Real-time location and quantification of damage in composite materials

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Abstract. This study demonstrates new techniques for processing and presenting data from digital image correlation. The techniques enable the real-time quantification of damage severity in composite specimens, as damage occurs during mechanical tests. The data is then presented in a novel format, called a damage-time map, that shows the spatio-temporal progression of damage in a specimen in a single figure. The developed techniques reduce the amount of time that experimenters must spend analysing large amounts of DIC data, freeing them to focus on developing a deeper understanding of damage mechanics.

Introduction

Composite materials have complicated damage mechanics, this is due to their heterogeneous microstructure and orthotropy. This complexity means that mechanical tests are essential to determine their material properties and to validate computational models. Over the past decade, digital image correlation (DIC) has become ubiquitous in mechanical testing and thus, when used, each test generates large quantities of data. When, combined with high-speed imaging these tests can result in tens of thousands of strain-fields. Processing this data is time consuming and thus it is typically only used qualitatively to observe surface strain at particular instances in time. When quantitative measurements are used it is normally in the form of a time series of strain or displacement at arbitrary locations.

Recently, techniques have been developed to quantify the severity of damage in composite specimens based on comparisons of surface strain on a virgin component with strain on a damaged component [1]. In this study the technique is further advanced by using it to compare the strain field on the surface of a specimen at different time-steps during mechanical testing. This yields a damage indicator parameter which can then be further processed, resulting in an indicator of accumulated damage and maps that show the spatio-temporal progression of damage.

Experimental Methodology

DIC was used to monitor strain on the surface of specimens during two distinct mechanical tests. The first test was a ceramic matrix composite (CMC) specimen loaded in tension at high temperature. The second test involved polymer matrix composite (PMC) specimens loaded in bending. These PMCs contained defective regions of misaligned fibres. In both tests the specimens were monotonically loaded to failure whilst DIC images were captured at regular intervals, resulting in hundreds of strain-fields for each specimen.

The dimensionality of the strain-fields was reduced by orthogonally decomposing them [2] into feature vectors consisting of at most 200 coefficients. The rate of change of the strain field was obtained by calculating the Euclidean norm of the difference between two sequential feature vectors and dividing this scalar quantity by the time elapsed between the two vectors. This rate of change quantity had three components; the first was due to measurement noise, the second was due to elastic deformation of the specimen and the third was due to damage being created in the specimen. The first and second components of the rate of change were nominally constant during the tests and thus were subtracted from the rate of change quantity to yield a damage indicator parameter. This parameter estimates the rate at which damage is created in the specimen, an example of this parameter for the CMC specimen is shown on the left of Fig 1.
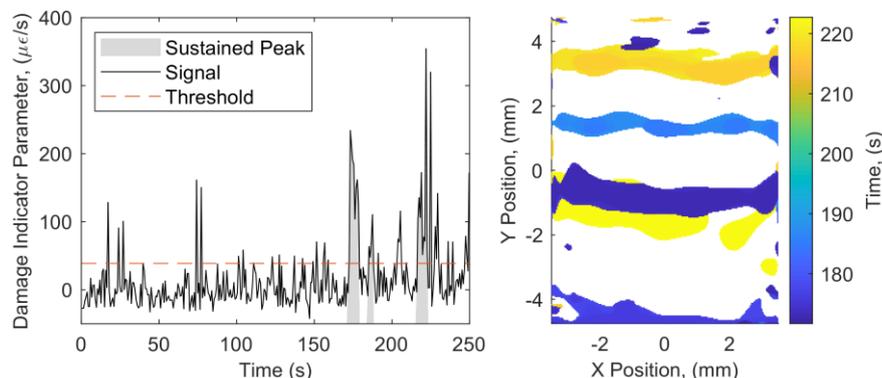
Fig 1: Damage indicator parameter for a CMC specimen loaded to failure in tension (left) and the damage-time map associated with the same specimen (right).

