Evaluation of Ambient Vibration Test Method for Historic Wooden Buildings Based on the Rigid Diaphragm Assumption

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Abstract
To retrofit historic wooden buildings to improve their seismic and wind resistance, the precise structural assessment to such loads is essential. However, little research has been done in Korea on the ambient vibration test (AVT) of historic wooden buildings for the collection of dynamic characteristics and the corresponding structural assessment. The reason for this is that, for wooden buildings, unlike reinforced concrete (RC) and steel buildings, a systematic in situ AVT method has not been established. In this paper, an in situ AVT method is presented for historic wooden buildings based on the assumption that rigid diaphragm action plays a role in the structural responses of wooden buildings. This assumption is reasonable when the roof and rafters restrain the rotation of columns, as do slabs in RC and steel buildings. The proposed method was employed in an evaluation of the dynamic characteristics of a small traditional wooden building to assess its applicability. The method was also applied to in situ AVT of eight historic wooden buildings that are designated as national treasures in Korea.

Keywords: historic wooden buildings; in situ measurement; ambient vibration test; dynamic characteristics; mode shapes

1. Introduction
Wooden buildings have traditionally been used primarily in East Asia, including Korea. Some of the historic wooden buildings still in existence have been designated as national treasures because they represent the characteristic architectural styles and construction techniques of their eras. Recently, the increasing number of earthquakes and severe typhoons resulting from climate abnormalities has drawn increased attention to seismic and wind resistance retrofitting of historic wooden buildings designated as national treasures.

To retrofit historic wooden buildings to improve their seismic and wind resistance, it is essential to evaluate their structural performance precisely. Previous studies on the structural performance of wooden structures have focused primarily on how to analytically model the structural elements such as beams and columns, and jointing elements such as the footing–column connections and the beam–column connections. Lee et al. suggested an analytical finite element model of historic wooden structures and verified their model using a scaled frame model (Lee et al., 2006). Hwang et al. (2008) investigated the resisting capacity of Korean historic wooden structural systems subjected to static loading.

Shaking table tests have also been conducted using scale models and full-scale models of historic wooden structures to assess the seismic behavior of whole buildings (Maeno et al., 2004, Suzuki and Maeno, 2006). Hwang et al. (2009) reported from a shaking table test of a scaled wooden building that the lateral resistance of a wooden structure to deformation is the result of all of the bending moments at the tops and bottoms of the columns due to rocking, as well as those at the beam–column connections due to the resistance of the tie beams.

However, it is nearly impossible to model historic wooden structures analytically or to duplicate wooden structures using scale models exactly. The reason for this is that it is not possible to disassemble and reassemble historic wooden buildings that are national treasures for the purpose of detailed investigation. Therefore, various non-destructive test (NDT) methods have been widely proposed for the structural assessment of historic buildings as alternatives (Kilic, 2014). The ambient vibration test (AVT), which is a fully NDT method, is especially suitable for historic wooden buildings since the test is performed by just measuring the response to ambient excitations such as micro-tremors and wind. It is shown that AVT provides information
on the global modal characteristics including natural frequencies, mode shapes, and modal damping ratios that are essential for the structural assessment of historic wooden buildings (Min et al., 2013).

Many researches on the use of AVT for historic wooden buildings have been carried out in Japan (Fujita et al., 2004, Suzuki and Maeno, 2006) and it was reported that a horizontal in-plane structure is not rigid but deformable. Therefore it is not easy to apply the systematic AVT method originally established for reinforced concrete (RC) and steel buildings directly to historic wooden buildings. However, it is also often impractical to perform AVT on historic wooden buildings while fully considering the characteristics of a non-rigid in-plane structure.

In this paper, an AVT method for historic wooden buildings is presented. This method is based on the assumption that rigid diaphragm action plays a role in the structural responses of wooden buildings. This assumption is reasonable when the roof joists and rafters restrain the rotation of columns, in a manner similar to slabs in RC and steel buildings. The proposed method was applied to an evaluation of the dynamic characteristics of a small traditional wooden building to assess the applicability of the method. The method was also applied to the AVT of eight historic wooden buildings designated as national treasures in Korea.

2. In Situ AVT Method Based on the Rigid Diaphragm Assumption

Three sensors for each floor of an RC or steel building are sufficient to identify two translational (x- and y-axes) and one rotational (z-axis) degree of freedom, as illustrated in Fig.1. (Yu et al., 2008, Kim et al., 2008). The reason for this is that it is assumed that the entire floor plan acts as a single rigid diaphragm against lateral loads when the columns of each floor are restrained by the floors (Clough & Penzien, 1975).

