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Evaluating environmental factors using microclimate survey and computer fluid dynamics analysis of Korean traditional wooden architectural cultural heritage: focusing on the Kim Myeong-KwanGotaek

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Abstract

Preservation of traditional wooden buildings is important to extend their life and to adapt them to modern society. Wood can be subject to decay, cracking, and discoloration when exposed to various climatic environmental factors, such as moisture and temperature. These issues can be particularly problematic for wooden architecture because they can compromise the durability of the building and reduce its aesthetic appeal. Therefore, in this study, we evaluated the microclimate environment of Kim Myeong-Kwan Gotaek, a wooden building important to the cultural heritage of Korea, using climate measurement equipment and computational fluid dynamics modeling. The results showed that relative humidity changes according to wind velocity and temperature. Therefore, heritage managers should aim to allow air to circulate inside such buildings as an effective strategy for preventing the decay of wooden architecture. The study provides valuable insights into how to preserve and extend the life of traditional wooden buildings. Our findings highlight the importance of developing practical measures based on analyses of the natural environment to protect such culturally important building for posterity.

Keywords Temperature, Relative humidity, Wind velocity, Preservation and utilization, Actual measurement

Introduction

Temperature and humidity are major climatic factors influencing wood decay in wooden architecture. High temperature and humidity levels in Korea make wooden architecture susceptible to damage. Nevertheless, many wooden architectural heritage structures in Korea are more than 200 years old, with most being constructed during the Joseon Dynasty (1392–1897). Korea's wooden architecture repair records indicate that it typically takes approximately 100–150 years before repairs are needed [1]. However, this repair time has shortened to 30–50 years owing to changes in climate and management methods. According to a study by [2], Korea's risk of wood decay has increased because of rapid changes in climate conditions between 2003 and 2012. Wooden architecture comprises mostly natural materials such as wood, soil, and stone [3]. Natural materials can be deformed both physically and biologically by climatic factors, such as temperature and humidity [4]. [5] reported that the walls of wooden buildings dry because of convection, and directly measured and analyzed the effect of a humid environment in an indoor swimming pool made of laminated wood [6]. Directly measured the

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climatic conditions of wooden architecture located in a mountainous area and presented a decay environment whereby temperature, humidity, and wind speed affected geographical conditions [7]. Moreover, a study by [8] reported on degradation in wooden buildings according to internal and external temperature and humidity. Used computational fluid dynamics (CFD) for a climate analysis at the Wanju Hwaamsa temple and suggested an alternative to improve air flow in it [3]. Furthermore, [9] determined the temperature and humidity at the Haeinsa Temple Janggyeong Panjeon, a World Heritage Site, to determine decay factors. Reported in a study of farmhouses in the Meiji period (1868–1912) that most were built in line with the prevailing wind direction [10]. As such, climate-related research is being conducted to examine issues that occur in wooden architecture, both domestically and abroad; however, direct examination of old wooden buildings is currently insufficient.

Visual inspection is common in investigations of architectural cultural heritage due to the scale of buildings and their outdoor environment. Therefore, it is difficult to ensure reliable results because evaluations differ depending on the experience and expertise of the investigator. To solve these problems, an objective analytical method based on physical measurements and statistical analysis is urgently needed. Also, in heritage conservation research, simulation modeling [11] can be used to visual [12] assess microclimate change and is an increasingly important tool [13].

Investigated the influence of temperature and humidity on desorption isotherms [14]. Focused on environmental moisture content changes in temperature-dependent sorption isotherms [15]. According to this, the moisture content of wood is around 15% at a relative humidity of 80%, and the moisture content increases as the relative humidity increases. According to [16], the moisture content of wooden buildings increases by 12–17% when the relative humidity is ≤ 80% and increases by 17–23% during cloudy conditions. At night, Korea's relative humidity tends to be > 80%, decreasing below this during the day. Although there is a time differentiation, these humidity changes occur regardless of the season.

According to a study by [17], wood can be dried at an average daily temperature of ≥ 7 °C, labeling a month with temperatures of > 25 °C "a good air-drying month." Evaluated the relationship between wood drying and wind [18]. In this study, the wind speed required for wood drying was 1–2 m/s, but a strong wind speed of 4–5 m/s is also applicable, owing to technological advances in equipment that determines the temperature, humidity, and wind speed. In wood conservation studies, [19] asserted that decay fungi thrive at temperatures between 25 and 30 °C and 80% humidity. Moreover, wood that has a moisture content of > 20% should be monitored for decay fungal growth. It is not the climatic environment of the measurement time that affects the moisture content of wood, but rather previous environmental conditions. Hence, it is necessary to measure and analyze temperature, relative humidity, and wind data over a certain period. Here, the data obtained from climatic equipment installed at the Kim Myeong-Kwan Gotaek site itself was analyzed rather than data collected from weather stations. The airflow around the building was also analyzed using CFD, which simulates the wind environment.

The aim of this study was to objectively analyze and evaluate the climatic environment of wooden architecture older than 200 years. We focused on the Kim Myeong-Kwan Gotaek (hereafter, referred to as "Gotaek") as a case study. We directly measured and analyzed the climate environment with a method developed through literature review. We also analyzed directly obtained field data of the climatic environment of these buildings. Our findings demonstrate that analyzing climate environment measurements is appropriate for investigating environments such as wooden cultural properties, and CFD simulation showed potential as it can predict changing conditions.

However, despite the potential of these methods, modeling and environmental condition determination need a defined process to increase legitimacy through continuous research. In addition, the amount of measurement equipment available is a limiting factor for measuring variables given the large sites containing many buildings and the degree of change in the outdoor environment. Nevertheless, this study confirmed the necessity of accumulating scientific data to preserve and utilize architectural heritage.

Materials and methods

Study site

The Gotaek in Jeongeup is a 230-year-old upper-class house built around 1784, designated as the National Folk Cultural Property No. 26 (1971). Figure 1 represents a panoramic view of the Gotaek, which has typical geographic features such as a mountain (the Cheongha) in the back (north) and a river (the Dongjingang) in the front (south). The house is in a southeast direction, facing away from the Hwagyeonsan Mountain, with an Ansan in the front. A pond in the front yard suppresses the energy of the Hwagyeonsan Mountain. In the Joseon Dynasty, upper-class houses were built based on geomancy, with the left side as the focal point of the arrangement [20].

There is a Munganchae in the front, Sarangchae in the east, Haengrangchae and Anchae in the north, Sadang in the northeast, and Ansarangchae in the west, and it is surrounded by a 1.7 m high fence.

Fig. 1 Aerial photo and view of Korean traditional architectural heritage (Kim Myeong-KwanGotaek)

In Korea, the "Munganchae" serves as the main entrance to and from a house and is a building connected to the wall that forms the boundary. The "Sarangchae" is the primary living space for men and functions as a social hub. The "Haengnangchae" is a building where servants live and is connected to the entrance door or serves to protect the main building. The "Anchae" is a living space for women and for preparing meals and is typically located as far away as possible from the main gate. The "Ansarangchae" is an additional living space for married children. The "Sadang" serves the function of worshipping ancestors and is usually located in an easily accessible place in the sarangchae where men live.

Jeongeup is located between latitude 35°27′–35°45′ and longitude 127°07′–126°43′. The geographical topography of Jeongeup is high in the southeast and low in the northwest. Jeongeup has a climate characteristic of the west coast of Korea, which includes heavy snowfall in winter. Northwesterly winds are common during this season, while southeasterly winds are common at other times. The average wind speed is around 1.5 m/s, the average annual temperature is around 13 °C, and the amount of precipitation is around 1,100 mm.

In Korea, the temperature has risen by 1.4 degrees in the last 30 years compared to the period of 1912–1941. The average annual temperature during the 2010s (2011–2017) was the highest at 14.1 °C. Precipitation has also increased by 124 mm during the past 30 years, showing significant variability. Summer has become 19 days longer, and winter has become 18 days shorter, resulting in regional droughts and floods [21]. As such, the climate of Korea has changed rapidly since 2000, increasing the risk of wood decay.

Buildings in the Honam region are characteristically laid out in consideration of the high-temperature and -humidity environment. The Gotaek is surrounded by the Dongjin River and mountains, so it is a topographical environment with high relative humidity. Therefore, the Gotaek is also laid out to separate the buildings as shown in Fig. 1. These grounds have been maintained in this way for more than 200 years since the Gotaek was built in the 1780s.

Nevertheless, since its designation as a cultural property (1971), there have been more than 40 times at which repair and maintenance, such as wood replacement, have been necessary. Approximately 2.5 billion won of public money has been spent on maintenance, with future management requiring a continuous budget [22]. Consequently, negative perceptions could arise that this heritage site is merely a "budget waster".

