

## Research Article

# Analysis of the Residual Deformation of Yingxian Wood Pagoda

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Received 11 October 2019; Revised 27 January 2020; Accepted 7 February 2020; Published 20 March 2020

Academic Editor: Dongsheng Li

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Cumulative damage and residual deformation of structural components of Yingxian Wood Pagoda over its existence have caused widespread concern. Because Yingxian Wood Pagoda is a very complex ancient wooden structure, previous studies on single-storey and multistorey ancient structures are not very applicable. In this study, the deformation to the pagoda at the components, storey, and overall structure levels was monitored considering residual deformation, component cracking, and component connection conditions. The effects of different factors were preliminarily identified, including the structural weight, external impacts such as earthquakes and artillery shells, differences in moisture content according to sunlight exposure, and the prevailing wind direction. The study findings are useful in diagnosing the health and causes of deformation of unique buildings such as this in order to develop effective repair and restoration measures.

## 1. Introduction

Yingxian Wood Pagoda (Figure 1) was built in 1056 CE and is located in Shanxi, China. It is a nine-storey wooden structure with a height of 67.58 m. The pagoda contains 26 colourful sculptures including Sakyamuni, Manjushri, and Samantabhadra of various sizes on the first, third, fifth, seventh, and ninth floors. It has received significant attention because of its importance in terms of religion, culture, history, architecture, structure, and art. However, the damage caused by various factors over the past millennium has reduced its bearing and deformation capacities. A detailed damage analysis is required to evaluate its safety.

The pagoda is placed on top of a 4.4 m high two-layer platform made of stone on the exterior and rammed earth in the interior. Figures 2 and 3 illustrate the octagonal plan and vertical section views of the pagoda. The circumscribed circle diameter of the bottom floor is 30.27 m, while the other floors gradually decrease in diameter from bottom to top. The columns on the first floor are arranged in three concentric octagonal rings; two of the inner rings' columns are buried in an adobe wall. There are 24 columns in the outer ring, 24 columns in the middle ring (and an additional 62

auxiliary columns), and eight columns in the inner ring (and an additional 44 auxiliary columns). The other eight floors each have inner and outer rings with eight and 24 wooden columns, respectively. The column diameter is approximately 55 cm. Except for the ninth floor, the columns on the other floors have several auxiliary columns. The bottom columns are on the foundation stone, and the columns of other floors are inserted in the beams on the upper part of the floor. The wooden frame, which consists of beams, columns, and *Dou-Gong* brackets, is the primary load-bearing part of Yingxian Wood Pagoda. Taking the third layer as an example, the major components are illustrated in Figure 4. The wooden components were identified to be made from larch (*Larix principis-rupprechtii* Mayr) except for the *Lu-Dou* layer, which is made from elm (*Ulmus rubra*). The column head is connected via mortise-tenon joints to the end of a beam, and *Dou-Gong* brackets are placed on the wooden beam to form a layer. The second, fourth, sixth, and eighth floors have similar structural features; the height of a column with diagonal braces is lower than that of the adjacent layers without diagonal braces. The third, fifth, seventh, and ninth floors have similar structural features; the column height without diagonal braces is higher



FIGURE 1: Map showing the location of Yingxian Wood Pagoda.

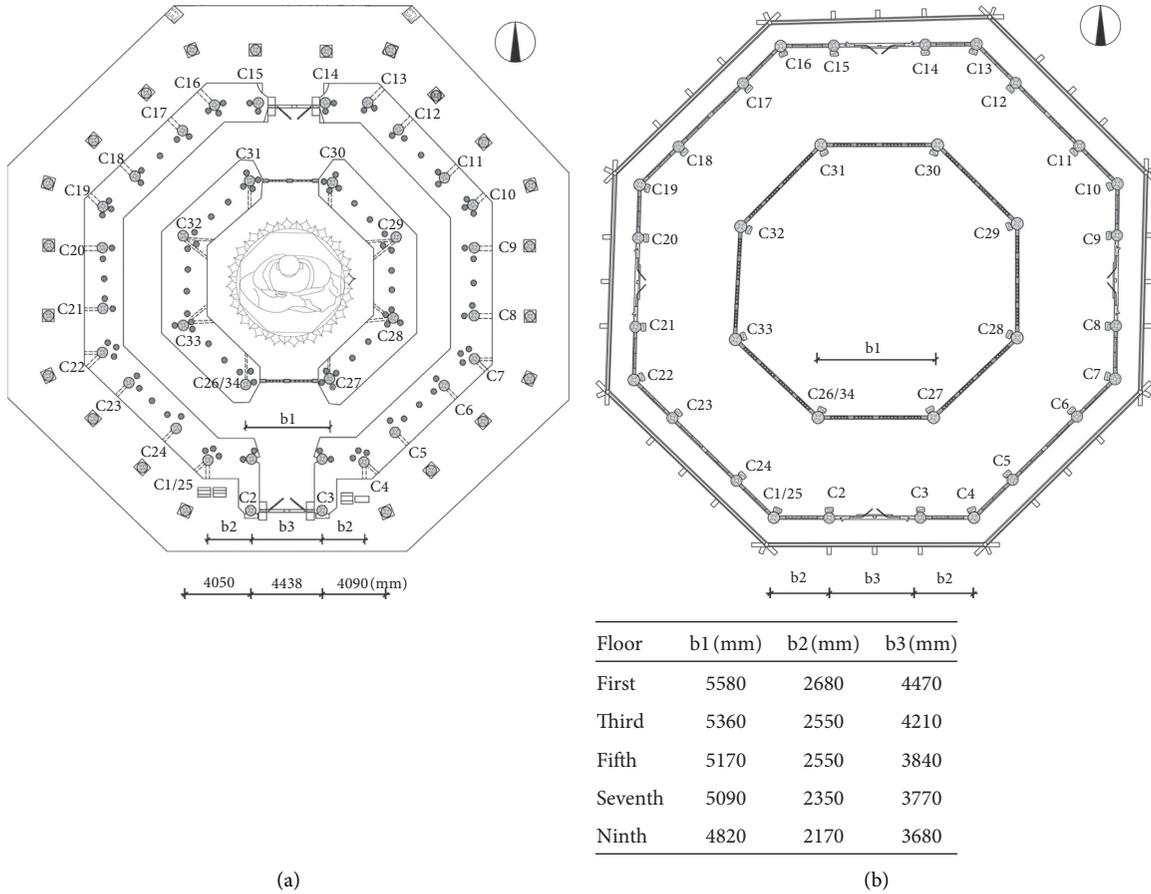


FIGURE 2: Continued.

