Ambient Vibration Measurements and Seismic Evaluation of Historical Japanese-style Wooden Offices in Taiwan

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Abstract
In order to conserve or reuse historic buildings in Taiwan which are located in an earthquake-prone area, it is critical to ensure their seismic capacity. The historical Japanese-style wooden houses are those of concern in this study. Three historical offices of this kind which were damaged in the 2010 Kaohsiung earthquake were selected. First, ambient vibration measurements were taken to investigate their natural frequency and vibration mode. Performance-based assessment for wooden buildings in Japan was adopted and modified to evaluate the seismic capacity of the offices. By comparing the evaluation results and the damage observed in the earthquake, applicability of the method was verified. Accordingly, a seismic evaluation method for the Japanese-style wooden buildings in Taiwan was established. In addition, the relationship between measured natural frequency and calculated base shear coefficient was investigated and compared to the empirical formula for wooden houses in Japan.

Keywords: Japanese-style wooden buildings; performance-based assessment; ambient vibration; bamboo-mud walls; lateral strength

1. Introduction
When conserving or reusing historic buildings in an earthquake zone, it is critical to ensure their seismic capacity. Since the 1999 Chi-Chi earthquake occurred in Taiwan, which caused severe damage to architectural heritage, domestic researchers have devoted much effort to studying the seismic performance of historical buildings. For example, in order to understand the structural behaviours of historic Japanese-style wooden houses, experiments were conducted on bamboo-mud walls to investigate their lateral strength (Chen et al. 2007).

Historical Japanese-style wooden houses are the subject of this study. Despite the accumulation of experimental data of essential structural elements, a thorough seismic evaluation method for an entire Japanese-style wooden building in Taiwan has not yet been established. Three historical offices of this kind, built in the 1950s and damaged in the 2010 Kaohsiung earthquake were selected. They were chosen because surveys on their construction details have been conducted by the co-author's architects' office which accordingly provides essential information for seismic evaluation. In addition, the offices were near to earthquake stations, thus reliable data of ground motions were available.

Ambient vibration measurements were first taken for the selected offices to investigate their dynamic characteristics, including natural frequency and vibration mode. Secondly, performance-based assessment using the capacity spectrum method (JSCA-Kansai 2014) developed for wooden buildings in Japan was adopted and modified to evaluate the seismic capacity of the offices. Modifications to the method were necessary as the construction details of the wooden buildings are not exactly the same in the two areas. Then, by comparing the evaluation results and the damage observed in the earthquake, the applicability of the method was verified. Accordingly, the seismic evaluation method for the Japanese-style wooden buildings in Taiwan was established. In addition, the relationship between measured natural frequency and calculated base shear coefficient of the offices was investigated, as the latter represents a critical index of seismic capacity (Hayashi et al. 2010; Saito et al. 2016). The relationship was also compared to the empirical formula obtained for wooden houses in Japan.

2. Ambient Vibration Measurements of Historic Japanese-style Wooden Offices
2.1 Outline of the Investigated Offices
The three surveyed offices were built in the 1950s with a similar structural system, composed of a timber frame connected by tenon-mortise joints and walls
filled with mud. The structural system is the same as that of traditional Japanese-style wooden houses except for two major differences: (1) a western style roofing frame, king-truss, and (2) a wooden frame anchored to a 60-90cm high and 25cm thick brick wall as shown in Fig.3. Steel bars are anchored into mortar joints for fastening of the sills of the wooden frame. Table 1. shows a summary of basic construction data and the exterior and interior of the offices. The surveyed buildings are abbreviated as school offices A, J and S hereafter. The cross-section size of the columns ranges from 10.5×10.5cm to 12×12cm at a spacing of 90.5cm. For infilled walls there are two construction types: bamboo-mud wall and lath-mud wall. The former is the most common type of wall observed in Japanese-style wooden houses. In contrast, the latter one is mainly adopted for the sidewalls of the main entrance and the horizontal band beneath the eaves. From Table 1., it can be seen that the interior wall of office A is a lath-mud wall. Furthermore, braces were installed to the inside, according to the preceding survey of the co-author's architects' office. The thickness of the mud wall is around 6 to 7cm. In addition, clapboards are frequently installed on the exterior side of the wall to reduce direct exposure to sunshine and raindrops. As for the roof style, school office A has a gable roof, and J and S school offices have hipped roofs. Figs.1. and 2. show the elevations and plan of the school office S. The ridge is along the EW direction, and the main entrance of the office is to the east side.

