The Novel Digital Image Correlation Technique in Predicting Behaviour and Failure of Hybrid Composite

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***Abstract*—This paper presents a technique in measuring deformation occurs on in-plane hybrid composite CFRP/GFRP. The challenging task of extracting mechanical properties of the hybrid composite is assisted with the use of Digital Image Correlation (DIC) technique. DIC is an innovative technique which able to capture full field deformation of tensile deformation. The complex deformation captured for hybrid composite in-plane tensile deformation and behavior using Digital Image Correlation (DIC) under static loading is a new area of study in literature. Generally, hybrid composite consists of more than one reinforcing sections or multiple reinforcing or multiple matrix sections or single reinforcing phase with multiple matrix phases. As a result of a compromise between the materials within the hybrid composite, the deformation and stress analysis are to be evaluated and tailored as each constituent of material carry their own desired mechanical properties according to a performance requirement. It is found in relation of stress-strain relationship of hybrid composite under tensile loading via DIC, the modulus of elasticity is found to record value around 92-97GPa which in theoretical benchmark located in between value of Modulus of Elasticity, E_1 for CFRP(120GPa) and GFRP(42GPa) which proves the occurrence of the hybrid effect. It is a new research area in utilizing digital image correlation (DIC) technique on hybrid composite rather than conventional composite in material characterization**

***Index Terms*—Digital Image Correlation; Hybrid Composite; Ncorr; Non-Contact Strain.**

I. INTRODUCTION

The major challenge for the composite engineer is to develop new stronger, tough and lightweight materials for supporting the latest design concept for complex shape structural. Composite are attractive material because of their properties such as high strength and stiffness leads to the application in the areas such as marine, aerospace and automotive. A composite material also can be defined as a combination of a matrix and reinforcement [1]. The tensile test is one of the mechanical testings that evaluating fundamental properties of engineering materials as well as in developing new materials and in controlling the quality of materials for use in design and construction. The main parameter that can be obtained during the tensile test is Ultimate Tensile Strength (UTS), Yield Strength (σ_y), Elastic Modulus (E), Poisson Ratio (ν), and percent elongation percent elongation (ΔL) [2]. The standard method for tensile testing of polymer matrix composites was described by ASTM D3039. Generally, hybrid composite consists of more than one reinforcing sections or multiple reinforcing or multiple matrix sections or single reinforcing phase with multiple matrix phases. As a result of a compromise between the materials within the hybrid composite, the deformation and stress analysis are to be evaluated and tailored as each constituent of material carry their own desired mechanical properties according to performance requirement [3]. The high-speed digital camera is used to capture a consecutive image during deformation and change the surface characteristics while load increase. This technique starts with the reference image as a static image and followed by a series of images at a different increment of the load which comprised of a series of deformed specimen images.

II. DIGITAL IMAGE CORRELATION TECHNIQUE

Digital Image Correlation is a non-contact, optical method which captures digital images of a surface of an object then performs the image analysis to obtain full-field deformation and measurements. This can be achieved by creating different methods like dots, grids, lines, etc, on the specimen surface [4]. This technique starts with a reference image (before loading) followed by a series of pictures taken during the deformation. Deformed images show a different dot pattern relative to the initial nondeformed reference image. These patterns difference can be calculated by performing a correlation of the pixels of the reference image and any deformed image, and a full-field displacement measurement can be computed. The strain distribution can then be obtained by applying the derivatives in the displacement field [5]. To apply this method, the object under study needs to be prepared with random dot pattern speckle pattern to its surface.

For surface deformation computation utilizing 2D Digital Image Correlation (DIC) technique, emphasized should be given on positioning of the specimen under testing, light intensity, and sources as well as the camera lens and its capability/resolution/frame rate of the camera. Accurate measurement relies heavily on imaging system configuration.

In principle, a sample with random speckle pattern sprayed on the surface must be positioned perpendicular to the camera to avoid any out of plane motion. After the entire load applied events, a series of images are taken before and after loading and deformation and finally stored in the computer for post-processing images to obtain displacement contour/field using DIC algorithm. Basically from technical perspectives, for 2D DIC, image resolution plays a vital role in measurement accuracy [6]. Figure 1 shows the fundamental principle of digital image correlation.

