Journal of Asian Concrete Federation

journal homepage: https://jacf.sfulib3.publicknowledgeproject.org/index.php/jacf

# Rebound-Based Diagnosis of Tile Detachment Near the Boundary of Detached Area for the External Tile Finishing Wall

Daiki Tanaka[a,*], Yosuke Ito[a], Shinji Kawabe[a], Junpei Yamamoto[a]

[a] *Nagoya Institute of Technology, Department of Architecture and Design, Nagoya, Aichi, 4668555, Japan*

**A B S T R A C T**

In Japan, periodic inspections of external tile walls are mandated by the Building Standards Act. Conventional hammering inspections are influenced by environmental noise and rely on human judgment. To address these limitations, a solenoid tapping device has been developed to evaluate tile detachment quantitatively based on rebound characteristics. However, previous studies mainly focused on the center of detached areas, without examining behavior near detachment boundaries.

This study investigates how the rebound ratio varies with tapping position relative to the detachment boundary using pseudo-void specimens with 200 mm and 300 mm square detached areas. Results show that as the tapping position approaches the boundary, the rebound ratio increases and becomes closer to normal tiles, indicating a transitional zone. This behavior was observed in the range of X = − 40 to − 5 mm from the boundary. A comparison between threshold-based detachment classification and actual detachment geometry confirmed that misclassification occurs within this zone. To address this, margins were quantified as +20 mm for 5 mm-thick mortar and +15 mm for 10 mm and 15 mm. An empirical equation was proposed to estimate the width of this zone as a function of mortar thickness. These findings improve the spatial accuracy of automated detachment diagnosis systems.

***Keywords:*** Solenoid, Rebounding, Boundary, NDT, Tapping DeviceTest

## 1. Introduction

According to the periodic inspection system based on Article 12 of the Building Standards Act in Japan [1], the investigation of external tile finishing walls is mandated for building owners and related parties. Hammering inspections for external tile finishing walls are often affected by environmental noise. To address this issue, the authors developed a technique [2] that detects tile detachment based on the rebound characteristics when the steel hammer head of a solenoid tapping device strikes the tile. In this technique, the rebound behavior generated by controlled tapping with a solenoid device was quantitatively measured without relying on sound, and tile detachment was diagnosed based on the reduction in rebound response compared to that of normal tiles. However, previous studies [2] mainly focused on the center of detached areas, without examining rebound behavior near the boundary between normal and detached tiles. Therefore, it is necessary to clarify the rebound characteristics near the detachment boundary in order to improve the accuracy of detachment diagnosis.

In this study, the compact solenoid tapping device [3] is used, and the following three points are investigated:

1)To clarify the influence of the distance of the tapping position from the detachment boundary on the rebound characteristics of the hammer head.

2)To present a method for calculating the estimated actual detached area by adding a certain margin to the range classified as detached in cases where the tiles in the detached area near the boundary are classified as normal.

* Corresponding author: Daiki Tanaka (tanaka.daiki@nitech.ac.jp)

DOI http://dx.doi.org/10.18702/acf.2026.12.2.53

Received: 02-Nov-2025; Revised: 16-Feb-2026; Accepted: 23-Feb-2026; Published online: 21-May-2026

ISSN 2465-7964, eISSN 2465-7972. Copyright © Asian Concrete Federation, All rights reserved.

3)To examine whether the actual detached area can be estimated using the tile wall surface of an actual building.

The purpose of this study is to obtain fundamental data for improving the accuracy of estimation in rebound-based diagnosis of tile detachment in external tile finishing walls.

## 2. Compact Solenoid Tapping Device

### *2.1 Tapping Unit*

Figure 1 shows the cross-section of the compact solenoid tapping device used in this study. The tapping unit of the compact solenoid tapping device mainly consists of a coil, an iron core, and a spring. The iron core taps the tile. The iron core has a diameter of 8 mm and a mass of 18 g. The tip of the iron core is machined into a conical shape. A spring with a spring constant of 0.113 N/mm and a free length of 20 mm is used. The wall surface is struck by the iron core through the following three steps:

1)A magnetic field is generated around the coil, attracting the iron core.

2)The magnetic field of the coil disappears.

3)The elastic energy of the spring causes the iron core to tap the tile wall surface, and after rebounding, the iron core stores elastic energy in the spring again.

Step 3) is repeated to perform multiple taps.

