The 5th International Symposium on Robotics in Construction June 6-8, 1988 Tokyo, Japan

THE DEVELOPMENT OF AN APPARATUS FOR DIAGNOSING THE INTERIOR CONDITION OF WALLS

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ABSTRACT

Methods to diagnose the condition of walls include the use of supersonic sound and infra-red light, but their use is difficult and accuracy is sometimes questionable. The conventional method of using a hammer and intrepreting the sound waves is also open to differing interpretation. The author has, however, adapted the hammering method and applied electronic techniques to the analysis of the damping properties of the sound waves produced, whereby accurate diagnosis can be made. Additionally, analysis can be conducted in real time by an unskilled operator, and can diagnose separation up to approximately 40 mm within the wall. The apparatus can be used in elevated positions by hand, or can be mounted on a wall traversing inspection robot.

1. Introduction

Exterior walls are commonly finished with tiling fixed with mortar as it provides an economical yet attractive appearance. However, such tiled walls are prone to deterioration, and if defects are not remedied, rain water will penetrate the wall resulting in the separation of tiles and mortar, leading to the dangerous condition of falling tiles. To prevent such defects, it is necessary to regularly monitor the condition of the wall and tiles.

Manual inspection, however, is hazardous because it must be carried out at high elevations. Additionally, the inspection work itself contains some drawbacks in that continuous inspection for a period of hours is likely to undermine an inspector's power of concentration preventing the inspector from making an accurate diagnosis. Another drawback is that different inspectors draw different conclusions, making quantification impossible.

To overcome the above disadvantages, the writer has reviewed methods for performing automated diagnosis of separation in tiled walls. As a result, it was discovered that striking the wall with a hammer and analyzing the sonic waves generated provides a relatively simple and accurate diagnostic method.

Favorable results were obtained after experimenting with prototype equipment developed for this method which utilizes sensors. Through this experimentation, the writer also succeeded in making the equipment more compact and lightweight for incorporation in a robot. A summary of this development is discussed below.

2. Review of Diagnostic Methods

The following methods are usable for diagnosing separation in a tiled wall surface.

(A) - Use of infrared light (IR)
(B) - Use of a Schmidt hammer
(C) - Use of ultrasonic waves
(D) - Use of a hammer

(A) The IR method is designed to detect slight temperature differences between sound and faulty wall sections, which arise from heat radiation within the building or externally from sunshine, etc. Poorer heat conductivity in separated section compared with those of the sound sections because of the discontinuity between the inside and outside of the wall. This temperature difference is used to diagnose separation by identifying it as a heat image using an IR ray camera.(1) This method is advantageous in that it does not require scaffolding or gondolas, but its drawback is the requirement of an open exposure of the wall surface and its application may well be limited to downtown areas where buildings are concentrated and roads are narrower. In addition, the method requires close attention since results are likely to be affected by stains or shadows on the walls, and by weather, etc.

(B) The Schmidt hammer method is designed to diagnose separation from the difference in repulsive acceleration forces developed by the hammer strike. If separation has developed in a wall, its repulsive acceleration is lower than that of a sound wall as the voids created by the separation absorb the impact of the hammer strike. The method uses this difference for diagnosis.(2) Originally, the Schmidt hammer method was used to measure compressive strength of wall surfaces. But as strong hammering is involved, the wall surface is likely to be damaged if this method is used. Consequently, if an entire wall surface has to be inspected continuously, external damage is likely.

(C) In the ultrasonic method, a medium such as water or grease is generally used for wall surface contact with the ultrasonic element.(3) If this method is used to continuously inspect the walls of an existing building, the use of such contact mediums are awkward to use, plus stable contact with the wall is lacking.

(D) The hammer-striking method is employed by an inspector who hammers on a wall manually and the sonic waves generated by the hammering are detected to make a diagnosis of separation by the difference in those sonic waves. If the wall is sound, striking it with an ordinary hammer results in slight vibration on the surface. When the surface of separated section is struck, however, the section vibrates differently, since the separated section does not form a unit. Therefore, the sonic waves are different between a sound and a separated section and diagnosis is made by identifying this difference. This method has long been applied by engineers, is proven, does not require special equipment and makes continuous diagnosis possible, but has the disadvantages as noted above.

