

DIC DEFORMATION MEASUREMENT IN CRACKED CFRP CROSS-PLY LAMINATES

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ABSTRACT

Digital Image Correlation (DIC) is a non-contact method to analyse the deformation of materials that can measure displacement or strain behaviour during tensile loading. In this study, DIC is used to measure the deformation of cross-ply carbon fibre reinforced plastics (CFRP) laminates and for the detection of damages in them. The objective of this study is to measure the deformation around the damages in cross-ply CFRP laminates by using the DIC system from both width and thickness directions. For this purpose, thick CFRP [0₄/90₂₄]_s and thinner [0/90₆]_s laminates were tested. In cross-ply laminates, usually a straight transverse crack will initially occur in 90 degree ply followed by the following damages such as delamination, fiber fracture, and etc. To start, straight transverse cracks are induced in the laminates by using an artificial crack method. Then, X-ray radiography is used to detect the location of the straight cracks in order to be used for DIC observation to examine the strain distribution around the existed cracks. The DIC observation from the surface of the laminate around the cracks area clearly showed how strain is distributed from one crack to another adjacent crack. From the result, secondary mode damages of matrix cracking such as oblique and curved cracks can also be observed and are being discussed in this paper.

1 INTRODUCTION

Carbon Fiber Reinforced Plastics (CFRP) laminates are increasingly utilized in the aeronautical and construction industries for their low weight, high strength, and high stiffness properties. Fiber reinforced laminated composites including CFRP exhibit various competing damage modes such as matrix cracks, delamination, fiber breakage, and etc. [1]. Transverse matrix cracks in cross-ply laminates have been experimentally and analytically studied vigorously back in the late 1970s until now. Delamination is reported as one of the damage in secondary damage mode in the laminates [1-4]. Delamination occurring in the laminates is mostly explained by the stress concentration around the transverse crack tip and also the high value of strain energy release rate [5]. Besides delamination, there are other types of cracks in secondary damage mode such as oblique and curved transverse cracks close to the straight cracks with no delamination [1]. Damages in this mode are shown schematically in Figure 1. Oblique crack in off-axis plies is another kind of damage in secondary damage mode which always occurs near to the straight transverse cracks while curved cracks usually form from two oblique cracks extended from the ply interface. Most of the analytical and experimental studies are focused on straight transverse cracks that fully propagates in the 90 degree ply and delamination induced by transverse cracks. Therefore, we believe that oblique and curved cracks have not yet been investigated in detail especially experimental study on the deformation measurement around the damages in CFRP laminates due to the limitation of measurement devices. Traditionally, strain gages have been used to measure the tensile strain to determine the mechanical properties of the

materials such as Young's modulus, tensile strength, and Poisson's ratio. Strain gages can only measure the average strain within the gage length and produces no information on the strain distribution in the measurement area. During tensile loading, deformation localization occurs and causes strain distribution to be non-uniform.

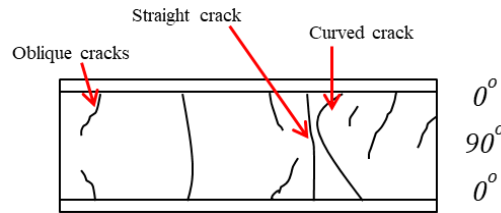


Figure 1: Schematic of the matrix crack pattern in CFRP $[0_4/90_{24}]_s$ laminate.

In this study, a Digital Image Correlation (DIC) method is employed to measure the strain distribution at the macroscopic level during a tensile test to a cracked CFRP cross-ply laminate. The advantage that DIC has over the standard method of using the strain gages or any other strain measuring system is that the DIC approach is a non-contact strain measurement that can give out the displacement and strain distribution in loading, transverse and shear directions. Also, it gives point-by-point strain field, while the standard method only gives uniform strain. DIC application is not limited only for tensile loading but it can be also applied to a body under other types of loadings. Therefore, the objective of this study is to measure the deformation around the damages in cross-ply CFRP laminates by using DIC system in various directions. For this purpose, thick CFRP $[0_4/90_{24}]_s$ and thinner $[0/90_6]_s$ laminates were tested. In laminates, usually a straight transverse crack will initially occur in off-axis plies followed by the following damages such as delamination, fiber fracture, and etc. To start, straight transverse cracks are induced in the laminates by using an artificial crack method. Then, X-ray radiography is used to detect the location of the straight cracks in order to be used for DIC observation to examine the strain distribution around the existed cracks. From the result, secondary damage mode of matrix cracking such as oblique and curved cracks also can be observed and are being discussed in this paper.