### *2.2 Measurement Unit*

The measurement unit consists of an infrared reflective proximity sensor and a reflector, which are used to measure the distance between the iron core and the wall surface. The distance from the tip of the iron core to the wall surface, calculated based on the displacement measured by the infrared reflective proximity sensor of the iron core, is defined as the "Core-to-wall Distance." The time history of this distance is recorded, and the measurement interval is set to 1 ms.

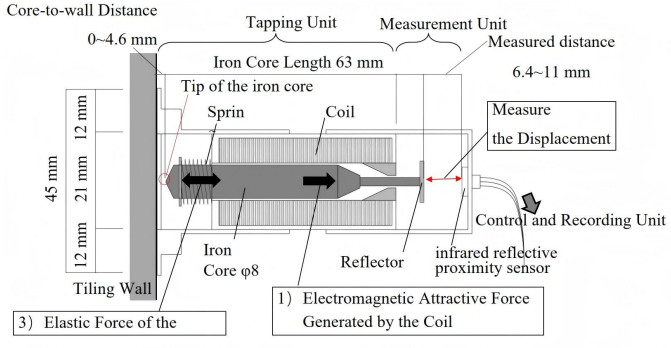



**Fig. 1** Cross-section of the Compact Solenoid Tapping Device

### *2.3 Control and Recording Unit*

A microcontroller board is used for the control and data recording of the device. The program simultaneously performs ON/OFF control of the current flowing through the coil, measurement of the core-to-wall distance by the infrared reflective proximity sensor, and data recording. The measured data are stored on a microSD card and checked on a PC.

## 3. Experiment Using Pseudo-Void Specimens

### *3.1 Pseudo-Void Specimens*

In this study, pseudo-void specimens conforming to the "Standard Specimen for Detached Tiles" specified in the Ministry of Land, Infrastructure, Transport and Tourism's Building Standards Improvement Promotion Project T1 [4] were used. Table 1 shows the materials and specifications of the pseudo-void specimens, Figure 2 shows their cross-section, Figure 3 shows the tapping positions for the 200 mm square detached area, and Figure 4 shows those for the 300 mm square detached area. 1 mm-thick polyethylene foam sheets were inserted at the interface between the concrete and the underlayment mortar to create a simulated detached condition. In this study, one side of the rectangular detached area was selected as the target detachment boundary, and the X-axis was defined as the direction normal to the detachment boundary. The distance from the detachment boundary was defined as positive on the normal side and negative on the detached side.

**Table 1** Material Specification and Composition of Pseudo-Void Specimen

| Material | Specification |
|---|---|
| Concrete | 1150 mm×6300 mm×215 mm |
| Water Absorption Regulator | Ethylene Vinyl Acetate Emulsion |
| Pseudo-void | Polyethylene Foam Sheet<br>Forming Ratio: 30 times、Thickness: 1 mm<br>Area: 300 mm square |
| Underlayment Mortar | Ordinary Mortar (Cement : Sand = 1 : 3)<br>Thickness: 10mm |
| Adhesive Mortar | Pre-mixed Mortar for Tiling |
| Tile | For Mortar Application,<br>45 mm×95 mm×7 mm |
| Joint Mortar | Pre-mixed Mortar for joint, Width: 5 mm |

As shown in Figures 3 and 4, to capture detailed variations near the detachment boundary, the tapping positions were set at 5 mm intervals within 30 mm on the detached side and 20 mm on the normal side from the boundary. Tapping positions on joint mortar were excluded to avoid the influence of joints on the rebound response. Based on the symmetry of the

detachment geometry, measurements were conducted up to the center of the detached area (X = − 150 mm) for the 300 mm square specimen, and positions further away were omitted assuming symmetric behavior. The same tapping position scheme was applied to the 200 mm square detached area.

