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Numerical-experimental hybrid method for stress separation in digital gradient sensing method

Rui Zhang*, Ran Guo, Heming Cheng

Engineering Mechanics Department of Kunming University of Science and Technology, Kunming 650500, China

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ABSTRACT

A numerical-experimental hybrid method for the stress separation in the digital gradient sensing (DGS) method is proposed in this study. In the proposed hybrid method, boundary conditions for a local finite element model, that is, nodal force along boundaries are inversely determined from experimental values obtained by the digital gradient sensing method. The hybrid method follows two stages. In stage 1, the DGS method measures the Cartesian stress gradient components directly and, subsequently, the sum in Cartesian stresses at all interesting points on the surface; stress sum are used to compute the unknown boundary conditions for the local model. In stage 2, the individual stress components are calculated by the direct finite element method using the computed boundary conditions from stage 1. The effectiveness is demonstrated by applying the proposed method to a stress concentration problem involving concentrated load acting on an edge of a large planar sheet. The individual stress components thus determined are summed and compared with analytical stress sum, confirming the effectiveness and accuracy of the proposed technique.

1. Introduction

Transparent materials have been widely used in electronic screen, aircraft cockpit canopy, windshield, etc. In practice, composite structures often surfer from the concentrated load during the service, which will cause the stress concentration and induce the local failure near the concentrated load zone. Therefore, the study of deformations, strains, and stresses of composites subjected to concentrated load is an important subject in evaluating strength and predicting service life for composite structures.

Optical methods such as photoelasticity, coherent gradient sensing method, moiré interferometry and holography have been widely applied in various domains. Especially in the experimental mechanics community optical methods have become more and more popular due to the special advantages of full-field measurement and non-destructive measurement. However, most of them have specific limitations in practical engineering applications due to their demand of special sample surface preparation or stringent stability requirements. In the last couple of decades, digital image correlation [1–5] (DIC) has emerged as a popular and effective deformation measurement optical tool and acquired widespread applications. Compared with the above-mentioned optical techniques for deformation measurement, DIC offers the following advantages: full-field measurement; easy specimen preparation; simple optical arrangement and experimental setup. DIC methods give objective displacement information over the whole field. Many research efforts have been devoted to improvement of the accuracy of displacement estimation; recently, finite element formulation of DIC [6,7] has been developed. The precision of displacement usually meets the need through various efforts. However, the DIC method suffers the drawback that the displacement data must be spatially differentiated to give the strains. The gradients of displacement (strain fields) can be calculated by a direct finite difference approximation, which will amplify the noise and give a poor result in experimental cases; this is especially true if the strains around the load application point are of interest. Many differentiation algorithms [8–11] have been developed to calculate strain fields from noisy displacement fields. As a result, the noise of the displacement field could be reduced and the strains could be exacted. However, the high-frequency part of the displacement is also eliminated and this is particularly harmful in the case of high displacement gradient. Recently, as an extension of the DIC based method, Periasamy and Tippur proposed a full-field optical technique called Digital Gradient Sensing (DGS) [12,13] which can quantify elasto-optic effect using the DIC method for mechanical characterization of optically transparent planar solids. The method can link angular deflections of light rays quantified using DIC to two orthogonal stress gradients under plane stress conditions. So, DGS measure Cartesian stress gradient components directly; subsequently, Periasamy [12] calculated the sum in Cartesian stresses or radial stress in a special

* Corresponding author.
E-mail addresses: zrui0310@163.com (R. Zhang), prof.guo@189.cn (R. Guo), chenghm650093@aliyun.com (H. Cheng).

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case of a stress concentration problem involving a line load acting on an edge of a large planar sheet. However individual stress components which directly relate to the material mechanical properties are preferred; and a stress separation method is essential. This is a similar issue as that for photoelasticity. Photoelasticity measures principal stress difference and the principal direction, and thus the stress components themselves cannot be obtained directly. Several methods have been proposed for stress separation in photoelasticity such as the shear difference method [14,15]; numerical analysis of the compatibility equation; oblique incidence and hybrid methods of photoelasticity and another experimental method [16–19]. However all the above methods for stress separation in photoelasticity are not suitable for that in the DGS method. Because, shear stress is not available when shear difference method implants in the DGS method. Hybrid experimental methods require a significant modification in the experimental setup which is a cause of inconvenience. And the other two methods are also impracticable due to their different measurement theories. On the other hand, several hybrid methods of photoelasticity and numerical analysis [20–22], and inverse analysis methods have also been proposed for the stress separation. Berghaus [20] provides a hybrid method with photoelasticity and Finite-element combined, from which displacements along free surfaces and axes of symmetry are obtained from photoelasticity and then perform the finite element method to get stress components. Yoneyama also provides a hybrid method with photoelasticity and Finite-element combined [22], from which tractions along boundaries are obtained from both principal stress difference and principal direction, and then perform the finite element method to get stress components.

