Material Deterioration Detection of Wooden Columns at the Nanyang Fuya Museum Using a Combination of Macroscopic Visual Inspection and Moisture Content Testing

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Wooden columns, as an important load-bearing wooden component of traditional wooden structures, determine the safety of an entire building. With the increase in material deterioration, the overall health and life of ancient buildings is affected. In this study, the deterioration of wooden columns of ancient buildings in the central axis of the Nanyang Fuya Museum was detected through a combination of macroscopic visual inspection and moisture content testing. The result was that the deterioration degrees and MCs of wooden columns located in the south direction, with good ventilation effect or with oil paint protection were lower than those of wooden columns located in the north direction, with poor ventilation effect or without oil paint protection. The deterioration degree increased with the increase of MC. The results of this research provide the basis for the analysis of the causes and risks of material deterioration.

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INTRODUCTION

The wooden frame of ancient Chinese buildings with a load-bearing responsibility has been passed down and maintained for thousands of years and has formed a unique Chinese architectural style. Nanyang Fuya Museum on Minzhu Street, Wancheng District, Nanyang City, Henan Province, China, and originally built in 1271 AD, was the government office for magistrates of Nanyang Prefecture in the Yuan, Ming, and Qing dynasties. This museum has a history of over 700 years and is a symbol of ancient feudal authority. The entire ancient buildings are rectangular in shape and are facing south, about 300 m long from north to south, 240 m wide from east to west, and with an area of over 72,000 m^2. The central axis is symmetrical, the main and subordinate are orderly, the main halls are located in the center, and the auxiliary rooms are located on both sides. Nanyang Fuya Museum belongs to a typical official architecture pattern, characterized by three-way patterns and several courtyards. In addition, its architectural layout features the front hall after the bedroom, left wen right wu, left zun right low. All main buildings are five rooms wide and predominantly use seven frame beams in accordance with the regulatory wooden frame system. Given that the Nanyang Fuya Museum is the only well-preserved and well-regulated government office among the 215 government offices in the Qing Dynasty, it is a specimen in studying the thoughts, culture, politics, and government building regulations during the feudal society. Lastly, the museum has high historical, cultural, and scientific value.

Most of the current ancient buildings were built during the Ming and Qing dynasties. Buildings with wooden frame systems on the central axis are the Entrance Door, Rite Door, Great Hall courtyard, YinGong Door, Secondary Hall courtyard, Screen Door, and Tertiary Hall courtyard. The main load-bearing components, such as columns, beams, purlins, and rafters, are predominantly made of timbers such as poplar, elm and so on. With climate change and rainfall increase, the Scheffer index in parts of China and even globally has been increasing rapidly (Ma *et al*. 2015), thereby resulting in some unavoidable potential threats to the wooden components in the wooden structure of ancient buildings. After over 700 years, wooden components, particularly the load-bearing columns of Nanyang Fuya ancient buildings, have been or are undergoing various degrees of decay owing to physical and chemical actions, man-made destruction, and microbial invasion. Decay caused by fungi inevitably led to changes in wooden components' anatomical structure (Bhatt *et al*. 2016; Bari *et al*. 2019; Diandari *et al*. 2020; Yang *et al*. 2022, 2021a), degradation of chemical compositions (Tomak *et al*. 2013; Bari *et al*. 2015; Tamburini *et al*. 2017; Cavallaro *et al*. 2017; 2019; Sun *et al*. 2020; Yang *et al*. 2020, 2021b), and reduction of physical and mechanical properties (Gu, 2016; Ueda *et al*. 2020). Given the increase of material deterioration, the overall health and life of ancient buildings would inevitably be affected.

Wooden columns, as an important wooden component of traditional wooden structures, determine the safety of an entire building. Comprehensive understanding of and research on the material deterioration of wooden columns in the ancient buildings of Nanyang Fuya will play an inestimable role in the overall safety assessment. At present, the traditional visual inspection method is used to detect and diagnose the material deterioration of wooden components. Given the continuous progress of science and technology, non-destructive testing (*e.g.*, stress wave, resistance meter, ultrasonic testings) (Dai *et al*. 2016; Chang *et al*. 2016; Zhang *et al*. 2021) have become optimal and common means of the material deterioration detection and evaluation of the health status of interior materials without harming the original shape and structure of wooden structures. Nevertheless, these non-destructive testing methods, particularly resistance meter testing, have caused some damage to wooden components.

The decay of wooden components in ancient wooden structure buildings is the result of the activity of timber-decaying fungi under appropriate conditions. The survival and reproduction of timber decaying fungi generally require the following conditions: abundant nutrients (rich carbon sources, *e.g.*, cellulose, hemicellulose; nitrogen sources; inorganic salts and auxin; and other chemical components), adequate water, suitable temperature (25 to 40 °C), acidic medium (pH of 4.0 to 6.5), and adequate oxygen (1.5 to 10 mmHg) (Guo *et al*. 2010). An important condition for the growth of timber decaying fungi is adequate moisture. Studies (Findlay *et al*. 1958; Brischke and Alfredsen 2020) have indicated that it can inhibit the growth of most timber decaying fungi in timbers when MC of the timber is below 20%. Guo *et al*. (2010) demonstrated that timber-decaying fungi cannot grow when MC of timber is below the fiber saturation point (28% to 30%). Schwarze *et al*. (2005) discovered that MC of timber in the range of 40% to 130% allows timber-decaying fungi to grow favorably. According to local and international research, regulating MC of timber (*i.e*., below 20% or above 150%) can effectively reduce or avoid the occurrence of decay.

The goal of this research was to utilize the traditional macroscopic visual method to comprehensively evaluate and study the material deterioration of wooden columns in Nanyang Fuya ancient buildings. To gain a scientific and precise evaluation of material deterioration, this research also proposed to determine the moisture content (MC) of wooden columns using a special instrument called a timber moisture meter based on the correlation between MC and the material deterioration of timber. This study will provide the basis and guide for the analysis of the causes and risks of material deterioration and design of the follow-up repair plan.

EXPERIMENTAL

Materials

The main objects of this study are the important load-bearing wooden components, particularly the wooden columns in buildings of the Entrance Door, Rite Door, Great Hall, Yin Gong Door, Secondary Hall (called Si Bu Tang), Screen Door, and Tertiary Hall (named Yan Si Tang), which are located at the central axis of Nanyang Fuya Museum (Fig. 1). Among them, the Entrance Door, which is the transition between the inside and outside and a symbol of Nanyang Fuya Museum, has six wooden columns. The Rite Door, which has 18 wooden columns, is not open in ordinary times except for important events, such as when the emperor was present and new officials took office, and people commonly used the east door on and off duty.

