Utilising Non-Destructive Inspection Information for Assessing the Damage Tolerance of Aerostructures

Dr. Stefanos Giannis, Sector Manager – Aerospace & Energy

O: +44 (0)1462 427 850

F: +44 (0)1462 427 851

E: stefanos.giannis@element.com

Outline

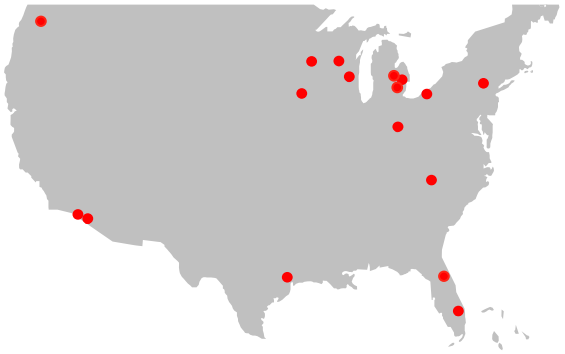
- Introduction
- Motivation
- NDT2DT Concept and Process
- Process Formulation & Validation
  - Flat Panel
  - Skin/stringer configuration
  - 90°-angled panel
- Graphical User Interface
- Concluding Remarks
- Acknowledgments

Element Materials Technology

- Operates globally from a growing network of laboratories sited across the US and Europe
- Material testing and inspection, failure analysis and product qualification testing in the Aerospace & Defence, Oil & Gas, Power Generation and Transportation sectors

USA

Huntington Beach, CA
Rancho Dominguez, CA
Jupiter, FL
Melbourne, FL
Des Moines, IA
Center Line, MI
Warren, MI
Wixom, MI
St. Paul, MN
Charlotte NC
Cincinnati, OH
Cleveland, OH
Newtown, PA
Houston, TX
Bothel, WA
New Berlin, WI
Wausau, WI



Europe

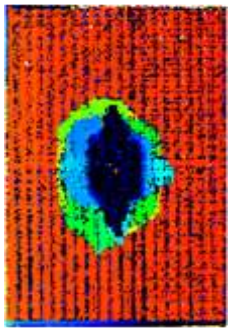
BE, Antwerp
DE, Herne
GB, Aberdeen
GB, Hitchin
GB, Sheffield
NL, Amsterdam
NL, Beek
NL, Breda
NL, Hengelo
NL, Rotterdam
NL, Veendam

Motivation

- Vast amounts of NDI data are collected...

  ...however, what is the level of understanding with regards to **what the data mean** and how can be **used more effectively**?
- NDI does not tell much about the residual strength of a component, however, coupled with testing and **simulation tools** could play an important role in determining the influence of the detected damage on the structural integrity
- Develop a link between realistic NDI data directly to the creation of a finite element numerical model

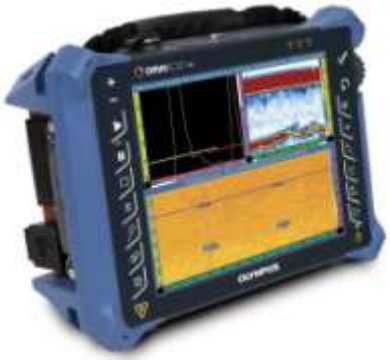
  Utilise damage material models (incl. fracture mechanics) to determine the damage tolerance of the structure



element™ WavelengthNDT LMS® ENGINEERING INNOVATION SPIRIT AEROSYSTEMS

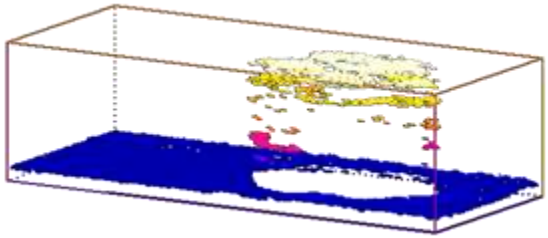
The NDT2DT Process

Use portable NDI equipment to detect damage



Composite aircraft structure

Generate local damage contour



NDT data interpreted and converted to an x, y, z array of the damage area

The NDT2DT Process

NDT output

CAD info

Create input for FEA solvers that will include ply detail from manufacturer's ply table, dropped ply location and the discretely modelled damage…

