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Overview on Testing Method of Internal Damage to Special-shaped Stone Components in Palace Museum

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Abstract. *Irregular historic stone components are very important parts of the ancient architecture in the Palace Museum. They have been subjected to deteriorations from surface to interior under the combined effects of many factors such as wetting and drying, salt dissolution and recrystallization, self-load, external load, and environment action. The internal damages in these stone components are difficult to detect but are crucial for the assessment of the intact of these components. In order to detect the internal damage of stone components, especially the special-shaped stone components, which cannot be tested by comment methods. Taking evaluation on preservation status of stone components in a qualitative and quantitative way， with application of ultrasonic computerized tomography and regular inspection, a convenient, safe, economical, efficient, and readable method for detecting the internal damage of irregular stone components can be established in order to detect any safety hazards as early as possible and provide data support for assessment and conservation, achieving a better preventive conservation.*

Keywords: *Special-shaped Stone Components; Nondestructive Testing; Preservation; Deterioration; Ultrasonic CT*

1 The Preservation Status and Characteristics of Stone Components in the Palace Museum

The Palace Museum has a large number of stone components with various types and exquisite carving craftwork, which have both cultural significance and practical functions, containing important artistic value, historical value and scientific value, particularly the marble waterspouts carved in the shape of hornless dragon's head. The shape of hornless dragon is used to symbolize royal status and fire prevention. It also has the functions of fixing balusters and draining off water, which is a perfect combination of practical and decorative architectural decoration.

1.1 Species and Preservation Status of Stone

Due to the long-term impact of environmental changes, stress erosion, and human destruction on the stone components of ancient buildings, a series of changes in material composition, structural structure, and even appearance that are not conducive to the safety of cultural relics or damage the appearance of cultural relics may occur, which is known as diseases of stone components. To promptly identify safety hazards and take appropriate handling measures. The Palace Museum conducted a long-term comprehensive investigation into the stone components of cultural relics and buildings exposed to physical environment. On the basis of collecting relevant basic information such as material types, sizes, disease types, preservation status, and current photos of stone artifacts, the factors leading to the occurrence of diseases and safety issues in stone artifacts were summarized and preliminarily analyzed. Gradually, stone component archives were established as reference materials for long-term protection and utilization.

Figure 1. Stone components in the Palace Museum.

From 2015 to 2016, through visual inspection, it was found in the special investigation of the visible diseases on the surface of stone components that there are six common stone types in the Palace Museum: Alabaster, which are mostly used for balustrades, the marble waterspouts carved in the shape of hornless dragon's head, balusters. Green White Stone Of Fangshan (Marble) is mostly used for Danchi or Danbi, vermilion steps of stone leading up to a palace hall, the Buddhist Mount Sumeru or terrace of palace with high-grade. Bluestone (Sandstone) is commonly used for the terraces and steps leading up to hall. Granite, used for paved way. Piebald stone, used for the ground of special building’s verandah. The Taihu stone is used to build rockeries. In the statistics of diseases, it was found that components looseness is the most common type of disease. The other main types and proportions of diseases are weathering, account for about 27.84%. Scaling, account for about 21.74%. Crack, account for about 21.20%. Shifting, account for about 16.97%. Weathering generally occurs in Bluestone. Crack is dominated by Green White Stone Of Fangshan and Alabaster. Scaling mostly occurs in Bluestone and Alabaster. It shows that the main types of stone diseases in the Palace Museum are comprehensive, and the main types diseases happen with similar quantity.

Figure 2. Mostly disease type of stone components(Top left: weathering; Upper right: scaling; Lower right: crack ; Lower right: shifting).

During the census, it was found that the disease areas were mainly concentrated in gully drain, steps, and terraces. Balustrades account for about 52.3%, which have Moderate and severe diseases, the marble waterspouts carved in the shape of hornless dragon's head account for about 21.4%, and balusters account for about 7.9%. Among these, there are 12.8% of balustrades, 19.6% of waterspouts, and 66.7% of balusters have serious diseases. The factors that cause its diseases include long-term rainwater erosion, plant growth, sunlight exposure, winter frost heave, and tourist trampling. In the short term, the diseases of the building foundation will not have a significant impact on building safety. In the long run, as the degree of cracking of components further intensifies and the weathering process of components further deepens, it will cause fatal harm to the building foundation. In addition, components such as balusters and the marble waterspouts carved in the shape of hornless dragon's head may cause destructive stress or structural defects during processing on the surface or inside of the stone due to aesthetic or practical requirements.

