Development of Automated Inspection Robot and Diagnosis Method for Tile Wall Separation by Wavelet Analysis

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Abstract

This paper describes the development of an automated inspection robot for detecting tile deterioration and a new diagnostic method for determining its existence and extent. The robot moves quickly along a vertical wall and stops to detect a tile's inner condition using a hammering sound. Tile separation commonly comprises outer exfoliation where the tile separates from the mortar concrete and inner exfoliation where the space between the substrate and the mortar concrete deteriorates. In order to detect these two modes by a hammering sound, we focused attention on wavelet analysis, which enables us to analyze the frequency element of the sound waveform. By comparing the wavelet volume rate expressing the characteristics of tile deterioration, a method of visually distinguishing the two exfoliation modes was established. The automated robot and the diagnostics method were used to perform a fast and highly accurate inspection of a tile wall.

1. Introduction

Tiles made from materials that are durable, fireproof, water-proof and decorative are used for external finishes on exterior walls of architectural buildings. However, many of these finishing materials have deteriorated with age and changes of building use. Typical deterioration symptoms include tile separation, cracking and layer separation. If they are left too long, tiles can break and large areas can suddenly fall off, and in extreme cases fatal accidents can occur. To prevent these problems, the deteriorated states need to be accurately confirmed and an appropriate repair method determined. External tile walls have previously been inspected by skilled workers using a hammering sound. However, this has led to variations in diagnosis, and it is feared that judgment can be impaired when work has continued for a long time at a great height.

In the high economic growth period after 1975 in Japan, more than 100,000 buildings were constructed in metropolitan areas. Thirty years have already passed since that period, and symptoms of tile deterioration have begun to appear. The Ministry of Land, Infrastructure and Transportation revised The Building Standard Law of Japan in 2008 with regard to the safety performance of exterior tile walls, requiring safety inspections of all tile walls ten years after construction.

As a background to tile inspection technology, for about ten years we studied several diagnostic methods and developed several kinds of inspection robots, finally resulting in the present robot system. The robot has a very compact body and shows good inspection performance for tile deterioration (Inoue, F., and Ohta, Y. (2004)). However, for the diagnostics method, some parameters indicating characteristics of sound waveform for detecting tile exfoliation have been found experimentally by applying mathematical functions, and used to diagnose symptoms of tile deterioration. These methods were found to be useful for the simple deterioration mode of tile surface separation, but not for the compound tile deterioration of separation of inner concrete layer, which can induce a fatal accident. Furthermore, it was very difficult for a skilled worker depending on his senses to distinguish between separation of outer tiles and inner layer deterioration.

This paper introduces a developed inspection robot and actual applications, as well as new diagnostic methods for compound tile deterioration using wavelet analysis, and these effects are explained in detail.

2. Development of Automated Inspection Robot

2.1 Outline of the inspection system using an automated robot

Figure 1 shows a schematic picture of the tile inspection system using an automated robot instead of a skilled worker. The inspection robot moves along the tiled face of the building while hanging from two wires suspended from a hanger truck and its sensors check various tile deterioration modes. The robot can be moved vertically by winding and unwinding these wires, and horizontally by moving the hanger truck. In an actual inspection, the robot is stopped at each tile face for a short time, and the deterioration conditions of the tile are examined by analyzing the impact sound of a small hammer and by observing camera data, and the diagnosis result is instantly indicated on a computer panel on the ground. All the tile tests and test result recordings are executed by automatic operation, except for a few manual operations.

