

Mechanical Properties Measurement of Soft Materials by Three-Dimensional Digital Image Correlation Method

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Abstract: The rapid development of soft materials in recent years gives revolutionary impact on electronics and biomedical industries. To better control the quality and key technology, mechanical properties of soft materials employed in electronics and biomedical industries must be accurately determined. By employing the non-destructive, non-contact and whole-field characteristics of the three-dimensional (3D) digital image correlation (DIC) method, epoxy resin used in photoviscoelasticity, mechanical properties of optical films used in backlight modules and artificial meshes used in biomedical applications were investigated in this paper. It was found that satisfactory accuracy and measurement range can be obtained from the 3D-DIC method on the measurement of mechanical properties of soft materials.

Keywords: soft materials, three-dimensional digital image correlation method, epoxy resin, optical films, artificial meshes.

1 Introduction

Technology is changing with each passing days. The imagination and special effects only used in movies come to realistic in daily lives. For example, the monitor can be as thin as a piece of paper and the electronic products can be easily curled are no longer just fantasies appeared in movies. The rapid development of soft materials has made the realization of those products.

Typically a three-dimensional (3D) digital image correlation (DIC) system includes two high resolution (1628 pixel x 1236 pixel) charge coupled device (CCD) cameras, several camera lenses, a laptop, a tripod with accessories and the software package. By employing the non-destructive, non-contact and whole-field characteristics of the 3DDIC method, measurement of mechanical properties of nonho-

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homogeneous materials and large strain are possible. With images taken by two CCD cameras from the area of interest (AOI) before and after deformation mechanical behaviors of the test specimen under different loads can be analyzed. In this paper, the 3DDIC method was used in combination with the uniaxial tensile test to investigate mechanical properties of epoxy resin used in photoviscoelasticity, optic films used in backlight modules and artificial meshes used in biomedical applications. It was proved that the 3D-DIC method possesses sufficient accuracy and measurement range for the mechanical properties measurement of soft materials.

2 Digital image correlation method

The DIC method was first proposed by Peter and Ranson in 1982 [Peters, Ranson(1982)]. Randomly distributed bright and dark speckle pattern was produced by impinging laser light on the specimen's surface. TV camera and digitizer were used to convert the light intensity information from the surface of the specimen into digitized image. By analyzing the two digital images of the specimen captured before and after deformation, displacement components can be obtained. Since then, many researchers have thrown themselves into the development and application of the DIC method

By employing the principle of the two-dimensional DIC method and the theory of solid geometry, Kahn-Jetter and Chu [Kahn-Jetter, Chu(1990)] used two in-parallel cameras perpendicularly to and focused simultaneously on the specimen's surface to extend the 2DDIC measurement system to 3DDIC measurement system in 1990. Luo, et. al [Luo, Chao, Sutton, Peters III(1993)] proposed 3DDIC measurement system based on the geometric relation of spatial coordinates between the test specimen and two CCD cameras and the principle of 2D-DIC method. The limitation of the perpendicularity of the two cameras to the surface of the test specimen was removed. Recently, with the advancement of both the computer hardware and software, the DIC method has been widely used in various engineering applications to determine displacement, strain and shape of engineering structural components. It is suitable from the measurement of the bridge to the scanning electron microscope, atomic force microscope and common optical microscope.

When employing the 3DDIC method, the essential presupposition is that the surface of the sample has sufficient characteristics. Originally existed or artificially produced random speckles could be these characteristics. The 3DDIC method uses the numerical interpolation and iteration techniques to compare with the image information before and after deformation, and to obtain the displacement and strain in the AOI.

The image before the object is deformed is selected as the reference image. As the

object starts to deform, according to the condition of deformation and the experimental period, a single image was taken as the deformed image or several images within a certain time interval were selected as the deformed image. Calculating the correlation between the reference and deformed images, the deformation of the object can be obtained

The 3DDIC system with the software package used in this paper is the VIC-3D system developed by Correlated Solutions Co. The accuracies of the in-plane and out-of-plane analyses of the system are 1/50,000 and 1/25,000 of the field of view (FOV), respectively. The accuracy of the strain measurement is 0.00015. However, the accuracy of the system is influenced by several factors, e. g., the dots per inch of the CCD cameras, the uniformity of the light source, the quality of the speckles and environmental disturbance.

3 Experimental background and results

3.1 Epoxy resin used in photoviscoelasticity

By following ASTM B557M [ASTM Test Designation B557M], the dimensions of the epoxy resin test specimen were selected. To verify the results obtained from the 3DDIC method, axial and lateral strains were also measured by strain gages. Least squares fitting were implemented on DIC results as shown in Fig. 1. The slope of the least-squares line is the Poisson's ratio, i.e. 0.358. As listed in Table 1 the Poisson's ratios respectively obtained from the 3DDIC method and the two sets of strain gages (0.362 and 0.338) are matched well. With the experimentally determined Poisson's ratio, further numerical simulation can be performed.

