Critical imaging parameters in time resolved digital image correlation (TRDIC): effect of optical blur during drop test on composite structures

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Critical imaging parameters in time resolved digital image correlation (TRDIC): effect of optical blur during drop test on composite structures

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ABSTRACT

High speed imaging is applied for drop test on composite samples. The effect of optical blur on image correlation accuracy is described. Blur magnitude is tuned by decreasing the exposure time (at constant sensor sensitivity) for the same drop test series on flyspecked composite plates, while focus, aperture and 1:1 magnification are kept constant. Frame rate (80-20kfps) and lighting are changed while keeping the same image contrast. Results show correlation quality is already altered with subpixel blur. This study enables to define blur criterion in high-speed imaging and completes study about sampling rate effect in time resolved image correlation by high-speed imaging.

Keywords: high speed imaging, blur, exposure time, digital image correlation, drop test, composites

1. INTRODUCTION

Digital Image correlation is a common tool to retrieve mechanical displacements in solid mechanics or in fluid mechanics. DIC can now be applied at “low” acquisition speed with very high-resolution sensors e.g. 60fps (frame per second) with 110Mpixels sensors. Conversely, frame rates up to millions fps have been reached using in situ image storage, but with limited resolution (~1Mpixel) and low number of captured images (~200images).

In fracture mechanics, drop test can be performed in low or high velocity. But even at low velocity, on small structures (about 5cm^2), the surface displacements are quite fast (1-5m/s). Previous works have shown the application of high-speed imaging on low velocity drop test for composite structures[1].

Sample displacements can be measured from the drop test machine, fully equipped with strain gages and trigger sensors, showing absorbed energy from the impactor and also producing energy vs time curves, sometimes presenting unexpected rebounds. Post mortem observation can lead to some misunderstandings of the failure process. Therefore, high speed imaging was applied to track crack propagation and also to show the “real time” effect of the crack propagation throughout the test… after recording in the rolling memory buffer of the high-speed camera[2].

These tests have been done with raw samples, and some have been carried out by painting the samples with black and white flyspeck for image correlation purposes. It is then possible to obtain the displacement maps, and then the deformation maps to link it with the machine curves as boundary conditions and the accurate simulation of the drop test. These tests have been carried out in optimal optical conditions to achieve highly reliable photographic results e.g. high frame rate and short exposure time, coupled with high resolution optics for optimal magnification. These conditions provide appropriate sampling time regarding deformation rate; blur free images to apply accurate correlation algorithm; sharp and contrasted

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flyspeck pictures leading to optimal window correlation to reach deformation localization. Some of these features are already discussed in the correlation literature[3] or community[4].

As these recommendations have been followed to get "nice images", effects of degradation from these optimal conditions will be discussed in this paper. In particular, blur appears when exposure time is kept long regarding object surface displacement. Blur is proportional to magnification and exposure time[5–7]. In classical imaging blur free image is reached when blur is less than one pixel. But with image correlation algorithm, reaching displacement sensitivity up to 1/100th pixel, blur free limit could be different. Therefore, tests have been carried out at different exposure time up to disallowing image correlation. Desired blur is generated by decreasing the exposure time (at constant sensor sensitivity) for the same drop test series on flyspecked composite plates, while focus, aperture and 1:1 magnification are kept constant. Frame rate comprised between 80kfps and 20kfps and lighting are changed while keeping the same image contrast. This study enables to define blur criterion in high speed imaging and completes study about sampling rate effect in time resolved image correlation by high speed imaging.

