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Structural characteristics and modal analysis of the Dong ethnic group's single-column drum tower: A case study of the Shudong drum tower

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Abstract: The drum tower is a representative of the Dong ethnic group's wooden architectural construction skills, with the Central-Column drum tower being one of its typical structural forms. To explore the structural characteristics and dynamic properties of the Central-Column drum tower, this paper takes the Shudong drum tower as the research object. Based on field survey data, it analyzes the floor plan selection, architectural structural features, and seismic structural characteristics. Using SAP2000 software, a three-dimensional finite element model of the Central-Column drum tower was established, and modal analysis was completed, revealing the dynamic characteristics of the Central-Column drum tower. The measured data, structural features, and modeling techniques described in this paper contribute to the study of drum towers from an architectural structural perspective.

1. Introduction

The Dong ethnic group is distributed across Guizhou, Hunan, Guangxi, Hubei, and Guangdong regions of China (as shown in figure 1), with a total population of nearly 3.5 million. The Dong people are skilled in architecture, and their wooden architectural construction techniques have been listed in the first batch of national intangible cultural heritage. The drum tower is considered a symbolic sample of Dong architecture and is viewed as the pinnacle of Dong wooden architectural construction.

Currently, research on Dong drum towers mainly focuses on the following aspects:

① Cultural symbolism[1-2], primarily exploring the social significance and cultural connotations of drum towers;

② Construction techniques and architectural aesthetics[3-4], emphasizing the study of wooden structures and geometric aesthetics;

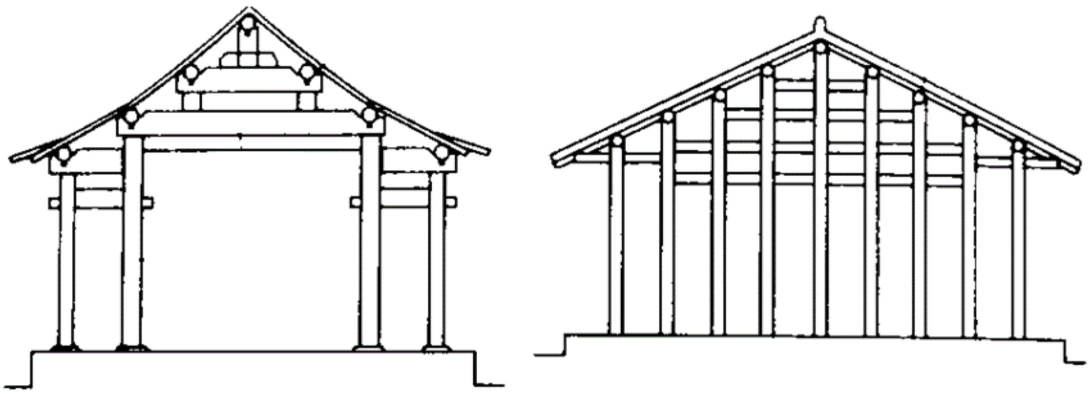
③ Mathematical logic[5-6], tending to analyze mathematical concepts and ideas presented in drum tower construction.

However, there has been relatively little research on Dong drum towers in terms of architectural structure, especially in engineering mechanics. The Central-Column drum tower is one of the most representative forms of Dong drum towers. This paper takes the Shudong drum tower as the research object, analyzing the floor plan selection and construction methods of single-column drum towers. Using SAP2000 software, a three-dimensional finite element model is established to explore the modeling method of mortise and tenon joints, and modal analysis is completed.

Figure 1: Distribution of Dong Ethnic group and Drum Tower.

2. Structural features of the Shudong Drum Tower

2.1. Structural features



(a) Post-and-beam structure (b) Column-and-tie-beam structure

Figure 2: Typical ancient Chinese wooden frameworks

Ancient Chinese wooden frameworks had three different structural methods: post-and-beam, column-and-tie-beam and log-cabin, with the post-and-beam and column-and-tie-beam being more widely used.

The post-and-beam wooden framework is constructed by erecting columns on stone bases along the depth of the building. Beams are placed on top of these columns, and then multiple layers of short columns (known as "gua zhu") and beams are stacked on top. On the topmost beam, ridge short columns are erected, forming a wooden framework (as shown in Figure 2a).