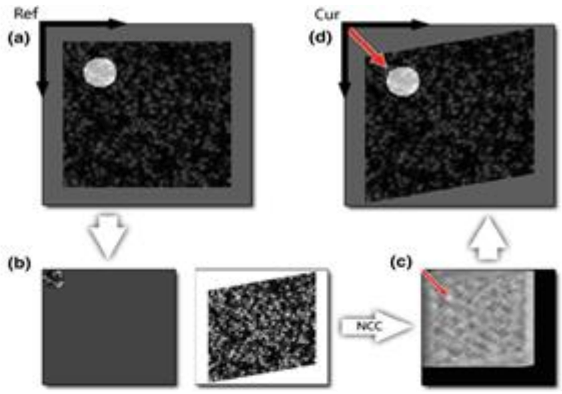

Figure 1: Illustration shows the sequence of searching initial guess and correlation. A reference subset (a) expanded to full size (b) superimposed with the current image to search for correlation (c). The position of the subset is recovered in the current configuration

III. METHODOLOGY

High-speed camera used for DIC for this research contains the sensor recording speeds of up to 200,000fps and 800 x 600 resolutions at 1000fps, Camera Display Unit (CDU) built in measurement, and storage and editing capability. Olympus I-Speed 2 camera is used to capture images for tensile and bending test. The features contain the sensor recording speeds of up to 200,000fps and 800 x 600 resolutions at 1000fps, Camera Display Unit (CDU) built in measurement, and storage and editing capability. Olympus I-Speed 2 camera is used to capture images for tensile and bending test. DIC system use optic method through stereoscopic sensor arrangement to analyze the deformation of object and emphasis on each point subset based on the grey value of the digital image to define the strain [7]. The camera is positioned perpendicular to the specimen under testing [Figure 2]. In order for the digital image correlation algorithm able to perform the correlation analysis, the speckle pattern must be sprayed onto the surface of the coupon [Figure 3]. The pattern must be contrast enough and small enough to capture the deformation. The technical specification of the high-speed camera is as follow:

- Frequency 60 – 200,000 fps; Shutter minimum of 1 micro second
- Nikkor 18-55mm lense, an open source software for DIC which is a Ncorr platform, with an installed Matlab version of 2012 and Microsoft Visual C++ as a compiler.

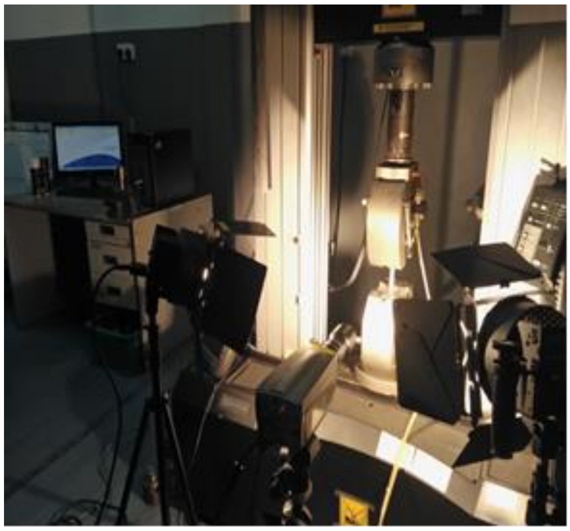

Figure 2: Setting up of DIC on the tensile test specimen

A. Sample Preparation

The prepreg is layup as per desired design requirement (sequence of layup and finer orientation). The metal plate is cleaned using wax to remove any dirt. The pressure is set to 6 bar which includes 5 bar set in the machine hot press and 1bar from the vacuum bag. Temperature is set to 120°C and let the temperature to be stable. Composite layups (prepreg layup) inside the vacuum bag is placed between the metal plates and the proses of the hot press as per intended pressure will take place. The dimension of the specimen has to follow the standard used, which is ASTM D3039. Figure 2 depicts the speckle pattern sprayed onto the tensile test coupon of the hybrid composite as well as it layup arrangement which comprises of CFRP and GFRP layers.