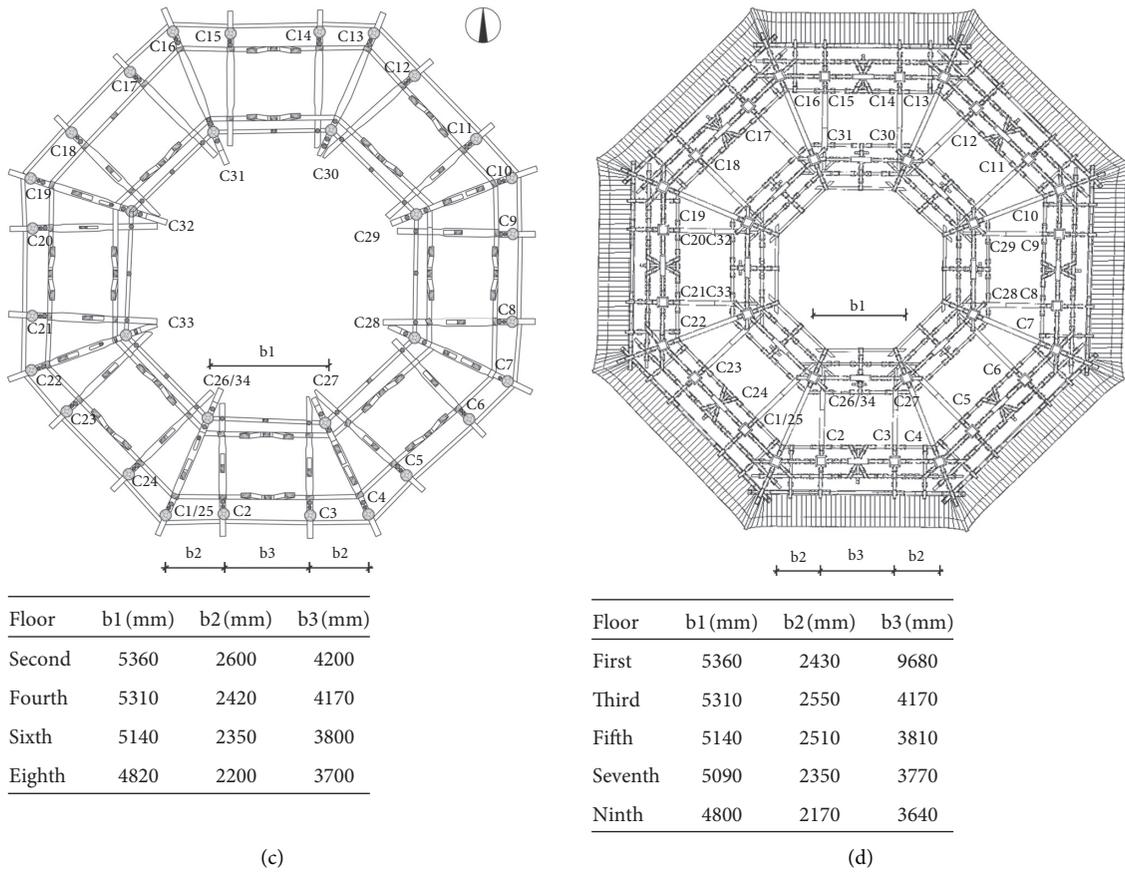


FIGURE 2: Column layout (a) on the first floor, (b) on the third, fifth, seventh, and ninth floors, and (c) on the second, fourth, sixth, and eighth floors. (d) Layout of the column heads and eaves on the first, third, fifth, seventh, and ninth floors.

than that of adjacent layers with diagonal braces. Each floor is stacked in the vertical section to form the pagoda body. Because of this unique structure, the pagoda has survived in a complex environment for nearly 1000 years. However, because of long-term corrosion of the surface wood, the effective cross section of various components has decreased, gap between components has expanded to reduce the connection capacity, and the damage and residual deformation due to various external loads have become obvious. The bearing and deformation capacities of Yingxian Wood Pagoda have decreased, which jeopardises its continued survival.

The annual average temperature of the surrounding area is 1.84°C with a minimum of -15.20°C in December and a maximum of 15.55°C in July. The annual average environmental humidity is 52.8% with a minimum of 36.2% in March and a maximum of 68.2% in August. The prevailing wind direction is southwest in November, which has the strongest winds [1]. The maximum wind speed is close to westerly wind with an average speed of 15 m/s at an altitude of 49.8 m. The foundation of Yingxian Wood Pagoda is hard, homogeneous, and undamaged; two obviously internal artificial caves for placing objects have been detected [2]. Experimental results for the *Dou-gong* brackets [3], mortise-tenon joints [4], and dynamic behaviours [5] in the pagoda partly revealed the local structural performance. Preliminary analysis of the damage and a simple evaluation of the bearing