2 EXPERIMENT

The materials used in this study and the properties of unidirectional materials are shown in Tables 1 and 2 respectively.

Raw material type	Prepreg (preimpregnated composite fiber)	
Resin system	T700SC/2592, Torayca	
Prepeg thickness (mm/ply)	0.15	
Laminate configuration	$[0_4/90_{24}]_s$	$[0/90_6]_s$
Laminate thickness (mm)	8.23	2.06

Table 1: Type of materials.

Material properties of each material are obtained by conducting monotonic tensile test using Tensilon RTF-1350 A&D tensile test machine with cross head speed of 1mm/min. Strain gages are used to measure the average strain for this loading. The tensile loading is done to examine the fracture strength, fracture strain and stress/strain where cracks initially occur so that the suitable applied stress/strain range for DIC observation can be decided.

Young's modulus in 0° direction E_1 [GPa]	123
Young's modulus in 90° direction E_2 [GPa]	8.68
Shear modulus G_{12} [GPa]	3.92
Poisson's ratio ν_{12} [-]	0.33

Table 2: Properties of unidirectional materials.

The prepregs are stacked according to the stacking sequences shown in Table 1 and cured in an autoclave at a temperature of 130 degree Celsius and pressure of 0.2 MPa. Laminates are then cut into the measurement shown in Figure 2 by using a composite material cutting machine (AC-300CF, Maruto Testing Machine). In order to make sure matrix cracks uniformly occur on the specimen for easier damage observation by X-ray radiography and DIC system, the artificial crack method is induced in this study. This method is explicitly explained by Fikry et al. [6] where artificial crack method can be done by making notches at both edges of the specimen by using a knife before pulling it in a tensile test machine with cross head speed of 1mm/min to a specific load. Then the specimen is unloaded back to zero and the notched edges are cut by using composite material cutting machine mentioned above at ± 5 mm from the edges.

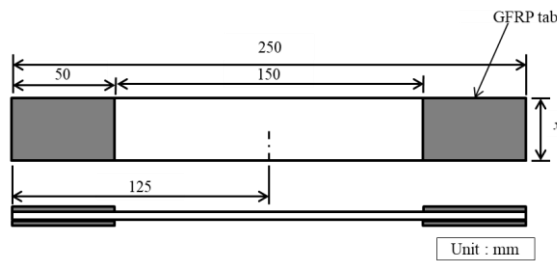


Figure 2: Specimen's measurement.

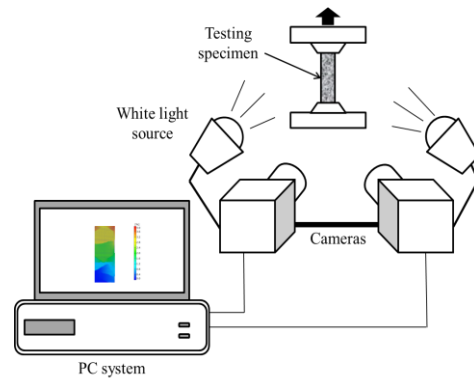


Figure 3: Schematic figure of DIC setting.

After removing the notched edges, the specimens are then placed in X-ray radiography device (M-100S, SOFTEX) in order to detect the location of matrix cracks. Comparing the X-ray image with the specimen, the position of visible matrix transverse cracks is marked on the specimen. The DIC software and cameras used in this study is GOM ARAMIS system. ARAMIS is a non-contact optical deformation measuring system that analyzes, calculates and documents deformation occurring on the materials. ARAMIS recognizes the surface structure of the measuring object in digital camera images and allocates coordinates to the image pixels. The first image in the measuring project represents the undeformed state of the object. After or during the deformation of the measuring object, further images were recorded. Then, ARAMIS compares the digital images and calculates the displacement of the object characteristics.