From the diagnostic methods described above, the hammer-striking method, using the difference in the sonic waves generated by striking, was the method chosen to diagnose wall separation because its performance is proven and makes continuous diagnosis possible.

3. Experimental Devices

In the experiments, tests were made by using a test sample in consideration of the reproducibility of data. Also, experimental equipment that enables simulation analysis was used as a device to review methods of analysis.

3-1 Experimental Equipment

Figure 1 shows a diagram of the experimental equipment. The surface of a wall tile, etc., is struck as shown. The sonic waves generated are picked up by a microphone for transmission to the wave form analyzer after converting them into electric signals to allow simulation of the diagnosis method with the analyzer. This wave form analyzer uses a computer which has a special frequency analysis board capable of high-speed operations, a wave form memory device in the input circuit, A CRT, printer and plotter in the output circuit to simulate free combinations of frequency, filtering and correlation analyses, etc. The analysis of hammering sounds was reviewed using this experimental equipment. Photo 1 shows this wave form analyzer.

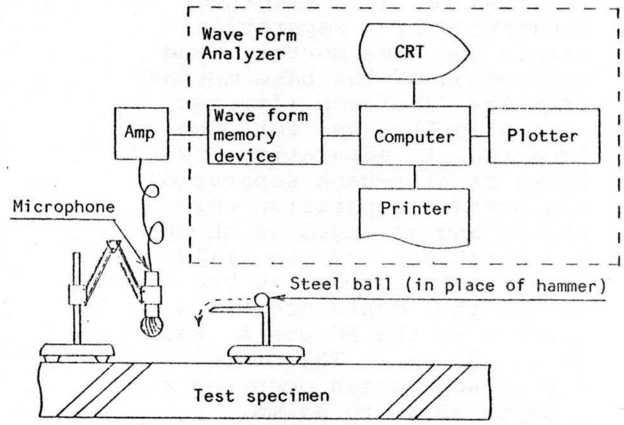

Fig. 1 Wave Form Analyzer

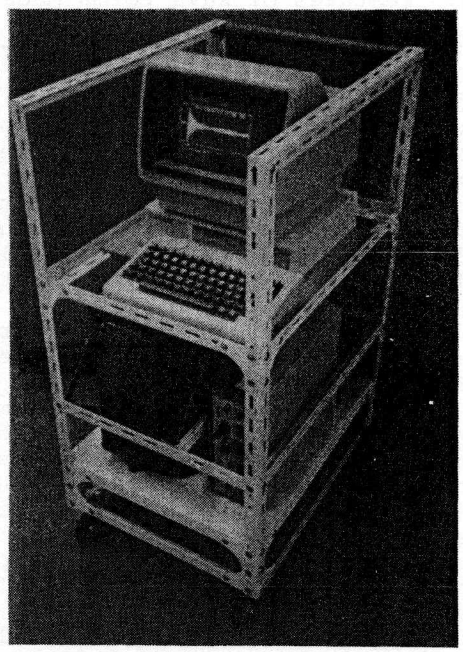

Photo 1 Wave Form Analyzer

3-2 Test Specimen

Figure 2 shows the front view of the test specimen used in the experiment. As shown, each test specimen is a tiled wall of a more complicated structure than a mortar wall. To make a test specimen, base mortar was laid in a thickness of about 20 cm on a PC board measuring 2,000 mm by 1,000 mm and covered with tiles. Tiles can be classified into porcelain, stoneware and ceramic tiles. Of these types, porce-lain tiles and stone ware tiles and stoneware tiles are used for exterior walls because because of their small coefficients of permeability. Therefore, porcelain tiles and stoneware tiles were arranged as shown to make the test specimens. Separation was created by inserting pieces of foamed styrol, etc., each having a thickness of 1 to 2 mm. Separation on an ordinary wall surface can be classified into 3 types: separation of tile from the base mortar (hereafter referred to as "tile-back separation"), separation within the base mortar, and separation of the base mortar from the skeleton ("mortar separation"). As for the location of separation, 2 types of tile-back separation and mortar separation were chosen and arranged as shown. The thickness of the tile used ranged between 10 and 15 mm and the depth from the surface to the PC board was 30 to 35 mm. Therefore, mortar separation occurred at a depth of 30 to 35 mm.