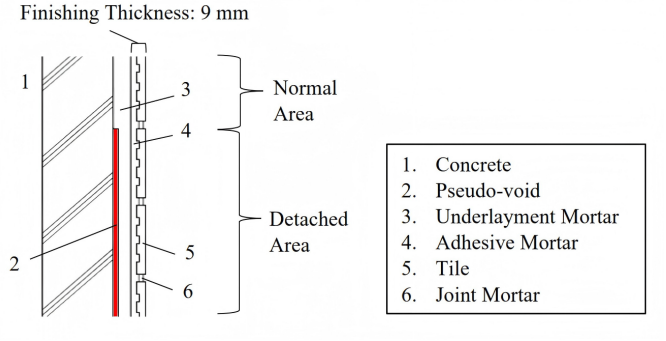



**Fig. 2** Cross-section of Pseudo-void Specimen

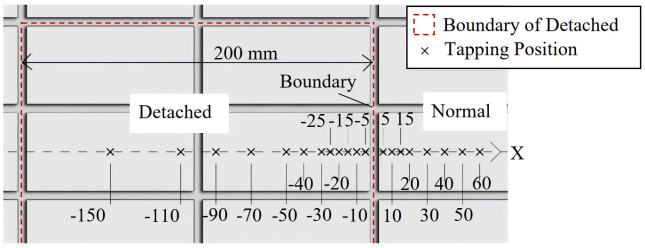



**Fig. 3** Tapping positions in the 200 mm square detached area

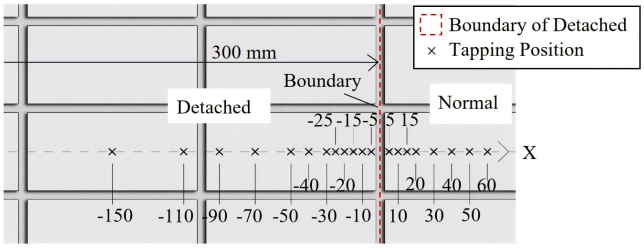



**Fig. 4** Tapping positions in the 300 mm square detached area

### *3.2 Experimental Method*

Figure 5 shows the experimental setup, and Figure 6 shows an example of the time history of the core-to-wall distance. The tip of the compact solenoid tapping device was pressed against each tapping position shown in Figures 3 and 4, ensuring close contact, and the tile was tapped. The displacement measured by the infrared reflective proximity sensor attached to the iron core was recorded. The recorded data were transferred to a PC, and the core-to-wall distance was calculated from the measured values. After the iron core rebounds from the wall surface, the restoring force of the spring reduces its velocity, and the moment when the iron core comes to a stop is defined as the peak. The first peak of the core-to-wall distance is defined as A1, and the second peak as A2. The ratio of A2 to A1 is defined as the rebound ratio, as shown in Equation (1):

$$\text{Rebound ratio} = \frac{A_2}{A_1} \quad (1)$$

The peak values A1 and A2 were identified as the first and second local maxima in the time history of the core-to-wall distance after impact. The rebound ratio represents the attenuation of the rebound motion and reflects the energy dissipation due to impact absorption in the detached area.

In this study, the diagnosis of tile detachment is based on the rebound ratio. According to previous research [2], the rebound ratio is larger in the normal area and smaller in the detached area. The iron core was actuated once for each tapping position.

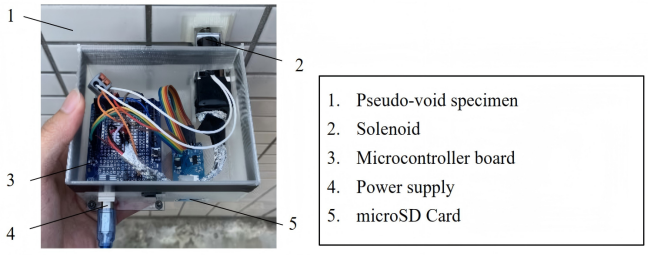



**Fig. 5** Experimental setup

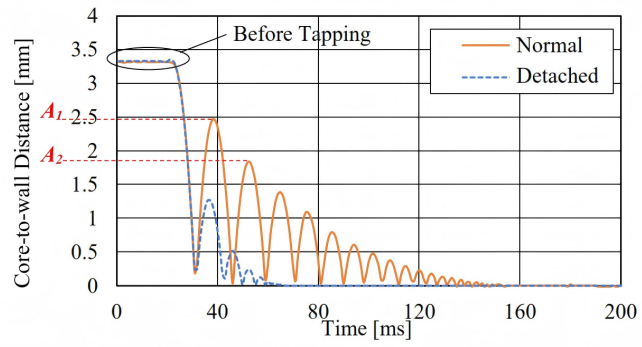



**Fig. 6** Example of time history of core-to-wall distance

### *3.3 Experimental Results and Discussion*

Figures 7 and 8 show the relationship between the rebound ratio and the distance from the detachment boundary for the 200 mm and 300 mm square detached areas, respectively.