This damage indicator parameter can then be used in one of two ways. Firstly, it can be monitored to detect when damage events occur, and subsequently the location of damage creation can be identified by subtracting the strain field immediately before the damage occurred from the strain field after the event. The resulting data for each damage event can be combined, resulting in a damage-time map, showing the spatio-temporal development of damage in the specimen. An exemplar damage-time map is shown on the right of Fig 1. The second application of the damage indicator parameter involved integrating it, resulting in an accumulated damage indicator. This can be used to quantify the amount of damage that has been created in a specimen.

Discussion

The algorithms described in the previous section were used to process data from a large set of specimens subjected to two different types of test. The CMC specimens were loaded in tension, resulting in cracks forming as the load increased. These damage events were detected using the damage indicator parameter by monitoring for periods where the parameter was above a threshold for a sustained period of time. The damage-time map formed from these events shows the morphology of the damage, as shown in Fig 1. The CMC specimen had a cross-ply lay-up with 0° plies running in the y-direction. The damage-time maps show that the damage was orientated in the horizontal direction, which was parallel to the 90° plies in the specimen. The technique only observed the surface strain and thus it was not possible to determine the depth of the damage. This technique is thus best suited to approximately locating damage before further inspection can be conducted to determine its precise location.

The PMC specimens were loaded in bending and thus failure occurred by delamination of the bottom ply on the compressive side of the specimen. The damage-time maps were able to show that damage progressively grew out from the central defective region of the specimen. A map for one of these specimens is shown in Fig 2. The accumulated damage indicator parameter for the specimen shows that there were two phases of this growth, one at approximately 700s and another at approximately 1050s, just prior to the specimen failing.
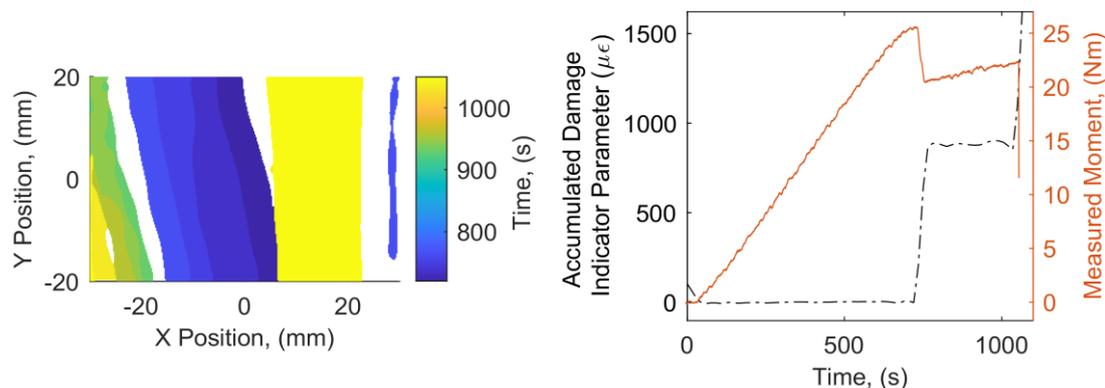
Fig 2: The damage-time map for a PMC specimen loaded in bending (left) and the accumulated damage indicator parameter associated with the same specimen (right).

The damage-time maps and accumulated damage indicator parameter offer new ways of processing large amounts of DIC data, requiring minimal labour by the experimenter. They are also computationally efficient to calculate, taking just 36ms for the damage-time maps to be updated after a new strain-field is captured. This means that the algorithm could be combined with live DIC, enabling mechanical tests to automatically stop at the onset of damage. This would make it easier to inspect large test pieces, such as those encountered in the aerospace industry, prior to catastrophic failure occurring.

Conclusion

This study demonstrates novel techniques for processing large amounts of digital image correlation data obtained from the mechanical testing of composites. The techniques were applied to data from different types of composites undergoing different forms of testing. By automatically processing large amounts of data, the time taken for engineers to analyse the results of tests is reduced allowing them to focus on more complicated aspect of damage mechanics.

References

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