact-Echo
- Infrared Thermography

These techniques vary in effectiveness, speed and cost and are typically useful when combined together. The methods are best employed during construction for quality assurance inspection. In many cases, however, they have been used after construction when flaws were discovered.

Random Demolition

In many cases, random demolition of masonry walls is employed in conditions where construction defects are known to exist or are expected. The masonry is saw cut at desired locations to cleanly remove the outer layers and expose any existing voids. If necessary, grout surrounding the reinforcement can be removed to verify the presence of reinforcing or the condition of lap splices between reinforcing bars.

Random demolition provides exact information about the condition of the walls, but only in the area tested. This information may or may not be typical of the conditions throughout the remainder of the structure. To draw reliable conclusions regarding the condition of other locations, a statistically significant number of test areas must be opened by demolition. This procedure may provide a reasonable estimate of deficient quantities, but it will not provide guidance on the locations and is, therefore, worthless for repair purposes. The labor and material cost of performing random demolition and then repairing the test locations can be prohibitively expensive and time consuming. Additionally, if the building is occupied, the building owner may prefer a less obtrusive alternative as random demolition is noisy, unsightly and creates large quantities of dust. In other cases, access to reinforced masonry may be restricted by interior walls, drop ceilings, or other exterior finishes and structures. Fig. 1 shows an example of an exploratory opening in a composite brick and concrete masonry wall.

Test Borings

Test borings are a less obtrusive method of evaluation testing. A small hole is typically drilled into the structural element. The drill operator can detect small and large voids by feel. A drill equipped with a depth gage can aid in the determination of void depth and size.

A borescope can be inserted to view the conditions on the inside of the cell. This type of testing is very helpful in performing mortar joint solidity surveys. Similar to random demolition, test borings only provide useful information where voids are identified. In solid cells, nothing will be viewable in the borescope. Test borings can be performed much faster than random demolition making it a more attractive alternative in occupied buildings. However, its application is limited by the size of the drill bit and is impractical to employ over large areas at closely spaced intervals. Still, overall inferences about the degree of grout solidity must be based on a statistically reliable sample.

Sounding

Sounding masonry walls is performed using a hammer to differentiate between solid and empty cells. The investigator gently taps the surface of the masonry and listens for subtle differences in the sound from the structure. The method can be an effective non-destructive method for locating voids in masonry depending on the characteristics of the structure. An experienced investigator can locate the beginning and end of a large void within a foot.

However, several problems exist with this method. Even if the sounding can be performed accurately on a given structure, it remains labor intensive and time consuming. The testing is extremely operator sensitive which can increase the potential for missed void locations. Differences in the surface condition of the block (i.e. fractured face block or thick surface coatings) can make differentiating the voided cells extremely difficult. Also, the method is most effective for large void areas where the sounding produces large audible differences. Smaller voids, partial voids and honeycombed areas may not produce a sufficient difference in the sound to identify. From a structural perspective, any discontinuity in the grout which is large enough to effect the transfer of stresses from the bars will be significant.

Impulse Radar

Another non-destructive test method which has been employed to identify voided grout cells is impulse radar (or ground penetrating radar). This method utilizes an antenna which transmits short pulses of electromagnetic energy into a material. As the energy pulse travels throughout the material, portions of the energy are reflected back to the antenna when a material with a different dielectric constant is encountered. The dielectric constant relates to the amount of electrostatic energy which can be stored per unit volume. Large differences in the dielectric constant dictate the amount of energy which is reflected at the interface of two different materials (such as grout/air and grout/steel interfaces). The antenna receives this signal and generates an output signal. The investigator then must interpret this signal to evaluate anomalous results.

Impulse radar is a powerful non-destructive technique which can provide information regarding not only the general locations of voided cells but also the locations of the steel reinforcement in the grout. The difference between the dielectric constant of an air void and grout is typically large enough to detect voids of significant size, but signals may become muddled or masked by reflections from reinforcing steel in the case of honeycombs or other small discontinuities. The test method is rapid and portable allowing, for example, an entire masonry wall, 10 ft. x 15 ft., to be scanned in several minutes. Although data may be collected quickly, the equipment operation and signal response interpretation must be performed by an experienced investigator to yield accurate results. The equipment used to perform impulse radar is also very expensive.

