Research on Structural Deformation Monitoring and Analysis of Ancient Castle Buildings Using Three-Dimensional Laser Scanning Technology

Yuhua Zhu*, Mu Xu, Xiaoke Nie
Beijing University of Civil Engineering and Architecture, Beijing 100044, China

ABSTRACT
Deformation monitoring refers to the measurement that monitors the change of monitored object using measuring instrument, and determines the deformation status of the target body by recording the changes of the representative discrete points on the target body. Its main purpose is to obtain the deformation characteristics of the spatial position and shape with time and vibration, and to analyze and judge the reasons for the deformation according to the obtained data. The three-dimensional laser scanning technology is also known as the real-scene replication technology. Compared with the traditional measurement technology, the three-dimensional laser scanning technology is high-speed, non-destructive, penetrating and accurate. Taking three-dimensional laser scanning as the technical medium and Deshengmen Gate (Watchtower) as an example, this paper provides technical analysis methods and case studies for the structural deformation monitoring of ancient castle buildings.

KEYWORDS: Deformation monitoring; Three-dimensional laser scanning technology; Ancient castle buildings; Deshengmen Gate

1. Diseases affecting ancient castle buildings
1.1. Common diseases of ancient buildings
The main structural systems of ancient buildings in China are mostly masonry or wooden structures, which are hard to preserve due to the properties and specialty of their materials and vulnerability to diseases, while offering us with brilliant artistic and scientific value [1]. The damage of wood structure mainly includes decay, insect pests, cracking, splitting, detachment, inclination, etc. The damage of masonry mainly includes wind erosion, alkalinization, hollowing, cracking, deformation, etc. [2]. Once these damages occur, the overall structural stability of the buildings will be destructed to various degrees, causing inestimable loss to culture and related science fields. Therefore, the work of monitoring the structure of heritage buildings must be implemented so as to minimize the risk of structural diseases occurrence of the ancient building [3].
1.2. Particularity of ancient castle buildings’ diseases
The special structure of ancient castle buildings determines the particularity of its damage and disease, which are mainly reflected in the following two aspects. First, the ancient castle buildings are a mixture of wooden structures and masonry structures, with the masonry parts largely exposed to the external environment, and therefore, the natural environment has a greater influence on the masonry portions of ancient castle buildings, which are specifically reflected in weathering, disruption, surface hollowing and other diseases. Second, the architecture of castle buildings universally takes up large areas of land and is often built on high ground. Hence, vibration created by the natural environment and human factors will pose a great threat to the foundation part of the building, which will cause different degrees of damage to the structural system of the building. To effectively resolve the potential structural safety problems in the architecture like ancient castle buildings, effective technical methods, tools and monitoring strategies should be adopted [4].

2. Three-dimensional laser scanning and deformation monitoring
2.1. Working system of three-dimensional laser scanning technology
Three-dimensional (3D) laser scanning mainly uses the principle of laser ranging, and transmits pulses to the monitoring target through laser equipment, thereby recording the 3D coordinates, texture, reflectivity and other information of free or dense points on the surface of the monitored object, and then records the 3D space coordinates of the monitored object [4].

2.2. Advantages of 3D laser scanning technology in the field of structural deformation monitoring of heritage buildings
Compared with traditional measurement methods, 3D laser scanning technology can more efficiently and accurately recreate the 3D model of the monitoring target and record its various graphic information from point to surface, overcoming the inaccuracy and low efficiency of traditional measurement methods. In the field of structural deformation monitoring of heritage buildings, the advantages of this technology can be summarized as the following four points:
(1) High speed: 3D laser scanning can record more 3D spatial information of monitoring targets through pulse signals within a certain period of time, thereby greatly saving the time of surveying and mapping.
(2) Non-destructiveness: 3D laser scanning uses electronic pulses to obtain external form and color information of ancient objects, without affecting the current state of heritage buildings, and can protect the authenticity and integrity of heritage with minimal intervention.
(3) Penetrability: The main structure of cultural relic buildings is mostly wooden column and beam frame structure. 3D laser can penetrate the gap between beam frames to record multi-level spatial dimension information, thereby effectively solving the complexity of surveying and mapping the wooden structure of ancient buildings.
(4) Accuracy: 3D laser scanning lays a dense point cloud matrix through a large number of pulse signals, which avoids the interference caused by factors such as external light and darkness, climate, and temperature during surveying and mapping, and ensures the accuracy of information obtained from monitoring objects [5].

