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ADEPT Project Final Report

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Project 2.3.4

Commercial-in-Confidence

Summary

The ADEPT project aimed to improve the effectiveness of the prediction of the overall behavior, including failure, of composite structures. The project sought to provide a valid alternative to the traditional building block approach used in the development and certification of aerospace composite structures. The four and a half year project, part funded by the United States Office of Naval Research (ONR), involved collaboration between the Cooperative Research Centre for Advanced Composite Structure (CRC-ACS), Massachusetts Institute of Technology (MIT), the Naval Research Laboratory (NRL) and Virginia Tech (VT). The NRL multi-axial loader was successfully upgraded, and demonstrated the capability to test up to 26 specimens per hour. This was integrated with a 2D and 3D full-field measurement system, and means developed to deal with the massive data output integration. Coupled with this, experimental design methods were developed to enable real time determination of load paths to minimise testing while ensuring that the full strain space is sampled. From this test data, both total and dissipated energy based methodologies were established and implemented into commercial FE codes to predict initiation and progression of damage in composite structures. Validation of the methods was completed using test data from open-hole tension, ply-drop and stiffened panel tests. Length scale effects were characterised and documented using photographic and CT scanning methods. Lengthscale was found to affect the failure initiation load, the final failure load and the failure mode and conversely, constitutive characterization was found to be independent of lamina layer thickness scaling. The ADEPT project demonstrated that there is a viable, cost effective alternative to traditional design and certification techniques for composite structures.

Comment [AO1]: Need to spell out acronym?

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Acknowledgements

The ADEPT project collaborators wish to acknowledge the invaluable support and guidance to the project outcomes of the responsible ONR Project Officer, Dr Ignacio Perez.

Comment [AO2]: Roger Crane? He's volunteered a lot of time throughout the project. And Israel?

Comment [j3]: Rojer is not formally associated with the project, but we can have a a second paragraph for all those including Roger that, helped Ignacio

I feel that we should have a special reference to Israel. JM

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1 Introduction

1.1 Overview

ADEPT - **A**pplication of **D**issipated **E**nergy density to com**P**osite s**T**ructures - project focused on improving the effectiveness of the prediction of the overall behavior, including constitutive response and failure, of composite structures. Despite over a quarter century of work on understanding and characterizing the failure of composite materials and their structures, the ability to predict such failure is still quite lacking. In large part due to this lack of understanding, composite structures currently are designed and certified/validated for safe operating by using a primarily empirically-based methodology known as the "Building Block Approach" along with "knockdown factors". This results in certain conservatism, with a fraction of the full capability of the basic material capacity utilised in the structural design. A key item that is lacking is the ability to effectively utilize data and observations made at length-scales associated with laboratory-sized specimens in predicting the actual behavior manifested in full-scale structures.

Comment [AO4]: US vs UK spelling? It's mixed throughout. (I can go through and edit if you like, but not sure if you care too much)

Comment [j5]: Since the funding organization is in the USA and per the specification of hte reporting process we shoul try to use tUSA English JM

These issues were first addressed in this work primarily via the effort of characterizing the overall behavior at the baseline level. From there, the issues associated with increasing levels of structural complexity and higher orders of structural lengthscale were characterized (e.g., stress field gradients, manifestation of different damage mechanisms). ~~and t~~The results characterized at lower levels ~~are~~ were ~~to be~~ used in associated efforts via the total or Dissipated Energy Density to bring that knowledge to the higher levels of complexity and lengthscale. With such an overall methodology established, the ability to guide the overall design process will be increased, thereby reducing the number of experiments which would substantially reduce cost and overall risk in structural development, as well as lead to fuller utilization of basic material capacity.

ADEPT was a collaborative research project involving the following partners:

- Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) - Key contributors to the CRC-ACS effort were staff from University of New South Wales (UNSW) and RMIT University (RMIT)
- US ~~Navy~~ Naval Research Laboratory (NRL)
- Massachusetts Institute of Technology (MIT)
- Virginia Tech (VT) - became a partner after Dr Tomonari Furukawa~~'s~~ moved there from UNSW

The project was funded through a NICOP grant from the US Office of Naval Research (ONR), which provided 50% of the initial budget.

The project started in July 2007 and was scheduled to finish June 2010. Due primarily to delays in testing, the project was extended until December 2011.

1.2 Aims and Objectives

The four-year research project aimed to develop a cost-effective, validated methodology for the determination of mechanical behaviour leading up to and including failure in complex fibre reinforced polymer composite structures.

The objectives of the project were as follows:

1. Build upon and extend the NRL data driven, constitutive material characterization approach to develop a methodology for the determination of mechanical behaviour in complex composite structures subjected to realistic loading conditions, which addresses degradation in structural performance and structural failure in as-produced and damaged composite structures.
2. Validate the methodology through testing on coupons and subcomponents at ambient conditions with a focus on issues of length-scales manifested across this range.
3. Develop an overall approach to couple the methodology with commercial software for calculating stress state and assessing overall structural behaviour.

This work focused on a carbon/epoxy system composites manufactured from uni-directional prepreg.

1.3 Background and Approach

Over the past decade, researchers at NRL have developed an approach that identifies constitutive behavior of advanced composite laminates by quantifying their deformation on a continuum basis. The novelty of this approach lies in this continuum-based methodology as well as the use of an automated multi-axial testing machine to rapidly and cost effectively conduct reliable material characterization. At the commencement of ADEPT, this methodology had been developed and utilized to create an energy density based failure model. In principle, the methodology may be applied to various constitutive and failure models, in order to provide the required calibration via experimental data. A number of current models were assessed for their suitability to be used in this manner with the composite material characterization methodology.

The ADEPT program aimed to extensively develop and generalize this data driven, constitutive material characterization methodology using an automated and custom-made mechatronic six-degree-of-freedom loading machine. The methodology to be developed included the determination of mechanical behavior, leading up to and including failure, in complex composite structures subjected to realistic loading conditions. It also addressed degradation in structural performance and structural failure, including issues of damage growth. An important component of the material characterization process involved the development of sophisticated experimental design techniques which was used to optimize the generation of experimental data and to ensure that the data spans the strain-state field.

In order to validate and appropriately adapt the methodology, a testing program was to be conducted testing coupons and small substructures at ambient conditions, with a focus on issues of extension through lengthscale range including observation and documentation of issues of damage initiation, damage growth, and final failure. To enable the widespread use of the developed methodology, a key aspect of the project was implementation of the methodology into commercial software for calculating stress state and assessing overall structural behaviour.

1.4 Activities and Milestones

The project activities and milestones are described in Table 1, including the lead organisation responsible for the delivery of each milestone.

Table 1: ADEPT Tasks and Milestones

Task	Milestone	Planned Dates	Milestone Description	Lead
TASK 1: Upgrade Multidimensional Loading System				
	Milestone 1: Upgrade NRL Multidimensional loading system incorporating whole field strain measurement.	1 Jan 07 – 30 Sep 08	The NRL multiaxis loading and material characterization system is to be refurbished and upgraded. This is to include the following sub-tasks: re-establish actuator functionality; enable grip functionality; incorporate boundary displacement subsystem; enable functionality of load-cell subsystem; adapt and implement a non-contact whole field displacement measurement method; system software integration; develop data reduction	NRL
TASK 2: Assessment of Constitutive Modelling and Failure Theories				
	Milestone 2: Critical review on constituent modelling and failure.	1 Jan 07 – 30 Sept 07	The critical literature review will incorporate: constitutive modelling; failure analysis; implementation in commercial finite element packages; application to a range of fibre reinforced plastic material systems.	CRC-ACS
	Milestone 3: Assessment suitability and select candidate techniques for further study	1 July 07 – 30 Jun 08	The assessment of the suitability of the various techniques for characterisation using the NRL system will include their reformulation in terms of energy density criteria. A ranking system will be developed for the various techniques and one to three criteria/techniques will be selected for further study	CRC-ACS
TASK 3: Generalization and Experimental Design				
	Milestone 4: Implicit constitutive modelling via ANN	1 Oct 06 – 31 Dec 07	Implicit constitutive models using ANN will be created for a range of fibre reinforced plastic material systems directly from experimental data without analytical formulations. The reductions of model errors and analytical formulation processes by this technique will be quantified to examine its superiority to the existing constitutive	CRC-ACS
	Milestone 5: Optimal Experimental Design	1 Jan 07 – 30 Jun 09	Optimal experimental design will focus on the use of the NRL multiaxial testing system, however, systems will be developed based on unidirectional and bidirectional testing. A whole field strain measurement system will be developed and the experimental design will be based on the use of such a system.	CRC-ACS
	Milestone 6: Constitutive characterization: deterministic and stochastic	1 Apr 07 – 30 Jun 10	In addition to the conventional deterministic constitutive characterization techniques, stochastic techniques, which take the characteristics of system and measurement noises into account, will be developed. Upon the characterisation of noises, the performances of the deterministic and stochastic techniques will be further	CRC-ACS
TASK 4: Material Characterisation				
	Milestone 7: Select and characterise a carbon/epoxy material system	1 Apr 07 – 30 Dec 09	A material system will be selected for further study. Coupons will be manufactured according to the design determined in MS5 and tested according to the optimal procedure developed in MS 5. The emphasis will be on testing in the NRL facility, however, some uniaxial and biaxial testing will be conducted at the CRC-ACS.	CRC-ACS
TASK 5: Develop methodology				
	Milestone 8: Development of simulation methodology - Coupons	1 Apr 07 – 31 Dec 08	Develop methodologies for the determination of mechanical behavior leading up to and including failure in fiber reinforced plastic composite structures, constructed from the characterised material system.	CRC-ACS
	Milestone 9: Development of simulation methodology - Substructure	1 Jul 08 – 30 Jun 09	Develop methodology for representative substructure	CRC-ACS
TASK 6: Incorporate into Commercial FE package				
	Milestone 10: Incorporate into commercial Finite Element package	1 Jul 07 – 30 Jun 10	Incorporate methodology into commercial FE package. Verify implementation for prediction of mechanical response.	CRC-ACS
TASK 7: Coupon and Small Structure Validation				
	Milestone 11: Testing coupons	1 Jan 08 – 30 Jun 09	Validate and appropriately adapt the methodology through testing coupons at ambient conditions, with a focus on issues of extension through lengthscale range including observation and documentation of issues of damage initiation, damage growth, and final failure.	CRC-ACS
	Milestone 12: Testing - Substructures	1 Jan 09 – 30 Dec 09	Validate and appropriately adapt the methodology through testing small substructures at ambient conditions through observation and documentation of issues of damage initiation, damage growth, and final failure.	CRC-ACS
	Milestone 13: Assess Capability of Methodology to Address Lengthscale Issues	1 Jun 07 – 30 Dec 09	Assess capability of methodology to address lengthscale issues.	MIT
	Milestone 14: Extension of methodology for damage progression	1 Jun 07 – 30 Jun 10	Extend developed methodology to predict the structural response beyond the initiation of failure.	CRC-ACS

Comment [AO6]: This table has tiny font. Can we remove the "milestone description" column, and put that in a separate table of paragraph of text? Not so critical I guess…

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1.5 Final Report Structure

This final report presents an overview of all activities that were undertaken with ADEPT. In Section 2, the constitutive modelling and failure theories review (MS2 and MS3) is summarised. In Section 3~~3~~, the upgrade of the NRL multi-axial loader (MS1) and characterisation testing (MS7) is described. Section 4~~4~~ presents a summary of the experimental design work undertaken (MS4, MS5 and MS6). In Section 5~~5~~, the validation testing is described, including open hole, ply drop (MS11) and stiffened panels (MS12). In Section 6~~6~~, the simulation methodology development and validation for coupons (MS8), substructures (MS9) and incorporation into commercial FE codes (MS10) is described. Also described in this section is the extension of the methodology for damage progression (MS14).~~ Section 4 presents a summary of the experimental design work undertaken (MS4, MS5 and MS6).~~ The methods and findings related to lengthscale (MS13) are described in Section 7~~7~~. The project outcomes and achievements are detailed in Section 8 of the report. A bibliography is presented containing all publications arising from the project, and key technical papers are presented in the appendices.

2 Critical Review on Constitutive Modelling and Failure

A review has been conducted of methodologies for modelling constitutive behaviour and failure in fibre-reinforced polymer composites. Methods for constitutive modelling were reviewed, and were classified as either explicit, implicit or hybrid, depending on the extent to which physically-based theories were used to describe the material stress–strain behaviour. The failure mechanisms of fibre fracture, matrix cracking, buckling and delamination were listed as the key damage mechanisms for a composite ply in a laminate. The characterisation of composite failure in terms of strength or fracture mechanics theories was covered, with reference to the methods for experimentally determining material limits.

A comprehensive review of failure criteria was presented, where criteria were categorised in terms of the failure type predicted, which included fibre, matrix, shear, ply, delamination initiation and delamination growth, with separate categories for tension, compression and general equations. This was followed by a review of common methods for damage modelling, which were all shown to relate to the concept of damage mechanics, in which damage equations are incorporated in the material constitutive behaviour. The issues of length scale were discussed, which is critical for an analysis approach to apply from scales ranging from the ply to the structural level. This was followed by a review of various finite element codes in terms of the implementation of user-defined material behaviour.

The various failure criteria and modelling approaches were discussed within the context of the DED framework. The difficult task of comparing failure criteria to each other was discussed, and the notable work in literature in this regard was highlighted. It was found that most criteria could be applied in combination with the DED approach, due to the incorporation of the DED function within the material stress-strain behaviour. Furthermore, the reducibility of failure criteria under certain conditions was noted, as was the direct relationship of most criteria to criteria based on energy density. The benefits of the successful application of a 6-DOF material characterisation approach were discussed, and reference was made to the 6-DOF loading machine developed at NRL.

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The details and outcomes of the review have been published in Refs. 13~~13~~, 28~~28~~ and 91~~91~~.

3 Characterisation Testing

3.1 Introduction

The task of characterization testing required the design execution and analysis of the following subtasks:

- 6-DoF loader system completion and validation
- Full field displacement and strain measurement method development and validation
- Specimen Testing
- Data management (flow and reduction)
- Characterization process

The sections that follow summarize the progress on each of these sub-tasks of the project.

3.2 NRL66.3 loader

Automated inverse methods for material constitutive characterization under multidimensional loading conditions have motivated the custom design, manufacturing and utilization of mechatronic loading machines. CMSL of NRL designed, built, validated and put into practice [26~~26~~, 55~~55~~, 81~~81~~] a mechatronic system capable of enforcing 6-DoF kinematic boundary conditions on deformable material specimens under testing, while at the same time measuring both the imposed kinematics and the corresponding reaction forces in a fully automated manner. ~~This system has a recursive nature as it consists of a hexapod configuration that repeats itself six times.~~

The system has recursive character that owes to the fact that the hexapod configuration is repeated 6 times. This is a design decision based on our desire to satisfy the above referenced requirements in an optimum manner. An overview of the geometric configuration is shown in the 3D CAD representation shown in Figure 1~~Figure 1~~. The numbers in parentheses are referring to the red numeric labels of Figure 1~~Figure 1~~ labeling the components of the system and they can be described as follows. The base (01) consists of a star-shaped I-beam configuration. The angle between any two successive I-beam elements is 120 degrees. An exact replica of the same beam configuration rotated by 60 degrees about the vertical axis of symmetry forms the top movable frame (10). The bottom base frame and the top movable frame are linked together through six actuators (03) formed by a hydraulic cylinder connecting the two frames through 12 universal joints as shown in Figure 1~~Figure 1~~. Each actuator consists of a main cylinder, a piston rod, an electro-hydraulic servo-valve, a magnetorestricive position transducer, an embedded valve controller with an analog to digital converter for communication with the external computer.

