FEASIBILITY OF USING STRING-TYPE STRAIN GAGES TO PREDICT THE DETERIORATION OF BUILDING FACADE ORNAMENTAL MATERIALS

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Abstract - A high percentage of building facades in Taiwan uses tiles for ornamentation. In recent years, accidents involving aging and deteriorating building facade tiles becoming detached from buildings or falling off and hurting people have occurred frequently. In addition to material factors, a main cause of the accidents is poor management because of the lack of efficient and low-cost tile diagnostic techniques.To reduce costs, this study employed interdisciplinary studies and integrated professions in the realm of automatic control, utilizing nichrome wire and micro-resistance judgment principles to design an innovative string-type strain gages specifically for testing building facades.Furthermore, acrylic models and concrete specimens were used to conduct feasibility studies on the string-type strain gages invented in this study. The changes in voltage caused by the gauges of various lengths and tension were compared with the simulation data from a compression test on concrete facade specimens; in addition, the relationships between tile detachment and voltage were analysed.By comparing the displacement of the decoration materials with the voltages measured from the string-type strain gages, the reliability of this application was confirmed.

Index Terms - Micro-Resistance,Public safety, Smart skin, String-type strain gages

I. INTRODUCTION

Incidences of falling tiles in Taiwan have become increasingly frequent in recent years, and this has undermined the aesthetic appearance of cities and buildings and threatened the lives and properties of users. Numerous cases have occurred in Taipei alone, such as property damage caused by falling tiles due to drastic temperature change [1], which endangers people's safety, especially at crowded locations [2]. Buildings in Taiwan have largely entered an aging stage, with the falling of building facade tiles due to natural deterioration becoming a normalcy. As shown in Fig. 1, because of the falling of external wall tiles at National Taiwan University Hospital, the entire building was covered with a safety net before refurbishment to prevent falling tiles from harming pedestrians.This study followed the arguments of building medicine to mitigate the problems of excessively high cost and poor construction in previous research questions that involved prelaying strain gages in the inner layer of a building's facade. Therefore, this study abandoned the conventional practice of embedding strain gages in the cement mortar layer, and adopted a nichrome wire to be applied alongside the diagnostic principle of micro-resistance to design an innovative string-type strain gages predictive model. The string-type strain gages can be placed on the decorative surface of an existing building facade during construction, and any surface microdeformation on the tile facade can be detected and recorded through the wiring network of the string-type strain gages. Subsequently, the obtained figures were compared with the micro-resistance figures to learn the level of exfoliation of the facade decorative materials.



Fig. 1 Entire National Taiwan University Hospital building covered with a safety net

II. LITERATURE REVIEW

Following progress in science and technology, building facades have been combined with new high-tech products to bring more convenience and safety to users and building administrators, with the expectation of providing basic safety protection and a healthy living environment. Parkdesigned window blinds with real-time automatic sensing and adjustment functions that can adjust the blind slats to achieve comfortable and healthy indoor temperature, humidity, and illumination levels[3]. Similarly, to achieve the smart construction regarding indoor temperature and illumination, some researchersintegrated sensors with glass into a smart

glass curtain wall that regulates indoor temperature and illumination based on external climate change[4]. The development of smart skins has primarily focused on receiving external signals or data to adjust indoor environmental maintenance systems such as air conditioning and lighting, thereby maintaining a safe, healthy, and comfortable indoor environment. In addition to the function of maintaining indoor environmental quality, smart skins can also be embedded with sensors for long-term observation of wall structures. However, for determining and monitoring the eigenvalues of the degradation of facade tiles and coating materials, studies on real-time and low-cost technologies for measuring the health condition of skin materials have been scarce.