2.3. The significance of 3D laser scanning technology in the application of castle buildings monitoring
The ancient castle buildings are high in position, huge in volume, often multi-layered and have high internal space. Traditional measurement methods cannot obtain all their spatial information accurately and quickly. At the same time, the wooden beam structure inside the building is more complex, and the complexity of its structure determines the higher requirements for measurement tools and measurement accuracy.
Compared with traditional measurement methods, 3D laser scanning has obvious advantages in measuring and analyzing structural problems. The first reason is that while ensuring the accuracy of the data, it can easily obtain the target position data that is reachable but difficult to measure; the second reason is that it can be used to analyze and process two planes with different height dimensions, so as to realize the transformation of the 3D model to two-dimensional visualization images. 3D laser scanning technology can achieve efficient and accurate acquisition of external information of monitoring targets, and prevent damage to the broken parts of ancient buildings caused by surveying and mapping. In monitoring the state of cultural relics, it not only guarantees the authenticity and integrity of ancient castle buildings, but also provides a good technical guarantee for the protection of cultural heritage.

In conclusion, the 3D laser technology can realize the non-contact monitoring, surveying and mapping survey of the structural deformation of tall ancient castle buildings. Supplemented 3D laser scanning technology, which acts as the leading means, with traditional measurement means, the problem of monitoring structural safety of castle buildings can be effectively solved, and rich and accurate data results and image performance can be provided. Thus, this is to a greater extent in line with China’s needs for preventive protection of cultural heritage.

3. Case study of Deshengmen Gate building

3.1. A brief introduction to the present state of Deshengmen Gate Castle building

The Deshengmen Castle complex was built in the early Ming Dynasty (1436 AD). The gate castle stands on a very tall brick wall with a “convex” shape in plane. The total height of the castle is 23 meters, and the east-west width is about 39.5 meters. The castle walls are slightly inclined from bottom to top, showing a sense of stability as a whole. The top ancient building in Deshengmen Castle is called the Arrow Tower. It is 34 meters wide from east to west, 12 meters wide from north to south, and has a total height of 19.3 meters. The Arrow Tower is a traditional Chinese wooden structure. It faces north and is surrounded by thick walls. It has the upper and lower roofs covered with green glazed tiles. The wall on the north side is 3 meters thick, and there are four layers of arrow-hole-shaped windows distributed from bottom to top for defense. On the other side, there are three square gates on the south wall, which are the main entrance of the ancient building of Deshengmen Castle. In August 1979, the Deshengmen Castle Complex was registered as a key cultural relic protection unit in Beijing, and in May 2006, it was listed as a national key cultural relic protection unit by the Chinese government.

3.2. Instruments selection and operation procedures

The steps of this operation mainly include two parts including data collection and point cloud registration. To solve the problems of excessive span and large space in the structure of Deshengmen Gate Castle building, the instrument RIEGL VZ-400 \cite{6} is selected for collection data in the operation, with its main technical data shown in Figure 1.

---

**Figure 1.** Main technical parameters of the 3D laser scanner
Point cloud registration mainly uses RIGEL’s supportive software RISCANPRO and the results of the registration are shown in Figure 2.

Figure 2. Display of the splicing results

3.3. Application of 3D laser scanning technology in the structure monitoring system of the Deshengmen Gate Castle building
For the ancient building structure monitoring system, it is in a transformation process from traditional manual inspection to automatic on-line monitoring, that is, the integration process of traditional inspection and scientific monitoring. The traditional manual technology has its inherent inaccuracy, long operation time and other disadvantages, while the automatic monitoring can maximize the efficiency to realize the transformation from technical invention to practical application, while the 3D laser scanning technology can play a certain transitional connection between traditional measurement and modern monitoring. The specific application is as follows:

3.3.1. Assisted traditional drafting
Through 3D laser scanning technology, the transformation from 3D scanning data to vectorized engineering drawings such as AutoCAD can be realized accurately and efficiently to form a complete technical drawing file. It can provide high-precision two-dimensional image data for heritage buildings for retention, and ensure the accuracy, integrity and measurability of the 3D model and image data. By measuring the point cloud data of Deshengmen ancient building, comparing with the ancient ruler and calculating the coincidence rate, we can infer and restore the structural size of Deshengmen old building built in the early Ming Dynasty and restore its original design drawing. Then, this original drawing can be used as a reference for analyzing the current construction situation. Some prediction forms are shown in Table 1.

