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High speed imaging for assessment of impact damage in natural fibre biocomposites

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ABSTRACT

The use of Digital Image Correlation has been generally limited to the estimation of mechanical properties and fracture behaviour at low to moderate strain rates. High speed cameras dedicated to ballistic testing are often used to measure the initial and residual velocities of the projectile but rarely for damage assessment. The evaluation of impact damage is frequently achieved post-impact using visual inspection, ultrasonic C-scan or other NDI methods. Ultra-high speed cameras and developments in image processing have made possible the measurement of surface deformations and stresses in real time during dynamic cracking. In this paper, a method is presented to correlate the force- displacement data from the sensors to the slow motion tracking of the transient failure cracks using real-time high speed imaging. Natural fibre reinforced composites made of flax fibres and polypropylene matrix was chosen for the study. The creation of macro-cracks during the impact results in the loss of stiffness and a corresponding drop in the force history. However, optical instrumentation shows that the initiation of damage is not always evident and so the assessment of damage requires the use of a local approach. Digital Image Correlation is used to study the strain history of the composite and to identify the initiation and progression of damage. The effect of fly-speckled texture on strain measurement by image correlation is also studied. The developed method can be used for the evaluation of impact damage for different composite materials.

1. INTRODUCTION

The development of ultra-high speed cameras, enhancement in imaging technologies, and powerful and affordable PCs for image processing have made non-contact measurement techniques such as Digital Image Correlation (DIC) more appealing in the field of experimental mechanics. The DIC method is optical metrology based on digital image processing and numerical computing and has been widely used as a powerful and flexible tool for the surface deformation measurement. Typically, full-field measurements of displacement or strain obtained from image analysis have been used for the identification of constitutive parameters from mechanical tests such as tensile tests. The full field measurement allows overcoming some limitations of standard test methods, such as the assumption of homogeneous strain and stress fields in the zone of interest and the use of measured global quantities to infer the values of constitutive parameters with the help of simple exact solutions [1]. For example, Moreira et al. [2] calculated the Young's moduli of polymeric nanocomposites using a combination of Digital Image Correlation and inverse analysis performed by means of the minimization of an error function comprising the difference between displacement fields obtained from the experiment and those calculated theoretically. Nunes and Reis [3] also applied DIC to study crack-tip-opening displacements and crack extension in polymer mortars reinforced with chopped glass fibres. DIC methods were limited to mostly quasi-static and low strain rate applications as the measurement of surface deformations and stresses in real time during a transient failure event, such as dynamic crack initiation and growth, is challenging due to a combination of spatial and temporal resolution demands [4]. However, recent developments have facilitated the use of high speed DIC for dynamic event testing [4-10].

Tiwari et al. [5] used a 2D-DIC method to make full field measurements during high speed impact conducted using the split Hopkinson Pressure Bar (SHPB) setup. High speed DIC has been used for many experiments including for fracture, and impact testing [6]. High speed imaging (HSI) is nowadays commonly used even on production site thanks to rugged high speed sensors. In the industrial sector, high-speed camera experiments were conducted on Printed Circuit Boards to fine-tune drop impact simulations [7]. However, Liu et al. [8] reported that synchronization difficulties and poor image resolution from high-speed camera limited the use of high speed imaging under impact loading rates. For example, in ballistic testing high speed cameras were used to measure the initial and residual velocities of the projectile but not for damage assessment [9]. The assessment of impact damage is typically done after the impact using visual inspection, ultrasonic C-scan or other NDI methods. The evolution of damage is identified from the force-displacement curve obtained from the impact experiment. The creation of cracks results in the loss of stiffness and a corresponding drop in the force history. However, the force-displacement data is not correlated to the actual creation and propagation of damage due to difficulties of setting up high speed camera equipment to observe the bottom surface of the impacted plate. For this application, the HSI integration is really specific and enables the user to better depict the successive events occurring upon the crack propagation. Furthermore, post mortem inspection of the cracked plate does not always show if the impactor was completely piercing the plate under study.