Submit to solver

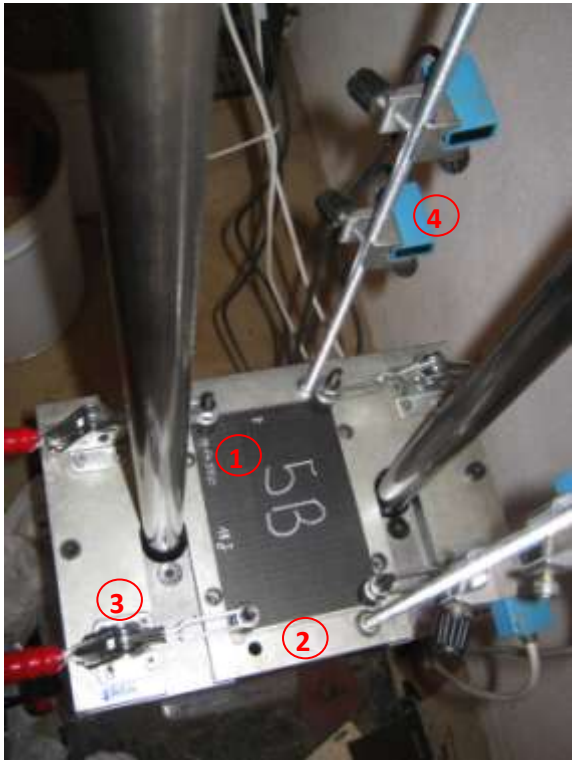
Evaluate effect of damage and determine damage tolerance of the structure

Process Formulation & Validation

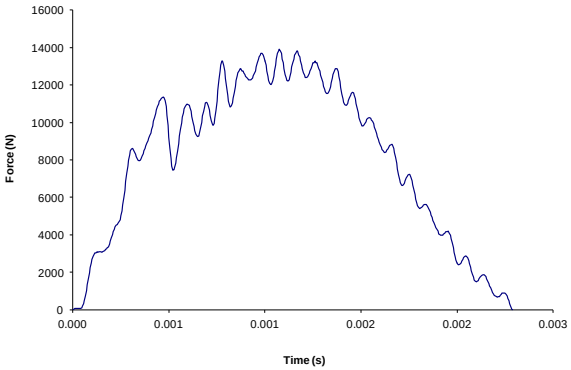
- Flat panel → wing cover
  - Simulated in-service impact damage
- Skin/stringer configuration → stiffened wing cover
  - Simulated in-service impact damage
- 90°-angled panel → spar
  - Simulated manufacturing defect at the corner radius

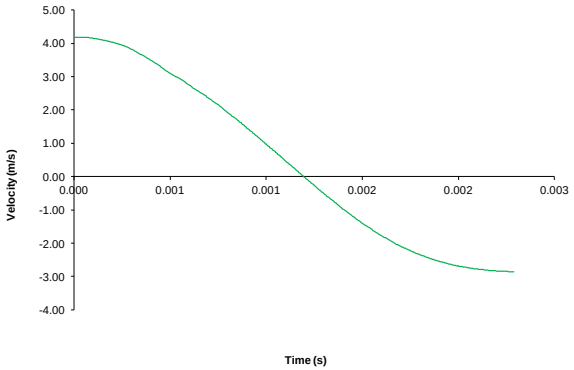
Flat Panel I Inducing the Damage

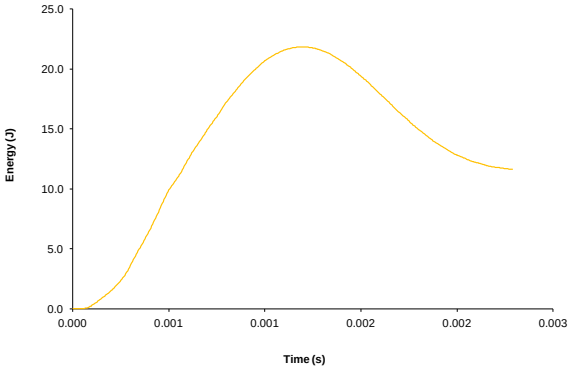
Low velocity/energy impact (≤40J)