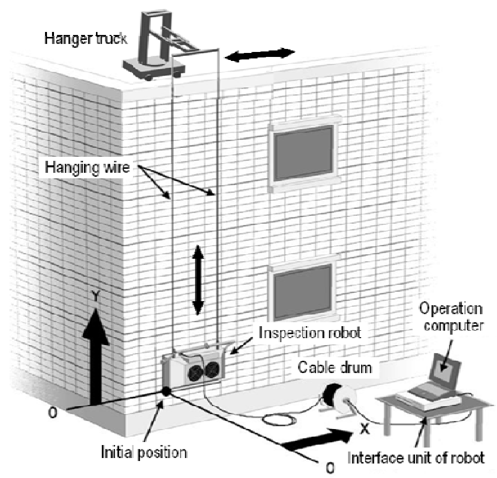


Figure1 Outline of the inspection system using an automated robot

2.2 Mechanism of Inspection Robot

Picture and Specification of the inspection robot is shown in Figure 2 and Table 1 respectively. The robot itself is composed of four parts; a wire winding part, vacuum fans, an inspection sensor part, and an operation and analysis part. By operating the wire winding part, the robot is situated vertically at a desired point. Two wires are rolled onto a rotating drum in the robot. The robot can climb up and down at a speed of 3-5 m/min in a height range of 40 m. The vacuum fans are used to press the robot body onto the tile face. The thrust force is more than 15 N, and the robot body is sufficiently stable against wind. The inspection part is composed of a mechanical hammer and a movement slide. The hammer can move to each tile position according to the tile size within a range of 450 mm. The hammer is electrically controlled by solenoid power and hits the tile face only once. The impact sound is measured by a small microphone installed near the point where the tile is hit. The total weight of the robot body is about 30 kg, and it can be operated easily even if the operator is not skilled or experienced in tile inspection.

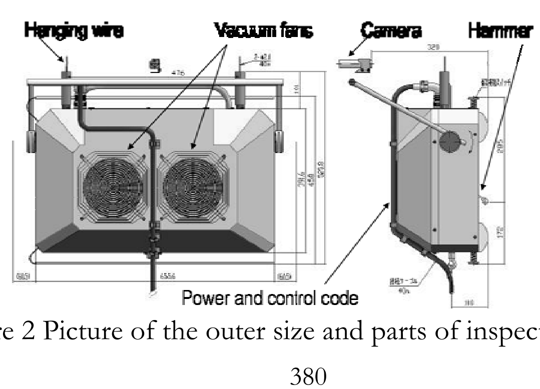


Figure 2 Picture of the outer size and parts of inspection robot

Table 1 Specification of the inspection robot

Inspection robot	Outer size	W780×L526×H250
	Weight	30 kg
	Power source	AC 100V
	Hanmmer Slide width	450 mm
	Climbing Speed	3-5 m/min.
	Thrast force	15 N
	Fan Power	100W ×2sets
	Measurement ability	450 m2/day
	Wire length	40 m
Hanger truck	Outer size	W1500×L1500×H500
	Weight	70 kg
	Operation	Manual
	Hanger top weigth	100 kg
Operation system	Drive interface	W310×L260×H50
	Controller	1 set

2.3 Analysis of Impact Sound and Conventional Diagnostic Methods

The inspection robot uses two analysis parameters to apply mathematical functions to express the characteristics of tile exfoliation (Inoue, F., and Ohta, Y. (2006)). The time from the point when an impact sound is measured to that when the value of each parameter value is calculated is very short, so the deterioration result can be diagnosed in real-time. The parameters are as follows.

(1) Peak rate value : C_f

This parameter is equal to the wave height value, and is the ratio of the maximum amplitude value X_{max} to the effective value of time waveform X_{rms}. It becomes higher when the tile is separated.

$$C_f = X_{\max} / X_{rms} \tag{1}$$

(2) Frequency cross correlation value: $\rho_{x,y}$

This parameter is the frequency cross correlation between the sound waveform for each tile and that of a normal tile. It becomes lower when the correlation with a normal tile is decreased when the tile is separated. N is the number of data, X and Y are the sound waveform of the test tile and a normal tile, respectively, and μ and σ are the average and standard deviation of X and Y, respectively.

$$\rho_{x,y} = \left\{ \frac{1}{N} \sum_{i=1}^{N} (X_i - \mu_x) \cdot (Y_i - \mu_y) \right\} \Big/ \sigma_x \cdot \sigma_y \tag{2}$$

