ANALYSIS OF DAMAGE DEVELOPMENT IN CFRP NOTCHED COUPONS WITH ENERGY-BASED MULTI-AXIAL FAILURE DATA

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Keywords: *CFRP composites, damage modelling, multi-axial material characterisation*

Abstract

A methodology that uses multi-axial testing and dissipated energy (DE) to characterise the mechanical behaviour of laminated composite materials has been implemented into an analysis approach. The goal of this approach is to quantify the damage development on a continuum basis and eventually relate this damage to the constitutive behaviour of the material. The approach was implemented into a commercial finite element package with a custom user subroutine. Double-notch characterisation specimens and open hole tension coupons were assessed. DE was predicted well in tension and in-plane rotation cases apart from a pure shear case where DE was excessive. DE magnitude was satisfactory in the open hole case and damage propagation well represented. Future work will involve advancing the technique to include DE-dependent constitutive modelling.

1 Introduction

Current structural design utilising fibre-reinforced composite materials is yet to fully exploit their capabilities due to the difficulties in capturing material behaviour up to and including failure. The present design and certification of composite structures is based on gathering and correlating experimental data from limited single axis tests and extrapolating this material data to real life scenarios. As with most other empirical methodologies, this is useful only for a specific problem and becomes difficult and dangerous to extrapolate the data to conditions and configurations outside the range of the tests. This involves considerable uncertainty, which leads to the requirement for tedious and expensive experimental testing at all critical length scales. As such, an approach that is based on characterising the material behaviour in the complete loading space has the potential to increase reliability and reduce the time and cost of the design and validation cycle, and may also allow the safe operation of composite structures with reduced conservatism.

The complex non-linear failure behaviour exhibited by composites precludes the use of traditional concepts such as isotropic fracture mechanics [1] that are successfully used with metallic structures. A plethora of composite failure criteria exist [2] but most are yet to provide a satisfactory degree of predictive capability, such as what would be required in more demanding applications like aircraft primary structures, possibly leading to heavy, overconservative design.

A methodology that uses multi-axial testing to efficiently characterise the mechanical behaviour of laminated advanced composite materials was developed by Michopoulos et al. [3-5]. In the current paper, this approach has been implemented into a commercial finite element (FE) package with the aid of a custom user subroutine. This approach involves determining the damage function of a material from a sequence of tests covering the complete loading space. From this testing the "dissipated energy density function" or DED function can be characterised. The volume integral of this DED function equals the energy dissipated during loading due to the various internal failure

events within the material. This mechanical strain-based DED function, fully characterised from experimental data, should be able to accurately describe material behaviour in terms of dissipated energy (DE) due to energy absorbing damage mechanisms, through the linear and non-linear regimes. This captures the collective behaviour of these failure mechanisms without needing to know the precise damage events. The DED function can be related to local stiffness changes and so potentially used to model non-linear material behaviour.

A multi-degree of freedom (DOF) experimental testing regime is currently being pursued using unidirectional carbon fibre-reinforced polymer (CFRP) epoxy tape specimens. The specimens have also been tested using FE data, to generate "synthetic" data. This synthetic data has been found to be particularly useful in troubleshooting and preparing the methodology for the introduction of experimental multi-axial loading data, including out-of-plane deformation. This paper focuses on the utilisation of the synthetic data to assess the development of damage in double-notched and open-hole CFRP specimens under 3 DOF loading.

2 Generation of Synthetic Data

A thorough discussion on the production of synthetic data was given by Orifici et al. [6], and only a brief outline is provided here. Firstly, the loading cases of interest are created as FE input files. For the work described in this paper, models were created in the commercial FE package Abaqus [7]. Modelling the configuration of the characterisation specimens, as shown in Fig. 1 was achieved using a single layer of quadrilateral shell elements.

To capture damage, the damage model for fibre-reinforced composites in Abaqus was employed, and the model solved using Abaqus/Explicit [7]. The damage model uses the Hashin criteria to capture the initiation and progression of four types of composite-specific failure modes including:

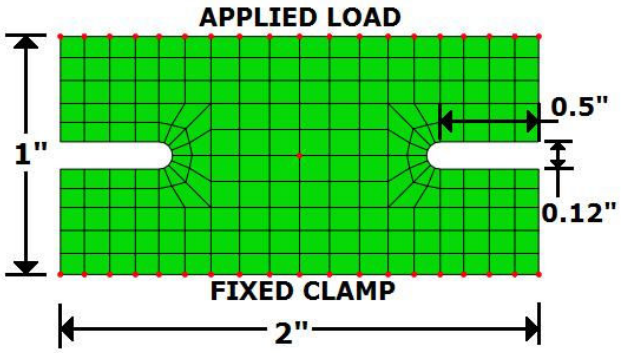

Fig. 1 Geometry and dimensions of the double-notch characterisation specimen.

