Strain-based monitoring of damage creation during the impact of composite materials

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Abstract. In this study, a technique was developed to monitor the damage created in composite specimens during impact testing. High-speed digital image correlation (DIC) was used to measure full-field strains as specimens were impacted. From the measured strain, damage severity was quantified. The technique further processed the strain data to yield damage-time maps. The propagation of damage during the events can be visualized through these maps. The developed technique potentially reduces the amount of time required for processing experimental data to reveal damage creation in complex materials.

Introduction

When used for vehicle structures, composite materials are likely to experience impact within their lifespan. This can degrade their strength and initiate delaminations that might propagate during service. This could lead to structural failures that put lives at risk. Therefore, experiments must be carried out to further understand their behaviour during impact due to the complex nature of their microstructure. DIC systems can be employed in experiments to track changes between surface strains. This creates a large amount of data that often stretches into memory size of gigabytes or even terabytes. This presents a bottleneck during analysis as researchers have to spend a lot of time interpreting the data. This study introduces a data processing technique that gives a better understanding of damage formation in carbon fibre reinforced polymer (CFRP) specimens during impacts.

Experimental Methodology

The experiments involved the use of a drop weight impact machine (CEAST 9340, Instron, USA) combined with a high-speed DIC system (Q-450, Dantec Dynamics, Germany) to monitor changes in strain fields on the bottom surface of CFRP specimens during the impacts. The specimens are 150mm by 100mm in-plane dimensions, and a thickness of 3.2mm. These specimens were made of unidirectional prepreg plies (RP542-4, PRF, UK) with a $[0_2/90_2/45_2/\text{-}45_2]_S$ layup. For impact, captured data from DIC systems operating at a rate of 10kHz often contains more than 200 strain fields. These strain fields contain substantial amounts of data, so orthogonal decomposition [1] was used to reduce the dimensionality of each strain field into feature vectors. Feature vectors are a group of coefficients that represent the surface strain on the specimen [2].

The Euclidean distance between two feature vectors representing sequential moments in time was then calculated and divided by the time difference to obtain the rate of change. This rate of change was assumed to have three elements: measurement noise, elastic deformation due to loading, and the creation of permanent damage in the specimen. Damage creation was the main interest of this study, and thus the contribution of elastic deformation and measurement noise to the rate of change had to be removed. A baseline value of rate of change was estimated based on the speed of the impactor, as it was found that the rate of change when no damage was created was directly proportional to the speed of the impactor.

A 95% prediction interval for the baseline was calculated to act as a threshold for detecting damage creation. Any rate of change that lies outside the prediction interval were identified as damage. This is because damaged regions have higher strain values than the undamaged. Subtracting the baseline value from the rate of change estimates the rate of damage creation, referred to as the indicated damage rate. This was then integrated with respect to time using the trapezoidal rule to yield the indicated damage severity. Therefore, the amount of damage created in the specimen could be quantified.

Damage-time maps were created by comparing feature vectors from just before and after damage events. Damage regions were detected by thresholding the strain difference between time steps. An iterative algorithm updated the map plotting the damage regions in colours that indicated when they formed. Pulse-echo ultrasound was employed to accurately measure the size of damage in the damaged specimen. The ultrasound data was then used to verify the estimated morphology given by the damage-time maps.

Discussion

A relatively high rate of change was found between 1ms and 3ms in comparison to the baseline as shown on the left of Fig 1. From the other perspective, the indicated damage severity graph shown on the right of Fig 1 reaches a peak of 12000με within 3ms and plateaued. These accumulations over time indicated the specimen has been permanently damaged during impact within the first 3ms after the impactor contacted the specimen. The time showing when damage occurred is comparable to the times indicated on the damage-time map shown in Fig 2. The damage-time map shown in Fig 2 contains some erroneous pixels at the top of the region of interest due to random high strain values at those location resulting from the DIC algorithm, however the damage itself is clear. The damage area initiated from the centre of the specimen, where the impactor first contacted it. Early-stages of damage creation shown in the damage-time map were tilted with an angle showing damage was created above the 45° plies near the top surface of the specimen first. Then large delaminations started to grow in the bottom interface 0.5ms later.