From Figure 7, in the 200 mm square detached area at X = -150 to -40, the rebound ratio becomes smaller near the center of the detached area (X = -100). On the other hand, from Figure 8, in the 300 mm square detached area at X = -150 to -40, almost no change in rebound ratio is observed. Furthermore, the rebound ratio increases as the thickness of the underlayment mortar increases.

From Figures 7 and 8, in both the 200 mm and 300 mm square detached areas at X = -40 to -5, the rebound ratio

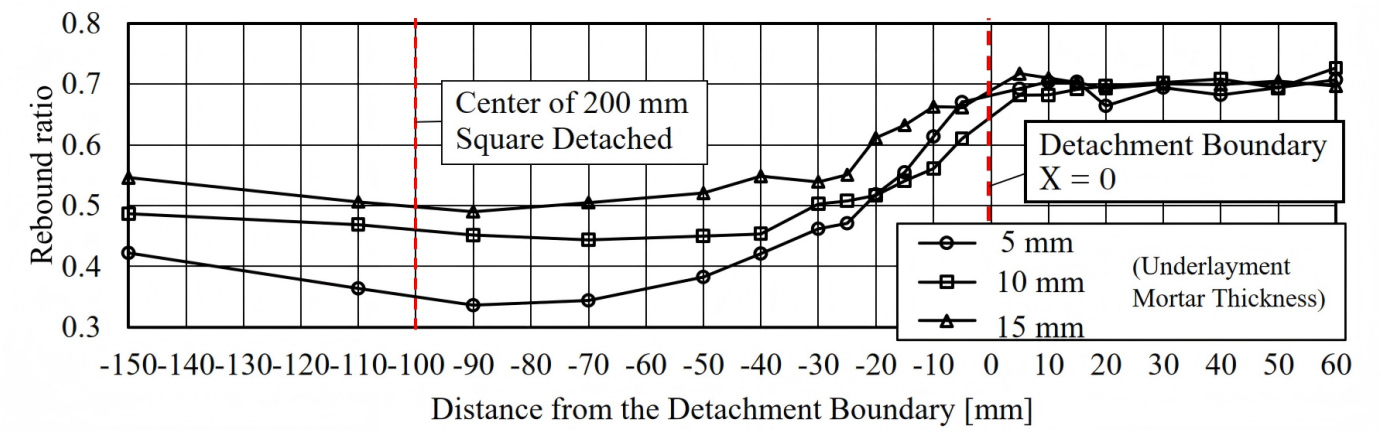



**Fig. 7** Relationship between rebound ratio and distance from the detachment boundary (200 mm square detached area)

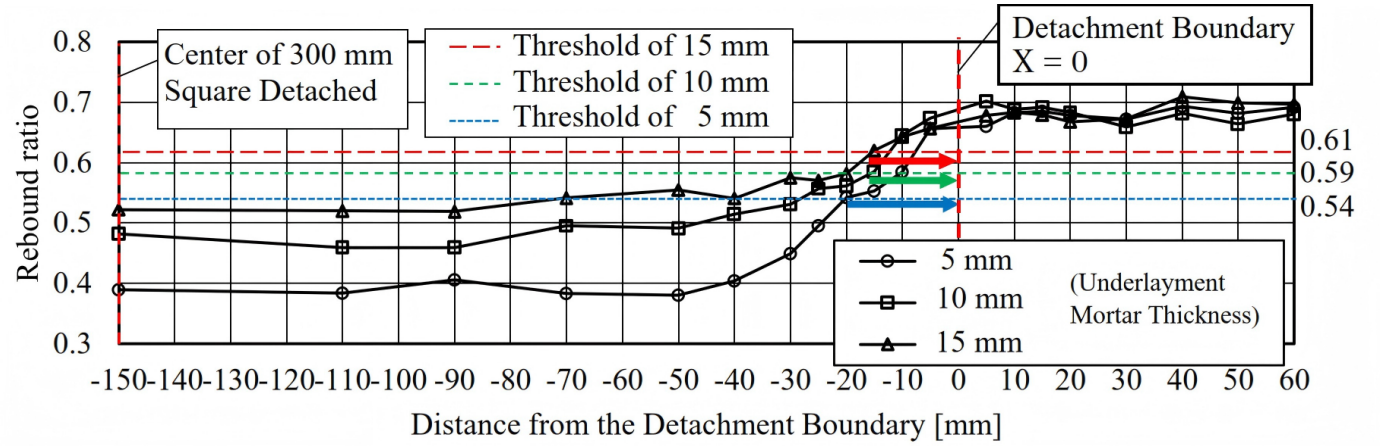



**Fig. 8** Relationship between rebound ratio and distance from the detachment boundary (300 mm square detached area)

increases as the tapping position approaches the detachment boundary, and becomes close to that of the normal area. From Figure 7, in the 200 mm square detached area at X = -5 to 60, the change in rebound ratio with distance from the detachment boundary is small. Similarly, from Figure 8, in the 300 mm square detached area at X = -5 to 60, the change is also small. Therefore, in the range X = -5 to 0, the rebound ratio is almost the same as that of the normal area, indicating that the detached tiles may be misclassified as normal.

Consequently, when detachment diagnosis is performed using a rebound ratio threshold as in previous research [2], a region exists within X > -40 where the detached area is mistakenly classified as normal. Therefore, depending on the thickness of the underlayment mortar, it is necessary to add a margin to the classified detachment area.

This tendency can be explained by the mechanical response of the detached layer. In detached areas, after the hammer head separates from the wall surface due to rebound, strain remains in the detached layer, resulting in a reduction in the kinetic energy after rebound and consequently a smaller rebound ratio. In addition, as the thickness of the underlayment mortar increases, the out-of-plane stiffness of the detached layer increases, reducing the residual strain and leading to a larger rebound ratio. This mechanism is consistent with previous studies [5].