capacity of the pagoda [6] brought attention to the complexity of the structural performance and difficult implementation of protective measures. In recent years, the residual deformation of columns on the third and fifth floors and serious damage to components on the first and second floors have attracted widespread attention, and many repair measures have been proposed. Experts from the National Bureau of Cultural Relics of China conducted research on protection and reinforcement schemes on 6–7 June 2002 and 28–29 September 2013, but failed to reach a consistent conclusion in terms of the architecture, structure, cultural relics, and other fields. A large amount of empirical data has been collected on the repair of single- and multistorey ancient wooden structures [7]; however, the methods used are difficult to apply to this pagoda. Yingxian Wood Pagoda is a high-rise building with large forces, a complex structure, numerous components (22,743 pieces), and large volume (2971 m<sup>3</sup> excluding auxiliary components that were added later). Therefore, a detailed analysis on damage to components and residual deformation is vital to the protection of Yingxian Wood Pagoda. In this work, on-site studies reported in the literature [1, 8] and multiple surveys and mappings [9–12] carried out over many years were used to classify and evaluate the damage to the columns, beams, and *Dou-gong* brackets. A preliminary analysis was performed on the residual deformation of the columns and overall structure. Furthermore, multiple reasons for the

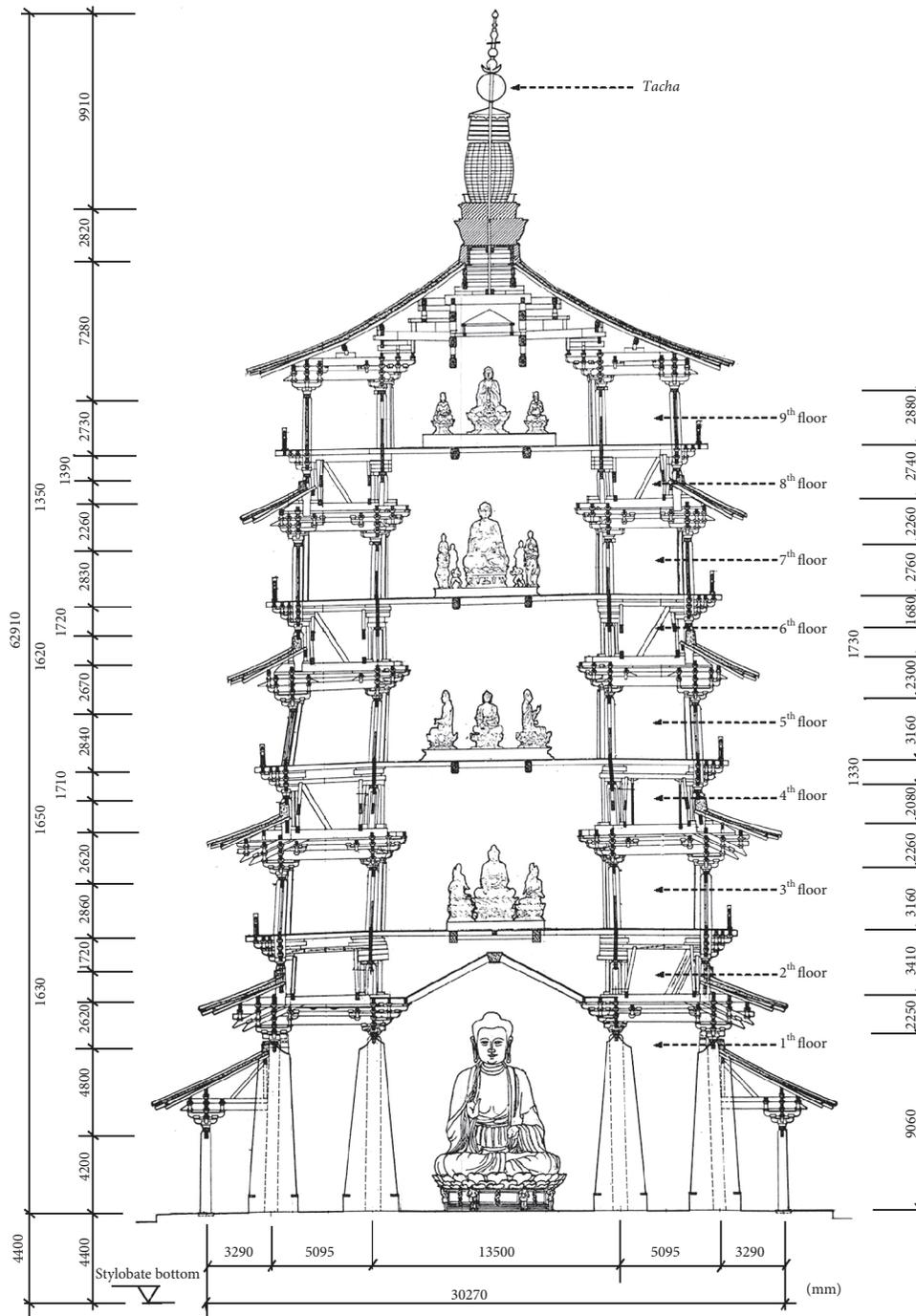


FIGURE 3: Elevation view of Yingxian Wood Pagoda. The elevations on the right and left indicate the outer and inner columns, respectively.

deformation of wooden structures were comprehensively analysed, which is helpful for the protection and restoration of ancient buildings.