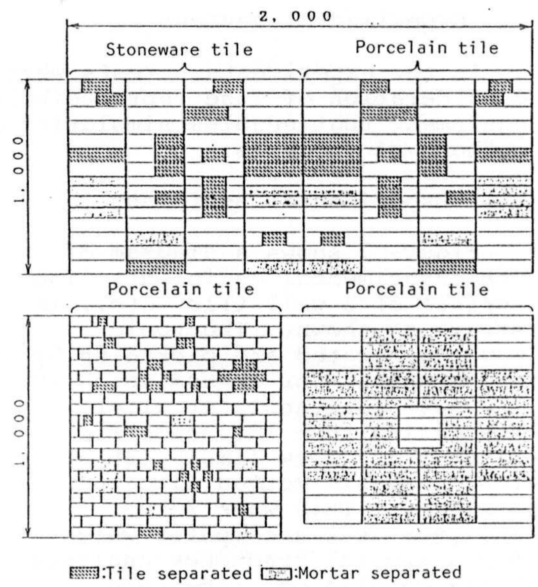

Fig. 2 Test Specimen

4. Features of Wave Forms Made by Striking

Figure 3 shows typical sonic wave forms generated when the indicated test specimen was struck using the same force. One sound example and one faulty example with separation are shown. Figure 4 shows a frequency spectrum of sonic wave forms of which the maximum is normalized as 1. Both sound and faulty examples are shown overlapping the analyzed spectrum. Figure 4 shows that, in both cases, the frequencies are contained between 1 kZ and 10 kZ. Consequently, it can be understood that frequencies other than this range are unnecessary for analysis but, as the frequency bands of both examples overlap to a great extent, it is difficult to simply discriminate using the frequency range.

In the case of the wave forms shown in Figure 3, a difference in amplitude value is observed between the sound and faulty specimens. Figure 5 shows the results of a statistical study of this difference. Approximately 30 strikes were made in each example of sound wall specimen. Mortar separation and tile-back separation to determine the maximum amplitude values of generated sounds, and the distribution of each was calculated on the assumption that these maximum values are distributed normally. Figure 5 shows these maximums normalized at 1. This figure shows that, in the example of tile-back separation, the maximum value is much greater than in the case of a sound wall, and its distribution just slightly overlaps with that of a sound wall. Therefore, tile-back separation can be unmistakably detected by merely watching for the maximum amplitude value. In the example of mortar separation, however, it is hard to detect since its distribution is similar to that of a sound wall.