2.2 Vibration Characteristics of Historical Japanese-style Wooden Offices

Ambient vibration tests were conducted in order to identify the predominant dynamic characteristics of the offices, including natural frequency and vibration mode. The in-situ tests were conducted after the 2010 Kaohsiung earthquake. As the wooden offices suffered only slight damage, it is justified to infer that the dynamic characteristics approximate to those before the earthquake. As shown in Figs.4.-5., three acceleration sensors were placed on the west, center and east roof frames and one on the ground in order to conduct simultaneous measurement for 5 minutes. Each sensor was able to detect two-direction planar vibration. A transfer function was calculated by dividing the recorded data at the roof frame to that on the ground in the frequency domain. In this way, natural frequencies of the building were derived from the peak frequencies of the transfer function. Meanwhile, planar vibration modes of the building were determined from the phases of transfer functions and the values of relative acceleration spectra at their natural frequencies. And between two measuring points, the mode shape was interpolated linearly.

Fig.6. shows the transfer functions in X- and Y-axes (ridge and beam directions) of the offices. The subscript of w, c and e represent the results at the west, center and east parts of the structure, respectively. Identified natural frequencies are listed in Table 2. For school office A, the fundamental natural frequency of 5.8Hz in the X-axis is higher than that of 4.6Hz in the Y-axis. The corresponding vibration mode is displayed in Fig.7. (a) and (b). In contrast, for school offices J and S, the natural frequencies in the X- and Y- axes are approximate. From the vibration mode shown in Fig.7. (c) and (d), it is clear that the office underwent torsional vibration. According to the survey results of historical wooden houses in Japan (Hayashi et al. 2010), natural frequency in the beam direction is usually higher than that in the ridge direction. However, in school offices A and S, natural frequency in ridge direction is higher. This is because, compared to residential houses, offices lack partition walls along the beam direction. Longer exterior walls in the ridge direction contribute to higher frequency along this direction.
2.3 Relationship between Yield Base Shear Coefficient and Natural Frequency

As yield base coefficient can reflect the seismic capacity of a wooden structure (Hayashi et al. 2010), once the relationship between yield base coefficient and natural frequency has been confirmed, natural frequency obtained by ambient vibration can be a practical approximate evaluation method. The yield base shear coefficients $C_y$ of selected wooden houses are evaluated in the ridge and span directions respectively, based on the capacity curve obtained by the method introduced in Section 3. The yield base shear coefficient is calculated by dividing the restoring force of capacity curve at the deformation angle of 1/30 radian by the building weight. Table 2. lists the natural frequency and yield base shear coefficient in the X- and Y- axes (ridge and beam directions) for the three offices. Additionally, Fig.8 compares the results with empirical formulae obtained for wooden houses in Japan. (Hayashi et al. 2005). It is evident that, for the same yield base shear coefficient, the corresponding natural frequency of wooden offices in Taiwan is lower compared to that of wooden residential houses in Japan. This might mainly be due to the brick walls beneath the wooden frame of the offices. When subjected to lateral loadings, the resistant stiffness, $K_B$ and $K_w$, of the brick wall and wooden frame are connected in series. Thus the resultant lateral stiffness $K = K_B K_w / (K_B + K_w)$ is lower than either $K_B$ or $K_w$. Accordingly, compared to the wooden frame having the same value of $C_y$ in Japan, the measured natural frequency decreases for the case in Taiwan. Nevertheless, in order to verify this inference, more in-situ test data are needed.

