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FULL-FIELD SURFACE AND INTERIOR DEFORMATION MEASUREMENT OF SANDWICH CORE MATERIAL USING DIGITAL SPECKLE PHOTOGRAPHY

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1. INTRODUCTION

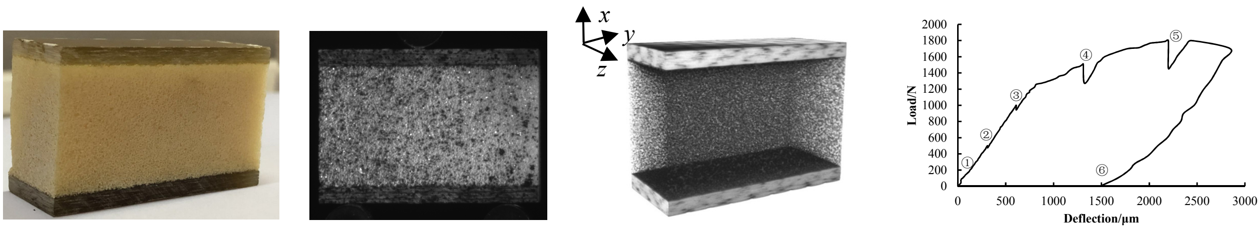
Composite materials are becoming more ubiquitous as engineering materials in aircraft, ships, bridges, and motor vehicles, because of their superior strength to weight ratio. Composite sandwich plates comprising of two face sheets and a polymer foam core are particularly advantageous as a ship building and wind turbine blade material because of its high bending rigidity. Knowing sandwich material's failure mechanism is, of course, of paramount importance in a safety design. Several experimental studies have been carried out to investigate the mechanical properties and failure mechanisms of composite sandwich plates and beams [1-3]. As a full-field measurement technique, DSP (Digital Speckle Photography) and DIC (Digital Image Correlation) have been used to analyze local core deformations and damage mechanisms [4,5]. However, these two techniques only provide the surface deformation. In order to fully appreciate the deformation mechanism of sandwich structures, it is paramount that the interior deformation be mapped and quantified. Recently the X-ray Computed Tomography (CT) technique has been used for in-situ testing of composite structures and in detecting interior damages [6,7]. However most of these studies are qualitative in nature. By taking advantage of the 3D volumetric imaging capability of X-ray CT, we recently developed an effective experimental strain analysis technique called DVSP (Digital Volumetric Speckle Photography) [8], whereby we can probe quantitatively and in detail the interior deformation of most opaque materials. DVSP is an extension of DSP technique in interior 3D displacement assessment. While DVSP was first developed to probe the interior deformation of geomaterials, we have also successfully applied it to probing the interior deformation of a woven composite beam and a composite sandwich plate [9, 10].

In this paper, we apply DSP and DVSP to mapping the deformation of a short and thick sandwich beam under three-point bending, respectively, and evaluate the results from those two methods and provide a comparison of the pros and cons of these techniques

2. MATERIALS AND METHODS

A Sandwich Beam under Three-Point Bending

Fig.1 shows the sandwich beam specimens under three-point bending. The specimen is made of E-glass Vinyl Ester composite face sheet with a polymer foam core [1]. The size is 50.0×20.0×32.0 mm^3. There are two specimens, one for DSP measurement, and the other for DVSP measurement combined with CT scanning. Fig.1(b) and (c) show the image with a digital camera and the X-ray reconstructed 3D image, respectively. Dark spots are the speckles sprayed on the surface of the specimen for the DSP method.



(a) specimen (b) the specimen in DIC experiment (c) X-ray reconstructed 3D image (d) loading history

Fig.1 : Images of the specimen.

In the experiment for DSP measurement, a sequence of images were captured by using a digital camera during the loading. The physical size of a pixel is 25×25 μm^2. In the experiment with CT scanning, the whole loading process was divided into 6 steps shown in Fig.1(d). In each step, the load is kept constant during the x-ray scanning. The reconstructed volumetric images have 890×360×530 voxels with the physical size of a voxel being 55×55×55 μm^3.

Theory of Digital Volumetric Speckle Photography(DVSP)

After a 3D volumetric image of an opaque specimen is recorded digitally via an X-ray CT before and after the application of load, the images are divided into sub-images with an arbitrarily selected unit volume of 32×32×32 voxels, for example. A 3D FFT (Fast Fourier Transform) is applied to a selected (one before and one after loading) sub-image pairs to reveal their spatial frequency spectrum. An numerical "filtering" process is performed on them. And then a further application of 3D FFT on the spectrum gives rise to a delta function G(ξ, η, ζ) whose coordinates (*u*, *v*, *w*) of the crest are nothing but 3D components of the displacement vector of all the volumetric speckles within the selected voxel array. The procedure is repeated over the entire volume of voxel array pairs. The result is a set of displacement vectors within the entire calculated volume. A schematic of the algorithm is illustrated in Fig.2.