Figure 3: Hybrid Composite CFRP/GFRP

B. Formatting Displacements

The Ncorr platform requires the user to input and define its displacement format which includes the measurement calibration and scale. These options were used to convert the displacements from pixels to real units. Figure 4 depicting the calibration of pixel/dimension in Ncorr platform.

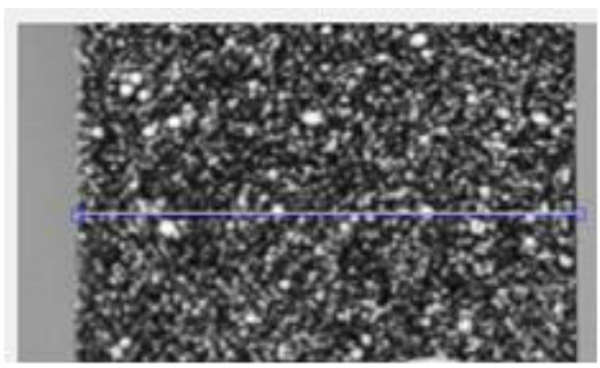

Figure 4: Formatting the measurement/scale in *Ncorr*

C. *Calculation of Strains*

The selection of the ideal strain radius is similar to the selection of the ideal subset radius, in that the smallest radius was desired which does not result in noisy strain data. The radius normally set to 13 because of the optimal radius as shown in Figure 5.

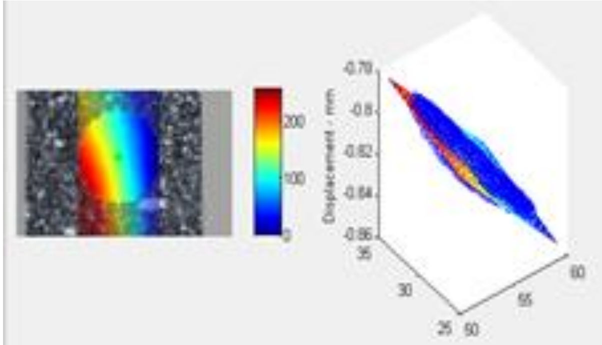

Figure 5: Selection of strain radius in Ncorr platform

D. *Plotting*

Lastly, it was assumed either the displacement has been formatted or the strain has been calculated. This was the last step of the analysis. The value of the strain shows in the direction of Ɛxx, Ɛxy, and Ɛyy as in Figure 6, Figure 7 and Figure 8 respectively. The strain contour depicted in Ncorr platform is very essential as it provides full-field 2D measurement on the surface of the specimen under study.