| Table 1. Summary of Construction Data of the Surveyed Japanese-style Wooden Offices |
|---|
| **School A (built in 1952)** |
| Plan: 15.8×10.3m |
| Wall height: 4.4m |
| Column: 12×12cm |
| Wall: lath-mud-plastered with braces and clapboards |
| Roof: king truss; Japanese-style roofing tiles |

| **School J (built in 1956)** |
| Plan: 15.8×10.3m |
| Wall height: 3.9m |
| Column: 12×12cm |
| Wall: lath-mud plaster; bamboo-mud plaster with clapboards |
| Roof: king truss; cement roofing tiles |

| **School S (built in 1958)** |
| Plan: 15.5×10.9m |
| Wall height: 3.6m |
| Column: 10.5×10.5cm |
| Wall: lath-mud plaster; bamboo-mud plaster with clapboards |
| Roof: king truss; Japanese-style roofing tiles |

Fig.4. Plan of Installation Locations of Acceleration Sensors. (G, W, C and E represent the location of sensors on the ground, at the west, center and east parts of the structure, respectively)

Fig.5. Photograph of Acceleration Sensor Installed on the Roof Frame
3. Seismic Performance Evaluation of Historical Japanese-style Wooden Offices

In performing the seismic performance-based evaluation for Japanese-style wooden buildings in Taiwan, first the framework of the capacity spectrum method developed in Japan (JSCA-Kansai 2014) is adopted. Then, modifications to the relationship between restoring force and deformation of essential resisting elements were made based on domestic experiment results. Lastly, the applicability of the method is verified by comparing the evaluation results with the observed damage to the surveyed offices.

3.1 Introduction of The Performance-based Assessment Method Developed for Japanese-style Wooden Buildings

The seismic performance of the three offices was assessed using the capacity spectrum method for wooden buildings developed in Japan. This method is called “Genkai tairyoku keisan” in Japanese. There are three major parts to this method as shown in Fig.9.: (1) capacity curve of structure, (2) demand spectrum of input shaking and (3) response of structure by capacity spectrum analysis. Fig.10. shows that, in obtaining the response deformation angle, the procedure needs comparison of the intersection points on the capacity curve and the demand spectrum at an equivalent stiffness and damping ratio. More details of the calculation procedure are introduced by the Japan Structural Consultant Association, Kansai (2014).

3.2 Settings of Load and Deformation Angle for Essential Resistance Elements of Wooden Buildings

The load-deformation angle relationship (capacity curve) of the whole wooden house is calculated by summing the force-deformation angle relationships of each structural element, such as frames, bamboo-mud walls, and clapboards. The load-deformation angle relationships for the essential resistance elements found in the Japanese-style wooden buildings in Taiwan are assessed using the capacity spectrum method for wooden buildings developed in Japan. This method is adopted. Then, modifications to the relationship between restoring force and deformation of essential resisting elements were made based on domestic experiment results. Lastly, the applicability of the method is verified by comparing the evaluation results with the observed damage to the surveyed offices.

Table 2. Natural Frequency and Yield Base Shear Coefficient of the Surveyed Wooden Offices

| Case | Ridge dir. (X-axis) | Beam dir. (Y-axis) |
|------|--------------------|--------------------|
| A    | 5.8                | 0.78               |
| J    | 3.7                | 0.66               |
| S    | 3.5                | 0.66               |

![Figure 6: Identified Natural Frequency of Wooden Offices by Ambient Vibration Tests.](image1)

![Figure 7: Vibration Modes of the Surveyed Wooden Offices](image2)

![Figure 8: Relationship between Natural Frequency, f, and Yield Base Shear Coefficient, C_y. (The empirical formula is for wooden houses in Japan provided by Hayashi et al. 2005)](image3)
list in Table 3. The settings for joint, penetrating tie beam, brace and bamboo-mud walls based on domestic experiment results were provided by Chen et al. (2007). However, for those lacking domestic data such as lath-mud walls and clapboards, Japanese research data are referred to (JSCA-Kansai, 2014; NPO Green Island Network, 2012). The values in Table 3 are obtained based on a standard specimen, which is 2.1m high and 0.9m wide. Thus when applying the data to buildings with different dimensions, modifications as explained in Table 3 are needed. Taking a 2.7m high and 1.8m wide frame as an example, for the settings of tenon-mortise joints and clapboards, the modification factors are 2.1/2.7=0.78 and 1.8/0.9=2.0, respectively.