With the rapid development of science and technology, many sensors have been used in construction projects, where measurement data are quantified and fed back for use in stages such as planning, design, construction, and maintenance to facilitate the creation of a more satisfactory design and enhance construction quality. The diagnostic principle of micro-resistance is widely applied in the construction industry. The principle is primarily applied to measure the health of buildings, bridges, and roads but rarely applied to measure the health condition of building facades. Examples of use of micro-resistance diagnostic principle include measurement of changes in swelling stress due to steel rebar corrosion in reinforced concrete cylinders [5]. Studies have noted that the micro-resistance diagnostic principle is mostly applied in the construction industry to observe the relationship between changes in ambient temperature and structure. Statistical data have shown that micro-resistance can detect an amount of strain of only 25%–30% [6]. The other research integrated a building information model, radio-frequency identification, and strain sensors to perform long-term building monitoring, and assessed the possible damage locations of buildings by monitoring quantitative data[7].

III. METHODOLOGY AND EXPERIMENT DESIGN

The experiment in this study was divided into two stages comprising four experiments. The first stage consisted of four acrylic model experiments (no.1–3), and the second stage involved an experiment using a reinforced concrete specimen (no. 4). In the first stage, to understand the relationship between the compressive force of the string-type strain gages and the voltage value, the corresponding voltage of the gage was measured using an acrylic as the substrate. During the second stage, a compression experiment was performed by imitating wall concrete to simulate the association between actual changes in wall tiles and voltage.

A. Acrylic Model Experiment

The acrylic model experiment consisted of the following three experiments. 1. An acrylic compression experiment involving a diagonally installed string-type strain gages (round length = 42.5 cm × 2 = 85 cm) that simulated a tile range with a dimension of 30 cm × 30 cm (L × W) (single-point force displacement simulation). 2. An acrylic compression experiment with a diagonally installed string-type strain gages (round length = 85 cm × 2 = 170 cm) that simulated a tile range with a dimension of 60 cm × 60 cm (L × W) (single-point force displacement simulation + initial tension value not set). 3. An acrylic compression experiment using a diagonally installed string-type strain gages (round length = 85 cm × 2 = 170 cm) that simulated a tile range with a dimension of 60 cm × 60 cm (L × W) (single-point force displacement simulation + initial tension value set to 1150 cN).A nichrome wire was laid on each of the aforementioned acrylic plates and the corresponding voltage values were measured through the displacement deformation process.

To simulate the relationship between wall expansion deformation and the voltage values, a supporting frame was fabricated to fix the acrylic experimental model. The supporting frame in this experiment was made of aluminum, and its upper and lower ends could be clamped onto the acrylic plate while the fixed-end screw could be used to adjust the tension of the string-type strain gages set on the plate. In addition, one or multiple compression devices could be added to the supporting frame. These devices were mainly used to simulate the extent of deformation of the acrylic plate due to the applied force; for example, a single turn of the displacement compression knob device resulted in compression with a 1-millimeter (mm) displacement, as shown in Fig. 2.

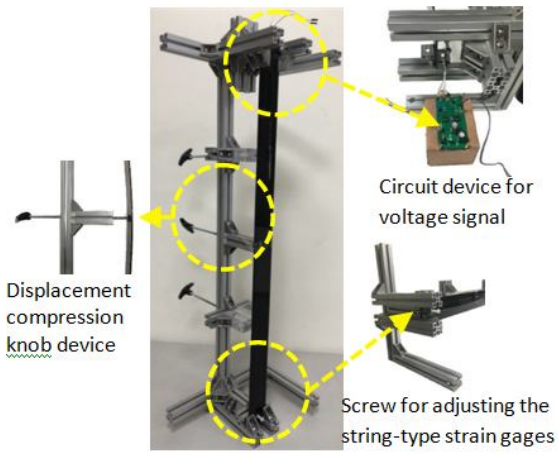


Fig. 2 Aluminum frame for the acrylic model experiment

B. Wiring of Reinforced Concrete Specimen

The reinforced concrete model experiment contained only one reinforced concrete specimen experiment that simulated the building facade. The specimen

dimension was 50 cm × 35 cm × 10 cm (L × W × H). This experiment also simulated the application of a diagonally installed string-type strain gages (round length = 42.5 cm × 2 = 85 cm) on a tile range with a dimension of 30 cm (length) × 30 cm (width) (single-point force displacement simulation). The wiring design of the string-type strain gages was divided into three layers. Layer 1 was laid between the reinforced concrete and cement mortar layers. Layer 2 was placed between the cement mortar layer and tiles. Layer 3 was placed on the tile surface, as shown in Fig. 3. Layers 1A and B, 2A and B, and 3A and B were each parallel to each other, whereas Layer 3C was positioned diagonally to Layers 3A and B.