Table 1. The form of data recovery

| Elements          | Measurement data | Rounding | Conversion to the construction ruler | Rounding | Coincidence rate |
|-------------------|------------------|----------|--------------------------------------|----------|------------------|
| 3-purlin beam     |                  |          |                                      |          |                  |
| W                 | 417              | 415      | 12.97                                | 13       | 99.76%           |
| H                 | 415              | 415      | 12.97                                | 13       | 99.76%           |
| 5-purlin beam     |                  |          |                                      |          |                  |
| W                 | 480              | 480      | 15.00                                | 15       | 100.00%          |
| H                 | 530              | 530      | 16.56                                | 16.5     | 99.62%           |

(Continued on next page)
Take the ancient slide rule as the standard. Using the 3D scan data after rechecking, the initial design drawings of the Deshengmen Gate Castle were drawn successfully (see **Figure 3**).

![Figure 3. Exhibition of drawing results](image)

### Table: Measured Data and Coincidence Rate

| Elements                  | Width (mm) | Rounding | Conversion to the construction ruler (mm) | Rounding | Coincidence rate |
|---------------------------|------------|----------|------------------------------------------|----------|-----------------|
| 7-purlin beam             |            |          |                                          |          |                 |
| H                         | 753        | 755      | 23.59                                    | 23.5     | 99.60%          |
| Ridge tie beam            |            |          |                                          |          |                 |
| W                         | 232        | 230      | 7.19                                     | 7.2      | 99.83%          |
| H                         | 345        | 345      | 10.78                                    | 10.8     | 99.83%          |
| Upper purlin tie beam     |            |          |                                          |          |                 |
| W                         | 232        | 230      | 7.19                                     | 7.2      | 99.83%          |
| H                         | 305        | 310      | 9.69                                     | 9.75     | 99.36%          |
| Lower purlin tie beam     |            |          |                                          |          |                 |
| W                         | 250        | 250      | 7.81                                     | 7.75     | 99.20%          |
| H                         | 278        | 380      | 11.88                                    | 12       | 98.96%          |
| Ridge purlin              | D          | 400      | 12.50                                    | 12.5     | 100.00%         |
| Upper principal purlin    | D          | 400      | 12.50                                    | 12.5     | 100.00%         |
| Lower principal purlin    | D          | 400      | 12.50                                    | 12.5     | 100.00%         |
| Eave purlin               | D          | 400      | 12.50                                    | 12.5     | 100.00%         |

**Figure 3.** Exhibition of drawing results
3.3.2. Analysis of existing structure problems
By overlapping and comparing the point cloud section with the original drawing, the deformation and
displacement of the wooden beam structure of Deshengmen Building can be judged more clearly and
accurately.
(1) Analysis of beams frames deformation
   The specific operation method is to align the processed point cloud section plane with the initial section
   of the beam frame based on the wooden column, fit the outer edge line of the beam frame along the point
   cloud section to the rectangle, then hide the point cloud section, analyze and compare the relative position
   relationship between the fitted rectangle and the beam frame in the initial drawing, and deduce the
deformation value of the wooden beam frame by measuring the difference between them along the
vertical direction.
Firstly, the beam frame is named A-F from west to east. Taking the beam frame of a as an example (as
shown in Figure 4), the point cloud profile of beam frame is overlapped and compared with the initial
drawing, aligned with the ridge purlin as the basic reference point, and the current profile of beam frame
is drawn from the point cloud image of the profile. The comparative analysis of the two shows that the
third beam group is offset by 16.3 mm from north to south, the fifth beam group is offset by 26.6 mm
from north to south, and the seventh beam is offset by 35.5 mm from north to south (see Table 2).