- Fibre rupture in tension;
- Fibre buckling and kinking in compression;
- Matrix cracking under transverse tension and shearing; and
- Matrix crushing under transverse compression and shearing

These damage modes are used to trigger a progressive loss in stiffness. As part of this, Abaqus calculates the energy associated with all damage processes, ALLDMD [7].

The FE results on their own however are not enough, as the goal is to replicate experimental output with the same data and layout as given by the test machine. To do this, a custom Python script [6] retrieves the data of interest such as DE and strains from the Abaqus results database and constructs a synthetic data test file, which is in the same format as actual experimental data files. Once all these data files have been prepared, the material characterisation can begin.

3 Material Characterisation Constants

It has been postulated [3] that there exists a scalar function ϕ which expresses a measure of the dissipated energy density per unit of volume of material, which only depends on the strains and the material used in the structure.

Determining the DED function for a material requires knowing the total dissipated energy experienced as well as the associated full-field strain distribution. The dissipated energy is the result of considering the total energy imparted to the specimen and the total recoverable energy after elastic unloading – the

instantaneous difference between the two is the current amount of dissipated energy. Strain measurement is achieved using full-field optical strain measurement systems, and in the case of synthetic data, the full-field strains are taken from the FE analysis.

An example of a typical history plot of dissipated energy for a model with the Abaqus damage model is shown in Fig. 2. Points of interest include the initial period of zero DE corresponding to the elastic loading regime of the material, then at approximately 0.3×10^{-3} seconds when the material starts to soften and energy is dissipated. By approximately 0.6×10^{-3} s energy is no longer being dissipated.

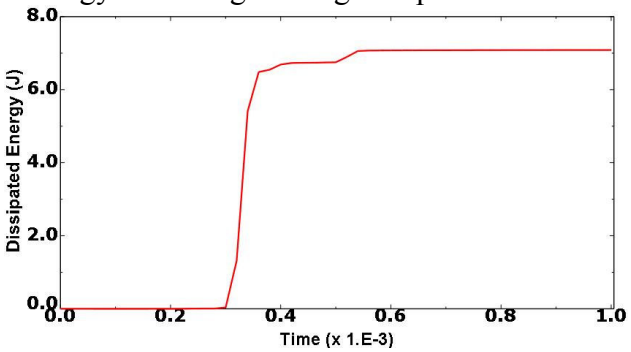

Fig. 2. ALLDMD for a simple longitudinal tensile case.

3.1 Extraction of DED coefficients

A material's unique DED characterisation constants are determined using the procedure explained in Ref. [3], written into Matlab©. The DED function can take any form expressed in terms of a set of unknown DED coefficients and known constant basis functions. In the interests of simplicity a simple linear form was chosen:

$$\phi = \int_{S_0} \left(c_1 \chi_1 \left(\varepsilon^P \right) V^P + \ldots + c_i \chi_i \left(\varepsilon^P \right) V^P \right) dx \qquad (1)$$

The variable c_i represents the material dependent characterisation constants and χ_i the basis functions depending only on strains. Both are defined for i distinct points in a strain space. The integral of the function over the structure, S_0 gives the total dissipated energy. The concept of a strain space is explained in detail in [3].

The general procedure used to derive the characterisation constants from experimental or synthetic test data is as follows:

1. Gather test strain and DE data for the structure being characterised.
2. Process strains to locate their positions within the strain space and construct the basis function matrix.
3. Solve for the vector of characterisation constants by minimising the error between the DE determined analytically and from test data.

Processing the strains involves taking their value at discrete points over the surface of a structure, for individual increments of a loading case and "locating" their position within the strain space. This is done by identifying whether the strain at a particular point is within certain ranges along each axis of the strain space, whereupon it is then said to reside inside a "strain space element". With its location identified, the magnitude of the strain in each axis of the element is non-dimensionalised and interpolation performed to weight the strains at chosen "known" locations of the element i.e. at the eight corners of the cube shaped strain space element (for 3 DOF). From Equation (1) above, each strain is also multiplied by the volume of the node (location) from whence it came. This process is repeated at all strain locations over the structure and for all increments in the loading regime. Thus a matrix of basis functions was created where the values are the result of the located and interpolated strain coordinates multiplied by the volumes associated with each of those coordinates.