Impact-Echo

In the impact-echo method, a transient stress pulse (sound wave) is introduced into a test object by a mechanical impact on the surface. The stress pulse propagates across the surface of the object along a circular wave front as an R-wave (Raleigh wave) and into the object along a spherical wave front as P-waves and S-waves. The waves are reflected by internal interfaces and external boundaries of the test object. The arrivals of these reflected waves at the surface where the impact was generated produce displacements which are monitored by a transducer. A schematic illustration of the impact-echo method is presented in Fig. 2.

Because it is difficult and time consuming to analyze the time domain waveforms and determine the arrival times of the reflected waves, the waveforms are transformed into the frequency domain using the fast Fourier transform (FFT) technique. The resulting amplitude spectrum is used to compare the dominant frequencies present in the wave form. In the case of reinforced masonry, the signal recorded for a solid grouted cell condition is significantly different from that of a voided cell.

Impact-echo is a portable, rapid test method. However, in comparison to the impulse radar method which produces output for a scan of a surface, impact-echo produces data for a discrete location, and as such, must be performed at regular intervals to produce comparable information. One of the advantages of using impact-echo over other techniques is the ability to detect smaller voids and honeycombs in the cells. This also makes it easier to identify the beginning and end of a void for delineation and repairs. Like the impulse radar technique, the impact-echo equipment requires an experienced investigator to interpret the signals. The equipment is moderately expensive.

Infrared Thermography

Infrared thermography is an excellent non-destructive test method for the detection of voids in masonry construction. Infrared cameras are used to detect thermal radiation and produce a visual display of surface temperature differences. Flaws such as voids or delaminations below the surface of a wall system create an air gap which affects the heat flow through the wall. Small variations in surface radiance are recorded and used to detect defects below the surface. In a reinforced masonry application, the radiant energy from the surface of a grouted cell is significantly different from that of a voided cell. These differences can be created by internal heating/cooling of the building or through solar energy gain on the exterior surfaces. Using a thermal camera to capture images on videotape, the radiant energy signature is easily observed and reviewed. Grout cells, for example, appear as vertical lines on the surface of the walls. Interruptions or staggers in these lines indicate voids or discontinuities in the grout cells. Fig. 3 shows an infrared image of a grouted wall that contains voids.

This method offers several advantages over other non-destructive techniques. The most useful aspect is that the video image produced by the camera allows the survey of large areas while simultaneously showing the proximity of the defects with respect to the structure. Unfortunately, many times on long uninterrupted lengths of wall, visual or thermal landmarks must be placed in the field of view to identify the relative location of a flaw. Testing of large areas can be performed quickly by an experienced operator with equipment which can be either hand held or mounted to a vehicle. Unfortunately, infrared testing is strongly dependant on environmental conditions. Factors such as cloud cover, wind speed, temperature, sunlight and precipitation can affect or prevent accurate testing. The method also becomes less effective as the void size decreases or the depth to the void increases. Overall, infrared thermography provides the most rapid assessment of large areas.

APPLICATIONS

As mentioned previously, most investigations of defective masonry construction benefit from the use of more than one technique. Typically this would involve the use of a non-destructive technique to identify areas of potential defects in the masonry system followed by selective demolition or probing to verify the effectiveness of the non-destructive technique and to delineate the problem areas for determining procedures for and estimating the quantity of repairs.

Case Study #1

Several buildings of a retail shopping center in the North Eastern United States were experiencing water infiltration, efflorescence, and blistering of the finish coating on the building exterior. Most of the observed symptoms indicated that water was infiltrating the structures and was being retained in some areas of the walls. All buildings were occupied at the time, and the testing was performed so as to minimize disruption to the occupants and customers of the retail stores.

The masonry walls were constructed of 8 inch and 12 inch concrete masonry units reinforced 3 to 4 feet on center. The ungrouted cells were filled with insulation to increase the thermal efficiency of the building. This provided a high thermal differential on the surface of the block between grouted and insulated cells. Infrared thermography was employed to identify potential problem areas in the buildings. Testing was performed at night during the winter months on the building exterior. The infrared camera was used to detect the internal heat of the building radiating through the grouted cells to the building exterior. Additional testing was performed during daytime hours using solar energy to heat the surface of the walls. Insulated cells, which reduce heat transfer, provided a high degree of contrast in the thermal image of the wall during both day and night testing.

Additional testing and verification of the infrared data was provided by performing test borings in areas identified as defects. The test boring data indicated that many of the smaller voids observed using infrared were in fact caused by allowing small quantities of core insulation to fall into cells prior to the grouting operation (see Fig. 4). Other areas were simply forgotten and remained ungrouted above a certain level.