2. METHODS

2.1 Experimental set-up

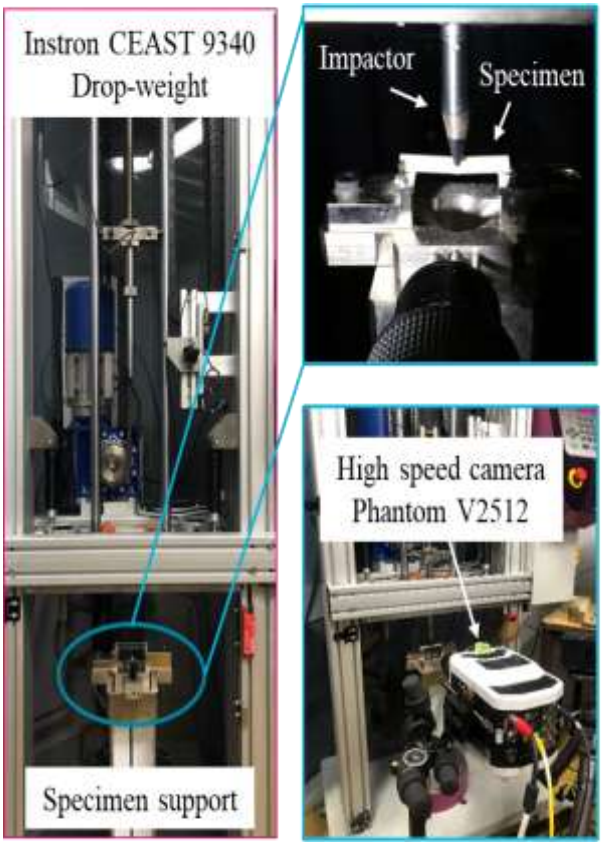


Figure 1 : Drop tower setup for Charpy impact test

Impact tests were conducted on an Instron CEAST 9340 drop-weight impact machine allowing the impact force monitoring. A Non-Crimp Fabric (NCF) biaxial glass fiber/polyester was chosen as material for this study. The laminated composite was manufactured by vacuum infusion of the resin into the stacked NCF-reinforcement. A total of 6 plies were stacked together, resulting in 3 mm thickness. All the specimens in this study were tested in edgewise (the applied load direction in parallel to the laminate) according to ISO 179-1 and the dimensions of specimen are 80 x 10 x 3 mm.

Experimental setup is shown in Figure 1. The drop test machine comprises optoelectronic trigger and instrumented impactor, the weight of which is 3.14 kg with a U-shaped head (**Figure 2**).

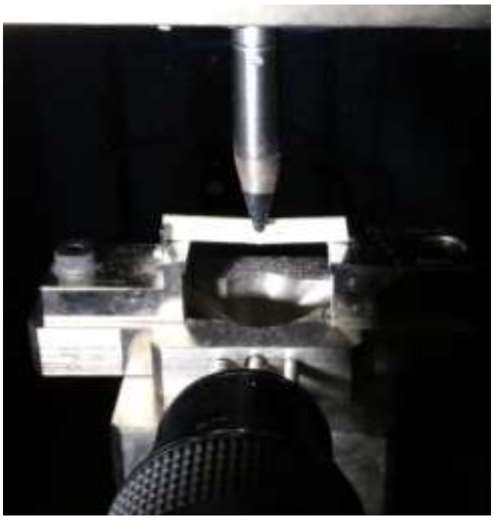


Figure 2 : Close up of sample and impactor, showing macro lens in front

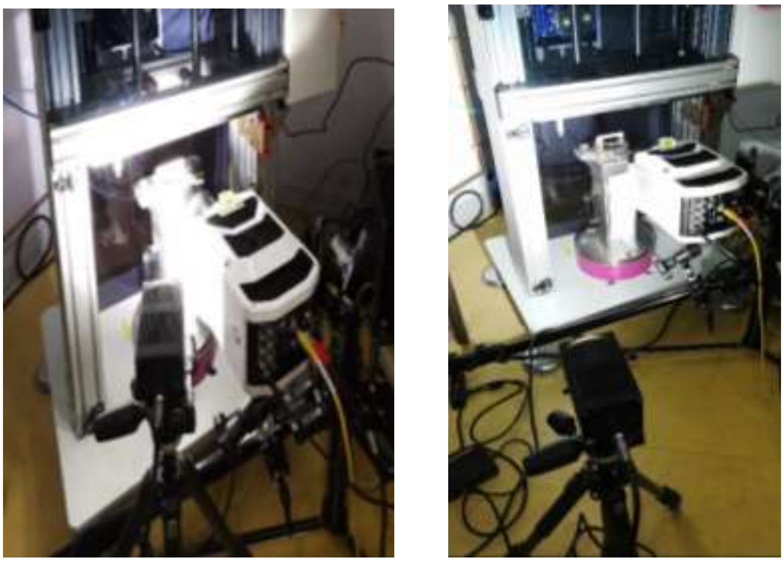
Impact test is conducted at 0.8 m/s velocity and a 5kg additional mass was added to the impactor weight to give an impact energy of 2.6 J. This kinetic energy is large enough to ensure the rupture of the specimen. The optoelectronic trigger is also linked to the high-speed camera. It is then possible to perfectly synchronize the data acquisition from the drop test machine and the rolling buffer memory images in FIFO mode timestamped by the trigger.