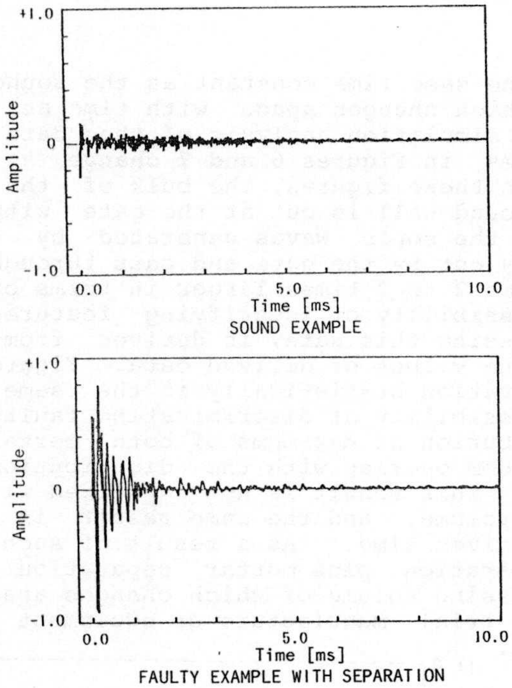

Fig. 3 Sound Wave form

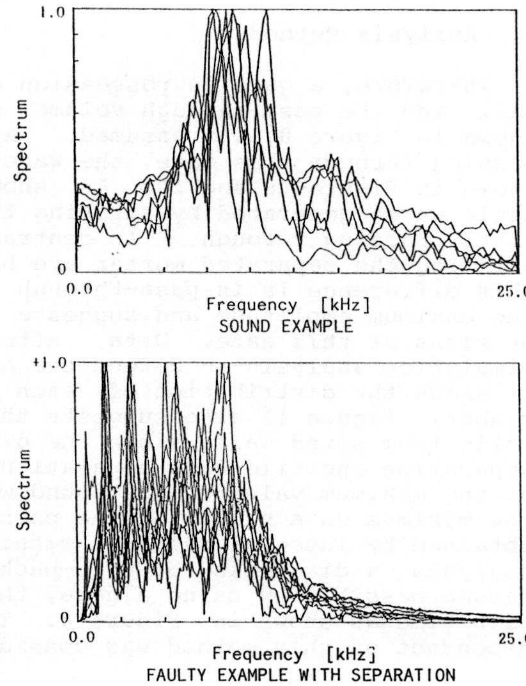

Fig. 4 Frequency Spectrum of Sound Wave Form

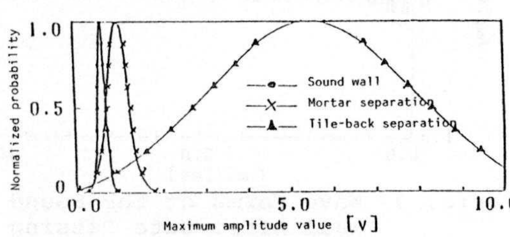

Fig. 5 Probability Distribution of Maximum Amplitude of Sound Wave Forms

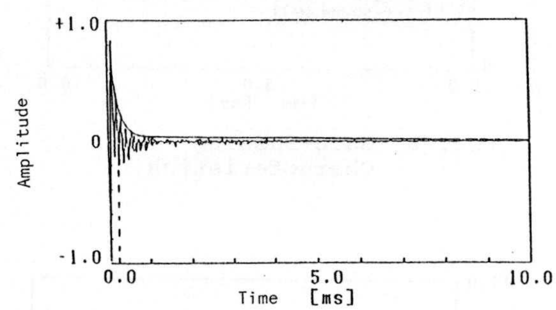

Fig. 6 Normalized Wave Form of Sound Wall

Figures 6 and 7 show typical sonic wave forms of which the maximums are normalized at 1 for the sound wall, and for the wall with mortar separation, respectively.

Comparison of Figure 6 with Figure 7 reveals a difference in the damping properties of the sonic waves generated by striking. If the time constants are calculated on the assumption that the damping properties of wave forms are a primary delay system, the time constant of mortar separation is roughly 3 times larger than that of a sound wall.

