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Structural characteristics and static-dynamic analysis of the plane frame of a drum tower with ringed-column hip-and-gable roof and column-and-tie-beam style

Pu Shuang[1,a], Huang Chuanteng[1,b,*], Cai Jilun[1,c], Fu Juan[1,d], Liu Junxiu[1,e], Tang Hongyao[1,f]

[1]School of Engineering, Zunyi Normal University, Zunyi, China
[a]pushuang1122@163.com, [b]huangct@yeah.net, [c]1589315815@qq.com, [d]fujuan@outlook.com
[e]2199115242@qq.com, [f]1692007347@qq.com
[*]Corresponding author

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Abstract: This study analyzes the characteristics of the Dong ethnic group's drum tower with a ringed-column hip-and-gable roof and column-and-tie-beam style (RHC style), focusing on its planar column network, timber framework system, and construction methods. Based on a modular design scheme, a 3-story RHC style drum tower was selected to establish a planar frame model. Static analysis under dead load and modal analysis were completed using SMIA software. The internal force distribution and mechanical property of this type of structure are discussed based on the internal force diagrams of the planar frame. The relevant analysis results can provide a reference for scholars studying drum towers.

1. Introduction

The Dong ethnic group is mainly distributed in the junction area of Guizhou, Guangxi, and Hunan provinces in China. The Dong people are skilled in architecture, and their wooden construction techniques have been listed in the first batch of national intangible cultural heritage. The drum tower (as shown in Figure 1) is considered a symbolic example of Dong architecture and is viewed as the epitome of Dong wooden structures.

Figure 1: The status of drum tower[*]

* Unless stated, the pictures in this paper are taken by the authors.

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

(1) Cultural symbolism. Ren et al.[1] consider the village as the foundation of Dong culture and the drum tower as the ethnic emblem of the Dong people, serving both social and cultural functions. Wu[2] regards the drum tower as the center of Dong villages and the heart of the community in Dong people's minds. These studies analyze the significance of drum towers in Dong people's production and life, and explore their cultural connotations and functional attributes.

(2) Construction techniques and architectural aesthetics. Cai and Deng[3] studied the classification methods of Dong drum towers from a structural technology perspective, based on the timber framework system and roof construction. They described the structural characteristics of the post-and-beam and column-and-tie-beam hybrid structures (PCS), and the column-and-tie-beam structure (CTS), and summarized the evolution of structural technology types and cultural transmission methods. Wu[4] through field investigations and verifications, elaborated on the construction techniques and methods of the bracket (*Dougong*) in Dong drum towers' spire, and summarized the design methods of *Dougong* structures in various representative drum towers. Yan et al.[5] believe that Dong drum towers not only meet daily life needs but also satisfy the tribe's desire for artistic imagery and beauty. They identified the beauty of architectural symmetry and balance, proportion and harmony, and primary-secondary structure in drum towers, and provided specific descriptions from these three aspects.

(3) Mathematical logic. Zhang and Luo[6-7] explored the mathematical culture of the Dong people using drum towers as a medium, as well as the application of various mathematical concepts in Dong life, from the perspective of researching and uncovering ethnic minority mathematical culture. They focused on discussing the mathematical ideas embodied in the structural construction of Dong drum towers and proposed new approaches for uncovering the mathematical culture of ethnic minorities.

Despite extensive research on Dong drum towers by various scholars, there is little literature analyzing and studying the structural mechanical properties of these towers. This paper focuses on the RHC style Dong drum tower as the research subject, analyzing its characteristics in terms of planar column network, timber framework system, and construction methods. A 3-story RHC style drum tower is selected to establish a planar frame model, and static calculations under vertical loads and modal analysis are performed. The internal force distribution and mechanical property of the drum tower structure are then discussed.