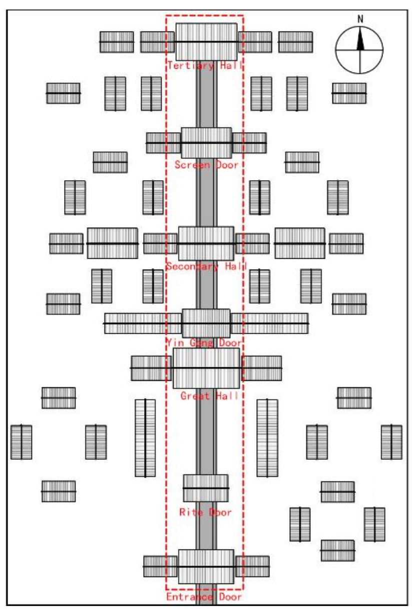


Fig. 1. Layout of Nanyang Fuya Museum

The Great Hall, which is supported by 18 large wooden columns, is the main hall and the center of the entire museum. It was where magistrates read imperial edicts, received officials, and held important ceremonies. The Yin Gong Door, which has 16 wooden columns, is also a ceremony door. “Yin Gong” is a Chinese phrase and literally means to greet guests respectfully. The Secondary Hall, which has 16 wooden columns, was the magistrate’s office, where the magistrate initially decided cases and deliberated judgment opinions. Civil cases and some cases not suitable for public trials were also determined in the Secondary Hall. The Screen Door, which has 10 wooden columns, is the door of the barrier and normally closed and only opened when receiving distinguished guests. Lastly, the Tertiary Hall, which has 12 wooden columns, was where the magistrate handled internal affairs, received superior officials, consulted on secret affairs, and dealt with privacy cases.

Macroscopic Visual Inspection of the Material Deterioration of Wooden Columns

Visual evaluation of the decay classification of wooden columns is based on the Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative in Ground Contact (BS EN 252: 2014) and Non-destructive Testing Methods and Decay Classification of Wooden Components in Ancient Buildings (LY/T 2146-2013).

Slight Decay (Grade I): Visible superficial decay at regional points or in a small area;

Medium Decay (Grade II): Area with decay depth of 2 mm is at least 10 cm^2, and decay depth of regional positions may exceed 5 mm;

Severe Decay (Grade III): Decay depth is above 3 mm in large areas and that of regional positions is over 10 mm;

Complete Failure (Grade IV): specimen is entirely devastated or nearly completely destroyed.

Determining MC of Wooden Columns

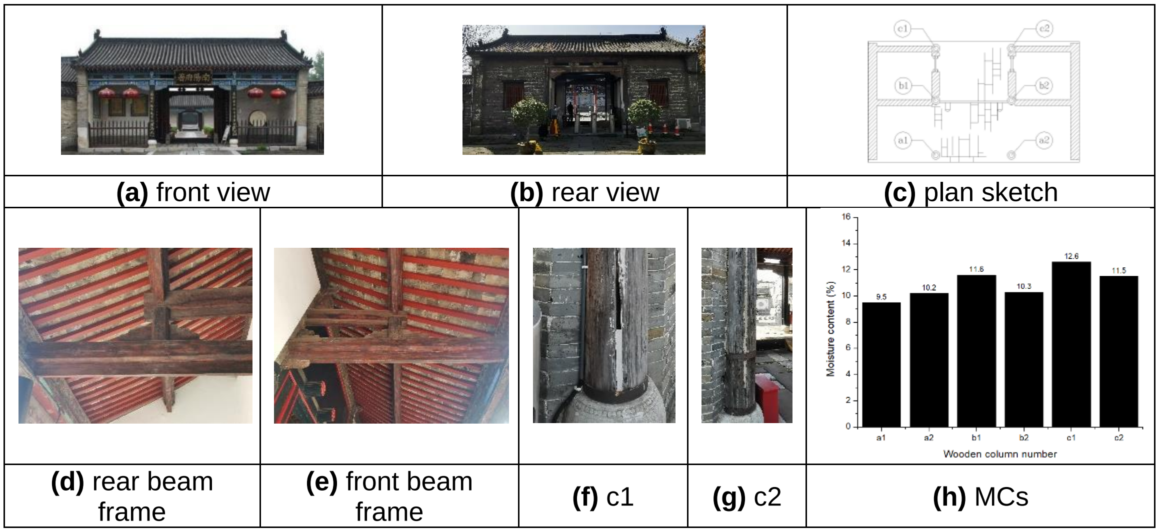
MCs of wooden columns were measured using a special instrument called timber moisture test meter (KT510). Eight points were randomly selected from the four directions of east, south, west, and north. The measured positions were below 1 m of the wooden columns. According to the measured results, the MCs in the south direction was 0.5 to 1.0% lower than those in the east and west directions, and 1.0 to 1.5% lower than that in the north, so average value of MCs was taken to explore the causes of decay and to provide a basis for predicting decay risk. MCs of the wooden columns were determined on July 6, 2022, with an ambient temperature of 34 °C and relative humidity of 59%.

RESULTS AND DISCUSSION

Analysis of the Material Deterioration and MCs in the Entrance Door

The Entrance Door, which has three rooms in width and two rooms in depth, is a five-purlin hard mountain building. It contains two front eave columns, two rear eave columns, and two central columns that are circular (Figs. 2 (a)-(c)). Central and front eave / rear eave columns are connected by double stepping crossbeams with beam fangs, and short columns are placed on the double stepping crossbeams (Figs. 2 (d)-(e)). Investigation has indicated no evident material deterioration in the two front eave columns (a1 and a2) and two central columns (b1 and b2). Nevertheless, significant cracks with width and depth up to 20 mm and 100 mm, respectively, appeared in the two rear eave columns (c1 and c2) (Figs. 2 (f)-(g)).

MCs of all columns in the Entrance Door were below 13%, as shown in Fig. 2 (h). The result is primarily consistent with the equilibrium moisture content (EMC) of 12% of local timbers in Nanyang City. There were no blocks of tall buildings in front and back of the Entrance Door, in which the space was comparatively vacant and the perennial lighting and ventilation effects were well maintained. When surrounding temperature increased and relative humidity declined, water of the interior wooden columns evaporated relatively rapidly into the air, achieving balance with the environment. Low MC of the wooden columns generally reduced the probability of decay. This condition is one of the main reasons why there was no apparent decay in all columns in the Entrance Door.



