DISSIPATED ENERGY BASED DAMAGE MODELLING IN CFRP NOTCHED COUPONS WITH MULTI-AXIAL FAILURE DATA

A.J. Litchfield[1]*, R.S. Thomson[2], S. Feih[1], A.C. Orifici[1]
[1] School of Aerospace, Mechanical and Manufacturing Engineering,
RMIT University, GPO Box 2476, Melbourne, Victoria 3001, Australia
[2]Cooperative Research Centre for Advanced Composite Structures Limited
506 Lorimer Street, Fishermans Bend, Victoria, 3207, Australia
* Corresponding author (a.litchfield@student.rmit.edu.au)

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

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. A DE based degradation model has been implemented and evaluated against the synthetic test data used to characterise the initial model. The energy based methodology has been shown to accurately predict the DE response for a range composite layups and geometries under multi-axial loading. A constitutive relationship between the DE and material stiffness was formed and was successful in demonstrating that the mechanics of the approach were sound. This relationship also highlighted that a more accurate prediction of material response could be achieved with further improvement of the material characterisation.

1 Introduction

Current structural designs utilising fibre reinforced polymer (FRP) composite materials are yet to exploit their full load-carrying capacity due to the difficulties in capturing material behaviour up to and including failure. The present design and certification of FRP composite structures is based on using experimental data from limited single axis tests and extrapolating this to actual structures. This becomes difficult and unsafe when extrapolating to conditions and configurations outside the range of tests and leads to the requirement for expensive experimental testing at all critical length scales.

In response, an approach has been developed based on characterising material behaviour in the complete loading space through multi-axial testing [1]. Generation of composite material data under multi-axial loading captures the unique non-linear responses created under combined loading – more relevant to in-service structures and also not captured by standard uniaxial testing. Accurately capturing and then modelling this behaviour has the potential to increase reliability and reduce the time and cost of the design and validation cycle by removing tiers of the building block approach. A better understanding may also allow the safe operation of composite structures with reduced conservatism.

In this work we build upon the implementation of the approach [2] and constitutive law functionality [3] to testing of the damage model on multiple specimens and multi-axial loading.

2 Multi-axial material characterisation

The analysis methodology uses an approach to characterise strain-induced damage based on the energy dissipated by a material undergoing irreversible damage processes [1]. As demonstrated in Fig. 1, the DE is simply calculated as the difference between the total absorbed energy (W) given by the integrated area under the force-displacement curve and the triangular recoverable elastic energy (R) area created by linearly unloading back to zero.

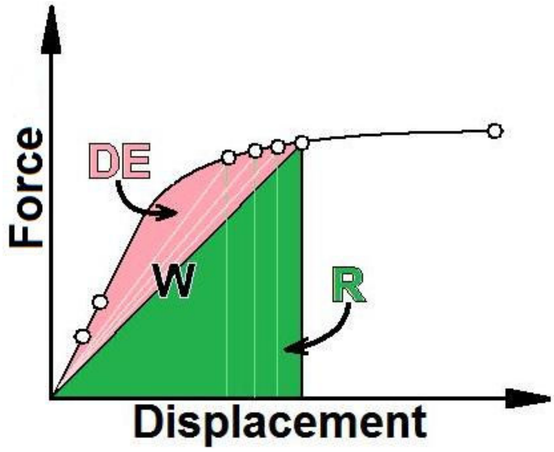

Fig.1. Idealised schematic of the total absorbed (W), recoverable (R) and dissipated (DE) energies.

The DE is considered a measured quantity since it is directly computed from these two measured energies.

A mechanical strain-based dissipated energy density (DED) function, fully characterised from experimental data, describes material behaviour in the linear and non-linear regimes in terms of this dissipated energy (DE) [4]. The DED function is determined via a data-driven inverse methodology based on the load-displacement response of a specimen. It has been postulated [1] that there exists a scalar function ϕ which expresses a measure of this dissipated energy density per unit of volume of material, which only depends on the strains and the material used in the structure, as shown in Eqn. 1.

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

The material dependent characterisation constants, c, represent the DED at known locations within the strain space. Variables χ and V represent the basis functions dependent upon strain and the volume at the point p, respectively. Both c and χ 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. Using Matlab [5], 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. To enforce this, the numerical optimisation is bounded by a minimum of zero. The characterisation constants are shown in Fig. 2.