In this paper, a method is presented to correlate the force- displacement data from the sensors to the slow motion tracking of the cracks propagation during an impact event on natural fibre reinforced composites. Natural fibres are considered a potential replacement to traditional composite reinforcements such as E-glass due to their low density, high specific properties, relative abundance, low cost of raw material, and positive environmental profile. Bensadoun et al. [10] reported that the use of natural fibres for high performance applications has been limited in part by a lack of data for loading conditions such as fatigue and impact. Impact loading can occur during the service life due to dropped tools, or collisions with loading and unloading fixtures and the resultant damage, such as delaminations and back-face splitting, can severely reduce the mechanical properties. Comprehensive study on the impact behaviour of natural fibre reinforced composites is therefore critical for their implementation in structural applications.

2. MATERIAL AND METHODS

The low velocity impact tests were conducted using a CEAST instrumented drop tower. Flax composites with thermoset and thermoplastic matrix were chosen for the study. Woven flax / polypropylene (PP) commingled fabric was supplied by Composites Evolution as Biotex Flax/PP. The thermoplastic composites were fabricated using a compression moulding method at a temperature of 210 °C and pressure of 50 bars for duration of 10 minutes. The drop tower setup shown in Figure 1 consists of an instrumented impactor that is secured to a carriage that falls along guideposts and collides with the plate. The weight of the impactor was 3.1 kg with a hemispherical impactor of diameter 20 mm. A Phantom V2512 high speed camera, coupled with long distance macro-zoom lens, was used for slow motion observation of the bottom surface of the composite plate during the impact event. A mirror setup placed at 45° below the composite plate allowed the camera to safely capture the impact event without fear of damage and also to shine about 15000 lumens from superLEDs cold light device. The images were acquired at a frame rate of 39000 fps and exposure time of 25 µs with a resolution of 786 x 786 pixels. The scale factor or magnification (M), which depends on the focal lens and the distance between the camera and object, was fixed to 69 µm per pixel. Photoelectronic switches used to measure the initial velocity and rebound velocity of the impactor also acted as the trigger for the image acquisition in rolling buffer FIFO memory mode. The drop height varied from 0.1 m to 0.3, 0.35, 0.4, and 0.5 m to give a range of kinetic energies of 3 J to 15 J. The impact tests were conducted at energies until there is complete perforation of the plate, in order to assess the absorbed energy behaviour of flax composites. Three specimens were tested at each condition to ensure the repeatability of the experiment.



Figure 1 Drop tower setup for impact testing of composite plates

The woven form of the composite plate with the yarns in 0 and 90 degrees creates a noisy signal for image analysis. Therefore, the bottom surface of the composite plate was painted with a thin layer of white powder (Figure 2a) to create a high contrast zone for the purpose of skeletonisation of the images during the cracking of the plate. We assumed that the added powder strength has a negligible effect on the impact response of the composite plate. A sputtered layer of black paint was coated on the bottom surface of one set of the flax composite plates over the first layer of white paint to give it an artificial granular fly-speckled pattern as shown in the Figure 2b. This texture creates an image signature and a subset of pixels must be statistically representative of the light intensity distribution of a material point located at the centre of the subset. This correlation is extended to the entirety of the selected region of interest (ROI) and the calculations return the kinematics of each digital pattern in the pre-defined virtual mesh.

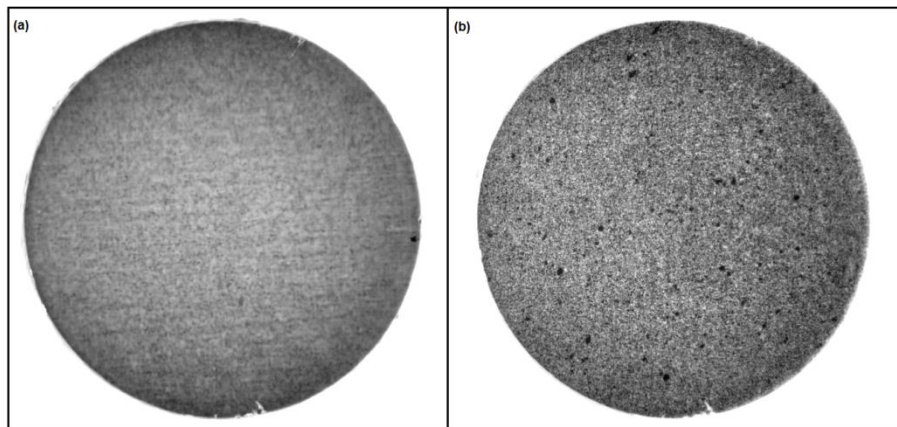


Figure 2 Surface of the flax composite plate with (a) white powder and (b) speckled pattern