2. Structural characteristics of RHC Style drum towers

2.1. The roof styles in Chinese ancient architecture

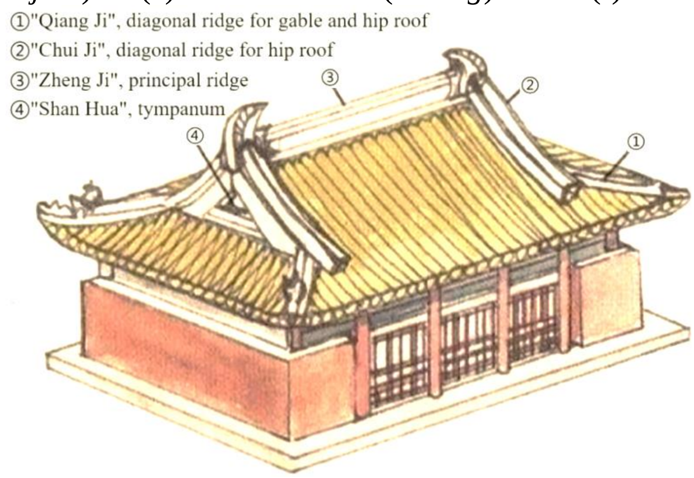
The roof styles of ancient Chinese architecture are very rich, with numerous classifications. They can be mainly divided into the following forms (as shown in Figure 2): Hip roof (*Wudian*), Hip-and-gable roof (*Xieshan*), Overhanging roof (*Xuanshan*), Flush gable roof (*Yingshan*), Pyramidal roof (*Zanjian*), and Truncated roof (*Luding*). Among these, the Hip roof, Hip-and-gable roof, and Pyramidal roof are further divided into single-eave (one eave) and multi-eave (two or more eaves) types. The Hip-and-gable roof, Overhanging roof, and Flush gable roof can evolve into Rolled ridge roof (*Juanpeng*). The Pyramidal roof has variations such as circular, square, hexagonal, and octagonal forms.

In addition to their functional purpose, the roofs of ancient buildings were also symbols of social status. The hierarchy of roof styles, from highest to lowest status, is as follows:

Hip roof > Hip-and-gable roof > Overhanging roof > Flush gable roof > Pyramidal roof > Truncated roof.

(a) Hip roof (*Wudian*) (b) Overhanging roof (*Xuanshan*) (c) Flush gable roof (*Yingshan*)

(d) Pyramidal roof (*Zanjian*) (e) Truncated roof (*Luding*) (f) Rolled ridge roof (*Juanpeng*)



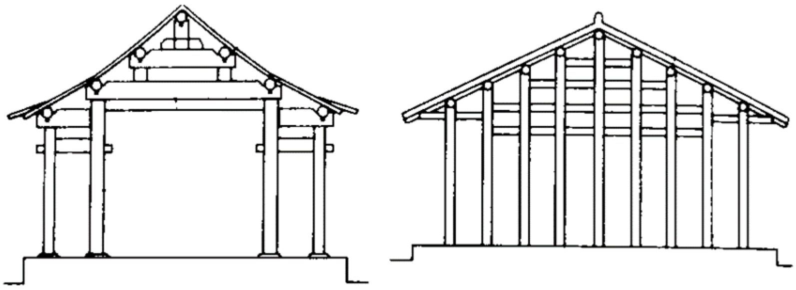
(g)Hip-and-gable roof (*Xieshan*)

Figure 2: Chinese ancient architectural roof styles diagram.

The Hip-and-gable (*Xieshan*) style roof has one *Zhengji*, four *Chuiji*, and four *Qiangji*. Unlike the Flush gable (*Yingshan*) and Overhanging (*Xuanshan*) styles, where the gable wall extends vertically from the *Zhengji* to the ground, the Hip-and-gable roof's structure is different at the gable ends. In a Hip-and-gable roof, the *Zhengji* is shorter than the distance between the two gable walls. This creates a triangular vertical area at the top, formed by the *Zhengji* and two *Chuiji*, which is called the Tympanum (*Shanhua*). Below the *Shanhua* is a trapezoidal roof surface that covers the ends of the *Zhengji*. This design effectively combines elements of both gable and hip roof styles, resulting in the distinctive Hip-and-gable appearance. This roof style is notable for its complex structure and elegant appearance, making it a popular choice in traditional Chinese architecture, especially for important buildings. The combination of vertical and sloping elements creates an interesting visual rhythm and helps to shed water efficiently.

2.2. The beam-column framework in Chinese ancient architecture

The ancient Chinese wooden frameworks had three different structural methods: post-and-beam (*Tailiang*), column-and-tie-beam (*Chuandou*) and log-cabin (J*inggan*), 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 (*Guazhu*) and beams are stacked on top. On the topmost beam, ridge short columns are erected, forming a wooden framework (as shown in Figure 3a). 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 (*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 3b).