Figure 4. Analysis chart of the frame deformation
### Table 2. Analysis of the A-F frame deformation

| Elements       | Position | Amount of deformation (mm) | Type of deformation | Viewing direction       | Direction of deformation |
|----------------|----------|-----------------------------|---------------------|-------------------------|--------------------------|
| 3-purlin beam  | A        | 16.3                        | Inclination         | From east to west       | From north to south      |
|                | B        | 4.8                         | Inclination         | From east to west       | From north to south      |
|                | C        | 8.7                         | Inclination         | From east to west       | From north to south      |
|                | D        | 9.0                         | Inclination         | From east to west       | From north to south      |
|                | E        | 12.5                        | Inclination         | From east to west       | From north to south      |
|                | F        | 13.4                        | Inclination         | From east to west       | From north to south      |
| 5-purlin beam  | A        | 26.6                        | Inclination         | From east to west       | From north to south      |
|                | B        | 20.5                        | Inclination         | From east to west       | From north to south      |
|                | C        | 6.5                         | Inclination         | From east to west       | From north to south      |
|                | D        | 18.3                        | Inclination         | From east to west       | From north to south      |
|                | E        | 13.5                        | Inclination         | From east to west       | From north to south      |
|                | F        | 14.6                        | Inclination         | From east to west       | From north to south      |
| 7-purlin beam  | A        | 35.5                        | Inclination         | From east to west       | From north to south      |
|                | B        | 26.3                        | Inclination         | From east to west       | From north to south      |
|                | C        | 15.2                        | Inclination         | From east to west       | From north to south      |
|                | D        | 16.2                        | Inclination         | From east to west       | From north to south      |
|                | E        | 20.5                        | Inclination         | From east to west       | From north to south      |
|                | F        | 30.7                        | Inclination         | From east to west       | From north to south      |

(2) Analysis of deformation of columns

The column deformation analysis encompasses the following steps: (a) extract the column section within the target range through the 3D point cloud model after slicing, selection and noise reduction; (b) observe from top to bottom; (c) simulate the central point coordinates and positions of the column head and column base of the target column by drawing a circle; and then (d) deduce the inclination amount and inclination direction of the whole column by measuring and analyzing the relative position of the central point coordinates of the two (as shown in Figure 5). Taking A and B beam frames as an example, after extracting the point cloud section within the target range, fit the circle center of the column head and column base. The column head is represented by a blue circle and the column base is represented by a red circle. Then, by measuring the distance between the circle centers, it can be seen that: A beam frame is offset by 6 mm from north to South and B beam frame is offset by 60.1 mm from north to south (see Table 3).

![Figure 5. Analysis chart of the column deformation](image)
Table 3. Analysis of the A-F post deformation

| Elements                      | Position | Amount of deformation (mm) | Type of deformation | Viewing direction       | Direction of deformation |
|-------------------------------|----------|--------------------------|-------------------|------------------------|-------------------------|
| **Middle column**             |          |                          |                   |                        |                         |
| A                             |          | 6.0                      | Tilt              | From top to bottom     | From north to south     |
| B                             |          | 60.1                     | Tilt              | From top to bottom     | From north to south     |
| C                             |          | 5.6                      | Tilt              | From top to bottom     | From north to south     |
| D                             |          | 23.3                     | Tilt              | From top to bottom     | From north to south     |
| E                             |          | 13.2                     | Tilt              | From top to bottom     | From north to south     |
| F                             |          | 22.7                     | Tilt              | From top to bottom     | From north to south     |
| **Principal column on the southern side** | |                          |                   |                        |                         |
| A                             |          | 3.4                      | Tilt              | From top to bottom     | From south to north     |
| B                             |          | 6.6                      | Tilt              | From top to bottom     | From south to north     |
| C                             |          | 8.4                      | Tilt              | From top to bottom     | From south to north     |
| D                             |          | 13.7                     | Tilt              | From top to bottom     | From south to north     |
| E                             |          | 5.1                      | Tilt              | From top to bottom     | From south to north     |
| F                             |          | 9.7                      | Tilt              | From top to bottom     | From south to north     |
| **Principal column on the northern side** | |                          |                   |                        |                         |
| A                             |          | 21.8                     | Tilt              | From top to bottom     | From north to south     |
| B                             |          | 13.9                     | Tilt              | From top to bottom     | From north to south     |
| C                             |          | 39.8                     | Tilt              | From top to bottom     | From north to south     |
| D                             |          | 23.7                     | Tilt              | From top to bottom     | From north to south     |
| E                             |          | 26.1                     | Tilt              | From top to bottom     | From north to south     |
| F                             |          | 13.5                     | Tilt              | From top to bottom     | From north to south     |