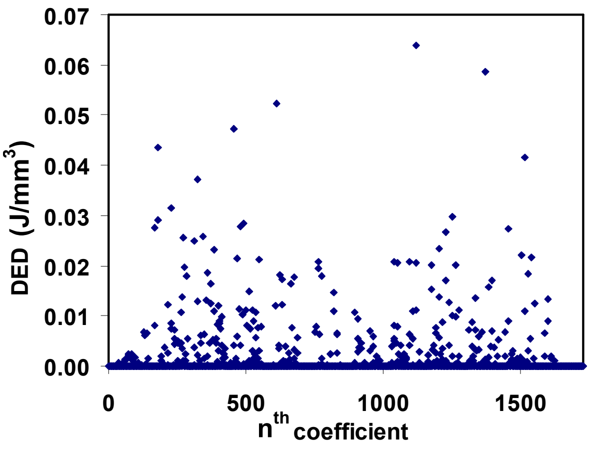

Fig. 2. Coefficients of dissipated energy density.

The volume integral of the DED function equals the energy dissipated by the various damage modes occurring within the material. This captures the collective behaviour of the damage mechanisms without needing to know the precise damage events. Once characterised, the DED function can relate the strain at any point in the material to the energy per unit volume dissipated due to the cumulative irreversible effects of all damage mechanisms. In this way, the DED function can then be related to local stiffness changes and be used to model non-linear material behaviour.

The DED function is characterised using an extensive set of multi-axial test data obtained from custom-built multi-axial mechatronic loader machines. These machines are capable of applying displacement paths embedded in multiple degree of freedom (DOF) loading spaces, or from suitably representative finite element (FE) models generating "synthetic" or virtual test data. Synthetic test data is suitably representative of experimental test data, and is more advantageous for development and demonstration of the analysis approach as it removes experimental error, variance and unknown damage modes and phenomena. Further discussion and detail on the generation and application of synthetic data is provided in a previous publication [6]. Briefly, three degree-of-freedom multi-axial data was generated by modelling the configuration of the double notch characterisation specimens, as shown in Fig. 3.

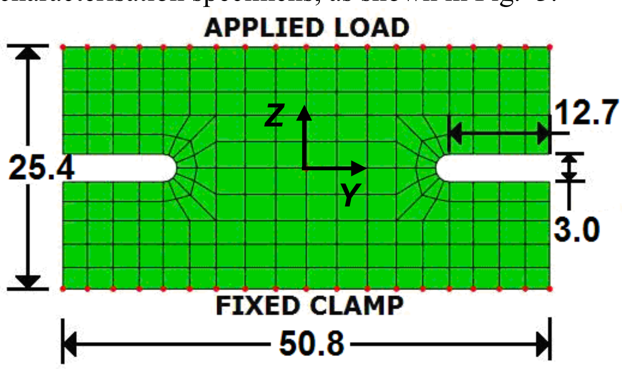

Fig. 3. Geometry and dimensions (mm) of the double-notch specimen.

Using the commercial FE software package Abaqus, this was achieved using a single layer of quadrilateral shell elements. To capture dissipated energy a 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: 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. During this process, Abaqus calculates the energy associated with all damage modes, ALLDMD [7]. Table 1 lists the ten unique loading combinations chosen to cover the loading space, as applied to four different layup configurations $[\pm 15]_{16}$, $[\pm 30]_{16}$, $[\pm 60]_{16}$ and $[\pm 75]_{16}$.

Table 1. In-plane 3DOF loadcase vectors

Loadcase	Longitudinal (Z) (m)	Shear (Y) (m)	In-plane Rotation (rad)
1	-0.001000	-	-
2	-0.000707	-	0.084853
3	-0.000707	0.000707	-
4	-0.000500	0.000500	0.084853
5	-	0.00100	-
6	-	0.000707	0.084853
7	0.000707	0.000707	-
8	0.000500	0.000500	0.084853
9	0.001000	-	-
10	0.000707	-	0.084853

To be able to analyse the development of damage within notched CFRP, the DED coefficients and strain space data were incorporated into Abaqus. This was done through the use of a “passive” subroutine written in the Fortran environment, which interacts with the numerical solver, reading in strains and outputting DE [2].

