Validation of Damage Models Using Full-Field Data of Open-Hole Composite Specimens

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Abstract. Full-field surface displacement and strain data is obtained using digital image correlation (DIC) from quasi-static tests of open-hole carbon fibre-reinforced polymer (CFRP) specimens under shear loading. The data reveals that the open-hole shear (OHS) strength depends on the laminate stacking sequence, i.e. the thickness of individual plies as well as the direction of the shear load relative to the laminate stack. The difference in strength is attributed to distinctly different failure mechanisms that are observed in the strain and displacement fields obtained by DIC. The experimental data is used to validate the capability of a finite element analysis (FEA) model to predict damage evolution and the OHS strength of multidirectional composite laminates. Hence, a new approach to validating finite element damage models for composites using full-field experimental data is presented.

Introduction

Damage models are a vital component in the design of loading-bearing composite structures across a wide range of industries. The ability to perform accurate validation of such damage models is an essential component in the assurance of the integrity of the design. However, model validation with experimental data often uses limited quantitative metrics (such as total displacement at a few points or a failure load), or qualitative comparisons of the whole field (such as visual comparison of strain contours) [1].

Therefore, the aim of the present work is to compare full-field experimental data quantitatively to FEA model data to comprehensively validate an advanced damage modelling framework, such as those used for the virtual testing of composites [2]. Open-hole tension (OHT) tests are often used for model validation due to the complex failure mechanisms that occur around the hole [3]. The OHS test offers an opportunity for validation based on different failure mechanisms, providing a useful benchmark for the predictive capability of composite damage models, and a valuable addition to the established OHT experiment.

Open-hole shear testing

The shear load was applied using the Modified Arcan Fixture (MAF) [4] developed for testing CFRP specimens to failure, as shown in Fig. 1a. A key feature of the rig are the anti-buckling rails that prevent twisting and out-of-plane buckling of the specimen.

The laminates are made from unidirectional IM7/8552 carbon/epoxy prepreg. The material was chosen due to being very well characterized, which provides a good basis for benchmarking the models. Two layups were tested: a blocked 'thick ply' layup of $[+45_2\ 90_2\ -45_2\ 0_2]_s$, and a distributed 'thin ply' layup of $[+45\ 90\ -45\ 0]_{2s}$. The specimen shape was designed to promote failure at the hole under a variety of loading directions (based on previous tests in [4]), which remained true for the shear case.

A displacement rate of 1 mm/min was set for the quasi-static load condition. The MatchID system was used to acquire images for stereo-DIC using 12 MP Blackfly cameras and process the image data into displacement and strain fields of the specimen surface. The two shear load cases considered were an 'aligned' case where the shear load was aligned with the surface direction of the +45° ply, and 'against' where the load was applied against the direction of the surface ply. This is shown in Fig. 1b.

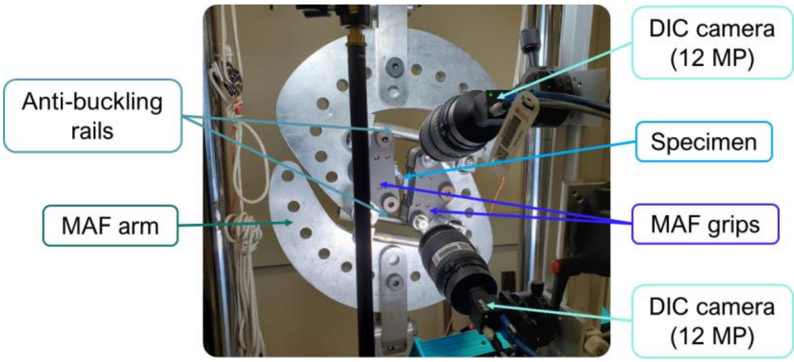

Figure 1a: The experimental setup.

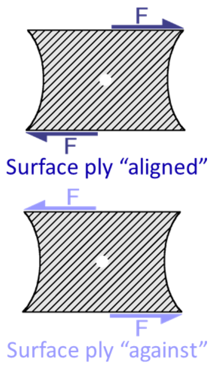

Figure 1b: The two shear orientation cases.

Experimental results

Similarly to previous work investigating open-hole tension and compression tests [5], a difference in strength between the two laminates was found. The thin ply laminate was on average 12.6% stronger than the thick ply laminate due to adjacent, differently-oriented plies preventing damage spread.

The direction of the shear load relative to the laminate stack also had an effect on the open-hole strength. The against case was 4.96% stronger for the thick-ply laminate and 2.51% for the thin-ply laminate. This was caused by a difference in failure mechanism: in the aligned case, delamination spread from the hole eventually causing an abrupt total delamination, while in the against case matrix cracks and fibre kinks accumulated to cause buckling and total cracking of the surface ply.

FEA-based damage model validation

After the experimental results were obtained, the next step is to investigate if a model could predict the lay-up effects observed. The model is explicit dynamic with quasi-static loading, modelled in ABAQUS. Both intra-laminar damage and inter-laminar damage (delamination) are modelled. A linear-elastic relationship is used up until failure occurs, which is handled as follows:

- Intra-laminar failure initiation is based on the LaRC03 criteria [6].
- Intra-laminar damage evolution is based on fracture toughness [7].
- Inter-laminar delamination uses cohesive zone models [8].

To perform a quantitative validation of the model using the DIC image data, some aspects of the processing require attention. The number and location of data points obtained from the model and the experimental image data are different, so interpolation is required. Further, the strain values obtained from DIC are spatially filtered according to the subset size and strain window. For the linear elastic region, the MatchID system offers a solution called 'virtual DIC' [9]. This approach involves importing the actual speckle pattern captured by the cameras into the FE model and deforming the speckle pattern using the deformation determined by the FEA. These simulated images are then processed using the same subset size and strain window as the DIC. This negates the requirement for interpolation and DIC filtering. Hence, the experimental and numerical datasets are directly comparable providing the basis for a quantitative benchmarking of the model outputs.

Another comparison challenge is the appearance of surface cracks, which produce sharp displacement discontinuities and appear as localised high strain in DIC data. Once failure criteria is exceeded in the FE model the elements are discounted, meaning the localised data will be different at cracks. The planned approach is to use a threshold strain criteria for failure in the DIC data to compare with plots of failed elements.

Conclusion and future work

Effects of ply thickness and loading direction on the OHS strength have been experimentally characterised, while the same experiment has been implemented in an FEA model. Future work will implement the virtual DIC approach to quantitively validate the model against the experimental data.

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