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Deformation monitoring of typical composite structures based on terrestrial laser scanning technology

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ABSTRACT

Terrestrial laser scanning (TLS) technology plays an important role in the field of deformation monitoring nowadays, and a lot of the architectures are arched composite structures, which are required to be further understood for their mechanical and physical properties. Only a theoretical numerical analysis is sometimes difficult and defective to achieve, due to varying loads and other factors influencing the stability and reliability of such structures. Therefore, measurements can improve the theoretical analysis in several ways. One of the most important issues is the deformation analysis within load experiments.

This paper focuses on the presentation of new possibilities for surface-based measurement techniques and their applicability in the deformation analysis of arched structures. The goal of this paper is to investigate the difference of load-displacement relationships between arched and beam structures though a static load experiment based on high accuracy TLS measurement techniques and the surface analysis method. In this paper, we try to reveal the influencing mechanism of 'prestressing-like' force and interpret why arched structures can withstand a surprisingly greater load than beam structures under the same conditions.

1. Introduction

Nowadays, a lot of architecture is made from composite materials, such as masonry which is made compositely from block and mortar, as the main load-bearing component. Masonry structures have been widely applied in civil and industrial buildings due to the super performances, for example, in durability, stability and thermal insulation, and the easy acquisition of raw material for manufacturing. However, because adhesion between the components of block and mortar is weak, the masonry structure usually exhibits low tension, shear and bending bearing capability. Therefore, the inspection of masonry structures is extremely important for safety reasons. Unfortunately, reliable and highly accurate monitoring and assessment of the structures are arduous tasks. Inhomogeneity of the composite masonry structures and uncertainties regarding the components themselves challenge the reliability of traditional pointwise testing and geometry simplification in theoretical models, especially for local mechanical analysis. Testing techniques are limited, particularly for precious historic constructions made of composite masonry structures, where some stricter requirements of protectiveness in investigation and testing are raised.

1.1. TLS measurement

Terrestrial laser scanning (TLS) technology is an efficient and accurate way to gain panoramic information which contains three-dimensional (3D) coordinates and intensities [1]. Therefore, the deformation analysis was carried out through the surface approximation of a point cloud. Furthermore, the 3D point cloud model can be obtained intuitively and accurately.

Two main principles generally exist for laser scanning: one is based on time delay and the other one on triangulation. Using the time delay principle, a laser is emitted, reflected by the object surface, returned and is received by a detector. The special distance is subsequently calculated with the time delay and velocity of light. These well-known systems are time-of-flight and continuous wave. Using the triangulation principle, one constructs a triangle between the points of the object, laser emission and laser observation. A solution is determined from the known emission and observation angle, and the base-distance [2].

High accuracy spatial coordinates of gridded dense points, which are vital and indispensable for the deformation analysis, can be collected by TLS measurement [3–6]. Although the 3D points data from the TLS measurement reflects panoramic surface information of the structures, the point cloud contains discrete data and is not glossy

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enough. This may cause inaccuracy if these points are employed directly. To avoid this, surfaces are created based on the point clouds. A good introduction to surface fitting can be seen in [7]. The objective of this research is to investigate the difference of load-deformation relationships of arched and beam structures based on TLS technology.

1.2. Surface approximation

Researchers approximate the point clouds using different mathematical surface functions. Khoshelham et al. [8] applied a robust plane fitting to extract the parameters. Yang et al. [9] used a dynamic parabolic approximation to reconstruct a triangular mesh that fits the underlying surface of the point cloud.

Other researchers also focused on surface fit to assess conditions [10,11]. A free-form B-spline curve is used by Garmann et al. [12] to monitor objects, for example, bridge structures. Zhao et al. [13] proposed obtaining a segment from control points or reparametrizing with tolerance to obtain a uniform curve in modeling. Park [14] expanded the idea of B-spline curve fitting, and proposed a new approach to B-spline surface fitting to rectangular grid points. Brujic et al. [15] presented a method for realizing improvements in the computational efficiency of fast and accurate fitting of a non-uniform rational B-spline.

Efforts have also been made to estimate the function parameters of the surface. Yang et al. [16] adapted an optimization procedure that minimizes a quadratic function at each step. Flöry et al. [17] considered techniques for surface fitting to point sets based on the L1-norm. Zhao et al. [18] adopted the Monte Carlo method to acquire the location of the knots of the B-spline curve.

2. Experimental

3D laser scanning technology is applied in the experiment to investigate the deformation and bearing capability of composite arched and beam structures. The laser scanner is used with the technical data sheet shown in Table 1 [19–27] where the manufacturer and model of the scanner is Z + F image.