A structural analysis was then performed to determine the actual reinforcement spacing requirements to provide adequate resistance of the design forces. The infrared data was used with the results of the structural analysis to develop a quantity estimate of repairs for the buildings.

Case Study #2

A retail shopping center located in Maryland was investigated using infrared thermography, impact-echo, and test opening techniques. During the construction of the buildings, one of the walls was undermined below the footing causing a partial failure of the wall with large cracks. Upon inspection of the area, significant defects were noted in the masonry construction with regard to grouting. This led to an investigation of similar walls throughout the shopping center.

Infrared thermography again was employed to identify grout voids in the masonry cells. Because the buildings were not occupied at the time of testing, testing of the walls was performed using principles of transient solar loading. Areas of grouted masonry provided a heat sink which gained and lost heat slower than the voided areas. Unfortunately, many areas of the building walls were obstructed by exterior appurtenances and column pilasters. Therefore, impact-echo was used as an alternate method in these areas. Because the exterior walls were constructed of split-faced units, impact-echo testing was performed on the interior side. Tests were performed on successive blocks in areas known to be voided and known to be solid grouted to check the effectiveness. Signals observed in areas of well consolidated grout could be identified by large frequency peaks corresponding with the approximate thickness of the wall (see Fig. 5). Areas which contained no grout behaved as a thin plate vibrating flexurally providing dominant low frequency peaks which would normally be identified as signals corresponding to depths much more than the actual thickness of the walls (see Fig. 6). The two very different signals made locating and delineating the voids relatively easy. Test borings in these locations verified the results of the impact-echo data (see Fig. 7).

A series of random demolition tests was performed to identify defects in the steel reinforcement laps. A covermeter was used to identify locations of probable splices in the walls, and the steel bars were then exposed at each bar end point. The lapped distance was measured and recorded in each location.

As before, this information was compiled and used in combination with a structural analysis to develop repair procedures and quantities.

Case Study #3

Two dormitory buildings were constructed using composite concrete and brick masonry for the exterior walls. The walls were designed with steel reinforcement placed within the grouted space between the inner concrete masonry and exterior brick masonry walls. The reinforcing steel was to be surrounded completely in grout, thus providing a multi-wythe composite wall section. As a result of leakage problems, it was discovered that the grout contained many small to large voided areas. Because these voids were not visible from the interior or exterior, a method for determination of their locations was needed. The following tests were considered: hammer sounding, drilling, rebound hammer, and infrared thermography. After further review, drilling, infrared thermography, rebound hammer, and hammer sounding were attempted. A hammer drill was used to verify the findings. It was anticipated that the rebound hammer would yield significantly different results over areas with voids compared to areas without voids. It was found, however, that the rebound hammer provided erratic results within areas with and without voids.

Hammer sounding (using a 16 oz. claw hammer) at first seemed to show promise, but was extremely labor intensive. There was not a significant difference in the sound of the voided versus the unvoided areas which lead to uncertainties in its use.

Infrared thermography was employed in hopes of picking-up differences in temperature between the voided versus unvoided areas. The investigation was performed in the summer, and the air conditioning of the buildings was not performing properly, thus not providing a sufficiently large temperature difference from the interior to exterior. For this reason, the testing was performed at dusk to capture difference in temperature due to radiant cooling effects. This procedure worked extremely well. Voids as small as a tennis ball were detected from 50 to 100 feet away from the building.

Comprehensive infrared thermography of the exterior walls was performed and recorded on elevation drawings for use by the repair contractor. The workmen used hammer sounding during the repair phase to better delineate areas which were not completely visible or difficult to establish with infrared thermography. Also, drilling was used as a quality assurance check on the grouting operations. After completion of the project, infrared thermography was again employed for quality assurance purposes.

CONCLUSIONS

Presently, there are many techniques available for the detection of voids in grouted masonry. They can be classified as destructive or non-destructive methods and can vary considerably in cost, speed, and experience requirements. In general, most investigations could be performed effectively by using a non-destructive test method in conjunction with selective destructive testing and verification to obtain quick and reliable information regarding the condition of the masonry and the repairs required to repair all necessary design or construction defects. The most effective procedure from a quality assurance standpoint is the infrared thermography method. This method should be employed for all reinforcing masonry projects during construction to help assure proper grout placement.

ACKNOWLEDGMENT

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Malhorta, V.M., and Carino, N.J., CRC Handbook on Non-destructive Testing of Concrete. CRC Press, Inc., 1991.