2.2 High speed imaging

High speed imaging in TRDIC drop test measurement requires high frame rates with good spatial resolution. This means the details of the flyspeck, painted onto the object surface, must be resolved to ensure localization and tracking of the damage generated by the impactor head. This high contrast ($C \approx 1$) pattern is then used to perform DIC computing of the interesting images series. This series is selected by manually sorting (nearby trigger) the onboard image FIFO rolling memory of the camera head just before the impactor contact and after the complete destruction of the sample. To reach frames rates over 20kfps, short exposure time ($\leq$ 50µs) must be enabled thanks to high intensity light source, fast optics and also minimal camera built-in global electronic shutter time. Of course, rolling buffer memory size must be large enough to cope with duration test, image size, frame rate and so camera throughput.

Full CMOS sensor from Vision research Phantom V2512 high speed camera is used to record the displacements of the object surface. This camera enables up to 26kfps at full resolution (1280x800) in 10bits. Previous tests have shown the optimal frame rate is about 80kfps with 1µs exposure time. This requires to reduce the sensor resolution down to 640x400 to ensure this frame rate regarding the constant 26Gpix/s throughput. Therefore, to image the flyspeck at desired resolution, the camera is equipped with Nikon 105mm 2.8 macro lens. The magnification is set to unity (1:1) by choosing the appropriate working distance between the lens and the object, as focus ring is disabled in macro mode. Magnification reached 28µm/pixel at 0.314m. Aperture f#4 provides some depth of field and so reduces blur generated by eventual out of plane displacement of the object surface. The high-speed camera, coupled with the macro zoom lens, is weighting about 10kg. Therefore, to ensure stable set-up, it is affixed on Manfrotto heavy weight tripod. This coupling is done by using friction control Pan-Tilt-Rotation Manfrotto tripod 3D head, able to support the camera. The quality of the images has to be perfect for further DIC processing. Hence the set-up is improved by adding two fine-coarse translation Manfrotto plates between the 3D head and the camera. These translation plates are coupled at 90° to enable 2D translations i.e. working distance (focus) and precise height. Image sharpness of the flyspecked object is then determined by maximizing the contrast of the live images.

IDT Veritas Constellation 120 LED array is the illuminating continuous light source delivering up to 92klux@0.5m and about 5klux@2m. The position and angle of illumination are changed (**Figure 3**) to reach the same image contrast and intensity at different exposure times without changing any of the other parameters (gain, sensitivity, aperture, focus…).



(a) 1µs exposure time (b) 20µs exposure time

Figure 3 : Sample illumination at constant image intensity and contrast: (a) 1µs, (b) 20µs exposure time

2.3 Digital Image Correlation with CinEMA

Digital image correlation (DIC) was conducted on the images obtained from the high-speed camera using in-house software called CinEMA[8]. A rectangular region of interest (ROI) as shown in Figure 4 was selected at the bottom of sample in the most stretched area to evaluate the in-plane axial tensile strain. The subset size was 64 x 372 pixels, the ROI is divided into grid and the distance between mesh points is defined by a step parameter (Gs= 3 pixels). The numbers of pixels to consider in the horizontal and vertical directions were defined by its correlation size C_s (V x H = 3 x 7 pixels) in x and y direction respectively.

