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Optimized finite element analysis model based on terrestrial laser scanning data

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ABSTRACT

The problem of the arch loading case is studied by the combination of finite element analysis (FEA) and B-Splines, which provides a highly accurate solution to the calibration problem of the FEA model. Attention is paid to the assessment of FEA by a high-accuracy two-dimensional B-Spline model using point clouds from terrestrial laser scanning (TLS) which is one of the most accurate measurement tools. In the current paper, a B-Spline-based optimized model, comparing to an idealized model, is applied in the FEA. Meanwhile, characteristics of arched nodal displacement and stress are discussed. The target function of the optimization is to reduce the displacement error. It is revealed that the B-Spline optimized model based on TLS data with high-accuracy could carry out FEA efficiently with fewer displacement errors, which is an important part of the automatic calibration of FEA. Finally, the equivalent stress in the post-computation is applied to predict the possible crack regions and carry out the damage monitoring.

1. Introduction

A methodology regarding the optimization of the finite element analysis (FEA) model with B-Splines is focused on in the present paper. This methodology is tested based on a two-dimensional (2D) arched structure which is widely used in the investigation. Hence, a high-accuracy geometric model based on the terrestrial laser scanning (TLS) data is obtained in the FEA optimization. The displacement error is optimized as the target function comparing it to the idealized model. The post-computation in the optimized FEA is adopted to predict the weak behavior of the structure.

1.1. Background

The FEA is widely applied to solve the civil engineering and structural mechanical problems and to predict the weak behavior in response to the loading experiment [1]. The numerical method is devised to represent discontinue structure and the overall behavior could be predicted using FEA [1]. Numerical investigators used a simple structure of a cantilever beam to demonstrate the feasibility of the appropriate expression of the force transferred to the structural member [2]. Additionally, most FEA models are based on the Ritz approach and focus on simplified structures under simple loading conditions [3]. A FEA computation incorporating the micro structure below the level of a single (mesoscale) finite element is described in [4]. Energy finite element analysis (EFEA) is utilized successfully for modeling complex structural-acoustic systems with isotropic structural material properties [5,6]. Aiming at efficient calibration, the FEA is linked with Monte Carlo simulation for the computation of the effective properties of random two-phase composites [7]. The particle swarm optimization method is applied for finite element model calibration and adopted to test a simple beam and unsymmetrical H-shaped structure [8].

A thorough and comprehensive development in the numerical method is critically important and essentially challenging to advance the technology further for the more accurate calibration of the FEA. In recent years, the FEA calibration has allowed the FEA to compute better to reflect the data measured and predict the future behavior in the engineering [8]. As an important part of FEA, the geometric model of the object in [9] has a decisive influence on the quality of the analysis results. The approximation about the geometric modelling based on B-Splines is a significant method in the FEA [9]. The related investigation is mentioned and some fixed parts of a curved FEA surface are partly replaced by the B-Spline surface [9]. Additionally, some researchers combine the point clouds directly with the meshing part in the FEA [10], by which the geometric modelling could be omitted during the FEA computation. The detailed advantages and disadvantages will be discussed in Section 2.1.

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1.2. Optimized factors in the computation model

From the perspective of the intended uses of the model, the validation process should be an accurate representation of the real world [11]. This is also a guide in the computational validation process which is proposed by the American Society of Mechanical Engineers [11]. However, a close form or unified solution could not be obtained throughout lots of structural problems. The displacement [12], loads [13], cracks [14], and stress [15] are commonly considered to be the validated factors in this process. The global response is now also determined when applying an equivalent frame method to the experiment [16]. A more simplified strategy is adopted by researching the collapse load and the deformation patterns and comparing the efficiency of a discrete element method to experimental data [17].

1.3. Geometric modeling based on B-Splines

TLS can be widely used as a reliable surface monitoring device to obtain the actual geometric model [18]. It has a high structural precision and can reveal the surface characteristics directly [18]. Based on TLS point clouds, polynomials [19] and B-Splines [20,21] are typical approximation methods to fit data points. Regarding point clouds from TLS, researchers [22] have described important mathematical surfaces from polynomial functions to Bezier and B-Splines functions to the non-uniform rotational B-Splines (NURBS) and depicted different approaches to determine the appropriate number of parameters automatically. By comparing the polynomial fitting, the B-Spline approximation obtains better accuracy in complex situations [23] and NURBS curves generated with the iteration obtains many advantages, such as gaining explicit expression, having locality and preserving convexity [20]. Hence, the B-Splines are popularly utilized in geometric model generation with freeform surfaces and curves in the computer application and the reverse engineering [24].