(a) Post-and-beam (*Tailiang*) structure (b) Column-and-tie-beam (*Chuandou*) structure

Figure 3: Typical ancient Chinese wooden frameworks.

2.3. The structural characteristics of RHC style drum tower

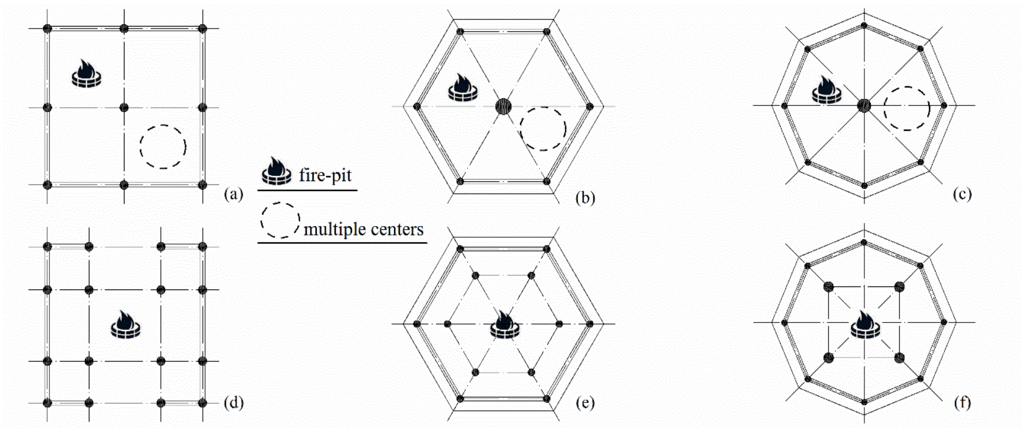
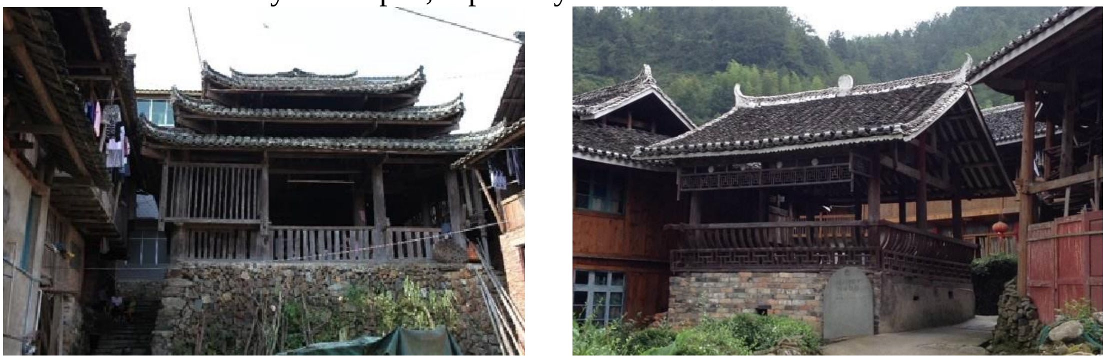


Figure 4: Plan of the SC drum tower and RC drum tower.