From Equation (1), multiplying the basis function by a set of material-dependent coefficients gives the DE. The coefficients, c, are chosen such that the basis function multiplied by the coefficients plus some error, e, will give the experimental dissipated energy, as shown in Equation (2), where n is the number of discrete locations the strain is sampled from and p is the number of loading increments.

$$\sum_{1}^{p} \sum_{1}^{n} c_i \chi_i \left(\varepsilon_n^p \right) V_n^p + e^p = DE^P \qquad (2)$$

This equation of basis functions and dissipated energies can lead to a highly over-determined system with no unique solution for c. Minimising the norm of the error vector e^p

provides the best approximation to the solution. In Matlab© a constrained linear least-squares curve fitting function was used to calculate the characterisation constants. Since the constants represent the dissipated energy density at known locations within the discretised strain space, they must be positive. In order to enforce this, the numerical optimisation is bounded by a minimum of zero and must produce coefficients which are non-negative.

3.2 Single and multi-sequence layup characterisation

3.2.1 Single layup

Confirming the feasibility of the methodology requires investigating a few preliminary cases before proceeding to characterisation specimens. As the physical experimental tests cover four non-symmetrical layup configurations ±15°, ±30°, ±60° and ±75°, their synthetic counterparts provide convenient baseline data for individual and group characterisation of the DED function. All four configurations have been analysed, though in the interests of brevity only the ±15° layup and combined characterisation will be discussed.

Mast et al. [3] recommended fifteen unique loadcases to obtain enough linearly independent samples of the critical regions of the strain space. Due to additional symmetry in the characterisation specimens analysed in the current work, this was reduced to ten unique loading cases for 3 DOF loading.

It was not known how many loadcases would be needed to adequately characterise a material nor whether the number of sample locations would be sufficient. From the pool of data created from the FE analysis, the ±15° layup was characterised using a single loadcase and then two loadcases, then three and so on. The strain and DE were requested at fifty intervals during any one loading cycle, which meant that fifty equations could be extracted from each loadcase. Initially working with square and evenly spaced intervals in the strain space meant that a 3×3×3 (27) node strain space was the maximum discretisation that could be applied using only one loadcase. A 4×4×4 or 64 node strain space would require at least sixty-four equations for the 64 unknown coefficients and at least one additional loading case, where two loadcases equals a hundred available equations. Fig. 3 shows the magnitudes of the 27 coefficients found to satisfy Equation (2) using just a single loadcase.

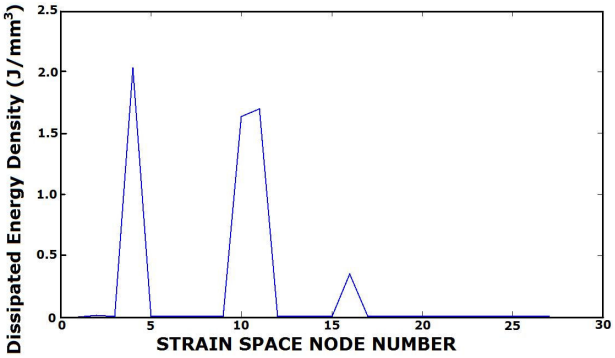

Fig. 3. Characterisation constants for ±15° layup using a single loadcase and 27 node strain space.

Assessing whether the characterisation constants were suitable was achieved via visual inspection of the coefficient magnitude plot as in Fig. 3. The density of non-zero coefficients, easily distinguishable through plotting of the magnitudes, is a straightforward indicator of the level of activity within the strain space. For a superior characterisation, more non-zero coefficients mean a greater coverage of the strain space has been achieved by the strains.

Additionally, the level of error associated with the characterisation constants was assessed using the normalised root mean squared error (NRMSE) metric. This was done by feeding the derived coefficients back into Equation (2), and calculating the total dissipated energy, as shown in Fig. 4. In this case the NRMSE was quite good at approximately 5.4%, though this suggests that some information was being lost either in the interpolation of the non-dimensionalised strain or due to the "coarseness" of the strain space discretisation.

Calculating the DE for the remaining loadcases using this 27 coefficient function is of little use as only one unique loading case was used to characterise the coefficients. Re-characterising the coefficients using all of the ±15° loadcases however, provided 500 equations and a 216 coefficient function, which produced an NRMSE of 9.4%. Although the

error increased, the robustness of the coefficients was improved as they were characterised from multiple loadcases meaning the subsequent damage function could be applied to differing loadcases. This result is typical of the four layups analysed and the individual NRMSEs did not exceed 9.65%.