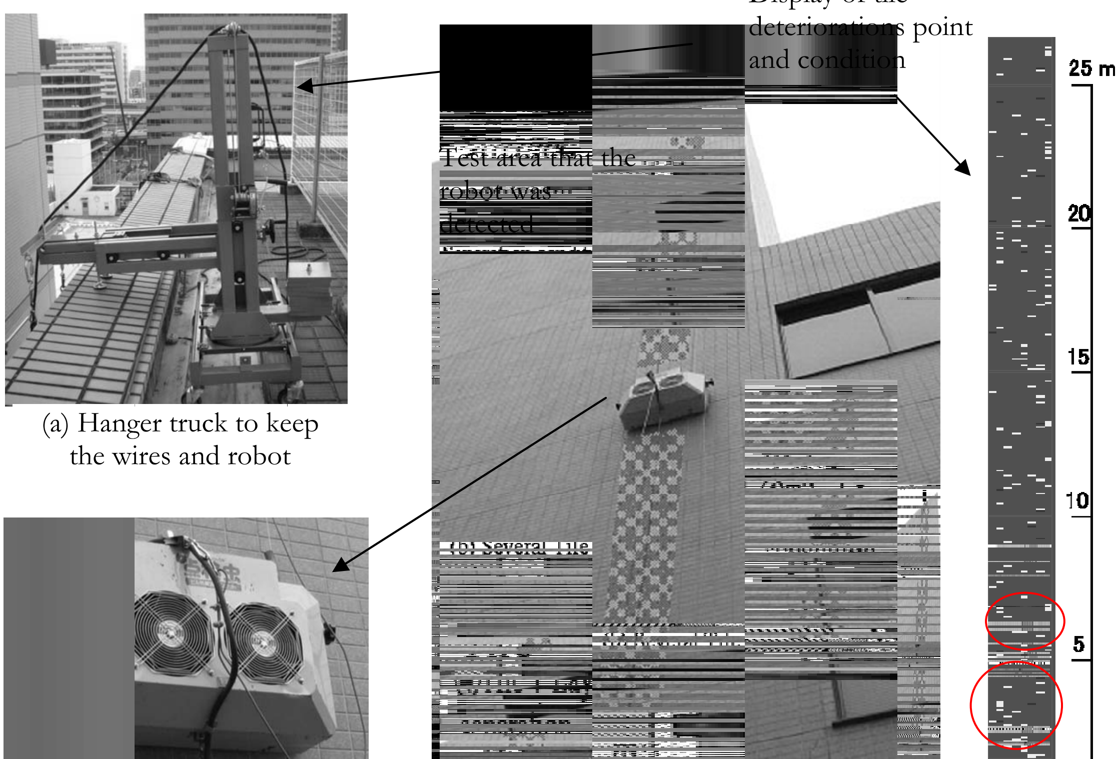
2.4 Application example of actual tile inspection and diagnostic result

An example of an actual tile inspection using the inspection robot is indicated in Fig.3. The tile wall, which was built 20 years ago, was about 25m high, and tile exfoliation and distortion of the wall was suspected. The robot was applied to shorten the work period and to accurately diagnose tile deterioration. At the actual site, the robot (Figure 3-(b)) was hung by wire from a hanger truck (Figure 3-(a)). The robot was moved up and down to continuously detect tile deterioration along a vertical line. In this case, the frequency cross correlation value $\rho_{x,y}$ was adopted as the diagnostic parameter.

The test range and the diagnostic result corresponding to the test point are indicated in Figure -(c). At the point that is short bar colored on the display, some abnormal tiles were detected. The red bar indicates that the value of the analysis parameter was lower than that of the yellow bar. In short, it is judged that tile deterioration corresponding to the red bar is very serious. Also, within some radius around the color bars, it is possible that a wide separation of the inner concrete layer including outer tiles may be generated. From the inspection result, the entire tile was quickly repaired and the danger of collapse of the outer wall was averted.

Up to now, tiles inspections of tens of buildings have been executed using this inspection robot and effective diagnostic results have been obtained. However, for the diagnostic parameters given in equations

(1) and (2), the deterioration state has not been determined in detail, or where or how separation has been generated. In particular, compound deterioration such as outward tail separation and inner concrete layer float could not be detected. In future, a more precise inspection and detection method will be needed.



(a) Hanger truck to keep the wires and robot

(b) Developed inspection robot

(c) Tile detection and indicating its diagnostic result

Figure 3 Actual tile inspection using the inspection robot and display the diagnostics result

3. New Diagnostic Method Using Wavelet Analysis

3.1 Characteristics of Tile around Deterioration for Finish Condition

The finish condition of a general tile wall is composed from the inside of the main concrete layer, the mortar layer, and the bonding tile layer, as shown in Figure 4. Many tile wall collapses are divided into the following two kinds of separations on the basis of an empirical rule.