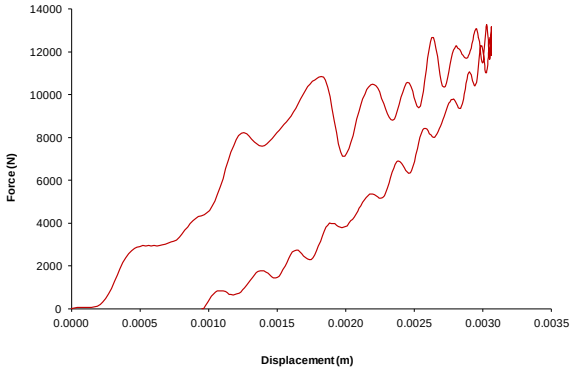


(1) Specimen; (2) Support fixture; (3) toggle clamps; (4) photocells





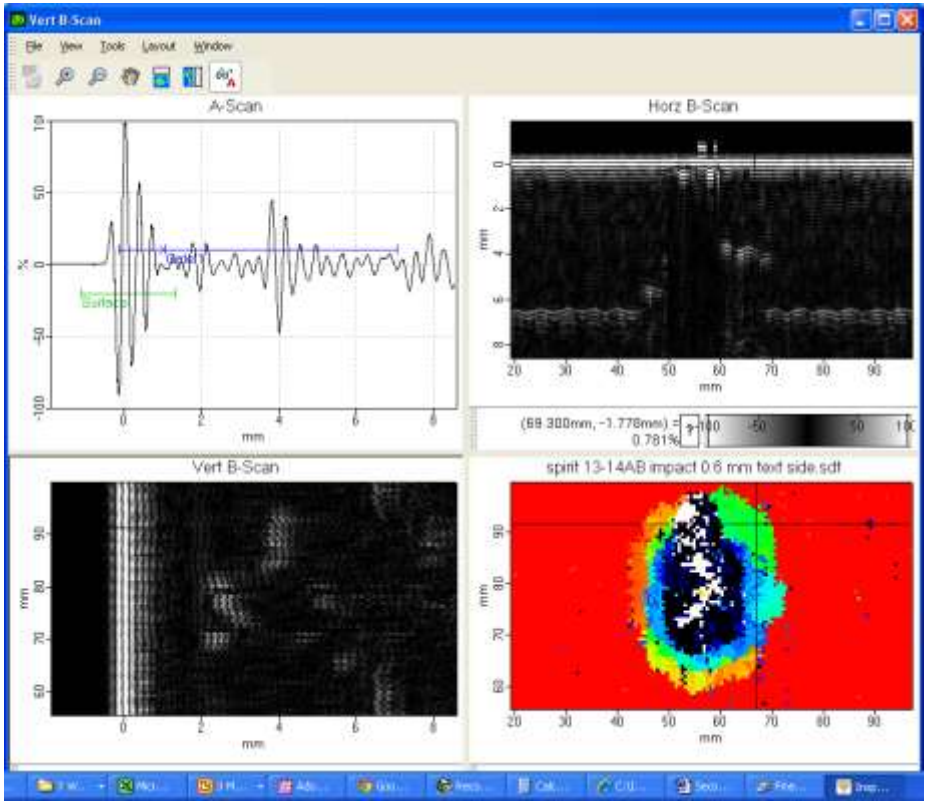




Flat Panel I Finding the Damage

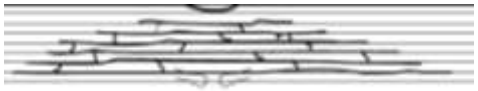
- Used Time Corrected Gain (TCG) approach to correct for loss in signal intensity due to attenuation in composite
  - Signal loss increases with ultrasound frequency and with thickness of structure
- Portable Olympus Omni scan MX
  - 64 element 5 MHz probe
  - Water coupling
- Immersion tank
  - 10 mm diameter 5 MHz immersion probe
  - Water coupling
  - Scan resolution 1 mm