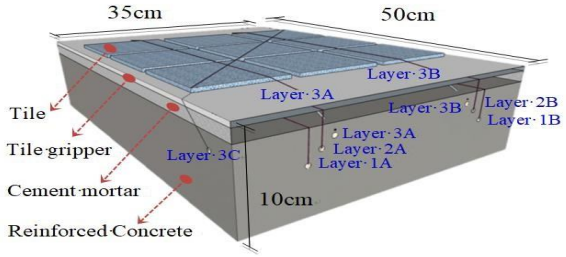


Fig. 3 String-type strain gages layout on the reinforced concrete specimen

C. Experimental Planning and Instruments

This study conducted four experiments, and detailed information regarding the specimen materials, monitoring range of the simulated tiles, length of the string-type strain gages, number of compression tests, compression points, and compression-induced displacement are shown in Table I. Experiments 1–3 involved compression (displacement) tests using the experimental aluminum supporting frame in Fig. 2. The deformation simulation of the acrylic plate was mainly achieved through the displacement generated by turning the displacement compression knob device, with a single turning resulting in a 1-millimeter (mm) displacement, which was used as the measurement interval to measure the voltage in each experiment. Finally, the corresponding trend between voltage values and amount of deformation was investigated using multiple regression analysis. Experiment 4 performed a compression (displacement) test by using the 250-kN material test system (MTS) (a dynamic material testing machine); the measurement of its displacement (from 1 to 10 millimeter) was controlled using a laser displacement sensor, as shown in Fig. 4.

TableIExperimental planning and descriptions

No	Specimen Material	Monitoring range of the simulated tiles	String-type strain gages Length (cm)	Number of Measure-ments	Compress-ion Point	Compression-Induced Displacement (mm)
1	Acrylic	30 cm × 30 cm	85	600	Central Point	from 1 to 10
2	Acrylic	60 cm × 60 cm	170	300	Central Point	from 1 to 10
3	Acrylic	60 cm × 60 cm	170 (Initial Tension =1150 cN)	600	Central Point	from 1 to 10
4	Reinforced Concrete	30 cm × 30 cm	Layer 1A=120 Layer 1B=120 Layer 2A=120 Layer 2B=120 Layer 3A=110 Layer 3B=110 Layer 3C=125	100	Central Point	from 1 to 10

In the planning of the strain gage for the concrete specimen, because the nichrome wire in the string-type strain gages had a dimeter of only 0.2millimeter(mm) and was extremely fragile, a heat-shrinkable sleevewas added to its outer layer to prevent contamination from influencing the measurement, as shown in Fig. 5. In the case of the acrylic model, the nichrome wire was placed directly on the acrylic plate. In the wiring procedure of the string-type strain gages for the experiments involving the acrylic model and reinforced concrete specimen, the functionality of the gage was confirmed using a low resistance potentiometer after wiring had been completed, and resistivity was captured using a signal processor. The information was then input to the computer through a data acquisition system, after which the measured resistivity signal was output to the computer through the signal processing circuit. A tension meter was used to ensure that the measured values could be compared under the standard of a consistent initial tension.