The two frames and the six actuators define the first hexapod configuration that forms the 6-6p linkage mechanism. By controlling the length of the actuators the 6-DoF pose of the top frame is controlled kinematically.

The base (04) supporting the lower grip (05) is connected to the fixed base (01) via a hexapod of steel rods. These rods contain at their mid-length strain gauge-based load-cells, with a capacity of 89 kN (20,000 lbf). This hexapod constitutes the second recursion.

In-line with the piston cylinders of the actuators are charge controlled piezoelectric load-cells (09) with a capacity of 220 kN (50,000 lbf) in tension and 130 kN (30,000 lbf) in compression. These load-cells constitute the third recursion of the hexapod system.

The upper grip (07) is connected to a double I-beam adaptor (08) which in turn is connected to the moving frame (10). Clearly, because of this connectivity the moveable grip is controlled by the motion of the top frame which is controlled by the motion of the actuators. The role of this adaptor double I-beam frame is to control the location of the upper (and moveable) grip in order to accommodate a particular range of specimen lengths. By shortening the height of the web on this frame taller specimens can be used for testing.

The last three recursions of the hexapod are three sets of linear displacement transducers. From inside to outside the first linear displacement transducers (06) in hexapod configuration are ACLVDTs connecting the bases of the two grip assemblies and essentially define the 6-DoF pose of the upper grip assembly. This is the fourth recursion of the hexapod system.

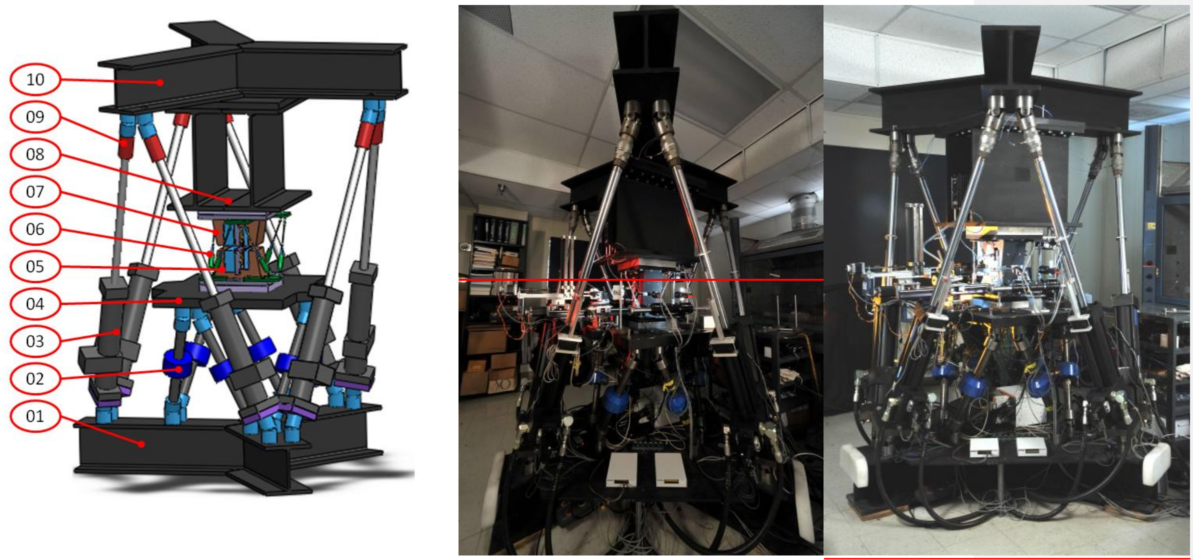


Figure 1: Left:3D CAD representation of the electromechanical subsystems of NRL66.3, Right: View of the built NRL66.3 functional prototype

Parallel to the actuating cylinders is a set of DCLVDTs (not shown in Figure 1~~Figure 1~~) that are measuring the extensions of the actuator piston rods and constitute the fifth recursion of the system.

Finally, not shown in Figure 1~~Figure 1~~, is the last set of displacement transducers that are magneto-restrictive devices and are used by the actuator valve controllers for closed loop control of actuator position. This is the sixth and final recursion of the hexapod configuration.

Three of the hexapod recursions are stiff (actuators and two sets of load cells) and three are compliant (three sets of displacement transducers).

3.3 ReMDiS 2D and 3D

The characterization methodology requires kinematic data measured on the surface of the specimen. In order to achieve this Meshless Random Grid (MRG) method for full field measurements was adopted and custom software was developed, validated and used.

The method has shown [1616, 3434, 4141, 4242] to perform very well compared to other methods for Full Field measurements and has been validated on a wide variety of test cases, including that of loading of open hole specimens of anisotropic material [4242]. Synthetic experiments have shown the excellent behaviour of MRG when used in conjunction with material characterization methods [4545].

MRG method was implemented in two software applications. The first one was solely for 2 Dimensional measurements and was named Remote Measurements of Displacement and Strain 2D (ReMDiS 2D) [4343] and the second one for 3 Dimensional measurements and was named ReMDiS 3D [6666]. These software applications have resulted in two invention disclosures filed by NRL [8888, 9090]. The main Graphical User Interface of ReMDiS 3D is shown in Figure 2.

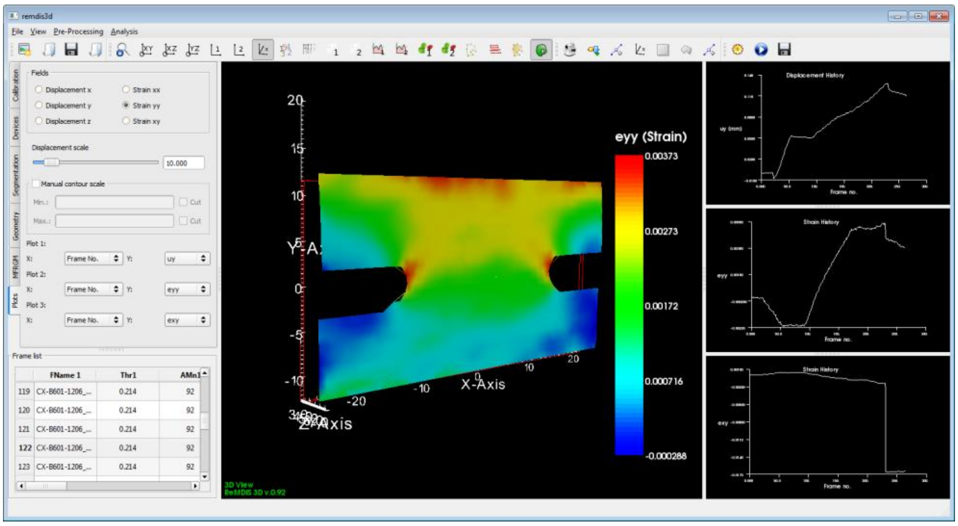


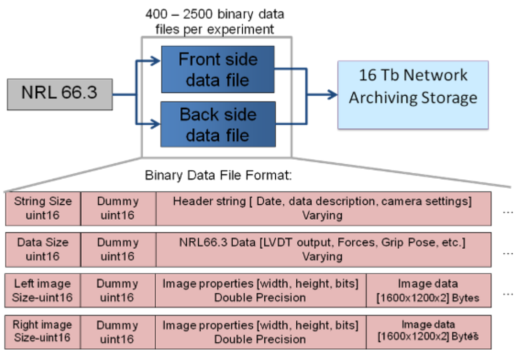
Figure 2: The ReMDiS 3D Main Interface

3.4 Data Flow and Data Reduction

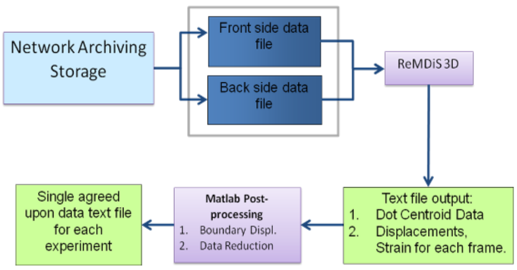
Because of the large amounts of data that have to be stored, manipulated and transformed throughout the characterization process, starting from experimental data acquisition, storage, archiving and conversion, a data flow procedure was introduced.

The overall data flow process is shown in Figure 3. The process of acquiring, combining, and storing to a Network Attached Storage (NAS) system is shown in Figure 3(a). The data consists of four images (two on the front side and two on the back side of the specimen) that are used by the Full-Field Measurement software, and from the kinematic and load transducer data as is acquired by the NRL66.3 sensors. Next the data is compressed using a parallel bzip2 implementation and transferred over the network to the NAS system. As shown in Figure 3 (b) prior to been processed, the data is converted to an appropriate text file with a format that is both human readable and text parser friendly.

Hexapod linkages as well as the grips and other deformable parts of the machine absorb energy, either reversibly or irreversibly thus introducing a parasitic behaviour that is undesirable from the perspective of the material constitutive characterization which is our ultimate goal. The existence of such behaviour was also validated by finite element analysis of critical parts of NRL 66.3 as shown in Figure 4. In order to eliminate those systematic aberrations introduced in the massive amounts of experimental data collected by NRL66.3, a data reduction methodology was introduced both on the kinematic (pose of the grip) and the reaction (forces and moments) that are critical input quantities of the material characterization process [7979].

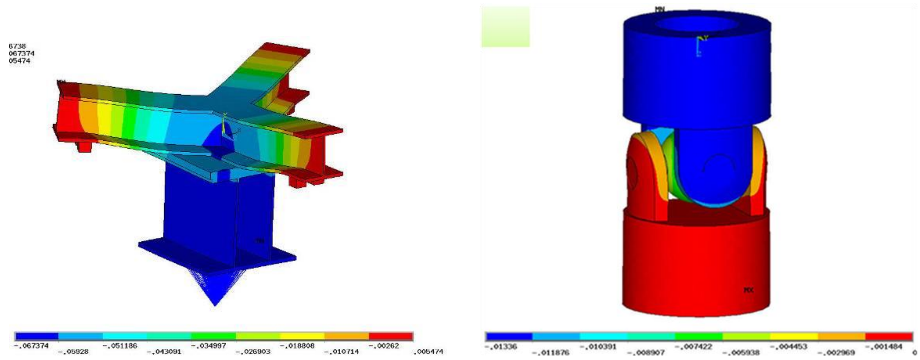


(a)



(b)

Figure 3: Data flow (a) Experimental data acquistion and storage (b) Conversion to characterization



(a) *(b)*

Figure 4: NRL66.3 Displacement plot of finite element analysis results of (a) Main Frame and (b) Joint

3.5 Characterization Process

The characterization methodology adopted at NRL is based on data-driven design optimization. The approach is based on the availability of massive experimental data representing the excitation and response behaviour of specimens tested by automated mechatronic material testing systems capable of applying multiaxial loading. Material constitutive characterization is achieved by minimizing the difference between experimentally measured and analytically computed system responses as described by surface strain and strain energy density fields. Small and large strain formulations based on additive strain energy density decompositions are introduced and utilized for constructing the necessary objective functions and their subsequent minimization.

In the case of the small strain formulation, two objective functions where chosen for the minimization. The first one relies on strains:

$$J^{\varepsilon} = \sum_{k=1}^{N}\left(\sum_{i=1}^{2}\sum_{j=i}^{2}\left(\left[\varepsilon_{ij}^{\exp}\right]_k - \left[\varepsilon_{ij}^{fem}\right]_k\right)\right)^2 , \qquad (1)$$

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where $\left[\varepsilon_{ij}^{\exp}\right]_k, \left[\varepsilon_{ij}^{fem}\right]_k$ are the experimentally determined and the FEM produced components of strain are at node k. The second objective function is based on an energetic formulation and is given by:

$$J^{U} \approx \oint_{\partial\Omega}\left(U^{\exp} - U^{fem}\right)^2 dS \approx \left[\oint_{\partial\Omega}\left(\sum_{i=1}^{2}\sum_{j=i}^{2}\sum_{m=1}^{2}\sum_{n=m}^{2}\left(s_{ijmn}\varepsilon_{ij}^{\exp}\varepsilon_{mn}^{\exp} - s_{ijmn}\varepsilon_{ij}^{fem}\varepsilon_{mn}^{fem}\right)\right)^2 dS\right], \qquad (2)$$

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The quantities $U^{\exp}, U^{fem}$ are the values of the surface strain energy density formulated by using the experimental strains and the FEM produced strains respectively.

In the case of finite strain formulation with dissipative terms, the objective function becomes:

$$J^{UF}(d, a_1, b_1, c_1, d_1, d_a^{\infty}, \eta_a) \approx \oint_{\partial\Omega}\left(U_{FSF}^{1} - U_{FSF}^{2}\right)^2 dS \approx \left[\oint_{\partial\Omega}\left(\sum_{i=1}^{2}\sum_{j=i}^{2}\sum_{m=1}^{2}\sum_{n=m}^{2}\left(U_{FSF}^{1} - U_{FSF}^{2}\right)\right)^2 dS\right] \qquad (3)$$

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with:

$$U_{FSF} = (1-d_v)W_v(J) + (1-d_d)W_d(\bar{\boldsymbol{C}}, \boldsymbol{A}\otimes\boldsymbol{A}, \boldsymbol{B}\otimes\boldsymbol{B}), \qquad (4)$$

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where W_d and W_v are the distortional and volumetric parts of the total energy and d_v is the damage parameter. A detailed description of the characterization process and of initial results is presented in [1818]. The application of the methodology on the data from the experimental results of the NRL testing campaign are presented in [8181]. A demonstration of the efficiency of the characterization procedure is presented in Figure 5, where the strain results are presented on the surface of the specimen, as they are measured by ReMDiS 3D and as they are calculated by the Finite Element Analysis, using the characterized material model.

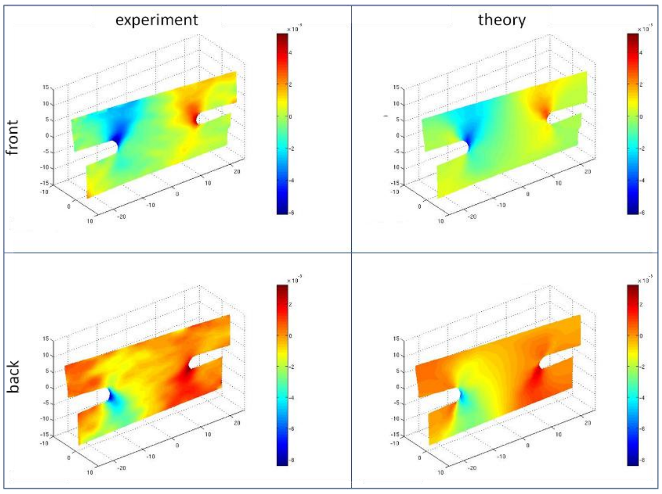

Figure 5: Comparison of experimental strains (left) with theoretical results using the characterized material properties (right)

4 Experimental Design and Optimization

4.1 Overview

The methods developed in association with experimental design and optimization are broadly classified into three topics:

- Constitutive modelling;
- Enhancement of constitutive modelling;
- Quantification of constitutive modelling and experimental design.