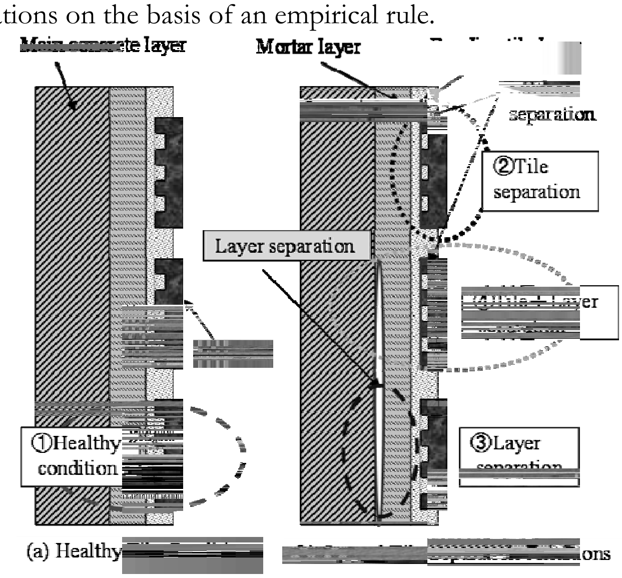


Figure 4 Patterns of the tile deterioration conditions

(1) Tile separation: the condition in which a tile space is generated by separation of the back or side of the tile from the bonding tile mortar.

(2) Layer separation: the condition in which a layer space is generated between the main concrete layer and the mortar layer, or between the mortar layer and the bonding tile layer.

Tile separation is a narrow deterioration that acts on the individual tile, but layer separation is a wide deterioration that acts on the thin layer, what we call "float condition", and then a large area of tile wall is likely to fall off the main concrete layer when the condition deteriorates. In an actual situation, tile separation and layer separation exist together in a complicated manner, and the condition around a tile is thought to be one of the following, as shown in Fig.4: ①Healthy condition, ②Tile separation only, ③Layer separation only, and ④Tile and Layer separation together. The next paragraph clarifies the method of diagnosing these four conditions.

3.2 Sound Waveform Analysis Method

Peculiar time waveforms corresponding to the tile condition were obtained as indicated in Fig.5 for the reflected sound when the tile is struck by the impact hammer. The rise of the impact time waveform measured at the normal tile (Figure 5-(a)) is lower and it decreases instantly. The rise of the impact time waveform measured at the deteriorated tile is higher and it decreases gradually (Figure 5-(b)), and the waveform frequency differs according to the deterioration condition. For a waveform having the characteristics of tile deterioration, wavelet analysis showing that the waveform can be transformed to the time and frequency range serially is considered to be suitable.

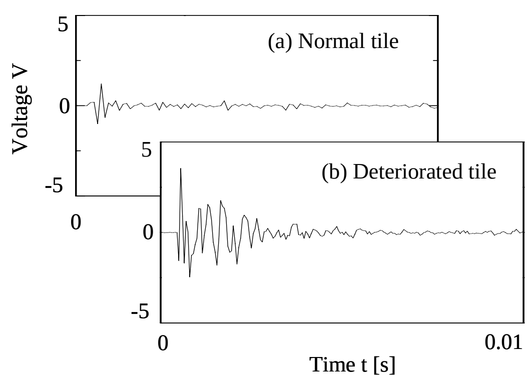


Figure 5 A peculiar time waveforms corresponding to the tile condition

3.3 Analysis by Wavelet Transformation

3.3.1 Introduction of wavelet transformation

The value of the wavelet transformation (W*f*) of time waveform *f*(t) to mother wavelet function φ(t) is given by equation (3) (Chui, C. K. (1992)) . Here, a and b express the constant scale number of the frequency and time axis for mother function φ(t) .

$$(W_\varphi f)(b,a) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{|a|}} \varphi\left(\frac{t-b}{a}\right) f(t)\ dt \qquad (3)$$

Using the wavelet transformation, it is very important what function is selected in the mother wavelet function $\varphi(\tau)$. Generally, analytical accuracy of the wavelet transformation is said to improve as the pattern and correlation of the measurement waveform and mother function improves. Therefore, an original mother function was designed using a new design approach explained in the next paragraph (Daubechies, I. (1992)).