The column-and-tie-beam wooden framework also erects columns along the depth of the building, but with closer spacing between columns. The columns directly bear the weight of the purlins without using elevated lift-beams. Instead, it uses multiple layers of horizontal tie beams (known as "chuan") that pass through the columns, forming sets of frameworks. Its main characteristic is the use of relatively smaller columns and tie beams to create a considerably large framework (as shown in Figure 2b).

The base of the drum tower is polygonal, often quadrilateral or octagonal, with a multi-angled roof. The number of floors in the drum tower is usually odd. Among the existing classification methods for drum towers, one of the more representative approaches is by Cai Ling[7], who conducted a classification study on the structural technology types of Dong Ethnic group's drum towers based on the perspective of major wooden structural systems and roof construction methods. This classification divides drum towers into two main categories: the post-and-beam and column-and-tie-beam hybrid structures (PCS), and the column-and-tie-beam structure (CTS) (as shown in Figure 3).

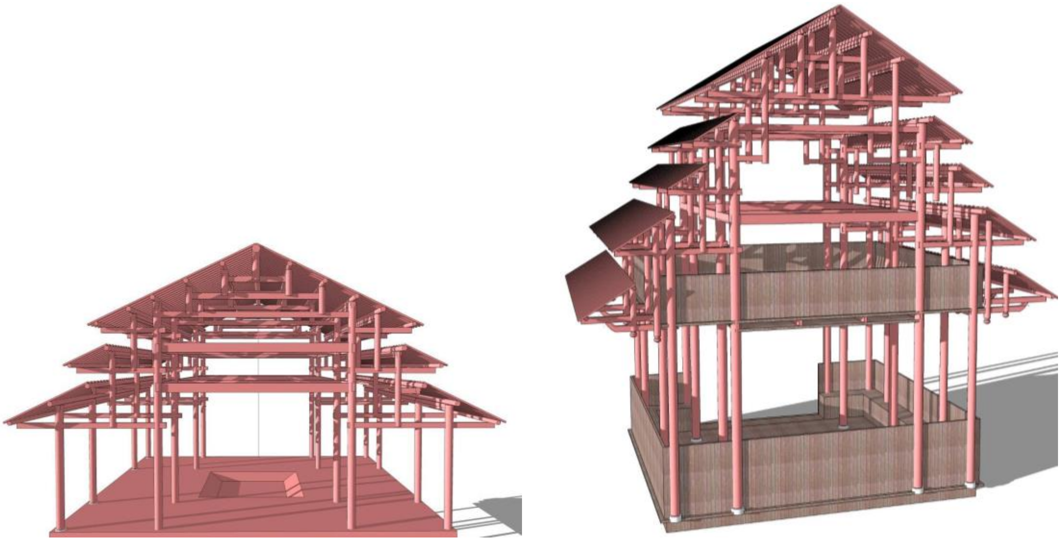


Figure 3: The PCS and CTS drum tower (the picture via Chen[8])

The CTS drum tower is a purely column-and-tie-beam wooden frame structure, where all purlins are supported by columns, and the columns are connected by horizontal tie beams. The top roof truss is integrated by purlins, tie beams, and bracket arms. This type of drum tower can be further divided into "central-column type" and "non-central-column type" based on the structural system and load-bearing characteristics of the roof.

The "central-column type" drum tower has a regular polygonal floor plan. Based on the penetration of its central column, it can be further divided into single-column drum towers (SC, Figure 4a-c) and ringed-column drum towers (RC, Figure 4d-f). The SC drum tower has a central column that penetrates through the entire structure, while the RC drum tower has no central column in the lower part, only featuring a "leigong" column (derived from Han Chinese architecture, it is a suspended column at the top of a pointed roof structure and was a primary lightning protection device in ancient architecture) in the upper-middle part of the structure.