In calculating the weight (mass) of the building, the weight of the roof and wall are taken into consideration. The weight of the roof is based on a piece of Japanese-style and cement roofing tile of 2.79 and 4.05kgf, respectively. In contrast, in the case of the wall, the weight per unit area for the bamboo-mud wall is 85 kgf/m², for the lath-mud wall 35kgf/m², and for the clapboards 10 kgf/m². Note that the calculation was only for the upper half part of the wall when considering the effect of seismic force.

The capacity curve can be obtained before an earthquake since it is solely based on architectural drawings and test data of critical structural elements. Once the demand spectrum of a certain quake is input, the performance of the building can be evaluated immediately after the earthquake. As the brick wall with the general dimensions of 60-90cm in height and 25cm in thickness are much more rigid compared to wooden units in the lateral direction, the deformation and influence of the brick wall is ignored in this study. Therefore only the response of the wooden structure is considered here.

3.3 Verification of Seismic Evaluation Results

On March 4, 2010, at 8:20 local time, a M₇.64 earthquake occurred in Kaohsiung, the largest city in southern Taiwan. According to the Central Weather Bureau (CWB), the epicenter of the main shock was located approximately 17.0 km SE of Jiashian Township. The earthquake was felt all over Taiwan Island (Fig.11). It was the most powerful earthquake in Kaohsiung since 1900. The maximum ground acceleration triggered by this quake was 310gal.

Figs.12. and 13. summarize the observed damage of school offices J and S after the earthquake. In general, the walls were damaged a bit more in the NS direction than in the EW direction. In contrast, for school office A, no prominent damage was reported to the authority. The nearest CWB earthquake station, CHY049, to the three offices, was at a distance of between 2 and 5km. Figs.14. and 15. show the recorded time history of acceleration and the corresponding response spectrum at CHY049. The peak acceleration (PA) of 176 and 158gal in NS and EW, respectively, reached CWB Intensity level V (PA greater than 80gal).

Seismic performance evaluation of the three offices was verified by comparing it to the observed damage. In calculating the weight of the building, the contribution of the porch is neglected as its roof area is only 5% compared to the whole roof area (Fig.2.). Among the three offices, school J is the heaviest whilst school A is the lightest (Table 4.). The results of weight divided by floor area display the same trend with that of building weight. This is because the gable style roof is covered with Japanese-style roof tiles for school A, resulting in a smaller roof area and lighter unit weight. The weight divided by floor area for the three offices ranges from 100 to 125kgf/m². Compared to the result of 255 kgf/m² for 30 traditional Kyoto residential houses (Suda and Suzuki, 2007), the unit weight of the wooden office is much lighter. This is mainly due to the wooden office lacking interior partition walls.
Fig. 13. Damage Situations of School Office S

(a) Spallings of plaster and mud at the east exterior wall around the entrance.
(b) Cracks and spallings of mud and plaster at the east interior wall.
(c) Spallings of mud, resulting in the exposure of a penetrating tie beam at the corner of the east interior wall.
(d) Detachment of mud around the corner and periphery of the wooden frame of the partition wall.
(e) Cracks and spallings of mud and plaster at the south interior wall.
(f) Extrusion at the middle part of the north wall.

Fig. 12. Damage Situations of School J Office

(a) Spallings of plaster and mud at the east exterior wall around the entrance.
(b) Cracks and spallings of mud and plaster at the east interior wall.
(c) Spallings of mud, resulting in the exposure of a penetrating tie beam at the corner of the east interior wall.
(d) Detachment of mud around the corner and periphery of the wooden frame of the partition wall.
(e) Cracks and spallings of mud and plaster at the south interior wall.
(f) Cracks at the corner and central part, detachment of mud and plaster at the north interior wall.

Fig. 14. Acceleration Recorded at CHY049

Fig. 15. Response Spectrum for CHY049. (h: damping ratio)
The responses of the three offices calculated by the Performance-based method are shown in Fig.17. The deformation angle and judged damage level are listed in Table 4. Then the corresponding damage level at a deformation angle is judged based on domestic experiment results of the bamboo-mud wall (Chen et al., 2007). For school A, the deformation angles of 0.5% and 1.0% in the EW and NS directions, respectively, representing no, and slight damage, corresponding well with the damage situation introduced in Section 3.3. The responses of schools J and S approximated to each other whilst school J underwent the largest deformation angle. According to the response of schools J and S, the damage to the two offices was judged as 'slight', except for school J in the NS direction which was judged as ‘moderate’. Compared to the summarized damage situation of the two offices shown in Figs.12. and 13., the evaluation method demonstrates good applicability.