Table 1: Poisson's ratios obtained from 3DDIC system and two sets of strain gages

Specimen	Poisson's ratio	Method
I	0.362	Strain gage set 1
II	0.338	Strain gage set 2
III	0.358	3D-DIC Method

3.2 Optical films used in backlight modules

Because of the light weight, thin volume and low power consumption, thin film transistor liquid crystal display (TFT-LCD) has replaced the cathode ray tube (CRT) in recent years and has become one of the major industrial products of Taiwan. The mechanical properties of the optical films used in backlight modules are essential for accurate numerical simulation of the TFT-LCD. Even stain gages could provide

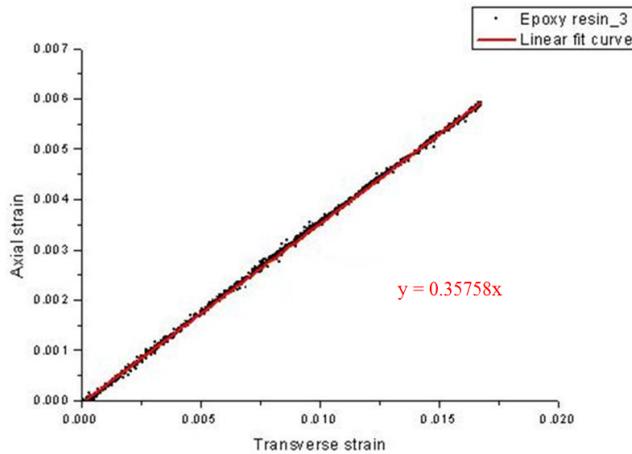


Figure 1: The strain results obtained from the 3DDIC system

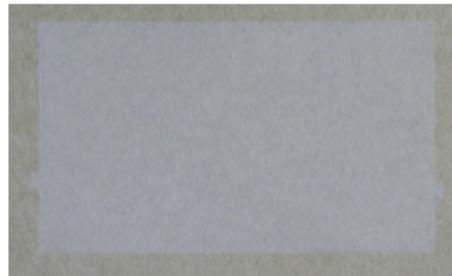
accurate measurement results; however, it may not be quite feasible to be adhered to the optical films. Furthermore, strain gage is a point measurement method. By employing the nondestructive, non-contact and whole-field characteristics of the 3D-DIC method, the whole-field deformation of the optical film can be measured. Uniaxial tensile test was employed in conjunction with the 3DDIC method to obtain the whole-field deformation of the two kinds optical films as shown in Fig. 2. The measurement results obtained from the 3DDIC method are listed in Table 2.

Table 2: Results obtained from the 3DDIC method

Specimens	Young's Modulus (GPa)	Poisson's Ratio
Diffuse Sheet	2.52	0.37
Prism Sheet	2.12	0.43

3.3 Artificial meshes used in biomedical applications

Many women have to face with the problems of pelvic organ prolapse (POP) after they give birth of a baby. According to the statistics, one of each three women above 45 years old has POP problem; one of each ten women above 80 years old had done the pelvic floor reconstructive surgery. According to the medical research, the implanted artificial mesh can incorporate and integrate with adjacent tissue and



(a) Diffuse Sheet



(b) Prism Sheet

Figure 2: Two types of optical films

support the force from the pelvis. However, the deformation and shrinkage of implanted artificial mesh may affect the nerve and blood vessels and cause painful sensation or failure. Most of the studies about artificial mesh were mainly concentrated on the biocompatibility or the inflammation reaction with human tissue, and rarely discussed the mechanical behaviors before and after implantation. In Figs. 3(a), 3(b) and 3(c) three kinds of commercially available artificial mesh, Gynemesh, Marlex and Mersilene are depicted. The meshed structure of those three artificial meshes is consisted of woven polypropylene

The mesh structure of the artificial meshes makes the application of strain gage almost impossible. Other optical methods based on optical interference are not applicable due to the discontinuous reflection of the meshed structure. The 3DDIC method was therefore used to investigate the mechanical properties of artificial meshes in the uniaxial tensile test. Consequently, the problem that the deformation information received from the traditional tensile test instrument is the displacement of the clamping end can be overcome. Furthermore, whole-field strain distribution

can be obtained. The experimental setup used in this paper is shown in Fig. 3 In-stron 8848 micro-tensile test machine was used to perform the uniaxial tensile test. The Flower Silkware Foundation was brushed on the surface of the test specimen to reduce its reflection. Speckle pattern of the test specimen was produced by using the fine black marker pen making dots randomly on the surface.