3.3.2 Design of original mother function

The order transforming from the actual data to the mother function is indicated below. A sound waveform measured from the normal tile was applied as actual data (Figure 6-(a)).

(1) Detection of an initial time of the waveform: First, the time at which the absolute value of the waveform reaches a maximum value is selected as indicated at P (Figure 6-(b)), and going back from P, the time at which the sign changes for the first time is specified as the initial time at Q (Figure 6-(a)).

(2) Detection of a finishing time of the waveform: Calculating the individual auto-correlation of the waveform, the first point at which the value of auto-correlation data is less than 0.1 is specified as the finishing time (Figure 6-(c)).

(3) Arrangement of the waveform: As the mother function should generally satisfy an admissible condition, the symmetry of the trimmed waveform is ensured by the following approach (Figure 6-(d)).

- The reverse of the time order and the sign of waveform
- Combinations of the trimmed waveform and the original waveform

(4) Normalization of the arranged waveform: By calculating the norm value of the arranged waveform, the entire waveform is divided by the norm value. Such a normalized waveform is defined as an original mother function.

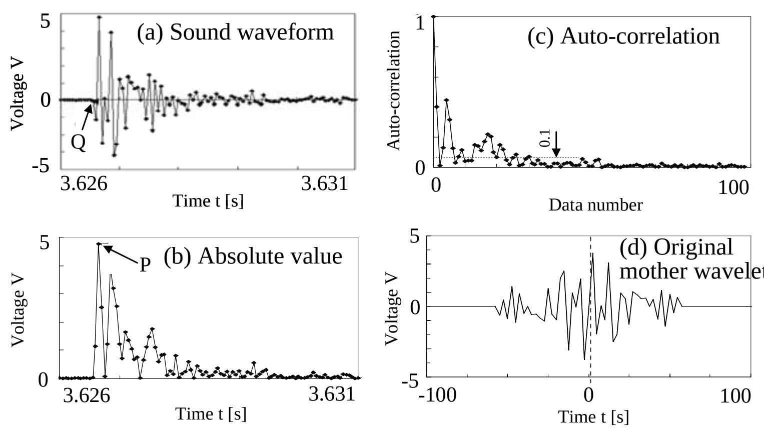


Figure 6 New approach of designing the mother function from the original waveform

3.4 Experimental Verification of Wavelet Analysis

3.4.1 Composition of test wall and experimental method

A test concrete wall where several tile deterioration patterns as shown in Figure 4 had been reproduced was constructed. A schematic picture of the test wall arranged in tile deterioration patterns is shown in Figure 7-(a). The wall face is constructed of mosaic tiles and four patterns (Type①～④) as mentioned in paragraph 3.1 were included into the wall.

Figure 7-(b) shows the finished condition of the tile and inner space. Tile separation was expressed by inserting a non-bonded sheet between the tiles and the bonding layer, and layer separation was reconstructed by making a thin space.

For the experimental apparatuses, an automated hammer device operated by solenoid power was made to strike the tile face once exactly as shown in Figure 8-(a). The hammer’s impact was kept at a suitable intensity by referring to basic experiments. The hammer device could be moved on the slider on the test wall as shown in Figure 8-(b).

In the experimental method of the tile inspection, the hammer strikes the tile face and the impact sound is measured by a small microphone installed near the striking point. The sound data is inputted to a memory recorder through the microphone amplifier and A/D transformation device. The obtained sound waveform is analyzed by the wavelet transformation and the condition of the tile deterioration is diagnosed.