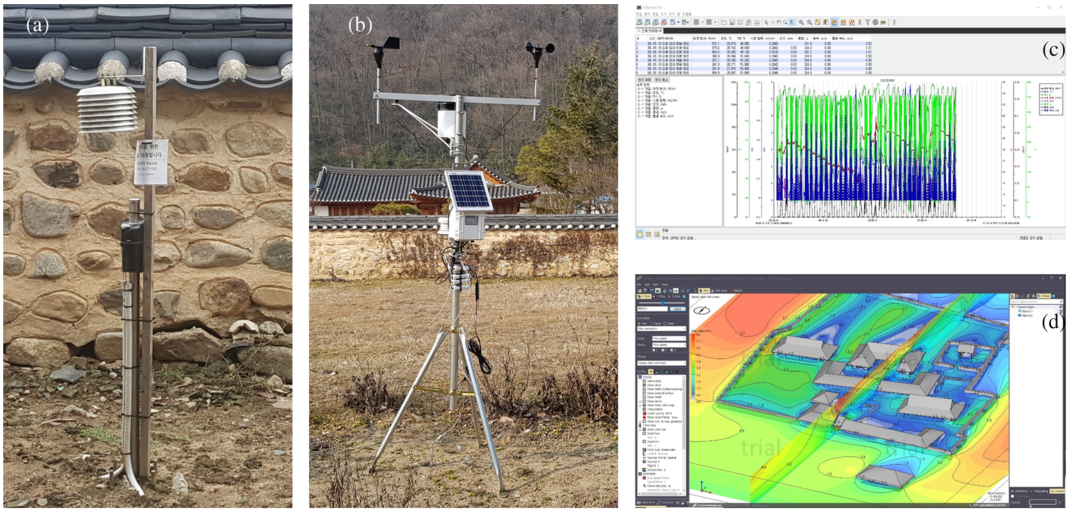
Figure 2 shows a photo of wood decay and repair work at the Gotaek. In this way, despite the building layout considering the natural environment, damage such as decay continues to occur even after designation as a cultural property. Therefore, it is thought that management decisions need be based on the scientific analysis of the relationship among relative humidity, temperature, and wind speed through direct measurements of the climatic environment of the place where the old house is located. Accordingly, the Gotaek was selected as the subject of study. The climate measurement of the Gotaek was conducted with permission from Jeongeup City.

Measurement methods and location

We measured changes in temperature, relative humidity, and wind speed to identify the microclimate of the Gotaek. The weather measurement equipment was installed as shown in Fig. 3. An onset HOBO data logger was installed from locations 1 to 6 for temperature and relative humidity measurements. We used the Onset HOBO U23 Pro V2 (U23-0001A), with a humidity measurement range of 0–100% (±2.5%). The temperature measurement range was −40–70 ℃ (±0.2 ℃). The HOBO device's measurement location was 1.2 m

(a) Deteriorated wooden roof structure of the Gotaek (b) Repaired wooden roof structure of the Gotaek

Fig. 2 Wood decay and repair of the Kim Myeong-KwanGotaek



(a) Temperature and relative humidity-measuring devices (c) HOBO ware program
(b) Wind velocity and direction-measuring devices (d) Flow Designer program(AKL)

Fig. 3 Meteorological equipment and program used above ground level, with measurement intervals between relative humidity and temperature automatically set to 10 min. The wind direction and wind speed in the Gotaek was measured by installing the Onset HOBO U30-NRC equipment at location A. The measurement range for wind speed was set at 0–76 m/s, and 0–360° (+5°) for wind direction. The wind direction and wind speed measurement locations were 2 m above the ground level. The measurement interval was automatically set to 10 min. CFD, which simulates wind flow, was used with the FlowDesigner program of Advanced Knowledge Laboratory Inc. (AKL).

The temperature, relative humidity, wind direction, and wind speed of the Gotaek were measured for 1 year from December 1, 2020, to November 30, 2021. Figure 4 indicates the measurement locations for temperature, relative humidity, wind direction, and wind speed. Temperature and relative humidity were determined at six points—three internal and three external. Wind direction and speed measurements were taken at point A. Table 1 indicate the names of the measurement locations. Table 1 shows the locations and names of climate measurements.

Table 1 Climate measurement locations

NO	Location	Latitude	Longitude
1	Anchae internal	35.6163	127.0199
2	Anchae back madang(external)	35.6163	127.0198
3	Sarangchae internal	35.6162	127.0202
4	Sarangchae front madang(external)	35.6161	127.0202
5	Ansarangchae internal	35.6161	127.0197
6	Ansarangchae front Madang(external)	35.616	127.02
A	Munganchae front	35.6159	127.0201

Results

Weather station and actual data analysis

We compared the Gotaek microclimate data with the Jeongeup Weather Station data (15.2 km away) for 1 year. Figure 5 shows the internal and external temperatures at the Gotaek and seasonal changes in average temperature and relative humidity at the Jeongeup Weather Station. As shown in Fig. 5a, the average temperature measured internally and externally at the Gotaek showed a small difference from that of the Jeongeup Weather Station. The difference in the

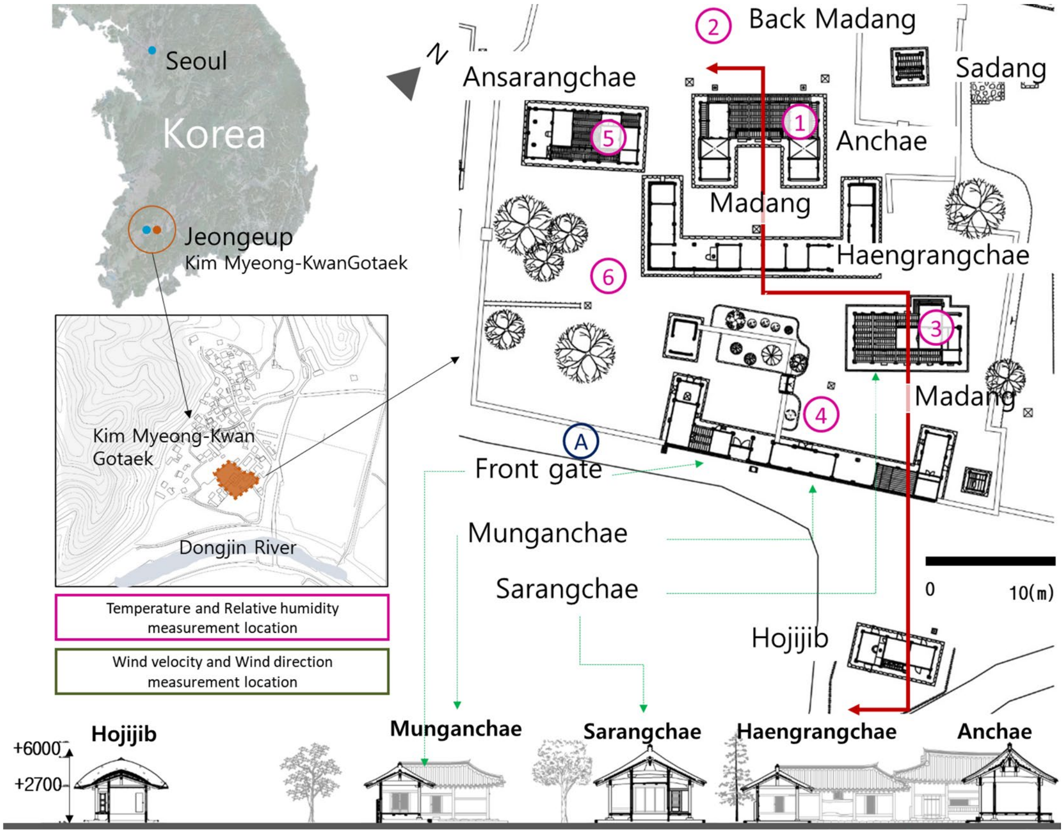
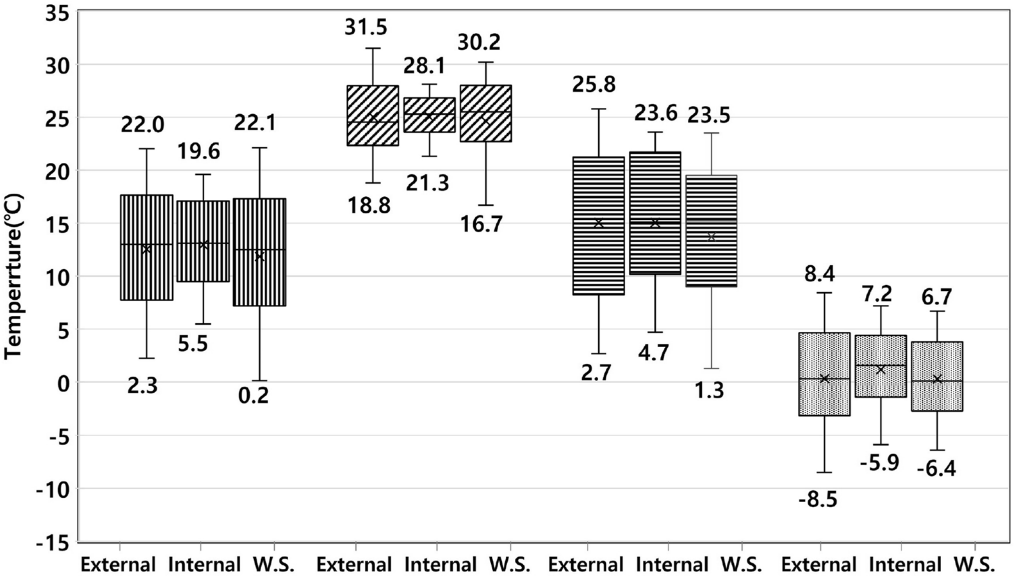
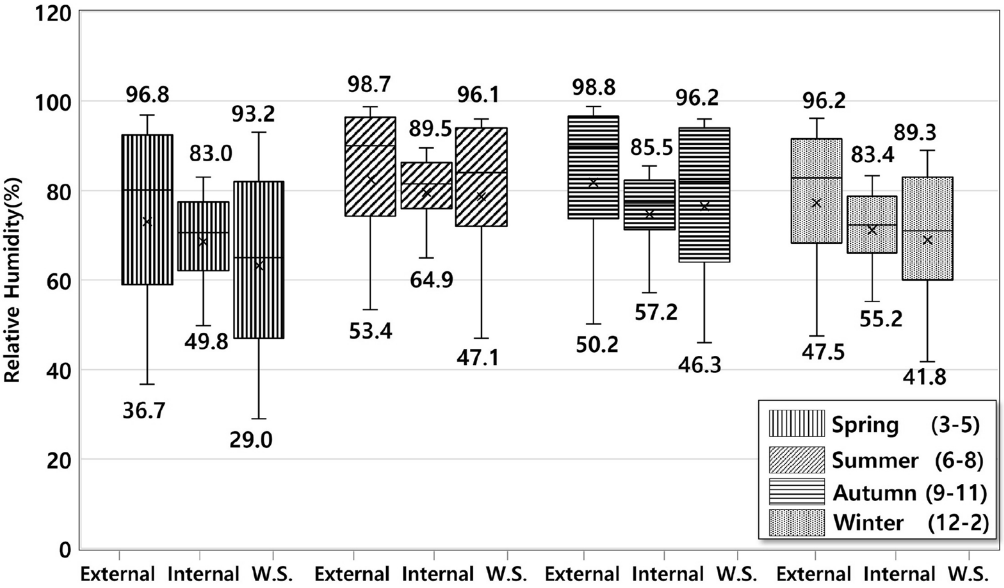