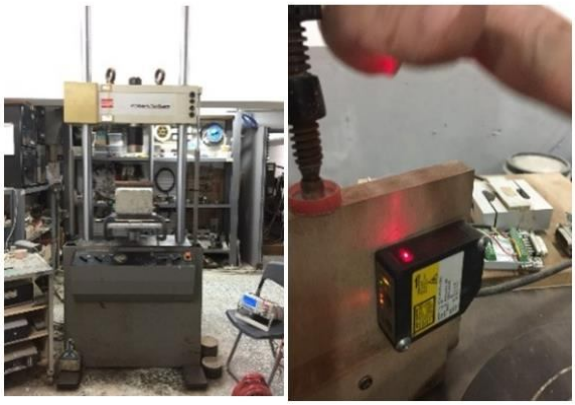


Fig. 4 MTS and laser displacement sensor

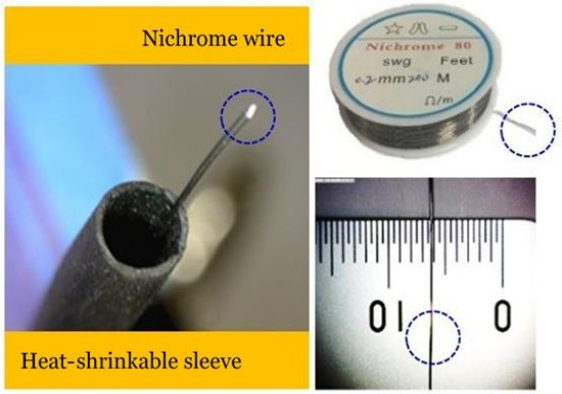


Fig. 5 Nichrome wire of the string-type strain gages

IV. RESULTS

A. Results of Experiment 1 Using an Acrylic Model

Experiment 1 mainly simulated the wiring plan of the string-type strain gages that was used to monitor the building facade tiles with an area of 30cm × 30 cm. A total of 600 measurements were conducted with every 10 measurements constituting a small cycle. Each small cycle involved measuring the voltage value from the compression distance of 1–10 millimeter (mm), and thus a total of 60 small measurement cycles were conducted. The experimental data consisted of six groups of values with 10 small cycles per group, all of which were subjected to polynomial regression. Six regression curves and formulas (y1–y6) were obtained, with the six curves exhibiting a consistent trend and their R2 values exceeding 0.999, indicating that the measurements in this study possessed reliability and validity, as shown in Table II. and Fig. 6.

Table II Polynomial regression of the experimental data in Experiment 1

Data Item	Regression Formula	R^2
1st set of data	$y_1 = 0.0233x^2 + 0.0701x + 0.032$	0.9994
2nd set of data	$y_2 = 0.022x^2 + 0.0832x + 0.0476$	0.9992
3rd set of data	$y_3 = 0.0234x^2 + 0.0722x + 0.0435$	0.9995
4th set of data	$y_4 = 0.0218x^2 + 0.0904x + 0.0287$	0.9994
5th set of data	$y_5 = 0.0226x^2 + 0.0747x + 0.0335$	0.9993
6th set of data	$y_6 = 0.0228x^2 + 0.0751x + 0.0133$	0.9996