3. RESULTS AND DISCUSSION

3.1 Crack tracking

Figure 3 shows the high speed camera images for a 6J impact. The initiation and propagation of macro-cracks at different moments of the impact are observed. A macro was written in ImageJ software [11] to measure the length of cracks from each image. The crack tracking algorithm has several steps beginning with the conversion of a reference image to 8-bit and running Median and Gaussian Blur filters to the image. Then each image from the high speed camera was treated with similar filters and subtracted from the reference image to isolate the cracks. The binary image is dilated and eroded to highlight the fissure and then a skeletonisation algorithm is used to trace the crack length with 1-pixel wide lines.

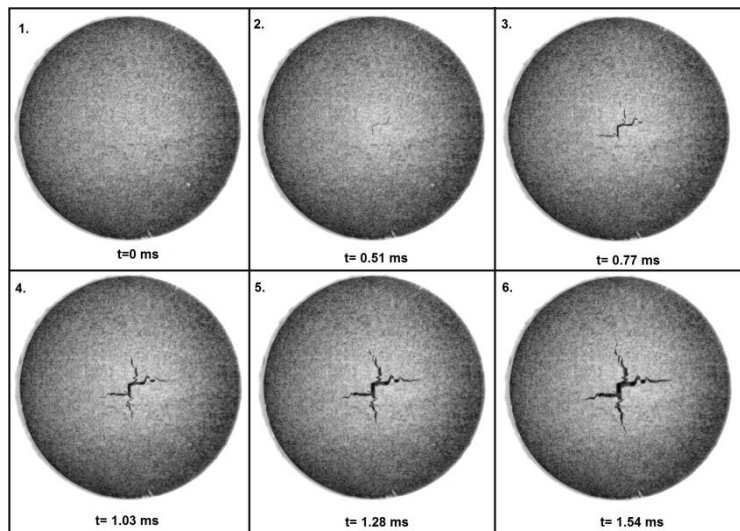


Figure 3 High speed images of initiation and progression of crack during 6J impact of Flax-PP composite

The total length of the cracks is measured at each time interval and the evolution of damage observed in the plate was correlated to the mechanical response of the composite plate. For clear colour composite, no preparation of the samples is required as dynamic range of the V2512 is really high. Figure 4 shows the evolution of crack length correlated to the force –time history obtained from the sensors. It can be observed that the force response has an initial linear region followed by yielding and finally an unloading phase after reaching the peak. The crack initiation occurs close to the stiffness change at critical force of 1100 N. The total crack length reaches a maximum at the end of the loading phase.

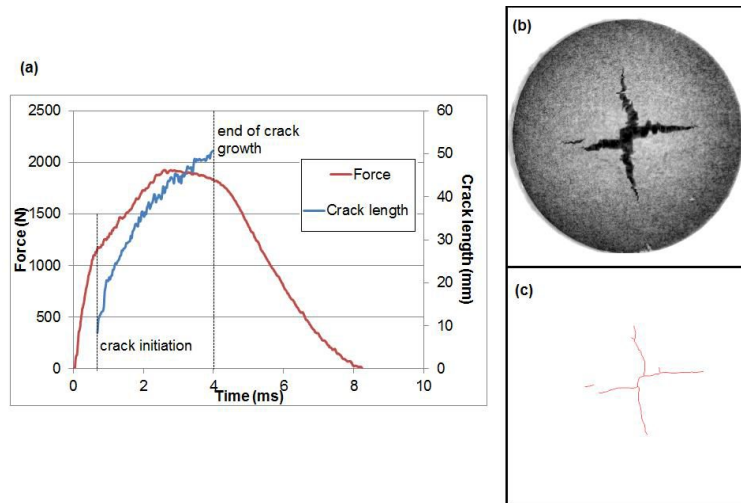


Figure 4 (a) Force – displacement curves for 6 J impact on Flax-PP composite; (b) Real time high speed image of the plate at maximum displacement; (c) Skeletonised image of the crack