Fig. 4 Locations of temperature, relative humidity, wind direction, and wind velocity measurement points



(a) Temperature



(b) Relative humidity

Fig. 5 Seasonal data from the Gotaek and the Jeongeup weather station (W.S.)

maximum and minimum average temperature between the Gotaek and Jeongeup Weather Station was 2 °C and 3–5 °C externally and internally, respectively. There was a large difference in seasonal daily temperatures measured in the Gotaek microclimate in the following order: autumn > spring > winter > summer. Regarding the difference in internal and external daily temperature in Fig. 5a, we found a difference of approximately 3–6 °C. In particular, in spring and autumn, the external temperature change differed by up to 20 °C.

This is an increase of more than 54% from summer, the season with the smallest daily temperature difference. The difference in internal daily temperatures in seasons except winter was up to 36% less than that of the Jeongeup Weather Station.

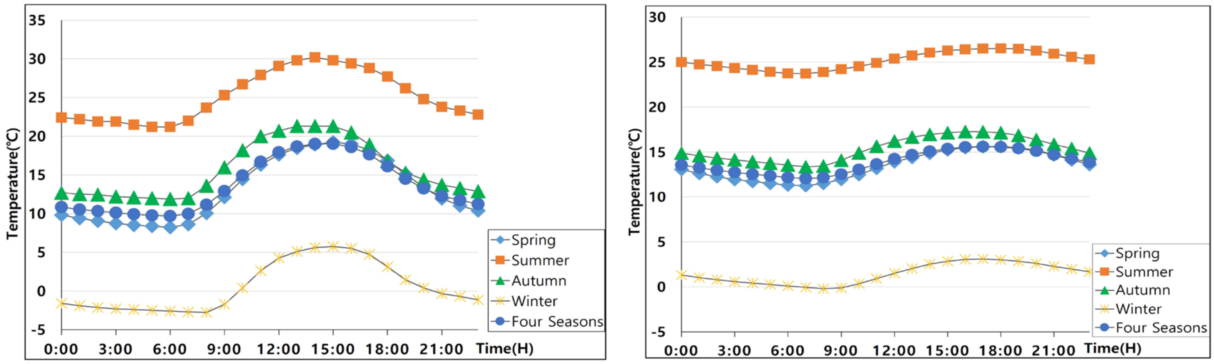
As shown in Fig. 5b, the results of the seasonal analysis of relative humidity revealed that the external Gotaek relative humidity varied within 10% of that at the Jeongeup Weather Station. However, internal relative humidity showed 10–20% more difference than external and Jeongeup Weather Station. In addition, the relative humidity deviation was 45–60% externally and 25–33% internally, with a narrow range of changes in the internal relative humidity. This indicates that the maximum internal relative humidity is low, but with a small degree of decline, so the relative humidity is maintained at a high level.

The range of relative humidity fluctuations was found to increase by more than 25% in spring than in summer and autumn, when the temperature was high. In addition, In summer and autumn, the Gotaek's external relative humidity exceeded 80% on average. If the relative humidity is maintained at >80%, the moisture content of wood increases with a moisture content of ≥20% causing decay and deterioration and leading to a decrease in durability. Therefore, it was found that it is appropriate to directly measure and analyze Gotaek rather than Weather Station data.

Distribution characteristics of internal and external temperatures and relative humidity by time in a season

Figure 6 represents the internal and external temperature distribution by time in a season. Compared to the average temperature per year, the fluctuation in external temperature by period varied by 2 °C in spring and autumn and 12 °C in summer and winter. Temperature changes were uniformly distributed within 8–11 °C, regardless of the season (Fig. 6a). Unlike the external temperatures, the internal temperature changes by time were uniformly distributed within 5 °C (Fig. 6b). For both internal and external, the average temperature for each season was high in the following order: summer > autumn > spring > winter.

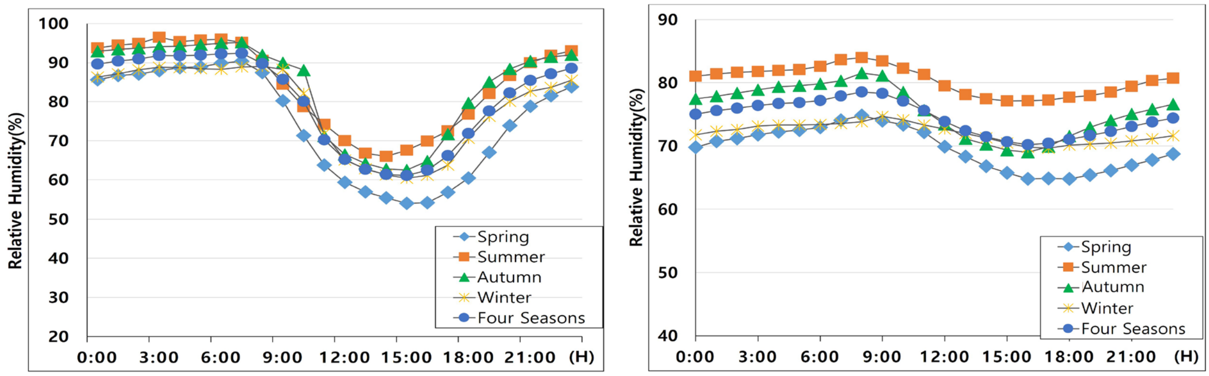
Figure 7 shows the distribution of internal and external relative humidity by time in a season. Based on the



(a) External

(b) Internal

Fig. 6 External and Internal temperature by season



(a) External

(b) Internal

Fig. 7 External and Internal relative humidity by season average annual relative humidity, the changes in internal and external relative humidity are distributed in an S-shape. Unlike temperature changes, the change in relative humidity was distributed within 10% of the annual average relative humidity, regardless of the season. Figure 7a and b show the change in relative humidity over time, showing a difference of more than 30% outside. However, the inside experienced a slight change of within 10%. Based on the relative humidity of 80%, the fluctuation range is the largest in spring, as it decreases by 25% externally and 15% internally. Conversely, summer showed the smallest fluctuation, with a decrease of 14% externally and 3% internally.