3.3.3. Creation of a finite element model for determination of warning thresholds

One of the important functions of structural safety monitoring for heritage buildings is the warning alert in case of structural safety breach. To enable timely warning, it is necessary to set a proper warning threshold. The current determination of warning thresholds relies on finite element analysis, that is, the target is decomposed into infinite elements and the mechanical properties of the target are analyzed by simulating factors such as materials and loads. Taking Deshengmen Gate Castle building as an example, specific analysis is done according to the following steps:

First, a model is created through Solidworks software with the data on the point cloud acquired using 3D laser scanning technology. In the modeling process, it is necessary to simplify corbel bracket and roofing, remove the outer building envelope, and retain the main structure.

Second, the structure model is imported into ABAQUS software and divided into infinite elements in the form of meshes, then they were given to each element material and loads and restraints on each portion, as shown in Figure 6 and Figure 7.
The deformation of such structure model was simulated under the dead load, and we can see the overall trend of structural displacement in the structure model due to the influence of the dead load. The calculation results show that, in the model, SMX, the maximum displacement is 14.8833 mm; this value and the ultimate structural load that it corresponds to can serve as a reference for warning thresholds of monitoring (as shown in Figure 8).
4. Conclusion
In recent years, there have been some gradual progress in the application of surveying, mapping and monitoring of cultural relics buildings. However, due to the rapid change of technology and the lack of relevant industry standards, 3D laser scanning technology lacks a systematic method induction and technology research system. There are some common problems: the methods are not applicable and the results are not practical. Therefore, it is necessary to study the localized and universal application method of 3D laser scanning in the field of heritage building monitoring. This paper attempts to take the Deshengmen Arrow Tower as an example, and puts forward several application methods of 3D laser scanning in the structural monitoring of towers. This research was funded by the Graduate Innovation Program of Beijing University of Civil Engineering and Architecture.

Funding
2021 Beijing Social Science Research Fund Project “Research on the Implementation Path of the Construction and Protection of the Beijing Section of the Great Wall National Cultural Park (Project Number: 21ZDA01)

Disclosure statement
The authors declare no conflict of interest.

References
[1] Guo B, 2021, Application of Three-Dimensional Laser Scanning Technology in Deformation Monitoring of Xinjiang Grand Theater. Geomatics & Spatial Information Technology, 44(S1): 225-227.
[2] Ding B, Shi RM, 2019, 3D Reconstruction of Historical Buildings Based on a Single Old Photo. Journal of Beijing University of Civil Engineering and Architecture, 35(3): 26-33.
[3] Liu K, 2017, Application of 3D Laser Geometry Acquiring Based on the Requirement of Ancient Architecture Conservation and Renovation, Beijing University of Technology, Beijing.
[4] Wang X, Jing D, Xu F, et al., 2021, Deformation Analysis of Shield Tunnel Based on 3D Laser Scanning Technology. Beijing Surveying and Mapping, 35(S7): 962-966.
[5] Deng S, 2015, Application of RIEGL VZ-1000 Three-Dimensional Laser Measurement System in Mountainous Terrain Surveying. Pearl River, 2015(04).
[6] Mu C, 2019, Application of the Riegl_VZ_1000 3D Laser Scanner in the Mapping of Major Geological Disasters. Beijing Surveying and Mapping, 33(S5): 579-578.
[7] Liu C, Sun C, 2008, Interpretation of the Measurement Data of the large Wooden Structure of the Main Hall of Baoguo Temple. Journal of Chinese Architecture History, 2008(00): 27-64.

Publisher’s note
Wiioue Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.