- **Quantify damage**
- **Portable vs. immersion tank**

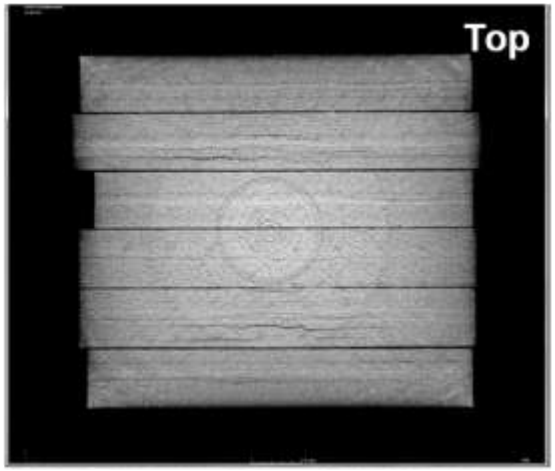


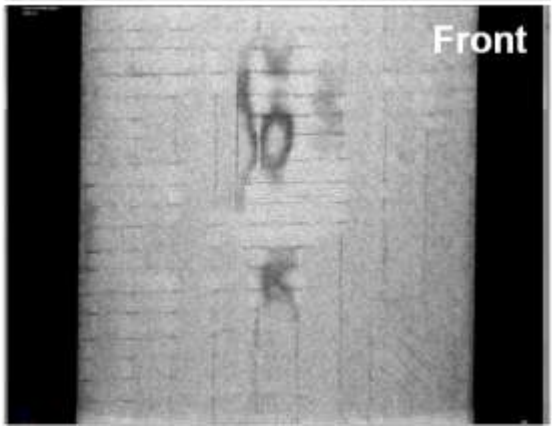
Flat Panel I Understanding the Damage

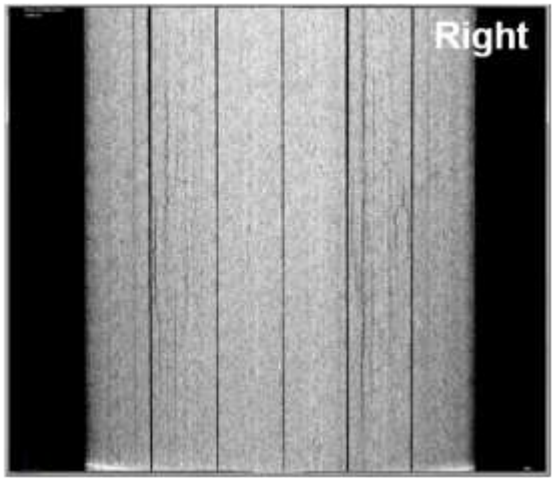
- Ultra-focus CT-scanning was used to determine hidden damage
- Damage mainly developing between bi-axial, tri-axial fabrics
- CT-scanning on four specimens revealed that the majority of the interfaces hidden for the ultrasound were also delaminated



