Estimating the Volume of Large-Size Wood Parts in Historical Timber-Frame Buildings of China:
Case Study of Imperial Palaces of the Qing Dynasty in Shenyang

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Abstract

Timber-frame buildings are an important architectural heritage of China, and they play a pivotal role in Chinese architectural history. However the restoration of wood components in ancient buildings has gained significant importance in recent years. Based on the modular theory of ancient Chinese architecture this research includes a case study on the Shenyang Imperial Palace, in order to determine a correlation between the volume of large-size wood parts and the building areas. Linear regression equations have been derived to estimate the volume of large-size wood parts efficiently, and the total volume of the large-size wood parts of the Shenyang Imperial Palace has been estimated as 2912.3 m³. It was found that the regression equations for the flush gable roof type buildings are accurate and can be applied not only to the case study in particular but also to other buildings as well. Finally, determining the volume will bridge the communication gap between the people concerned with restoration and the timber suppliers, which is an increasing concern in China with regard to preservation of ancient buildings and historical monuments.

Keywords: Historical timber-frame buildings; Large-size wood part; Shenyang Imperial Palace; Qing Dynasty

1. Introduction

Timber-frame buildings have played a pivotal role in Chinese architectural history, and they are a main element of ancient Chinese architecture (Ma, 2003). The exquisite structure and elegant modeling of these buildings is not only significant for Chinese architecture but also adds to the cultural heritage of the world. Until the year 2010, 29 world cultural heritage sites had been approved in China and 14 of them are related to timber-frame buildings1. At the national level, there are 1080 historical building complexes that are listed as protected sites and more than half of them are timber-frame buildings2. However, as a biomass material, wood has inherent natural defects. It is vulnerable to microbial assault and the effects of physical and chemical factors. Therefore, the restoration of wood components in ancient buildings has gained significant importance (Chen, 2007).

The International Council On Monuments and Sites (ICOMOS) under the United Nations Educational, Scientific and Cultural Organization (UNESCO) has "principles for the preservation of historic timber structures", in short, it includes preservation of the "same tree species", "tree quality", and "building techniques". The Chinese restoration law for historic buildings has also outlined that the materials used for restoring these buildings should be the same as the original material as much as possible. Although these outlines suggest the basic methodology of maintenance for timber-frame buildings, acquiring large-size wood parts for maintenance purposes is currently a serious problem, not only in China but also in Japan (Osawa et al. 2004). This is because it takes a very long time to regenerate quality timber suitable for restoring large-sized wooden buildings.

At present, there is a lack of information exchange between the people concerned with restoration and the timber suppliers (Yamamoto, 2011). Moreover, the constant lack of planning between them makes the availability of resources for restoration difficult and time consuming. In order to bridge this gap and to ensure proper planning for the availability of timber, it is very important to estimate the volume of large-size wood parts for not only each structure but in a

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more holistic way to all similar structures in a region. This will help create a database, which can be used for information exchange between the people concerned with restoration and the timber suppliers.

However, due to historical and social reasons, the architectural maps of these historical buildings are insufficient and unavailable in some circumstances. Furthermore, the task of making a building plan for each of the existing ancient buildings is time-consuming and capital-intensive. Even though the architectural maps exist, calculating the volume of each part one by one is not an easy task either.

In China, the official building standards "Ying-tsaoa-shi were created during the Song Dynasty (960A.D-1279). Ts'ai is a module for measurement that was divided into 15 equal parts, called fen and the width of the ts'ai was measured as ten fen. The height and breadth of every building, the dimensions of every member in the structure, the rise and curve of the roofline etc., in short, every measurement in the building, was to be made in terms of the fen of the grade of ts'ai used. There are eight sizes, or grades, of ts'ai, which are determined by the type and official rank of the building to be erected. A similar module system has also been used in "Kung-ch'engtso-fatsei", a book published in the Qing Dynasty (1644-1912) in which "tou-kou" has been stated as the basic module instead of "Ts'ai" (Liang, 2001). Concisely, certain basic modules or structural components are intricately related to the grand style building structure and influence its dimensions.

Much work has been conducted by contemporary researchers (Liang, 1981; Chen, 1993; Yu, 2002; Zhang and Liu, 2007) for a systematic study on each part of the timber-frame buildings in different dynasties with satisfactory results. Emphasis was placed on verifying the modular-based constructional techniques for individual structures, as mentioned in the above books thereby justifying it but somehow a detailed study of the total volume of these structures on a large scale has not been conducted.