To solve the problem above, it is necessary to strengthen the frequency of inspection work and use scientific detection methods to conduct the stone material internal damage recognition. As well as conducting in-depth research on the disease trend of stone components. After investigating into those achievement, proposing corresponding protective measures and mastering development trend of disease on stone components timely in order to achieve the goal of nipping the risk in the bud.

1.2 Classification of Disease and Standardization of Terminology

In the past 20 years, international academic organizations and cultural relic protection groups have gradually introduced disease terminology systems that are applicable to their respective situations. However, due to the accumulation of multiple factors, the deterioration of stone materials often results in a certain degree of complexity. There are differences in interpretation and understanding of professional terms used in the description and magnitude determination of degradation forms under context switching, resulting in the lack of a unified universal standard internationally. At present, the most influential and applicable disease classification system in the field of cultural relics protection i*s the Illustrated Glossary on Stone Observation Patterns* which recommended by ICOMOS-ISCS. The terminology of stone deterioration used in this terminology list is in English as the common language, and the characterization of stone diseases is used as the basis for defining disease types. It demonstrates strong objectivity and operability in the investigation and identification of stone cultural relics' diseases. In 2007, China issued the Classification and Legend on the Determination of Ancient Stone Objects (WW/T0002-2007) specification. Corresponding the identification and recording methods of typical disease types to photos, a standardized and unified expression method has been formed in the recording and evaluation of stone cultural relics' diseases.

On the basis of the above specifications and in combination with the investigation and research results of the special-shaped stone components of the Ming and Qing official buildings in the Palace Museum, the disease descriptions of the special-shaped stone components are classified and graded. Based on the professional terms and classification methods of the existing domestic and foreign relevant standard literature, the activity nature of the disease is rated according to the activity nature, and create a computing model of disease risk assessment.

Table 1. Classification and state of disease on stone components (reference to *Illustrated Glossary on Stone Observation Patterns*)

Category	Diseases	Description	State
Structural Damage	Crack	Fracture	Stable
		fissure	Progressive
		Splitting	Progressive
	Mechanical Damage	Impact damage	Stable
		Cut	Stable
		Scratch	Stable
		Abrasion	Stable, Progressive
		Perforation	Stable, Expanded, Progressive
	Deformation	/	Expanded, Progressive
Ingredient Loss	Detachment	Blistering	Expanded, Progressive
		Bursting	Expanded, Progressive
		Delaminatiom	Expanded, Progressive
		Scaling	Expanded, Progressive
		Disintergration	Expanded, Progressive
		Fragmentation	Expanded, Progressive
	Weathering	Erosion	Expanded, Progressive
		Microkarst	Expanded, Progressive
		Ditting	Expanded, Progressive
		Efflorescence	Expanded, Progressive
		Subflorescence	Expanded, Progressive
External Adhesion	Pollution and Discoloration	Crust	Expanded, Progressive
		Deposit	Expanded, Progressive
		Discolouration	Expanded, Progressive
		Film	Stable
		Graffiti	Stable
		Patina	Stable
		Soiling	Stable, Expanded, Progressive
	Biological Colonization	Alga	Expanded, Progressive
		Lichen	Expanded, Progressive
		Moss	Expanded, Progressive
		Mould	Expanded, Progressive

Stone components have a long-term exposure in physical environment, stress cracking may occur when the components have insufficient bearing capacity. In addition, non-bearing crack also occur when components are affected by external environments or their own defects. According to the protection experience accumulated in the Palace Museum for many years, in combination with the national standards *Stone and brick collection's disease and illustration (GB/T 30688-2014)* and *Specification for Compilation of Conservation and Restoration plan of Ancient Stone Objects (WW/T0002-2007)*, focusing on the disease of components made by alabaster in the Palace Museum. According to the cause of disease of stone cultural relics and the degree of correlation between internal damage, it could be divided into three categories:

structural damage, ingredient loss, external adhesion, subdivided into 30 types further, considered with the characterization of disease. Revolving about the relationship between characterization of disease and internal defects of components which made by alabaster. Combined with the development of different diseases and their influence on the stability of stone cultural relics, the nature of disease activity can be divided into three states: stable state, expanded state and progressive state that may develop or cause other diseases under external conditions, according with the example in Table 1.