1.4. Framework

The idealized and simplified FEA models are typically selected to carry out the FEA computation [25]. However, FEA calculation with the simplified model is considered as a crude approximation of the real physical behavior [26]. Errors caused by the differences in models are obvious [27]. Hence, the fineness of the FEA geometric model has a great influence on the quality of the computational results. This research develops a methodology to generate a 2D B-Spline-based geometric model of FEA using TLS, which aims at a solution to calibrate the FEA computation with the accurate free-form model.

The freeform curves are the basis for the freeform surfaces [28]. Whereby, the 2D arched structure is addressed in the present research. A novel calibration methodology is proposed in Fig. 1 to investigate the changes in the loading process. Point clouds, as the input data of the FEA calculation, could be obtained accurately by the TLS. The boundary extraction is necessary to capture the edges of the 2D model. Both parts form the input step in the methodology which will be explained in Section 2.1. An idealized model is generated firstly, according to the boundary points extracted. Based on the free-form approximation, the B-Spline technology is chosen as the approximation method for the TLS data extracted. Hence, the B-Spline curves and the B-Spline geometric model are obtained. These two models and the B-Spline curve forming the modelling step will be discussed in Section 2.1. Meanwhile, the idealized model and the B-Spline model are considered as the reasonable FEA model in this calculation which is described in detail in Section 2.2. After the computation, the calibration process is assessed by comparing the B-Spline model and the idealized model. The target of the calibration and the optimization is to reduce the nodal displacement error. It will be discussed in details in Section 2.3. Finally, the post-computation is carried out with the advantage of the FEA to predict the crack regions of the structure. The prediction part will be described and discussed carefully in Section 2.3.

2. General process

2.1. Input and modelling

The FEA calculation of the complex structure could be quickly obtained by modelling the geometric feature ideally from the original construction information [29]. However, problems regarding the accuracy are also obvious in the final displacement progress of idealized FEA calculations [30]. The reason is that the detailed concave and convex parts of the structural shape are usually ignored by the simplified model [30]. Consequently, the model-shape-based calibration should be considered significant and the modelling based on the actual geometric feature is necessary.

TLS is a highly efficient measurement method to obtain information regarding millions of points per second to provide comprehensive information about a complex structure in current applications. With the help of TLS, complex models with detailed characteristics could be clearly described in lots of applications, for example, heritage recording [31] and rock-fall analysis [32]. Therefore, the FEA calculation based on a free-form shape rather than an idealized shape is possible and realizable with the application of TLS in this methodology.

It is common to approximate point clouds from TLS by free-form curves and surfaces with mathematical methods [19]. The final purpose of the free-form curves and surfaces and the shape construction is to approximate and construct all kinds of natural objects. This could be based on the use of point clouds obtained by TLS which could well capture uncertain data gaps and irregular edges and surfaces [22]. In lots of applications, B-Splines are the especially important mathematical method in the reverse engineering subject [22]. With the application of B-Splines, the actual structural model could be obtained by fitting curves and surfaces which are based on the measured point clouds.

By comparing the B-Spline approximation model with the idealized model used in FEA calculation theoretically, the idealized model could only reflect the total characteristics of the object shape but ignore some irregular detailed characteristics. However, the details ignored might cause incorrect displacement behavior and unexpected results in the later operation steps and loading process. With the assistance of control points and knot points, B-Spline approximation can model the complex structure using more detailed and accurate characteristics. Consequently, the B-Spline approximation method is applied in this paper.

Researchers in [9,10] carried out some similar investigations by combining a TLS-based model and the FEA calculation. Functional B-Spline approximation of the TLS-based surface with the adjustment is applied in the FEA calculation to obtain an accurate geometric imaging [9]. The innovation lies in the fact that this investigation applies the curvature resolution to delete some noisy points from the TLS and simplified geometric primitives are partly replaced by the B-Spline surface [9]. In this way, the calculation task has been reduced [9]. However, the problem appears to be that detailed shape characteristics are also ignored during the process of deleting the points. Meanwhile, local B-Spline approximation could not allow to cover the whole surface. Therefore, more accuracy regarding the whole surface approximation is reduced due to the local corrector. A semi-automatic procedure called CLOUD2FEM transforms the point clouds directly from TLS to FE mesh generation and the FEA calculation of a historical building is carried out to show the effective automation of the procedure [10]. This procedure combines the points with the nodes in the meshing part innovatively [10]. Using the points detected in the process, nodes of the grids are selected and used to generate the polygon grids [10]. Hence, the meshing model is applied directly in the later FEA calculation, which avoids the redundant process from the geometric model to the grids generation [10]. Alternatively, the