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Experimental Investigation of Damage Detection Based on a Novel Optical Method

Mark Sandor*, **James Cheung**

Department of Mechanical Engineering, University of Newcastle, New South Wales, Australia

Email address:
Mark.Sandor.Newcastle@gmail.com (M. Sandor)
*Corresponding author

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Abstract: In this article, the stress concentration in homogenous material was studied using an optical method of caustics. The study on stress concentration is of great research value to evaluate the damage inside materials. In this work, one optical experimental method, caustics method, is introduced to study the mechanical behavior of an elastic plate of transparent material. The governing equations of caustics method which is used to represent the optics-mechanics relation of the singular yield close to the external load are derived based on the exponential asymptotic expansion. The experimental result shows this optical method as a nondestructive methodology can be used to detect the damage in load zone with high accuracy.

Keywords: Stress Concentration, Optical Experimental Method, Damage Detection, Optical-Mechanics

1. Introduction

In recent years, damage evaluation of high stress concentration is a complex issue in industry [1-5]. A large amount work has been done in this field to enhance the fidelity of damage assessment methodologies, using a wide range of sensors and detection techniques, for different kinds of materials [6-12]. However, local damage detection is still a challenge with commercial sensors. A lot of effects have been dedicated on both simulation techniques and experimental methodologies of damage evaluation and detection. Zhang et al. developed a probable way to approach this issue is through modeling techniques, which are effective on predicting damage evolution starting from the microscale to higher length scales. Their model is capable of capturing the crack growth rate and direction with high simulation efficiency and accuracy [13, 14] Ye et al. applied a novel non-destructive technique, impact-echo method, to detect damage in concrete structures. They performed experimental validation on real data collection to validated the propose approach. The comparison results demonstrated effectiveness of the propose method. [15, 16] Experimentally, traditional test methods using gauges and sensors are limited to detect stress in some locations for complex geometry and boundary conditions. Also, the size of gauge is another limitation to obtain accurate strain and stress information at the microscale. Therefore, a lot of work has been done to develop the structural health monitoring (SHM) which is critical to multidisciplinary application. [17-20] As a comprehensive technology, SHM integrates sensors and sensing techniques, damage detection algorithms, and prognosis for accurate estimation of component life. Compared with traditional experimental methods, the optical experimental methods are not only a nondestructive measurement but also capable of capturing whole stress/strain field information. Therefore, the optical mechanical experiment methods as a nondestructive testing method can be widely used to detect stress distribution and monitor local damage precursor.

One optical mechanical experiment method, caustics method, was widely used in the study of damage detection. A straightforward relation between caustics size and material deformation in loading zone can be built based on optical circuit and mechanical response of material. Manogg et al. first studied the governing function of stress field using caustics method. [21-25] Theocaris [26, 27], Rosakis [28, 29] and Kalthoff [30] further developed the caustics method and applied it in multiple different materials and loading conditions. In caustics method, an optical circuit was designed using two parallel convex lenses which are set in a distance (see Figure 1). This circuit can generate a semicircle caustics which can be observed by a Charge Coupled Device (CCD). A sample of transparent resin material is placed between the two convex lenses in this optical circuit. With external load, the sample will be deformed and result in twisty light path in this optical circuit. Therefore the caustics observed using the CCD can provide the strain information of the sample using optical governing functions. The obtained caustics size (as shown in Figure 2) at crack tip can be used to detect the local strain information at the microscale. There are a lot of advantages of the caustics method including nondestructive, easy to set up, insensitive to surrounding vibration, high accuracy, and applicable in on-site monitoring [31-35].

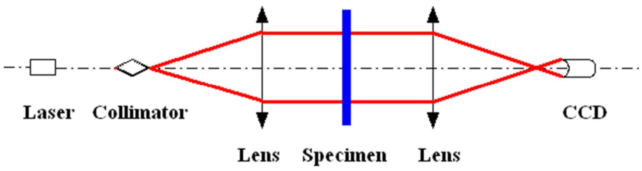

Figure 1. *Optical circuit of caustics method.*

In this paper, the governing function of caustics method for a transmission circuit will be derived in section 2. The steps of the optical experiment will be introduced subsequently. The caustics experimental results will be discussed and compared with theoretical estimation in the following sections.