Rigid motion in Fig.2. is the movement of all of the points in a plane such that the relative distances between the points and the relative positions of the points remain the same. Three appropriately selected translational vectors are sufficient to calculate all eight translational vectors shown in Fig.1.(b) for a floor in rigid motion. For RC and steel buildings, it is reasonable to assume rigid diaphragm behavior of the floor. The three-vector measurement method illustrated in Figs.1. and 2. is therefore typically used in the AVT of such buildings.

Traditional single-story wooden buildings, however, have only beam–column frames, rafters, and joists, without floors that connect columns, as shown in Fig.3. Further, all members are connected to each other without any connecting materials such as nails or screws. Therefore, it may not be reasonable to apply the three-vector measurement method directly to the AVT of traditional single-story wooden buildings.

Use of two sensors for each column or the use of the eight-vector measurement method, in which two sensors are used for four corner columns, is necessary to measure the plane motion of a historic single-story wooden building accurately. Using two sensors for every column or four corner columns is, however, difficult to do in practice when sensor installation is obstructed by walls. Even when sensor installation is possible, the numerous sensors required result in a laborious data processing effort.

If the roof and rafters of a traditional wooden building restrain the columns against lateral loads in a manner similar to floor slabs in RC and steel buildings, it is reasonable to apply the three-vector measurement method based on the rigid diaphragm assumption. In
this study, the appropriateness of the rigid diaphragm assumption in evaluation of historic single-story wooden buildings was experimentally verified by comparing the three-vector and eight-vector AVT methods in application to a full-scale wooden building.

3. Experimental Verification of Rigid Diaphragm Assumption

3.1 Description of a Full-Scale Wooden Building

In situ AVT was carried out on a full-scale wooden building, Keumranjung, located on the grounds of Kyungpook National University, Daegu, Korea (Fig.5.) to assess the applicability of the rigid diaphragm assumption experimentally. Keumranjung, built in 2011, is a small pavilion with a plan area of 25.92 m². It is 7.2 m x 3.6 m, with a height of 5.2 m (Fig.5.). It was decided to perform the experimental verification of rigid body assumption using Keumranjung because it was built by the Korean traditional construction method and thereby the mechanical joint condition matches closely to those of historic wooden buildings. Because the floor installation is one-sided, its behavior is asymmetrical in the longitudinal direction (the x-direction) but symmetrical in the transverse direction (the y-direction).

3.2 In Situ AVT Methods

Two accelerometers were installed orthogonally on four columns (columns ① through ④ in Fig.5.(a)), and the ambient vibration over 30 minutes was measured for use in applying the eight-vector measurement method. Three accelerometers, two on column ① and one on column ③, were then installed, and the ambient vibration over 30 minutes was measured for use in applying the three-vector measurement method.

The servo-type accelerometers with measurement range of 1 g were installed on the tops of columns (Fig.5.(b)). A sampling frequency of 200 Hz was used. Because impact loads are not typically allowed in the measurement of vibration of historic wooden buildings that are designated as natural treasures, only AVT is performed in this study. Acceleration time histories measured over a period of 30 minutes by two accelerometers (x₁ and y₁) installed on column ① are shown in Fig.6. The measured accelerations were very small, with amplitudes of less than 5x10⁻⁴ g.
frequencies, damping ratios, and mode shapes, from the measured ambient vibration records. The SSI method yields estimates of modal parameters obtained from singular value decomposition of the block Hankel matrix, which is composed of correlation matrices of responses (Peeters and Roeck, 1999). Because the recorded data are not transformed into one frequency domain and because the dynamic parameters are extracted from the state space equation obtained directly from the time series of the data, this method is often used in system identification when the input force is not known (Cho et al., 2012).

To classify the singular values and to detect abrupt changes in the modal properties, a stabilization chart was constructed for state space equations of varying orders. The resulting stabilization chart is presented in Fig.7., along with the average power spectral density (PSD) of the measured acceleration data. Circles in Fig.7. denote the identified singular values. The orders of the state space equations used in the SSI range from 12 to 40 in increments of two. It can be seen that the peaks of the PSD occur near 1.5 Hz, and singular values near that frequency are consistent with the order of the state space equations varying from 12 to 40.

The identified natural frequencies and damping ratios are summarized in Table 1. and Fig.8. illustrates the corresponding mode shapes. The values of the natural frequencies and damping ratios are averaged for orders of 12 to 40, and the mode shapes shown in Fig.8. are averaged as well. It can be noticed from Fig.8. that the first two modes are rotational modes and the third mode is a translational mode in the longitudinal direction. This is consistent with the asymmetric nature of the structure in the transverse direction.