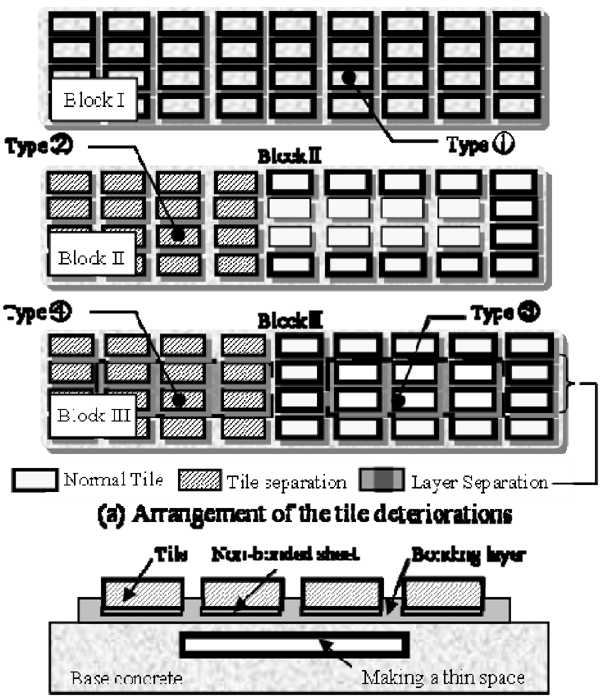


Figure 7 Schematic picture of the test wall arranged the tile deterioration patterns

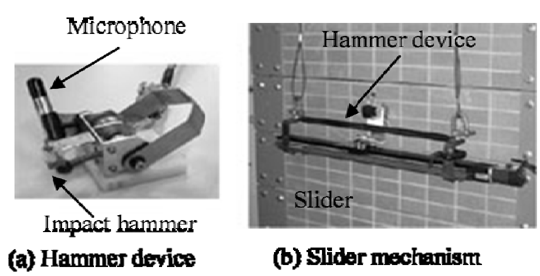


Figure 8 Experimental apparatuses developed hammer device and slider

3.4.2 Visualization of tile patterns of deteriorations by wavelet analysis

Fig.9 shows an example of each tile deterioration pattern visualized on the wavelet plane by wavelet analysis. A sound waveform of the normal tile was used as a mother wavelet function. The following features were confirmed:

- Type ① : The plane of wavelet intensity, was a low level on the whole and the peak wasn't seen in a frequency and time range.
- Type ② : A higher peak appeared in a high frequency range when the hammer was struck. The peak decreased instantly and the plate became almost flat.
- Type ③ : A moderate rise appeared in the high frequency range when the hammer was struck. It decreased instantly, but an undulation in a low frequency range continued for a long time.
- Type ④ : As for Type ②, a higher peak appeared in a high frequency range. Further, as for Type ③, it decreased instantly, but an undulation continued in a low frequency range.

Taking these results into consideration, at tile separation, it can be assumed that the peak appears in the high frequency region because part of the tile that separated from the bonded tile oscillated at natural frequency. However, at layer separation, it can be assumed that the undulation in a low frequency range continued for a long time because void resonance was generated in the layer space.

When the tile separation and layer separation took place in the tiles, the appearance of the characteristics on the wavelet plane corresponded to that of the characteristics combining both separations linearly.

Therefore, the existence of each tile separation is independently judged by observing the characteristics on the wavelet plane. In short, the existence of tile separation is detected by the characteristics of the frequency range on the wavelet plane, and that of layer separation is detected by that of the time range. By visualizing the wavelet analysis, the tile deterioration condition could be inferred.

3.5 Quantity Diagnostics with Wavelet Analysis

3.5.1 Inducement of volume function

Figure10 shows an example of a typical wavelet plane displaying the two tile deterioration modes and the related range of their separation. The related range of tile separation is α and that of layer separation is β. To develop a quantitative method for determining the characteristics of ranges α and β, the volume function of wavelet intensity is calculated in the each range as indicated by equation (4) and the quantity diagnostic method is introduced.

$$F = \int_{f_1}^{f_2} \int_{t_1}^{t_2} I(f, t) dt\, df \tag{4}$$

Figure11 shows the expected areas of the volume value normalized by the average value of Type ① being a normal tile. The entire areas are distributed over about four patterns of the normal tile area, the tile separation area, the layer separation area, and the combined separation area. From the areas of each tile separation pattern, a horizontal line of the diagnostics value D_α dividing the existence of the tile separation and a vertical line F_β of the diagnostics value D_β dividing the existence of the layer separation is decided. The condition of deterioration can be easily determined by comparing the values of F_α, and F_β.