As shown in Fig. 4, rubber was used as the end tab and was adhered to the test specimen by cyanoacrylate to avoid the test specimen to be damaged by the clamping mechanism or slippage occurs when tensile test is performed. Fig 5 shows the original image used for analysis by VIC-3D software. The histograms of the average Young's modulus and the average Poisson's ratio of the three kinds of artificial meshes are shown in Figs 6 and 7, respectively. Young's modulus of six kinds

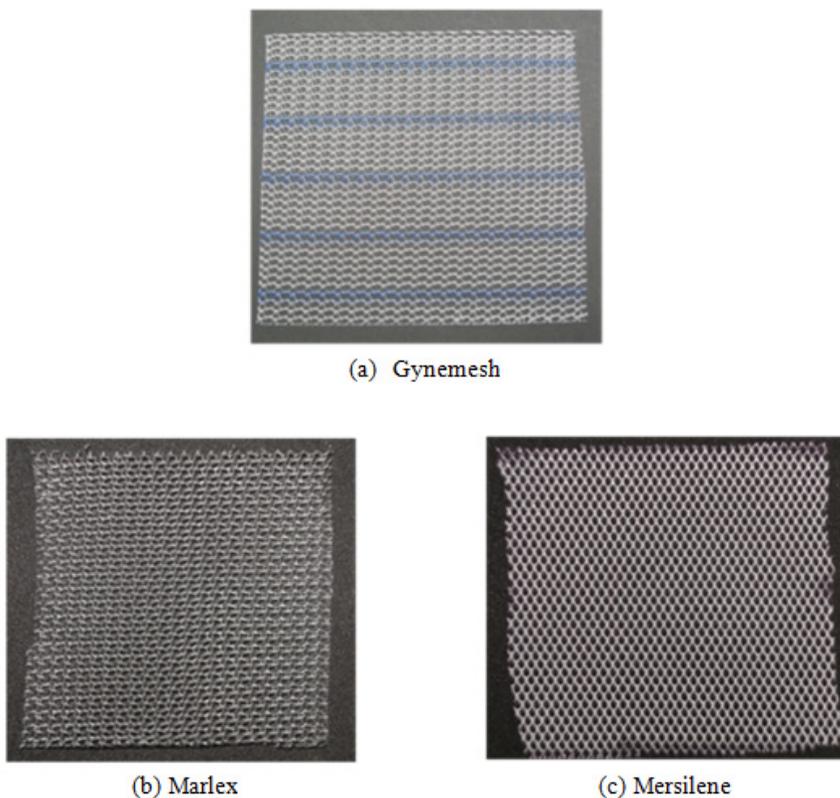


Figure 3: Photographs of the three types of artificial mesh.

of test specimens of artificial mesh obtained from the 3D-DIC method and tensile test are listed in Table 3. In Table 3, KA stands for knit axis and CKA stands for

cross knit axis. Gynemesh KA (Marlex KA, Mersilene KA) and Gynemesh CKA (Marlex CKA, Mersilene CKA) stand for test specimens of Gynemesh (Marlex, Mersilene) prepared by cutting the artificial mesh along and across the knit axis, respectively. As indicated in Table 3, except the case of Marlex, values of Young's modulus of CKA specimens are larger than those of KA specimens for both Gynemesh and Mersilene. In addition, except the case of Mersilene KA, the values of Young's modulus obtained from the 3D-DIC method are relatively larger than those obtained from the tensile test. It should be pointed out here that Young's modulus obtained from the tensile test was based on the definition of the engineering strain, i.e. the strain distribution was assumed uniform across the test specimen. However, necking phenomenon appeared in the artificial mesh specimens during tensile test, i.e. transverse strain was increased significantly from the clamping end to the center of the specimen. Results listed in Table 3 obtained from the 3D-DIC method were collected from the central part of the test specimens where the strain distribution was more uniform. Furthermore, the effect of transverse deformation on the axial strain was also considered in the 3D-DIC method. Therefore, the results obtained from the 3D-DIC method are more accurate than those obtained from the tensile test.

Table 3: Comparison of Young's modulus of six kinds of test specimens of artificial mesh obtained from 3D-DIC method and tensile test

Young's Modulus (MPa)	Tensile Test	3D-DIC Method
Gynemesh KA	8.76	9.04
Gynemesh CKA	14.34	18.86
Marlex KA	15.37	22.63
Marlex CKA	0.93	1.15
Mersilene KA	29.93	26.69
Mersilene CKA	14.37	18.91

Comparison of maximum loads of test specimens of Gynemesh and Mersilene obtained from tensile test and provided by Gynecare are listed in Table 4. Significant difference is noted. It is believed that the size of the specimen makes the difference. Unfortunately, there is no standard for the dimensions of the test specimen made from the artificial mesh. Even the difference exists; however, a common trend for the results obtained from tensile test and Gynecare was found. The maximum load of Gynemesh specimens in the KA and cross knit axis (CKA) axis are almost the same. In addition, the maximum load of Mersilene specimens in the KA is twice of that in the CKA.