For the constitutive modelling, the methods developed include the energy-based characterization [2525,5757,6060,7171], the implicit constitutive modelling using hierarchical neural networks [5533,33,4949,5050,1919], the explicit deterministic constitutive modelling using singular value decomposition (SVD) [88,66], the explicit stochastic constitutive modelling using Kalman filter (KF)

[29~~29~~,31~~31~~,32~~32~~,39~~39~~,47~~47~~,14~~14~~], and the generalized theory for constitutive modelling [7~~7~~,40~~40~~,73~~73~~,74~~74~~,75~~75~~,20~~20~~23~~23~~].
For the enhancement of constitutive modelling the methods developed included nonlinear characterization [48~~48~~,70~~70~~,77~~77~~], multi-camera data fusion [58~~58~~,72~~72~~,22~~22~~], the probabilistic strain field measurement [76~~76~~,83~~83~~,84~~84~~,78~~78~~,87~~87~~] and the estimation of inner strain field measurement.

The quantification of constitutive modelling and experimental design has seen the achievements of the quantification of constitutive modelling, the experimental validation [60~~60~~,15~~15~~,69~~69~~], the load path determination [9~~9~~8~~8~~,60~~60~~,71~~71~~], and the implementation into ANSYS.

By the development of the above methods, the constitutive modelling up to nonlinear behaviour and the optimal constitutive modelling has been made possible.

4.2 Summary of Outcomes

By the development of the above methods, the following have been made possible in regards to the objective of the project, which is the prediction of mechanical behaviour and failure in composite structures:

- Constitutive modelling up to nonlinear behaviour;
- Optimal constitutive modelling.

Figure 6 shows the schematic diagram of the framework developed to characterize the multi-axial behaviour of composites using an out-of-plane loader in an online manner where the estimation of the inner strain, the multi-axial stochastic characterization [7~~7~~,40~~40~~,73~~73~~,74~~74~~,75~~75~~,20~~20~~,23~~23~~] and the out-of-plane loading control [8~~8~~9~~9~~,60~~60~~,71~~71~~], the multi-camera data fusion [22~~22~~,58~~58~~,72~~72~~], probabilistic displacement and strain measurements [76~~76~~,83~~83~~,84~~84~~,78~~78~~,87~~87~~] and quantifications are highlighted by red broken lines.

When a specimen has been newly deformed, multiple digital cameras measure the full-surface displacement by tracking the dots marked on the specimen whereas the load cell measures the force acting on the boundary of the specimen. The measurements are all described probabilistically by considering measurement uncertainties. The probabilistic full-surface displacement measurements by multiple cameras are then fused to create a single probabilistic full-surface displacement by using the multi-camera data fusion where the boundary displacement is particularly extracted for the derivation of total external work. The displacement is further used to derive a probabilistic surface strain. If the specimen is thick, the surface strain measurement does not derive the total strain energy since the inner strain is not identical to the surface strain. The inner strain is estimated by taking a hybrid experimental-computational approach.

Since the energy-based method characterizes material iteratively at every acquisition of measurements, let us suppose that we have the latest nonlinear material model. Having the boundary displacement and force measurements acquired, we can perform a finite element analysis (FEA) using the material model and the boundary conditions and derive both the surface strain and the inner strain where the computed surface strain is expected to match the measured surface strain well. The four causes that may create the difference are the surface strain measurement error, the boundary displacement and force measurement error

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and the truncation error of the FEA and the truncation error of the material model. Since the errors are modeled with uncertainties, the developed approach probabilistically constructs a corrector and better estimates the inner strain from such knowledge. The estimation of the inner strain results in having all the boundary displacement/force and the full-field strain information probabilistically, so that the stochastic energy-based characterization is possible.

As the characterized material model is described with uncertainty, the process to link the characterization to loading path planning and control is the quantification of uncertainty where the differential entropy is derived as the quantity in accordance to the past work. The path planning problem using the out-of-plane loading is NP-hard. The path planning has thus been developed by applying model-reduction techniques and an improved model-predictive control strategy.

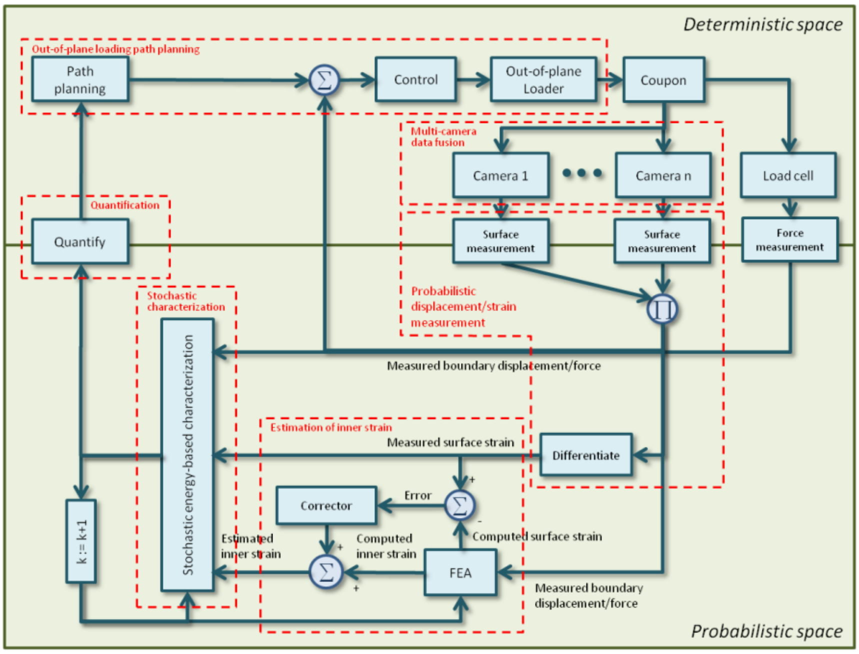


Figure 6: Schematic diagram of the developed framework that achieves the optimal constitutive modelling

Figure 7 shows the result of the multi-axial nonlinear constitutive modelling by the developed method where the behaviour of aluminium specimens is shown as an example [1515,6060,6969]. As shown in the figure, a multi-axial nonlinear constitutive model showing the constitutive relations in [ε_1, ε_2]-σ_1, [ε_1, ε_2]-σ_2, ε_6-σ_6, have been developed. In addition, the known elastic moduli of aluminium have been successfully identified. Composite materials exhibit more deformation than aluminium. This result confirms the applicability of the developed method to the multi-axial nonlinear constitutive modelling of composite materials.

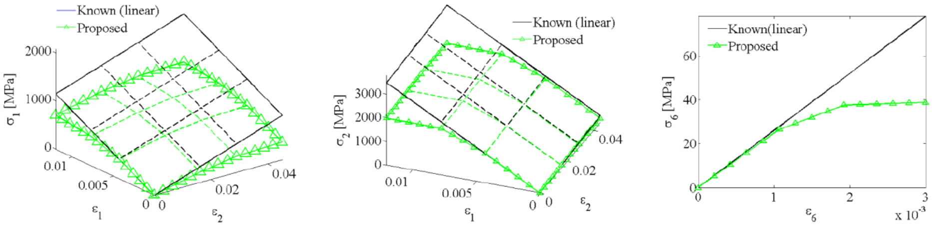


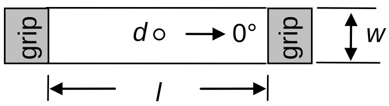
Figure 7: Result of multi-axial nonlinear constitutive modelling

5 Validation Testing

Experimental testing was conducted on validation specimens of different configurations and length scales. The goal of the experimental testing was to achieve two convergent aspects: investigate key length scale effects experimentally; characterise failure at each length scale. The results of the validation testing are necessary in order to validate any analysis methodology developed, and understand how to link between scale levels. The results of each configuration are summarised in the following sections. The methods and outcomes of the validation testing have been published in Refs. 38~~38~~, 56~~56~~, 68~~68~~, 82~~82~~, 93~~93~~, 95~~95~~ and 96~~96~~.

5.1 Open hole

Open-hole (OH) tension specimens were selected for validation at a coupon level using a standard specimen. The goal was to represent a real structural detail, e.g. for a bolted joint. Scale effects were incorporated in two ways: "In-plane" scaling of geometry (length and width scale with diameter); ply thickness scaling. The specimen definition is summarised in Figure 8. A first batch of specimens was manufactured and tested, but the specimens suffered hole damage during manufacture, and the full-field strain measurements were not consistent, so another batch was manufactured and tested. During testing, the stress at onset of non-linearity, σ_{NL}, was determined from a strain gauge close to the hole, and corresponded to a deviation of 5% from a linear fit to the initial load-strain results. The results of the OH testing are presented in Figure 9 and Table 2, where Figure 9 gives the average stress results for damage initiation and ultimate failure, and Table 2 summarises the damage modes seen in the tests after ultimate load.



	d	*w*	*l*
OH-00	0.0	25	170
OH-05	12.7	50	170
OH-10	25.4	100	370

Number of specimens

OH-	**00**	**05**	**10**
$[+45, 0, -45]_{4S}$	3	3	3
$[+45_4, 0_4, -45_4]_S$	3	3	3

Figure 8: OH specimen details, dimensions in mm (not to scale)

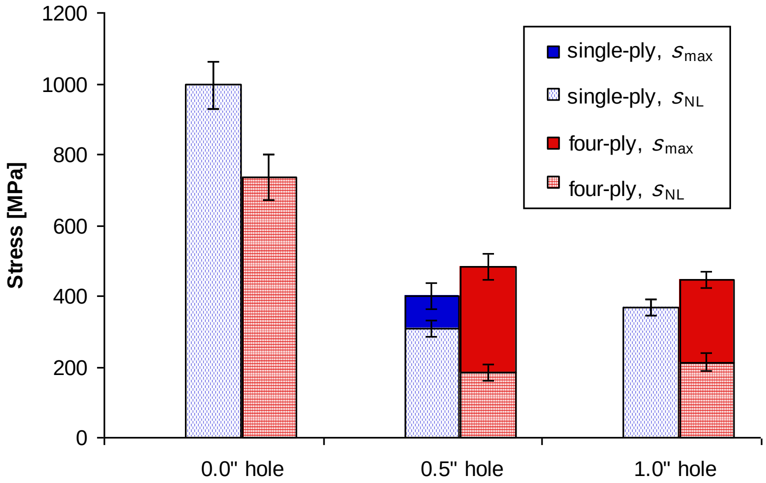


Figure 9: OH specimen, average stress results for 5% non-linearity and maximum stress

Table 2: OH specimen, dominant failure mode at maximum stress

Specimen		Dominant Failure Mode		
		0.0” hole	**0.5” hole**	**1.0” hole**
single ply	$[+45, 0, -45]_{4S}$	grip / tension	tension	tension
four ply	$[+45_4, 0_4, -45_4]_S$	grip / tension	delamination	delamination

From the results, increasing the hole size (in-plane scaling) reduced the failure stress but delayed the onset of non-linearity slightly. Increasing the ply thickness changed the failure mode from tension (catastrophic) to delamination, which increased the ultimate load due to the progressive nature of delamination damage. Subsequent interrupted tests with C-scans showed that the onset of non-linearity for specimens with thicker plies was caused by the onset of delamination at the hole edge. In this way, the non-linearity in in-plane strains was linked to the progression of out-of-plane damage. This aspect was confirmed with full-field REMDIS2D data, where the in-plane strain component normal to the loading direction was found to be more sensitive and suitable to indicate delamination onset.

5.2 Ply-Drop

Ply-drop (PD) specimens were designed incorporating a region of ply drops, or ply termination. Ply drops are commonly used in composite structures to change laminate thickness, though generate high through-thickness (interlaminar) stresses. Ply drop specimens were investigated to provide validation results at this key structural detail in which out-of-plane stresses feature prominently. The specimen definition is summarised in Figure 10, and laminates with two ply thicknesses were investigated. The experimental results are summarised in Figure 11 which presents the loads recorded for different failure events.

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The experimental results showed variable behaviour, particularly considering testing was conducted on different testing machines over an extended period of time. Despite this, variable behaviour was seen also for nominally identical specimens tested contemporaneously on the same machine. PD specimens showed a range of failure mode that included cracking noises, a failure event leading to at least at 10% load drop, and ultimate failure in net tension. The 10% load drop was associated with a damage pattern of intralaminar (transverse) and interlaminar (delamination) cracks propagating from the start of the ply drop region on the thinner end. The specimens with thicker plies showed earlier and more consistent onset of cracking noises and the 10% load drop, whereas the thinner ply specimens showed less progressive damage.

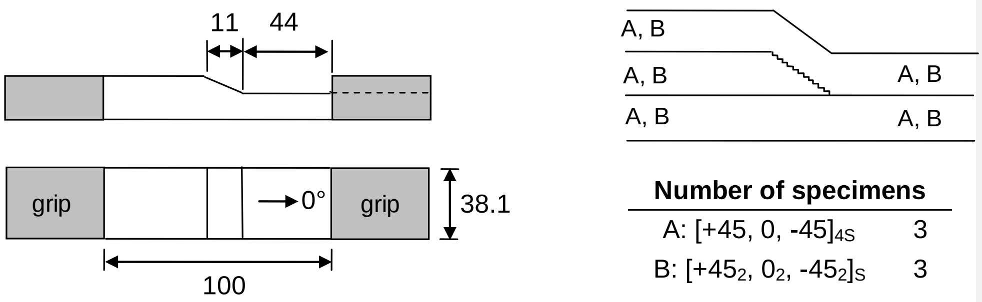

Figure 10: PD specimen details, dimension in mm (not to scale)

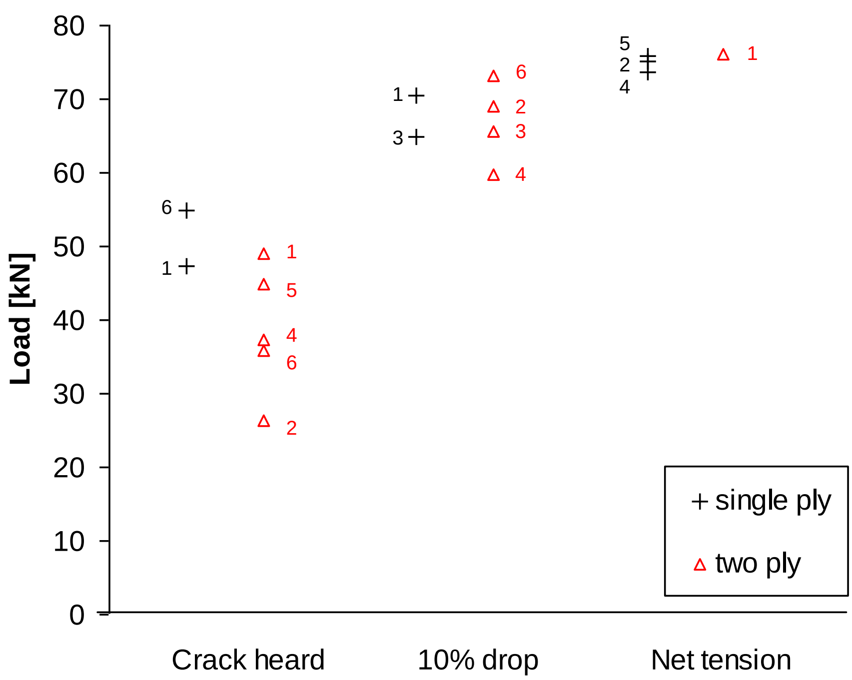

Figure 11: PD specimens, failure event loads (specimen numbers shown for each event)

5.3 Stiffened Panels

A stiffened panel design was investigated that was based on previous CRC-ACS research on a composite postbuckling aircraft structure. This represents validation at a substructure level, which is representative of a typical aerospace structure. Three 3-stiffener panels were manufactured. One test was conducted of a full 3-stiffener panel in compression until ultimate load, after which it was concluded that a full 3-stiffener panel was not suitable for validation purposes. This was because it showed large geometric non-linearity, limited material non-linearity, complex boundary conditions and catastrophic failure. The remaining two panels were cut into single-stiffener specimens, and tested in tension in two configurations based on the orientation of the 45° plies relative to the load path. The specimen definition is shown in Figure 12 and Figure 13. The specimens were loaded in the skin on one end and the stiffener on the other. Two specimen types were investigated as shown in Figure 12. For Type 1 specimens, failure of the grip tabs was seen on the end where the stiffener was loaded, so the stiffener grips were re-designed and sections of the specimen skin were cut out to accommodate. For each specimen Type there was a further variation, which was defined using the orientation of the outer 45° plies in the symmetric skin section.