### *3.4 Method for Setting Additional Margin to the Classified Detachment Area*

Taking the 300 mm square detached area as an example, the threshold rebound ratio distinguishing detached and normal areas was determined for each underlayment mortar thickness based on the experimental results of the pseudo-void specimens, and the range requiring an additional margin was obtained. Considering data scatter, the rebound ratio for the normal area was set to 0.7. In order to enable robust classification using the rebound ratio, a threshold value between the representative values of normal and detached conditions is required. The threshold was defined as the average of this value and the rebound ratio at the center of the 300 mm square detached area (X = -150) for each underlayment mortar thickness. This approach follows the method adopted in previous research [2], where a balanced criterion between normal and detached states was used. As a result, the thresholds were 0.54 for a underlayment mortar thickness of 5 mm, 0.59 for 10 mm, and 0.61 for 15 mm. At the intersection points of these threshold lines with the corresponding rebound ratio curves in Figure 8, the absolute values of the distance

from the detachment boundary represent the distances where tiles are actually detached but are classified as normal. Thus, it is considered necessary to add margins of +20 mm for 5 mm-thick underlayment mortar, +15 mm for 10 mm, and +15 mm for 15 mm.

Figure 9 shows an example of adding the margin for the 300 mm square detached area with a 5 mm mortar thickness. By increasing the classified detachment range by +20 mm from the threshold, an appropriate detachment boundary can be determined.

From the relationship between the required margin distance and the underlayment mortar thickness obtained from the pseudo-void specimen experiments, an approximate curve can be derived, enabling estimation of the required margin distance for actual buildings. Assuming that the relationship between the required margin distance D (mm) and the underlayment mortar thickness t (mm) can be expressed by a power approximation, Equation (2) is proposed. The coefficient of determination for this approximation is $R^2$ = 0.892.

$$D = 30.514t^{-0.278} \quad (2)$$

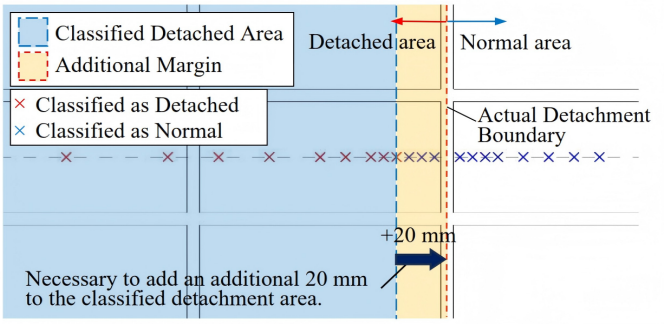



**Fig. 9** Example of the additional margin range for the estimated detachment area of the pseudo-void specimen (300 mm square detached area, 5 mm underlayment mortar thickness)