Then, DIC apparatus is set up as shown in Figure 3 where tensile machine is different with the one used to obtain the mechanical properties of the laminates. The tensile test machine used in DIC observation is Shimadzu AG-X Plus and the cross head speed for this loading is maintained at 1mm/min. ARAMIS sensor unit is operated on a stand in order to optimally position the sensor with respect to the specimen. For the measurement setup, two cameras are used (stereo setup) that are calibrated prior to measuring. The specific cracks contained observation area in this study is about 20mm x 18mm so that the software measuring volume that has been selected is 35mm x 29mm. The suitable lens size for this measuring volume is 75mm with resolution of 2448 x 2050 pixels (Titanar

75mm, sensor used is ARAMIS 5M) while for calibration of the cameras, CQ1CP20 30X24 calibration panel is used. To facilitate the correlation, a stochastic pattern is applied to the specimen surface in order to provide a random grey-level a variation at the sufficient quality of which is fundamental to the precision of the measured displacement data. The stochastic pattern in this study was created by black and white color sprays where black spray was first applied as the fundamental while white sprays was carefully applied above the black surface. After creating the measuring project in the software, images are recorded in various load stages of the specimen where the frame frequency is 0.5Hz. When the area to be evaluated is defined and a start point is determined, the measuring project is computed. During computation, ARAMIS observes the deformation of the specimen through the images by means of various square or rectangular image details, called facets (In this study the facet size is 18 x 18 pixels which gives 0.45mm x 0.45mm). A homogenous field of displacements is assumed inside each facet. The value of strain was calculated by differentiate the distribution of displacement. Hence, it is difficult to obtain a smooth strain distribution. So, in order to reduce the effect of the displacement measurement error, the displacement distribution was functionally approximated by a least squares method in ARAMIS, and then the strain was calculated by differentiating the function. The gage length is 0.4mm where in order to ensure the required accuracy of the measurement of displacements on a body surface, the individual facets are overlap by 2 pixels.

3 RESULTS AND DISCUSSION

A part of the laminate with three existed adjacent transverse cracks (Fig. 4(a)) is selected and the DIC strain distribution result for the selected area is shown in Figure 4(b). Figure 4(c) shows the plotted average strain distribution towards the specimen length. The direction y in the figure indicates the loading direction, x is width (straight transverse cracks) direction while z is the thickness direction of the specimen.

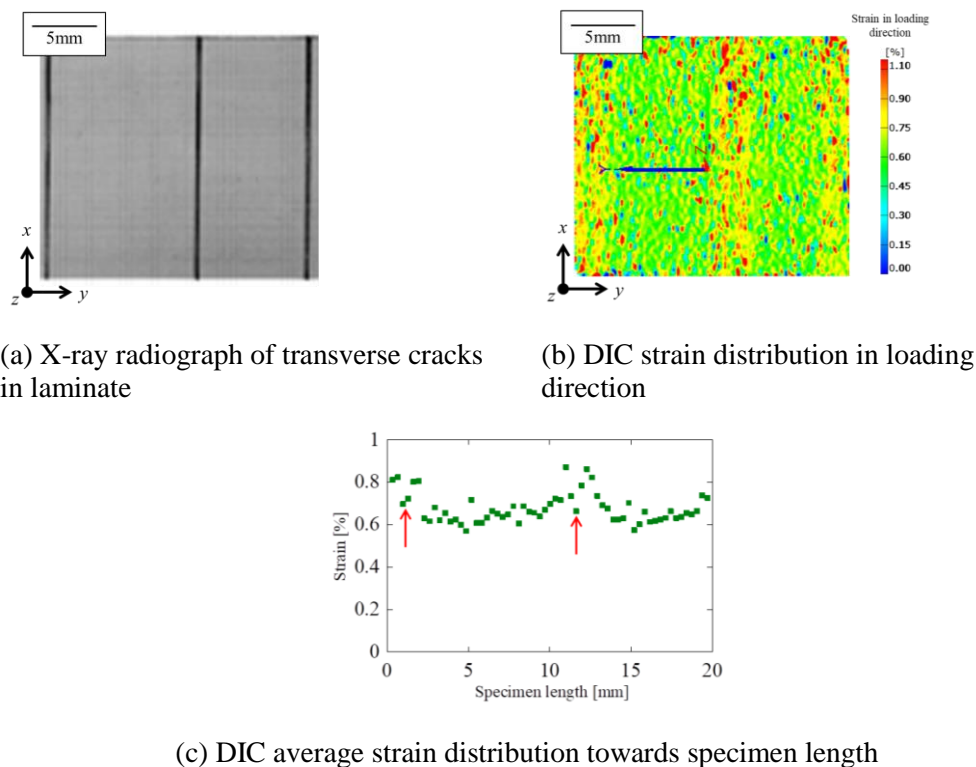


Figure 4: Crack observation from surface direction of $[0/90_6]_s$ laminate by (a) X-ray radiography (b) DIC.