4. Conclusions

In this study, the seismic capacity of the historical Japanese-style wooden buildings is the area of concern. Three historical offices of this kind which were damaged in the 2010 Kaohsiung earthquake were selected. By comparing with the observed damage to the offices, the applicability of performance-based assessment revised from that originally developed for wooden houses in Japan was verified. Accordingly, the seismic evaluation method for Japanese-style wooden buildings in Taiwan was established. Ambient vibration tests were also conducted to investigate the dynamic characteristics of the wooden offices. Meanwhile, the relationship between measured natural frequency and calculated yield base shear coefficient was investigated and compared to the empirical formula for wooden houses in Japan. It was found that, due to brick walls being beneath the wooden frame resulting in lower lateral stiffness, for the same yield base shear coefficient the corresponding natural frequency of wooden offices in Taiwan was lower.
Table 3. Settings of Essential Resistance Elements (Standard specimen: 2.1m high, 0.9m wide)

| Resistance element               | Reference                                                                 | Load at various deformation angle (Unit: N) | Modification rules                              |
|----------------------------------|---------------------------------------------------------------------------|---------------------------------------------|-----------------------------------------------|
|                                 |                                                                           | 0.8% | 1.6% | 3.3% | 6.7% |                                  |
| Tenon-mortise joint              | Chen et al. (2007)                                                        | 69   | 108  | 186  | 216  | Inversely proportional to frame height |
| Penetrating tie beam             |                                                                            | 88   | 127  | 127  | 127  | Inversely proportional to frame height |
| Brace                            |                                                                            | 470  | 706  | 706  | 706  | Proportional to brace and horizon     |
| Bamboo-mud wall                  | Chen et al. (2007)                                                        | 1245 | 2274 | 3175 | 3430 | Proportional to frame                 |
| 0.9m wide                        |                                                                            | 2342 | 3244 | 4420 | 4831 | Proportional to wall thickness        |
| 1.8m wide                        |                                                                            | 510  | 931  | 1303 | 1411 | Proportional to the height ratio      |
| Bamboo-mud hanging wall          | JSCA-Kansai (2014)                                                        | 960  | 1332 | 1823 | 1989 | Proportional to hanging wall          |
| 0.9m wide                        | Chen et al. (2007)                                                        | 2940 | 2940 | 2940 | 2940 | Proportional to frame width           |
| 1.8m wide                        |                                                                            | 2940 | 2940 | 2940 | 2940 | Proportional to height ratio of 1/3   |
| Lath-mud wall                    | NPO Green Island Network (2012)                                           | 1215 | 1215 | 1215 | 1215 | Proportional to the height ratio      |
| Lath-mud hanging wall            | JSCA-Kansai (2014)                                                        | 480  | 1000 | 1999 | 1999 | Proportional to frame width           |
| Clapboards                       |                                                                            | 1493 | 1493 | 1493 | 1493 | Proportional to frame width           |

Table 4. Evaluated Results for the Surveyed Wooden Offices

| Case | Weight (kN) | Weight/ Floor area (N/m²) | Weight/ Number of columns (N) | Ultimate strength (kN) | Deformation angle (%) | Damage level |
|------|-------------|---------------------------|------------------------------|------------------------|-----------------------|--------------|
|      |             |                           |                              | NS | EW  | NS | EW  | NS | EW  |                  |
| A    | 143.6       | 980                       | 2881                         | 77.5 | 114.7 | 1.0 | 0.5 | Slight | No              |
| J    | 234.9       | 1205                      | 3783                         | 123.8 | 166.2 | 1.8 | 1.3 | Moderate | Slight          |
| S    | 198.0       | 1156                      | 3548                         | 127.9 | 154.6 | 1.5 | 1.1 | Slight | Slight          |

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