## 2. Residual Deformation of the Columns and Main Structure

The safety and reliability of the pagoda were analysed considering measured deformation data, component cracking, and the connection condition of the components. A digital level and total station instrument were used to

measure the component deformation, establish the global coordinate system at the building site, and obtain the coordinates at the columns' top and bottom. Based on the dimensions and position information of various undamaged components in the pagoda reported in the literature [8], their actual relative positions were measured three times in 1991 using level station instrument [12] and in 2000 and 2011 [9] by total station instrument [11]. The position change information of each component was calculated as the difference of the measured data to the literature data. By comparing the contradictions or data errors of several

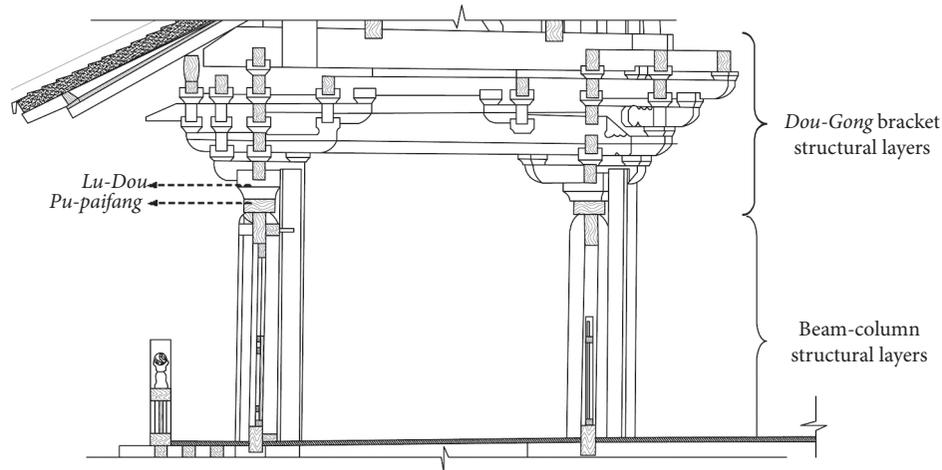


FIGURE 4: Major components of the third layer.

measurements, the pagoda was complementally measured and checked in May 2018.

**2.1. Residual Vertical Deformation of the Columns.** The wooden pagoda base is filled and tamped; the direct bearing layer is tamped silt, and the layer below is naturally deposited silt. Its traits have changed from the original state to a stable state after compression. The groundwater is phreatic at a depth of 1.8–2.0 m below the pagoda. According to the existing study [8], the height of the two-layer platform is 4.40 m. However, the land has been levelled several times, and a recent survey indicated that the height is 3.65 m. The pagoda has an independent irregular square stone foundation for the columns, and the inner and middle columns on the first floor are buried in an adobe wall. No obvious cracks were found on the wall surface. The relative height difference at the feet of the middle columns was 55 mm. The feet of the inner columns were difficult to observe; thus, it was assumed that there is no difference in the settlement.

Figure 5 shows the difference between the vertical position of each column head (or column foot) and the average vertical position of all the column heads (or column feet) of each floor. The column head of each floor essentially changed as the position of the column foot. The position of the column heads on the first to fifth floors and ninth floor generally had a greater difference than the column feet mainly because of the length error of the column itself and inconsistent tilting. The elevations of the heads of the inner columns on the first, third, fourth, and fifth floors were significantly higher than the other columns of the corresponding floor, which is based on the requirements of the architectural and structural functions during the design and construction. Moreover, compared to the foot of the outer columns, the elevations of the inner columns on the third and fifth floors generally increased because their vertical structure was stacked by several beams (Figure 6). In contrast, the outer columns had some *Dou* (Figure 6) between the beams, which led to different compressive deformations because of their diverse levels of vertical bearing stiffness. Under huge pressure, the inner columns on the second floor

were completely cracked, and many auxiliary columns were added. The inner columns had more obvious settlement than other columns on the same floor. However, this type of vertical displacement was not manifestly transmitted to more than five floors; this was presumed to be due to adjustment during construction and self-adjustment by the structure.

Table 1 presents the relative values for the vertical load of each column foot calculated according to the component size and dead load of the roof. Live loads were not considered. The inner columns usually had greater loads than the outer columns, which may be why the former had higher measured elevations than the latter. This result is consistent with data obtained from the modulus of the ancient building: the inner column heights were greater than those of the outer columns by 37, 6, 40, 42, 32, 11, -7, 0, and 13 cm from the first to ninth floors, respectively [8]. The height difference between the inner and outer columns on the second floor was small; this is possibly because the building function needed the second floor to remain level and the height of the inner layer on the first floor was too high. In the measured deformation data, several columns had significantly different heights, such as 2C19 on the second floor, 5C20 on the fifth floor, 8C17 on the eighth floor, and 9C19 on the ninth floor (Figure 5). This may have been due to adjustments or construction errors.

The beam end sections, *Gong* roots, and *Dou* brackets were compressed perpendicular to the grain, whereas the columns were compressed parallel to the grain. The residual vertical deformation of the beam directly connected to the column head (Figure 7) was very obvious because it was concentrated by the column head and *Lu-Dou* bottom. The average residual vertical deformations of such beam ends were measured to be 70, 19, 56, 13, 41, 16, 28, 16, and 22 mm from the first to ninth floors, respectively, and the measured average residual vertical deformations of the other members of the column head subject to horizontal compression perpendicular to the grain were 130, 32, 130, 28, 41, 19, 25, 17, and 17 mm, respectively. The values were markedly higher on the first and third floors than on the other floors because of serious damage. Columns under pressure,