As such, internal and external seasonal relative humidity was higher in summer and autumn than in spring and winter. These environmental factors can affect the moisture content of wood.

As a result of analyzing the actual microclimate data, the temperature and relative humidity changes between internal and external showed time-dependent differences. This seems to be due to the difference in the specific heat of building materials, such as stone, soil, and wood, along with sunlight. In addition, the wind flow is not as smooth inside as it is outside because there is a wall inside the room. Thus, it was determined that the climate analysis method using actual measurements is appropriate when the environment surrounding the structure is diverse, such as the Gotaek.

External and internal correlation regarding temperature and relative humidity changes

Internal and external correlations at the Gotaek were analyzed for changes in temperature and relative humidity. The correlation coefficients of six measurement locations were calculated using Eq. (1):

$$\mathrm{r}_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{(n-1)S_x S_y} \tag{1}$$

where ¯x and ¯y and Sx and Sy are the averages and standard deviations of x and y, respectively. Table 2 shows the correlation coefficient for each measurement location based at Anchae back madang (location 2, external). The closer the correlation coefficient is to ± 1, the stronger it is.

Table 2 shows the temperature and relative humidity. The outside of the Gotaek showed a strong correlation of 0.98 or higher. This means that the external climatic environment of the Gotaek is not affected by the measurement location and distance. The external and internal temperature correlation coefficient of the Gotaek was 0.6–0.8, which is moderate. The correlation coefficient

Table 2 Correlation coefficients by measurement location

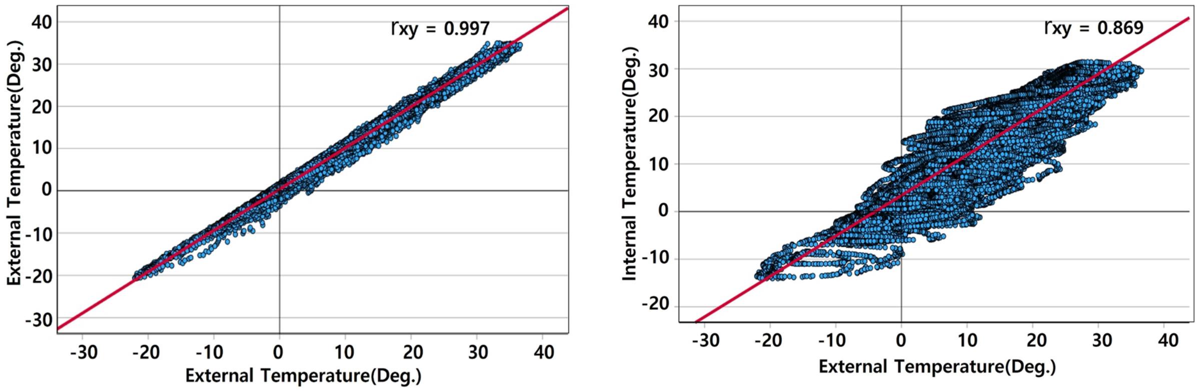
(a) Temperature

No	Location names	Correlation coefficient			
		Temperature			
		Spring	Summer	Autumn	Winter
1	Anchae internal	0.786*	0.632*	0.772*	0.725*
3	Sarangchae internal	0.869*	0.674*	0.884*	0.837*
4	Sarangchae external	0.997*	0.98*	0.987*	0.99*
5	Ansarangchae internal	0.773*	0.658*	0.851*	0.827*
6	Ansarangchae external	0.998*	0.983*	0.99*	0.99*

(b) Relative humidity

No	Location names	Correlation coefficient			
		Relative humidity			
		Spring	Summer	Autumn	Winter
1	Anchae internal	0.366*	0.394*	0.307*	0.185*
3	Sarangchae internal	0.762*	0.543*	0.723*	0.604*
4	Sarangchae external	0.995*	0.983*	0.983*	0.988*
5	Ansarangchae internal	0.449*	0.454*	0.588*	0.563*
6	Ansarangchae external	0.997*	0.991*	0.992*	0.992*

[*] The correlation is significant at level 0.01. [Based on Anchae back madang(external) (location 2)]



(a) 2. Anchae external – 6.Ansarangchae external

(b) 2. Anchae external – 3.Sarangchae internal

Fig. 8 Temperature data correlation graph by measurement location

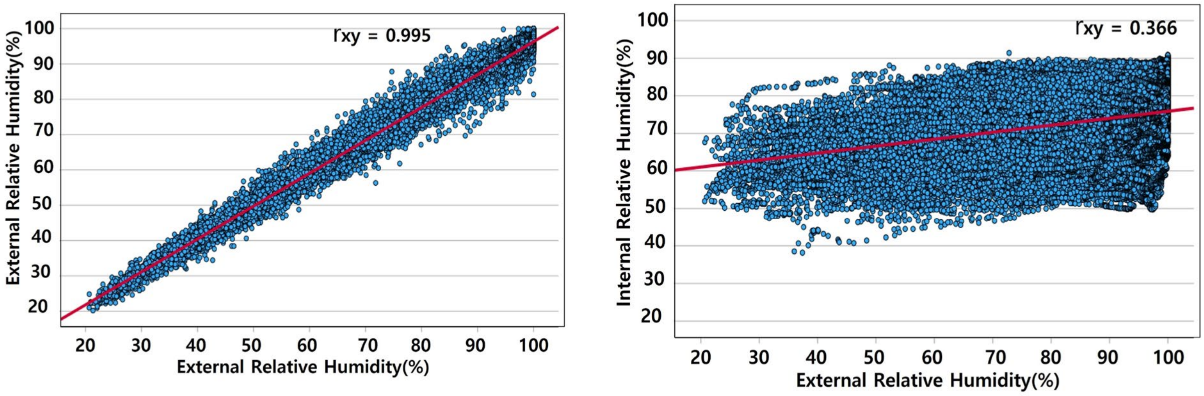
for relative humidity was 0.1–0.7, with differences by season and measurement location.

Figure 8 shows a correlation graph of annual average temperatures according to the measurement location. Figure 8a shows the external and external correlation coefficient of 0.997, and Fig. 8b shows the internal and external correlation coefficient of 0.869. The correlation graph in Fig. 8b shows a wider distribution than that in Fig. 8a. Therefore, it seems appropriate to interpret correlation coefficients in Table 2 of 0.98 or higher as strong correlations. These results were similar to those for the relative humidity correlation graph in Fig. 9. This analysis is important for wooden architecture because the main structural material dividing the internal and external is wood. Cracks may occur in the wood depending on the difference in temperature and relative humidity between the internal and external environments. Therefore, to comprehensively analyze the characteristics of location and season, it is necessary to measure internal and external climate simultaneously.

Distribution of wind speed and direction by time

The wind speed measured for 1 year was summarized and analyzed as the average wind speed by period (Fig. 10). The average wind speed measured for 1 year in 10 min intervals did not exceed 0.4 m/s. The average wind speed by period increased from 8 AM to 12 PM and remained consistent until 2 PM. The wind then gradually decreased from 2 to 6 PM and remained constant in the evening. Figure 10b shows that the maximum wind speed during the measurement period was 2–3 m/s from 8 AM to 6 PM; thereafter, it was maintained at ≤2 m/s. Figure 11 illustrates the analysis of the seasonal wind direction.