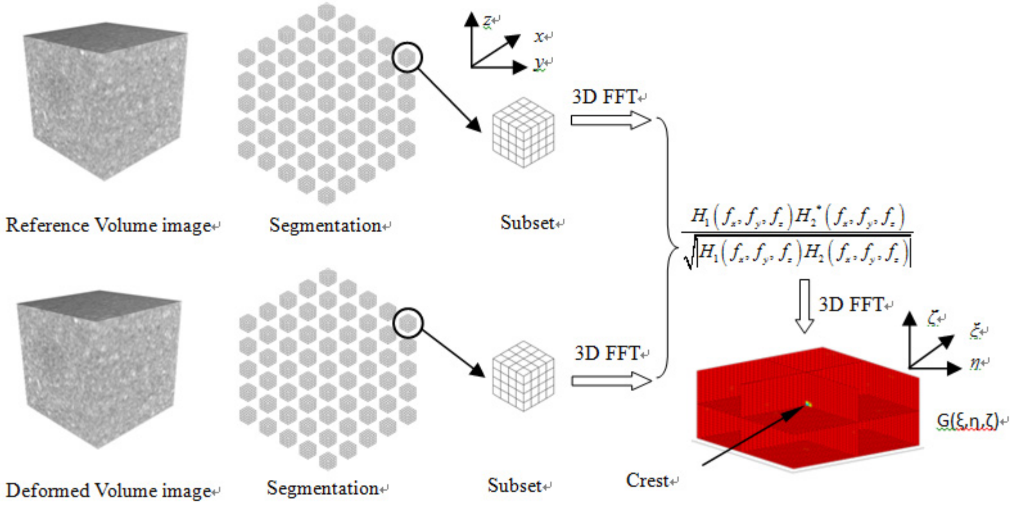
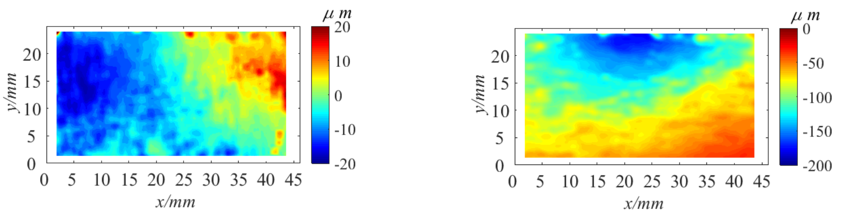


Fig.2: Schematics demonstrating the processing algorithm of DVSP.

3. RESULTS AND DISCUSSIONS

Based on the images from the two experiments, the displacement fields were calculated by using DIC and DVSP methods, respectively. In DSP method [11], the size of a subset is 128×128 pixels whereas in the DVSP method, the micro-structure of the core was treated as volumetric speckles and the size of a volume subset is 32×32×32 voxels. The deformation of the core region was calculated. Fig.3 shows the displacement fields of *u* and *v* corresponding to *x* and *y* axis based on the DSP results, and Fig.4 shows the displacement fields *u*, *v* and *w* of 3 sections along *z*=1.8mm, 9.7mm and 17.6mm of the beam as calculated by DVSP. The loading in both cases was 500N.



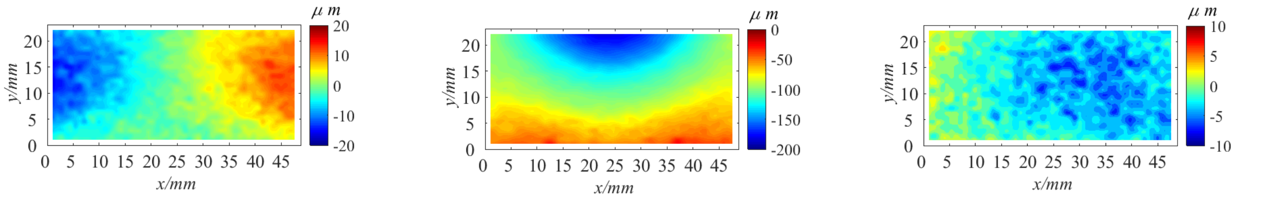
(a) *u* field (b) *v* field

Fig.3 : Displacement fields of the surface with DSP.