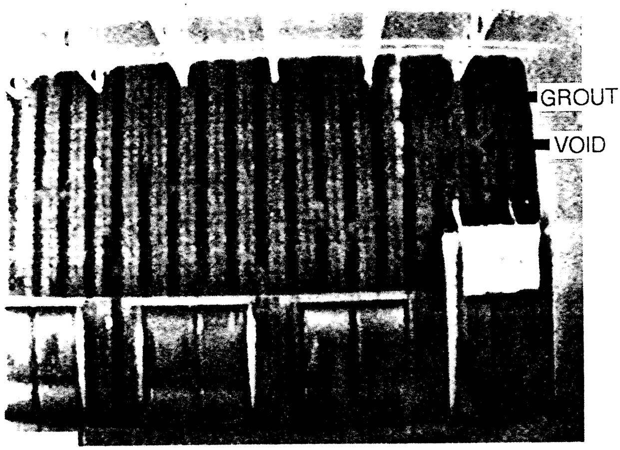

Fig. 3 — Infrared image of grouted and reinforced concrete masonry wall.

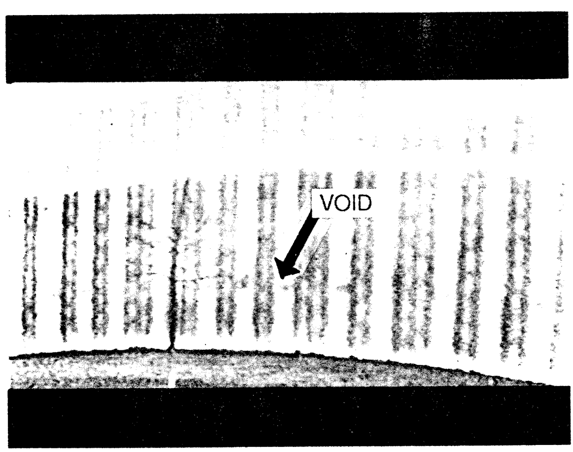

Fig. 4 — Infrared image of small voids as a result of misplaced insulation in grouted cell.

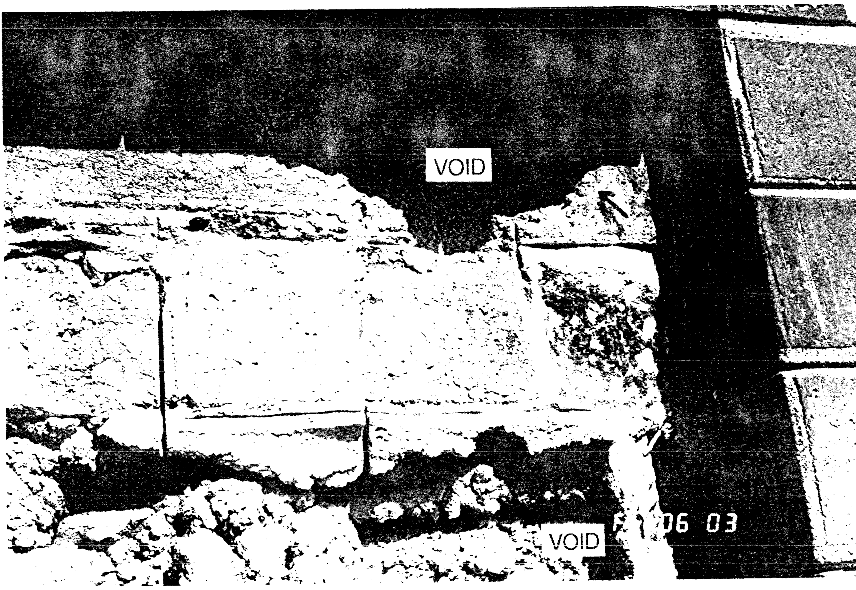

Fig. 1 — Exploratory opening in a composite brick and concrete masonry wall containing voids in the grouted collar joint.