The experiment contained mainly a composite arched structure, a load system, two supports at two ends of the specimen and a TLS scanner. The load is added at four positions and the direction is downwards, as illustrated in Fig. 1. The left support is stable and the right one moves horizontally. The TLS scanner was set on the second floor and canned from above the arch where the distance is about five meters from the arch.

The scanner observed more area of the top surface of the arch, compared with being set at other standpoints. Although the laser beam cannot reach into the shade of the steel beams, surface approximation will fit the whole top surface of the arch according to the point clouds obtained. When the top surface retains a regular shape during deformation, which means no oscillation, the polynomial surface approximation can be reliable.

A composite arched structure was modeled and analyzed under static loading, as presented in Fig. 1. During the experiment, every epoch loaded for about 20 min and paused for about 10 min for measurement, where the load speed is around 33 N/s. The dimensions of the arch are about 2 m in length, 1 m in width and 0.1 m in thickness.

Table 1
Main technical data sheet of TLS scanner.

Laser system	
Beam divergence	0.22 mrad
Resolution range	0.1 mm
Resolution	0.0018°
Accuracy	0.007° rms
Scanning speed	≤50 r/s (3000 r/min) max.

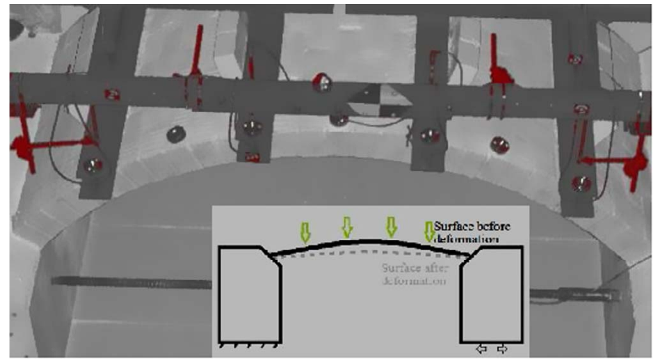

Fig. 1. The sketch of experiment setup.

3. Analysis

Deformation of composite structures develops by, for example, shrinkage, temperature change and loading. When composite material is under uniaxial compressive loading, there are four major stages in the development of cracks and failures. The first stage is shrinkage, where the tensile stresses lead to no-load bond cracks before the point of 30 percent of the compressive strength. In the second stage, when the load is over 30–40 percent of the compressive strength, stable bond cracks will develop. In the third stage, when the load reaches the discontinuity limit, i.e. beyond 50 or 60 percent of the compressive strength, local mortar cracks develop and propagate. The fourth stage begins after critical stress. More mortar cracks occur and continuous micro-cracks form. The curve is markedly unlinear [28], which shows an example of stress-strain curve and stress-crack opening curve for concrete in tension. The tensile capacity drops to zero when the crack is completely formed. When the tensile strength is reached, micro-cracking occurs in a fracture process zone near the point of highest tensile stress, and the tensile capacity of this concrete drops rapidly with increasing elongation [28].

A composite arched structure to investigate the surface-based deformation of typical composite structures is described in Fig. 2, where the green parts correspond to the concrete material and the orange parts are bricks.

The deformation of the top surface of the composite arched structure is analyzed where the polynomial surface fit the point clouds of the object surface well and has no large oscillation. Second order polynomial surface function is calculated and the least-squares method is adopted to estimate the unknown coefficients. The order of polynomial function influences the accuracy of the surface, which is the standard deviation between the point clouds and the surface, for polynomial surface approximation. The order of the polynomial function is modified to get a best-fit polynomial surface. The error analysis of different order polynomials is listed in Table 2, which is calculated and analyzed with standard deviation.

The error of the 3rd, 4th and 5th order polynomial surface for the arch is shown in Table 2, where the error decreases to a minimal value and then largely increases. It indicates that the 4th order polynomial

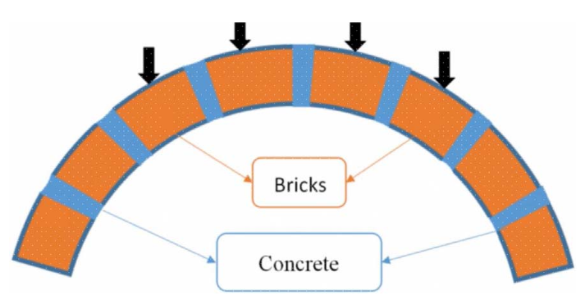

Fig. 2. The sketch of composite arched structure.