2 Testing Methods and Technical Approaches

It is an important component of carrying out preventive protection work for stone components with non-destructive testing or micro damage technology for scientific diagnosis. A relatively mature theoretical and practical foundation has been accumulated both domestically and internationally. By way of illustration，acoustic and ultrasonic testing methods which have been widely used, as well as rebound tester, ground penetrating radar, and X-ray radiographic inspection. Most of the existing domestic academic achievements focus on the research on the deterioration of weathering and mechanism of disease on the surface of stone. This has been seen in the case of the weathering degree of Buddha statues in Yungang Grottoes and the detection of Suzhou Tiger Hill Pagoda, nonload bearing element with special-shaped section (such as stepping stone, terraces, etc.), using 3D laser scanning technology on characterizing the depth of weathering and peeling and conduct tilt displacement monitoring of stone artifacts. Another example of applications in non-destructive testing is Guyue Bridge and carried drum like stone of Qingjing-Huacheng Pagoda at Xihuang Temple, rayleigh waves or ultrasonic transmission waves were used for detecting the development and trend of internal cracks in components with deadweight and internal process structure (such as the marble waterspouts carried in the shape of hornless dragon's head of the Hall of Supreme Harmony). For primary structures with regular material shapes (such as stepping stones, terraces), a router can be used to measure surface weathering, and Ultrasonic combined with Infrared Technology can be used to measure the situation of blistering, shifting, and the effect of Grouping of cracks caused by changes of moisture content. X-ray diffraction (XRD) can be used for the detection of physical and chemical properties of stone components, such as composition of minerals, phase transformation, porosity, etc.

Actual conditions of scene, where stone components settled, the cost of testing, and status of testing objects, especially the small contact surfaces and multiple sizes of the section of special-shaped stone components, that caused by the high demand for the selection of detection technology. Therefore, the detection equipment needs to meet the requirements of normal position, non-destructive, portable, and visible in operation, providing main technical support for monitoring the mechanical properties, materials, and environmental state as well. The data presented by the detector needs to be intuitive, that keep tabs on the degree of performance degradation, functional degradation, quantitative information management of stone components accurately.

Ultrasonic testing technology is sensitive to discontinuities surface, has better defect detection or measurement of penetration depth. At the same time, ultrasonic technology also has some limitations and challenges on the need to contact the surface of an object to transmit ultrasound, the need of coupling media to promote the transfer of sound energy to the specimen.

Having difficulty detecting rough, irregular or uneven materials, and materials with low sound transmission or high signal noise, such as cast iron. And the possibility of missing linear defects parallel to the sound beam Reference standards are required for equipment calibration and defect characterization.

Based on the experience and achievements of past conservation practices, the Palace Museum has selected terraces with clusters and the fragile waterspouts on Hall of Supreme Harmony and Hall of Martial Valor as the detection objects. Firstly, carried out routine investigation to the obvious diseases on surface of stone components, and the degree of disease is graded according to the degree of disease. Identify components with deterioration characteristics as instrument detection objects, and use the mechanical detection equipment which developed by the School of Civil Engineering at Tsinghua University, with testing technology based on ultrasonic CT theory to detect surface and internal damage of special-shaped stone components.

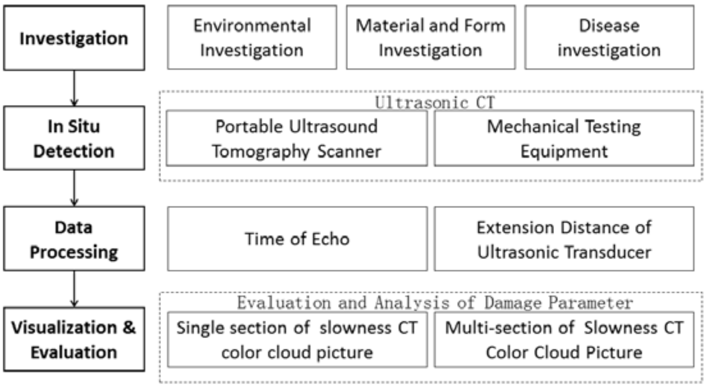

Figure 3. Non destructive testing process of stone components.

The mechanized detection device has a circular track equipped with an ultrasonic probe and a hydraulic telescopic link. Capable of detecting horizontal components with radius of section within 400 mm, horizontal depth within 500 mm, and height less than 1600 mm. All the radius of section of vertical components should below 400 mm and a vertical height between 1000mm and 1600 mm. The detection device can rotate the ultrasonic probe within a 360 ° range and achieve the expansion and contraction of the probe. The basic principle of using ultrasonic technology for material inspection is to use ultrasound to penetrate through the material. The changes in acoustic characteristic parameters can reflect the condition of internal damage in materials, the denser the material is, the faster the wave through. Besides, it should be considered that the curved surface of components will cause the wee contact area, relatively fixed angle of ultrasonic probe may diminish accuracy of detection. In order to ensure that the ultrasonic equipment can effectively collect data, medical ultrasonic coupling patch is used as the medium for the ultrasonic probe contact to create effective contact between the probe and the component surface.