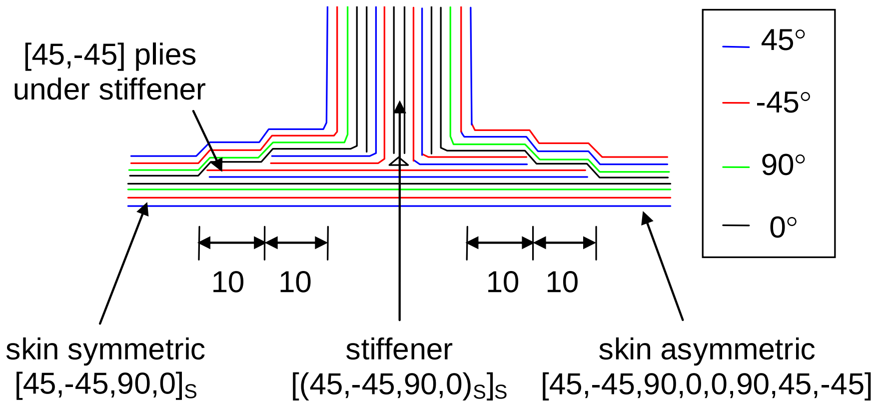

Figure 12: SP specimen, layup definition and ply drop region dimensions (mm)

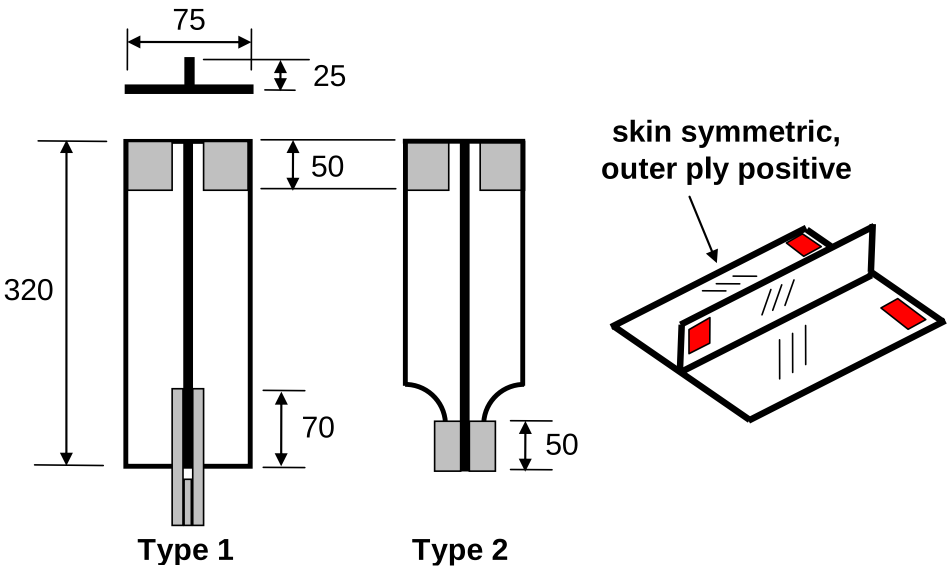

Figure 13: SP specimen details, dimension in mm.

The experimental results are summarised in Table 3 and Figure 14, where Table 3 summarises the test results and Figure 14 shows the failure modes. During experimental testing, some specimens displayed a "damage event" prior to the ultimate load or "failure", where the damage event was characterised by a clear deviation in strains and load with accompanying noise. For some specimens minor cracking noises were heard that were not associated with any strain or load behaviour. The load for any damage event, and the final failure load are summarised in Table 3, which also lists the failure location for each specimen. The Type 1 specimens failed in the tabs attached to the stiffener, where the Type 2 specimens all failed in the skin cutout region. Failure at the skin cutout region was characterised by fibre failure and delamination. For specimen #3, delamination was also seen at the end that the skin was loaded, though the other specimens did not show damage at this location. Higher failure loads were seen for Type 2 specimens with negative 45° outer plies, though the damage event occurred earlier relative to the final failure.

Table 3: SP specimens, results summary

Specimen	Type	Skin outer 45° plies	Failure location	Damage event (kN)	Failure load (kN)
# 1	1	positive	stiffener tab	-	44.2
# 2	1	negative	stiffener tab	-	47.0
# 3	2	negative	skin cutout	52.0	56.4
# 4	2	positive	skin cutout	49.4	48.4
# 5	2	negative	skin cutout	41.0	49.1
# 6	2	positive	skin cutout	46.0	45.4

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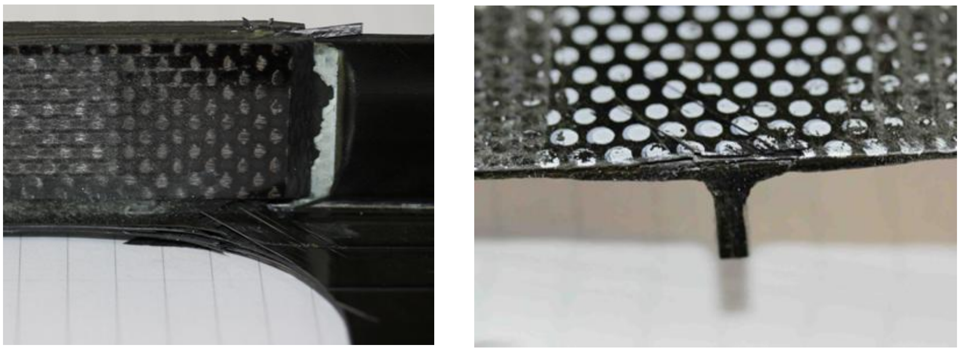

Figure 14: SP specimens, failure modes. Left: Skin cutout, stiffener-loaded end (specimen #3 shown). Right: Delamination, skin-loaded end (specimen #3 only).

6 Simulation Methodology Development and Validation

6.1 NRL

For the general case of a composite material system we consider that a modified anisotropic hyperelastic Strain Energy Density (SED) function can be constructed to encapsulate both the elastic and the inelastic responses of the material. In the case of the Finite Strain Formulation the energy can be written in a double additive decomposition manner. The first being the decomposition of the recoverable and irrecoverable SED, and the second being the decomposition between the volumetric (or dilatational) W_v and the distortional (or isochoric) W_d parts of the total SED. For a material with two principal directions, this decomposition can be expressed by:

$$\begin{aligned} U_{SSF} &= U^{R}_{SSF}(\alpha_i; J, \bar{\mathbf{C}}) + U^{I}_{SSF}(\alpha_i, \beta_i; J, \bar{\mathbf{C}}) = \\ &= [W_v(J) + W_d(\bar{\mathbf{C}}, \mathbf{A} \otimes \mathbf{A}, \mathbf{B} \otimes \mathbf{B})] - [d_v W_v(J) + d_d W_d(\bar{\mathbf{C}}, \mathbf{A} \otimes \mathbf{A}, \mathbf{B} \otimes \mathbf{B})], \end{aligned} \tag{5}$$

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where α_i, β_i are the elastic and inelastic material parameters of the system, respectively. A rearrangement of these decompositions, such as the volumetric vs. distortional decomposition, which appears on the highest expression level, leads to the expression:

$$U_{FSF} = (1 - d_v) W_v(J) + (1 - d_d) W_d(\bar{\boldsymbol{C}}, \boldsymbol{A} \otimes \boldsymbol{A}, \boldsymbol{B} \otimes \boldsymbol{B}), \tag{6}$$

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with the damage parameters $d_k \in [0,1], k \in [v, d]$ defined as

$$d_k = d^{\infty}_{ka} \left[1 - e^{\left(-\frac{a_k(t)}{\eta_{ka}} \right)} \right] \tag{7}$$

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where $a_k(t) = \max_{s \in [0,t]} W^{o}_{k}(s)$ is the maximum energy component reached so far, and $d^{\infty}_{ka}, \eta_{ka}$ are two pairs of parameters controlling the energy dissipation characteristics of the two components of SED. In this formulation, $J = \det \underline{\boldsymbol{F}}$ is the Deformation Gradient,

$\bar{\boldsymbol{C}} = \underline{\boldsymbol{F}}^T \underline{\boldsymbol{F}}$ is the right Cauchy Green (Green deformation) tensor, $\boldsymbol{A}, \boldsymbol{B}$ are constitutive material directions in the undeformed configuration, and $\boldsymbol{A} \otimes \boldsymbol{A}, \boldsymbol{B} \otimes \boldsymbol{B}$ are microstructure structural tensors expressing fiber directions. Each of the two components of SED are defined as:

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$$
\begin{aligned}
&W_v(J) = \frac{1}{d}(J-1)^2 \\
&W_d(\bar{\boldsymbol{C}}, \boldsymbol{A} \otimes \boldsymbol{A}, \boldsymbol{B} \otimes \boldsymbol{B}) = \sum_{i=1}^{3} a_i (\bar{I}_1 - 3)^i + \sum_{j=1}^{3} b_j (\bar{I}_2 - 3)^j + \sum_{k=1}^{6} c_k (\bar{I}_4 - 1)^k + \\
&+ \sum_{l=2}^{6} d_l (\bar{I}_5 - 1)^l + \sum_{m=2}^{6} e_m (\bar{I}_6 - 1)^m + \sum_{n=2}^{6} f_n (\bar{I}_7 - 1)^n + \sum_{o=2}^{6} g_o (\bar{I}_8 - (\boldsymbol{A} \cdot \boldsymbol{B})^2)^o
\end{aligned} \tag{8}
$$

where the strain invariants are defined as follows:

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$$
\begin{aligned}
&\bar{I}_1 = tr\bar{\boldsymbol{C}}, \quad \bar{I}_2 = \frac{1}{2}(tr^2\bar{\boldsymbol{C}} - tr\bar{\boldsymbol{C}}^2) \\
&\bar{I}_4 = \boldsymbol{A} \cdot \bar{\boldsymbol{C}}\boldsymbol{B}, \quad \bar{I}_5 = \boldsymbol{A} \cdot \bar{\boldsymbol{C}}^2\boldsymbol{B} \\
&\bar{I}_6 = \boldsymbol{B} \cdot \bar{\boldsymbol{C}}\boldsymbol{B}, \quad \bar{I}_7 = \boldsymbol{B} \cdot \bar{\boldsymbol{C}}^2\boldsymbol{B}, \quad \bar{I}_8 = (\boldsymbol{A} \cdot \boldsymbol{B})\boldsymbol{A} \cdot \bar{\boldsymbol{C}}\boldsymbol{B}
\end{aligned} \tag{9}
$$

The corresponding constitutive behavior is given by the second Piola-Kirchhoff stress tensor according to:

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$$S = 2\frac{\partial U_{FSF}}{\partial C} \tag{10}$$

or the usual Cauchy stress tensor according to

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$$\boldsymbol{\sigma}_{FSF} = \frac{2}{J}\boldsymbol{F} \cdot \frac{\partial U_{FSF}}{\partial C} \cdot \boldsymbol{F}^T \tag{11}$$

Under the FSF formulation the material characterization problem involves determining the 36 coefficients (at most) of all monomials when the sums in the expression of distortional SED are expanded in Eq. (8), in addition to the compressibility constant d and the four parameters used in Eq. (7). It follows that potentially there can be a total of 41 material constants.

In order to validate these constitutive models and the respective characterization methodology, we exercised finite element simulations using these models for four distinct specimen geometries. The first geometry was that of the characterization coupon under multiaxial loading. The second was that of open-hole specimens in tension. the third was that of a ply-dropoff specimen. The final one was that of stiffened panel substructures under tension. Actual experimental data from testing all these specimens were collected by the use of load cells, full field displacement and strain methods and strain gauges. Finally, the theoretical predictions were compared with the experimental ones in terms of strain field distributions and load-strain responses. The comparisons demonstrated excellent predictability of the determined constitutive responses with the predictions always within the error band of the methods used to collect the experimental data.

The first validation simulation was performed for the typical double notched characterization specimen. It is important to emphasize that the experimental data obtained from the associated tests were not used in determining the constitutive constants (material parameters) that are determining the associated constitutive model. Representative validation predictions of excellent quality were presented for two loading paths in [8282]. Similarly, in the same publication [8282] we are providing validation results for the open hole and stiffened panel specimens.

6.2 CRC-ACS/RMIT

A methodology has been developed to model the degradation in material behaviour of CFRP laminates using energy-based data characterised from multi-axial testing. Key steps in the development of the methodology include the characterisation of a dissipated energy density (DED) function from test data, and incorporating the DED function into a constitutive model to capture material degradation. Both of these aspects have been incorporated into commercial software packages and validated in comparison with numerical and experimental test data. Each aspect is summarised in the following section. The development and validation of the methodology have been published or presented in Refs. 2121, 4646, 5151, 6363 and 6464.

It is assumed that the dissipated energy per unit of volume of material associated with load-induced damage development is a material property, which is dependent on only strain. A scalar interpolation function is assumed to define the DED, where the DED is known at fixed locations within the strain space, and interpolated to any other arbitrary strain coordinate. The total strain space is discretised into subspaces, where the boundaries of each subspace are the locations of known DED. Characterisation of the DED function for a given material therefore requires determining the set of constants mapping DED at subspace boundaries for a given strain space discretisation.

The constants of the DED function are determined using an optimisation procedure from a set of equations. Each equation compares DE from a test data point to a predicted DE found by summing DE throughout the structure at discrete points, and is given by

$$DE^{p} = \sum_{n=1}^{N} c_i \chi_i \left(\varepsilon_n^{p}\right) V_n + e^{p} \qquad (1211)\ (1)$$

where DE^{p} is the dissipated energy at a given test data point, N is the number of summation points, c_i are the unknown characterisation constants, χ_i are the interpolation functions that depend on the strain vector ε_n^{p} at a summation point, V_n is the volume at a summation point, and e^p is the error between the test and predicted DE.

Characterising the DED function for a material requires knowing the total dissipated energy experienced as well as the associated full-field strain distribution for a given test data point. Strain measurement is achieved using full-field optical strain measurement systems or FE analysis. Equation (1)(11) is applied to each data point, and is used to generate a large matrix of equations. An optimisation scheme in Matlab© [11] that minimises the error terms is applied to determine the most suitable characterisation constants. Since the constants are DED values, they must be positive. To enforce this, the numerical optimisation is bounded by a minimum of zero.

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To demonstrate the characterisation process, numerical analysis was used to generate virtual or synthetic "test" data. The synthetic test data was 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.

The double-notch characterisation specimen was used, as summarised in Figure 15. The specimen layup was $[\pm\theta]_{16}$, and four layups (θ = 15°, 30°, 60° and 75°) were investigated. Ten loadcases were defined in a 3-DOF loading space that combined in-plane tension, shear and rotation, summarised in Figure 15. There were 100 data points from each specimen test, so that in total there was 40 tests and 4000 data points.