3 Analysis utilising the DED characterisation

The analysis methodology was applied to the double-notch coupons with several laminate types and open hole tension specimens of varying laminates and geometries. The double-notch coupons were investigated under a range of multi-axial loading combinations of in-plane tension, shear and rotation. The progression of DED and material softening was studied, and compared to both experimental data and analyses using separate damage models available in Abaqus [7].

Each loadcase used to generate the characterisation data was repeated whilst overlaying the passive subroutine. In this way the ALLDMD energy measure from Abaqus could be compared with the DE prediction using the DED methodology. In the interests of brevity, only one example will be given; Fig. 4 shows a close comparison was achieved and this demonstrates that the DED was well characterised for the strain states encountered. The initiation and overall behaviour of the DE is well captured, despite the complex loading and strain state. Interestingly, more accurate DE predictions were often achieved for bi or tri-axial loadcases than for uniaxial cases.

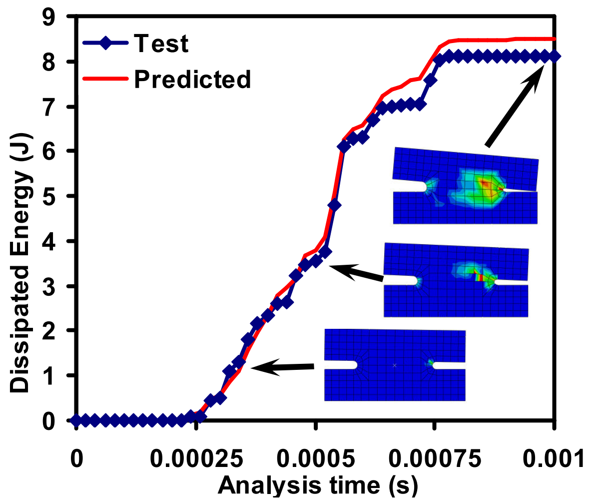

Fig. 4. The progression of DE for a $[\pm 30]_{16}$ double notch specimen under simultaneous compression, shear and rotational displacement.

The purpose of the multiple layup configurations and double-notch geometry was to achieve the greatest coverage of the strain space for a given material. Achieving this, the DED characterisation constants could then be applied to a layup and geometrical configuration not explicitly tested.

Open holes are a prevalent feature of composite aircraft structures, and are relevant to structural features such as bolt holes as well as more generally to notched composite behaviour. Using a specimen configuration previously investigated in experimental testing [8], Fig. 5 provides an example of the progression of DE and associated local DE contours for an open hole $[45/0/\text{-}45]_{4S}$ CFRP coupon under displacement controlled loading, as compared with the Abaqus DE parameter ALLDMD.

Despite neither the ±45° nor 0° layup angles being included in the characterisation data, the appropriate material response has been captured in the multi-axial data. The DED methodology has again closely captured the initiation and progression of the DE. The steady increase in DE with the slow spread of diffuse damage modes is accurately captured, as well as the sudden increases in DE following high energy damage events such as fibre breakage occurring over a small incremental displacement.

The results of the investigation indicated the broad functionality of the analysis methodology across a range of geometries, layups and load combinations. Critically, the results further confirmed the approach of using material data characterised from a single configuration tested under multi-axial loading for the response predictions of other specimen configurations and loadings using the same material.

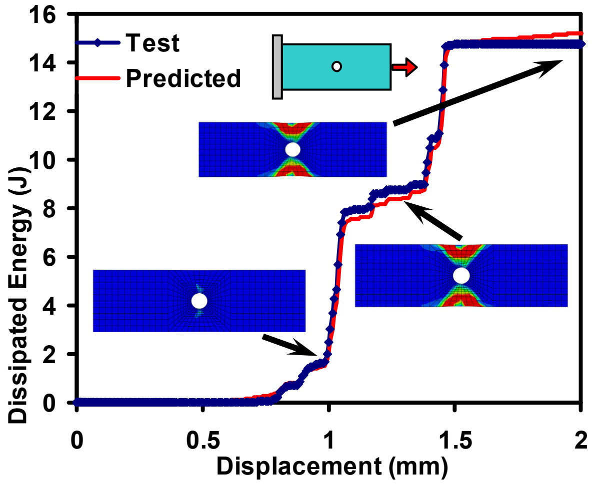

Fig. 5. The progression of DE in an 12.7 mm open hole specimen under tensile displacement, DE contour shown for the 0° ply.