The Shudong drum tower is the earliest and most typical example of SC drum towers. Built in the ninth year of the Chongzhen era of the Ming Dynasty (1636), it is the only fully preserved SC drum tower in Liping County, Guizhou Province. As shown in Figure 5, this four-eaved pavilion drum tower has 5 floors and is approximately 15.8m tall. Except for the first floor, which has supporting columns for expansion and decoration, the entire drum tower is penetrated from top to bottom by a central golden column, serving as the main load-bearing component.

From the exterior, the Shudong drum tower gradually narrows inward from bottom to top, forming a layered shape of upper and lower eaves. From the interior, with the central column as the exact center, horizontal tie beams (known as “chu shui fang”) and corner cantilever beams (known as “jiao tiao fang”) of varying diameters interlace around the central column, connecting into a whole. The first layer of beams supports the second layer of short columns, and this structural form is repeated up to the sixth layer. All components of the entire drum tower are connected using mortise and tenon joints. Table 1 shows the measured dimensions of the core components of the Shudong drum tower.

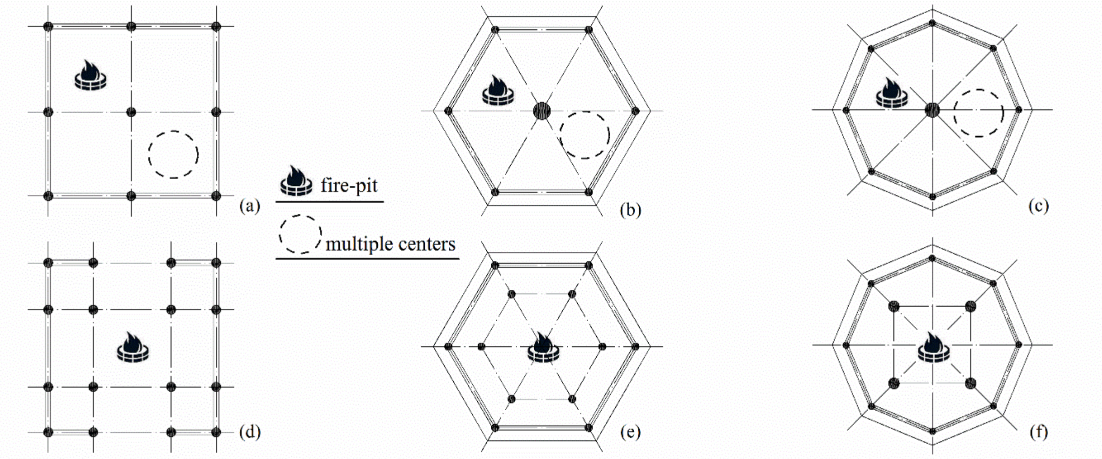


Figure 4: Plan of the SC drum tower and RC drum tower

Figure 5: Shudong drum tower①

Table 1: Dimensions of the Shudong Drum Tower.

	Section size (cm)	Height (cm)	Quantity	Distance (cm)
Central golden column	Ø 50	1580	1	-
Eave column	Ø 32	350	8	290
Height of the first floor	-	400	-	-
Hypostyle column	Ø 45.6	*	4	310
Fire-pit	280×280	-	1	-
Short column	Ø 32	*	8/floor	*
* Owing to the restriction of the surroundings on site, the accurate data was not measured.				

2.2. Seismic-resistant structural features

(1) Connection between columns and column base stones

According to field investigations, as shown in Figure 6, the connection method between the columns and column base stones in Dong Ethnic group's drum towers is a flat, floating placement. The upper main wooden structure is not ideally rigidly connected to the lower foundation. The

① Unless stated, the pictures in this article are taken by the authors.

column base stones provide horizontal friction and vertical support, while the column base does not transfer bending moments. This connection method allows for both controlled sliding displacement and rotation under certain conditions. Under horizontal seismic action, the relative displacement between the column end and the column base stone can dissipate energy through sliding and reduce the overall stiffness of the structure, increasing the structural period and thus reducing seismic effects, achieving an isolation effect.