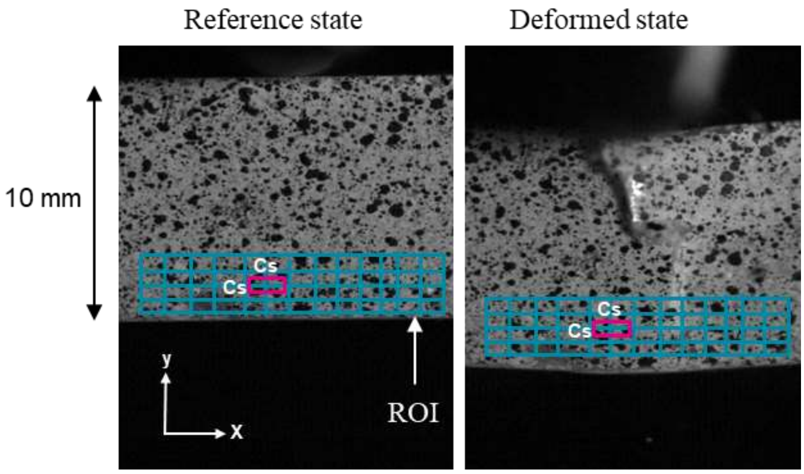


Figure 4 : Principle of image correlation with reference and deformed image

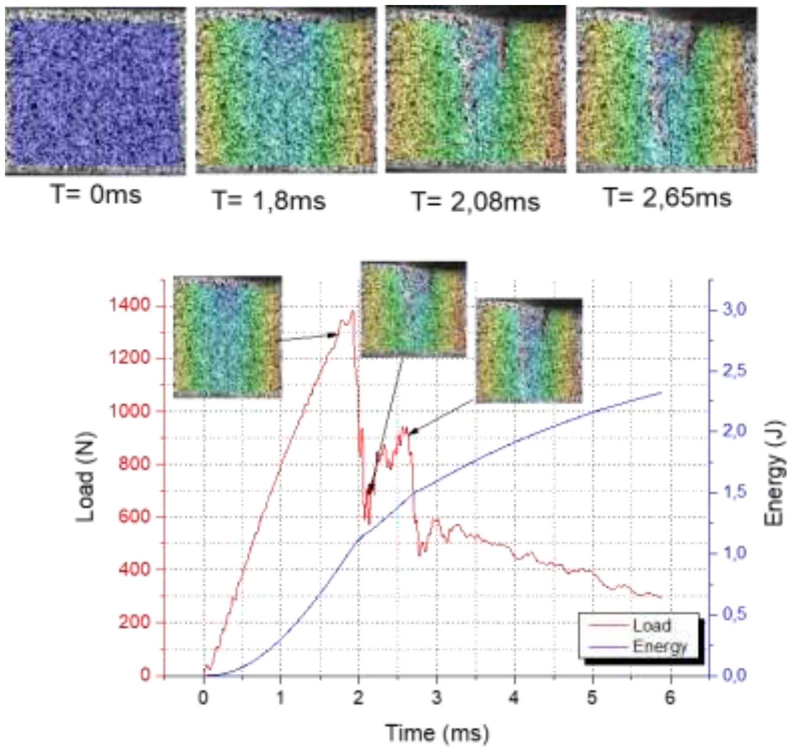


Figure 5 : TRDIC results of damage history growth, 83kfps. Color shows vertical deformation (light blue<0<red, white NAN)

This procedure has been successfully applied to follow damage propagation and crack generation on [0,90] plies sample (**Figure 5**).

3. RESULTS

3.1 Effect of frame rate

Different tests were completed, between 18kfps up to 170kfps, to finally produce an excellent images sequence to perform DIC processing, allowing to resolve the different aspects of the Charpy impact on the samples. This leads to set the frame rate at about 83kfps, achieving a good compromise between resolution and frame rate.

To evaluate the effect of time sampling, the DIC results, e.g. the average in-plane axial strain in the most stretched area of the plate during its bending deformation, are compared for different frame rates by resampling only the native 83000fps film. This perfectly reproduces the effect of frame rate as shown on the same experimental sample.

The results presented show the evolution of the DIC deformation of the sample at different frame rates. The native movie is acquired at 83kfps and the image series is then downsampled by 1/N of images to 41500, 20750 and 11857fps respectively. Correlation is then applied with the same parameters and the effect of frame rate is clearly demonstrated as smoothing operator, even displacing the peak (**Figure 6**). In particular, the optimal frame rate is about 83000fps to clearly resolve the crack shown in the zoomed curve. To increase the frame rate from 83kfps to 170kfps, the spatial resolution must be decreased. The smoothing of the image is now generated by the spatial resolution and the image quality is dropping drastically i.e. it is not possible to perform accurate DIC results in terms of crack localization.