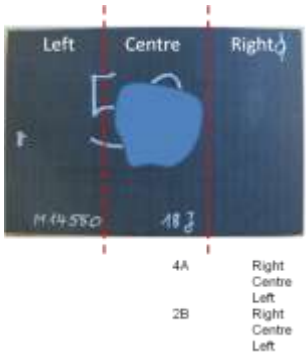
4A R





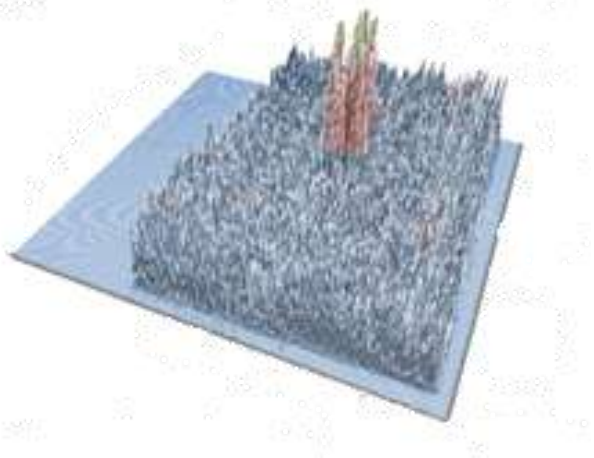


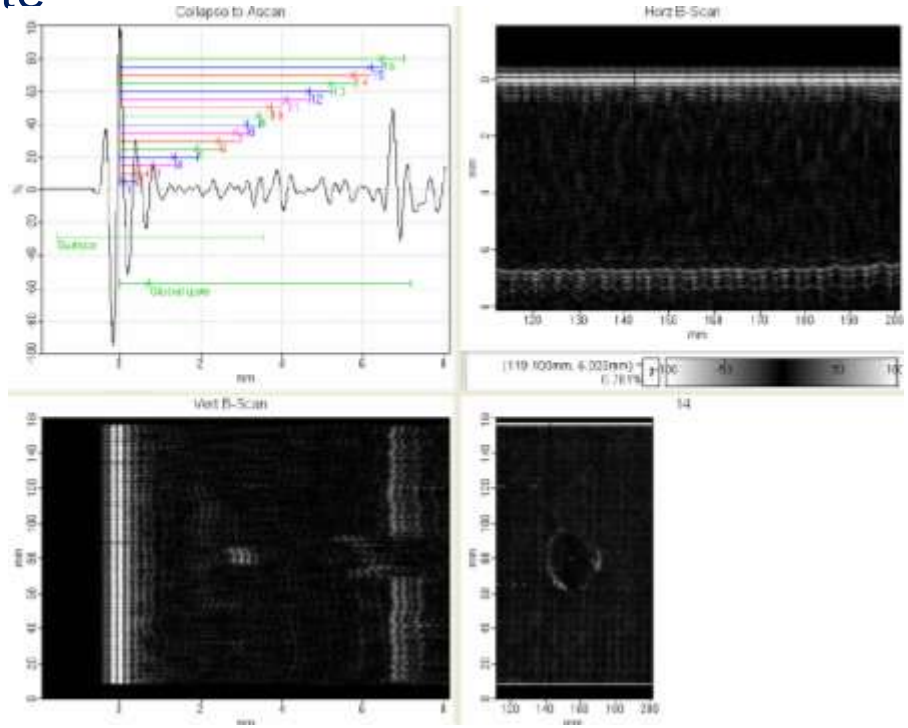
4A R



Flat Panel I Exporting the Damage

- Using ultrasound intensity information produced slices every **x** mm through the thickness (ply –ply or fabric-fabric interface) by appropriate gating the signals
- Extracted intensity data for each gate
- Gated signal intensity with nominal values 0 – 100



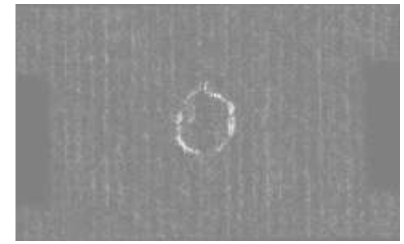


Flat Panel I NDT Output Description

number of columns

number of lines

Gated signal amplitudes of nominal value 0 – 100, where 0 means black (grey) and 100 means white



Header part

[Axis Lengths]
283 182
[X Axis Range]
0 169.8 mm
[Y Axis Range]
0.33 120.45 mm
[Data Range]
-100 100 %
[Data]

Data part (x →, y ↓)