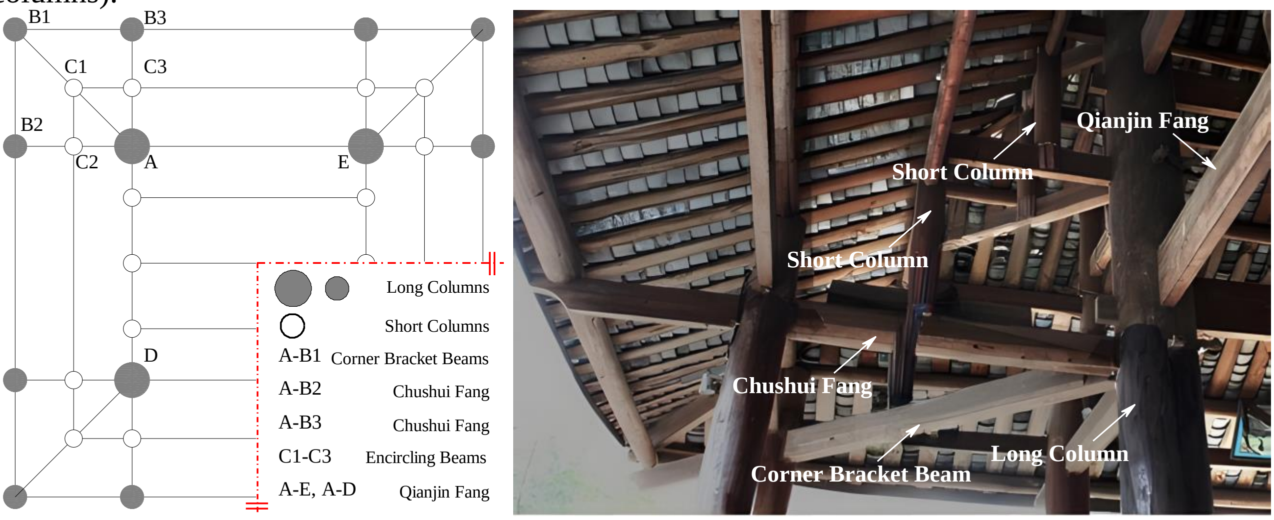
Among existing drum tower classification methods, Cai[8] is particularly representative. Based on the timber framework system and roof construction methods, Cai categorized drum towers into two main types: the post-and-beam and column-and-tie-beam hybrid structures (PCS), and the column-and-tie-beam structure (CTS). The CTS 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 towers have a regular polygonal plan and are further divided into “single-column” drum towers (SC, Figure 4a-c) and “ringed-column” drum towers (RC, Figure 4d-f). In RC drum towers, there is no central pillar at the lower part, only a “*Leigong* column” (derived from Han architecture, it's a suspended column at the top of a pointed roof, serving as the main lightning protection device in ancient architecture) in the upper-middle part of the structure. This enlarges the central space, allowing for a fire pit where the central column would have been, greatly enhancing the centripetal nature of the interior space. Consequently, RC drum towers have been extensively developed, especially after 1949.



(a)The RHC style drum tower (the Jiang Bian drum tower in Pingzhai Village. (left)
(b)The Overhanging roof column-and-tie-beam style drum tower. (right)

Figure 5: The RHC style and Overhanging roof drum tower.

The RHC style drum tower (Figure 5a) has a quadrilateral base plan with a hip-and-gable roof rising from the middle. Compared to Overhanging roof drum towers (Figure 5b), its external form is more substantial, with multiple roof layers and a hip-and-gable roof standing out among the numerous dwellings in the village, making it more distinctive. Figure 6a shows an upward view of the interior of a 3-story (2 roof layers + 1 hip-and-gable layer) RHC style drum tower, Figure 6b shows the roof (from the inside). As shown, vertical components include *Long Columns* (know as "*Luo Dizhu*", the core vertical component in the structure that directly transfers the vertical load to the foundation and runs through the entire structure) and *Short Columns* (know as "*Guazhu*", transfer columns, not extending to the ground), while horizontal components include *Chushui Fang* (orthogonal "main beams" connecting inner and outer long columns), *Corner Bracket Beams* (diagonal "main beams" connecting inner and outer long columns), *Encircling Beams* ("secondary beams", connecting the main beams), and *Qianjin Fang* ("main beams", connecting internal long columns).