It can also be seen from Fig.8. that the original rectangular shapes are not preserved. In particular, the upper longer side is shortened, while the lower longer side is lengthened, resulting in a trapezoidal third mode shape as shown in Fig.8.(c). Therefore, it can be concluded that the assumption of perfect rigid diaphragm action is not valid for this traditional wooden building.

### 3.3 Dynamic Parameter Identification Result of Three-Vector Measurement

The equipment and measurement settings used for the eight-vector measurement method were also used for the three-vector measurement method. The orders of the state space equations adopted in the SSI method were also 12 to 40. The stabilization chart and average PSD of the measured acceleration data obtained using the three-vector measurement method are shown in Fig.9. Table 2. and Fig.10. summarize the natural frequencies, damping ratios, and mode shapes obtained using the three-vector measurement method.

It can be seen from Fig.10. that the mode shapes obtained using the three-vector measurement method are almost identical to those obtained using the eight-vector measurement method. That is, the first mode is a rotational mode with a rotational center at the left side; the second mode is a rotational mode with a rotational center at the right bottom corner; and the third mode is a translational mode in the x-axis direction.

The planar shapes of the modes obtained using the three-vector measurement method, however, maintain their rectangular shapes without any distortion. The reason for this is that the three-vector measurement method applies the rigid diaphragm assumption in calculating the mode shapes.

![Fig.8. Identified Mode Shapes when the 8-Vector Measuring Method is Used](image-url)

**Fig.8. Identified Mode Shapes when the 8-Vector Measuring Method is Used**

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**Table 1. Natural Frequencies and Damping Ratios Identified Using the Eight-Vector Measurement Method**

| Mode     | Natural Frequency | Damping ratio |
|----------|-------------------|---------------|
| 1st mode | 1.4623 Hz         | 1.26 %        |
| 2nd mode | 1.6071 Hz         | 1.12 %        |
| 3rd mode | 1.7284 Hz         | 1.27 %        |
3.5 Comparison of Modal Characteristics

To assess the validity of the rigid diaphragm assumption in evaluation of the modal characteristics of traditional wooden buildings, the dynamic properties obtained using the three- and eight-vector measurement methods were compared. The results of the comparison are shown in Table 3 and Fig. 11. The natural frequency and damping ratio errors in Table 3 were calculated on the basis of the results obtained using the eight-vector measurement method. The mode shape error, $\varepsilon$, was obtained using the following equation:

$$\varepsilon(\%) = \left|\frac{X - Y_1 + |X - Y_2|}{2X}\right| \times 100$$  \hspace{1cm} (1)

where $X$ is the diagonal length of a mode shape obtained using the three-vector measurement method and $Y_1$ and $Y_2$ are the diagonal lengths of a mode shape obtained using the eight-vector measurement method.

Table 3. Comparison of Dynamic Properties Identified Using the Three- and Eight-Vector Measurement Methods

| Mode     | Natural Frequency error (%) | Damping ratio error (%) | Mode shape error (%) |
|----------|-----------------------------|-------------------------|----------------------|
| 1st mode | 0.06                        | 13.10                   | 0.05                 |
| 2nd mode | 0.36                        | 0.0                     | 0.87                 |
| 3rd mode | 0.45                        | 7.97                    | 0.90                 |

Note that two diagonal lengths are used for the eight-vector measurement method in Eq. (1) because the rectangular shapes are not preserved. The mode shapes are not unique values, unlike the natural frequencies and damping ratios. A value of $\varepsilon$ is used in Table 3 considering that the ratio of the length of the longer side to the length of the shorter side of the wooden building is 2:1 (Fig. 5).

It can be seen from Table 3 that the natural frequency error between two measurement methods is very small, with values of less than 0.5%. However, the damping ratio error is relatively large. Considering that the uncertainty of the damping ratios is larger than that of the natural frequencies when ambient vibration data...
are used, this discrepancy between the two methods can be considered insignificant (Haviland, 1976).

The mode shape errors are also very small, with values of less than 1%. This means that the mode shapes are not significantly different from the original rectangular shapes, even though the original shapes are not perfectly preserved by the rigid diaphragm. That is, some degree of diaphragm action occurs due to the roof rafters and joists, even though there are no floor slabs constraining the lateral movements of the columns. Therefore, it can be concluded that it is reasonable to apply the three-vector measurement method to in situ AVT of historic single-story wooden buildings.