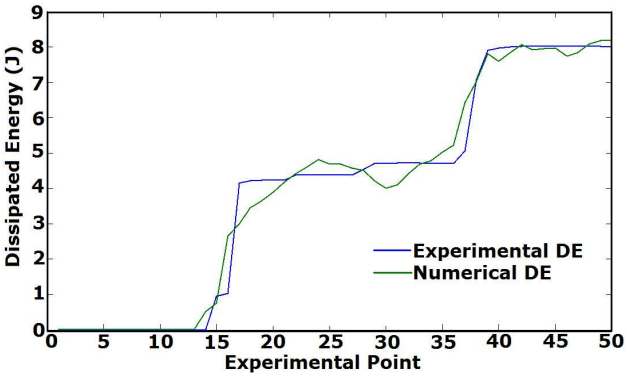

Fig. 4. Total DE predicted for the ±15° layup by the numerical method for the same loadicase used to characterise the constants in Fig. 3.

3.2.2 Multiple layups

Grouping the four layup configurations together with ten loadcases each and fifty increments per loadcase, gave 2000 equations. Using this large number of equations, the maximum discretisation was applied to the strain space in the form of 12×12×12 or 1728 nodes, which separated the strain space into 1331 discrete elements. Once again minimising the error in Equation (2) gave the coefficients as shown in Fig. 5. In this Figure, the large number of non-zero coefficients indicates that the strains have been successfully weighted over a greater number of coefficients, thus providing a higher resolution DED function.

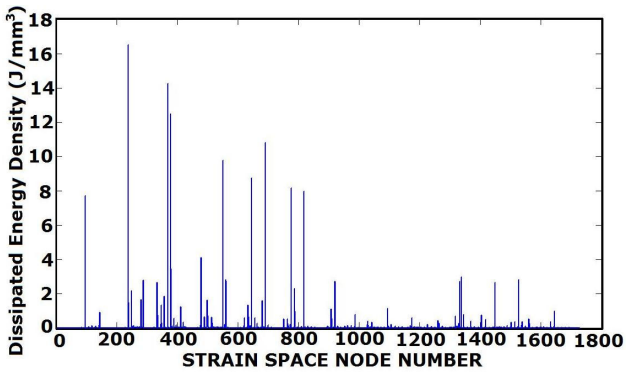

Fig. 5. Characterisation constants from characterisation of the material using all loadcases and layups.

A greater number of coefficients and strain space elements implies reduced error due to the linear interpolation, and also means that the contribution of a strain path to the total dissipated energy can be weighted towards several sets of strain space nodes rather than just one or two sets. It was observed during the characterisation that the strains from all loadcases originated from the centre of the strain space or $\varepsilon_{11} = \varepsilon_{22} = \varepsilon_{12} = 0$. This meant that the central element/s of the strain space had an inordinate number of strains weighted towards their coefficients. This can not only artificially magnify the DE for small strains but can also mean material behaviour at small strains would be clouded by the competing behaviours of differing loadcases condensed onto only 8-16 coefficients out of 1728.

To alleviate these issues, before the group case was characterised the discretisation of the strain space was modified. Instead of evenly spaced intervals, a two-way bias was applied to more highly discretise the central region of the strain space. This new interval layout and increased discretisation afforded by the greater number of equations available, gave a final NRMSE of 3.25%. The quality of the fit is also demonstrated by feeding the coefficients back into Equation (2), as shown in Fig. 6.

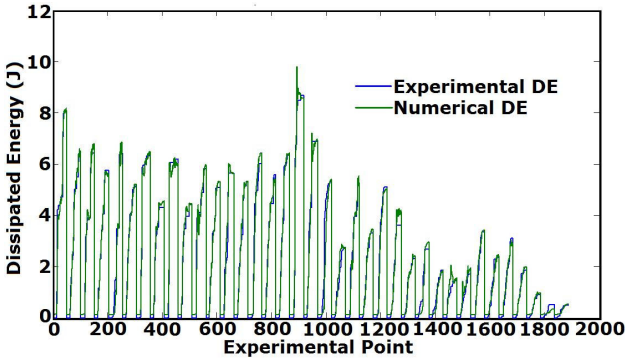

Fig. 6. DE predicted at all the test points by the numerical method for the characterisation loadcases using all four layups.

Despite slight non-zero DE at small strains, Fig. 6 demonstrates that concatenating the four layup data sets produces DED coefficients that effectively recreate the DE seen across 37 individual synthetic loadcases with varying degrees of non-linearity.

4 Implementation into FEA

To be able to analyse the development of damage within notched CFRP coupons it was necessary to implement the DED coefficients and strain space data into an FE package and assess whether the methodology could capture behaviour in differing geometries and layups.