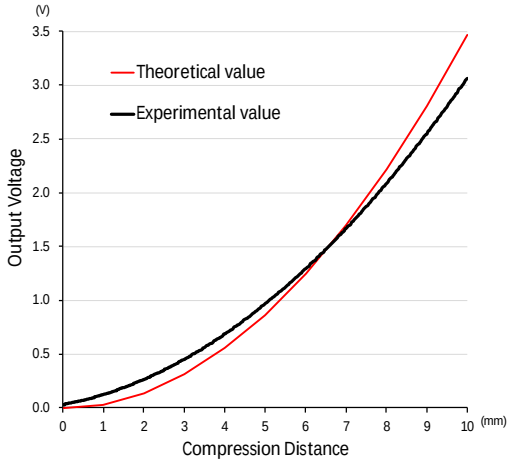


Fig. 6 Result analysis for Experiment 1

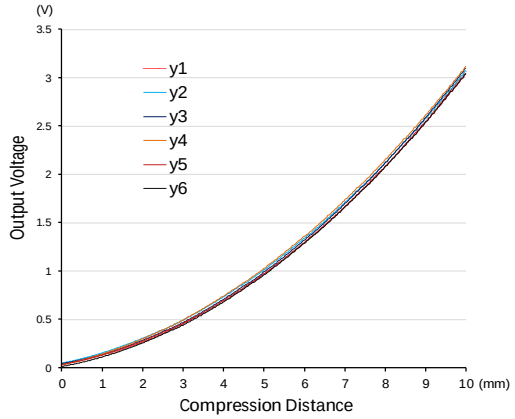


Fig. 7 Comparison between theoretical and experimental values in Experiment 1

The values in Fig. 7 were the averages of 60 pieces of data produced from the compression distances of 1–10 millimeter (mm). For example, the voltage value corresponding to 1 millimeter (mm) in Fig. 7 was the average of the 60 pieces of test data, and the curve of the experimental value was the polynomial curve from the regression of the 10 points of 1–10 millimeter (mm) ($y = 0.0233x2 + 0.0701x + 0.032$, $R^2 = 0.9994$). As illustrated by the comparison between experimental and theoretical values in Fig. 7, a greater deformation in the nichrome wire resulted in a greater corresponding measured voltage, and the two lines not being completely consistent may have been a result of some experimental errors. However, based on the experimental results of Experiment 1, the planning and application of the string-type strain gages possessed preliminary feasibility.

B. Results of Experiments 2–3 Using Acrylic Models

Experiments 2–3 mainly simulated the wiring plan of the string-type strain gages monitoring the building facade tiles with an area of 60cm × 60 cm. Experiment 2 conducted 300 measurements, with every 10 measurements constituting a small cycle. In each small cycle, the voltage values at compression distances from 1 to 10 millimeter (mm) were measured. Thus, totally 30 small cycles of measurement was performed. The experimental data contained three groups of

values with 10 small cycles per group, all of which were subjected to polynomial regression, yielding three regression curves and formulas (y1–y3), as shown in Fig. 8. The three curves did not exhibit a consistent trend, and the values of y1–y3 differed substantially from the theoretical value; this phenomenon was believed to be caused by insufficient initial tension when the string-type strain gages was deployed.

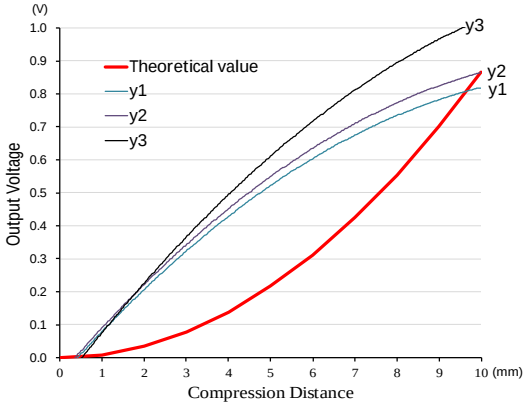


Fig. 8 Result analysis for Experiment 2

Experiment 3 was conducted primarily to understand whether Experiment 2 had resulted in a great error due to the initial tension not being set. Experiment 3 shared similar conditions with Experiment 2, the differences being that the total number of test points was increased to 600 and the initial tension was set to 1150 cN for a more strained string-type strain gages during the experiment. In Experiments 2 and 3, because the area of the tiles monitored was 60cm × 60 cm, which was larger than that of 30cm × 30 cm in Experiment 1, the total length of the string-type strain gages was longer. Fig. 9 shows the results of Experiment 3 after the initial tension had been set; the results demonstrated that although trend lines y1–y6 were not close together, the direction of their trends was consistent and matched that of the theoretical value. The results of Experiment 3 indicated that in addition to the error value increasing with the monitoring area, setting the initial tension for the string-type strain gages was necessary.