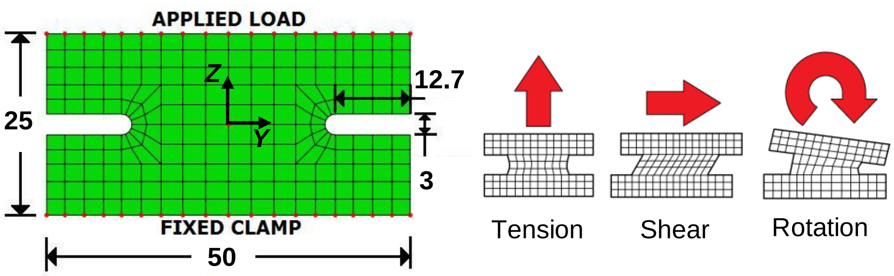

Figure 15: Left: Geometry and dimensions (mm) of the double-notch specimen. Right: Basic single axis loadcases.

The analysis was conducted using the commercial FE package Abaqus/Explicit 6.8 [22]. Models used a single layer of quadrilateral shell elements, with the mesh shown in Figure 15. A damage model for fibre-reinforced composite materials was applied, which uses criteria for fibre and matrix failure in tension and compression to control progressive material softening. As part of the damage model, the solver calculates the energy associated with all damage modes, ALLDMD, which is a key comparative parameter.

Different strain space discretisations were investigated to study the influence of the discretisation on the error in comparison with test data. It was found that increasing the density of discretisation and biasing the discretisation for higher density at lower strains both increased the accuracy of the characterisation constants in predicting test data.

A comparison between the experimental and numerical DE for all data points is presented in Figure 16, plotted one after another. For this characterisation, the strain space is divided into 11 segments per axis, and the discretisation is biased towards lower strains. This shows the close comparison between test and predicted DE across all loadcases and specimens. This is significant considering the data points covered ten loadcases and four laminates, and further demonstrates the applicability of considering damage on a continuum basis as a function of only strain.

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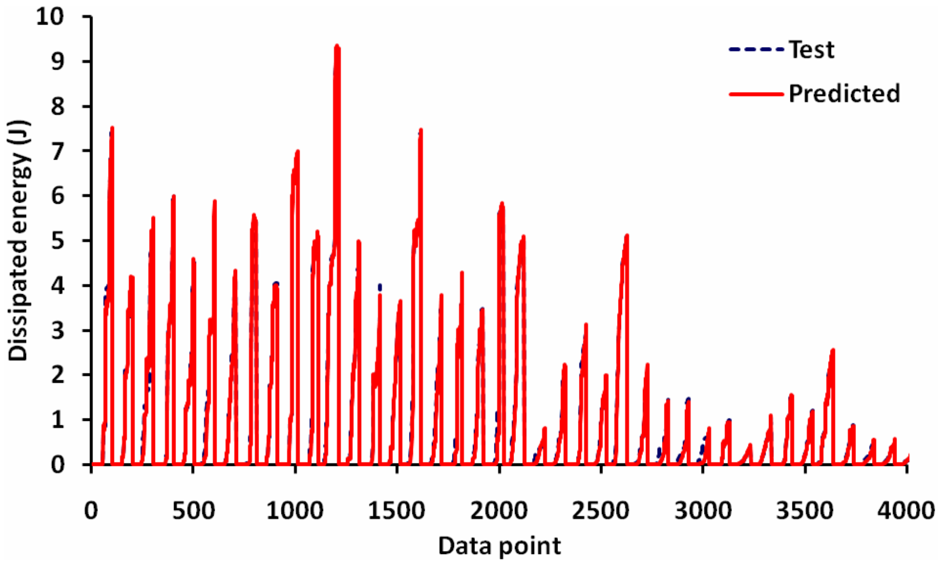

Figure 16: Material characterisation, 11 segments per strain axis, biased, test and predicted DE, all loadcases.

The material characterisation data was incorporated into an analysis approach for predicting DE within an FE analysis. The analysis approach was implemented with the user subroutine VUSDFLD, which is a subroutine available for user-defined field variables in Abaqus/Explicit [22]. The VUSDFLD subroutine is called by the FE solver for every material point whenever material calculations are being performed. The subroutine receives the strain vector as input and then calculates the DE for the given strain vector using the characterisation constants, interpolation functions and element volume.

The analysis approach was applied to a range of specimens to demonstrate the assessment of damage development, in comparison with test data. This included single element models, double-notch characterisation specimens and open-hole tension specimens. Synthetic "test" data was generated using separate analyses incorporating the Abaqus damage model. The DE in the test data was taken from the ALLDMD parameter. For the analysis approach, the total DE was determined in post-processing by summing the predicted DE from all elements.

The analysis approach was applied within the same analysis as the Abaqus damage model, so that both calculations of DE were conducted with a single analysis. Although the analysis approach was not linked to any material softening, the use of a more realistic strain field including material softening provided a more suitable assessment of the predictive capability. This also ensured that all other aspects of the analysis, including the mesh, loading and solver parameters, were identical for the test data and analysis approach.

The results of the analysis for the characterisation specimen are shown in Figure 17 and Figure 18, where Figure 17 shows the predicted DE development for one specimen, and Figure 18 compares the test and predicted total DE across a range of specimens.

These results show that the analysis approach captured the DE initiation and development very well and gives good comparison with the test results across all loadcases and laminates. In all cases the analysis approach captured the initiation and early progression of DE, which is particularly important as this corresponds to the beginning of damage and the non-linear regime. The analysis approach also captured the nature of the DE response in terms of the sharp increases in DE, which were caused by step-like increases in the underlying strain field as a result of the softening in the Abaqus damage model.

Overall, the results confirm that the characterisation constants provide an accurate definition of the DE development across the broad range of strains seen in the characterisation specimens, and demonstrate the application of the characterisation data within an analysis approach.

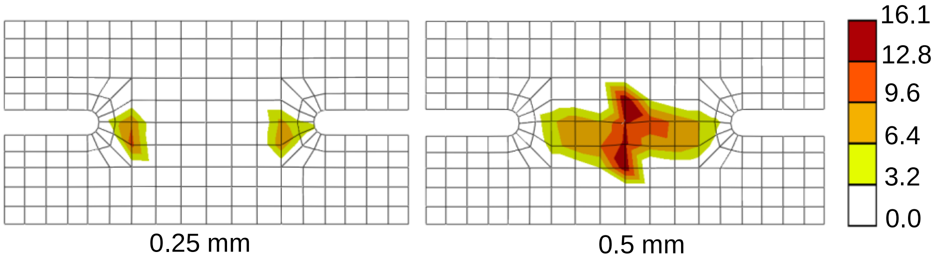

Figure 17: Characterisation specimen, $\theta = 15°$, pure tension loadcase, predicted DE (mJ) in top surface ply at different applied displacements

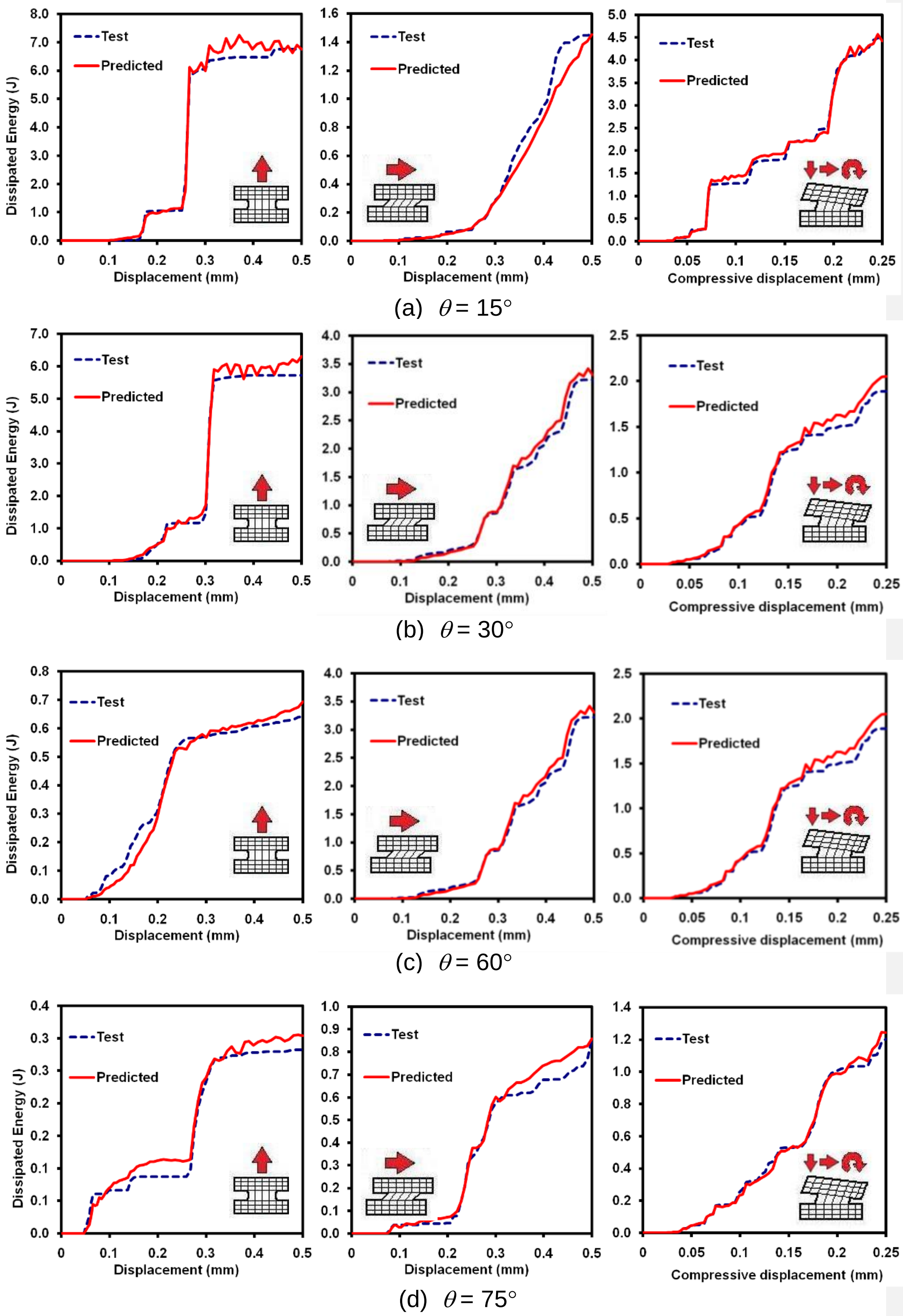

Figure 18: Characterisation specimens under single axis and combined loading, test and predicted DE. Left: Tension, Middle: Shear, Right: Compression + Shear + Rotation.

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7 Lengthscale Findings (MIT-NRL)

The particular objectives of this specific length scale work, which supported the goal and objectives of the overall effort, were to develop an understanding of the issues associated with bridging the lengthscales involved in the behavior and failure of composite structures and to use this understanding in the development of a prediction methodology for the behavior of such structures.

7.1 Approach

The investigation of lengthscale effects utilised specimens tested using NRL mechatronic loading machine as a system identifier apparatus that generates the required data by exposing the material system to loading sequences that stimulate all strain states by which a material can ever be influenced. A literature review was also conducted to document the knowledge that exists surrounding damage, failure, and effect of lengthscales in composites and their structures. This helped to provide background of the topics related to the project and in planning an approach to accomplish the project goals. This included the development of a "question tree" in order to identify the information that is needed, what exists, and what needs to be sought.

From that overall perspective, the central effort in this work was on developing a methodology that allows the characterization at the basic material and laminate level to be employed as greater structural complexity is introduced in considering lengthscales of increasing magnitude (e.g., subelement, element, subcomponent, and component as used in the Building Block Approach as described in the extended report [9494]). This works to provide the needed information involving various behaviors and complexities. One such complexity includes gradients in stress fields due to overall structural configurations and details (e.g. holes) and those gradients due to overall structural response (e.g. buckling). Furthermore, there are stress gradients at various lengthscales due to the presence of damage or various as-produced anomalies. Work then proceeded to coordinate with outcomes from the assessment of current failure models. The technique described in the overall effort resulted in a fundamental characterization quantity, dissipated energy density, that is, a volume-density quantity. This quantity is basically independent of scale and is thus applicable across all lengthscales. The quantity can be used in a pointwise fashion in considering the issues across the various lengthscales, and thus to "translate" the data through the lengthscales including with damage present. This, however, depended upon the specific failure models chosen, so the details of further effort depended on such outcomes. The effort also included a probabilistic assessment as basic behavior is not deterministic and thus probabilistic/statistical aspects were included at that basic level along with means to incorporate these aspects across the lengthscales included. This must also involve probabilistic aspects associated with production of actual structures as well as loading of actual structures.

A key part of this investigation was the testing work that took place at the levels of coupons and small substructures including observations and documentation of damage initiation and growth up through final failure. The planning process for testing and the subsequent data results were essential in assessing the outcome from this specific work. Furthermore, this process was not simply a serial effort as there was an interaction and interdependence of the various objectives and related work. The overall effort required integrated coordination among the researchers at the three primary locations where the work took place.

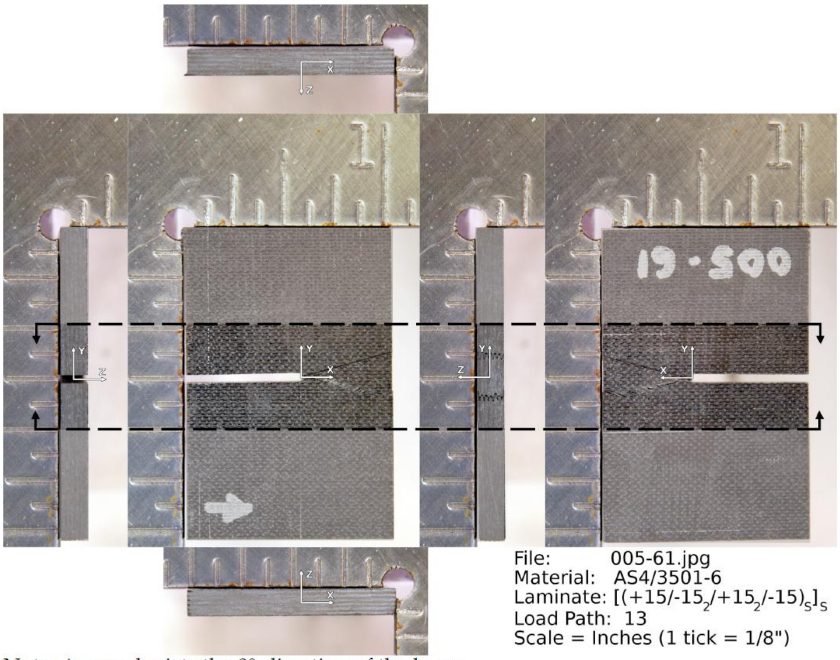
The work that took place on the development and refinement of procedures to document damage and the subsequent documentation of damage illustrates the relationship between these items and the associated levels of structures, as well as the cooperation among the various research sites. In the work on damage documentation, the approach taken was able to characterize the damage based on its basic characteristics, but also regarded the specifics of the structure and loading associated with such. Considerations included being aware of and capturing the various lengthscales associated with these various factors.