4.1 Subroutine environment

The solver in Abaqus is able to interface with external files and execute commands through the use of user subroutines written in the Fortran environment. To this effect, a subroutine was coded to fetch the characterisation constants and strain space information and subsequently calculate the energy dissipated by damage during an analysis. The constants and the strain space details are mutually dependent – the coefficients are of no use without details of the strain space used to characterise them.

Once an analysis has begun, the subroutine is called by the solver at certain times during the analysis period. In the first instance the subroutine reads in the characterisation data as previously mentioned, in addition to a list of the areas of each element in the model being analysed. Once initialised, the process of calculating the DE is exactly the same as the process used in characterising the DED constants, albeit now the unknown is the DE not the coefficients. When called by the solver, the subroutine first requests the strains at the material point for which it is being called. Then as in the process described in Section 3.1, the position of the strain is located within the strain space whereupon it is then non-dimensionalised and interpolated. This value is multiplied by the area of the element from which the material point came and the ply thickness. Finally multiplying this value by the characterisation constants provides the energy dissipated by the current level of strain in a particular element. The total DE for the model is found by summing energies from all elements

4.2 Characterisation specimens

For initial runs, the methodology was tested using pure in-plane loading cases, i.e. pure tension, shear and in-plane rotation (rotation about the x-axis as given in Fig. 7). All the models assessed using the DED methodology were solved elastically with no damage model. The DE predicted by the subroutine was then compared with the Abaqus parameter ALLDMD, which was calculated internally as part of the Abaqus damage model.

4.3 DED and Synthetic Data Comparison

Fig. 7 to Fig. 11 illustrate the comparison between the numerical DE and the Abaqus ALLDMD parameter for the ±15° layup.

Under pure tensile loading, the strain field is fairly uniform except in the region of strain concentrations. In Fig. 7, the numerically predicted DE suggests that the strain field has indeed been affected by the presence of the notch, leading to almost twice as much energy being dissipated at the notch region when compared with the central and far-field regions of the specimen. The blue contours or lower values of DE directly surrounding the notch are due to the way the element area is calculated and will be addressed in the future.

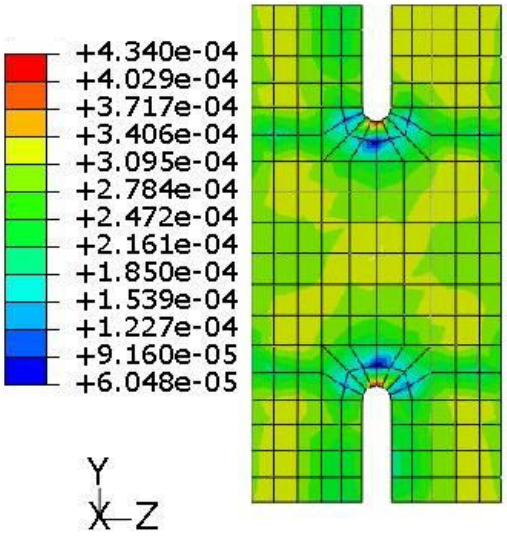

Fig. 7. DE (J) in the middle ply under constant displacement loading along the z-direction.

The ability of the methodology to predict the DE under pure tensile conditions is further supported when observing the total amount of energy dissipated by the specimen. It is important to note that this is an elastic model with no damage model and hence no changes in strain due to damage. For the tensile case, the total DE was predicted to within 2% of the DE given by Abaqus when taking the final failure to be at approximately 3.2×10^{-4} s. The sudden and sharp drop in the reaction force is reflected by the steep increase in numerical DE as the strain level crossed into new areas of the strain space with DED coefficients of greater magnitudes.

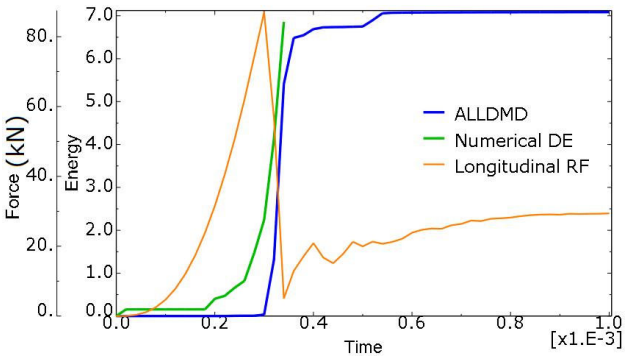

Fig. 8. Comparison between the numerical DE in J (green) and the Abaqus DE parameter (blue), and the reaction force along the z-direction (orange)

Currently, deciding when to terminate the prediction of DE by the methodology is a very important issue. The numerical procedure has not yet been taught how to deal with large amounts of non-linearity, and without a constitutive model dependent on DE, elastic models will keep loading with strains eventually exceeding the strain space dimensions. This essentially means that beyond 3.2×10^{-4} s, the large change in strains due to the softening and even slight stiffening of the model can cause massive over-predictions in the amount of DE. This is an ongoing consideration related to the characterisation phase of the DED methodology as the code attempts to reconcile large changes in strain, for little or no change in the dissipated energy values predicted by Abaqus.

