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Three-dimensional measurement of CFRP deformation during high-speed impact loading

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ABSTRACT

The deformation of carbon fiber reinforced plastics (CFRPs) caused by projectile impact governs the absorption or dissipation of kinetic energy of the projectile. However, three-dimensional (3D) numerical information about the CFRP deformations caused by the projectile impact is not yet available. Therefore, a 3D measurement was conducted to evaluate the deformation process and deformation behavior of the CFRPs under high-velocity projectile impact, and to subsequently evaluate the performance of the CFRPs. CFRPs having two different stacking sequences were used as the specimens. For measuring the deformation, a high-speed stereovision system comprised of two high-speed video cameras was adopted. An SUJ-2 sphere projectile was impacted against a specimen plate using a light-gas accelerator at an impact velocity of approximately 175 m/s, and the deformation was recorded by synchronously capturing the images using this system. The captured images were converted to stereo images by a 3D correlation method. The stereo images clearly revealed numerical differences in the deformation of the CFRPs having different stacking sequences. The result accuracy of the 3D measurement was verified by comparing their results with the direct measurement results. Moreover, the stereo images corresponded to the results from a numerical simulation of the CFRP deformations, which both qualitatively and quantitatively confirms the validity of the simulation. This 3D measurement method is a powerful and useful tool for evaluating the performance of CFRPs during high-velocity projectile impact.

1. Introduction

Carbon fiber reinforced plastic (CFRP) is a composite material that is widely used in making important parts of high-speed rotation equipment in uranium-enrichment systems and in fly-wheel energy storage systems because of its high specific strength and high specific elasticity. It is also used in the structural components of aircraft and spacecraft, and is a promising candidate for reinforcements in buildings at nuclear power plants. Furthermore, since the above-mentioned equipment and craft are at increasing and inevitable risks from foreign object damage (FOD) by impact, it is important to understand the FOD behavior of the CFRPs in order to effectively use them in engineering applications.

A previous study [1] on the energy absorbed by CFRP plates during impact of a projectile revealed that the amount of energy absorbed by a CFRP specimen after a low-velocity impact was dependent on its size and shape. In contrast, during a high-velocity impact, the specimen underwent localized deformation and the amount of energy absorbed by it was only slightly influenced by its size and shape.

In another study [2], it was found that a projectile impact in the velocity range of 500–1230 m/s caused damage to the front layer of a CFRP plate in a fluid-like manner [3], in which the specimen behaved like a liquid near the projectile. In a fluid manner, the mass, the momentum, and the kinetic energy are conserved at the front and back of the shock wave. Therefore, its energy absorption was not significantly affected by the properties of the reinforcements. However, the rear layer appeared to have been fractured in an extrusive manner. The higher tensile fracture strength of the reinforcements in the rear layer resulted in a higher absorbed energy. In yet another study, high-speed camera observations showed that specimens underwent extensive deformation during projectile penetration, which resulted in a higher absorbed energy [4].

These studies revealed that the deformation of CFRP specimens plays an important role in their absorbing or dissipating kinetic energy of a projectile during impact. Even though the in-plane strain has been experimentally calculated by the fine-grid technique [5], quantitative three-dimensional (3D) numerical

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information of the CFRP deformation during projectile impact is yet to be experimentally obtained. Such quantitative values are essential for evaluating the qualitative performance of CFRPs. Yoshimura et al. [6] performed a numerical simulation of CFRP specimens under projectile impact and found differences in the damage to different kinds of CFRPs. In a specimen with a high fracture toughness, delamination did not increase and the damage area was concentrated around the impact point. Therefore, the ballistic limit range for penetration was lower.

In this study, for elucidating the mechanism of energy absorption by CFRPs and evaluating their performance during projectile impact, 3D measurements in the deformation process, and behavior of the CFRPs during high-velocity projectile impact were conducted using a high-speed stereovision system for the evaluation. For validating the performance of our 3D measurement method, the 3D measurement results were compared to those of the side-view measurement and those of a numerical simulation of the CFRP deformation.

2. Experimental methods

2.1. High-speed stereovision system

2.1.1. Fundamental principles

Stereovision is a technique for obtaining 3D positions from two 2-dimensional measured points. The 3D coordinate position can be identified by matching the two measured points [7]. Given an object point P and the homogeneous form for the two-dimensional projections p and p′ on both image planes in a stereovision system consisting of two cameras, the system has a geometric constraint between p and p′ known as the epipolar constraint. The relationship can be written by the epipolar equation shown in Fig. 1, which shows a stereovision system and the epipolar constraint. In the figure, c and c′ are the camera optical centers. The plane consisting of points P, c, and c′ is the so-called epipolar plane, and the bold lines on both the image planes are epipolar lines. The epipolar equation can be combined with the known position of a point in the left image plane (e.g., p) to define the corresponding line in the right image plane along which the matching point, p′, is located. Therefore, as shown in the figure, the search process to locate the matching point, p′, is confined to a limited line region along the epipolar line defined by the epipolar equation. To identify the measured points of p and p′ on the image planes, the 3D position of the object point P is