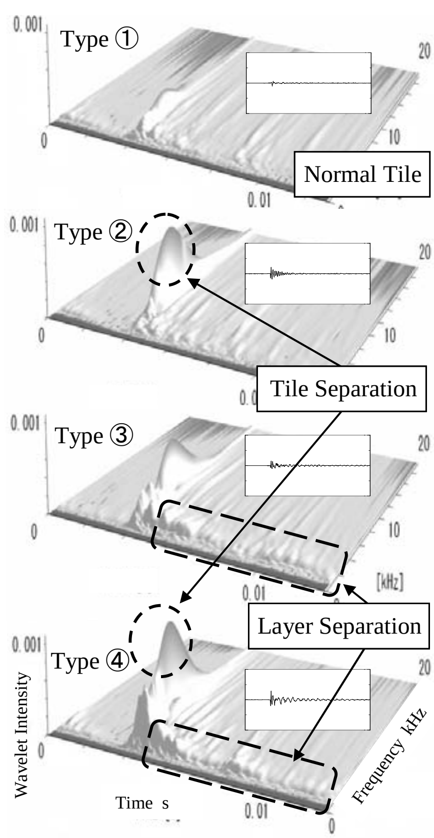


Figure 9 Visualization of each tile deteriorations Patterns on the wavelet plane

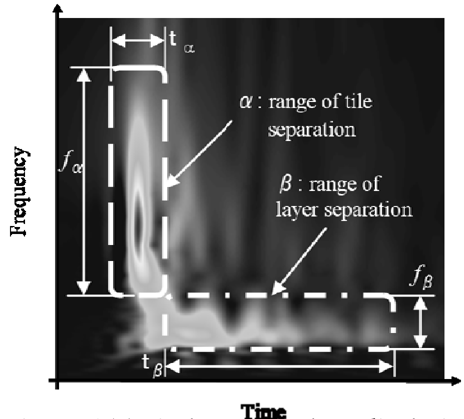


Figure10 Typical wavelet plane displaying two tile separations and related range

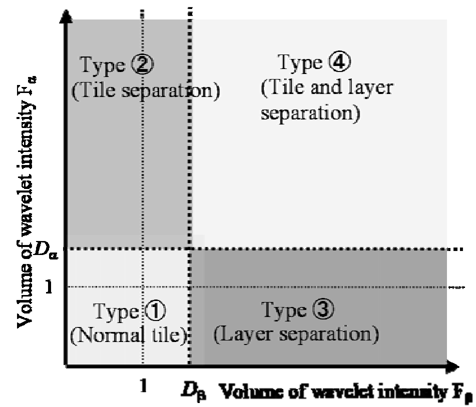


Figure11 Typical wavelet plane displaying two tile separations and related range

3.5.2 Effect of mother wavelet functions and evaluation of quantity diagnostics

In order to evaluate the effect of the mother function for wavelet transformation, the wavelet plane was analyzed by mother functions and the volumes were calculated as indicated before. For the mother function, (a) Gabor-(8), (b) Shannon, (c) Mexican, and (d) Anti-symmetry which were used. (a) Gabor-(8) and (b) Shannon were suitable for determining the characteristics of frequency range, and (c) Mexican, and (d) Anti-symmetry were suitable for determining that of the time range. However, to include the scale effect of the tile itself, for example of mass, length, material etc., the mother function was handmade as mentioned in 3.3.2. (e) Orignal-1 was made by only sound waveform and (f) Orignal-2 was made by processing the natural resonance of the sound.

Fig.12 shows the volume of each wavelet plane corresponding to the choice of the mother functions. The layer separation was able to detect by all the mother functions. However, when using (b) Shannon, (c) Mexican, (d) Anti-symmetry, and (e) Orignal-1, it was difficult to distinguish the tile separation. However, (a) Gabor-(8) and (f) Orignal-2, could diagnose both the tile and layer separation clearly, and especially when selecting (f) Orignal-2, it was understood that the value of compound deteriorations in type ④corresponded to the value that combined both the tile and layer separations linearly. The diagnostic value for the existence of each tile separation was mostly assumed at the D =1.7 and D =2.5 quantitatively. A good diagnostic method was established using wavelet analysis and selecting the mother function.