Table 4: Comparison of maximum loads of test specimens of Gynemesh and Mersilene obtained from tensile test and Gynecare

Maximum Load (N)	Gynecare	Tensile Test
Gynemesh KA	96.43	69.72
Gynemesh CKA	96.91	67.53
Mersilene KA	117.34	66.17
Mersilene CKA	59.58	34.43

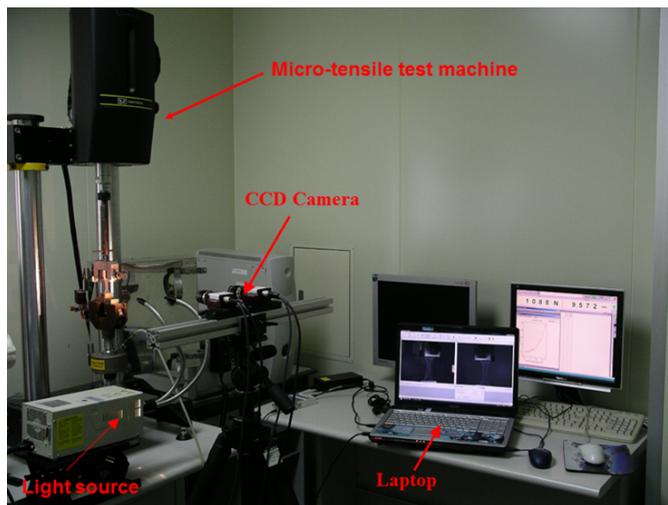


Figure 4: Photograph of the tensile test setup with the VIC-3D system.



Figure 5: The artificial mesh after spraying the speckles. Rubber end tabs were adhered onto the two ends of the test specimen

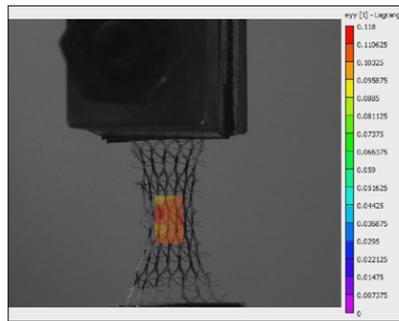


Figure 6: The original image analyzed by VIC-3D

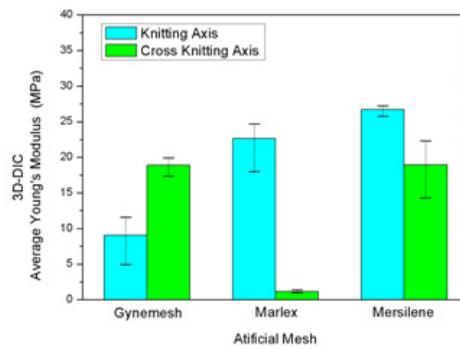


Figure 7: The histogram of average Young's modulus obtained from the 3D-DIC method.

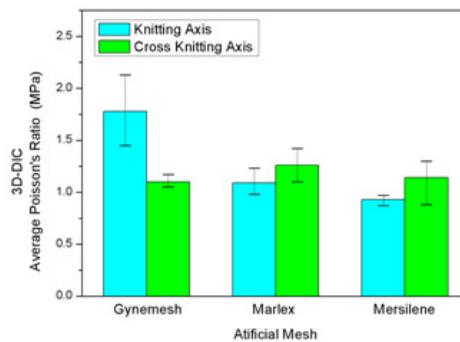


Figure 8: The histogram of average Poisson's ratio obtained from the 3D-DIC method

4 Conclusions

The paper-like soft materials have given revolutionary impact on electronics and biomedical industries. If the mechanical properties of soft materials can be accurately measured, the key technology and quality of electronics and biomedical industries can be better controlled. In this paper, Poisson's ratios of three epoxy resin specimens determined by the 3DDIC method and the two sets of strain gages are well-matched. Thus, the accuracy of the DIC method was proved. Furthermore, Young's modulus and Poisson's ratio of three artificial meshes and optical films were also accurately determined by the 3D-DIC method. Therefore, regardless of the material of the test specimen is, with sufficient characteristics either naturally existed or artificially produced on the surface of specimens; the sufficient accuracy and measurement range for the mechanical properties measurement of soft materials by the 3D-DIC method were validated.

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