In general, many final details of the work downstream could not be identified until earlier results were available. Thus, there continued to be (re)considerations and updates to overall and specific approaches and their details as the work moved forward. This included the details of the damage documentation.

7.2 Failure Mechanisms Documentation

Over the course of the project, many key steps were taken working towards the three primary tasks: assessing current failure models; developing an overall methodology to work through the lengthscale levels through to full-scale structures; and planning the experimental programs to acquire needed knowledge and to work through the chosen failure approaches and the overall methodology. A question tree was developed using information and knowledge from an extensive literature review. Answers from the question tree helped in planning the test program for the project.

A key contribution from the project includes procedures to document and characterize damage for use in the overall project. Baseline procedures were established using specimens from a previous NRL project and then refinements were made while applying the initial procedures to the open-hole tension specimens of this project. In particular, the procedures as previously established were implemented on current project specimens and three areas in the initial procedures were identified where improvements were needed. The first of these is a consistent means to handle specimens that had failed into two or more pieces during testing. The second area is a consistent manipulation of specimen images and/or documentation procedures in order to return the planar dimensions to the virgin (untested) dimensions. The third of these is a better identification of the size of the damage grid and damage sketch dimensions within specimen types to maintain comparable regimes of documentation of damage. The aim of these refinements is to make the overall procedures more robust and to enable the procedures to be implemented on a broader class of composite specimens. This will ensure consistent comparisons across specimens of various lengths and configurations. These refinements were pursued in parallel with the use of the damage documentation procedures to document and characterize the damage in the open-hole tension specimens tested. By the close of the project, the procedures were applied to 210 previously tested NRL IPL specimens, an example is shown in Figure 19, and twenty-one open-hole tension specimens.



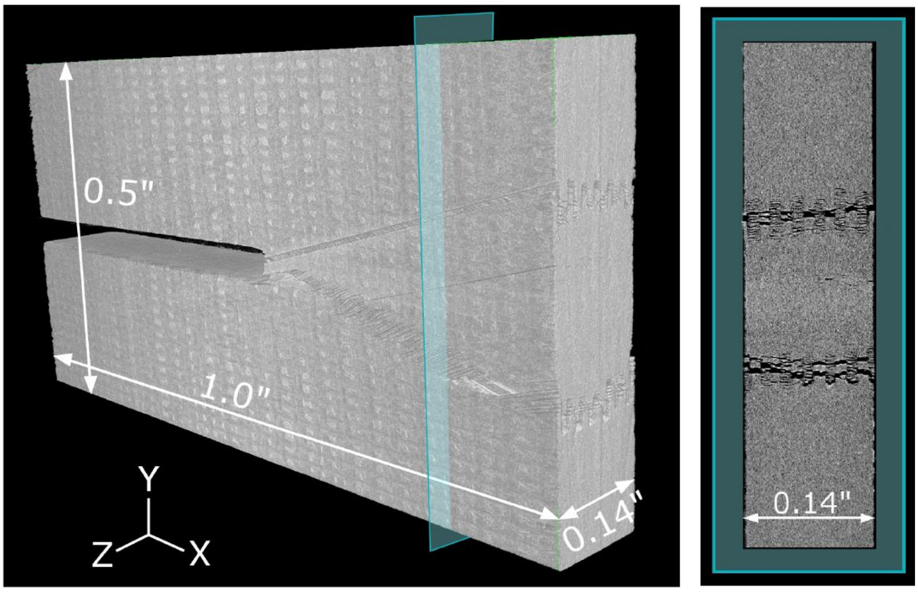
Note: Arrow depicts the 0°-direction of the layup.

Figure 19: Example of an optical documentation photograph of a previously tested NRL IPL composite specimen made of AS4/3501-6 graphite/epoxy with a stacking sequence of $[(+15/-15_2/+15_2/-15)_S]_S$

Figure 20: Photo documentation of OHT specimen OH-A051-04

An additional thirty specimens were received from CRC-ACS during the last weeks of the project. Damage documentation of these specimens was begun but did not conclude by the end of the project. Preparation to implement the damage documentation procedures on the other project specimens that were to be tested in associated parts of this overall program was also completed. However, due to the delays in specimen production and testing, these were not worked. This includes the remaining open-hole tension and ply-drop specimens from CRC-ACS, the stiffened panel specimens, and the basic level double-notch characterization specimens from NRL. The preparation was done to expedite the implementation of the damage documentation procedure once the specimens had been tested and shipped to MIT.

A major achievement made during the course of this project involved finding and utilizing the methodology of computed microtomography in investigating damage in the composite specimens. This technique creates a digital representation of three-dimensional volumes from scans of physical/experimental composite specimens, as shown in Figure 21. Therefore, damage, damage paths, and interaction of damage modes throughout the volume of the specimen can be investigated without any specimen preparation and with no destructive sectioning. During the course of the project, scans of thirty-one specimens were made; ten which were base-level previously tested NRL IPL specimens, and twenty-one which were open-hole tension specimens from CRC-ACS. From these scans, damage mode interactions as well as damage paths were studied throughout the volume of the specimen. Without the microtomography scans, the stitch cracking in the NRL IPL specimens would not have been identified, as shown in Figure 22, and the identification of significance of the improper hole preparation of the OHT specimens, resulting in unanticipated damage locations, may not have been made.



(a) *(b)*

Figure 21: (a) Virtual 3-D volume of the specimen shown in Figure 19 virtually recreated by computer microtomography, and (b) end on section view

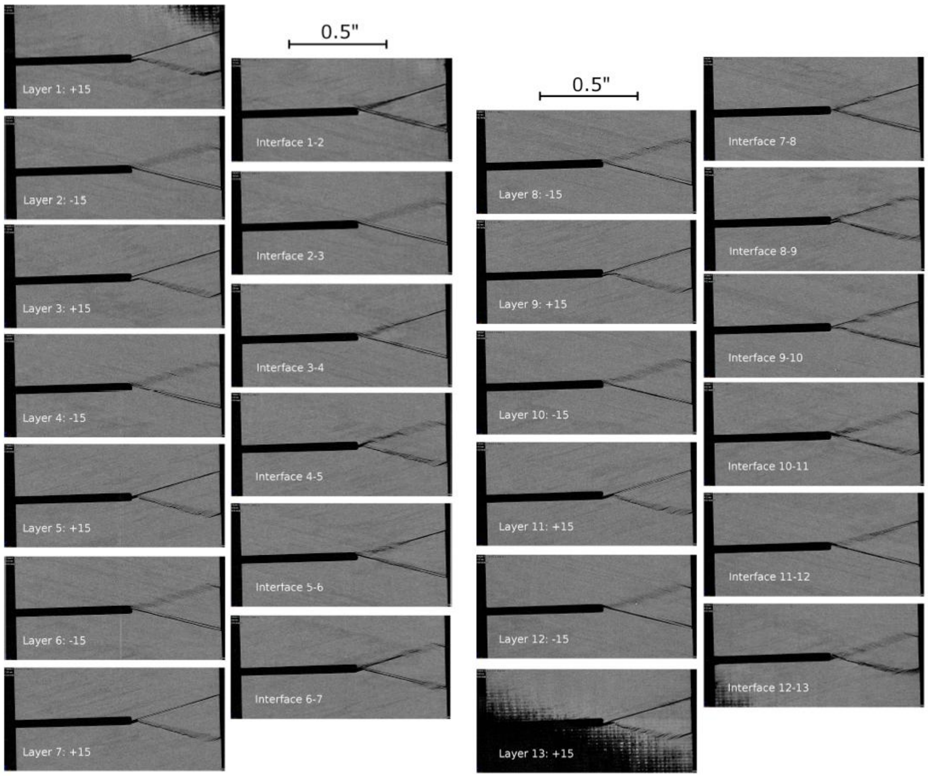


Figure 22: Virtually sectioned views of the specimen shown in Figure 19 with the views shown being from the front, with material virtually removed (sectioned) through the thickness from the front surface down

Damage information collected from all the specimens was added to the Damage Comparison Database. This comparison database allowed damage trends and lengthscale effects to be investigated across specimens of varying structural levels, a task that was previously inaccessible. Although the database was primarily filled with the originally tested NRL IPL specimens, results showing lengthscale effects were able to be initially identified from this database.

Overall, the work performed during the course of the project advanced the knowledge and methodology of utilizing lengthscales to better understand how damage mechanisms change as the level of testing changes. While few of the planned levels of testing were complete by the close of this part of the project, promising results were emerging from the limited data in the comparison database. An outcome that is ready for use in future projects is the damage documentation procedure, which allows damage to be characterized in a standardized process for various composite specimens (i.e., specimens of different geometries, structural features, loadings). This will allow means to readily identify issues associated with lengthscales and levels of testing. It is recommended to continue pursuing the methodology of lengthscales as a means to reach an understanding of the changes in mechanisms affecting the material response and damage process in composite structures.

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Due to the delays in testing, analysis of only a certain number of specimens was completed, as shown in Table 4. The results of the analyses completed to date have been entered into a customised database to enable comparison of the characteristics of failure. With the addition of further data, this database will be a valuable resource for identifying lengthscale effects in composite structures.

Table 4: Summary of post-test analyses completed

Specimen Type	Test Location	Number of Specimens Assessed	
		Planned	Completed
In-Plane Loader[1]	NRL	0	210
Double Notch[2]	NRL	1152	0
Open-Hole Tension[3]	CRC-ACS	36	21
Ply-drop[3]	CRC-ACS	12	0
Stiffened Panels[2]	CRC-ACS	2	0

Notes: 1. Specimens available from previous work conducted at NRL
2. Specimens not available before post-test analysis work finished
3. Specimen arrival delayed

7.3 Relation to Energetic Analysis

In order to establish an assessment on how modeling and simulation can be used to address ply thickness length scale issues, full FEM analysis were performed on both the characterization and open hole specimens.

Figure 23 and Figure 24 show the difference between the 1 ply and the 4 ply configurations of the characterization specimen in terms of the surface distributions of the strain components and the elastic strain energy density respectively. The loading chosen involves rotation about all 3 axes. Based on the observation that these two configurations do not show drastic differences, one may be inclined to declare that there are no scale effects differentiating these two cases.

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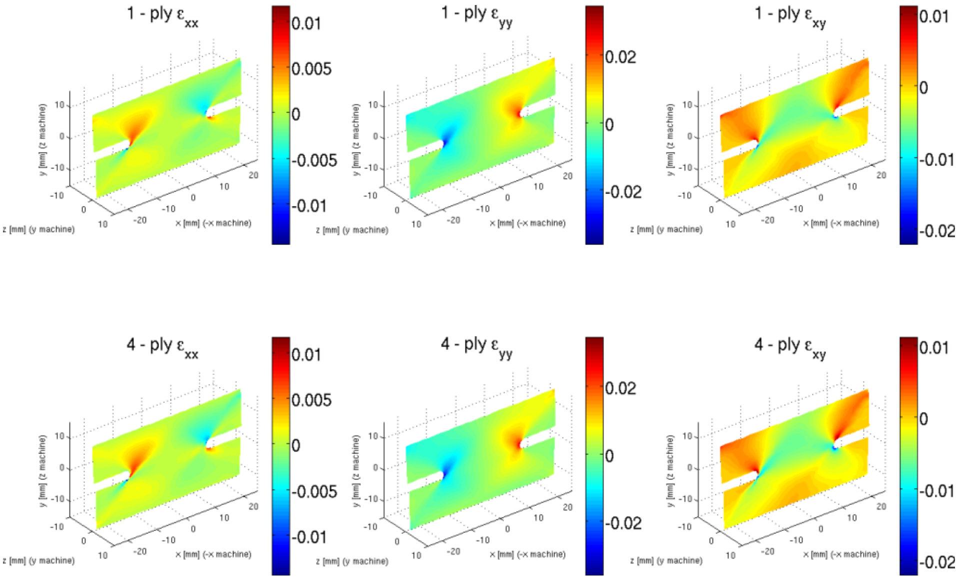

Figure 23: Comparison of strain components for 1-Ply and 4 – Ply characterization specimens under rotational loading about each of the three axes

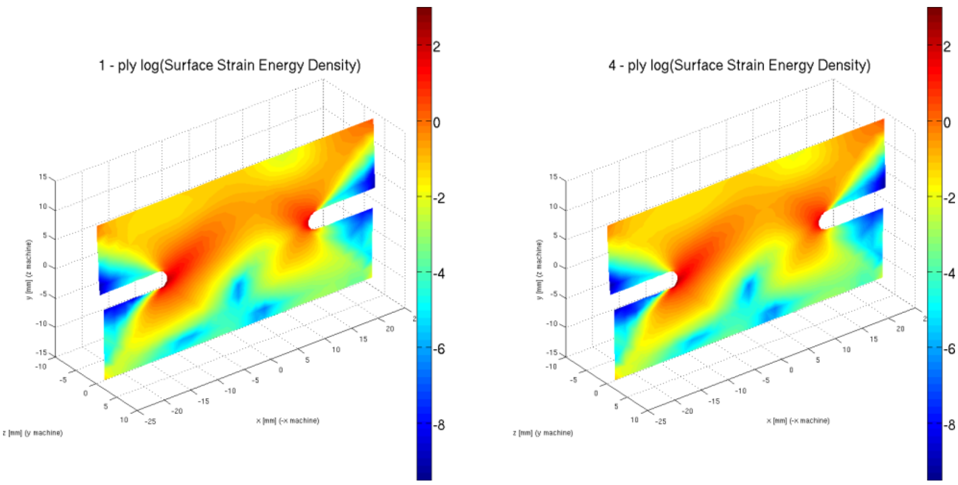

Figure 24: Comparison of surface energy for 1-Ply and 4 – Ply characterization specimens under rotational loading about each of the three axes

However, if one observes the evolution of the strain energy stored into the material, and specifically the dissipated energy spent for material damage, as shown in Figure 25, it is easy to observe that the 4-ply specimen accumulates dissipated energy much faster than the 1-ply laminate and the first jump indicating the activation of a dominant failure mechanism occurs much faster for the case of the 4-ply specimen.

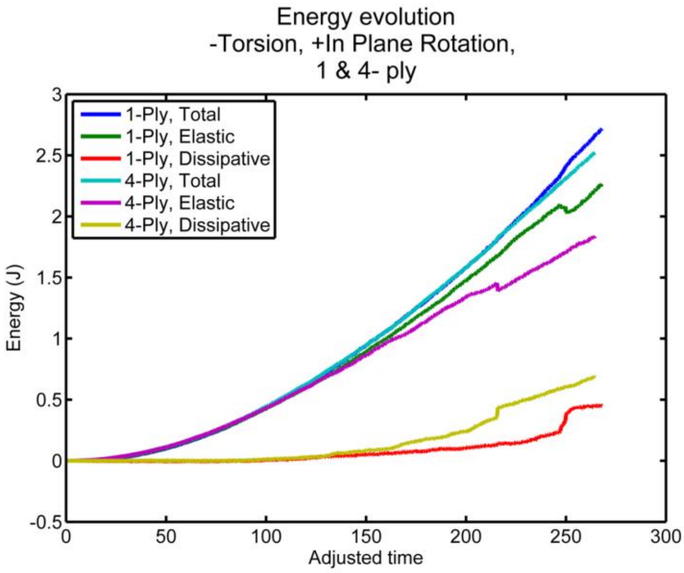

Figure 25: Comparison of total, elastic and dissipative energy distribution for 1-Ply and 4 – Ply characterization specimens under rotational loading about each of the three axes

In addition, the through-thickness distribution of strain energy density as shown in Figure 26 is very different for the two cases. While the 1-ply shows a relatively smooth distribution, the 4-ply distributions jump dramatically when the layers change orientation, demonstrating extreme at interior layers.