Figure 4. Detection methods(Left: Portable Ultrasound Tomography Scanner; Right: Mechanical Testing Equipment).

The mechanized detection device has two probes. The section of objects divided into 16 parts, each at an angle of 22°, each cross-section needs to collect 64 sound time data. Record the elongation distance and make proper records during each expansion and contraction of the ultrasonic transducer, in order to determine the geometric profile of the single cross-section and calculate the ultrasonic sound path while data processing. Reset the ultrasonic transducer, move the base to the next section and repeat the detection steps. After the detection, use Matlab software to output a single cross-section Color map of slowness and a three-dimensional model of internal damage, which can intuitively determine the type and scale of internal damage, based on which can evaluate and analysis the damage parameter indication.

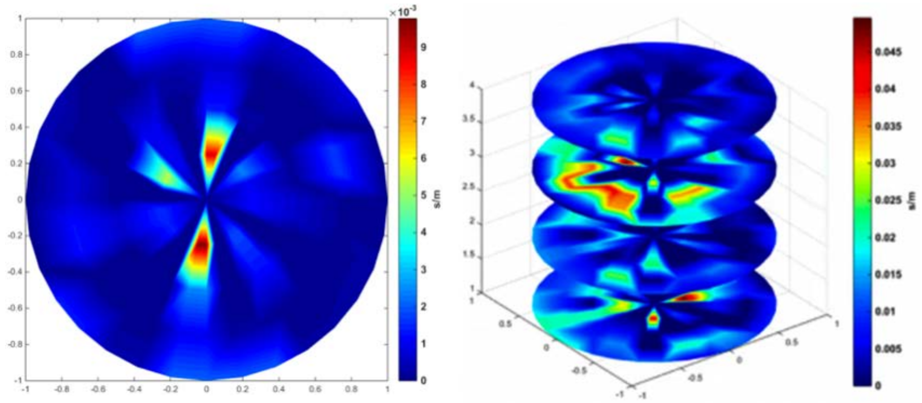

Figure 5. Visualization(Single section of slowness CT color cloud picture and Multi-section of Slowness CT Color Cloud Picture).

The purpose is to establish an inspection process combine visual observation, handheld device detection and instrument detection, which based on ultrasound CT technique. To establish a protection process that starts with identifying, analyzing the causes, evaluating the status, taking treatment, and regularly monitoring. The focus of research on the protection of stone components is on the visualization, quantitative, and qualitative of the degree of disease development of internal damage inside of stones, as well as the development of scientific and systematic management methods. A normalized conservation and management system of stone components including visual inspection and comprehensive geophysical exploration, the work of regular monitoring on stone components even buildings will reduce the risk of sudden changes, predict the occurrence of disasters in advance and respond timely. Precise positioning of risks or diseases where damage happened will be easy. The sooner treatment we take, the lower potential risk we get.

3 Conclusions

The detection of internal damage in irregular historic stone components by ultrasonic method proposed by this paper still has many problems, such as the difficulty in determining the transmission path of ultrasonic pulses in the medium during ultrasonic testing of irregular sections of components, which cannot guarantee the high detection accuracy. The guided wave generated by the distance between the ultrasonic emission and reception probes can cause an obvious ultrasonic slowness area interfering with the ultrasonic CT signal. Another important aspect is the requirement of a significant amount of manpower and time costs on detection, making it difficult to be applied on large-scale detection and data analysis. The protection of stone cultural relics is closely related to the safety of the building itself and the personal safety of the audience, making the conservation work essential and there is still a long way to go. Therefore, the protection and research work of stone cultural relics should focus more on the following four aspects: basic data collection, disease analysis, special protection projects, and research education, which need to be graded and gradually carried out according to the degree of urgency. Understanding of stone cultural relics should be strengthened through conducting a systematic investigation, summary, and research on the types, materials, and distribution of all stone materials in the Palace Museum, as well as the types and distribution of existing diseases; Key special analysis on the internal diseases of stone materials needs to be conducted. Selection of protection materials and methods should be based on improving the current situation where the original protection and reinforcement materials might have a negative impact on the appearance of stone cultural relics, effective protection methods should be selected for the restoration of stone cultural relics to ensure open safety. Early warning and management of the safety of stone cultural relics and audience safety should be highlighted.

The most important thing is to setup standards and operational norms for management and protection work. Advanced, reliable, and mature repair and protection experience, quantifying the degree of disease and refining operational specifications need to be drawn. Long term documentation of the achievements of conservation work, and timely summarizing and conducting evaluation work need to be conducted, in order to form suitable stone cultural relics management and protection guidelines for the Palace Museum through continuous practice and to make development from rescue protection to preventive conservation.

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