3.2 Digital Image Correlation with CinEMA

Digital image correlation is based on the principle of comparing small zones (or subsets) of the digital images of the specimen surface coated with a random pattern. The image correlation is performed by comparing subsets from the reference or undeformed sample and subsequent deformed states to directly provide full-field displacements and strains. In the 2-D DIC, the in-plane displacement fields designated by $u(x, y)$ and $v(x, y)$ correspond to the displacement that minimizes a similarity criterion between reference and deformed subsets. The image processing after the test is based on a three-step DIC approach developed in-house called CinEMA. The definition of the parameters used for the DIC and the details of the algorithm is explained in greater detail in [12-13]. A square region of interest (ROI) as shown in Figure 5 was selected with its centre on the middle of the composite plate and including the expected region of crack propagation. The ROI is divided into grid like structure by defining the number of rows and columns. The distance between mesh points is defined by a grid step parameter ($G_s = 8$ pixels). Each point of the virtual mesh corresponds to the centre of a subset which has its own unique pattern. This pattern, defined by its correlation size ($C_s = 20$ pixels) in the horizontal and vertical directions, is the representative area of the material point that is tracked in part of the ROI. The number of points to consider in the horizontal and vertical directions are defined by the number of step parameters ($N_s = 10$ pixels in x and y direction).

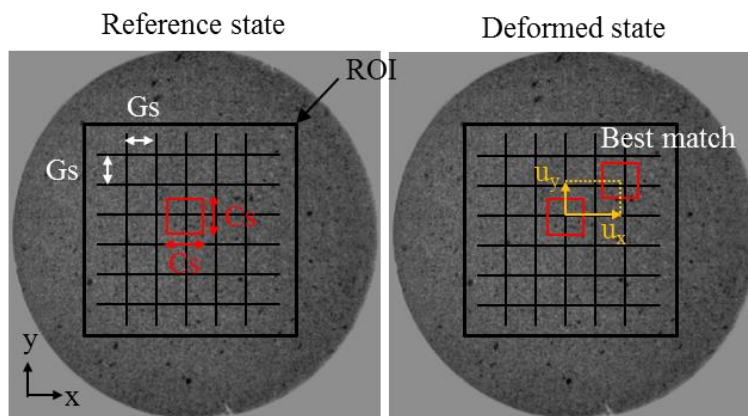


Figure 5 Principle of image correlation with reference and deformed image

These correlation parameters were chosen to establish a reliable mechanical response of the material in the central zone near the point of impact. During the impact measurement, cracks and splitting initiated in the middle of the specimen and propagated radially in the fibre yarns directions, i.e. 0° and 90° . In the first step, the rigid body displacement is calculated by a 2D cross correlation of the selected subimages. In the second step, the DIC processing leads to an incremental displacement file. In-plane displacement fields $u(x,y) = (u_x(x,y), u_y(x,y))$ of a point $M(x,y)$ were evaluated for each point of a virtual mesh in the ROI of the sample including the crack zone. The peak of the correlation function was detected at a subpixel accuracy by interpolation and this process is repeated for the entire image to get full-field in-plane displacements. In the third step, the calculation of the displacement gradient around a considered point allows the calculation of the in-plane Green Lagrange strain tensor E . Figure 6 shows the strains calculated for an impact of 6J. It can be seen that the strain values in the xx-direction and yy-direction closely follow one another, supporting the biaxial loading response of the composite plate.