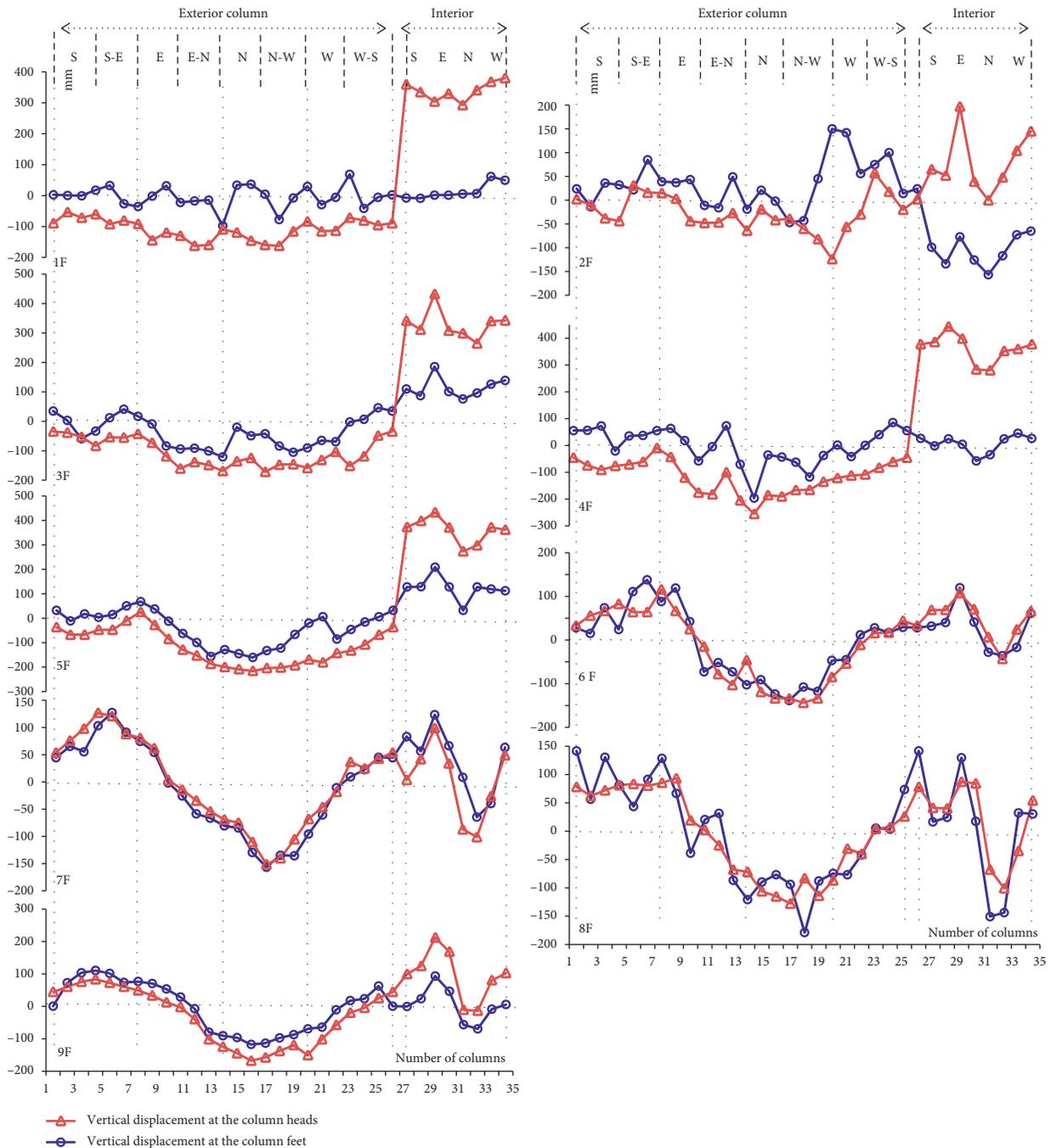


FIGURE 5: Vertical displacement at the column feet and heads.

inclination, splitting, and other damage caused large differences in the vertical height. The measured averages showed that the column heights on the first, third, fifth, seventh, and ninth floors decreased by 26, 23, 21, 19, and 18 mm, respectively. The column heights of the second, fourth, sixth, and eighth floors decreased by 22, 18, 17, and 16 mm, respectively.

Note that the columns on the north side and adjacent sides on each floor of the pagoda showed greater settlement than those on the other sides (Figure 5). This is because the north and adjacent sides of the pagoda were less exposed to sunlight; thus, their components experienced greater humidity. This

cumulatively increased the compressive deformations of the components on these sides, which generated a trend of vertical deformations. For the inner columns, C26, C27, C30, and C31 of each floor carried high vertical loads; therefore, their vertical deformations were also greater. C30 and C31 had greater vertical deformations than C26 and C27, which was mainly due to discrepancy in the water content.

**2.2. Residual Horizontal Deformation.** During the design and construction of Yingxian Wood Pagoda, most columns were designed to incline (*Ce-Jiao*) based on the building

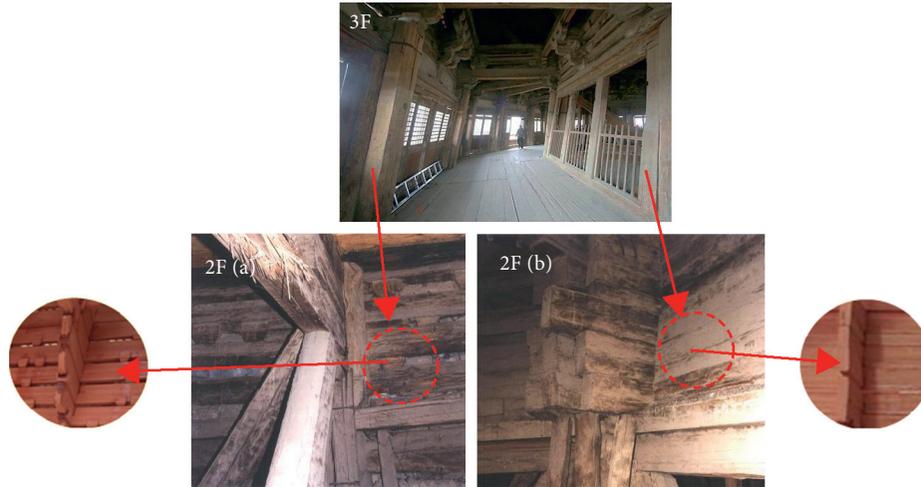


FIGURE 6: Beam construction under the (a) outer and (b) inner columns.

TABLE 1: Measured relative dead loads of the column feet.