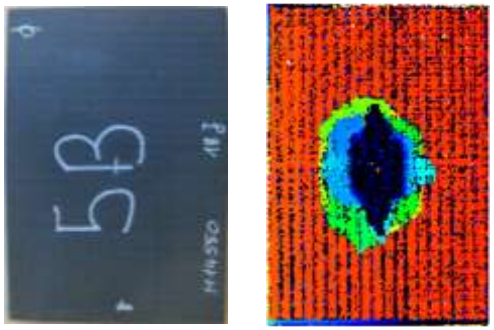
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781
0.781	0.781	0.781	0.781	0.781	0.781	0.781	0.781	1.563	2.344	1.563	0.781	1.563	3.125
0.781	0.781	0.781	0.781	0.781	0.781	0.781	1.563	3.125	3.125	6.25	4.688	7.031	8.594
0.781	0.781	0.781	0.781	0.781	1.563	3.125	3.906	4.688	18.75	12.5	28.125	27.344	18.75
0.781	0.781	0.781	0.781	0.781	0.781	4.688	6.25	17.188	32.813	39.844	44.531	68.75	28.906
0.781	0.781	0.781	0.781	0.781	1.563	4.688	17.188	17.969	53.906	64.063	64.063	44.531	33.594

.....

.....

Flat Panel I NDT2DT Process Overview

Ultrasonic Scan