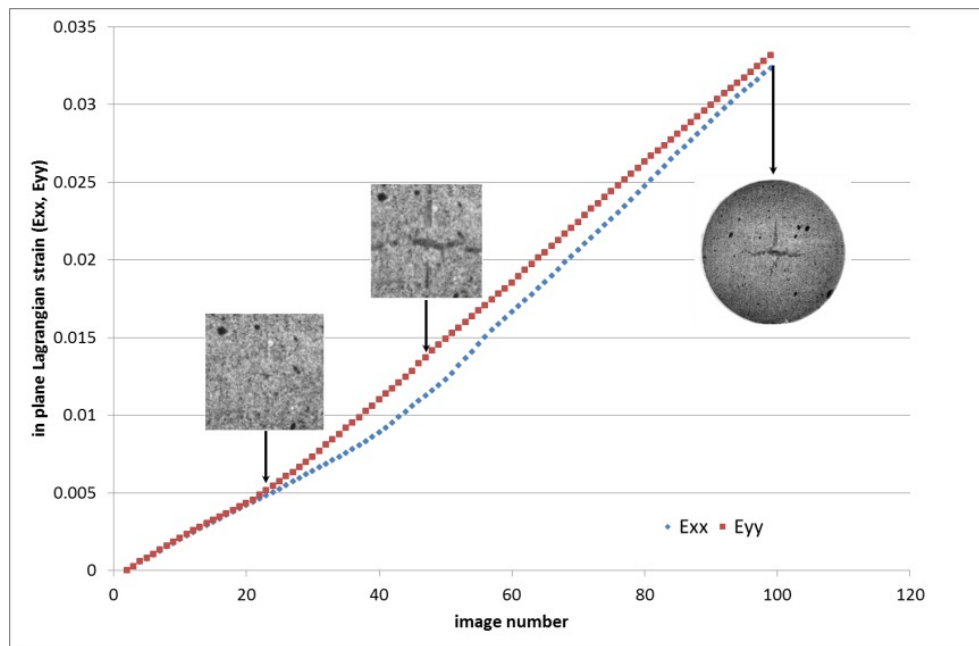


Figure 6 Lagrangian strains calculated by DIC method for 6J impact on flax-PP composite

The displacement contours and strain distributions obtained from the Digital Image Correlation for the flax - PP composites impacted at 6J are shown in Figure 7. The results of the plate corresponds to the 21st image from the beginning of the impact (corresponding to time of 0.54 ms). It can be seen that this image represents the beginning of the cracking and this initiation is clearly identified by the DIC program. The U_x and U_y displacement fields are qualitatively similar except that they are perpendicular to each other. The initiation of cracks appear to not be symmetric but with stable crack growth, the crack lengths are identical in the x and y directions.

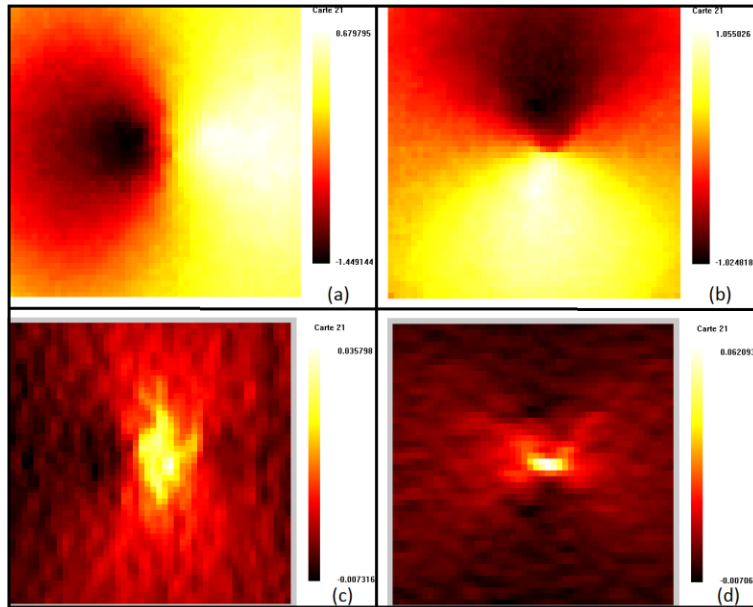


Figure 7 (a) and (b) Displacement contours in U_x and U_y direction; (c) and (d) Strain contours in the xx and yy directions

The results of the digital image correlation for composites painted with a fly-speckled pattern were compared to the results obtained for the white paint. Figure 8 shows the E_{yy} strain profile along the longitudinal axis (x direction). It can be observed that both methods were able to identify the region of high strain associated with the fracture surface close to the centre of the sample. However, the composite samples with white paint have a noisy signal compared to the surface painted with speckled pattern. This suggests that the random pattern generated with the black paint has a positive impact on the accuracy of the DIC results in the high strain region.