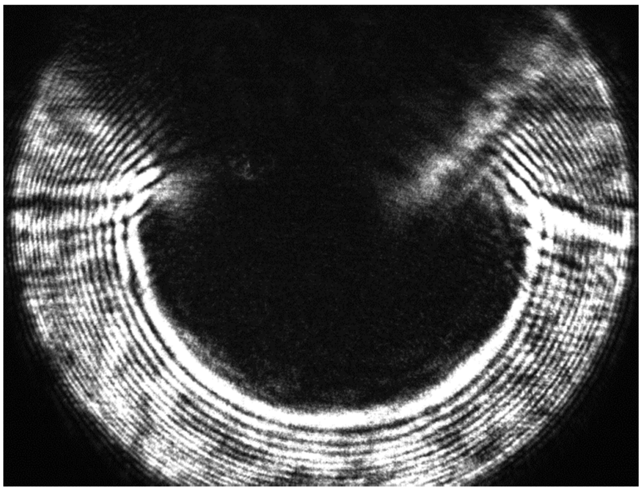

Figure 2. *Caustics at crack tip using optical method.*

2. Optical Experimental Methods

There are two kinds of optical methods of caustics, the transmission method and the reflection method. The transmission caustics method was used in this study. In the transmission caustics method, the laser passes through the transparent sample and results in caustics after two convex lenses. In the reflection caustics method, the laser is reflected by aluminum film which is bonded on sample surface to result in caustics. For transmission caustics method, both the off-plane deflection of the sample surfaces and the bias of the laser in the transparent sample will be considered in the governing function. The optical circuit of caustics method was shown in Figure 1. Parallel light was generated using the first convex lens. The laser will include the deformation information of the sample after passing through the transparent sample. After the second convex lens, the laser is converged again and captured by the CCD. On account of the bias circuit resulting from sample deformation, the image captured by the CCD is from the reference plane instead of the sample surface. In this paper, the local coordinate of the sample is set to be (x, y) and local coordinate of the reference plane is set to be (X, Y). The distance between the sample and the reference plane is Z_0.

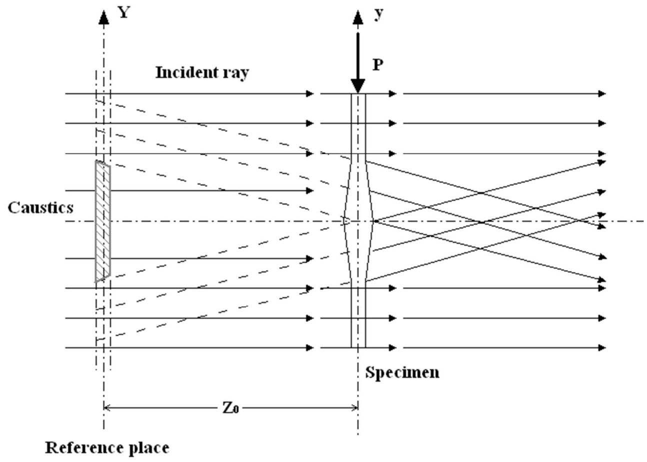

Figure 3. *Schematic light circuit of caustics method on sample with stress concentration.*

The relation of pixel points on the sample and the reference plane can be built based on optical and geometric functions. This is a basic function of the caustics method. The relation of pixel points on sample (x, y) and reference plane (X, Y) can be described as:

$$\mathrm{X} = \lambda x + z_0 \frac{\partial \delta S(x,y)}{\partial x} \quad \mathrm{Y} = \lambda y + z_0 \frac{\partial \delta S(x,y)}{\partial y} \tag{1}$$

where λ is amplification factor which is determined by the layout of the optical circuit, $\delta S(x,y)$ is the difference of the light paths. In this study, the amplification factor λ is 1 because parallel light was used in this test. The difference of the light paths can be described as:

$$\delta S(x,y) = 2d(n_0 - 1)\int_0^{1/2} \varepsilon_z d\left(\frac{z}{d}\right) + 2d\int_0^{1/2} \delta n_0 d\left(\frac{z}{d}\right) \tag{2}$$

where n_0 is the original refractive index of the sample material, and d is the thickness of the sample. The first item of Equation (2) represents the difference of light paths resulted from the sample thickness changing. The second item of Equation (2) represents the difference of light paths resulted from the change of the refraction index. For optical isotropic and homogeneous material, the relation between change of refractive index and principal stress is shown as:

$$\delta n_0 = A(\sigma_x + \sigma_y + \sigma_z) \tag{3}$$

Where A is optical-mechanical consistent. For plane stress condition, the Equation (2) can be simplified as:

$$\delta S(x,y) \approx cd\left(\tilde{\sigma}_x + \tilde{\sigma}_y\right) \quad (4)$$