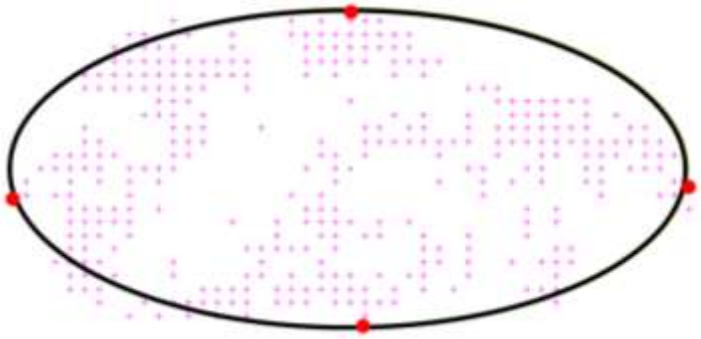


Wavelength NDT

NDT data in text file

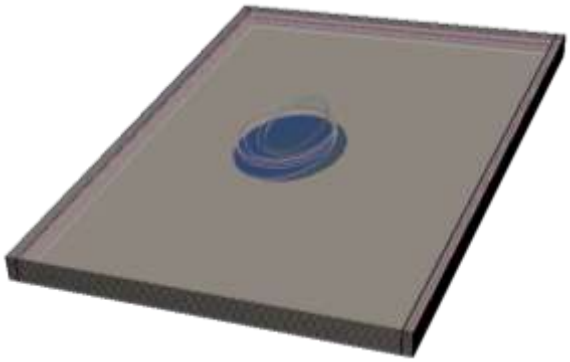
ELEMENT
Python script

Abaqus™ Sketch



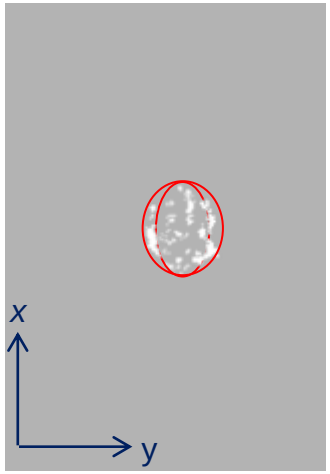
ELEMENT
Python script

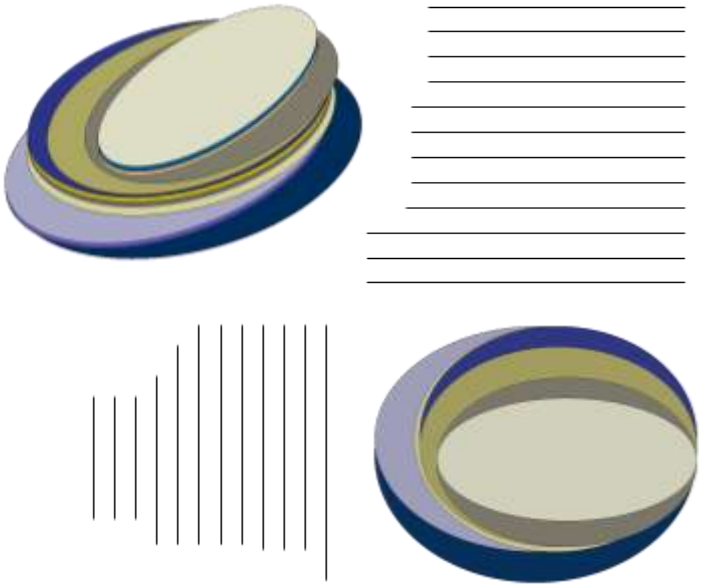
FE Model



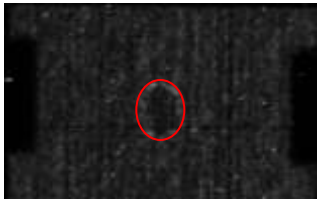
Rules for Determining Ellipse Vertices

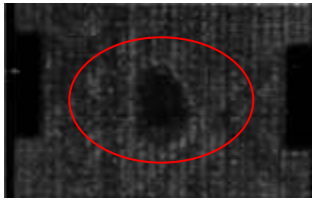
- Extremes are inherited from previous layer





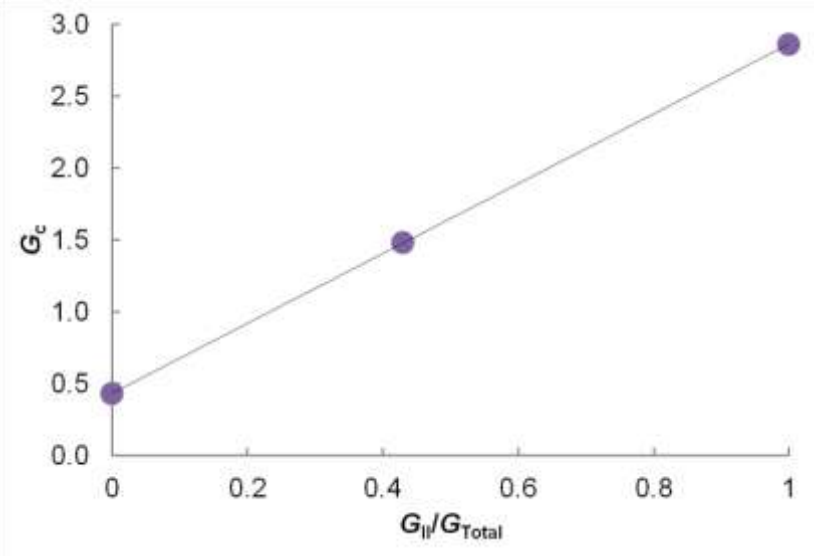
- High scatter of points for layers distant from scan surface → damage size is proportionally limited by damage from previous layer