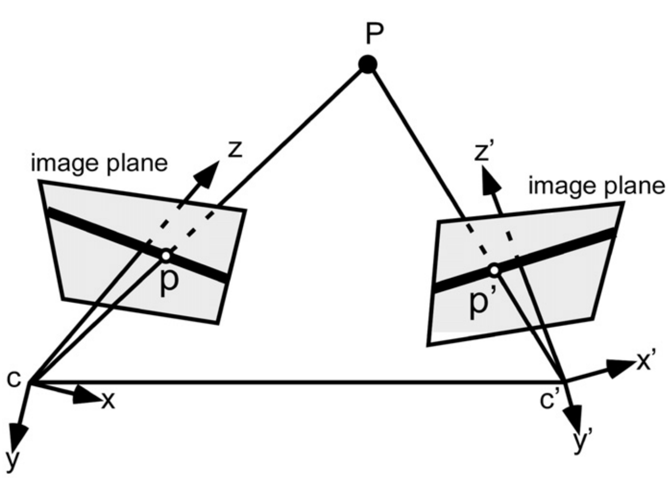

Fig. 1. Illustration on fundamental-concept of recovering the three-dimensions using two cameras and an epipolar constraint.

obtained. Detailed explanations and theory of this geometry are available elsewhere [7].

2.1.2. Experimental setup and experimental procedures

The high-speed stereovision system comprised two high-speed video cameras (Shimadzu, HPV-1 and HPV-2). The CFRP plate deformation was recorded using the system having a shutter speed of 1 μs (1,000,000 fps) at a resolution of 312 × 260 pixels with an exposure time of 0.5 μs in a viewing (capturing) field of 72 × 60 mm^2. The optical axis angle between the two high-speed video cameras was set to approximately 30°. The cameras were triggered by an external TTL pulse and 100 frames were synchronously captured. The used Nikon imaging lenses had a focal length of 200 mm. The distance between the lens and the specimen was approximately 1.6 m. A short-arc power flash (Nisshin Denshi Kogyo, SA-200 F) was used to illuminate the specimen. Fig. 2 shows the experimental setup for the measurement.

To measure the deformation, random patterns were made on the CFRP specimens [8–10]. In Fig. 3, a typical random pattern (dot-pattern, speckle-pattern) on a specimen is shown, which could be made only by spray painting. It initially was a thin-coating of white spray paint and then a random-dot painting using a black spray paint. The feature of the random pattern was as follows: the average size (diameter) of dots in the random pattern was 136 μm and the sizes of the dots were widely distributed in a range from several micrometers to 2.5 mm.

To calculate the specimen deformation, micro-regions were generated on the captured images. The movement direction and the distance between the micro-regions were determined from two anteroposterior images using pattern recognition software (Correlation Systems, VIC-3D) based on digital image correlation principles [7]. An area of 50 × 50 mm^2 on the specimens was measured for the calculation. The synchronously captured images were converted to stereo images by applying the principles in Section 2.1.1.

Before capturing the synchronous images, the two-camera geometry and the camera parameter, e.g., focal length and image center, were calibrated using a predetermined dot-pattern calibration plate to ensure accuracy of the converted stereo images [7]. During the calibration process, the plate was moved in and out of the photographed plane or specimen position with different orientations, and several synchronized calibration images were acquired by both cameras. The calibration plate had 12 × 9 dots in a 2.2 mm-diameter with a pitch of 5 mm, and the 12 × 9 dots approximately filled the viewing field. Three of the dots were easily identified, which had a white part in their centers as shown in Fig. 3.

Fig. 4 shows an example of two anteroposterior images (original image and deformed image) for the calculation [7]. In the original image, the micro-region $dx \times dy$ with the center of $o_k(x_i, y_i)$ was defined and this region was called the subset region $O(o_k)$. In the deformed image, the subset region $D(d_l)$ was defined by the size of $dx \times dy$ and the center position of $d_l(x_i+\Delta x, y_i+\Delta y)$. $D(d_l)$ is shifted in the measured area of the deformed image with a certain periodic shifting for a correlation analysis (subset

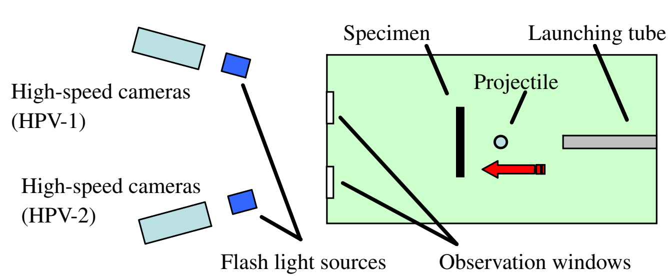

Fig.2. Experimental setup for 3D measurement.