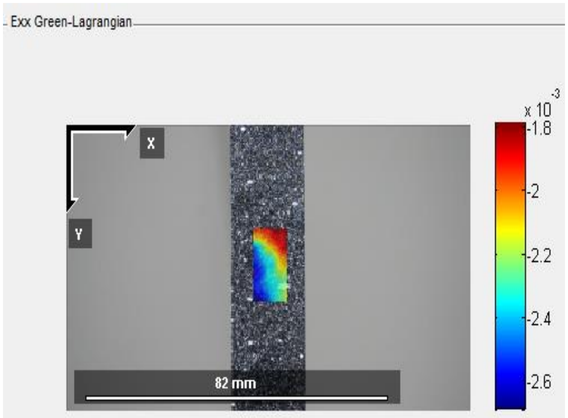

Figure 6: Strain ε_{xx} data plot in *Ncorr*

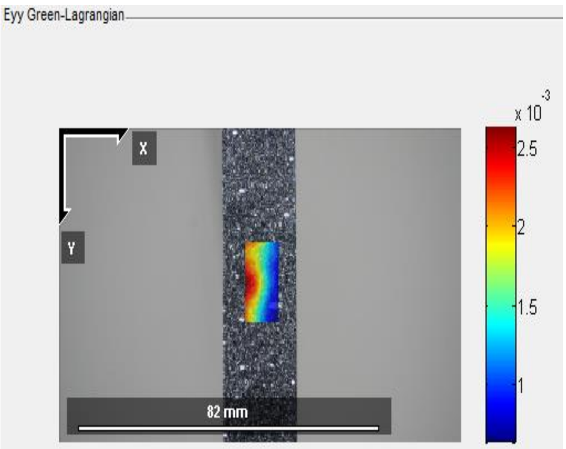

Figure 7: Strain εyy data plot in *Ncorr*

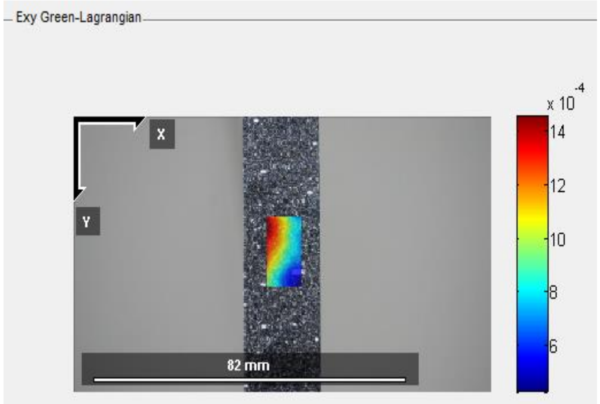

Figure 8: Strain εxy data plot in *Ncorr*

IV. Mechanics Of Composite

The stress-strain relationship is an essential principle for mechanics of composite study. Material under study, Hybrid Composite (CFRP/GFRP) is a combination of unidirectional composites which possess orthotropic material properties which have different elasticity deformation behavior at longitudinal and transversal direction with respect to fiber orientation. For an orthotropic system, the stress-strain relationship is given as follows:

$$\sigma_1 = E_1\varepsilon_1 \text{ and } \sigma_2 = E_2\varepsilon_1 \quad (1)$$

where E_1 and E_2 are the two elastic constants. Poisson's ratio is defined as the strain perpendicular to a given load direction to the strain parallel to a given load direction (Nettles, 1994). It is fundamental to understand the stress-strain relation which then corresponds to the behavior of hybrid composite under tensile loading which is shown in deformation form via Ncorr platform.

V. Results

A. *Output from Ncorr Post-processing*

The output from Ncorr platform is obtained in the form of quantification of contour displacement in X and Y direction (global axis) which represented in the notation of U and V as in *Ncorr* platform. The other essential readings and findings are a strain in xx, strain in yy (loading direction/tensile direction) and in-plane shear strain, xy direction. Figure 9 depicts the displacement in Y for hybrid composite at 2000N, and Figure 10 correspond to load at 7KN.

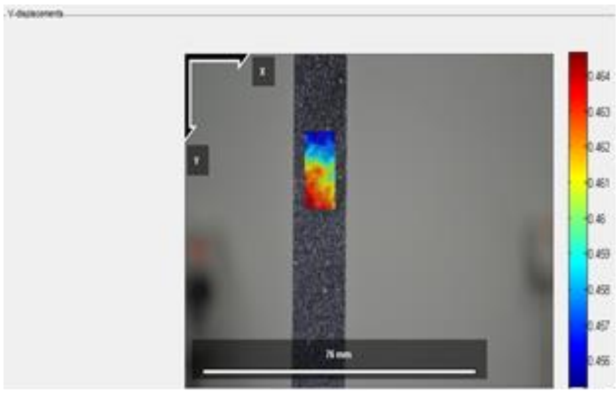

Figure 9: Displacement in Y where maximum recorded 0.4654mm at 2000N for hybrid composite

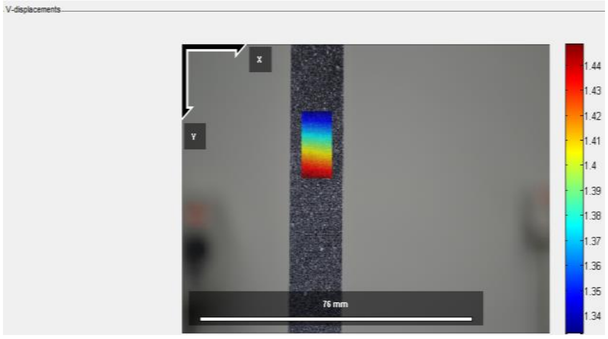

Figure 10: Displacement in Y where maximum recorded 1.4525mm at 7000N.