## 4. Experiment on the Tile Wall of an Actual Building

### *4.1 Tile Wall of the Actual Building*

Figure 10 shows the tile wall of an actual building, and Figure 11 shows the area near the detachment boundary. Three inspectors conducted hammering inspections using a standard tile test hammer. The ranges classified to include a detachment boundary are indicated by blue diagonal lines in Figure 11, and the tiles identified as detached are enclosed in red boxes in Figures 10 and 11. Grooves were cut along the joints with a cutter, and the tiles identified as detached were removed. It was confirmed that detachment occurred at the interface between the concrete underlayment and the underlying mortar. Figure 12 shows the removed tiles, and the wall surface after tile removal. From the observation of the wall surface, it was found that 45 mm × 95 mm mosaic tiles with a thickness of 7 mm were attached, the underlayment mortar thickness was approximately 1.5 mm, and the total finishing thickness was 9 mm, which was similar to the pseudo-void specimens.

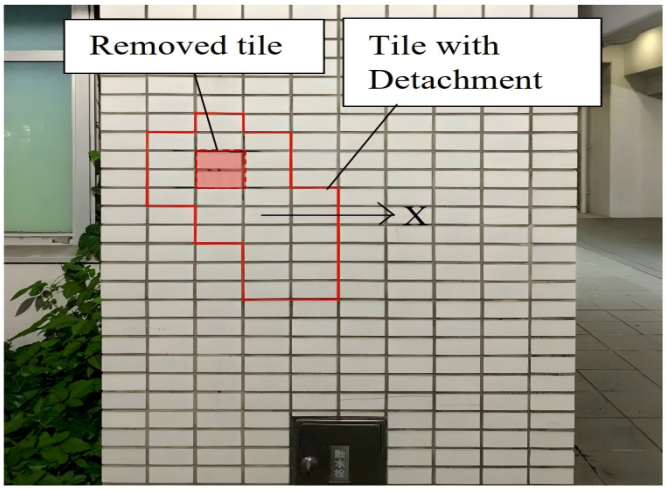



**Fig. 10** Tile Wall Surface of the Actual Building

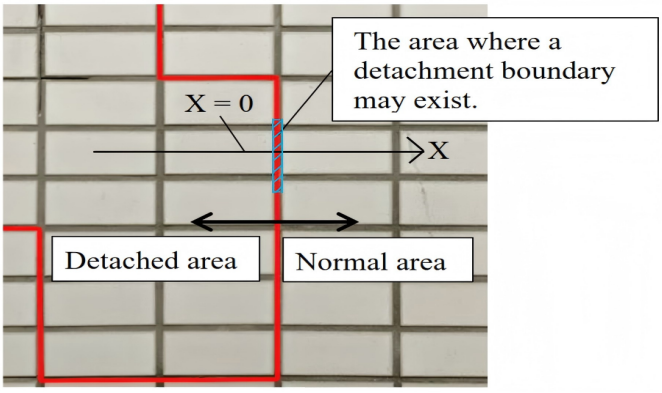
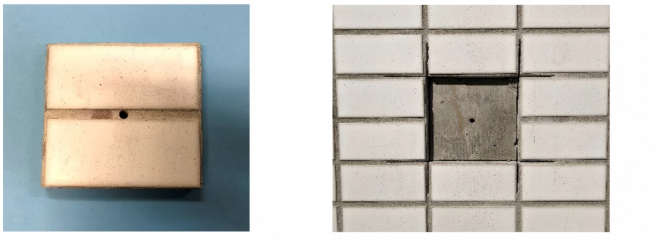



**Fig. 11** Tile Wall Surface of the Actual Building



**1) Removed Tiles** **2) Wall Surface after Tile Removal**

**Fig. 12** Tile Removal from the Actual Building Wall Surface

### *4.2 Experimental Method*

The X-axis was defined in the normal direction of the short side of the tile. The position 20 mm to the left of the right edge of a detached tile was defined as X = 0 (hereinafter referred to as the "reference position" ), and the experiment was conducted in the same manner as in Chapter 3.