(a) front view **(b)** rear view **(c)** plan sketch

(d) rear beam frame **(e)** front beam frame **(f)** c1 **(g)** c2 **(h)** MCs

Fig. 2. Material deterioration and MCs of wooden columns in the Entrance Door

Analysis of the Material Deterioration and MCs in the Rite Door

The Rite Door and both sides of the barrier, which have three rooms in width and two rooms in depth, are all five-purlin hard mountain buildings. Except for the front and rear eave columns in the Rite Door, which are rectangular, the other wooden columns are circular (Figs. 3 (a)-(c)). Central and front eave/ rear eave columns are connected by double stepping crossbeams with beam fangs, and short columns are placed on the double stepping crossbeams (Figs. 3 (d)-(e)). Investigation has indicated that the wooden columns in the Rite Door and both sides of the barrier are decorated with black oil paint. A slight decay (Grade I) with decay height of about 100 mm was observed at the root of the right rear eave column (c4) in the Ming Room of the Rite Door. Parts of the surface oil paint decoration had different degrees of peeling. Most wooden columns had no evident material deterioration and are well preserved (Figs. 3 (f) and (h)).

Figure 3 (i) shows that MCs of the six front eave columns (a1-a6) and four central columns (b1-b4) in the Rite Door and both sides of the barrier were below 15.3%. Meanwhile, those of the two central columns (b5-b6) and six rear eave columns (c1-c6) were above 20%, among which those of columns b5 and c4 were up to 23.6%. Accordingly, there was a high decay risk. The Rite Door is 26-m away from the Entrance Door and 54.5-m away from the Great Hall. There were no blocks of tall buildings in front and rear of the Rite Door building, and the space was comparatively vacant with good lighting and ventilation effects throughout the year. Although MCs of the central and rear eave columns were comparatively high, water in the interior columns was gradually equilibrated with that in the environment, which considerably decreased the probability of decay. This condition is one of the main reasons why no apparent decay was discovered in all columns in the Rite Door.

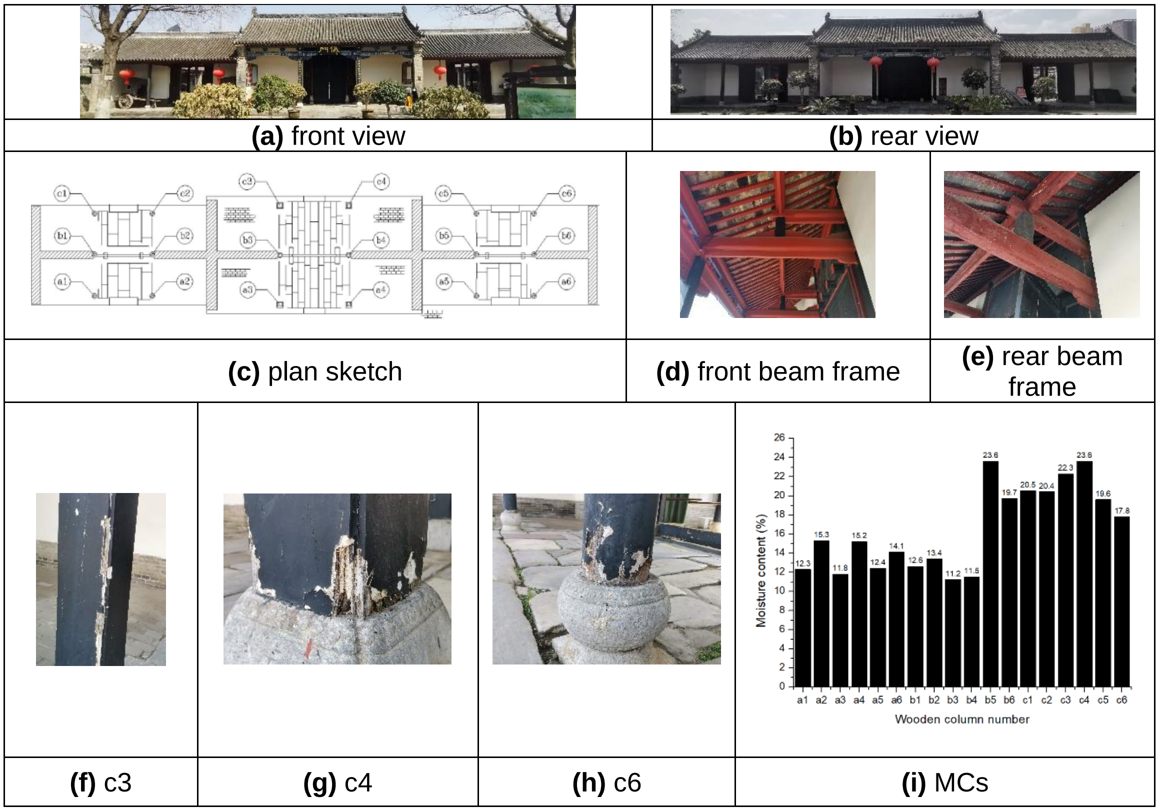
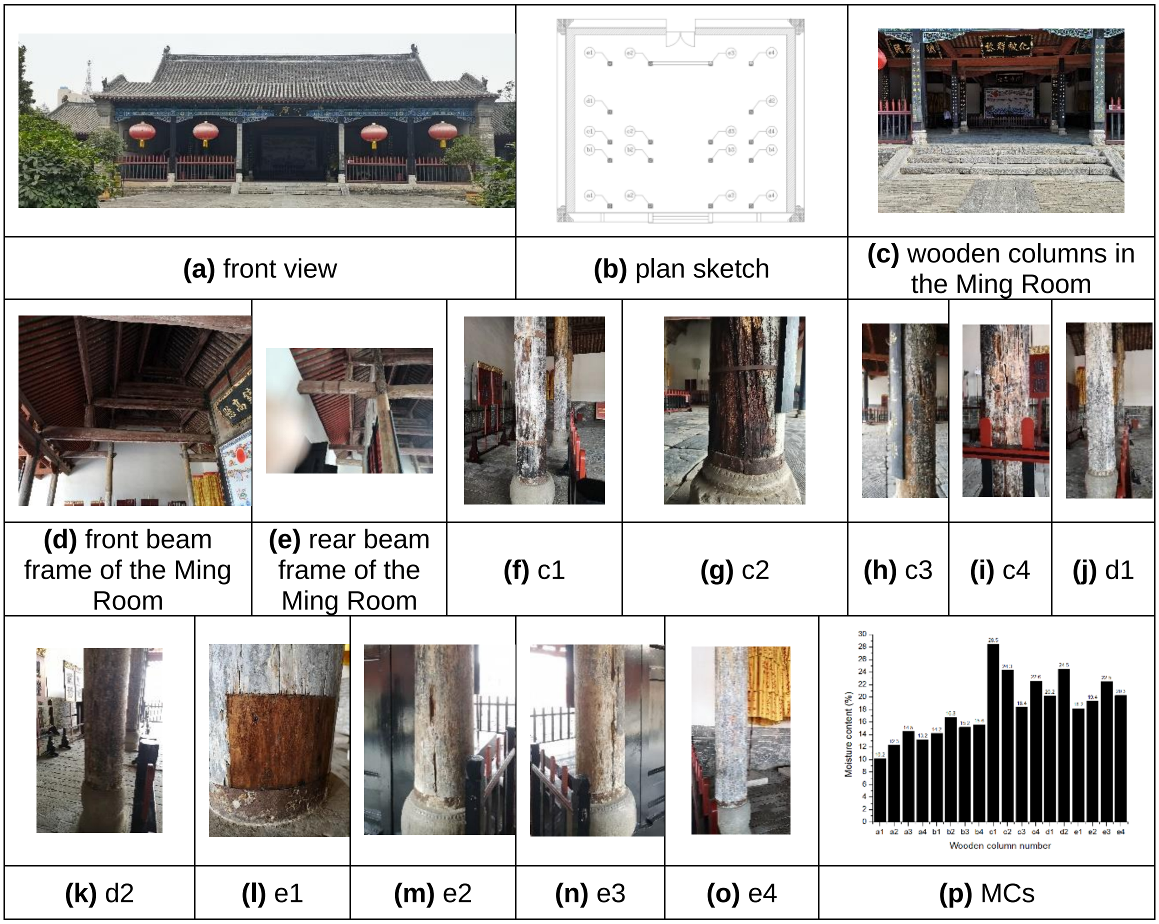