In practice, violation of the rigid diaphragm assumption can be detected by installing one more sensor when the three-vector measurement method is employed. The extra sensor should be installed in the x-axis direction on a column on which only one other sensor is to be installed (e.g., column ③ in Fig.5.(a)). Violation of the rigid diaphragm assumption can be detected easily by comparing the two diagonal lengths of each mode shape.

4. Application of Three-Vector Measurement Method to AVT of the Historic Wooden Buildings Designated as National Treasures

4.1 Description of Buildings

The three-vector measurement method was applied to eight historic wooden buildings that are designated as national treasures in Korea (Fig.12.). These buildings are located in Gyeonnam Province, Korea. Three of these buildings—Geungnakjeon, Josadang, and Murayngsujeon—were built during the Goryeo dynasty (Table 4.). Especially, Geungnakjeon is the oldest wooden building in Korea. The other five buildings were built during the Joseon dynasty. All eight buildings have rectangular plans with the ratios of the longer-side dimension to the shorter-side one ranging from 1.53 to 1.99:1 (the exception is Janggyeompanjeon). The lateral resistances of eight buildings are provided by wooden structures while exterior clay walls are installed to provide weather protection.

The same accelerometers, data logger, and measurement settings as those used in the verification example were used for in situ AVT of the eight historic wooden buildings. Only three accelerometers were used and these accelerometers were installed on the tops of columns. The dynamic properties determined from AVT using the three-vector measurement method are presented in Table 5. and Figs.13. to 15. The first-mode natural frequencies of the historic wooden buildings range from 1.3051 Hz to 3.1674 Hz, and the damping ratios range from 1.06% to 2.25%.

![Figures](a) Geungnakjeon, Bongjeongsa (b) Daewungjeon, Bongjeonsa (c) Younsanjeon, Eunhaesa (d) Murayngsujeon, Buseoksja (e) Josadang, Buseoksja (f) Janggyeompanjeon, Haeinsa (g) Sebyunggwan (h) Daewungjeon, Tongdosa

Fig.12. National Treasure Wooden Buildings Under Investigation

| Building                  | Built    | Dimension (mm) |
|---------------------------|----------|----------------|
| Geungnakjeon, Bongjeongsa | 13th century | Width 11,725, Depth 7,001, Height 5,449 |
| Daewungjeon, Bongjeonsa   | 14th century | Width 13,432, Depth 8,179, Height 7,638 |
| Yeongsanjeon, Eunhaesa    | 1375     | Width 31,160, Depth 10,380, Height 7,540 |
| Murayngsujeon, Buseoksja  | 1376     | Width 18,754, Depth 11,501, Height 8,589 |
| Josadang, Buseoksja       | 1377     | Width 9,284, Depth 3,967, Height 4,181 |
| Janggyeompanjeon, Haeinsa | 1488     | Width 60,507, Depth 8,980, Height 6,277 |
| Sebyunggwan               | 1604     | Width 33,976, Depth 17,004, Height 10,383 |
| Daewungjeon, Tongdosa     | 1641     | Width 15,822, Depth 11,078, Height 9,833 |
Even though all buildings are rectangular in shape, only three buildings were found to have their first translational mode in the transverse direction and their second translational mode in the longitudinal direction (Case I). Three of the buildings were found to have their first translational mode in the longitudinal direction and their second translational mode in the transverse direction (Case II). The third mode was found to be a rotational mode for both Cases I and II.

For two of the buildings, the first mode was found to be a translational mode in the transverse direction, and the second mode was found to be a rotational mode (Case III). The third mode for these buildings was found to be a translational mode in the longitudinal direction.

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The diversity of modal directions illustrated in Figs. 13 to 15 is attributable to the lateral resistance of historic wooden buildings being affected by not only the plan proportions but also the number of columns in each direction, the diameters and heights of the columns, the depths of the beams, the depths of the beam–column connections, and various other factors.
5. Conclusion

The applicability of the three-vector measurement method based on the rigid diaphragm assumption to historic wooden buildings was experimentally investigated by comparing the results of the three- and eight-vector measurement methods. The three-vector measurement method was found to be applicable to in situ AVT of historic single-story wooden buildings, even though such buildings do not behave rigidly to some degree.

In situ AVT of historic wooden buildings that are designated as national treasures in Korea were performed using the three-vector measurement method. The direction of the first mode was found to depend not only on the plan proportions of the building but also on various other factors.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (NRF-2010-0023976).

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