Figure 11 shows the strain in yy direction (tensile loading direction) for hybrid composite corresponds to 4000N while Figure 12 depicts the increment of strain yy at 7000N.

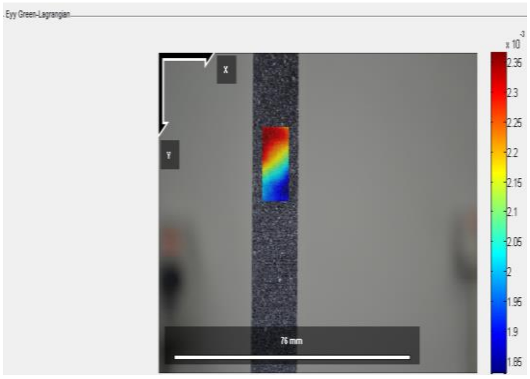

Figure 11**:** Strain contour for Ɛyy which average at 0.0018 for 4000N

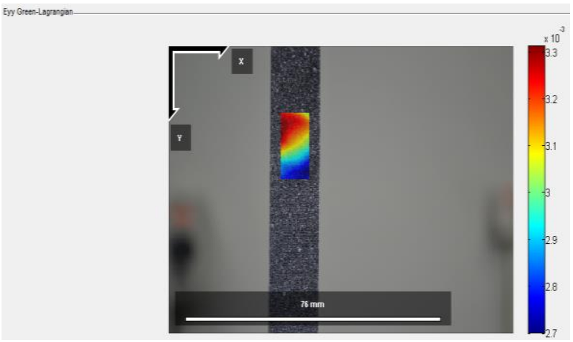

Figure 12: Contour of strain, Ɛyy which average at 0.003 correspond to7000N

Figure 13 shows the contour plot of strain in transverse direction corresponds to 7000N. Contraction expected to occur for tensile loading coupon, which shows the poisson effect for the CFRP and GFRP layers forming the hybrid laminate.

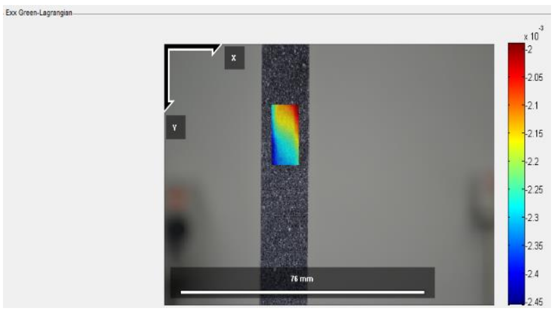

Figure 13: Contour of strain, Ɛxx average at -0.0019 for loading of 7000N

Figure 14 shows the in-plane shear strain xy, full field contour at 3500N where it accounts mostly near zero proximity due to the fact that it is unidirectional 0 degree with respect to tensile loading for both CFRP and GFRP respectively. Meanwhile, for Figure 15, which represents higher tensile loading acting on the specimen, the in-plane shear is higher in terms of value, 0.0011 which in hypothesis might due to the poisson effect, compatibility phenomena between plies of CFRP/GFRP that has a different modulus of elasticity [8].

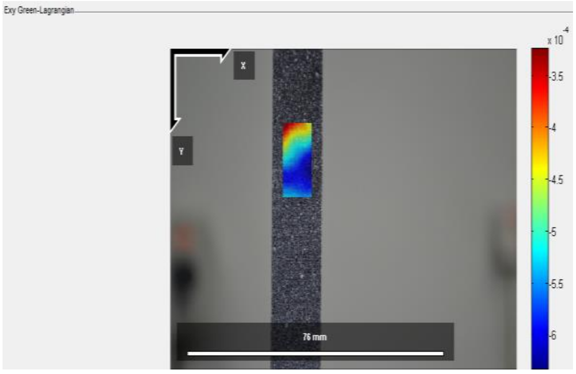

Figure 14: Contour plot of in-plane shear strain, ε_{xy} maximum recorded at 0.0006 corresponding to 3500N.