The technique encountered some difficulties when dealing with the pure shear loading case as is shown in Fig. 9. Once the specimen entered the non-linear regime the numerical DE rapidly increased in a seemingly infeasible manner.

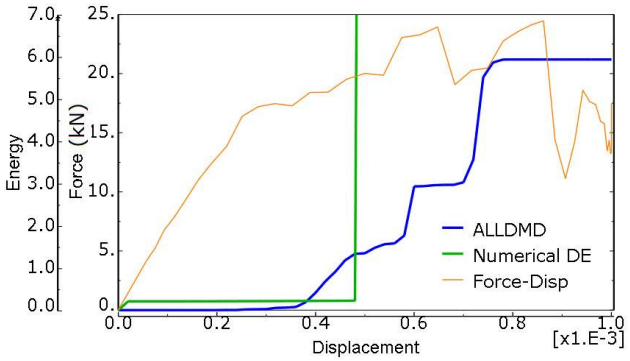

Fig. 9. Comparison between the numerical DE and the Abaqus DE parameter, with the force-displacement history. Specimen loaded along the y-direction.

Possible causes for this behaviour are not immediately clear; when considering the pure rotation results as shown in Fig. 10, the comparison between the numerical DE and ALLDMD is much closer after stopping at the first sign of softening. Yet the numerical DE still seems to initiate energy dissipation at an earlier stage – as was also the case in the pure tensile simulation in Fig. 8. The very close comparison achieved with the pure tensile case suggests that the ε_{22} and ε_{12} directions are not discretised well enough or that more loadcases with shear and rotational components are required to better characterise the material behaviour.

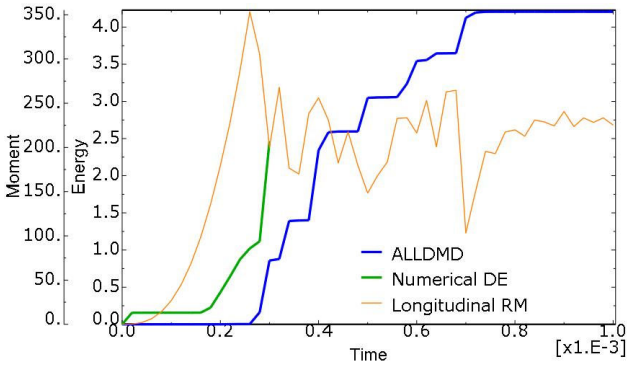

Fig. 10. Comparison between numerical DE, the Abaqus ALLDMD parameter, and the reaction moment along the z-direction. Specimen loaded under pure rotation.

Conducting an additional biaxial simulation with both tensile and shear displacements, and comparing the resultant dissipated energies again supports the

importance of the experimental testing or synthetic data covering as much of the strain space as possible. Fig. 11 shows the result of such a simulation where reasonable correlation is seen between the two dissipated energies despite the poor performance of shear on its own. Fig. 11 also illustrates how the DED method is still able to predict DE for a multi-axial loading case where non-linear material behaviours due to the combined loading are beginning to take hold.

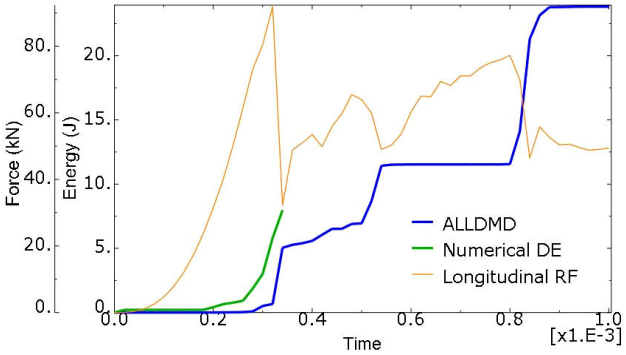

Fig. 11. Comparison between the numerical DE and the Abaqus DE parameter, and the reaction force along the z-direction for a biaxial loading case.