Relative dead load	Column number			
	C1 (C25), C4, C7, C10, C13, C16, C19, C22	C2, C3, C5, C6, C8, C9, C11, C12, C14, C15, C17, C18, C20, C21, C23, C24	C26 (C34), C27, C30, C31	C28, C29, C32, C33
Ninth floor	1	1.10	4.71	1.87
Eighth floor	1	1.09	4.42	1.78
Seventh floor	1	1.09	2.82	1.30
Sixth floor	1	1.09	2.87	1.27
Fifth floor	1	1.08	2.10	1.08
Fourth floor	1	1.08	2.11	1.08
Third floor	1	1.09	1.78	0.97
Second floor	1	1.10	1.82	0.98
First floor	1	1.10	1.52	0.87

modulus and experience [8]. The inclination direction of each corner column pointed to the vertical axis of the circumscribed centre of the regular octagon of a floor; the other columns were inclined perpendicular to the vertical plane where the regular octagonal edge was located. The dotted lines in Figure 8 present the initial design of each column head relative to the column foot, while their actual inclination is shown as solid lines in the east-west and north-south directions. The middle and inner ring columns on the first floor were wrapped in the adobe wall, which resulted in a large lateral displacement stiffness on this floor. A plurality of diagonal braces were arranged between the columns and beams of the second, fourth, sixth, and eighth floors, and the columns were relatively short. Their lateral displacement stiffness was greater than that of the third, fifth, seventh, and ninth floors, which had relatively tall columns and no diagonal braces.

*2.2.1. Residual Horizontal Relative Deformation at the Head and Foot of Columns.* Because the middle and inner columns on the first floor of the pagoda were buried in the adobe wall, only the tilting condition inferred from the modulus of the ancient building [8] was evaluated. The column inclinations on the second floor were less than

those of the initial design, which increased the distance between the inner and outer columns. The outer column inclined outward, which reduced the column-beam tensile function. In addition, the inner columns on the second floor were cracked and supported by many auxiliary components, which weakened their structural function.

Compared to the initial design, the columns on each floor had disparate degrees of inclination (Figure 8). Specifically, most columns on the third floor were inclined to the northeast; 3C22, 3C23, and 3C33 were inclined more than 300 mm to the east, and 3C23 and 3C24 were inclined more than 300 mm to the north. 4C9–4C19 and 4C32 on the fourth floor were tilted to the east, whereas the other columns inclined less than the initial design. All columns on the fifth floor were inclined to the east; 5C18–5C20 and 5C32 were inclined more than 300 mm, and 5C24 was inclined approximately 499 mm. Columns 6C1 and 6C14–6C17 on the sixth floor showed increasing inclination in the north-south direction. For the seventh floor, all columns on the north and south sides were inclined to the north, and the columns on the south, southeast, east, and northwest sides were inclined to the west. All columns on the eighth floor were inclined to the north, whereas most columns were inclined in the east-west direction less than the initial design.

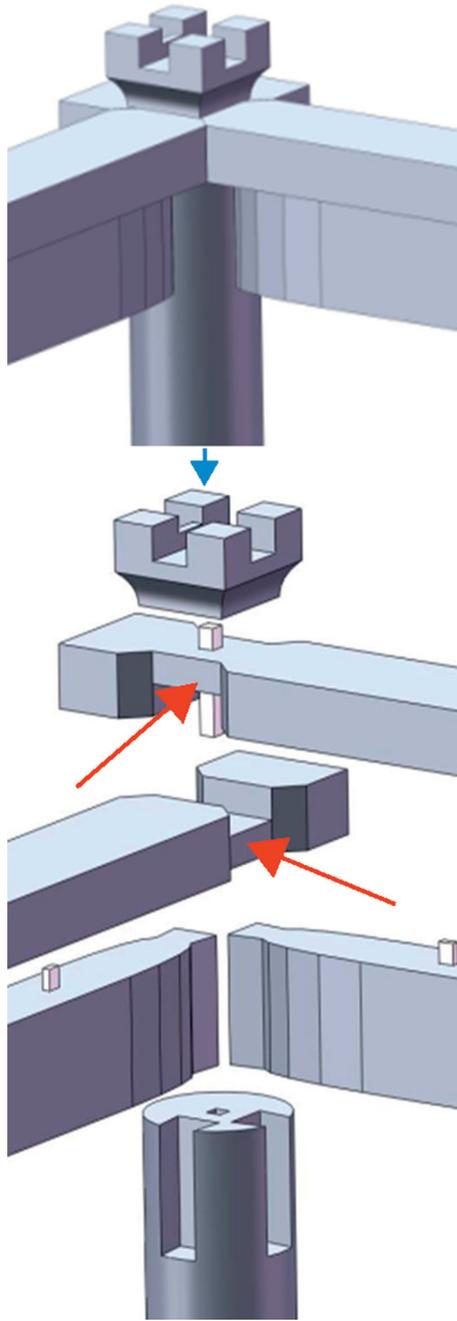


FIGURE 7: Connection of the beam-column frame. The red arrows indicate the weak parts of this frame.

For the ninth floor, all columns were inclined to the north, and the columns on the south, southeast, east, and northeast sides were obviously inclined to the west.

The columns on the west and southwest sides of the third floor and the west and northwest sides of the fifth floor were heavily inclined because of artillery shells from wars in 1926 and 1948 and showed bullet marks. Accidental shelling actually produced large deformations in local areas, which increased the residual deformation of the corresponding floor. The continuous effect of wind for nearly 1000 years and the long-term difference in water

contents of components caused regular trends in the residual deformation of each floor because the prevailing winds in the Yingxian County are in the northwest direction.

*2.2.2. Residual Horizontal Deformation of the Overall Structure.* Figure 9 illustrates the residual horizontal deformation at the centre of each structural layer (column layer formed from the column feet to the heads, and beam-bracket layer formed from the top of the stud beam to the top of the bracket) of the pagoda relative to the horizontal central projection of the regular octagonal stone base at the bottom of the platform. This was obtained by combining the deformations in the east-west and north-south directions. The horizontal offset for the first floor was averaged from the data of the eight corner columns of the outer circle that could be measured.