The main hypothesis of this research focuses on the fact that if a module-based constructional technique exists and there is a relationship between each part of the building, there may also exist a relationship between the building area and total volume of large-size wood parts which can be applied as an efficient method for estimating the total wood volume of building sites. Thus, the main objective is to clarify if there is any correlation between the building area and the volume of large-size wood parts by estimating the volume of large-size wood parts of buildings in the Shenyang Imperial Palace.

2. Description of the Study Area

Construction of the Shenyang Imperial Palace began in AD 1624-1625 (Qing Dynasty) and was completed in the year 1783. It is one of the most well preserved of the two palace buildings in China. The geographical extent of the Palace is from latitude 41°47' 39" to 41°47' 49" and longitude 123°2' 49" to 123°27' 03". It was named a national key cultural relic protection unit by the State Council in 1961. On July 1, 2004, it was listed as the 28th cultural heritage of the Ming and Qing Imperial Palace expansion projects by the UNESCO World Heritage Committee. The building space comprises of three parts: the western, the middle, and the eastern parts. The length from north to south is 280 m, and that from the east to west is 260 m, thus covering a total area of approximately 60,000 m². It includes 67 buildings in total (Piao, 2010). Fig.1 illustrates the plan of Shenyang Imperial Palace and the 28 sample buildings.

![Fig.1. Plan of Imperial Palaces in Shenyang (Piao, 2010)](image_url)

1. The pavilion of Lord Zuoyi 2. The Imperial Carriage Warehouse 3. The Xiangfeng Pavilion 4. The Shishan House 5. The Linzhi Palace 6. The Qingning Palace 7. The Dong Qijian Tower 8. The Jiezi Palace 9. The Yihe Hall 10. The Yangqing Palace 11. The Yongfu Palace 12. The Jisi House 13. The Jingdian Pavilion 14. The Chongmao Hall 15. The Qijian Hall 16. The Taimiao Temple 17. The Wensu Pavilion 18. The Yangxi House 19. The Jijian Hall 20. The Fenghuang Tower 21. The Daqing Gate 22. The Chongzheng Hall 23. The Taimiao Gate 24. The East gate of Chongzheng Hall 25. Taimiao East house 26. The Rihu Tower 27. The East wing Palace 28. The Dazheng Hall

3. Methods

3.1 Data collection

The statistical data of each large-size wood part of the building was based on the following sources:

1. The Building plans including the floor plan, building-section plan, and the cross-section plan (scale 1:30, 1:40, & 1:50) drawn by the Tianjin University were used to measure the three dimensional sizes of large-size wood parts on each of the buildings.
2: On-field work included measuring the diameter (at the lower bottom) of the average-size eave columns for each building. This was done to verify the accuracy of measurement of the building plans to the measurements conducted personally, (on-site) in all the 28 samples chosen for the research.

3: The building area of each structure is defined as the eaves-to-eaves area of a building. Data is based on the Report for Application of World Heritage Status for the Ming and Qing Imperial Palace expansion project.

3.2 Definition of large-size wood parts
There are two types of carpentry in ancient Chinese architecture: Major and Minor. "Major or structural carpentry concerns the design and construction of the skeleton and its components; "Minor or non-structural carpentry involves elements such as windows, doors, and ceilings (Yu, 2002). In this research, four main wood parts were selected to represent the "Major and are defined as large-size wood parts (Table 1.). The "Major also includes bracket set "dou-gong (which connects columns, beams, and roof members) and is not considered as a single large-size wood part in this research. This is because of its minimal number (8 out of 67; Piao, 2010) and that such a small representation could not provide significant results.

Table 1. Investigated Wood Parts

| Category name | Part name                           |
|---------------|-------------------------------------|
| Column        | Eave column/hypostyle column/central column |
| Beam          | 7-purlin beam/5-purlin beam/3-purlin beam/Baotou beam |
| Purlin        | Ridged purlin/intermediate purlin/eave purlin |
| Tiebeam       | Architrave/ridge tiebeam/purlin tiebeam/ eave tiebeam |

3.3 Sample selection and analysis
Shenyang Imperial Palace includes 67 single buildings classified according to roof forms as follows:

Table 2. Sample Selection

| Roof Forms      | Number of Buildings | Samples Selected |
|-----------------|---------------------|------------------|
| Flush gable roof| 38                  | 21               |
| Gable and hip roof | 16               | 5                |
| Round ridge roof | 6                  | 1                |
| Pyramidal roof  | 6                   | 1                |
| Kuiding roof    | 1                   | 0                |