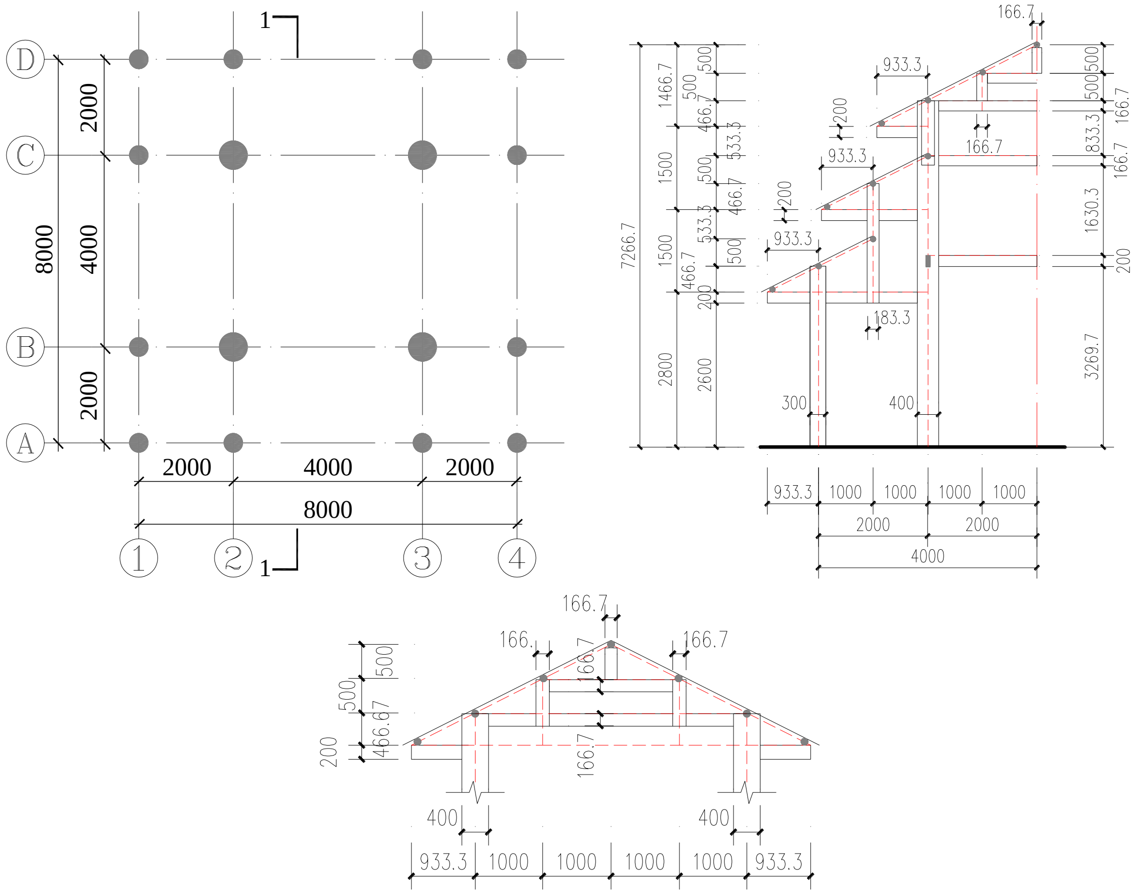


(a)The roof schematic of RHC style drum tower. (left)
(b)The roof of RHC style drum tower (from the inside). (right)

Figure 6: The structural characteristics of RHC style drum tower.

3. Design scheme of RHC style drum tower

Zhang[9] proposed a modular design method for drum towers. Following this approach and based on folk practices (as opposed to "official" practices), this paper designed a 3-story (2 roof layers + 1 hip-and-gable layer) RHC style drum tower. The plan dimensions, structure profile map, and hip-and-gable roof profile map are shown in Figure 7a-7c respectively. It should be noted that traditional timber structures use "*Chi*" as the unit (1 Chi = 333.3 mm), so some component and structural dimensions may not conform to modern architectural design modules.



(a) The plan dimensions of RHC Style Drum Tower (mm). (upper left)
(b) The structure profile map (1-1) of RHC style drum tower (mm). (upper right)
(c) The profile map of the hip-and-gable roof (mm). (lower)