4 DED based analysis for constitutive modelling

After implementation, the subroutine was then made "active" by incorporating a constitutive material law [3]. The stiffness of the material was progressively degraded using a single damage factor, *d*, calculated based upon a relationship between the DE and the total absorbed energy imparted, given by

$$W - DE = (1-d)W; \qquad d = \frac{DE}{W} \tag{2}$$

For consistency with the characterisation approach it was assumed that all components of the orthotropic compliance matrix were degraded by the same amount, yielding the matrix given in equation (3).

$$\begin{bmatrix} (1-d)C_{11} & (1-d)C_{12} & (1-d)C_{13} & 0 \\ & (1-d)C_{22} & (1-d)C_{23} & 0 \\ & & (1-d)C_{33} & 0 \\ sym & & & (1-d)C_{44} \end{bmatrix} \tag{3}$$

A flow chart of this analysis procedure is shown in Fig. 6. During an analysis, once the new strain increment is calculated, the magnitude of DE is then calculated from the current strain state and the resultant damage factor, *d*, found. If DE is zero, then *d* will be zero and the material will remain undamaged. Once the DE increases, the new stress state is calculated for the degraded material stiffness and passed back to Abaqus along with the internal energy ready for the next increment.

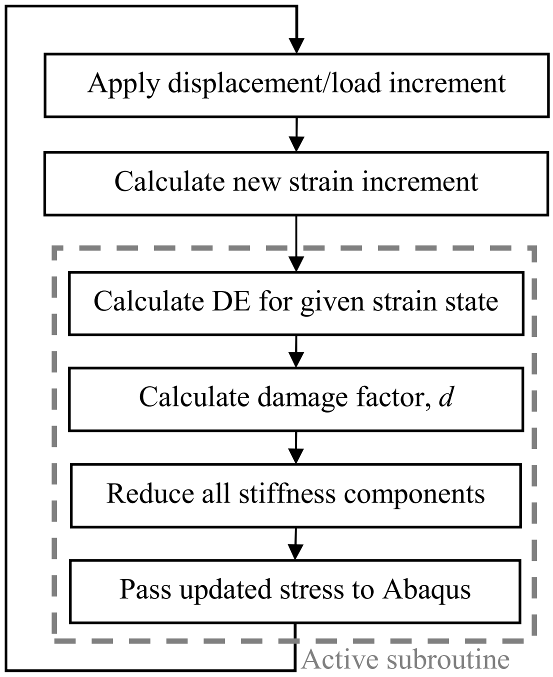

Fig. 6. Active VUMAT subroutine process.

In previous work [2], the functionality of the method was demonstrated and analyses of only single axis loading cases performed. Fig. 7 shows the progression of the damage factor at three severe locations for the double-notch $[\pm 30]_{16}$ laminate during loadcase 4 from Table 1.

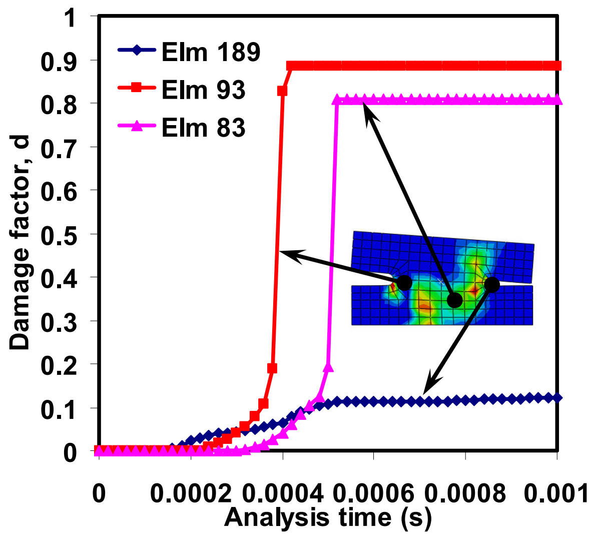

Fig. 7. Evolution of the damage factor at three element locations over an analysis.