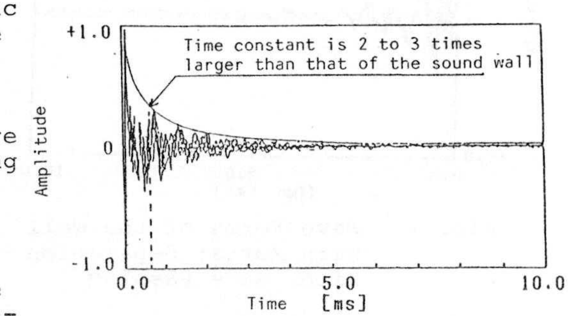

Fig. 7 Wall with Mortar Segregation

5. Analysis Method

Therefore, a gate in possession of the same time constant as the sound wall, and the pass-through volume of which changes apace with time as shown in Figure 8, was assumed. After simulation analysis of the data passing through this gate, the wave forms in Figures 6 and 7 change as shown in Figures 9 and 10. As shown in these figures, the bulk of the sonic waves generated by striking the sound wall is cut at the gate with little passing through. In contrast, the sonic waves generated by striking the separated mortar are hardly cut by the gate and pass through. This difference is in pass-through volume 2 to 3 times larger in terms of the maximum amplitude and suggests a possibility of identifying features by means of this gate. Data, after passing this gate, is derived from simulation analysis to detect the maximum values of derived data. Figure 11 shows the distribution of each derivation statistically in the same manner. Figure 11 also suggests the possibility of discriminating faulty walls from sound walls since the distribution of maximums of both mortar separation and tile-back separation seldom overlap with the distribution of the maximum value of the sound wall. This result is not equalized with the maximum data value of the passing volume, and the same result is obtained by integral calculus within a given time. As a result of such analysis, a diagnosis of tile-back separation plus mortar separation became possible by using a gate, the passing volume of which changes apace with time as shown in Figure 8. Thus, trial manufacture of equipment dependent on this method was considered.