The projection functions of transmission caustics method are derived by Equation (1) and Equation (4):

$$X = \lambda x + cdz_0 \frac{\partial(\tilde{\sigma}_x + \tilde{\sigma}_y)}{\partial x} \quad (5)$$

$$Y = \lambda y + cdz_0 \frac{\partial(\tilde{\sigma}_x + \tilde{\sigma}_y)}{\partial y} \quad (6)$$

The caustics is generated by focusing imaging of projection of unlimited pixel points. Therefore, based on optical theory, the necessary and sufficient conditions of caustics imaging are that the Jacobian determinant of the projection functions should be zero:

$$J = \frac{\partial(X,Y)}{\partial(r,\theta)} = \begin{vmatrix} \frac{\partial X}{\partial r} & \frac{\partial X}{\partial \theta} \\ \frac{\partial Y}{\partial r} & \frac{\partial Y}{\partial \theta} \end{vmatrix} = 0 \quad (7)$$

The above Equations (5), (6) and (7) are the governing functions of the caustics method. They are used to describe the relation of the pixel points on sample plane and reference plane. For stress singularity issue, the stress and external load can be described as:

$$\sigma_r = -\frac{2P}{\pi r}\cos\theta, \sigma_\theta = 0 \quad (8)$$

A relation between external load and caustics pixel points can be derived using Equation (5), (6) and (8):

$$X = -r\sin\theta - \frac{2Pcdz_0}{\pi}\frac{\sin(2\theta)}{r^2} \quad (9)$$

$$Y = r\cos\theta + \frac{2Pcdz_0}{\pi}\frac{\cos(2\theta)}{r^2} \quad (10)$$

where c is optical parameter determined by sample material.

3. Experimental and Simulation Results and Discussion

A transparent polyacrylamide sample is used in this study. The polyacrylamide material is considered as isotropic and homogenous. The material properties are listed in Table 1. The dimension of the sample is 100mm×40mm×6mm. A pre-crack, of which the length is 10mm, was set at the middle of the top surface, as shown in Figure 4. An external load is applied at the position of the pre-crack, perpendicular to the sample top surface.

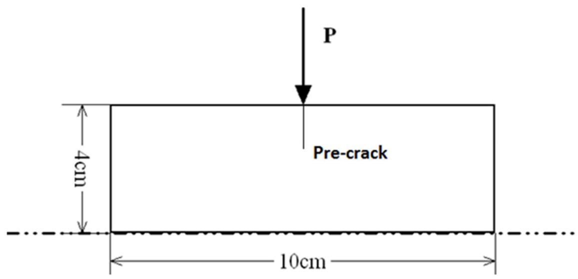

Figure 4. *Sample geometry and external load.*

Table 1. *Material properties of the polyacrylamide.*

Young's Modulus	Poisson's Ratio	Optical Parameter c
3.24 GPa	0.35	-1.08×10^{-10}

A numerical model was built to calculate the caustics size based on Equation (9) and (10). The simulation results for different loads were collected and compared with the optical experiment results, as shown in Figure (5).

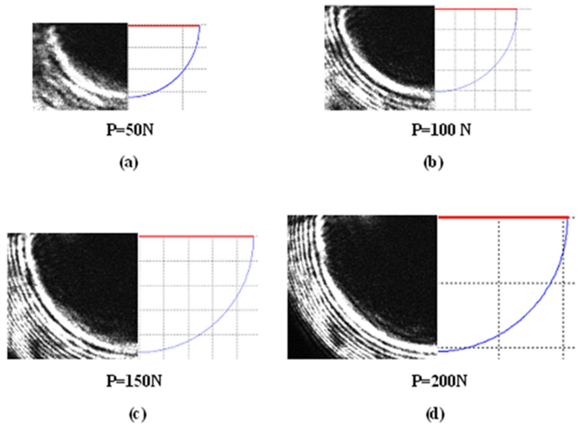

Figure 5. *Comparison of caustics between optical method test and simulation.*

From Figure 5, the experimental caustics size matches well with the simulation result calculated using Equation (9) and (10). Therefore this optical method is capable of evaluating the stress concentration at crack tip. The sizes of caustics based on theory and test under different loads (from 0 to 200N) are compared in Figure 6. The error between test and theory are less than 10%. This result indicates the caustics method is very accurate to evaluate the local stress.