Each structural layer had different inclination directions and degrees, but the overall structure was inclined in the northeast direction. Within the height ranges of 0–22.18, 22.18–28.16, 28.16–31.00, 31.00–47.57, and >47.57 m, the structure was inclined in the northeast, southeast, northeast, northwest, and northeast directions, respectively. As mentioned earlier, the prevailing wind in Yingxian County is in the northwest direction, and the components were subject to long-term effects from slight differences in water content. This is the main reason the whole pagoda was inclined to the northeast. Note that the severe inclinations of column layers (19.32–22.18 m and 28.18–31.00 m) affected by artillery shells were the main hidden risk to the pagoda's safety. Some scholars have tested and analysed the dynamic characteristics of the pagoda and pointed out that the third and fifth floors mainly vibrated in the second and third modes, which is another major reason for the increased residual deformation [13]. The serious tilting of the iron *Tacha* to the east was because of the rotation of its base around the horizontal axis.

In recent years, several researchers have focused on the seismic performance of ancient buildings, and various simulation studies and solid earthquake damage investigations have consequently been conducted [14–17]. In the past millennium, the pagoda has experienced many earthquakes, which undoubtedly caused its residual deformation to increase. Recent earthquakes, such as the magnitude 6.1 Horinger earthquake in 1976, magnitude 7.8 Tangshan earthquake in 1976, and magnitudes 6.1 and 5.8 Yanggao earthquakes in 1989 and 1991, respectively, have produced similar effects [18].

The horizontal displacement angle from the top of the foundation stone to the top of the lotus throne (4.4–57.67 m) of the overall structure was  $1/80$ . The horizontal displacement (177 mm) angle of the column layer (19.32–22.18 m) exceeded  $1/16$ , and the ratio of the average column radius (302 mm) to the height of the structural layer was  $1/9.4$ . The horizontal displacement (116 mm) angle of the column layer (28.18–31.00 m) exceeded  $1/25$ , and the ratio of the average column radius (288 mm) to the height of the structural layer was  $1/9.9$ . Xie et al. [19] set the

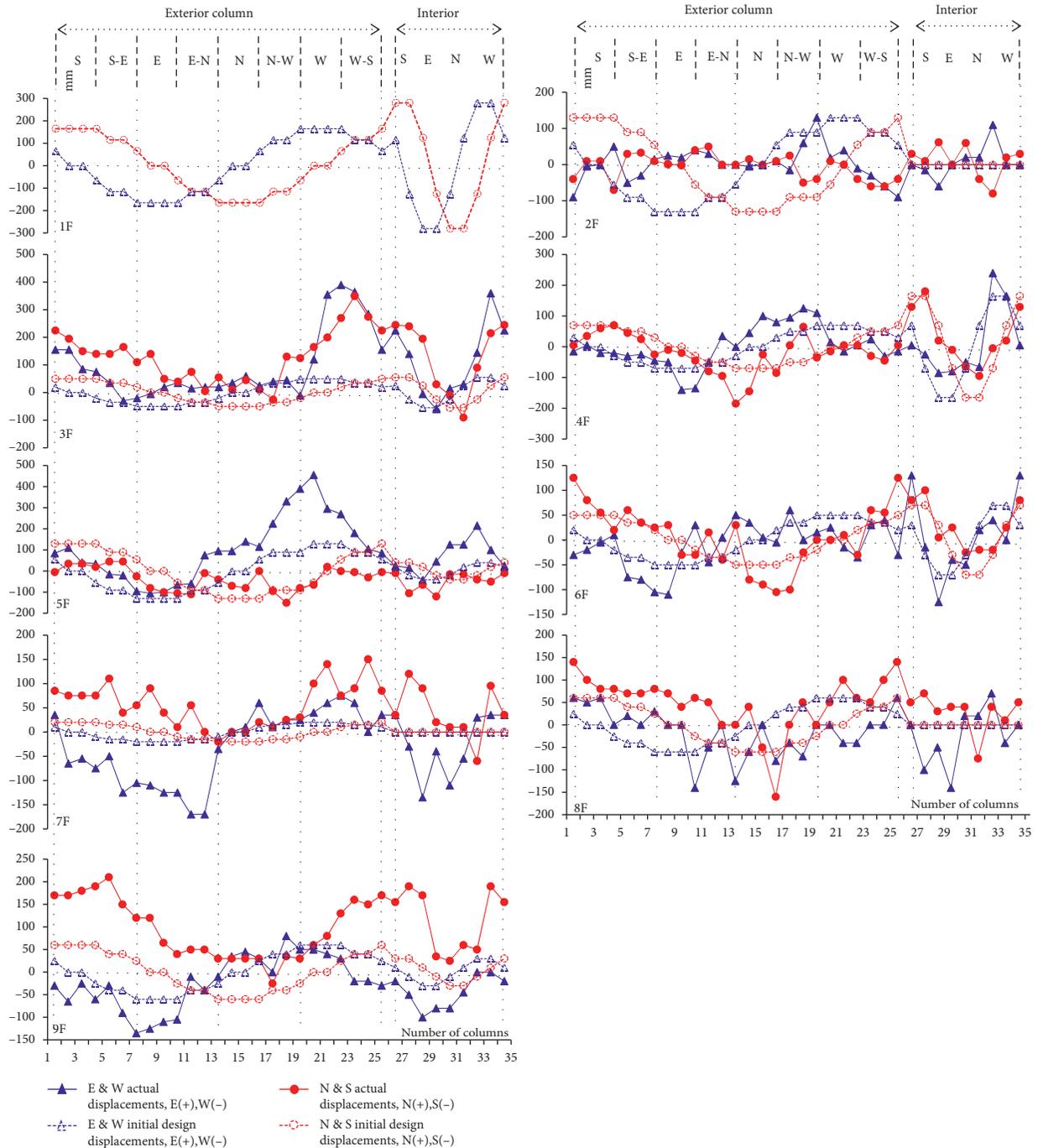


FIGURE 8: Horizontal displacements at the column heads.

lateral displacement limit of a single-storey wooden structure to the radius of the column.