Fig. 3. Material deterioration and MCs of wooden columns in the Rite Door

Analysis of the Material Deterioration and MCs in the Great Hall

The Great Hall is composed of the front roll shed building and rear hard mountain building, with five rooms in width and three rooms in depth (Fig. 4 (a)). All wooden columns are circular, except for the front eave columns in the front roll shed building, which are rectangular. Column reduction was adopted in the front golden column in the Ming Room of the rear solid mountain building, thereby substantially expanding the internal space (Figs. 4 (b)-(c)). There are six-step crossbeams between the front eave and rear golden columns, and double stepping crossbeams between the rear golden columns and the rear wall are adopted (Figs. 4 (d)-(e)). The current investigation revealed that the surfaces of eave columns, which contain four front eave and four rear eave columns (a1-a4, b1-b4) in the front roll shed building, are painted with black oil paint decoration. No evident material deterioration was detected, except for some black oil paint decoration falling off (Figs. 4 (a) and (c)). Material deterioration and MCs of wooden columns in the hard mountain building was more evident and severe. Root decay instances of front eave columns c1 and c2 were serious (Grade III) with decay height of up to 600 mm. Pier connection technology was adopted at the root of front eave column c1, and surface decay area of column c2 root reached over 1/2 of its surface area (Figs. 4 (f) and (g)). Medium decay (Grade II) was found on the surfaces of front eave columns c3 and c4 and has been repaired using the patching method (Figs. 4 (h) and (i)). No evident decay was observed, but some small cracks were revealed in front golden columns d1 and d2 (Figs. 4 (j) and (k)) and rear golden column e4 (Fig. 4 (o)). The root of rear golden column e1 was decayed severely (Grade III), and the embedded package method was adopted (Fig. 4 (l)). Local decay (Grade II) was observed on the surfaces of rear golden columns e2 and e3, and local removal treatment was adopted (Figs. 4 (m) and (n)).

As shown in Fig. 4 (p), MCs of the eight front and rear eave columns (a1-a4, b1-b4) of the roll shed in front of the Great Hall were maintained below 16%. In the four front eaves columns (c1-c4), two front golden columns (d1, d2), and four rear golden columns (e1-e4) of the hard mountain building in the rear of the Great Hall, MCs were above 20%, among which column c1 was as high as 28.5% with high decay risk. Exceptions were columns c3, e1, and e2 which had much lower MC. This condition is one of the main reasons for the serious decay of the wooden columns.



(a) front view **(b)** plan sketch **(c)** wooden columns in the Ming Room **(d)** front beam frame of the Ming Room **(e)** rear beam frame of the Ming Room **(f)** c1 **(g)** c2 **(h)** c3 **(i)** c4 **(j)** d1 **(k)** d2 **(l)** e1 **(m)** e2 **(n)** e3 **(o)** e4 **(p)** MCs

Fig. 4. Material deterioration and MCs of wooden columns in the Great Hall

MCs of the wooden columns in the front roll shed were considerably lower than those in the rear hard mountain building. The following reasons are presented. ① The eight eaves columns in the front roll shed are located in the south direction, and the perennial temperature is higher than that in the north direction. ② The Great Hall is 54.5-m away from the Rite Door. There are no blocks of tall buildings in front of the Great Hall, so the space is comparatively vacant. Similarly, there is no wall in front of the Great Hall, so the ventilation effect is maintained year-round. ③ Surfaces of the eight eave columns in the front roll shed were painted with black oil paint, which also prevented water from entering. Nevertheless, the hard mountain building is located on the shady side of the Great Hall, and the general lighting effect is insufficient. In addition, the hard mountain building is only 3.15-m away from the rear Yin Gong Door, so the ventilation effect is considerably inferior to the rolling shed. Studies (Chen *et al*. 2018) have indicated that water in the air easily led to the formation of condensed water on the surface of stone column foundation due to the cooling of steam in the air. If the ventilation effect around the wooden columns is poor, then the column roots will rapidly absorb the condensed water through capillary action and flow from the column root to the top along the timber pores.