For the accuracy of the regression model, different types of buildings were sampled as much as possible. However, buildings that are the same in all respects were not included in the sample. "Bei ting" of the "Kuiding roof" is a special case, which cannot be counted as a building and therefore was excluded in the samples. By applying this sampling strategy, a total of 28 sample buildings were selected (Table 2). Daqing gate was considered as an example of a sample that expresses the name and position of each measured part in the buildings (Figs.2., 3., and 4.; were modified by the author after Tianjin University). Table 1. shows the names of each large-size wood part of the Daqing gate.

$$ V = l \cdot h \cdot w \cdot n $$

$$ V = \frac{\pi}{4} \cdot d^2 \cdot l \cdot n $$
Where, $V$ is the total volume of a single wood part; $l$ is the length of a wood part; $h$ is the section height; $w$ is the section width; $d$ is the section diameter; and $n$ is the number of wood parts.

The results of total volume for each wood category (column, beam, purlin, tiebeam) are listed in (Table 3.). The Ordinary Least Square (OLS) method was used to show the correlation between volume of large-size wood parts and building area.

4. Results and Discussion

4.1 Summary of the volume of large-size wood parts on a single building

Fig.5. shows that measured data (field work) on eave columns (single part) and measured data (from building plans) indicate a very good coincidence, with $R^2=0.94$; the samples are not significantly different (Two-sample Kolmogorov-Smirnov Test, $p=0.94$). This suggests that the data measured on the building plans for eave columns are accurate and any measurement from the building plans alone is also accurate for any statistical analysis (Wang et al., 2006). Four types of structural wood part of each building were calculated, as shown in (Table 3.). This was done on-field visits to the office of Shenyang Imperial Palace four times between May and August 2011. The range of total volume of a single building is between 15.11m$^3$ (No. 25) to 112.42m$^3$ (No. 28). The building area ranges from 70.60m$^2$ (No. 23) to 446.51m$^2$ (No. 2). The range of m$^3$/m$^2$ is from 0.14m$^3$/m$^2$ (No. 15) to 0.39m$^3$/m$^2$ (No. 20).

![Fig.5. Comparison with Measured Data on Building Plan and on Fieldwork; the Solid Diagonal is the 1:1 Line](image)