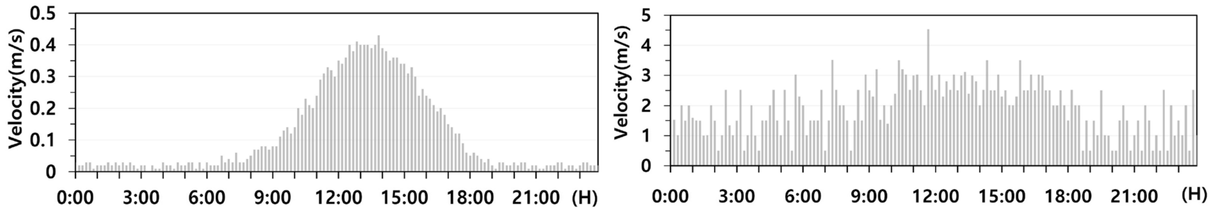
The main wind direction angles at the Gotaek are SSW and E with changes per season: spring (SSW, E), summer (E), autumn (E, N), and winter (SSW). The main wind



(a) 2. Anchae external – 4.Sarangchae external

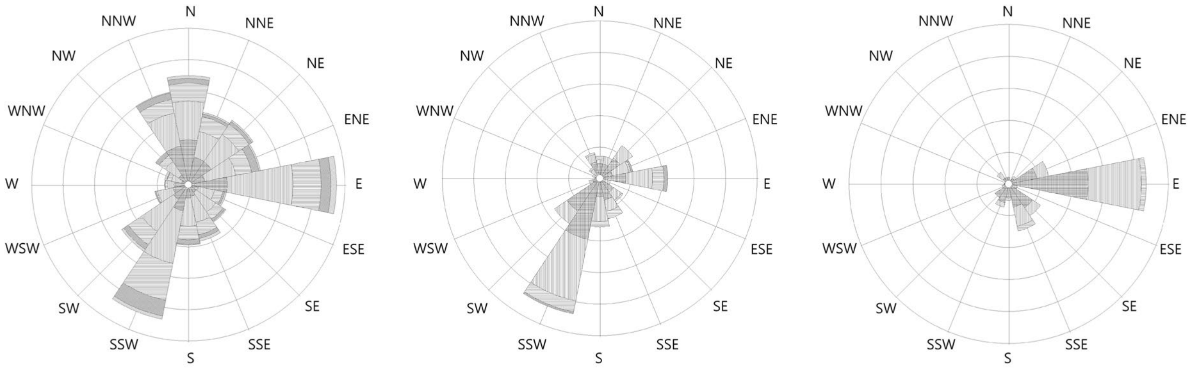
(b) 2. Anchae external – 1. Anchae internal

Fig. 9 Relative humidity data correlation graph by measurement location

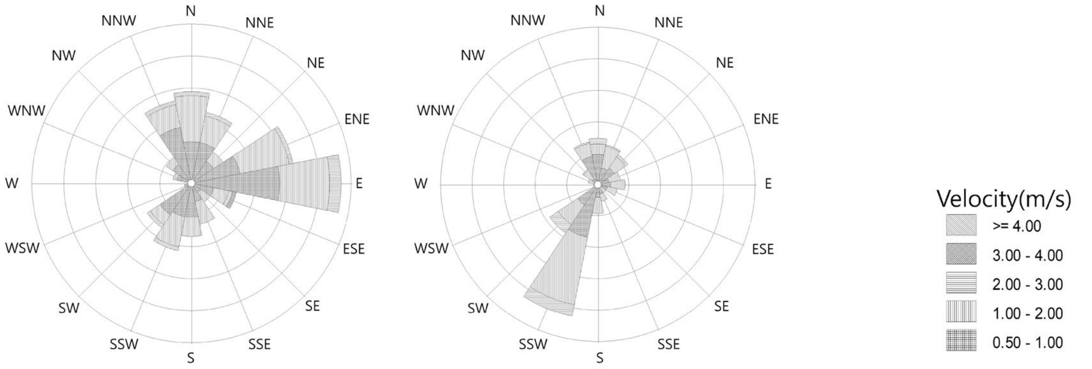


(a) Mean (b) Max

Fig. 10 Mean and maximum wind velocities by time of day



(a) Season (b) Spring (c) Summer



(d) Autumn (e) Winter

Fig. 11 Changes in wind direction by season

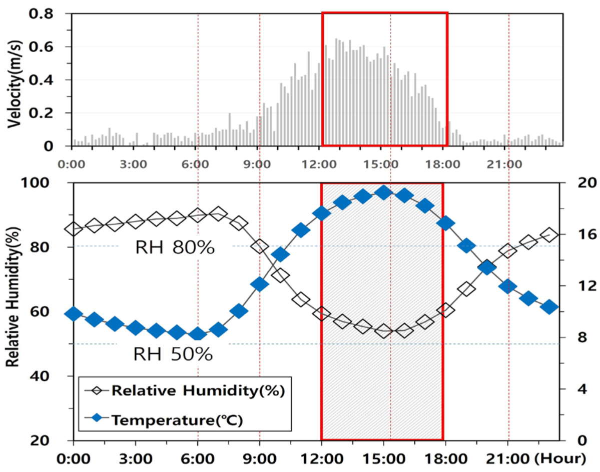
direction angle was measured within the N-SSW range although this changes per season.

Temperature and wind speed correlation regarding changes in relative humidity

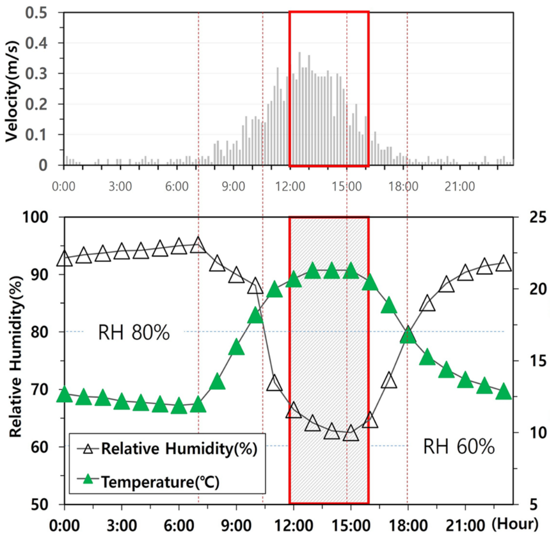
Changes in relative humidity, temperature, and wind speed at the Gotaek were compared as shown in Fig. 12. According to the distribution by period, the temperature rose between 6 AM and 3 PM, the wind speed increased until 12 PM and remained constant until 3 PM and the relative humidity decreased until 3 PM. After the maximum values were reached, the temperature, relative humidity, and wind speed changed in opposite directions, with a wide range of change.

The analysis was based on a relative humidity of 80%, a value that affects the moisture content of wood. As a result, the time to keep the relative humidity lower than 80% was the longest at 12 h in spring, 9 h in summer and winter, and the shortest at 7 h in autumn.

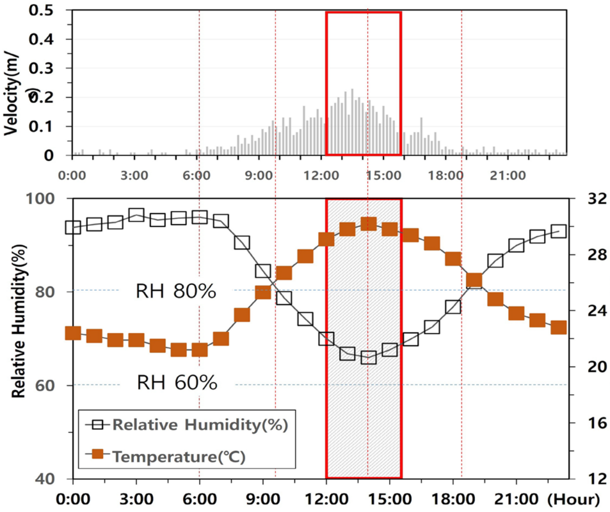
This means that the wood-drying period is short in spring and long in autumn. The average annual wind speed measured at the Gotaek was < 0.4 m/s with wind speeds in spring and winter exceeding this. In spring, the relative humidity of < 80% remained 2–3 h longer



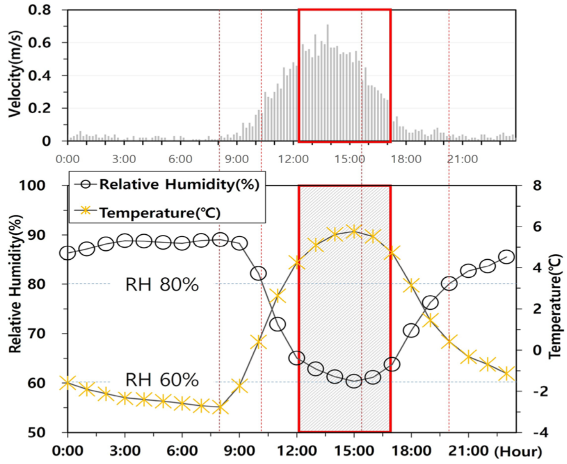
(a) Spring



(c) Autumn



(b) Summer



(d) Winter

Fig. 12 Comparative analysis of changes in wind speed, temperature and relative humidity by season

than in summer and autumn. In addition, in spring, the relative humidity was 10% lower than in summer at times when the wind speed was strong. As such, the relative humidity was low in the season when the wind speed was relatively strong. Furthermore, the time when the relative humidity was the lowest was found to be within 2 h after the wind speed reached its maximum value.