As the strain field triggers the increase in DE the damage factor can also be seen to steadily increase, reaching almost 90% stiffness loss in areas of intense DE. The resultant DE comparison for this loadcase is shown in Fig. 8.

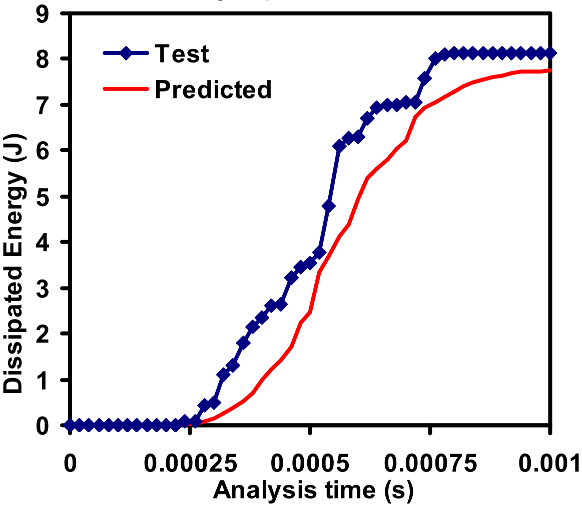

Fig. 8. The progression of DE for a $[\pm30]_{16}$ double notch specimen under simultaneous compression, shear and rotational displacement using the VUMAT subroutine.

The predicted DE initiates and tracks well with the Hashin DE but does not achieve the same accuracy as before. This effect is also more pronounced when observing the more extreme case of $[\pm15]_{16}$ under tensile displacement, as shown in Fig. 9. Under this loadcase the material experiences large step changes in the strain field as high energy absorbing damage mechanisms suddenly occur (fibre fracture).

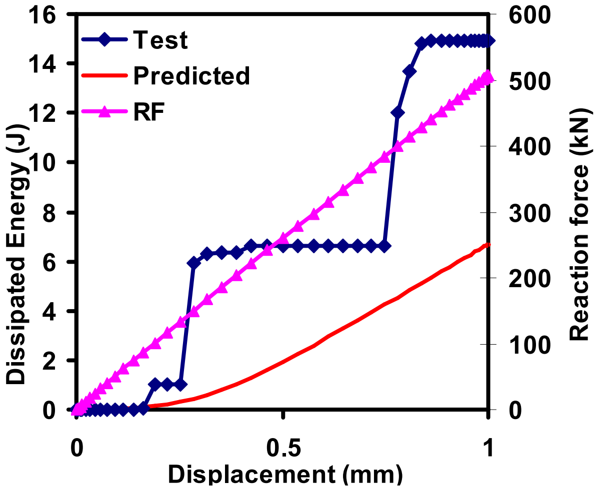

Fig. 9. The progression of DE and the longitudinal reaction force for a $[\pm15]_{16}$ double notch specimen under tensile displacement using the VUMAT subroutine.

Since the magnitude of DE controls the level of stiffness degradation and the stiffness affects the next strain increment, the large changes in strain have not occurred and as a result the DE presents a smooth progression and the reaction force does not indicate a drop in load carrying capacity.

Examining the material response in detail it was found that the local DE at each element was not the same as the local DE response of the characterisation data. In the interests of isolating the cause of the linear global response, the local DE from the characterisation data was recorded for each element. This DE history was then used as input for the VUMAT analysis. This allowed the performance of the single parameter damage model to be assessed without depending upon any mismatch in local DE. Fig. 10 illustrates how this affected the multi-axial loadcase using the $[\pm30]_{16}$ laminate as previously shown in Fig. 8. The compressive component of the longitudinal reaction force was found to more accurately reflect the behaviour seen in the characterisation data. The degradation in stiffness changed the strain field and the resultant DE prediction also improved over the initial analysis given in Fig. 8.