4.4 Open-hole specimen

Simulation of OH specimens allows for an assessment of the methodology on a very common feature of aerospace structures. Strain concentrations such as holes exist all over an aircraft from riveted joints to cut-outs. Of the six OH experimental configurations investigated by Orifici et al. in a companion paper [8], one configuration was chosen for a preliminary investigation using the DED methodology.

The configuration investigated used a 24-ply AS4/3501-6 laminate with ply sequence $[45,0,-45]_{4S}$ and a hole of diameter 25.4 mm. The specimen dimensions and loading conditions are given in Fig. 12.

The results of the numerical analysis for an elastic model using the DE data and a model applying the Abaqus damage model are shown in Fig. 13. Interestingly, the stability and reduced non-linearity afforded by a larger specimen with a small displacement loading means that the numerical DE is still an acceptable magnitude at the full extent of the displacement. It still appears however to have experienced the same over prediction upon entering the non-linear portion of the loading regime.

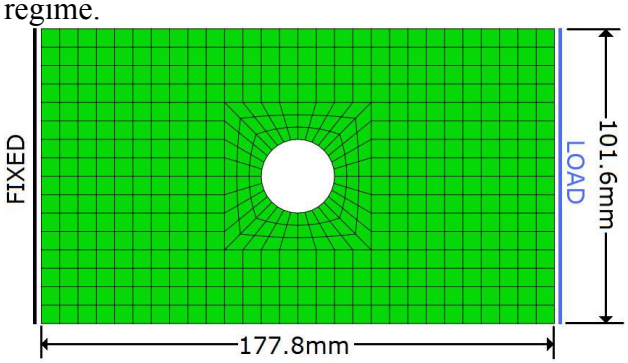

Fig. 12. OH FE model, clamped on one end and loaded on the other, with free edges.

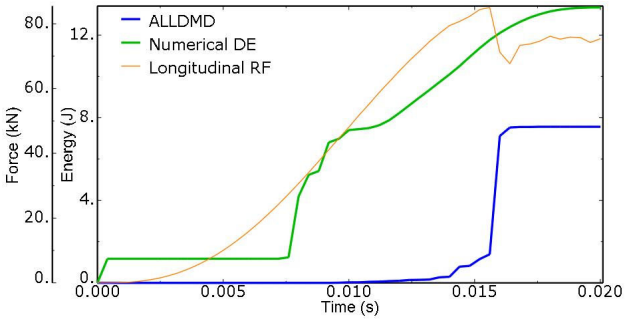

Fig. 13. Comparison between the numerical DE and the Abaqus DE parameter ALLDMD, and the longitudinal reaction force along the z-direction.

Again, the numerical DE has initiated earlier than predicted by the Abaqus ALLDMD parameter and also reached a greater magnitude once loading has finished. A current limitation with the subroutine used in this analysis was the use of a constant element area. This was initially used to simplify coding and reduce analysis time. However, this can have the effect of slightly magnifying the DE at the lower strain levels experienced over the majority of the specimen, giving the impression of early initiation, and over-estimation towards the end of the analysis as the strains affected by the stress concentration are multiplied by a larger area than necessary.

Fig. 14 shows a contour of the maximum in-plane strains, where as expected higher strains were seen at the hole edges. This contour corresponds to the surface 45° ply, where the 0° plies would be carrying the majority of the load.

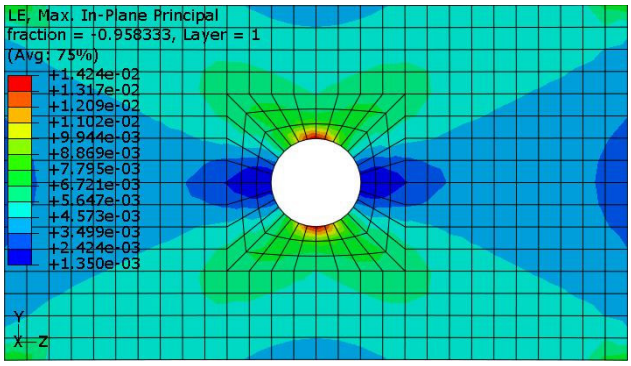

Fig. 14. Maximum in-plane principle strain at 90.6% of the total displacement.

By visualising the DE in contour form, the progression of DE can be observed. This is seen in Fig. 15, which shows DE at axial displacements of 0.1 mm, 0.49 mm and 0.90 mm.