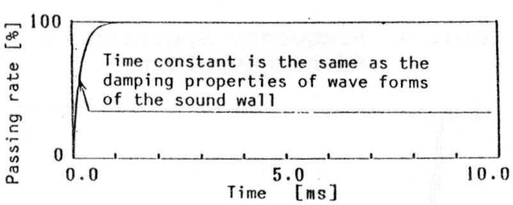

Fig. 8 Gate-Passing Characteristics

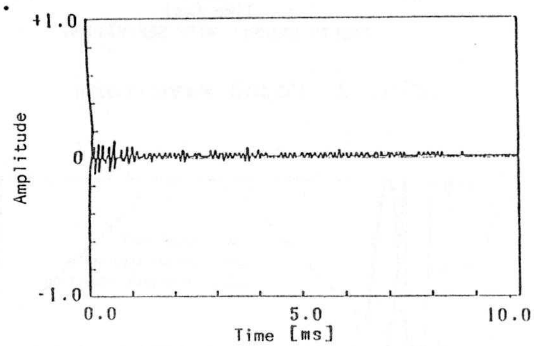

Fig. 9 Wave Forms of the Sound Wall After Gate Passing Amplitude

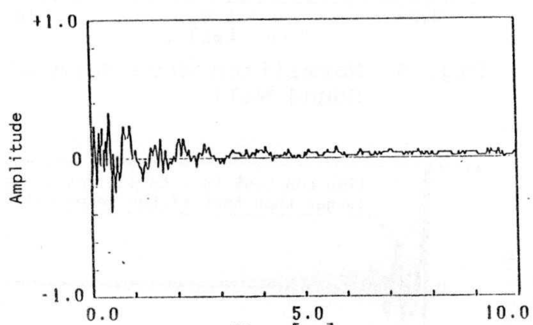

Fig. 10 Wave Forms of the Wall With Mortar Separation After Gate Passing

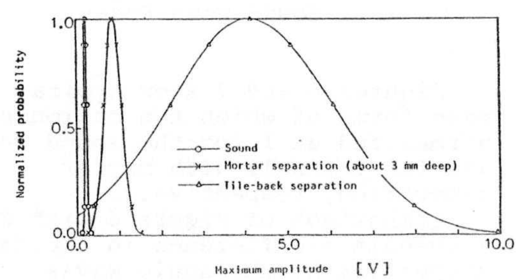

Fig. 11 Probability Distribution of Wave Form Maximums After Gate Passing

6. Diagnostic Equipment

Figure 12 shows the block diagram of the diagnostic method described above as incorporated in the equipment. Its functioning is outlined below. First, a driving signal is generated by the driving signal generating circuit for transmission to the hammer-driving circuit, the trigger-generating circuit, and the judging circuit. Upon receipt of the driving signal, the hammer-driving circuit drives the hammer to strike the wall. Striking sounds generated in the wall are picked up by the microphone, converted into electrical signals for transmission to the gate circuit and the trigger-generating circuit via the filter circuit. The trigger-generating circuit times the timing of the driving signal and outputs a trigger to the gate circuit if a striking sound of precise timing is input. The gate circuit keeps the passing volume at zero until the trigger is received, and immediately after receiving the trigger, it increases the passing volume in accordance with the characteristics shown in Figure 8 and, after a time lag useful for analysis, after 10 ms for example, it reduces the passing volume to zero again. During the interim, the data that passed the gate circuit is sent to the judging circuit for integration, processing of maximum value detection, etc., and quantification of the deviations from the standards obtained for a sound wall and the results are output to the display circuit and external device. The display circuit uses 3 different color lamps (LED 6) to show "sound...with blue, separation likely...with yellow, and separation...with red" based on the assessed results and showing the results instantly, as well. The operation of this diagnostic equipment is all by analog circuit. Real-time processing provides high-speed operation, and the time required between wave form input to the assessed display result is about 10 ms at most.

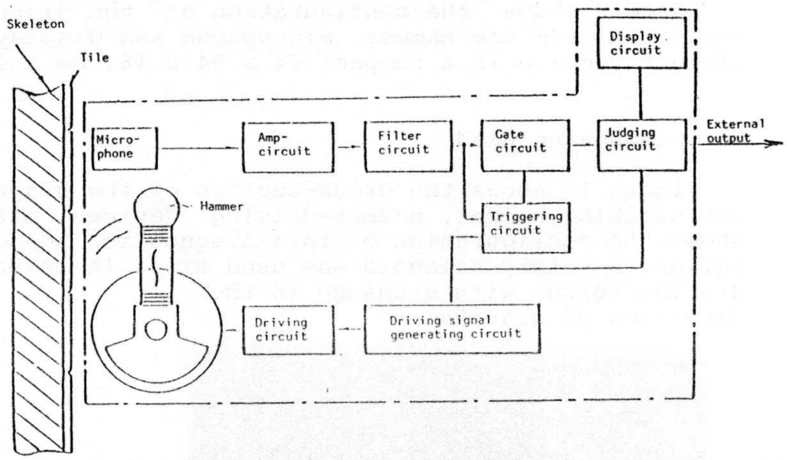

Fig. 12 Block Diagram of Diagnostic Circuit

When a wall is inspected using this method, however, the inspector is required to move along the wall while striking it with a hammer. Therefore, it is advantageous to split the equipment into a moving section incorporating the hammer, microphone, etc., that can move over an entire wall to be inspected and the non-moving section including the diagnostic circuit that does not have to move, in order to make the moving section as compact and lightweight as possible. Therefore, these two sections were separated and the diagnostic head that incorporates the hammer, microphone, etc., and the

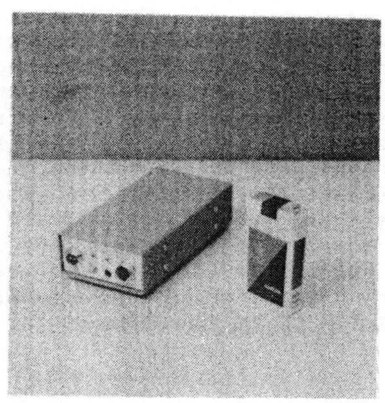

Photo 2 Diagnostic Circuit Section

diagnostic circuit section housing the diagnostic circuit were manufactured separately.

Photo 2 shows the configuration of the diagnostic circuit section separated from the hammer, microphone and display circuit. The diagnostic circuit section is a compact 44 x 94 x 180 mm and with a weight of 600 g.

7. Diagnosing Head

Figure 13 shows the cross-section of the diagnostic head which houses the striking hammer, hammer-driving devices, microphone, etc. Photo 3 shows the configuration of this diagnostic head. As the hammer-driving device, a rotary solenoid was used since it is barely affected by the driving torque with a change in the direction of gravity.