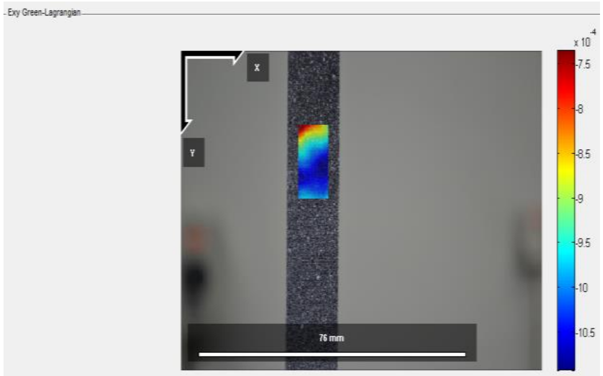

Figure 15: Contour plot of in-plane shear strain, ε_{xy} maximum recorded at 0.0011 corresponding to 6500N loading.

Figure 16 depicts the fiber breakage/bridging phenomenon of hybrid composite occurs at the failure load captured from a high-speed camera. The use of high-speed camera enable the prediction of failure and pre-failure detection of composite material from the physical image captured by the high-speed camera and deterioration/deviation in strain measurement computed in *Ncorr* post-processing platform

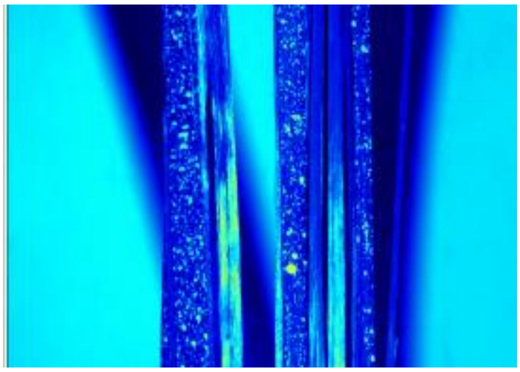

Figure 16: Fiber bridging leading to total failure of hybrid composite

VI. DISCUSSION

Approximation of Modulus of Elasticity in yy direction for hybrid composite is calculated using equation (1), where the strain of yy is obtained from DIC method described before. Stress in yy direction which acted on the principal direction of the hybrid composite is computed with the relation, of force divided by cross section area of hybrid composite tensile coupon under loading.

$$E_1 = \frac{\sigma_1}{\varepsilon_1} \tag{2}$$

where

$$\sigma_1 = \frac{P}{A}$$

Cross-Sectional Area, A = (1.525mm/thickness X 15mm/widthn= 22.875mm^2

Taking Figure 11 and Figure 12 for inputting the strain yy into Equation (1) with corresponding stress yy, it yields the results of:

97146.32MPa
and
92730.58MPa

from the contour plot of strain yy and inputting back into Eq 1. The modulus of elasticity in the longitudinal direction, E_1 for CFRP is around 120GPa and modulus of elasticity for GFRP unidirectional 0 degree in accordance to ASTM D3039 is in the range of 40 to 45GPa. Hence the value obtained from DIC for hybrid composite is expected to locate within the proximity range in between CFRP and GFRP. The figure approaches 100GPa is explained by the fact that CFRP layers (3 layers as per layup) play a dominant factor in the stress-strain behavior of hybrid composite. The manufacturer data sheet of CFRP and GFRP is referred for validation of the value obtained from DIC [9].

VII. CONCLUSION

The hybrid effect is obtained with the calculation from the modulus of elasticity for hybrid CFRP/GFRP resulted in 94.5GPa (average). This is in between the value of CFRP and GFRP alone which accounts for 120GPa and 42GPa respectively. Digital Image Correlation (DIC) non-contact full field deformation measurement tool for uniaxial tension testing. The prime important to design the hybrid composite is a selection of the type of compatible fibers and also the level of their properties. The result shows that the value of Young Modulus (E) from DIC output of strain yy, for the hybrid composite is lies between the values for the single composite. It shows that the hybrid composite has a more favorable balance between the inherent advantages and disadvantages of the single composite. Digital Image Correlation (DIC) is an innovative method for measuring the deformation and value of strain. DIC is also low-cost non-contact strain measurement technique challenging the conventional method such as strain gauge, extensometer, etc.

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