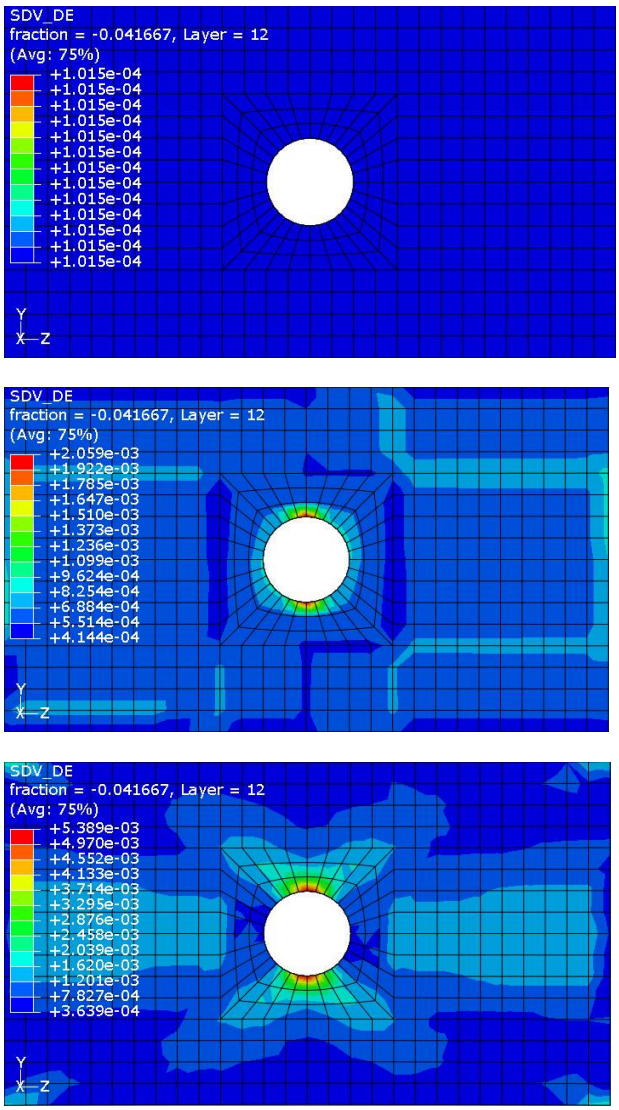

Fig. 15. DE contours at applied displacement.
Top: 0.1 mm. Middle: 0.49 mm. Bottom: 0.91 mm

At an axial displacement of 0.5 mm, approximately 0.002 J per ply or 0.5 J over the full thickness has been dissipated just in the immediate region at the edge of the hole. At 0.91 mm axial displacement, DE has progressed further from the hole edge with the outer reaches now at a similar level of DE as the previous maximum. DE has also increased to 0.13 J over the thickness in the region adjacent to the hole. In the analysis using the Abaqus damage model, ALLDMD begins to record energy being dissipated at around 0.012s, quickly reaching 8 J total DE. Interestingly, if not for the early initiation, the numerical DE would also be close to 8 J before entering the non-linear regime and increasing again sharply.

Switching from a uniform element area to element specific areas has been found to delay the initiation of DE and reduce the overall magnitude in analyses of CH specimens. After assigning the correct areas for the OH model, a similar change in the DE is expected to occur. Referring to Equation (1), the DE equals the volume integral of the dissipated energy density function and for this reason the area and thickness, and hence volume attributed to a strain coordinate is very important.

More recently, work has focused on integrating a constitutive model based on DE, whereby the DE signals the softening of the material and true non-linear damage progression can occur. This later work will provide a proper basis on which to validate the methodology and will be the subject future publications.

6 Conclusion

An energy-based methodology that uses multi-axial testing and dissipated energy to characterise a linear dissipated energy density function, has been implemented into a commercial FE package. The DED function is postulated to be a property of the material, and has been determined for a composite laminate material. In this function the coefficients represent the magnitude of dissipated energy density at known locations in a discretised strain space. Incorporating data characterised from "synthetic" experimental data, the methodology was tested on double-notch characterisation

specimens and early comparisons indicate mixed results. A satisfactory prediction of the DE was achieved for pure tensile loading whilst pure rotation and pure shear loading cases resulted in slight over-predictions and early initiation. Interestingly the prediction improves for a biaxial loading case combining tensile and shear loading. Applying the methodology to a more relevant problem in the form of an OH specimen was successful in rendering accurate DE contours showing DE progression and energy magnitudes in line with the DE predicted by the FE solver. Material volume attributed to strains and coverage of the strain space have been identified as important factors in achieving an accurate and robust constitutive model relying on DE.

Acknowledgements

This research is part of the Research Program of the CRC-ACS, and is partly supported by the US Office of Naval Research under NICOP grant N00014-07-1-0514. The authors gratefully acknowledge Mr David Elder of CRC-ACS for assistance with the synthetic data packages.

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