Analysis of the Material Deterioration and MCs in the Yin Gong Door

The Yin Gong Door, which has five rooms in width and three rooms in depth, is a five-purlin hard mountain building with front and rear corridors. It contains four circular front eave columns, four rectangular rear eave columns, and two rows of circular golden columns (Figs. 5 (a)-(b)). The front porch belongs to a roll shed gallery structure. Front eave and front golden columns are connected by tie beams, and there are double stepping crossbeams on the tie beams. The beam structure between the two golden columns is a three-frame beam, three-frame beams support short columns, short columns directly bear the ridge purlins, and there are purlin beams under the ridge purlins. Rear eave and rear golden columns are connected by tie beams and single stepping crossbeams (Figs. 5 (c)-(e)). The current investigation detected that the surfaces of the four front eave columns (a1-a4) and the four front golden columns (b1-b4) of the Ming Room and secondary rooms are decorated with black oil paint. Nearly no evident material deterioration was discovered, except for some black oil paint decoration falling off (Fig. 5 (a) and (c)). The rear golden column (c1) in the western secondary room had serious overall decay (Grade III) with decay height of 1.5 m, there was evident pier connection repair treatment below 1 m, and there was a serious crack 20-mm wide, 425-mm long, and 40-mm deep in the middle part of column c1 (Figs. 5 (f)-(g)). The rear golden column (c2) on the western side of the Ming Room had no evident decay except for some small cracks (Fig. 5 (h)). Decay was highly evident at the root of the rear golden column (c3) on the eastern side of the Ming Room (Grade II), and the decayed area accounted for about 1/3 of the surface area (Fig. 5 (i)). The rear golden column (c4) in the eastern secondary room had serious overall decay (Grade III), there was evident pier connection repair treatment, and there was a large hole at the pier connection position (Figs. 5 (j)-(k)). Significant decay instances were found at the roots of the rear eave column (d1) in the western secondary room (Fig. 5(l)) and rear eave column (d4) in the eastern secondary room (Fig. 5 (o)). Moreover, ratio of the actual bearing area between the bottom surface of the column and the column base to the original section area of the column foot was about 4/5 (Grade III). The root of the rear eave column (d2) on the western side of the Ming Room was significantly decayed (Grade III), the embedded package method was adopted for the local decay, and a large knot defect was found at the column root (Fig. 5 (m)). The overall surface of the rear eave column (d3) on the eastern side of the Ming Room was significantly decayed (Grade III) (Fig. 5 (n)).

As shown in Fig. 5 (p), MCs of the four front eave columns (a1-a4) and the four front golden columns (b1-b4) in Yin Gong Door remained at 16% to 19%, which was considerably higher than those of the two front eave columns (10% to 15%) in the Entrance Door and Rite Door. MCs was above 20%, except for columns c1 and c4 in the four rear golden columns (c1-c4) and four rear eave columns (d1-d4), and what calls for special attention is that MC of column d2 was as high as 30.5%, facing high decay of risk. Decay degrees of the wooden columns in Yin Gong Door were considerably greater than those of the front Entrance Door and Rite Door (Figs. 2-4). There are two main reasons for this result. ① Perennial light duration of Yin Gong Door is insufficient. Yin Gong Door is only 3.15-m away from the front Great Hall, the height of which is markedly higher than Yin Gong Door, making it almost always in a shady environment, further resulting in lower surrounding temperature and higher relative humidity. ② Ventilation effect of Yin Gong Door is comparatively poor because of a relatively closed quadricle courtyard formed by Yin Gong Door, the rear Secondary Hall, and the east and west wings. Condensed water formed on the surface of the stone column foundation cannot be rapidly evaporated. Hence, the wooden column roots can rapidly absorb this part of the condensed water through the capillary effect, consequently enhancing MCs of the column roots.

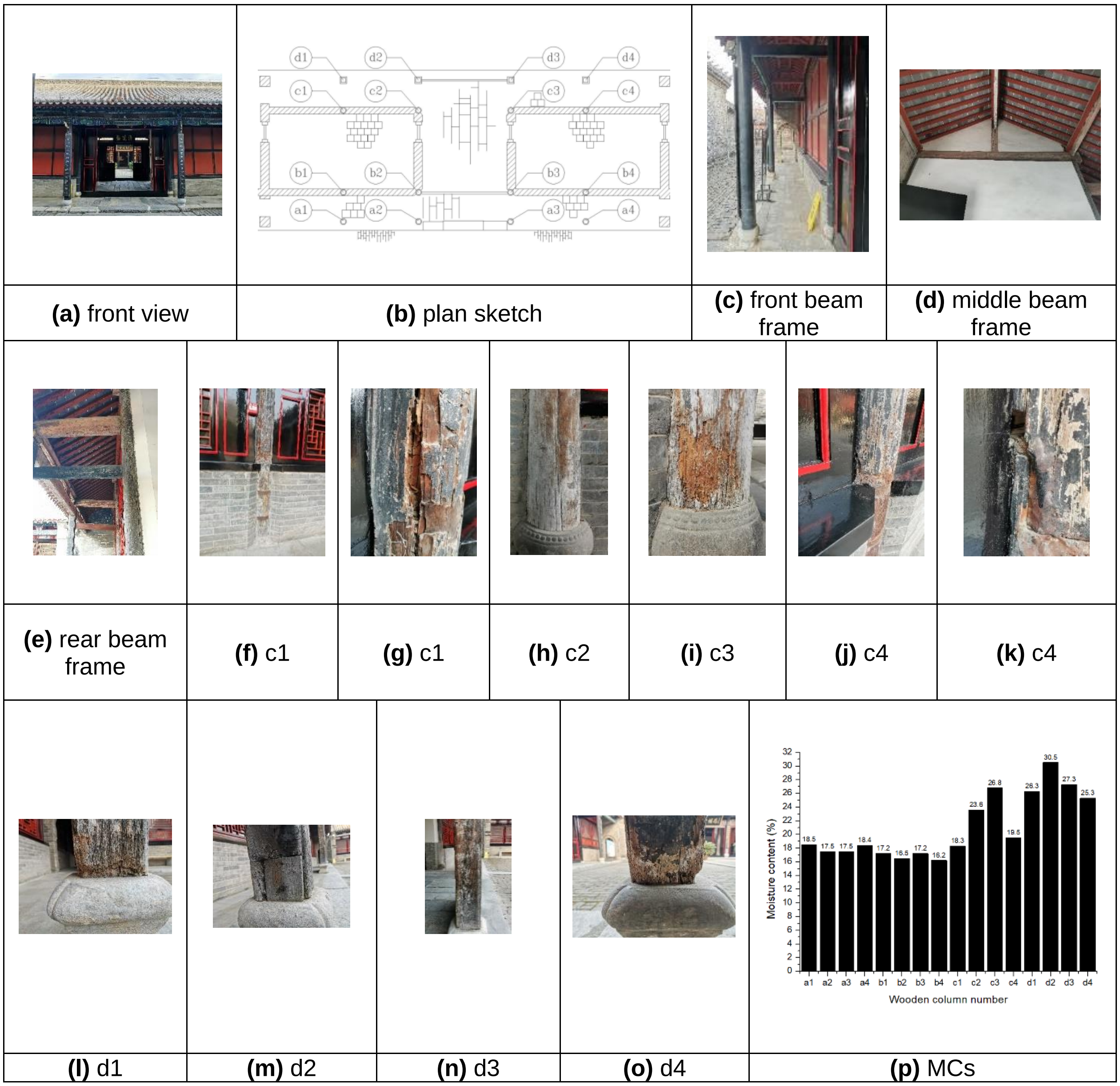
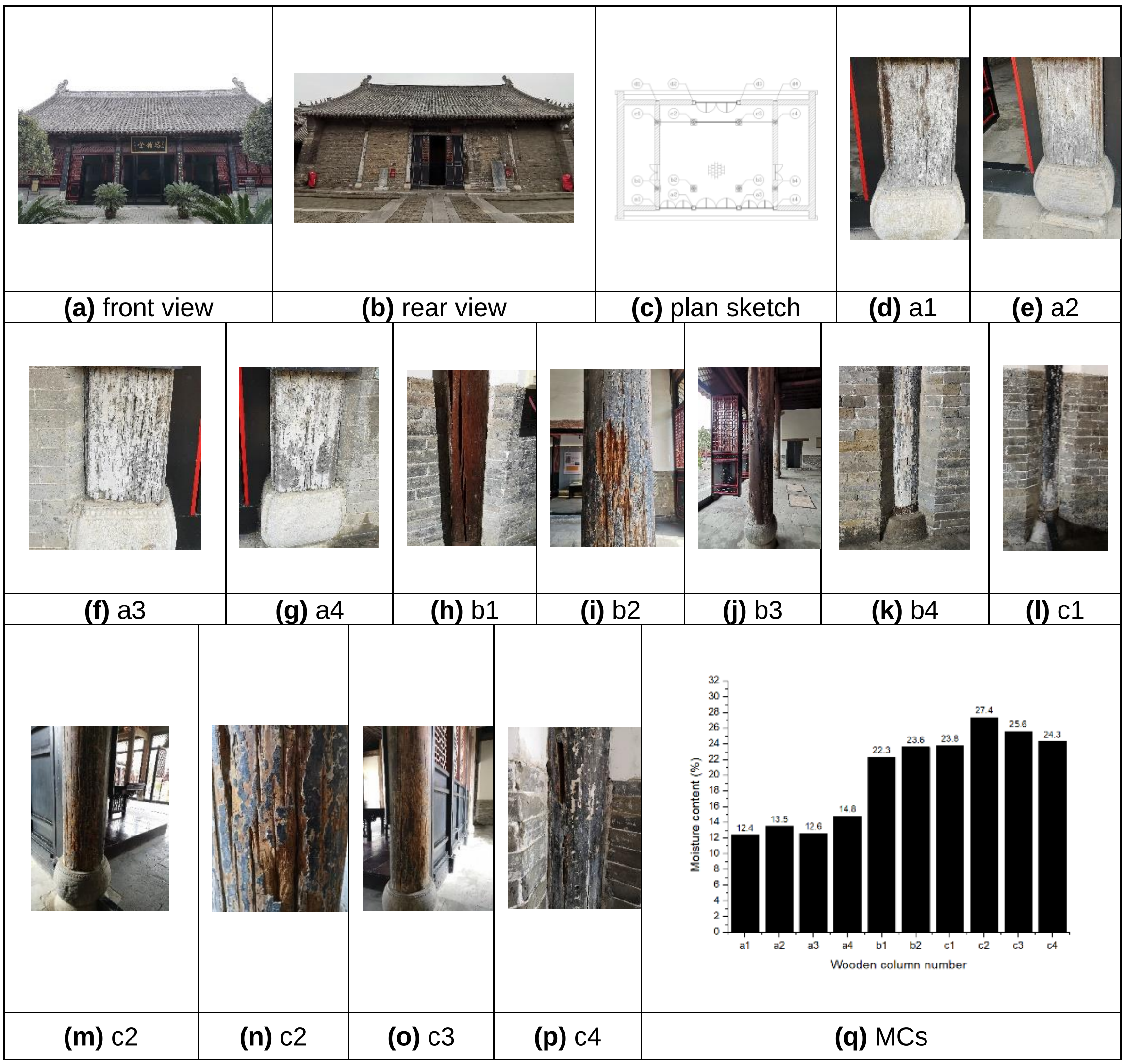