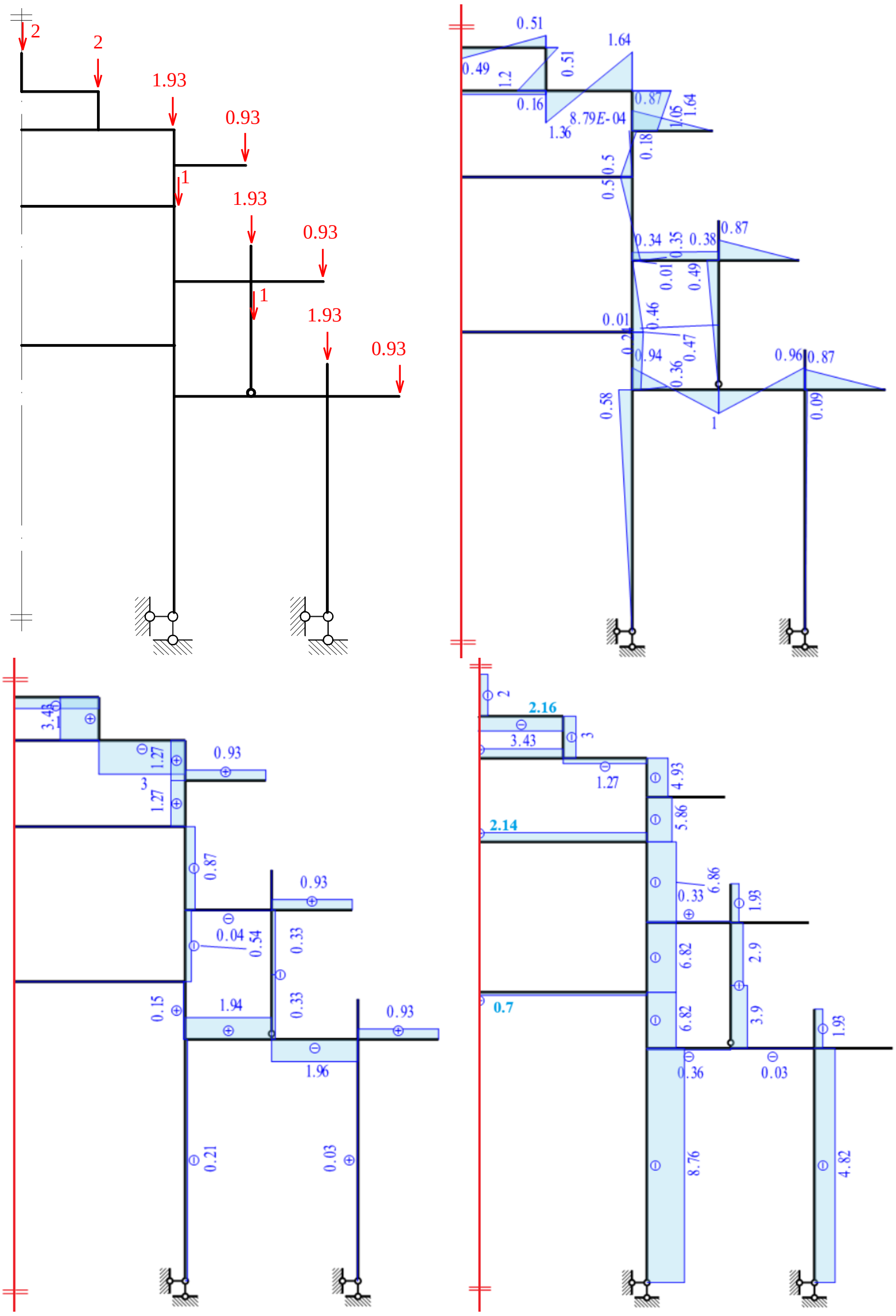
Figure 7: The design scheme of a RHC style drum tower

4. Static and dynamic analysis of RHC style drum tower

4.1. Statical analysis of dead load

The planar frame of axis ② is selected as the analysis object. Purlins are simplified as concentrated loads acting on the frame. Since this paper only analyzes the distribution and relative magnitude of internal forces in structural members, the sum of the self-weight of purlins per unit length in the longitudinal direction and the self-weight of the roof within a 500 range of horizontal projection is set as a unit load of 1. The calculation diagram of the drum tower's planar frame is shown in Figure 8a.

Figure 8b shows the bending moment diagram of the drum tower's planar frame. As shown, under vertical loads, the bending moment is largest at the ends of *Qianjin Fang* of the top floor. This is because most of the load from the hip-and-gable roof is transferred to the *Qianjin Fang* as concentrated loads through *Short Columns* (acting on the *Qianjin Fang*). Therefore, in traditional timber structures, the mortise and tenon joints between columns and beams are almost always made in a "penetrating" form to increase the constraint strength of the nodes and reduce the deflection and internal forces of the members.



(a) Calculation Diagram (1= unit load). (upper left)
(b) Bending Moment Diagram (unit load·m). (upper right)
(c) Shear Force Diagram (1= unit load). (lower left)
(d) Axial Force Diagram (1= unit load). (lower right)

Figure 8: The calculation diagram and internal force diagram

Figure 8c shows the shear force diagram of the drum tower's planar frame. Combining the bending moment distribution and member lengths, the shear force in the *Qianjin Fang* of the top floor is still relatively large. It can be seen that the *Qianjin Fang*, which connects the *Long Columns* and also functions as a "transfer beam", is both a vulnerable and core component of the drum tower structure. This helps to identify key areas for structural health inspection and reinforcement of drum towers. Figure 8d shows the axial force diagram of the drum tower's planar frame. Evidently, the *Long Columns* (sometimes called "eave column"), as core vertical components, bear significant axial forces. Among these, the internal *Long Columns* with the largest tributary area bear the maximum axial force. This mechanical analysis conclusion is consistent with the common practice of selecting the largest size columns for these positions.