In this study, a hybrid method is proposed for stress separation in DGS. The interesting area is subdivided into quadrilateral elements, nodal forces along boundary are obtained by stress sum in DGS, and then individual stress components are obtained by FEM directly. The numerical-experimental hybrid method is applied to a large planar sheet under compression test. Stress components near a line load are obtained. Sum of measured stress components at each point are directly compared with the analytical predictions for this problem. Finally, the results are summarized and conclusions are drawn.

2. Theoretical background

2.1. Experimental procedure

Fig. 1 schematically illustrates the typical experimental setup for DGS. The experiment contains a speckle target, a test transparent specimen and a digital camera. The target plane surface must have a random speckle pattern. The transparent specimen to be tested is placed in front of and parallel to target plane at a distance Δ. White light sources are used to illuminate target plane uniformly. The camera is placed in front of the test specimen at a long distance L ($L \gg \Delta$) with its optical axis normal to the specimen surface, imaging the target plane surface through the specimen in the region of interest. The image captured under no-load is referred to as reference image or undeformed image. The image captured under loading is referred to as deformed image. The speckles on the target plane are compared to the undeformed image due to local change of the thickness and refractive index at a load. So displacements recorded using DIC can be related to angular deflection fields. These angular deflections can further be related to in-plane stress gradient, as discussed in the following section.

The measurement principle of DGS as shown in Fig. 2 is as follows: Thickness of a transparent specimen is B and refractive index is n_0 in no-load state. Cartesian system, (x, y, z) and (x_0, y_0, z_0) are chosen on the specimen and target plane respectively, so that the z axis is perpendicular to the specimen (or target plane). When the target plane surface is imaged through transparent specimen, a point P on target plane corresponding to O on specimen is imaged in reference state. When imposing load, thickness and refractive index of specimen are all changed due to local stress, thus, a neighbor point Q corresponding to O is imaged in deformed state. That is light rays OP in reference state corresponding to OQ in deformed state. The spatial vector PQ with known Δ can be related to angular deflections of light rays. The

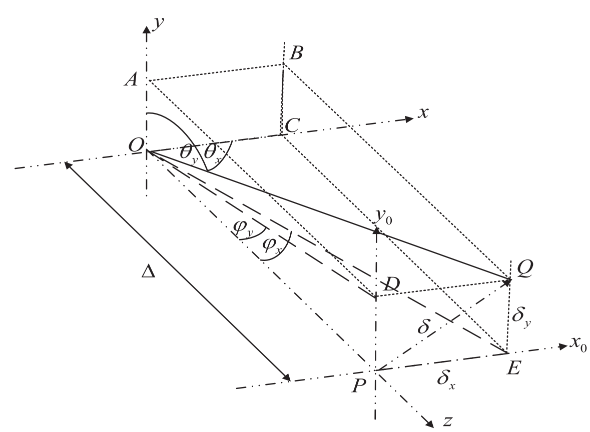

Fig. 2. Schematic of the working principle of DGS.

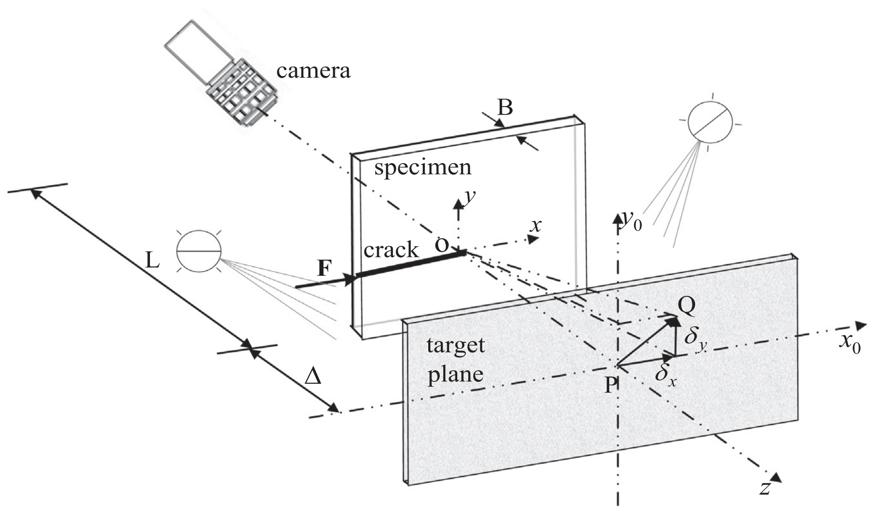

Fig. 1. Experimental setup for DGS.