### Table 3. Summary of Each Sample Building

| Building Names         | Building Types         | Column (m$^3$) | Beam (m$^3$) | Purlin (m$^3$) | Tiebeam (m$^3$) | TV (m$^3$) | Area (m$^2$) | m$^3$/m$^2$ |
|------------------------|------------------------|---------------|--------------|----------------|----------------|------------|--------------|-------------|
| No. 1 The pavilion of Lord Zuoyi | Gable-and-hip roof | 7.09          | 4.22         | 8.31           | 0.74           | 20.36      | 132.84       | 0.15        |
| No. 2 The Imperial Carriage Warehouse | Gable-and-hip roof | 15.59         | 33.99        | 19.29          | 10.15          | 79.02      | 446.51       | 0.18        |
| No. 3 The Xiangfeng Pavilion | Flush gable roof     | 33.87         | 16.29        | 13.13          | 13.06          | 76.36      | 258.81       | 0.30        |
| No. 4 The Shishan House | Flush gable roof     | 8.48          | 18.12        | 6.17           | 8.23           | 40.99      | 176.84       | 0.23        |
| No. 5 The Linzhi Palace | Flush gable roof     | 14.72         | 35.54        | 13.80          | 6.48           | 70.53      | 333.58       | 0.21        |
| No. 6 The Qingming Palace | Flush gable roof     | 28.40         | 48.36        | 22.41          | 12.88          | 112.05     | 444.55       | 0.25        |
| No. 7 The Dong qijian Tower | Flush gable roof     | 21.54         | 11.57        | 8.73           | 12.19          | 54.03      | 274.81       | 0.20        |
| No. 8 The Jiezhi Palace | Flush gable roof     | 10.37         | 10.55        | 12.84          | 12.47          | 46.24      | 186.43       | 0.25        |
| No. 9 The Yihe Hall | Gable-and-hip roof    | 6.03          | 13.08        | 6.97           | 6.79           | 32.86      | 137.52       | 0.24        |
| No. 10 The Yangqing Palace | Flush gable roof    | 21.82         | 26.05        | 15.80          | 7.96           | 71.63      | 286.40       | 0.25        |
| No. 11 The Yongfu Palace | Flush gable roof    | 21.82         | 17.82        | 11.71          | 5.82           | 57.17      | 286.37       | 0.20        |
| No. 12 The Jisi House | Round ridge roof     | 5.09          | 10.78        | 16.76          | 9.21           | 41.85      | 145.94       | 0.29        |
| No. 13 The Jingdian Pavilion | Gable-and-hip roof | 43.31         | 24.44        | 8.08           | 14.36          | 90.19      | 313.25       | 0.29        |
| No. 14 The Chongmo Hall | Gable-and-hip roof   | 41.80         | 22.60        | 11.82          | 16.02          | 92.24      | 306.85       | 0.30        |
| No. 15 The Qijian Hall | Flush gable roof     | 4.82          | 7.24         | 3.91           | 3.63           | 19.60      | 136.70       | 0.14        |
| No. 16 The Taimiao Temple | Flush gable roof    | 15.86         | 13.34        | 7.92           | 2.98           | 40.09      | 206.98       | 0.25        |
| No. 17 The Wensu Pavilion | Flush gable roof    | 35.17         | 25.47        | 22.29          | 16.74          | 99.66      | 402.78       | 0.25        |
| No. 18 The Yangxi House | Flush gable roof     | 11.79         | 13.85        | 14.21          | 9.66           | 49.51      | 241.00       | 0.19        |
| No. 19 The Juijian Hall | Flush gable roof     | 7.09          | 14.58        | 18.80          | 8.41           | 48.88      | 244.17       | 0.20        |
| No. 20 The Fenghuang Tower | Gable-and-hip roof | 71.78         | 17.68        | 4.98           | 20.45          | 114.89     | 292.53       | 0.39        |
| No. 21 The Daqing Gate | Flush gable roof     | 26.54         | 30.13        | 14.47          | 19.79          | 90.93      | 369.66       | 0.25        |
| No. 22 The Chongzheng Hall | Flush gable roof    | 30.71         | 26.05        | 18.68          | 11.90          | 87.34      | 380.25       | 0.23        |
| No. 23 The Taimiao Gate | Flush gable roof     | 6.47          | 4.38         | 4.84           | 3.43           | 19.12      | 70.60        | 0.27        |
| No. 24 The Chongzheng East gate | Flush gable roof | 7.87          | 6.67         | 3.78           | 4.81           | 23.13      | 109.04       | 0.21        |
| No. 25 Taimiao East house | Flush gable roof    | 3.01          | 7.30         | 3.39           | 1.41           | 15.11      | 70.82        | 0.21        |
| No. 26 The Rihua Tower | Flush gable roof     | 14.35         | 8.40         | 7.48           | 4.57           | 34.80      | 123.35       | 0.28        |
| No. 27 The East wing Palace | Flush gable roof   | 5.39          | 12.15        | 7.27           | 2.36           | 27.17      | 143.50       | 0.19        |
| No. 28 The Dazheng Hall | Pyramidal roof      | 38.90         | 17.77        | 8.05           | 47.70          | 112.42     | 401.12       | 0.28        |

Note: TV = total volume of large-size wood parts on a single building; Area = single building area; $m/m^2$ = wood volume per sq. m; TV is the sum of column, beam, purlin, and tiebeam. *Single Building Area is defined here as the architectural area (eaves-to-eaves) of the first floor. The names of the building samples in column 1 come from the translated versions available from the plan at the entrance of the Imperial Palace, and there is no relation between the names and the types of buildings; for example, the building named Rihua Tower (No. 26) is not actually a tower but a flush gable roof building.
(Pearson's product-moment correlation, cor = 0.904); the sample of the areas, as well as the sample of the volumes, are not significantly different from the normal distribution (sample of areas, p = 0.32; sample of volumes, p = 0.13). The coefficient of determination involved in the simple linear regression (Eq. 3) has a strong positive value ($R^2 = 0.82$).

$$y = 0.2516x - 2.6307 \quad (3)$$

Where, $y$ is the volume of large-size parts, and $x$ is the building area.

In Fig.6., sample No. 20 (Feng Huang Tower) shows a relatively higher deviation value. This is because Feng Huang Tower is the only three storied building located at the center of Shenyang Imperial Palace; therefore, the volume of the large-size wood parts per square meter is relatively higher than the other samples. On the other hand, sample No. 2 (The Imperial Carriage Warehouse) shows a relatively higher deviation value because it was used as a storage house and not as a dwelling; therefore, the volume of large-size wood parts per square meter is relatively lower than the other samples.

$$y = 0.2283x - 1.0633 \quad (4)$$

where $y$ is the volume of large-size wood parts, and $x$ is the building area.