4.2. Modal analysis

Based on the dimensions of the drum tower components, a consistent mass model is adopted. For beam elements with a diameter of 200mm, distributed linear mass $\bar{m}=1$ and cross-sectional stiffness EI=1are assigned. For other components, the distributed linear mass and cross-sectional stiffness are calculated proportionally according to their diameters. Modal analysis is performed using SMIA software. Only the first 6 mode shapes and natural frequencies are presented here, with the results shown in Figure 9.

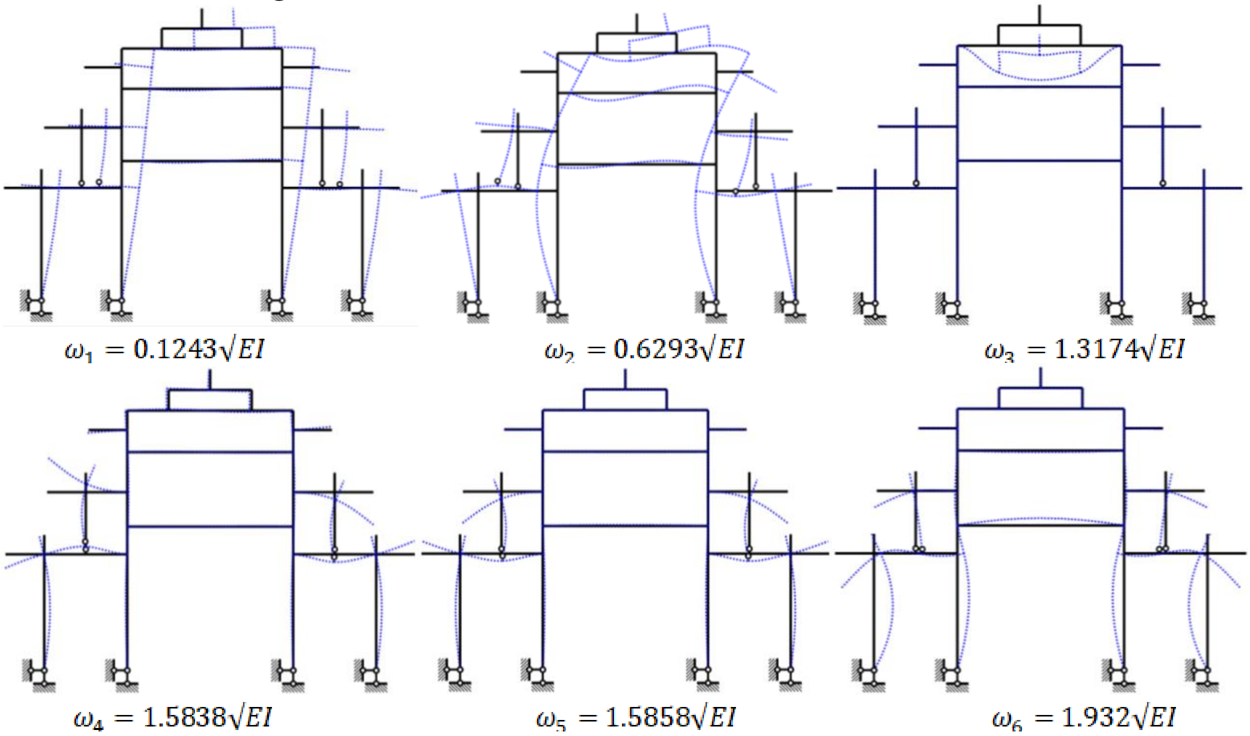


Figure 9: Modal analysis (first 6 mode shapes and natural frequencies)

5. Conclusion

Drum towers possess ethnic cultural value, timber construction value, and aesthetic value. This paper has conducted a preliminary discussion on the structural construction and analysis of RHC style drum towers, obtaining qualitative conclusions. From a structural perspective, drum towers have diverse types, complex details, and irregular surfaces. Further in-depth research is needed, in collaboration with the broader scientific community, to develop more refined models of drum tower structures.

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