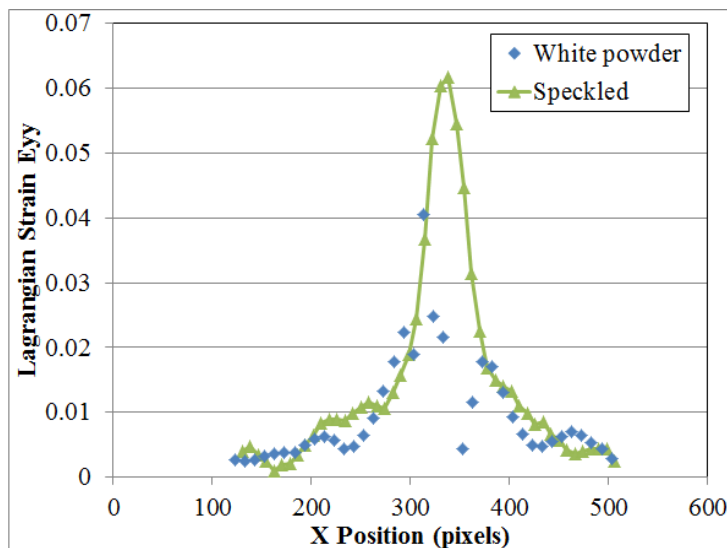


Figure 8 Comparison of DIC results for white paint and speckled pattern

This study presents a promising methodology for the tracking of crack lengths and for the use of Digital image correlation for studying the damage evolution in biocomposites. However, there are still some significant challenges

regarding the use of high-speed camera and DIC for impact damage assessment. One of the main problems is that the out-of-plane displacement of the specimen leads to a change in the image-to-object distance [14]. It is possible that the magnification of the images will change considerably due to the out-of-plane displacement, which will lead to errors in the calculation of in-plane displacements. Even though out-of-plane displacement during the impact can cause a strain error in the 2D DIC measurements, a 3D DIC based on the principle of binocular stereovision can help overcome this problem. Pankow et al. [15] have shown that large out-of-plane displacements can be captured by a 3-D DIC system. It is possible to adapt this stereo-correlation system for impact assessment in the future. Nevertheless, Reu and Miller [6] pointed out that despite its drawbacks, two-dimensional information is more than adequate in a number of applications.

4. CONCLUSION

The evolution of impact damage is usually identified from the force-displacement curve obtained from the experiment and from post-damage inspection methods. Optical instrumentation shows that the initiation of damage cannot be clearly identified simply by the force-displacement curve and the experimental data is not usually correlated to the actual creation and propagation of damage. So the assessment of damage requires the use of a local approach such as that presented in this paper. A method was proposed to use high-speed imaging for in-situ observation of the creation and propagation of transient damage in natural fibre composites. A macro was written in ImageJ software to measure the cracks lengths from images obtained from Phantom high-speed camera. The cumulative length of the crack was measured at each time interval and the evolution of damage observed in the plate was correlated to the mechanical response of the composite plate. The creation of cracks results in the change of stiffness in the force-history and a corresponding growth of cracks in the image analysis. In literature, the DIC technique has been successfully used to measure the mechanical properties in quasistatic strain rates but their use for high-speed image processing has been limited. In our study, we applied DIC technique on impacted samples coated with white paint and with speckled patterns. The displacement contours and strain distributions were calculated using in-house program CinEMA. From the strain contours it was possible to identify the initiation of the cracking. A comparison of the DIC results obtained for the plain white painted sample and the speckled sample shows that the random pattern generated with the black paint has a positive impact on the accuracy of the DIC results. The proposed method better depicts the successive events that lead to the breakage of composites and can be a valuable tool to study the impact behaviour of not only natural fibre-reinforced composites but other materials as well. Ultra-High Speed imaging for impact assessment in a three-dimensional mode would increase the accuracy of the strain analysis by taking into account the out-of-plane displacements, and it has been recommended for future study.

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