By comparing the linear regression equations (3) & (4), it can be inferred that the parameter 0.2516 in Eq. (3) is relatively higher than that in Eq. (4), which is 0.2283. This is because the volume of most of the other types except the "Flush gable" roof type has a relatively higher wood volume per square meter, which affects the slope of the fitting line. This also validates the fact that the different roof forms in China are related to the volume of large-size wood parts. Therefore, in future research it is highly recommended to apply the OLS regression model for each of the roof types to obtain better and more accurate results.

Flush gable roof type buildings comprise more than half the total number of buildings at Shenyang Imperial Place. This type is the most common form in the North-Eastern part of China (Piao, 2007). Analyzing the single type of flush gable roof type building the resultant $R^2 = 0.90$ (Fig.7.) that is relatively stronger and shows a similar trend as Fig.6. Fig.6. is the cumulative result of all the roof types with minor or negligible deviations. Thus, it can be inferred that for each of the roof types, the trend line is similar. The total samples included more flush gable roof type buildings, hence the linear regression equation $y = 0.2283x - 1.0633$, with $R^2 = 0.90$, is reasonable and can be applied to areas ranging between 70.6m$^2$ to 446.51 m$^2$ (see No. 23 and No. 2 in Table 3.) in other flush gable building sites.

### 4.3 Estimation of total large-size volume of Shenyang Imperial Palace

The linear regression equation (3), which is calculated from 28 sample buildings, was used for estimating the volume of large-size wood parts of every single building in the Shenyang Imperial Palace.

$$y = \sum_{i=1}^{67} (0.2516x_i - 2.6307)$$

where $x$ is the building area of a single building, $y$ is the total volume of large-size wood parts at Shenyang Imperial Palace

By replacing the value of $x$ in Eq. (5) with 67, which is the total number of buildings in the Shenyang Imperial Palace; the summation of the total volume of large-size wood parts for all the buildings is 2912.3m$^3$. 

$$y = 0.2516x - 2.6307 \quad R^2 = 0.82$$

![Fig.6. Correlation between Total Volume of Large-Size Wood Parts and Building Area (28 Samples)](image)

![Fig.7. Correlation between Total Volume of Large-Size Wood Parts and Building Area (Flush Gable Roof Type Only)](image)
The hypothesis has been testified by the case study of Shenyang Imperial Palace. The results reveal that the volume of large-size wood parts is significantly related to the building area. The method of OLS used for the regression models shows a positively strong trend in the Shenyang Imperial Palace. Therefore, if the building area for a certain range is known, then the total volume of large-size wood parts can be efficiently estimated.

However, Eq. (5) has its limitations. The buildings of Shenyang Imperial Place have a relatively moderate volume (Piao, 2007), which is also illustrated in Table 3. (Column 7, labeled TV). This means that the model may not be applied successfully to all the buildings which were built during the Qing Dynasty. Another limitation of this research was the unavailability of samples for each of the roof types in abundance at the Shenyang Imperial Palace. The reason for this is that there are some buildings of the same architectural size with 39 samples which were not included in this research. Also the sample size for the roof types except the flush gable roof type (Table 2.) is too small to apply the stratification technique. Increasing the sizes of samples of other roof types could result in a more accurate estimate of the number of large wood parts.

5. Conclusion
Based on the case study of Shenyang Imperial Palace, it can be concluded that the large-size wood parts of each single building are strongly correlated ($R^2 = 0.82$) with its building area. With the help of Eq. (5), the total volume of large-size wood parts of the Shenyang Imperial Palace has been estimated as 2912.3 m$^3$.

Regression analysis of a flush gable type roof showed a relatively strong $R^2$. This was because the Shenyang Imperial Palace not only had many examples of this particular roof type, but also because these examples were of varying ranges of area and size. Thus, the Eq. (4) can be used not only for this case study area in particular, but also for other flush gable roof type buildings.

The method used in this paper is proposed to estimate the volume of large-size wood parts more efficiently using the measurements of the building area. This method could also be applied to prepare a regional database for historic Chinese timber structures. This database can bridge the communication gap between the people concerned with restoration and the timber suppliers.

However, this research comprises a large sample size for the flush gable roof type only; whereas, for others, the sample size was not very satisfactory. Moreover, different Chinese dynasties have different architectural modules; hence, much research has to be conducted in the future to study these dynasties in detail.

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Notes
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2) Report from the State Administration of Cultural Heritage http://www.sach.gov.cn/tabid/96/InfoID/16/trtid/96/Default.aspx
3) ICOMOS 1999, Principles for the preservation of historic timber structures, Adopted by ICOMOS at the 12th General Assembly in Mexico http://www.international.icomos.org/charters/wood_e.pdf
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