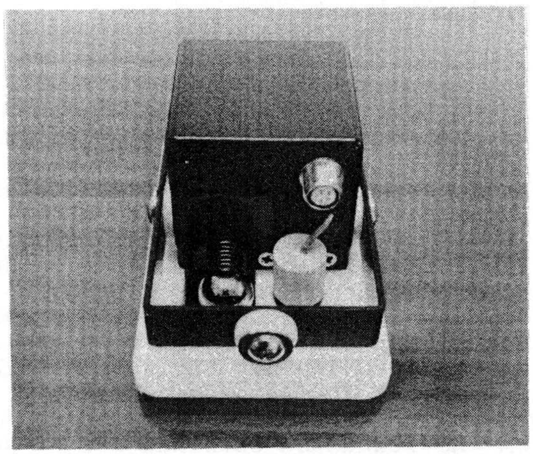

Photo 3 Diagnostic Head

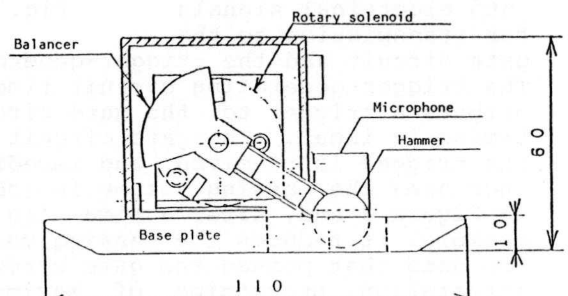

Fig. 13 Diagnostic Head

The rotary shaft of the rotary solenoid is projected from the center like that of an ordinary motor. When an electric current is applied, this rotary shaft rotates through a given angle and stops and resumes the original position when the current is cut.

The hammer is fixed on this rotary shaft via a spring, and on the opposite side of the hammer, a counterweight (balancer) is fixed to balance the hammer weight with the moment of rotation. As a rotary solenoid is used to drive the hammer and a balancer is also used, striking can be accomplished using constant power without regard to the direction of striking. As the hammer stroke in striking the wall, has to be kept constant, a base plate was provided to ensure its constant contact with the wall and it is so designed that the hammer strikes the wall through a hole in this base plate. When the solenoid is powered, the hammer moves in the direction of the wall and strikes the wall by the rotation of the solenoid. When the current is cut, the hammer also resumes the original position. By using this mechanism, the wall is truck continuously allowing the generated sounds to be picked up by a microphone positioned right next to the hammer for transmission to the diagnostic circuit.

The frequency of wall striking can be accelerated up to 20 cycles/sec, but normally, frequency is reduced to 10 to 15 cycles/sec. In contrast, the diagnostic speed of the diagnostic circuit is very high as noted earlier. Since it is capable of making 100 diagnoses a second, diagnosis can be made without any problem at such a frequency. As the base plate of the diagnostic head slides along the wall during diagnosis, a Teflon panel, with a low coefficient of friction, is used and all four of the edges are tapered to slide over slight dents and projections on the wall. The thickness was increased to 10 mm to minimize sliding noise and the frequency range lowered in order to reduce adverse effects on the diagnosis. The diagnostic head measures 60 x 70 x 110 mm and weighs 440 g and realization of the objective of developing a compact and lightweight apparatus was achieved.

8. Diagnostic Result

An example of the diagnostic results of existing buildings using this experimental apparatus is discussed below.

The display colors in Figure 14 (which correspond to the lamps on the sensor unit) show the results of inspection made using this apparatus of an existing exterior wall of tiles. A bonding strength test of the same wall was also conducted and the result is compared in Table 2 with the diagnostic result using the present equipment. This table shows that blue diagnostic results using this equipment coincided with sufficient bonding strength, yellow results with low bonding strength, and red results with lack of strength. In this case, the sections displayed in red and yellow require repair. It was also confirmed that the diagnostic results of the same wall using the conventional hammer striking method coincided with the above results. Table 2 compares diagnostic results using this equipment on the exterior wall tiles of another existing building with the results of actual wall conditions confirmed by chipping the tiles. The base mortar of this wall was too thick for the portable cutter to adequately reach the skeleton. Although the bonding strengths could not be measured accurately, mortar separation, event at a depth of about 45 mm is detected by this equipment as shown in the table. In addition, several tests were made to compare machine diagnostic results with human diagnostic results, and all matched well.