Fig. 5. Material deterioration and MCs of wooden columns in the Yin Gong Door

Analysis of the Material Deterioration and MCs in the Secondary Hall

The Secondary Hall is a seven-purlin hard mountain building with five rooms in width and three rooms in depth, and contains four rows of columns (four front eave, four front golden, four rear golden, and four rear eave columns). The front and rear eave columns are rectangular, and the front and rear golden columns are circular (Figs. 6 (a)-(c). The eave columns and golden columns are linked by the main aisle exposed tiebeam, the beam structure between the two golden columns belongs to five-frame beam, there are tiebeams under the beam, five-frame beams support short columns, short columns bear three-frame beams, and purlins are erected on each beams. There is a ceiling on the five-frame beam. The present investigation indicated that the oil paint on the surfaces of the four front eave columns (a1-a4) (Figs. 6 (d)-(g)) and the four rear eave columns (d1-d4) (Fig. 6) (b) has chipped off to varying degrees. Although no decay phenomenon was discovered, the different degree of weathering was evident.



(a) front view | **(b)** rear view | **(c)** plan sketch | **(d)** a1 | **(e)** a2 | **(f)** a3 | **(g)** a4 | **(h)** b1 | **(i)** b2 | **(j)** b3 | **(k)** b4 | **(l)** c1 | **(m)** c2 | **(n)** c2 | **(o)** c3 | **(p)** c4 | **(q)** MCs

Fig. 6. Material deterioration and MCs of wooden columns in the Secondary Hall

The weathering characteristics are as follows: surfaces become rough and color turned gray and white, among others. The reason is that the front eave columns are located in the south direction, and the lignin of the columns resulted in photodecomposition under ultraviolet light for a long time. Norrstrom (1969) revealed that the extent of UV absorption of lignin in timber can reach 80% to 95% and that of carbohydrates from 5% to 20%. Therefore, coating the surface of wooden components can successfully reduce the photochemical decomposition of lignin and ultimately reduce damage to wooden components under long-term light conditions. The front golden column (b1) in the western secondary room had some extreme dry shrinkage cracks with width, depth, and length of 20, 60, and 120 mm, respectively (Fig. 6 (h)). Dry shrinkage cracks would lead to the reduction of shear capacity along the grain of wooden components, resulting in a risk of splitting of wooden components and the entire building structure after reaching a certain depth (Cabaleiro *et al*. 2017). In addition, the presence of dry shrinkage cracks would lead to the easy entry of rain water and fungi into the wooden components, consequently accelerating the decay of wooden components (Chen 2019). The left front golden column (b2) and right front golden column (b3) in the Ming Room were severely decayed (Grade III). The right front golden column (b3) has been repaired using the patching method, with the patching height up to 1.8 m (Figs. 6 (i)- (j)). There were many insect holes on the surface of the left rear golden column (c2) in the Ming Room, demonstrating that insect erosion was severe. Decay was also exceptionally severe (Grade III), with the decay height over 1 m and the decay area accounting for about 3/4 of the surface area. Part of the severe decays were repaired using the patching method (Grade III) (Figs. 6 (m)-(n)). The surface of the right rear golden column (c3) in the Ming Room was evidently decayed, with decay height of 800 mm (Grade II) and some small cracks (Fig. 6 (o)). Local decay appeared on the surface of the rear golden column (c4) in the eastern secondary room, and local decay was removed (Grade I) (Fig. 6 (p)). Nevertheless, no evident decay was discovered in the front golden column of the eastern secondary room (b4) (Fig. 6 (k)) and the rear golden column of the western secondary room (c1) (Fig. 6 (l)).