Table 3 shows the correlation between the change in relative humidity measured over a year, along with the temperature and wind speed. The correlation coefficient showed slight differences by season. Looking at the correlation between relative humidity and temperature in Table 3, it was high in the order of summer > spring > winter > autumn. This was different from the order of average temperature measured at the Gotaek, which was

Table 3 Correlation coefficient of temperature and wind speed to relative humidity change

Based on relative humidity	Season	Spring	Summer	Autumn	Winter
Temperature (℃)	−0.103*	−0.535*	−0.697*	−0.251*	−0.393*
Wind speed(m/s)	−0.446*	−0.511*	−0.256*	−0.355*	−0.451*

* The correlation is significant at level 0.01

summer > autumn > spring > winter. The correlation between changes in relative humidity and wind speed was high in the order of spring > winter > autumn > summer, same as the pattern of seasonal wind speed in Fig. 12.

These results are presumed to be due to the natural environment, in which the measured temperature is lower in spring than in autumn, but the wind is strong, and the leaves on trees are smaller than in autumn, allowing them to receive more sunlight. As such, wind has an additional effect on the change in relative humidity in conjunction with temperature. Currently, no one lives in the Gotaek, so it is difficult to manage ventilation to lower the relative humidity of building internally and externally. Therefore, it seems necessary to open windows or build a ventilation system during the time when the relative humidity is high. Only then can it be possible to continuously extend the life of traditional buildings that have been maintained for 200 years.

Skewness and kurtosis by measurement location

The distribution shape was analyzed for skewness and kurtosis to identify the range of changes in relative humidity and temperature affecting the Gotaek. On the basis of 1-year measurements, Table 4 shows the skewness and kurtosis of seasonal data by measurement location. Equation (2) represents skewness, and (3) kurtosis:

$$S_k = \sum_{i=1}^{n} \frac{[(x_i - \bar{x})/S]^3}{n-1} \tag{2}$$

$$K_t = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^4}{\left(\sum_{i=1}^{n} (x_i - \bar{x})^2\right)^2} \tag{3}$$

where n is the number of data, S the standard deviation, x_i the raw data, and $\bar{x}$ the mean.

The kurtosis and skewness analysis according to the climatic environment and season by measurement location (inside and outside the building) is positive and negative. Therefore, it is considered valuable because it is possible to visually understand the numerical value of the difference according to the season.

In other words, if the skewness value is negative (−), it is skewed to the right and has a long tail in the negative direction, and if it is positive (+), it is skewed to the left and has a long tail in the positive direction (Fig. 13). If the skewness value is close to zero, it takes the form of a normal distribution that is almost symmetric. If kurtosis is positive (+), the standard deviation is smaller, so the distribution is sharper than the normal distribution. In the case of a negative value (−), it has a gentle distribution shape and with a value close to 0, a normal distribution shape.

According to [23], the normal distribution shape is < 3 for skewness and < 8 for kurtosis. This means that the

Table 4 The Skewness and Kurtosis of temperature and relative humidity by season

Classification		1	2	3	4	5	6
(a) Temperature							
Spring	Skewness	0.062	0.048	0.018	0.031	0.11	0.009
	Kurtosis	−1.096	−0.667	−0.96	−0.691	−1.119	−0.714
Summer	Skewness	−0.067	0.327	−0.138	0.323	0.04	0.247
	Kurtosis	−0.716	−0.2	−0.921	−0.164	−0.531	−0.209
Autumn	Skewness	−0.595	−0.117	−0.011	−0.107	−0.1	−0.138
	Kurtosis	−0.668	−0.876	−0.925	−0.902	−0.975	−0.912
Winter	Skewness	−0.529	−0.008	−0.406	−0.1	−0.461	−0.083
	Kurtosis	0.97	0.718	0.963	0.774	0.94	0.756
(b) Relative Humidity							
Spring	Skewness	−0.181	−0.625	−0.278	−0.631	−0.202	−0.634
	Kurtosis	−0.532	−0.841	−0.756	−0.824	−0.572	−0.833
Summer	Skewness	−0.851	−1.199	−1.365	−1.206	−0.624	−1.201
	Kurtosis	0.962	0.826	3.641	0.915	0.82	0.991
Autumn	Skewness	0.015	−1.019	−1.14	−1.042	−0.429	−1.022
	Kurtosis	−1.066	−0.023	2.06	0.069	−0.008	0.034
Winter	Skewness	−0.23	−0.811	−0.176	−0.826	0.067	−0.787
	Kurtosis	−0.274	−0.147	−0.06	−0.009	−0.177	−0.072

1. Anchae internal, 2. Anchae back madang (external), 3. Sarangchae internal, 4. Sarangchae front madang (external), 5. Ansarangchae internal, 6. Ansarangchae front madang (external)

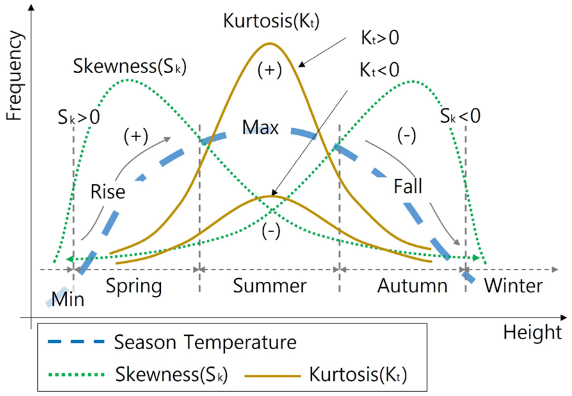


Fig. 13 Skewness and kurtosis distribution

measured data values are included in the normal distribution, so there are no errors or outliers in the measured data.

As can be seen in Table 4, the skewness and kurtosis of temperature and relative humidity were within the normal distribution standard. Looking at the skewness to find out the shape of the temperature distribution, spring and summer had a positive (+) value for each measurement location and were distributed in a high direction. On the other hand, autumn and winter had negative (−) values and were distributed in a lower direction. The relative humidity had a distribution shape in which the skewness had negative values at all locations. This shows the seasonal climate change pattern as shown in Fig. 13.

However, the skewness of the internal temperature in summer had a negative (−) value and was distributed in the low direction, but maintained a certain level. Table 4 shows that the kurtosis of temperature is positive (+) only in winter. The kurtosis of relative humidity was positive (+) in summer and autumn. If the kurtosis is a positive (+) value greater than 0, it has the shape of a distribution with higher kurtosis than the normal distribution. This means that the temperature and relative humidity distributions are formed close to the center, and the climate deviation is small. In particular, the skewness of the internal relative humidity during the summer season was highly distributed as negative (−). In addition, the kurtosis was positive (+) and concentrated close to the mean, indicating that the distribution deviation was small.

When the relative humidity distribution deviation is small, the time that moisture has to leave the wood is short. This is because the relative humidity in Korea rises by more than 80% and becomes almost 100% at night. Wood absorbs moisture during this time. To lower the relative humidity at night to the lowest level during the daytime, sunlight and wind are needed. Therefore, the larger the lowering width, the longer the dehumidification time and the lower the moisture content of the wood is. This means that even if the wood absorbs moisture again, there is a dehumidification process to minimize the growth of decaying bacteria.

It is difficult to manage moisture content, which affects the durability of wood, in architectural cultural heritage such as Gotaek. Also, the measured climate showed different patterns of change according to season. Therefore, it was found that management to widen the climatic environment distribution deviation between summer and autumn with high relative humidity was necessary.

Evaluation of wind flow via CFD analysis according to specific conditions

Finally, CFD analysis was performed based on climate data measured at the Gotaek to study the wind flow (Fig. 14).

It was found that wind is an important influencing factor in lowering the relative humidity. Therefore, wind flow according to management conditions in the Gotaek was evaluated. There were three analysis conditions: 1. according to whether the main gate and windows were open or closed, 2. according to trees, and 3. according to the level of restoration of destroyed buildings.

The reason for these conditions.

1. Ventilation is affected by whether the door is open or not.
2. Many trees are planted around the old house, which obstructs the wind flow.
3. Korea's architectural heritage is interested in restoring some buildings to their original form after they were destroyed. (Level of restoration: the level to which a destroyed building has been restored to its original form.)

AKL Inc's CFD simulation program is compatible with SketchUp, so the Gotaek was modeled and used. The airflow distribution analysis was run with a wind speed of 3 m/s occurring at 20 m above the ground. The Gotaek modeling size is 57 m × 75 m × 10 m. The grid size of the CFD experiment model is 154 m × 186 m × 40 m, and the mesh is 95,448. The airflow used in the analysis was formed with $a = 0.15$, the airflow distribution in the suburbs, and the standard κ—ε was used as the turbulence model.