*4.3 Experimental Results and Discussion*

Figure 13 shows the relationship between the rebound ratio and the distance from the reference position for the actual building. As in the pseudo-void specimen experiment, the threshold rebound ratio distinguishing detached and normal areas was set to 0.53. The distance from the intersection of the polyline in Figure 13 and the threshold line to the range identified as the detachment boundary by hammering inspection was 27 to 32 mm. On the other hand, from Equation (2), the required margin distance D for a underlayment mortar thickness of 1.5 mm was 27.3 mm.

Therefore, the detachment boundary estimated using the margin distance calculated from Equation (2) corresponds well to the range classified as detached by hammering inspection. Hence, by applying the correction using Equation (2) to the rebound-ratio-based results of the compact solenoid tapping device, the detection accuracy of the detachment boundary can be improved.

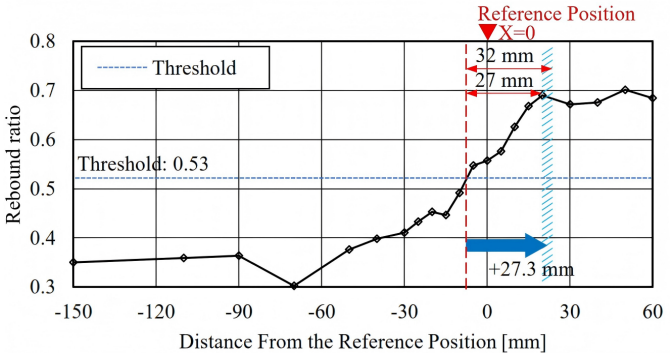



**Fig. 13** Relationship between rebound ratio and distance from the reference position (actual building)

## 5. Conclusions

1)For both the 200 mm and 300 mm square detached areas, in the range X = -40 to -5, the rebound ratio increased as the tapping position approached the detachment boundary, becoming closer to the value in the normal area, indicating the existence of a transitional zone.

2)The required margin distances to account for misclassification near the boundary were +20 mm for a 5 mm-thick underlayment mortar, +15 mm for 10 mm, and +15 mm for 15 mm, respectively.

3)By applying the equation proposed in this study to the rebound-ratio-based diagnosis using the compact solenoid tapping device, the detection accuracy of the detachment boundary can be improved.

**CRediT authorship contribution statement:**

Daiki Tanaka: Conceptualization, Methodology, Writing - review & editing

Yosuke Ito: Conceptualization, Methodology, Writing - review & editing

Shinji Kawabe: Conceptualization, Methodology, Supervision

Junpei Yamamoto: Conceptualization, Methodology, Writing - original draft

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgments**

This study was supported by the Japan Science and Technology Agency (JST), Support for Pioneering Research Initiated by the Next Generation, Grant Number JPMJSP2112. The authors would like to express their sincere gratitude to M. Yamada of Nagoya Institute of Technology, M. Watanabe of M&T Co., Ltd., and K. Yamasaki and Y. Kuriaki of LIXIL Corporation (at that time) for their valuable cooperation, technical advice, and generous assistance throughout this research.CRediT authorship contribution statement:

**References**

[1] Ministry of Land, Infrastructure, Transport and Tourism (MLIT) (2008) "Notification No. 282 of the Building Standards Act"

[2] Sugimoto, Y., Kawabe, S. and Ito, Y. (2020) "Detection of Tile Detachment on External Tile Finishing Walls Using Rebound Characteristics of a Solenoid Tapping Device," Proceedings of Tokai Chapter Architectural Research Meeting, Vol. 58, pp. 25-28

[3] Yamamoto, J., Ito, Y., Tanaka, D. and Kawabe, S. (2024) "Effect of Spring Constant and Free Length of the Small Solenoid Tapping Device on Detachment Diagnostic of the External Tile Finishing Wall," Proceedings of the Japan Concrete Institute, Vol. 46, No. 1, pp. 1837-1842

[4] Ministry of Land, Infrastructure, Transport and Tourism (MLIT) (2016) "Building Standards Improvement Project T1 FY2015-2016," https://www.mlit.go.jp/common/001183683.pdf (Accessed: Oct. 30, 2025).

[5] Tanaka, D., Ito, Y. and Kawabe, S. (2024) "INVESTIGATION OF WALL DEFORMATION BEHAVIOR DURING TAPPING FOR DETACHMENT DIAGNOSTIC OF THE EXTERNAL TILE FINISHING WALL BY REBOUND CHARACTERISTICS" , Journal of Structural and Construction Engineering (Transactions of AIJ), Vol. 89, No. 823, pp. 917-926