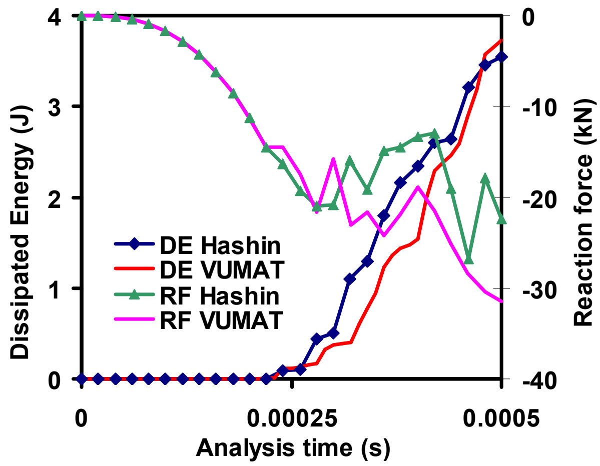

Fig. 10. Longitudinal compressive force and DE progression for a $[\pm30]_{16}$ double notch specimen under compressive, shear and rotational displacement.

Interestingly, matching the local DE history proved that when an accurate DE response is generated, the associated force-displacement response of the material matches the characterised material. This exercise demonstrated that even a single damage factor, applied to the entire stiffness matrix, was capable of producing realistic force-displacement responses.

The form of the constitutive relationship based upon the DE was not the primary factor governing the material response, but rather the accuracy of the local DE prediction. This suggests that improving the local DE prediction will directly affect the local initiation of stiffness degradation, load redistribution and further failure. Considering this, it follows that the accuracy of the remainder of the material response is highly dependent on the behaviour of the analysis in the first few increments of damage.

As previously described, the calculation of DE is based solely upon the strain field, characterisation constants and material volume. Initiation and behaviour of the global force response appears to be linked to the initial energy dissipation; improving the characterisation of the strain/DE relationship at the beginning of non linearity is desirable and is the subject of ongoing research.

Conclusion

Comparing the analysis methodology results to synthetic data sets and Abaqus analyses demonstrated a number of benefits and also challenges involved in applying damage data that incorporates the cumulative effect of all damage mechanisms. In particular, the identification of failure initiation and the robust prediction of local dissipated energies were found to be critical areas of further research. The DED methodology has been proven to provide accurate global predictions of DE, across a range of composite layups and geometries, when provided with accurate strain fields. When replicating the global DE response driven by sudden, high energy failure events, the initiation and progression are well captured when using the passive subroutine. When the damage onset is more gradual the comparison is slightly improved. The implementation of a DE-based constitutive model using a single parameter damage model demonstrated realistic behaviour. A better global material response will be achieved with further improvement in the local DE prediction.

Acknowledgements

This research is part of the Research Program of the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) Limited, and is partly supported by the US Office of Naval Research under NICOP grant N000140-71-05-6-8.

References

[1] Mast, P.W., Nash, G.E., Michopoulos, J.G., Thomas, R., Badaliance, R. Wolock, I. “Characterisation of strain-induced damage in composites based on the dissipated energy density: Part I to III”, *Theoretical and Applied Fracture Mechanics*, Vol. 22, pp. 71-125, 1995.

[2] Litchfield AJ, Thomson RS and Orifici AC. “Analysis of damage development in CFRP notched coupons with energy-based multi-axial failure data”. *27th Congress of the International Council of the Aeronautical Sciences*, Nice, France, 19-24 September 2010.

[3] Litchfield AJ, Thomson RS and Orifici AC. “Response characterisation in CFRP notched coupons with energy-based multi-axial failure data”. *14th Australian International Aerospace Conference (AIAC-14)*, Melbourne, Australia, 28th February to 3rd March 2011.

[4] Michopoulos JG, “Mechatronically Automated Characterization of Material Constitutive Response”, *WCCM VI in conjunction with APCOM’04*, Sept. 5-10, 2004, Beijing, China, 2004.

[5] The Mathworks, “Matlab”, http://www.mathworks.com

[6] Orifici AC, Michopoulos JG, Elder D, Herszberg I. “In-plane damage and failure modelling for the development of a multi-axial characterisation methodology”, *13th Australian International Aerospace Congress (AIAC-13)*. Melbourne, Australia, 9-12 March, 2009.

[7] Abaqus 6.8 Documentation, Dassualt Systèmes Corporation, Providence, RI, USA, 2008.

[8] Orifici AC, Thomson RS, “The effect of ply thickness and notch size in CFRP tension specimens”, *14th Australian International Aerospace Conference (AIAC-14),* Melbourne, Australia, 28 February - 3 March, 2011.