The Flow Designer wind direction condition was set to Southwesterly with a wind speed of 3 m/s. The analysis point was set to less than 1.5 m above the ground.

The color displayed in the CFD analysis represents the wind strength. Blue corresponds to 0 m/s, while red corresponds to 4 m/s. The arrows indicate the direction

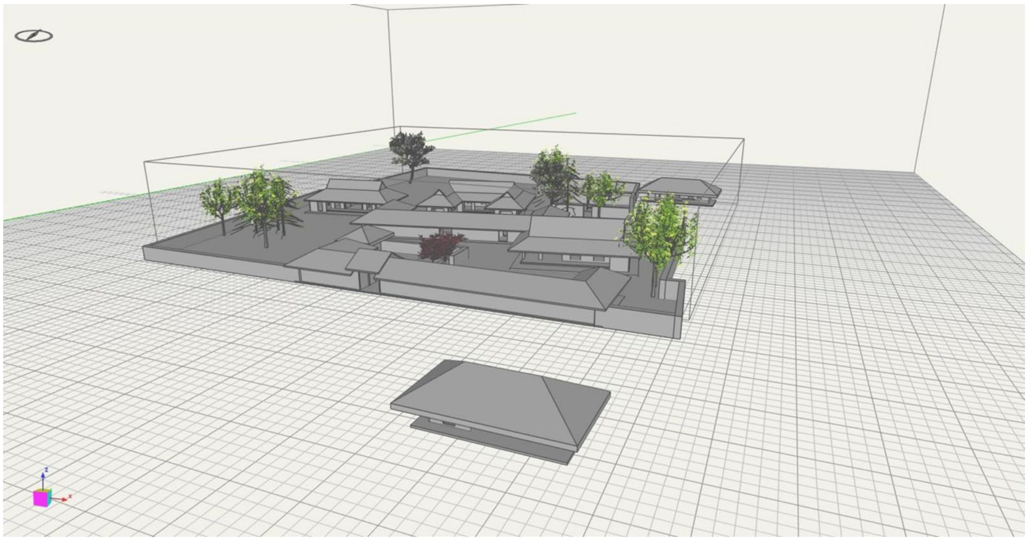
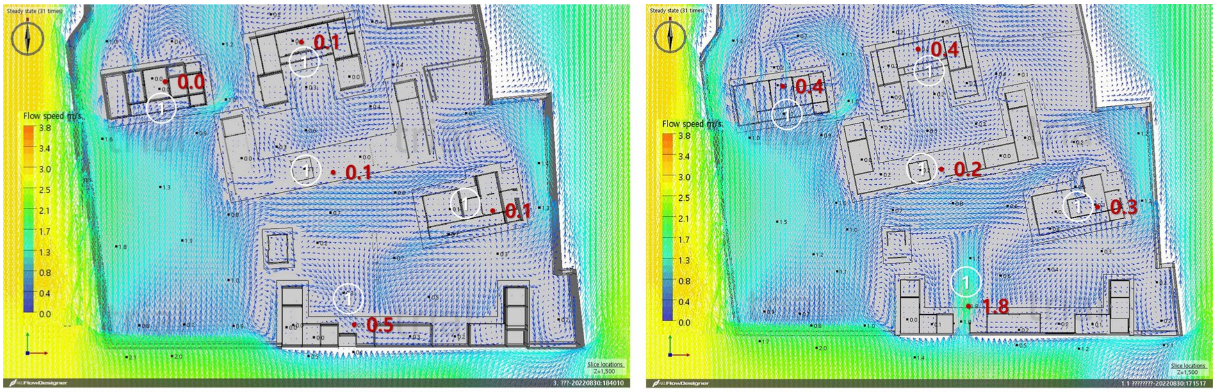


Fig. 14 CFD modeling (Flow Designer program(AKL))



(a) Airflow with the door closed (b) Airflow with the door open

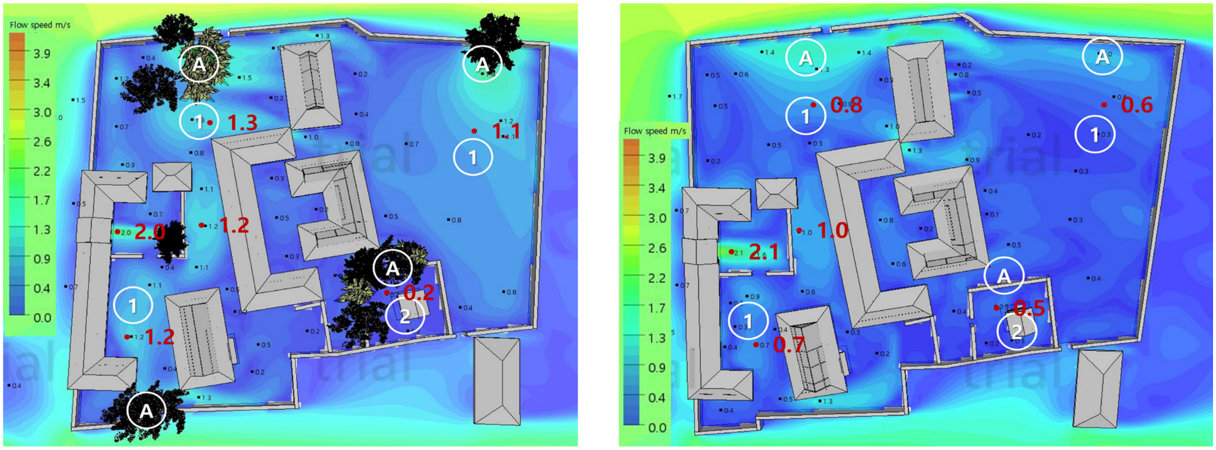
Fig. 15 Computation fluid dynamics (CFD) analysis by opening/closing of the doors and windows

of the wind, and the size and density indicate the wind speed and volume.

Airflow analysis according to open or closed doors and windows

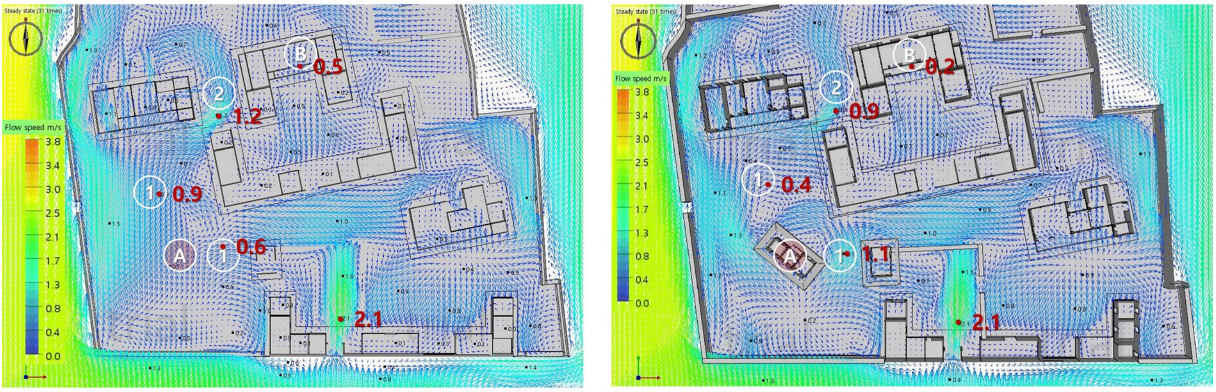
The actual measurement of conditions at the Gotaek indicated different temperature and relative humidity between the inside and outside of the building, but the change patterns are similar. It was confirmed through actual measurements that the relative humidity was affected by the wind flow. Figure 15 shows the results of the CFD analysis of airflow depending on whether a door or window is open. In Fig. 15b, unlike in Fig. 15a, both the door and window are open. The simulation showed that wind speed and air volume increased at location ①. In particular, location ①, at the back, showed an increase in wind speed of more than 100% after opening the doors and windows. Just by opening the door like this, it is possible to ventilate the room to control the relative humidity. However, it was found that opening the door on a cloudy day with high air moisture content raises the internal humidity instead.

Color indicates wind strength, and the arrows indicate wind direction, and the size and density indicate wind speed and volume. (Unit (m/s).



(a) Airflow according to trees (b) Airflow following tree removal

Fig. 16 Computational fluid dynamics (CFD) analysis according to trees in the Gotaek.(Unit (m/s))



(a) Airflow before building restoration (b) Airflow after building restoration

Fig. 17 Computational fluid dynamics (CFD) analysis according to building restoration. (Unit (m/s)). Level of restoration: the level to which a destroyed building has been restored to its original form

Analysis according to the presence/absence of trees

Figure 16a shows the trees currently planted in the Gotaek. The trees were placed in real locations and their heights and widths were taken into account. We acknowledge that there are differences from the actual appearance. However, the purpose was to determine the wind flow according to the presence of wood, not to derive the exact wind speed value.