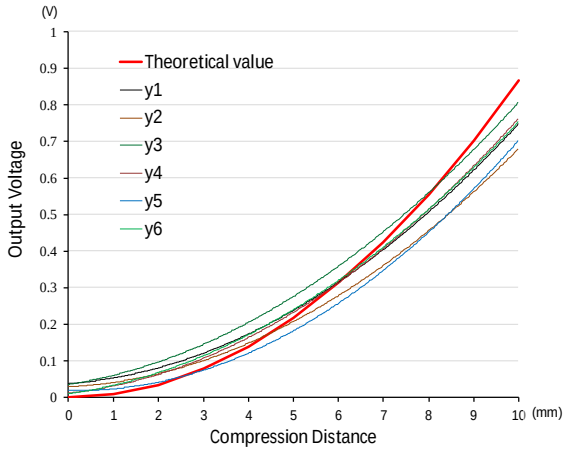


Fig. 9 Result analysis for Experiment 3

C. Results of Experiment 4 Using a Reinforced Concrete Model

Experiment 4 was conducted primarily to understand the feasibility of the practical application of the string-type strain gages in the specimen simulating building facades, as shown in Fig. 12. A single-point compression force was exerted on the back of the specimen by using the 250-kN MTS, as shown in Fig. 13. The compression distance in Experiment 4 was 1–10 millimeter (mm) and the voltage values of seven string-type strain gages were simultaneously measured. For each compression of 1 millimeter (mm), multiple data were collected by a computer. The system measured several voltage values in seconds, but the number of data varied in each compression process. Each string-type strain gages measured the voltage a total of 11992 times from 1–10 millimeter (mm). The voltage values measured by each string-type strain gages at each displacement distance was averaged (e.g., average voltages for 0–1 millimeter and for 1–2 millimeter), and thus each gage possessed an average voltage value at each displacement. Fig. 14 shows the analysis results of the seven regression curves, with the R^2 of all seven curves being greater than 0.98, indicating that these curves possessed satisfactory reliability in terms of their trends.



Fig. 12 Facade of reinforced concrete specimen



Fig. 13 Compression test that used the MTS to apply force on the back of the specimen

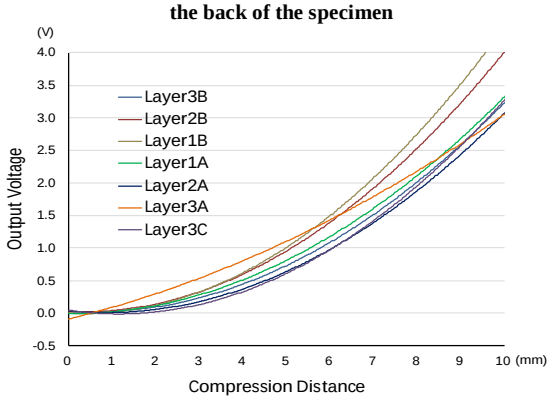


Fig. 14 Result analysis for Experiment 4

Fig. 15 shows the results of the comparison between the experimental values of Layer 3C and the theoretical values. The main reason for choosing Layer 3C was so that in future applications, adopting a post-installed construction planning technique for surface tile layers will be not only easy to construct and maintain but also relatively inexpensive. The comparison results revealed that in addition to the trend consistency between the compression distance and the corresponding voltage value, the two curves remained almost equidistant to each other, indicating that the results possessed some level of validity.

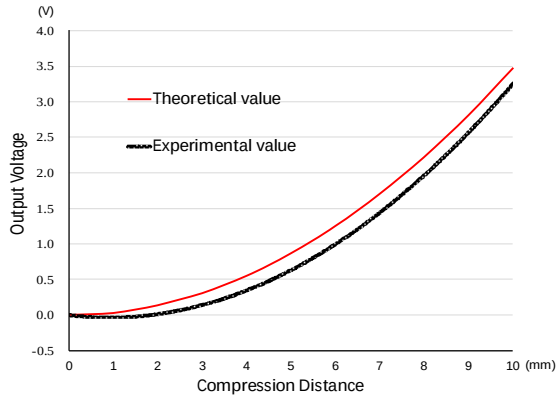


Fig. 15 Comparison between theoretical values and experimental values of Layer 3C

DISCUSSION AND SUGGESTION

In the result analysis of the acrylic model experiment, the trend lines were not close together, indicating that the data contained some experimental errors. Discussions revealed that the nichrome wire in the experiment was bare and susceptible to wind and interference that affected its resistivity, and the wire length and material homogeneity also caused errors. In addition, compression of the acrylic device was performed manually, hence the failure to accurately control the compression distance of the acrylic with the screw, resulting in experimental errors. The experimental errors in Experiment 4 involving the reinforced concrete model were mainly due to numerous instances of spatial noise in the basement laboratory, which affected the accuracy of the data and resulted in different voltage values for the two string-type strain gages in the same layer. The different experimental and theoretical values in the result analysis resulted from a shape change during the simulation of specimen under compression, after which it remained incapable of completely matching actual damages in building walls. In addition to experimental errors, the initial tension setting was a problem that warranted discussion. In Experiment 3, the central single-point compression experiment was reconducted so that the string-type strain gages could possess the same tension and to ensure that the gage measured the strain under the same tension, thereby verifying that tension was the cause of variation in the voltage values. Future studies on the tension of string-type strain gages could investigate the level of tension that enables the string-type strain gages to acquire the optimal condition.