Figure 6: The connection between columns and column base stones

(2) Wooden frame and mortise-tenon connections

Dong Ethnic group's drum towers use wooden frames for load-bearing, with SC drum towers mainly relying on the central column and eave columns for support. As shown in Figure 5, all beam-column components use mortise-tenon connections, which are equivalent to semi-rigid joints. The deformation of these joints is between that of ideal rigid joints and ideal hinged joints. Under seismic action, the semi-rigid connection method can dissipate energy through sliding, friction, and compression between the members converging at the joint, while also reducing structural stiffness and increasing the period to reduce seismic effects, which is advantageous for earthquake resistance.

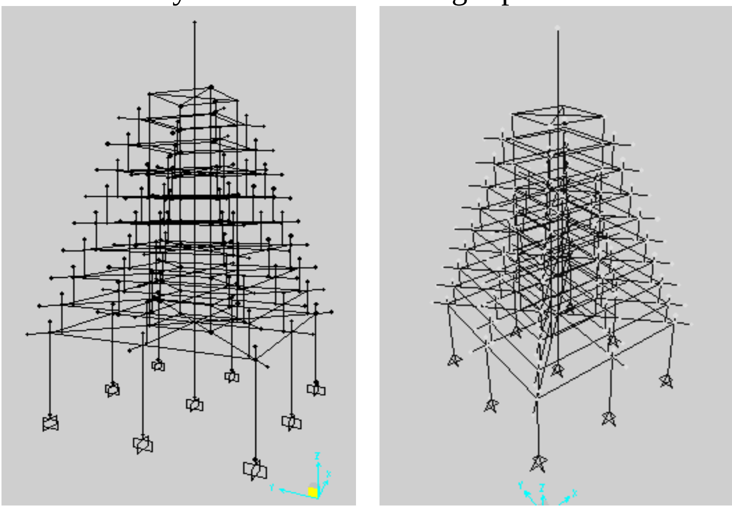
(3) Roof truss system

The roof truss system itself refers to the roof part of the wooden structure building. In the SC drum tower discussed in this article, it is equivalent to the tower top of the drum tower (as shown in Figure 7). The tower top is mainly connected to the main wooden structure using bracket sets (known as “dou gong”), interlocking spaces, and mortise-tenon connections. This connection method serves to coordinate the rigidity of the building. In the event of seismic action, it dissipates seismic energy, greatly reducing the effect of earthquakes on the tower body, thus providing an earthquake-resistant effect.

Figure 7: The connection between the tower top and the main body of the drum tower

3. Finite element model and analysis results of the SC drum tower

Spruce was chosen for modeling. According to the properties of commonly used wood in "Wood Science," f_u=40.8MPa, f_t=96.2MPa, density is 0.005g/mm^3, and Poisson's ratio is taken as 0.2. Following Jia[9], the semi-rigidity of mortise and tenon joints is realized by releasing the ends of line objects. Custom methods are used to define plastic hinges, with beam hinges being P-M3 type and column hinges being P-M2-M3 type. Based on the actual connection between columns and column base stones, this paper established both fixed and hinged models for column bases, as shown in Figure 8. The modal analysis results for the single-pillar drum tower are shown in Table 2.



(a) Fixed models (b) Hinged models

Figure 8: Finite element model of the SC drum tower

Table 2: Comparison of vibration period and frequency of the SC drum tower

Boundary conditions	**Mode shape**	**Period**	**Frequency**	**Angular frequency**
fixed	1	1.176	0.851	5.344
	2	1.066	0.938	5.892
	3	0.423	2.365	14.861
	4	0.422799	2.3652	14.861
	5	0.147787	6.7665	42.515
hinged	1	0.225	4.449	27.957
	2	0.200	5.000	31.414
	3	0.132	7.595	47.719
	4	0.13167	7.5948	47.719
	5	0.044939	22.252	139.82

4. Conclusions

Drum towers possess ethnic cultural value, wooden construction value, and aesthetic value. This paper conducted a preliminary discussion on architectural construction, seismic-resistant features, and modal analysis of single-pillar drum towers, using the Shudong drum tower as the subject. The premise of structural analysis is accurate measurement of structural components, and the simulation method for mortise and tenon connections directly affects simulation accuracy. However, due to the variety of drum tower types, complex detailing, and irregular surfaces, further in-depth research is needed in collaboration with the broader scientific community to achieve fine-grained modeling of drum tower structures.

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