In order to investigate the phenomenon occurred in previous section, we tried to make a DIC strain observation from the thickness direction of the laminates. Unfortunately, due to the limitation of our DIC system to detect a very small measuring area which is the edge surface area of the $[0/90_6]_s$ laminate (with thickness of 2mm), we did only DIC strain observation from the thickness direction of thicker $[0_4/90_{24}]_s$ laminate with the edge thickness of about 8mm. Figure 5 shows the DIC observation from the thickness direction of $[0_4/90_{24}]_s$ laminate where (a) is the displacement distribution and (b) is the strain distribution. This figure shows that the cracks formed in 90 degree ply of the laminate are not only straight transverse cracks but also some other cracks called secondary damage mode's matrix cracks. This may be the reason why the strain value dropped at the center of the cracks area of DIC strain distribution as shown in Figure 4(b, c). In this figure we can see three distinctly different types of matrix cracks which are straight transverse cracks, oblique (partial angled) cracks and curved cracks. Curved crack is a matrix crack that initially forms as partial angled crack extending from the ply interface oriented at an angle less than 90 degree while oblique crack is a crack that forms incompletely through the off-axis ply near a straight crack. These cracks can be observed near a straight crack and grow toward the straight crack. There are also occurrences of two curved or oblique cracks located on one side of a straight crack. A similar observation is reported by Groves [7].

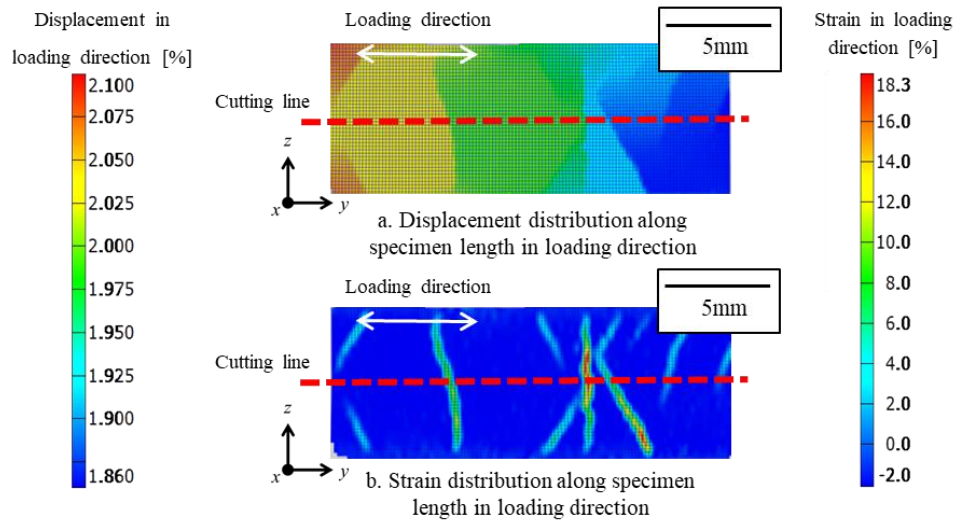


Figure 5: DIC observation from the thickness direction of $[0_4/90_{24}]_s$ laminate.

In order to explain the occurrence of the cracks in this secondary damage mode, we observed the DIC shear strain distribution from the thickness direction of the $[0_4/90_{24}]_s$ laminate. Figure 6 shows the DIC strain in loading direction and shear strain distribution observation at earlier stages where oblique and curved cracks have not yet occurred in this laminate. As shown in (b), shear strain in the red circles marked as ' k ' at the upper left and the lower right area near the straight crack is larger than the shear strain of other non-cracked area on the laminate. On the other hand, at the upper right and lower left area around the cracks highlighted with red circles marked as ' j ' showing a larger negative shear strain where this is a normal phenomenon where the shear strain value can be positive or negative value due to the symmetrical properties of matrix cracks in laminates. This can be observed clearly also in (c) where shear strain in straight lines along the specimen length labelled as 1-6 in w area in (b) is plotted against the specimen length. The area highlighted in yellow in this graph is the average shear strain value based on the shear strain at each point. From this relationship, we can observe the points where shear strain are highest and with the possibility of the initiation of the oblique cracks. This is then confirmed by comparing this figure to Figure 5(b), where the location of oblique cracks is exactly

at the points with the highest shear strain. The larger distribution of shear strain in this area shows that this area has high accumulation of maximum principle stress. This may be the reason that caused the initiation of the oblique cracks seen in Figure 5(b). While for curved cracks, we can conclude that when two oblique cracks propagated from opposite side of each other, they meet and combine to become a curved shape near to the existed straight crack.