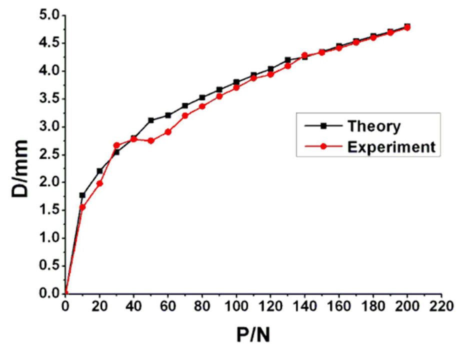

Figure 6. *Comparison of caustics diameter in experiment and simulation under different loads.*

From Equation (9) and (10), the external load can be estimated directly using the size of the caustics obtained in the optical experiment. The comparison between estimated load using optical test and operating load is shown in Figure 7. From the comparison, the error between experimental estimation and operating load is lower than 20% when external load is between 0 and 50 N. This error is significantly decreased to lower than 10% when external load is higher than 50N. This error can be further reduced to lower than 5% when external load is higher than 100N.

The error in this caustics method can be attributed to several possible reasons. First of all, the external load applied on the sample surface is considered to be a line load in the governing function. But the contact surface between the indenter and sample surface in this test cannot be a line because of the limitation of the indenter size. This will result in some errors in the final results. Also, there is very high requirement of accurate optical circuit setting for caustics method. Therefore the accuracy of the dimensions in the optical circuit, such as the distance between two lens, lens and CCD, and lens and sample, will introduce some errors in the external load calculation. Besides that, the polyacrylamide material might be inhomogeneous and anisotropic locally at the crack tip at the microscale. The minor difference of actual material properties in crack tip and the material properties used in the governing function will introduce some errors. Finally, the accuracy of the measurement of the caustics size can result in some errors as well. The lower external load will results in smaller caustics size which is harder to measure accurately. This can also explain the reason the error will be reduced with a higher external load. Overall, the error between estimated load and operating load can be further reduced by using sharper intender, setting accurate optical circuit, preparing high quality materials and improving the accuracy of the caustics measurement. The experimental results indicate the caustics method is capable to estimate the external force accurately. The statistical and uncertainty analysis of the measurement will be discussed in authors' extended work in future.

There are several advantages of the caustics method to detect external load and stress field information. First, the caustics method is nondestructive. The test is all based on optical circuit. There is no sensors planted inside the sample or glued on the surface of the sample. So no damage or destruction are involved in the tested material. This provides the possibility to apply this novel optical methodology in the structural health monitoring to detect crack propagation in metallic and composite structures, which can be potentially implemented into airframe structures. Another advantage of the caustics method is this methodology is easy to set up. In the optical circuit, only one laser generator, two convex lens, and one CCD are required. There is no strict requirement on the environment conditions like temperature, humidity and surrounding vibration. This provides the possibility to use this method in variable environment conditions. Also, as discussed before, the caustics method has very high accuracy (error is less than 5% when external load is higher than 100N in the test). This is competitive to traditional test method using sensors. Finally, the governing function to estimate the external force or local stress is straightforward. The only input parameter to obtain the load is the diameter of the caustics. Therefore it is potential to be used in on-site monitoring and damage estimation.

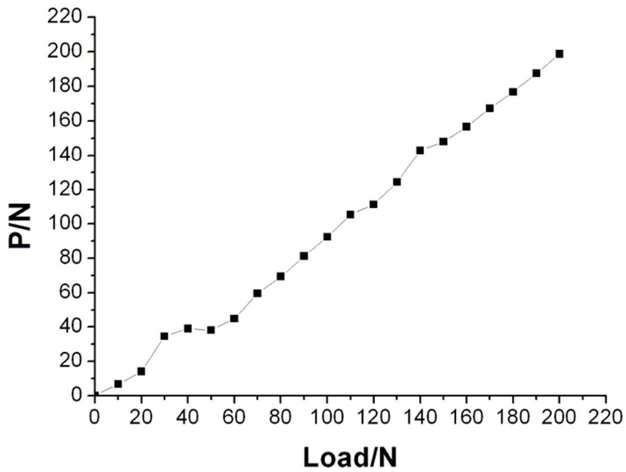

Figure 7. *Comparison between estimated loads using caustics method (P) and operating loads (Load).*

4. Conclusion

In this paper, an optical experimental method of caustics was used to study the stress singularity issue. The caustics size was estimated using a numerical model generated from governing functions. The relation between external load, material properties and caustics size was discussed. The experimental results were compared with theory and the caustics method was validated to be capable of estimating the external load and local stress. This study provides possibility to apply this optical method of caustics in damage detection and structure health monitoring.

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