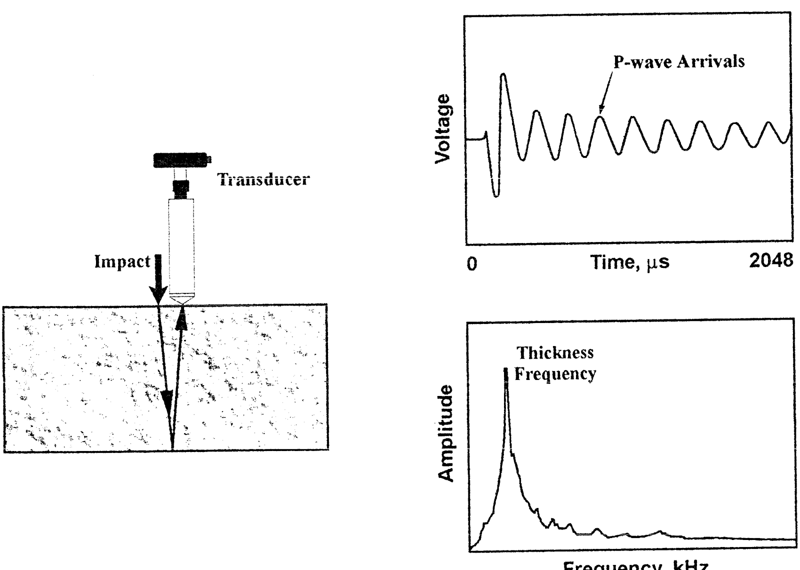

Fig. 2 — Schematic illustration of the impact-echo method.

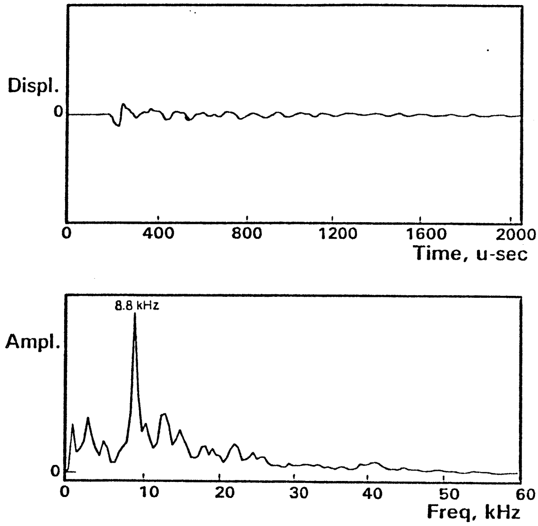

Fig. 5 — Typical solid masonry block response.

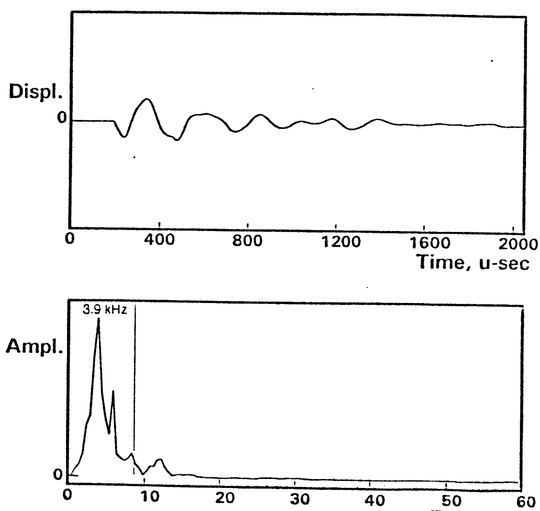

Fig. 6 — Typical hollow masonry block response.

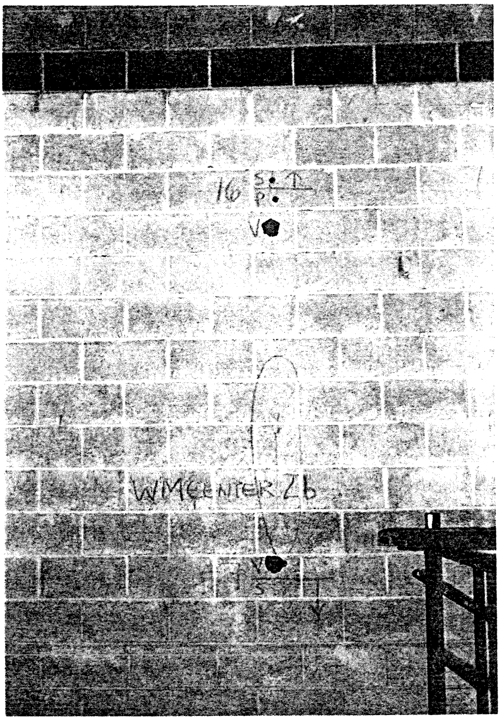

Fig. 7 — Verification of impact-echo testing.