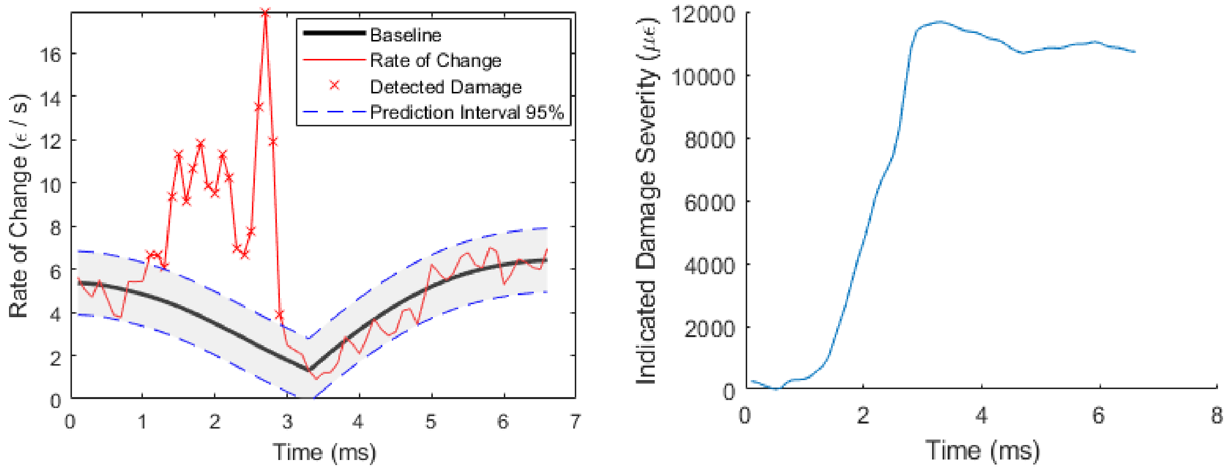

Fig 1: Rate of change graph for a quasi-isotropic CFRP specimen impacted at 30J and its corresponding 95% prediction interval of the rate of change if no-damage was created (left) and the indicated damage severity for the same specimen (right).

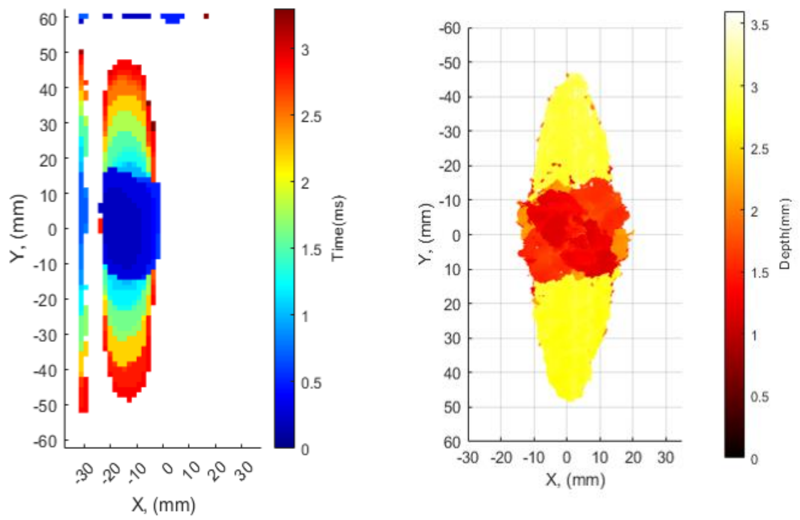

Fig 2: Damage-time map for a CFRP specimen impacted at 30J (left) and corresponding ultrasound image showing the shape and size of damage (right).

Conclusion

An algorithm has been introduced for monitoring damage creation in composite materials by tracking differences between sequential strain fields captured using a high speed DIC system. The algorithm enables identification of the location of damage, determination of when the damage was formed and estimation of the severity of the damage. The algorithm has been applied to a set of specimens impacted at different energy levels to provide a better understanding of how composite materials behave during impacts.

References

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