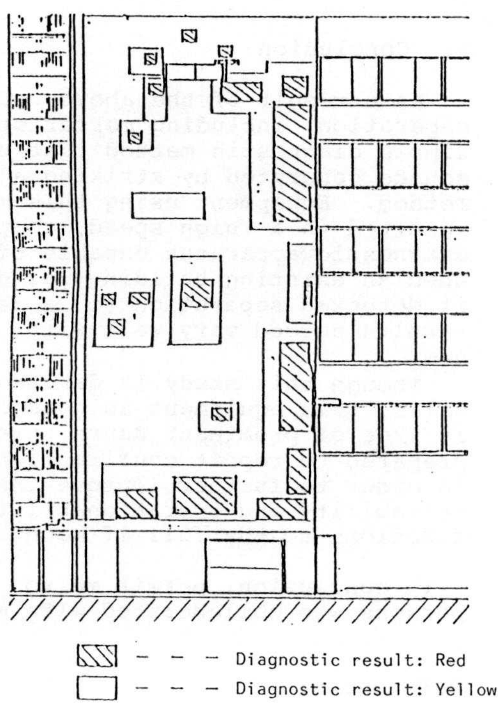

Fig. 14 Diagnostic Results

Table 1 Diagnostic Results Using the Present Diagnostic Equipment and Bonding Strength of tile

Diagnostic Result	Data No.	Adhesion Strength (kg/cm^2)	Depth of Separation (mm)	Remarks
Blue	1	9.56		Sound
Blue	2	7.71		Sound
Average of blue		8.64		
Yellow	3	3.39	35	Voids in base mortar
Yellow	4	2.31	11	Insufficient tile adhesion
Yellow	5	1.85	11	Same as above
Yellow	6	3.39	43	Honeycombing in base mortar
Yellow	7	2.47	27	Upper mortar separated
Yellow	8	0.40	11	Groove completely separated from mortar
Average of yellow		2.30		
Red	9	0.15	11	No mortar in groove

Small porcelain tiles were used on the wall measured.

Table 2 Test Results Using the Present Diagnostic Equipment and Condition of Wall Separation

Diagnostic Result	Data No.	Adhesion Strength (kg/cm^2)	Depth of Separation (mm)	Remarks
Blue	E1-1	12.6*	---	No separation
Blue	E1-2	14.6*	---	Same as above
Blue	E1-3	12.6*	---	Same as above
Yellow	N2-1	---	45	Separation between skeleton/mortar
Yellow	N2-2	---	45	Same as above
Yellow	N2-3	---	45	Same as above
Red	N1-1	1.4	27	Voids in mortar
Red	N1-2	0	11	Tile back separated
Red	N1-3	0	11	Same as above

*While the depth to the skeleton is 45 mm, the cutting depth is 25 mm.
It is possible that these figures differ from the actual condition.

9. Conclusion

As a result of the above study, it was determined that diagnosis of separation, including mortar separation, can be made with a relatively simple diagnostic method that uses the difference in damping properties of sounds generated by striking a wall using the conventional hammer-striking method. Equipment using this method was experimentally constructed and resulted in a high-speed, compact and lightweight (1.04 kg in all) diagnostic apparatus capable of making 10 to 15 diagnoses per second. When an existing building was diagnosed using this experimental equipment, it detected separation to a depth of about 45 mm, and the diagnostic results agreed very well with the results of tensile strength testing, etc.

Though this study is devoted to the diagnosis of separation of tiled walls, this equipment is considered usable for mortar walls if its surface is free of prominent dents, projections or elastic coating. The writer is prepared to report confirmation tests in the future regarding mortar walls in order to further improve the equipment which features high levels of reliability and operationability and which is capable of exercising its functions to the full if mounted on a robot.

In conclusion, permit me to express my deep gratitude to all those persons who collaborated with me in this study.

References:

(1) Arai: "Tile exterior wall diagnostic detector dependent on IR sensors"

(2) Takano, et al: "Examination of dilapidated mortar wall with a Schmidt hammer".

(3) Kimura et al: "Nondestructive Inspection Manual," pp.446-447, The Japan Society of Nondestructive Inspection, Feb. 1972.