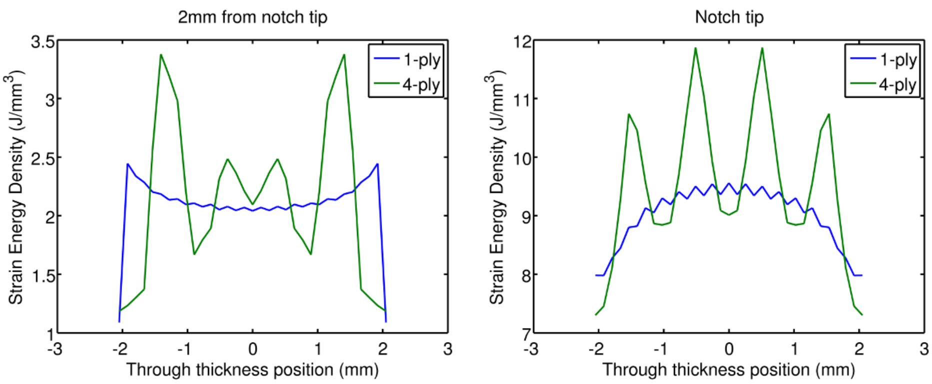

Figure 26: Comparison of elastic strain energy density distribution as a function of the through thickness dimension for 1-Ply and 4 – Ply characterization specimens under rotational loading about each of the three axes, at two locations: notch tip (left) and 2 mm from notch tip (right)

Similar observations can be made from Figure 27 and Figure 28 for the case of the open hole specimen in tension. This situation suggests that failures will initiate at the interior layers of the specimens, as is corroborated by the post-test photos of the specimens as shown in ~~Figure 28 and~~ Figure 29 and Figure 30.

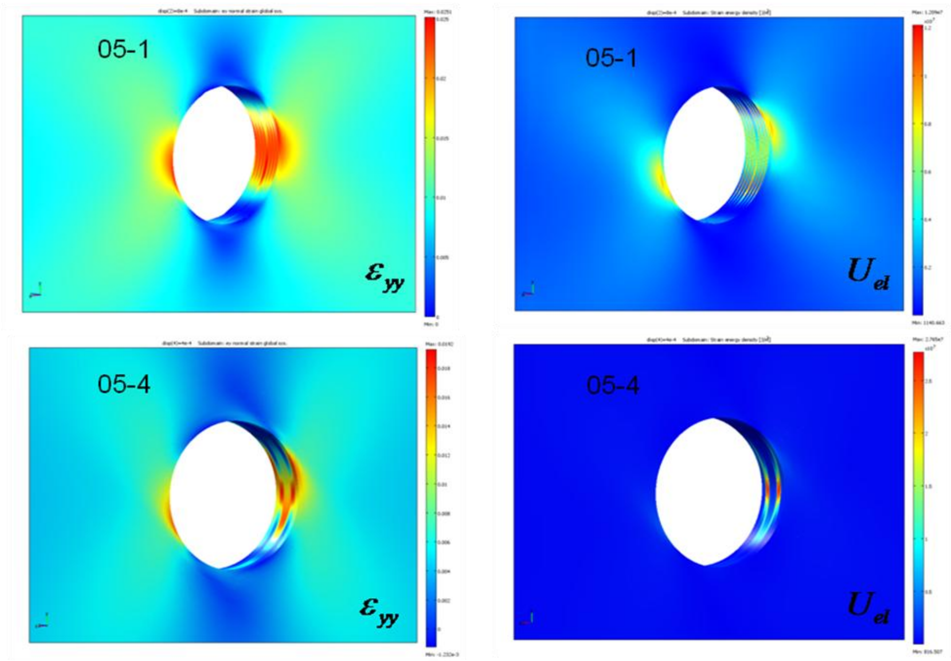

Figure 27: Comparison of y-component of strain distribution (left) and elastic strain energy density distribution (right) for 1-Ply (top) and 4 – Ply (bottom), open hole specimens under tension

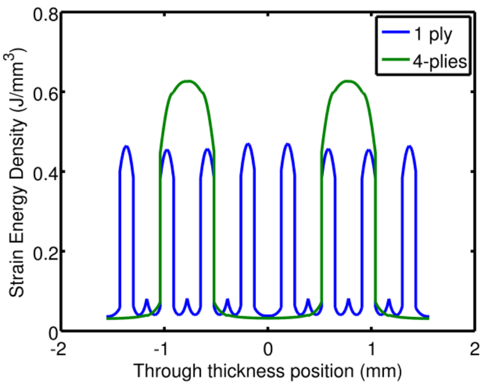

Figure 28: Comparison elastic strain energy density distribution as a function of the through thickness dimension at the edge of the hole where the x-axis intersects the hole, for 1-Ply and 4 – Ply, for open-hole specimens under tension

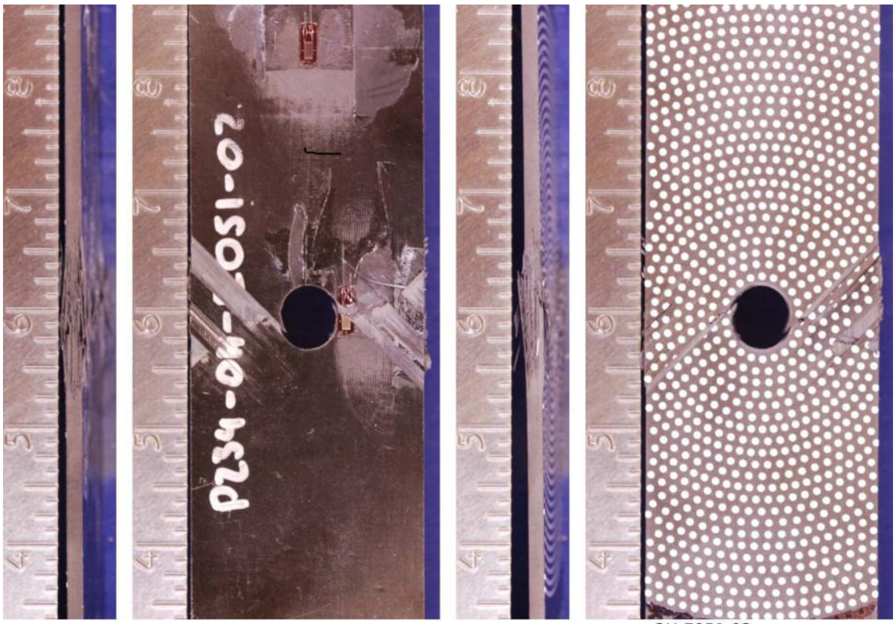

Figure 29: Post-test documentation of failure for 1-ply open-hole specimen under tension

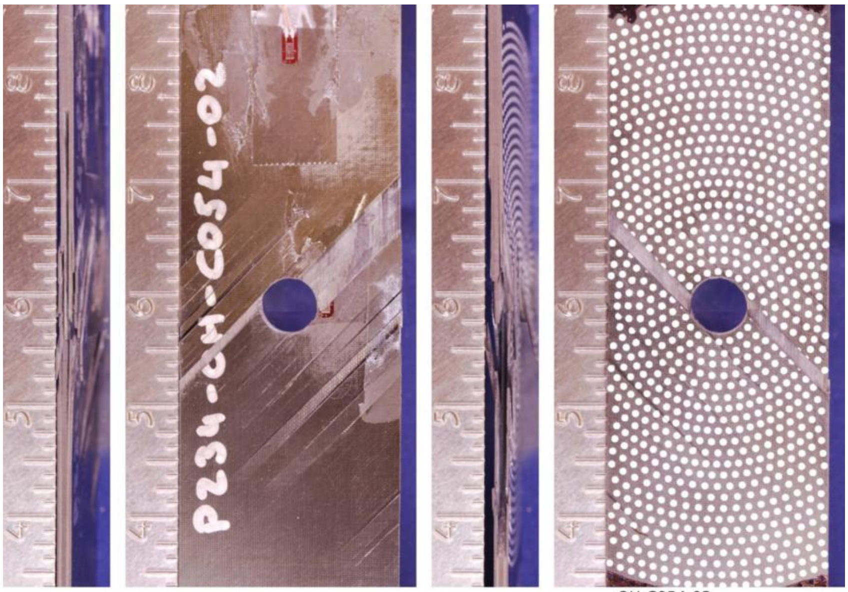

Figure 30: Post-test documentation of failure for 4-Ply open-hole specimen under tension

Therefore, the utilization of total and dissipated strain energy density as a measure characterizing damage seems to correlate well with experimentally observed failure behaviors. It is important to realize that the energy based analysis is capable of capturing the lengthscale effects of the layers without requiring special adjustment of its mathematical form, as long as a full 3D analysis is conducted.

In an effort to demonstrate that all polynomial failure criteria may be related to energy density representations, we have proved that indeed all failure criteria expressed as polynomials of the stress or strain components and their products are indeed special truncations of the general energy density [1111, 2727, 3434].

8 Project Outcomes and Achievements

8.1 Project Outcomes

Measured against the project objectives stated in Section 1.21.2, the project delivered the following outcomes:

1. Extend the NRL data-driven, constitutive material characterization approach to develop a methodology for the determination of mechanical behavior in complex composite structures:

- Successfully upgraded and commissioned the NRL 6DOF multi-axial loading frame
- Demonstrated the ability to test 26 specimens per hour
- Composite material system (AS4/3501-6) characterised by testing 1152 coupons tested
- Energy based methods developed to predict the response of composite materials and structures including degradation
- Two methods (REMDIS-2D and 3D) for full field displacement and strain measurements developed, validated and used
- Experimental design and optimization methods have been developed which can be broadly classified into the constitutive modelling, the enhancement of constitutive modelling, and the quantification of constitutive modelling and experimental design.

2. Validate the methodology through testing on coupons and subcomponents at ambient conditions with a focus on issues of length scales manifested across this range
    - Coupons and subcomponents testing completed –open-hole, ply-drop and stiffened panels
    - Length scale investigated through ply thickness on CH, open hole and ply drop specimens
    - Length scale investigated also in hole diameter
    - Length scale effects characterised through extensive documentation of failure behaviour and via CT scanning

3. Develop an overall approach to couple the methodology with commercial software for calculating stress state and assessing overall structural behavior
    - Energy density characterisation approaches developed and validated
    - Energy density methods implemented into commercial FE code (Abaqus and Ansys)
    - Methods evaluated for linear response, and response with degradation
    - Validation against coupon test data completed

8.2 Lesson Learnt

The ADEPT project involved close collaboration between the project participants. Specimens manufactured by CRC-ACS were tested by NRL. Specimens tested by CRC-ACS and NRL were evaluated by MIT. Experimental design methods developed by VT were implemented by NRL. The full-field strain measurement system developed by NLR was used by CRC-ACS. Constitutive models developed by NRL were evaluated, adapted and implemented by CRC-ACS. Therefore, the project participants were reliant on one another in order to complete their designated activities.

Therefore, the development and maintenance of key relationships through communication was of fundamental importance. In this regard, the experience in this project was very positive. Clear communication was essential to effective project delivery, and email, Skype, collaboration server, teleconferences and visits were all used. Despite this, inefficiencies, delays and miscommunications did occur.

The manufacture and testing phases of the project presented some difficulties. The carbon epoxy material system chosen proved to be particularly difficult to process and prepare test specimens. The resin flowed freely during curing, so special measures had to be taken to avoid bleed. The system was also very brittle so cutting and machining operations had to be conducted using very strict procedures that took some time to develop. Consequently, the required quality of specimen manufacture and preparation was not always maintained. ~~For future projects, a more robust material system should be used.~~ Due to the extended time period during which testing was undertaken, the testing equipment and methods were not always consistent which introduced some variation. Testing should ideally be conducted in a more continuous manner using the same apparatus and personnel.

Comment [j8]: Deleted this per Paul's comment

The effort required to complete some aspects of the program was underestimated. There is a need to allow for unforeseen problems in developing the research plan. The upgrade of the NRL 6DOF loader was beset by various weather related problems tha caused flooding of the pump room which delayed commissioning by approximately 2 years. This included very long lead time for some replacement parts, storm damage, and complexities involved in resolving issues related to achieving the required accuracy. At the completion of the project, however, the NRL 6DOF loader performance exceeded original expectations and can be used with confidence in future projects. The delays in commissioning the N~~L~~RL 6DOF loader impacted the development and validation of the dissipated energy based methods for failure prediction and the post-test characterisation of the test specimens.

8.3 Estimate of Economic Benefit of New Methodology

The extremely high cost of certification of aircraft structures manufactured from composite materials is widely seen as an impediment to the more widespread use of these materials. In particular, the cost of certification is a barrier for the introduction of new materials with improved performance into aircraft programs. For civil aircraft structures, the methodology for demonstrating compliance with the airworthiness regulations is most clearly defined in FAA Advisory Circular 20-107B [3~~3~~]. This specifies the use of the building block approach, as illustrated in Figure 31, which is also referred to as the testing pyramid. The width of the pyramid represents the number of tests, while the height represents the test complexity.

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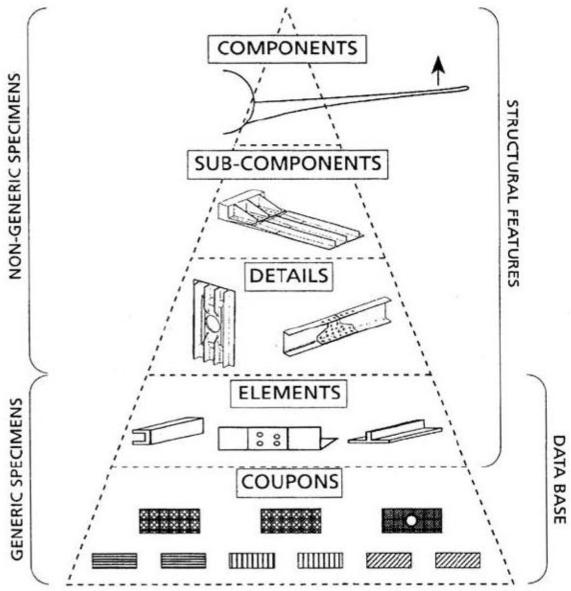

Figure 31: Building block approach for certification of composite aircraft structures

The building block approach has been developed in response to the recognised difficulties associated with scale and complexity in composite structures. To compensate, tests are conducted at increasing levels of complexity. At each stage, analysis and design methods must be validated. At the completion of the process, the safe operation of the aircraft will have been established with respect to the static, fatigue and damage tolerance performance.

As an example, the certification of the Boeing 777 all composite empennage structure was reported by Fawcett et al. [44]. A summary of the coupon and element level tests conducted in this program is presented in Table 5. These tests were conducted at the critical environmental conditions: room temperature dry; cold temperature dry; hot temperature wet. In addition, multiple detail and sub-component level tests were undertaken. For the component testing, two full scale structures were tested that were representative of the production articles. The first test demonstrated the static strength, while the second demonstrated the fatigue, damage tolerance and repair integrity.