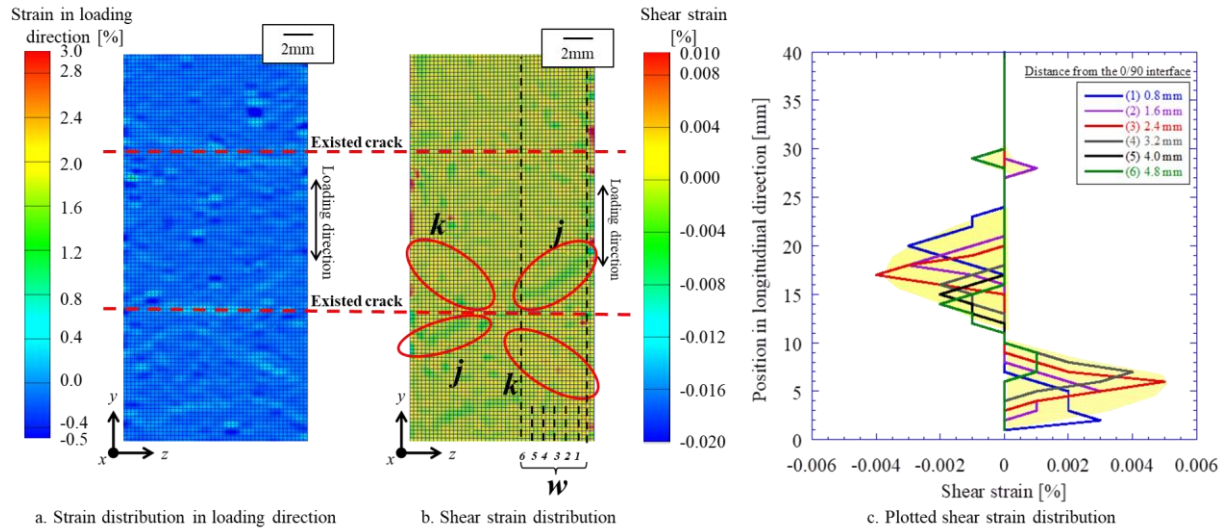


Figure 6: Strain distributions around the existed cracks before the formation of secondary damage mode of matrix cracking from the thickness direction of the specimen.

FE analyses of oblique cracking by Jalalvand et al. [1] providing supporting evidence for the postulated growth mechanism such like in the result of this study. They examined the stress distribution around the straight transverse crack. From the result of the distribution of maximum principal stress in the 90 degree ply, they reported that principal stress is higher at the areas around the interface near to the existed straight cracks. This suggests that if a crack initiates from the area with high values of maximum principal stress, the crack would propagate in an oblique manner towards the closer transverse crack. The DIC observation of oblique cracks in this study is in a good agreement with the result in this analysis

4 CONCLUSIONS

The deformation measurement around damages in CFRP cross-ply laminates is experimentally investigated by using DIC in this study. The crack can be clearly indicated by the DIC strain distribution where the strain values are higher at the cracks area compared to area with no cracks. We found a phenomenon where the strain values at the center of the crack area dropped for each crack. The occurrence of matrix cracking in secondary damage mode such as oblique and curved cracks is a possible reason for this phenomenon. Usually, the straight crack is formed first followed by oblique cracks and curved cracks that occur close to existing straight cracks. The orientation and location of the oblique and curved cracks corresponded to the orientation of the principal stresses in the vicinity of a straight crack and this is proved by the DIC deformation observation and previous analysis study. These types of matrix cracks may also contribute to degradation of laminate's mechanical properties such as stiffness reduction and etc. From this study we can conclude that DIC method can be applied for the deformation measurement of any material from any direction including the shear direction and etc. This method will be used efficiently in our future works in order to study about the damages especially in composite materials.

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