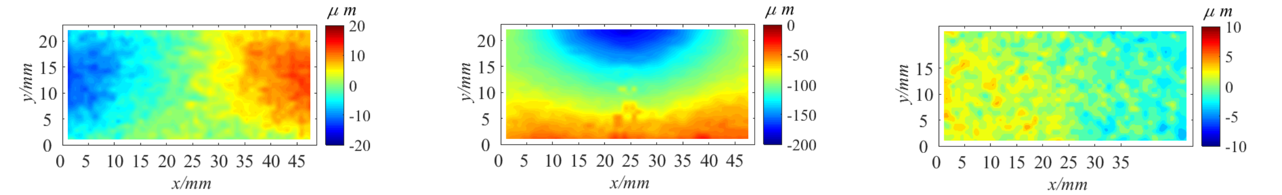
Compared Fig.3 with Fig.4, *u* and *v* field contours from DVSP are much smoother than these from DSP. The reason is that the volumetric subset in DVSP has much more information than the subset in DSP, which improves the robust of correlation searching. In Fig.4(c), (f) and (i), it is noted that the specimen has the deformation along *z* axis. In 2D DSP method, it is assumed that only the in-plane deformation occurs in the surface, and the out-plane deformation will be neglected. The actual deformation along z axis would result in measurement errors of DSP.

Due to the transverse shear stress effects, warping phenomenon will occur on the transverse section of a composite beam. DVSP is a good choice to validate those phenomenon. In Fig.5, *u* fields of the section at the middle length between the upper and the left supports are shown. With the loading increment, the warping section is clearly visible.

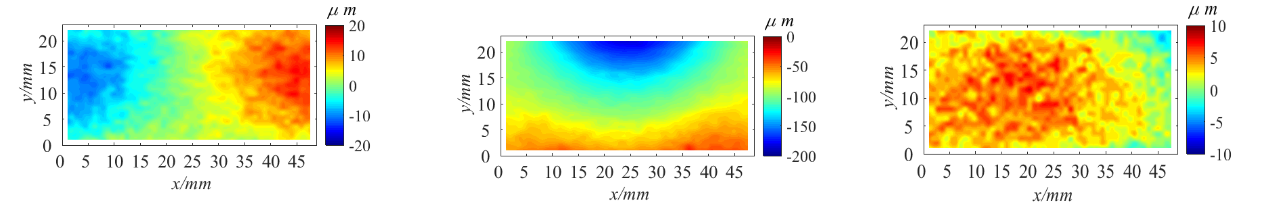
Using the surface measurement technique such as DIC or DSP the size of the speckles can be varied because they are spread onto the specimen surface artificially. For a volumetric technique such as DVSP or DVC (Digital Volume Correlation) [12] the speckles are part of the material's interior structure. Thus, it cannot be modified. If the interior texture of a material does not lend itself to be treated as volumetric speckles these techniques are not applicable at all. When the material's internal texture can be treated as volumetric speckles and the internal deformation of the specimen is needed DVSP or DVC technique is obviously a superior choice. But if only the surface deformation is the only needed information, DIC or DSP is a better one in that one can optimize the size and contrast of the speckles to yield better results.



(a) *u* field of the section at z=1.8mm (b) *v* field of the section at z=1.8mm (c) *w* field of the section at z=1.8mm

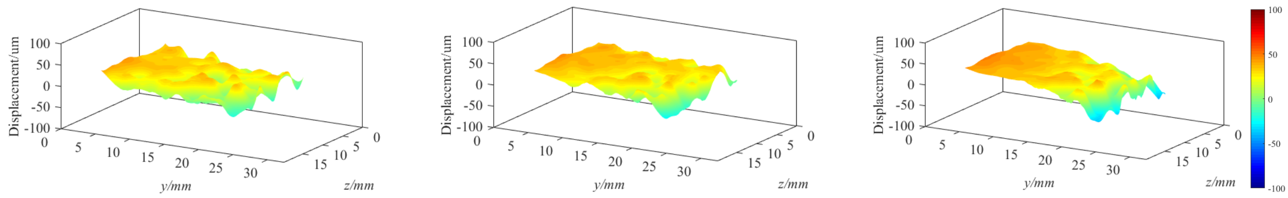


(d) *u* field of the section at z=9.7mm (e) *v* field of the section at z=9.7mm (f) *w* field of the section at z=9.7mm



(g) *u* field of the section at z=17.6mm (h) *v* field of the section at z=17.6mm (i) *w* field of the section at z=17.6mm

Fig.4: Displacement fields of three different sections with DVSP.



(a) Loading 1000N (b)Loading 1500N (c) Loading 1800N

Fig.5: u fields of the middle section between the upper and left support of the sandwich specimen.

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