### 3. Repair Discussion

According to the historical records, Yingxian Wood Pagoda has been repaired six times, in 1191, 1320, 1508, 1722, 1866, and 1928–1935 CE. Most of the repairs involved partial reinforcement of a single component in the traditional manner (Figure 10). However, owing to the weight of the pagoda itself and its complex structure and components,

which differ significantly from those of other single- or multistorey ancient buildings, it is difficult to apply the maintenance techniques used on other ancient wooden buildings to the pagoda.

Considering the protection and reinforcement plans of Yingxian Wood Pagoda, experts from the State Administration of Cultural Heritage of China conducted two studies and failed to reach a consistent conclusion. Replacing the *Dou-Gong* brackets, which have a severely reduced effective load area and have become severely damaged on the beam ends, has long been controversial and it is difficult to provide

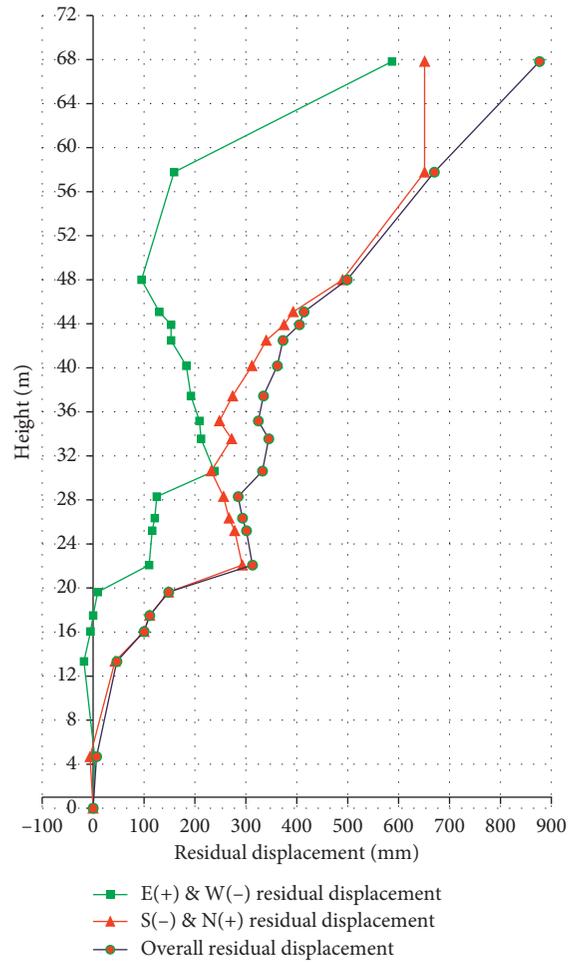


FIGURE 9: Residual horizontal deformation at the centre of each structural level relative to the central projection of the foundation.



FIGURE 10: Partial reinforcement conducted on different components of Yingxian Wood Pagoda over the years, such as columns, beams, and *Dou-Gong* brackets.

a suitable repair method. To reduce the lateral displacement of the wooden tower, auxiliary columns were added except for the ninth floor. The experts attempted to reduce the severely inclined third and fifth column structural layers by adding auxiliary components, but no consensus was reached; hence, further analysis and research are currently underway.

Although various studies have reported computational modelling results for other structures [20, 21], the anisotropy and nonlinearity of wooden structures and the complex types and degrees of damage make the calculation model and the corresponding parameters of the wooden components of ancient buildings complex. The existence of and damage to the joint gaps between the components lead to variations in the stiffness of these joints with load and deformation; thus, it is difficult for the load calculation model to accurately predict the actual condition. As a result of the large volume of Yingxian Wood Pagoda, as well as the large number of components and various types of damage, it is difficult for the calculation model to predict its current condition. Therefore, one of the main challenges is to develop models for proper computational analysis. The evaluation of the ultimate deformation capacity of wooden structures requires the use of test results. Although some test results have been reported in the literature [22–24], Yingxian Wood Pagoda requires the use of transplantation analysis of the results. These areas will be studied in future repair research work.

#### 4. Conclusion

The residual deformation of Yingxian Wood Pagoda and cumulative damage are the main hidden dangers to its continued existence. This study analysed the residual deformation of its various layers and its overall structure along with the influencing factors and provides a foundation for its protection and repair.

- (1) The heads of the inner column had significantly higher elevations than other columns on the first, third, fourth, and fifth floors, but the feet of the inner columns were generally higher than the feet of the outer columns on the third and fifth floors to meet the required architectural and structural functions. The beam ends, *Gong roots*, and *Dou* were all pressured with obvious residual deformation perpendicular to the wood grain.
- (2) The third, fifth, seventh, and ninth floors of the pagoda had less lateral stiffness than the adjacent floors; therefore, they had greater residual horizontal deformation than adjacent floors. On each floor, the beam-bracket structural layer had a smaller residual horizontal deformation than the column structural layer because of a greater lateral displacement stiffness. The overall structure was inclined to the northeast compared to the initial design. The horizontal interlayer displacement angles of the third column structural layer and fifth column structural layer exceeded 1/16 and 1/25, respectively, toward

the northeast. They are the weak parts of the wooden pagoda and are still in constant deformation. The horizontal displacement angle of the whole structure (4.4–57.67 m) is 1/80.

- (3) The repair of Yingxian Wood Pagoda requires further detailed research on traditional and modern repair methods, as well as more detailed calculation model analysis.

#### Data Availability

The figure and table data used to support the findings of this study are included within the article.

#### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

#### Acknowledgments

This study was supported by the National Natural Science Foundation of China (grant no. 51338001). The authors would like to thank the Shanxi Cultural Relic Bureau and Yingxian Cultural Relic Protection Department for their assistance.

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