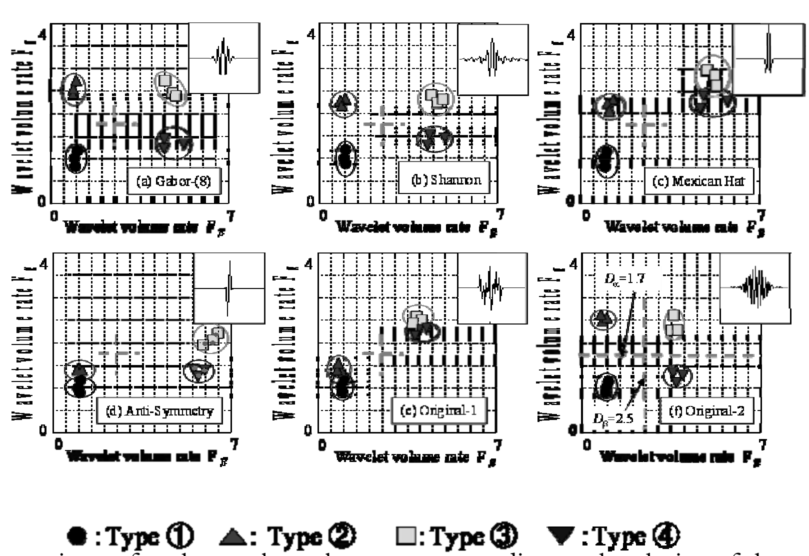


Figure 12 Comparison of each wavelet volume corresponding to the choice of the mother functions and evaluation of the quantity diagnostics

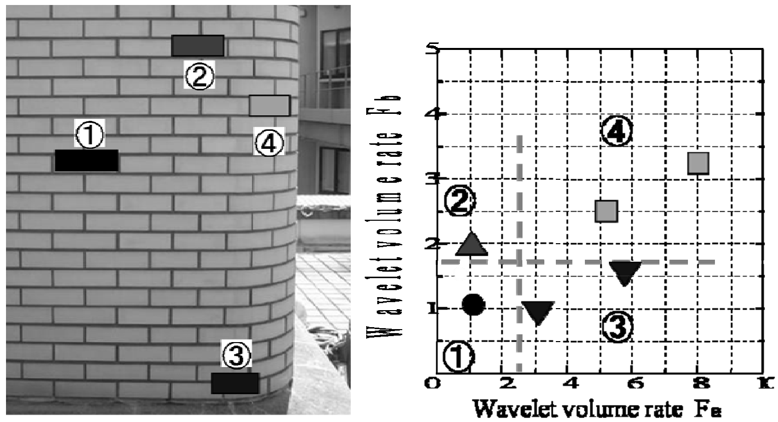


Figure 13 Wavelet volume rate and the position of deterioration by wavelet analysis

3.6 Inspection Result of Actual Tile Wall by Wavelet Analysis

The tile wall of the actual high building was inspected by applying wavelet analysis with the original-2 as the mother function. Figure13 shows the value of the wavelet volume and the position of tile and layer separation. Although the diagnostic of the compound tile deteriorations wasn't detected by the conventional method, each truth was drawn out by the wavelet analysis. Accurately understanding tile deterioration is very useful for the repair technology of the tile wall, as this will suppress accidents related to tile deterioration and improve safety around buildings with tiled walls.

4. Conclusions

An inspection robot and a new diagnostic method using wavelet analysis was reported as a method for inspecting tile deterioration. The following results were obtained.

- The inspection robot can detect a tile's inner condition by a hammering sound. The deterioration result can be instantly determined in real time by two detective parameters. This is a very useful and convenient device for inspecting for tile deterioration.
- In the inspection method for compound deterioration, a new diagnostic method using wavelet analysis was developed. Considering the design of the mother functions and inducing these functions, the most efficient mother function being the original-2 was found by experimental results. Using this function, both tile and layer separation could be clearly diagnosed. A good diagnostic method was established using wavelet analysis.

Finally, the authors thank all who supported the development of the inspection robot and the diagnostics method using wavelet analysis.

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