The wind flow showed different patterns depending on the presence of trees.

In the case of Fig. 16b, where Tree Ⓐ was removed, the wind speeds of location ①, including the Ansarangchae madang, decreased by $\geq$38.4%. However, the wind speed of the Sadang location ②, increased by 150% following tree removal. Therefore, it is appropriate to remove trees from location ②, and maintain those at location ①. In summary, trees affect the flow of wind, and therefore should be planted according to the locational characteristics of the building.

Analysis according to building restoration

In Fig. 17b, the wind was disturbed and spread to the surroundings by the restored building Ⓐ as shown in location ①. Wind speed also increased by 83.3%. However, it was found that wind speed and air volume decreased inside the Anchae Ⓑ. The restored building Ⓐ is believed to be responsible for the 25% decline in wind speed at location ②, situated between the Anchae and Ansarangchae, as compared to Fig. 17a. It is therefore necessary to examine the impact of building restoration on the surrounding climatic environment when restoring a destroyed structure.

Discussion

The climate measured at Kim Myeong-KwanGotaek was different from the weather station. In addition, there was a difference in temperature and relative humidity fluctuations measured inside and outside the Gotaek. The range of change in temperature and relative humidity in the internal was smaller than that in the external. This means that the internal climatic environment changes only within a certain range. Wood is a material that dehumidifies and absorbs moisture according to climate change. Therefore, if the change in relative humidity is constant, the moisture content is constant. When the wood moisture content is maintained above 20%, the temperature rises, creating an environment suitable for the growth of decay fungus. Therefore, it is necessary to manage the climate environment so that the moisture content of wood can change.

The annual average wind speed of the wind measured externally at the Gotaek did not exceed 0.4 m/s. However, there were differences depending on the season. The average wind speed by season was strong in the order of spring > winter > autumn > summer and showed the same pattern as the range of change in relative humidity. Wind intensity rose from 8 AM to 12 PM and remained constant until 2 PM. Furthermore, the main wind direction of the Gotaek was southwesterly (SSW) in spring and winter and east wind (E) in summer and autumn. This seems to be due to the geographic influence of Cheongha Mountain in the north and the Dongjin River in the south. In addition, it was found that the rate of decrease in relative humidity increased when the wind speed was maintained above a certain level, such as in spring and winter.

Seasonal climatic factors of Kim Myeong-KwanGotaek were investigated through correlation analysis. As climatic factors that lower relative humidity, both temperature and wind showed a strong correlation in spring. In summer, only temperature showed a strong correlation. Interestingly, the correlation with temperature was stronger in winter than in autumn when solar radiation is high. Winter was also the second windiest season after spring. Therefore, it was the season with the highest decrease in relative humidity since spring. The reason why autumn has a weaker temperature correlation than winter is that the trees in Gotaek have an effect. Currently, the trees of the Gotaek are mainly planted on the south side of the building. In other words, in autumn there are many leaves on the trees to create shade. However, in winter, the trees do not have leaves, so buildings and grounds can receive a lot of sunlight. Therefore, it is judged necessary to consider the direction and density when planning trees where the building is located.

Wood drying occurs during the daytime when the temperature rises and the relative humidity decreases. The temperature of the optimized distribution shape for this environment is positive (+) in skewness and negative (−) in kurtosis. Furthermore, for relative humidity, both skewness and kurtosis are negative (−). The external of the Gotaek showed an optimized distribution shape. However, both skewness and kurtosis were negative (−) for temperature in summer, and the average temperature was high. For the relative humidity in summer, the kurtosis was positive (+) both inside and outside. As such, if the kurtosis is positive (+), then the measured values are concentrated around the average, meaning that the humidity is high. Therefore, it was found that in summer, care should be taken to manage not only the outside but also the inside relative humidity.

Through the analysis of the climate measurement data of the Gotaek, it was found that there was a difference depending on the measurement location. In particular, it was found that there is a correlation between temperature and wind in the change in relative humidity. The summer outdoor environment of the old house is an environment in which it is difficult to dry wood due to high temperature and relative humidity. However, wind speed was stronger in spring and winter than in other seasons, so the correlation of lowering relative humidity was higher. Therefore, in order to lower the relative humidity, it was found that the wind must blow along with the temperature.

The air flow of the Gotaek was evaluated through CFD simulation. Even in the case of cultural assets where people do not live, such as Gotaek, when the windows are opened, the flow of internal and external air was improved. In addition, when the trees densely planted in the shrine of the old house were removed, the airflow was improved by more than 100%. Finally, the wind speed of the main house was reduced in the simulation in which the destroyed building of the Gotaek was being restored. Therefore, a plan considering the internal air flow is required. As such, the evaluation of the flow of air according to the location environment of cultural properties through CFD simulation was meaningful.

Through this study, it was confirmed that securing actual measurement data is objectively meaningful for analyzing the climate environment of architectural cultural properties. Therefore, measuring the microclimate of the target area and comprehensively analyzing it through CFD simulation is considered a low-cost way to manage damage to cultural properties. To continuously extend the life span of national architectural cultural assets, it is important to accumulate meaningful data through such research. In addition, based on this, it is necessary to make efforts to prepare empirical maintenance and management plans.

Conclusion

We tried to find out about the climatic environment of the location where a wooden building has been maintained for a long time. Accordingly, data of the actual climate environment of the Gotaek was analyzed, and the airflow environment was evaluated using CFD simulation. The conclusions are summarized as follows:

A) The microclimate measured at the Gotaek showed a difference from that indicated by date from the Jeongeup weather station. In particular, in the case of summer and autumn when the average relative humidity was high, installing climate measurement equipment at the site can increase accuracy. Therefore, when using weather station data, it is necessary to consider the climatic environment characteristics of the location.

B) The temperature and relative humidity values of the inside and outside of the Gotaek were different even at the same time. Differences in measured values between the internal and external can cause an imbalance in wood moisture content changes. Therefore, it is necessary to manage the environment of wooden buildings so that the internal climate changes according to the external climate change during the daytime.

C) The wind at the Gotaek was found to be affected by the location of Dongjin River in the south and Cheongha Mountain in the north. Therefore, it is judged that the Gotaek was placed in the southeast direction in consideration of climate factors from the beginning of construction. As such, the layout plan considering the natural environment seems to be the cause of maintaining the wooden architectural cultural heritage for 230 years.

D) Through the correlation analysis, it was found that the decrease in relative humidity is a relationship that is additionally affected by wind with temperature. In the Gotaek, the wind speed was found to decrease in summer and autumn when the relative humidity was high. Therefore, a ventilation management plan is needed to compensate for the decrease in wind speed from 12:00 pm to 5:00 pm. It is recommended to improve the environment by applying a ventilation system along with arrangement considering natural ventilation. However, in the case of an artificial ventilation system, care must be taken so as not to damage the landscape of cultural assets.

E) Korea has four distinct seasons, so there are many climate fluctuations by season and time. Therefore, the distribution of measurement values by location was analyzed based on skewness and kurtosis. Relative humidity has high average density when skewness is negative (−) and kurtosis is positive (+). In the climatic environment of the Gotaek, spring is the ideal season, but summer requires relative humidity management both internally and externally. As such, it is necessary to secure meaningful data through actual measurement when the field environment is diverse.

F) To preserve wooden architectural cultural assets from decay, it is necessary to scientifically inspect the climatic environment. In addition, it is possible to suggest an improvement plan through CFD analysis of the air flow in the internal and external of the Gotaek. As such, through this study, it was found that microclimate measurement and CFD simulation are meaningful. Therefore, it is necessary to recognize that analyzing the microclimate environment is one of the ways to extend the life of cultural assets at low cost.

In this study, the climatic environment according to the construction conditions and environment of the site was measured and analyzed. Based on this objective, the results were derived through CFD analysis. It was proved that a scientific approach is necessary to develop a preservation plan for wooden buildings. In particular, East Asia, including Korea, has many wooden buildings that are over 100 years old. Therefore, it is hoped that related research will be continuously conducted in the future.

In this study, the equipment was installed outdoors, so it was not possible to measure in multiple locations due to limitations in equipment quantity. In addition, it is regrettable that a clear correlation with the natural environment could not be analyzed because the moisture content of wood could not be measured. Lastly, there are many variables according to the natural environment in field measurement. Nevertheless, we want to continue research by supplementing a number of variables. Therefore, we want to preserve buildings with historical value and provide meaningful data that can be used for future architecture.

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Author contributions

YS designed the study. YS conducted the experiments, analyzed the data and wrote the paper. YS contributed to the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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