As shown in Fig. 6 (q), MCs of the four front eave columns (a1-a4) in the Secondary Hall (Si Bu Tang) remained at 13% to 17%. MCs of the four front golden columns (b1-b4) and four rear golden columns (c1-c4) were above 20%. Note that MC of column c4 was as high as 28.9%. The four rear eave columns (d1-d4) had no evident decay phenomenon on the surface, but MCs were above 20%. Note that MC of column d1 was as high as 41.2%, with a comparatively high risk of decay. The Secondary Hall (Si Bu Tang) was surrounded by walls. The four front golden columns (b1-b4), four rear golden columns (c1-c4), and four rear eave columns (d1-d4) formed a comparatively closed environment. Moreover, ventilation effects and light conditions were not as good as the front eave columns (a1-a4), which were located in the south direction and well-ventilated. Hence, MCs of the columns retained relatively higher and the deterioration phenomenon was more evident. Compared with the four front eave columns (a1-a4) in the roll shed building of the Great Hall, MCs of the four front eave columns (a1-a4) in the Secondary Hall (Si Bu Tang) were 2% to 3% higher than those in the roll shed building of the Great Hall. The reason may be that none of the oil paint coating (Fig 6 (d)-(g)).

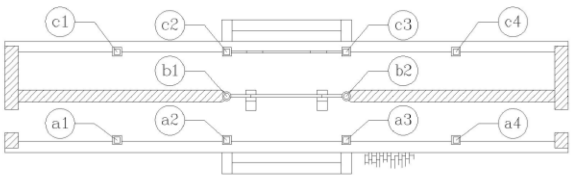
Analysis of the Material Deterioration and MCs in the Screen Door

The Screen Door, which has five rooms in width and two rooms in depth, is a three-purlin hard mountain building. The front and rear eave columns are rectangular, while the two central columns in the Ming Room are circular (Figs. 7 (a)-(c)). Front/rear eave columns and central columns are connected by single stepping crossbeams, and there are eave purlins on the single stepping crossbeams. The roof of the Ming Room is 0.65-m vertically higher than that of the secondary rooms on the left and right (Figs. 7 (a)- (d)). Investigation has indicated that the surface of the front eave column (a1) in the western secondary room indicated slight decay (Grade I) (Fig. 7 (e)). Surfaces of the front eave columns (a2 and a3) in the Ming Room were painted with black oil paint decoration, and there was no evident material deterioration except part of the oil paint decoration falling off from the surfaces (Fig. 7 (f)). The front eave column (a4) in the eastern secondary room (Fig. 7 (g)) and the two central columns in the Ming Room (b1 and b2) (Fig. 7 (f)) were seriously decayed (Grade III), the front eave column (a4) had evident embedded package method, while columns b1 and b2 had pier connection technology with a pier connection height over 600 mm. All four rear eave columns (d1-d4) were seriously decayed (Grade III) to differing degrees. Among them, the roots of the rear eave column (c1) in the western secondary room (Fig. 7 (h)) and east rear eave column (d3) in the Ming Room (Fig. 7 (j)) had an evident embedded package method with height of about 300 mm. The roots of the western rear eave column (d2) in the Ming Room (Fig. 7 (i)) and eastern rear eave column (d4) in the eastern secondary room (Fig. 7 (k)) were repaired by pier connections with pier connection heights of 900 mm in column d2 and 500 mm in column d4.

As shown in Fig. 7 (l), MCs of the four front eave columns (a1-a4) in the Screen Door were kept below 15%. MCs of the two central columns (b1-b2) and four rear eave columns (c1-c4) were above 22%, among which that of column c2 was up to 27.4%, with a comparatively high decay risk. The Screen Door is 18-m away from the Secondary Hall and the space is comparatively vacant. The four front eave columns (a1-a4) are located in the south direction without wall shielding, in which perennial lighting and ventilation effects were retained well. In addition, surfaces of the columns were protected by black oil paint decoration, which kept MCs comparatively low. The Screen Door, tertiary hall, and the east and west wings of the Tertiary Hall formed a comparatively closed quadrangle, and the ventilation effect was relatively poor. In addition, the two central columns (b1-b2) and four rear eave columns (c1-c4) were in the shade, and the lighting conditions were not as good as the front eave columns (a1-a4). Thus, MCs of the columns were comparatively high.

(a) front view

(b) rear view



(c) plan sketch

(d) front and rear beam frames

(e) a1

(f) a2, a3, b1and b2

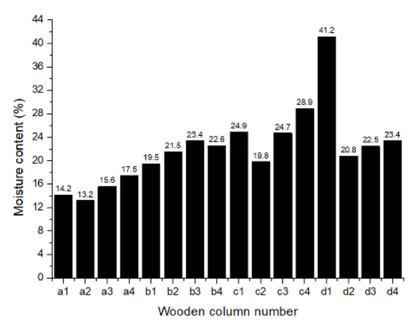
(g) a4

(h) c1

(i) c2 in the Ming Room

(j) c3 in the Ming Room

(k) c4



(l) MCs

Fig. 7. Material deterioration and MCs of wooden columns in the Screen Door

Analysis of the Material Deterioration and MCs in the Tertiary Hall

The Tertiary Hall is a seven-purlin hard mountain building with five rooms in width and three rooms in depth. It contains three rows of columns: four front eave columns, four front golden columns, and four rear golden columns. All columns are circular (Figs. 8 (a)-(c); the front eave corridor belongs to a roll roof shed. The front golden columns and front eave columns are connected with baotou beams (Fig. 8 (c)), and the rear golden columns and rear wall are connected with single stepping crossbeams. The status survey indicated that wood oil paints on the surfaces of the four front eave columns (a1-a4) (Figs. 8 (d)- (g)) and the four front golden columns (b1-b4) (Figs. 8 (h)-(k)) almost fell off. Although no evident decay phenomenon was discovered, various degrees of weathering were marked because of the photodecomposition of the lignin of wooden components under ultraviolet light for a long time. Slight decays have shown in the four rear golden columns c1 and c4 (Grade I), while columns c2 and c3 were fundamentally well preserved (Figs. 8 (l)-(o)).