Table 5: Coupon and element tests conducted under the Boeing 777 empennage certification program [4]

Test Type	Number of Tests
Ply properties	235
Long-term environmental exposure	200
Laminate strength	2334
Interlaminar strength	574
Radius details	184
Crippling	271
Stress concentrations	118
Effects of defects	494
Bolted joints	3025
Durability	385
Bonded repair	239
Total	**8059**

The immediate potential benefit of the methodology developed and validated within ADEPT falls within the coupon and element level of the testing pyramid. The double notch specimens tested in the multi-axial loader can potentially replace the following tests:

- Ply properties
- Laminate strength
- Interlaminar strength
- Stress concentration

In combination with validated analysis techniques, the methodology developed could potentially eliminate the need for the following tests:

- Radius details
- Crippling

Based on the Boeing 777 empennage example, this represents over 3700 tests with different specimen configurations. This could be replaced with, in the case demonstrated in this program, 1152 multi-axial tests on specimens of identical geometry under a defined wide range of load combinations.

The use of automation has been demonstrated in this program to provide enormous efficiencies. Manual testing for certification is a labour intensive process with careful test set-up and conduct, all overseen by a designated representative from the certification authority. It is estimated the 3700 tests described above represents over 4 man years of testing time alone if conducted using traditional approaches. ADEPT showed that tests could be conducted at a rate of 26 specimens per hour. Testing under different environmental conditions would be expected to be at a lower rate.

A comparison of the testing costs between the traditional method and that using the multi-axial loader are presented in Table 6. In this table, the specimen preparation cost is assumed to include recurring materials, manufacturing, inspection and instrumentation costs. The testing time is the time taken to conduct each test. These costs and times are based on the assumption that the tests are classed as certification tests and as such have more stringent requirements. The costs do not include data reduction and reporting. It is estimated that a saving of over $900,000 could be achieved. However, the most significant saving is in testing time, where it is estimated that over 900 man days of effort could be saved on testing alone. This represents a dramatic improvement to turn-around time for the testing, and could significantly lessen the barriers to the introduction of a new improved material into an aircraft development program.

Table 6: Cost comparison between traditional and proposed coupon and element testing

Approach	Test Type	Number of Tests	Specimen Prep (USD)		Testing (USD)		Test Duration (Hours)	
			Unit Cost	Total	Unit Cost	Total	Unit Time	Total
Traditional	Ply properties	235	100	23,500	150	35,250	2	470
	Laminate strength	2334	100	233,400	150	350,100	2	4668
	Interlaminar strength	574	100	57,400	150	86,100	2	1148
	Radius details	184	250	46,000	150	27,600	2	368
	Stress concentrations	118	150	17,700	150	17,700	2	236
	Crippling	271	500	135,500	150	40,650	2	542
	Total	**3716**		**513,500**		**557,400**		**7432**
6-DOF Multiaxial Loader	CH-specimens	1152	100	115,200	20	23,040	0.05	58
	Saving			**398,300**		**534,360**		**7374**

Further savings could be realised using the methodology developed in this program through the addition of a system for automated reporting of the required material parameters, including statistical analysis of the raw data. Longer-term economic benefits include a reduction in the number of detail and sub-component level tests required in the development and certification of composite structures as lengthscale information is generated in the coupon tests. As these higher level tests are very expensive and time consuming, significant cost savings could be made. In addition, it is also important to recognize and acknowledge that a primary part of the overall process is the need for the overall damage documentation.

Comment [j9]: to address Paul's 2nd comment

8.4 Ongoing Activities

The RMIT PhD candidate, Mr Andrew Litchfield, is due to complete his PhD project by March 2013. His research area focuses on the development, implementation and validation of a constitutive model based on the dissipated energy density approach. His thesis will include the results of ongoing efforts to validate the model against coupon and structure test data and therefore provide details on the strengths and weaknesses of the approach.

Similarly, the MIT PhD candidate, Mr Jeff Chambers, is due to complete his project soon. His research area focuses on the characterisation of the damage and failure modes,

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identifying the characteristic influences of lengthscale. His thesis will include further documentation and analysis of the coupons tested in the project.

8.5 Future Research Directions

The key outcomes of ADEPT relate to the commissioning of the NRL multiaxial loader and the associated testing regime, development and implementation of constitutive modelling based on the total and dissipated energy and establishing a fundamental understanding of lengthscale issues related to composite materials.

Future research directions that extend the knowledge gained in the current project are described following:

1. Modification of the NRL 6-DOF loader to enable testing of composite coupons under critical environmental conditions (for example -60<T<90°C and up to 90% relative humidity) and simultaneous exposure to electromagnetic generalized loading. Testing under such conditions is a common requirement for aircraft material characterisation programs.

1.Modification of the NRL 6-DOF loader to enable testing of composite coupons under cyclic loading consitions to account for strain induced damage accumulation. Testing under such conditions is a common requirement for aircraft material characterisation programs.

1.

4.2. Detailed investigation into the behaviour and failure characteristics of composite laminates under multi-axial loading, with comparison to baseline uni-axial testing data. Use of the multi-axial loader makes possible loading the material in load combinations that have previously only been extrapolated. This work would make an important contribution to the worldwide effort to develop an improved understanding of the failure mechanics of composites. This would also assist in the development and acceptance of improved methods for composite failure prediction.

5.3. In the current project, lengthscale effects in composites were investigated based on changes to the energy dissipation, structural response and through post-mortem investigation. This identified a gap in knowledge regarding the effect of lengthscale on the initiation and growth of damage in composites. Such a fundamental understanding can be gained through a dedicated project making use of the NRL multiaxial loader in combination with newly evolving X-Ray microCT imaging techniques with the resolution required to identify failure failure mechanisms initiation and evolution. The possibility of in-situ testing and microCT scanning should be explored.

6.4. The constitutive modelling approach should be expanded to fully consider through-thickness damage modes. Under certain loading modes, delamination can have a strong influence on failure initiation and progression. Inclusion of these this damage modes at a structural level rather than through material degradation in the constitutive model requires additional experimental characterisation and will make use of improved computational capacity to solve the more complex problems.

4.5. Investigate if there is a canonical minimum subset of experiments and a minimal loading path subspace that can produce an acceptable constitutive characterization in

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Comment [AO10]: Should we add a point regarding further consideration of a 6-dof space instead of a 4-dof space? Perhaps John could write this or at least comment. I think the 4-dof loading excited enough of the 6-dof strain space that we may not need to go to the 6-dof loading, which may never be practical. John may have a different view, which may tie in to future work with Tomo.

Comment [j11]: Deleted this becasue both of the total energy approaches developed in the project by NRL DO INCLUDE through thickness damage modelling.

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order to further economize in the cost of specimens and time required for the experiments.

6. Develop a dynamically determinable loading path trajectory process with the NRL 6-DOF loader, to avoid the systematic spanning of the loading path subspace that defines the number of specimens.

~~4.~~7. Develop material certification protocols based on the knowledge acquired from thsi effort, aiming in the rapid insertion of materials into structural composite platform applications.

~~4.~~8. Expand the length scale analysis beyond the sizing of the lamina thickness, to the sizing of the specimen itself. This effort will determine if indeed additional parameterization of the total or dissipated energy density is required.

9 Conclusion

The ADEPT project aimed to improve the effectiveness of the prediction of the overall behavior, including failure, of composite structures. The project sought to provide a valid alternative to the traditional building block approach used in the development and certification of aerospace composite structures. The objective was to significantly reduce number of tests, time and cost through the adoption of an automated, multi-axial testing methodology, the development of an associated means of predicting the response of composites including failure based on total and dissipated energy density, and an understanding of lengthscale effects.

The custom built NRL 6 DOF multi-axial loader was successfully upgraded and validated. The machine demonstrated increased accuracy, and was capable of testing up to 26 specimens per hour. This was integrated with a 2D and 3D full-field measurement system, and means developed to deal with the massive data output integration. Experimental design methods were developed to enable real time determination of load paths to minimise testing while ensure that the full strain space is sampled. Implicit, deterministic and stochastic modeling techniques were developed in support of this effort.

Energy density based methodologies were developed and adapted to predict initiation and progression of damage in composite structures. The data generated in the characterisation testing of 1152 specimens in the NRL 6DOF loader was used to develop ~~a~~ characterization ~~vector~~ data unique to the material. These energy density methods were implemented into commercial FE software, enabling methodology to be more widely adopted and evaluated. Validation of the methods was completed using test data from open hole, ply drop and stiffened panel tests. Importantly, the methods were found to be able to predict the response of composite structures up to the initiation of damage. The progression of damage could also be predicted, but further evaluation and validation of the methods is required to improve confidence in these predictions.

Length scale issues in composites were partially evaluated and characterised (based on the thickness of the lamina layer) with the effect on strength and failure characteristics evaluated experimentally and failure characteristics documented using photographic and CT scanning methods. During testing, it was observed that lengthscale could affect the failure initiation load, the final failure load and the failure mode. This was confirmed through post-test analysis, the results of which have been entered into a database to enable further analysis. In terms of the constitutive response, it was demonstrated that the performed characterization could capture the actual behavior of the specimens regardless of length scale. Therefore, energy density approaches can capture scale effects naturally without requiring special parameterization This suggests that -as expected by virtue of the fact that energy density is a quantity normalized by geometry- constitutive response can be predicted for all scales at least as far as the lamina thickness. . Further work is required to complete post-test analysis of all specimens tested in the project to enable more complete documentation of lengthscale effects in composites and more testing is required for additional length scale parameters describing the scaling of the specimen itself as opposed to just the size of the lamina thickness..

The project produced an extensive number of publications, including 19 journal publications, 64 conference publications and 3 patents.

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Patents

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89. Michopoulos, J.G., Hermanson, J.C., and Iliopoulos, A.P., "A recursive Hexapod for Multiaxial Material Testing", US Navy Case #100,731, Patent Disclosure Sept 20, 2010, Provisional Patent Application was filed on August 4, 2011.

90. Iliopoulos, A.P., Michopoulos, J.G. and Andrianopoulos, N.P., "A Workbench for Three Dimensional Remote Measurement of Displacement and Strain Fields Through Digital Imaging", Navy Case #101,258, Provisional Patent Application was filed on August 4, 2011.

Reports, Theses and Presentations

Comment [AO12]: Has Pan finished? I would have thought so, didn't he start at the same time as Michael? I know he moved to VT with Tomo.

91. Orifici, A.C., Herszberg, I., Thomson, R.S., "Critical Review on Constitutive Modelling and Failure", CRC-ACS Technical Report, CRC-ACS, Melbourne, Australia, December 2007.
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93. Heiskanen, B., "Experimental Investigation of Damage Modes and Scale Effects in Notched Composite Specimens", BEng (Aero) Thesis, RMIT University, October 2010.
94. Lagace, P. and Chambers, J., "Lengthscale Issues in the Mechanical Behavior and Failure of Composite Structures", TELAMS REPORT 2011-1, Technology Laboratory for Advanced Materials and Structures, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts, May 2011.
95. Ladpli, P., "Experimental Damage Modes and Scale Effects in Notched Composite Specimens", BEng (Aero) Thesis, RMIT University, October 2011.
96. Orifici, A.C., 'Test Results: CRC-ACS', in ADEPT Final Review Meeting, 17 November 2011, Melbourne, Australia.

~~Non Peer-Reviewed~~Other Publications

97. NRL News Release, NRL Robotic Loader System Achieves Composite Material Testing Milestone, 9/6/2011 - NRL News Release 86-11r. 8870 republications.
98. Science Newsline Physics & Chemistry, http://www.sciencenewsline.com/physics/2011090618130029.html and http://www.sciencenewsline.com/apps/news/read?f=2011090618130029&n=1&continue=y
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Appendix A – Key Publications

Include pdfs of the following in the appendix:

- Orifici, A.C., Herszberg, I., Thomson, R.S., *Critical Review on Constitutive Modelling and Failure*, CRC-ACS Technical Report, CRC-ACS, Melbourne, Australia, December 2007.
- Orifici, A.C., Thomson, R.S., 'The effect of ply thickness and notch size in CFRP tension specimens', in *14th Australian International Aerospace Congress*, Melbourne, Australia, 28 Feb - 3 March, 2011
- Orifici, A.C., 'Test Results: CRC-ACS', in *ADEPT Final Review Meeting*, 17 November 2011, Melbourne, Australia.
- Litchfield, A.J., Thomson, R.S., Michopoulos, J.G., Orifici, A.C., 'Energy-based material characterisation from multi-axial test data for damage analysis in CFRP notched coupons', ~~*International Journal of Numerical Methods in Engineering*~~*Computational Mechanics* (submitted ~~June~~ xxx 2012).
- Furukawa, T. and Michopoulos, J.G., "Computational Design of Multiaxial Tests for Anisotropic Material Characterization," International Journal for Numerical Methods in Engineering, 74, pp. 1872-1895, 2008
- Michopoulos, J.G., "On the Reducibility of Failure Theories for Composite Materials", J. of Composite Structures, 86 (2008), pp. 165-176.
- Michopoulos, J.G., Hermanson, J.C. and Furukawa, T., "Towards the Robotic Identification of Constitutive Response of Composite Materials", J. of Composite Structures, 86 (2008), pp. 154-164.
- Iliopoulos, A.P., Michopoulos J.G. and Andrianopoulos, N.P., "Performance Analysis of the Mesh-Free Random Grid Method for Full-Field Synthetic Strain Measurements", 2010, Blackwell Publishing, Ltd., J Strain (2010) 1, doi: 10.1111/j.1475-1305.2010.00786.x in print.
- Michopoulos, J.G., Hermanson, J.C., Iliopoulos, A.P., Lambrakos, S. and Furukawa, T. "Data-Driven Design Optimization for Composite Material Characterization", J. Comput. Inf. Sci. Eng. 11, 021009 (2011), DOI:10.1115/1.3595561.

Comment [AO13]: Can you check with Andrew if he submitted to Computational Mechanics? IJNME knocked it back.

Documentation Page

Document Number: CRC-ACS TR120XX	**Project Number:** P2.3.4

Title: ADEPT Project Final Report

Author(s) and Affiliation(s): Rodney Thomson (CRC-ACS), Adrian Orifici (RMIT), Andrew Litchfield (RMIT), John Michopoulos (NRL), John Hermanson (NRL), Athanasios Iliopoulos (NRL), Tomonari Furukawa (VT), Paul Lagace (MIT)

Summary: The ADEPT project aimed to improve the effectiveness of the prediction of the overall behavior, including failure, of composite structures. The project sought to provide a valid alternative to the traditional building block approach used in the development and certification of aerospace composite structures. The four and a half year project, part funded by the United States Office of Naval Research (ONR), involved collaboration between the Cooperative Research Centre for Advanced Composite Structure (CRC-ACS), Massachusetts Institute of Technology (MIT), the Naval Research Laboratory (NRL) and Virginia Tech (VT). The NRL multi-axial loader was successfully upgraded, and demonstrated the capability to test up to 26 specimens per hour. This was integrated with a 2D and 3D full-field measurement system, and means developed to deal with the massive data output integration. Coupled with this, experimental design methods were developed to enable real time determination of load paths to minimise testing while ensuring that the full strain space is sampled. From this test data, total and dissipated ~~energy~~ energy density based methodologies were established and implemented into commercial FE codes to predict initiation and progression of damage in composite structures. Validation of the methods was completed using test data from open-hole tension, ply-drop and stiffened panel tests. Length scale effects were characterised and documented using photographic and CT scanning methods. Lengthscale was found to affect the failure initiation load, the final failure load and the failure mode. However, the resulting constitutive characterization was found to be independent of length scale. The ADEPT project demonstrated that there is a viable, cost effective alternative to traditional design and certification techniques for composite structures.

Keywords: Multi-axial testing; Dissipated energy; Strength prediction; Lengthscale effects

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