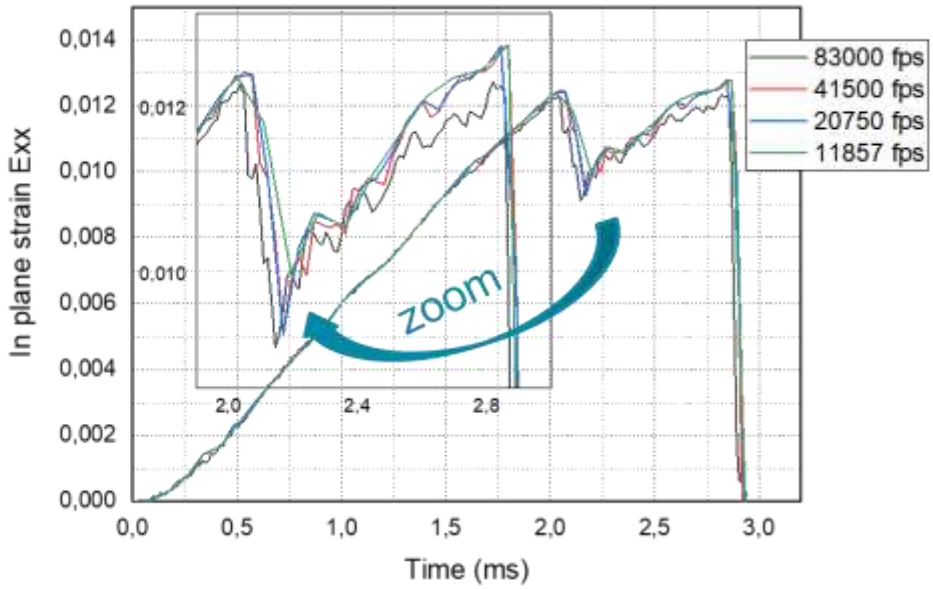


Figure 6 : Sensitivity to temporal sampling for axial tensile strain ε_{xx}

With sensor manufacturing also under development, Vision Research just released the Phantom TMX7510 enabling 75Gpx/sec throughput (e.g. 1280x800@76kfps) for all framerates and resolutions thanks to back side illuminated CMOS sensor, still coupled with rolling memory buffer. This sensor will ensure higher spatial resolution as it is not necessary anymore to reduce the resolution of the camera to reach the minimal temporal resolution. It will produce crispy images for the same frame rate, or enable to reach faster frame rate while reducing the spatial resolution thanks to the 76Gpix/s throughput at constant resolution.

For ultra high-speed imaging of ballistic impact or catastrophic destruction, it is now also possible to reach up to 250Mfps, but solely for 8 images memory recorded on 8 different sCMOS sensors with 4ns exposure time (e.g. PCO Dicam C8).

3.2 Exposure time and sensitivity to optical blur

Drop test series are carried on flyspecked composite plates from the same vacuum resin infusion sequence Desired blur is generated by decreasing the exposure time while camera sensitivity and gain, lens focus, aperture and 1:1 magnification are kept constant. This is enabled by gently enhancing the distance and/or angle of the light source and keeping the same intensity and contrast at rest. Commonly, the optical blur is given by:

$$B\ (pix) = V_P \cdot T_{exp} / M,$$

with V_P (m/s) the object velocity, T_{exp} (s) the exposure time, and M (m/pix) the magnification, respectively.

The blur B is directly generated from the variation of exposure time T_{exp}, while $V_P \approx$ 1m/s~, and M=28µm/pixel. This leads to B α 1/M for T_{exp} = 1µs yielding to B=3.57.10^{-2} pixel, which is greatly under the correlation algorithm detection threshold.

The effect of optical blur on the accuracy of the measurement is studied here. **Table 1** shows acquisition parameter, frame rate was changed from 83kfps to 18kfps by keeping in memory the results from Section 3.1. Exposure time is increased from 1µs to 55µs while keeping the same image contrast. Parameters used for the determination of the DIC strain were also kept constant for all tests. It is clearly shown blur is affecting DIC measurements when it is more than 1 pixel. As the painted flyspeck is rather complex, no further improvements of the images have been carried on

Table 1 : Acquisition parameters for blur generation

TEST	Frame rate	Exposure Time	Mag (µm/pixel)	Blur (pixel)	Results
1	83000 fps	1 µs	28	0.035	Correlation
2	83000 fps	11 µs	28	0.39	Correlation
3	41500 fps	11 µs	28	0.39	Correlation
4	41500 fps	23 µs	28	0.82	Correlation
5	20000 fps	46 µs	28	1,64	Decorrelation
7	18000 fps	46 µs	28	1,64	Decorrelation
8	18000 fps	55 µs	28	1,96	Decorrelation

CONCLUSIONS

High-speed imaging is a major tool in fracture mechanics, in particular in case of complete damage of the sample because it enables to capture the displacement/strain even up to total breach. In this work, Charpy impact test was used to conduct impact onto laminated composite samples and a high-speed camera (26Gpix/s) was added to the experimental setup to track in real-time the damage progression of the macro-cracks at the front surface of the impacted sample. Frame rate and exposure time of the camera were altered within the series of measurements. Effects of these acquisition parameters on DIC results were analyzed in order to assess the optical setup suitable to high quality measurements. High magnification is obtained to enhance spatial resolution and so to enable localization of the crack. Due to the small size of the samples, magnification of 1:1 (28µm/pixel) on the sensor requires very short working distance. Regarding temporal resolution, optimal conditions are reached when the time sampling is high enough to resolve the crack sudden appearance, coupled with short exposure time to avoid optical blur. To quantify the impairment due to blur, exposure time has been increased up to get optical blur larger than 1pixel. The effect of motion blur has been evaluated at the step of the digital image correlation results. Further experiments will be conducted at higher impactor speeds to correlate these measurements at different load rates. Future works will also try to recover correlation by preprocessing blurred flyspeck images.

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