As shown in Fig. 8 (p), MCs of the front eave columns (a1-a4) and front golden columns (b1-b4) in the Tertiary Hall (Yan Si Tang) were retained below 15%, while those of the rear golden columns (c1-c4) were maintained at 20% to 24%. Ventilation and illumination conditions of the golden columns (c1-c4), which were in a relatively closed environment because of the surrounding of the four walls, were worse than the front eaves columns (a1-a4) and front golden columns (b1-b4). Although there was no apparent decay phenomenon, as shown in Fig. 8, MCs remained high, and there was still a high decay risk. In addition, oil paint decorations on the surfaces of all wooden columns fell off to different degrees. Without the protection of oil paint decorations, the possibility of absorbing moisture from the air was considerably enhanced, thereby possibly further leading to an increase of MCs and enhancement of the decay risk of wooden columns.

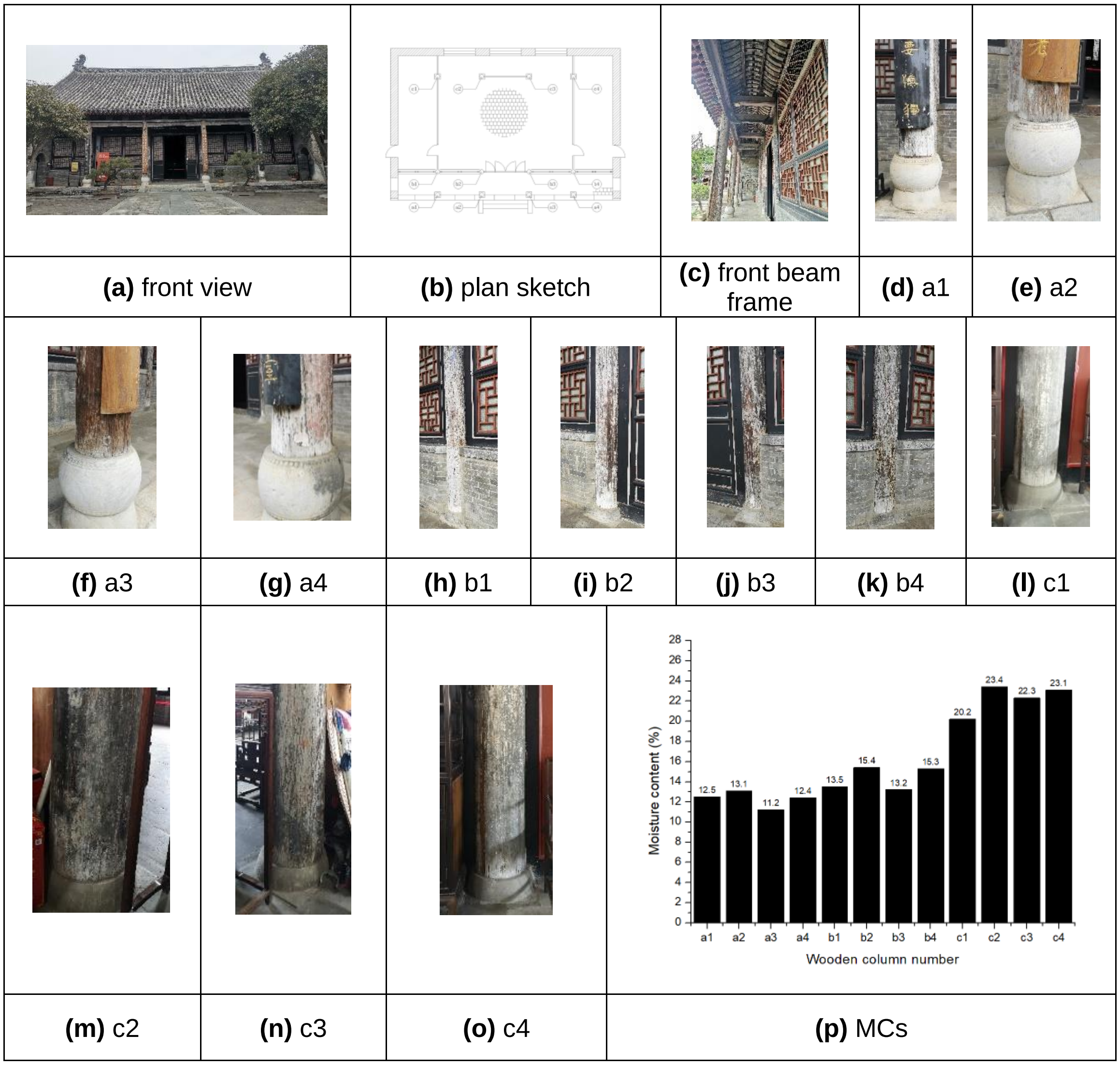


Fig. 8. Material deterioration and MCs of wooden columns in the Tertiary Hall

Under the condition that the nutrients, temperature, pH and oxygen content are satisfied, the water content in the wooden components plays a key role in the growth of fungi. From the above observation of macroscopic deterioration degree and measurement of MCs, we find that the higher the MCs, the higher the material deterioration degree. With the increase of decayed degree, the basic density of wooden components declines, moisture absorption increases, and MC also increases, eventually leading to an increase of decay risk of wooden components. The lower the MC of wooden components, the lower the decay risk. MC of wooden components in the 30% to 60% range means high decay risk. Consequently, the grade of MC was adopted to predict the decay risk of wooden columns and to explore the reasons for the current material deterioration phenomenon according to the grade of MC in this research.

CONCLUSIONS

1. Deterioration degrees of the front eave columns and front gold columns located in the south direction were lower than those of the rear eave columns and rear golden columns located in the north direction. Deterioration degrees of wooden columns with good ventilation effect were lower than those of the wooden columns with poor ventilation effect. Deterioration degrees of columns with oil paint protection were lower than those without oil paint protection.
2. MCs of the front eave columns and front golden columns located in the south direction (in the range of 10% to 15%) were lower than those of the rear eave columns and rear golden columns located in the north direction (in the range of 20% to 30%, some up to 40%). MCs of columns with good ventilation effect were lower than those of the columns with poor ventilation. MCs of the columns with oil paint protection were lower than those without oil paint protection.
3. Suggestions on protection measures: It is recommended that all wooden columns be treated with preservative to strengthen durability. End sealant should be adopted to seal the ends of column roots to prevent the condensed water formed on the stone column bases from entering the column roots through capillary action. Paint coating on the surfaces of all wooden columns should be used to slow down water vapor uptake from the air into the interior wooden columns through the horizontal grain direction.

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