The experiment in this study involved the use of acrylic and concrete, and the resulting experimental values were in the same direction as the trend of the theoretical values, thereby demonstrating the feasibility of using the string-type strain gages to diagnose the falling of building facade tiles. Regarding possibilities for tile displacement, in addition to actual damage and falling, other interfering factors include temperature variation between day and night. The acrylic compression experiment revealed that the voltage value returned to 0 when the compression distance was 0. Therefore, when voltage value was used to diagnose the symptoms of tile deterioration and falling, if the voltage value returned to 0 within 1 day, it could be viewed as a normal contraction caused by the close adhesion between the tiles and structure. The voltage value increasing and remaining at a certain value or continuing to rise may have been a sign of tile deterioration, and further investigation into tile hollowing, protrusion, or falling off is recommended. In addition, the experiment revealed that tension led to errors in the resistivity of the string-type strain gages, and thus future experiments should perform verification by applying varying levels of tension to obtain the optimal value for uniform tension in subsequent applications. The tension should be unified in future to ensure the accuracy of the experiment, and simulation and diagnosis should be performed in advance using acrylic to enable the experimental value of the acrylic experiment to approach its theoretical counterpart. At the same time, the association between the microchange and voltage value of actual tiles should be determined through the concrete experiment.

An artificial neural network is expected to be introduced in future studies; in the network, the weights of transmission would be constantly modified through monitored learning to reduce the gap between the output value and expected value to achieve the desired results, thereby increasing the accuracy of the output of the string-type strain gages. In future, through the application of the string-type strain gages alongside an artificial neural network for diagnostics, the falling of tiles may be prevented in advance, and maintenance can be performed before occurrence of such an event. Many houses in Taiwan are decorated with tile facades. If the findings of this study are feasible for future application, other wires could be used to replace the string-type strain gages after the system has stabilized.

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REFERENCES

[1] Sie, Z. H., & Cai, D. Y.Cracks in Facade Tiles on 12th Floor due to Suspected Cold Water—Hood of Luxurious Car Impaled，Eastern Broadcasting Co， Retrieved from: https://news.ebc.net.tw/news.php?nid=94530, Jan 2018.

[2] Jhong, H. L.Severe Cracking of Building Facade—Tourists at Ningxia Night Market Exposed to Danger，Liberty Times，Retrieved from: http://news.ltn.com.tw/news/life/breakingnews/2199570, Sep 2017.

[3] Park, C. S. Occupant responsive optimal control of smart facade system, Eighth International IBPSA Conference, Aug 2003.

[4] Lee, E. S., Selkowitz, S. E., Hughes, G. D., Thurm, D. A. Market transformation opportunities for emerging dynamic facade and dimmable lighting control systems. Lawrence Berkeley National Laboratory, Aug 2004.

[5] Li, Y. F. & Sie, Y. M. A Study on the CFRP Confine the Reinforced Concrete Cylinder Specimen to Measure the Swelling Stress of Steel Rebar Corrosion，Journal of Chinese Corrosion Engineering, 17(1), 13-26, Mar 2003.

[6] Ge, Y., Elshafie, M. Z., Dirar, S., Middleton, C. R. The response of embedded strain sensors in concrete beams subjected to thermal loading. Construction and Building Materials, 70, 279-290, Jul 2014.

[7] Zhang, Y., & Bai, L. Rapid structural condition assessment using radio frequency identification (RFID) based wireless strain sensor. Automation in construction, 54, 1-11, Feb 2015.

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