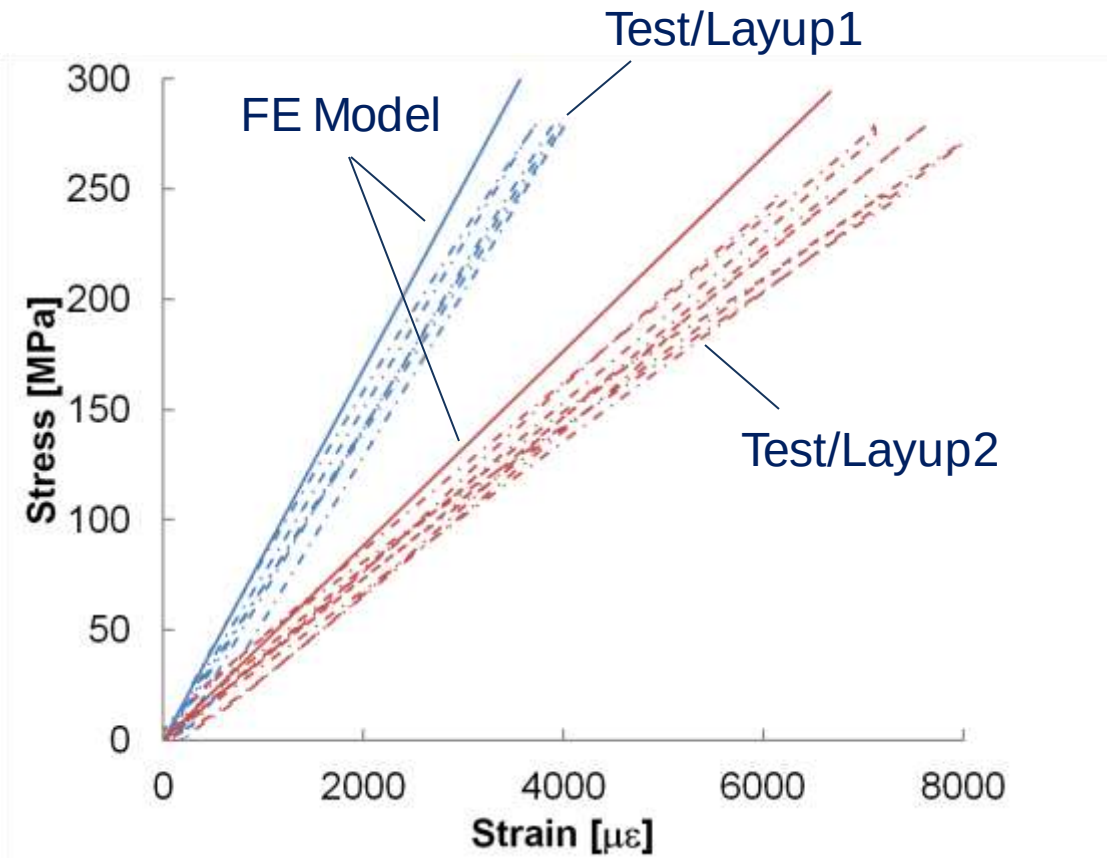
Techniques of Modelling Damage

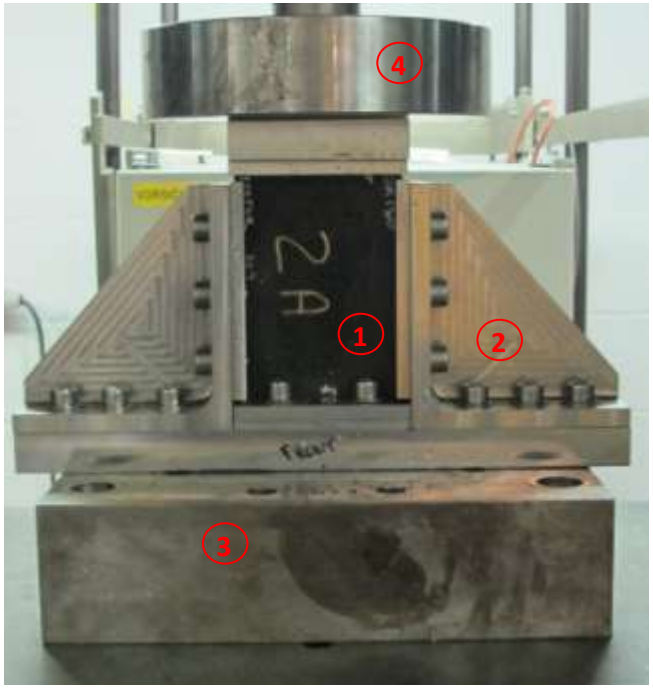
- Virtual Crack Closure Technique (VCCT)
  - Based on linear elastic fracture mechanics (LEFM), requires pre-existing crack in the model
  - Crack propagates when $G > G_c$ (Critical strain energy release rate)
  - Usually requires high mesh refinement around the crack tip, but not necessarily in Explicit solver
- In-plane strength based Hashin Criteria
  - Fibre failure in tension
  - Fibre buckling and kinking in compression
  - Matrix cracking in transverse tension and shearing
  - Matrix crushing in transverse compression and shearing



Flat Panel I Undamaged Response

- Validate the undamaged model response

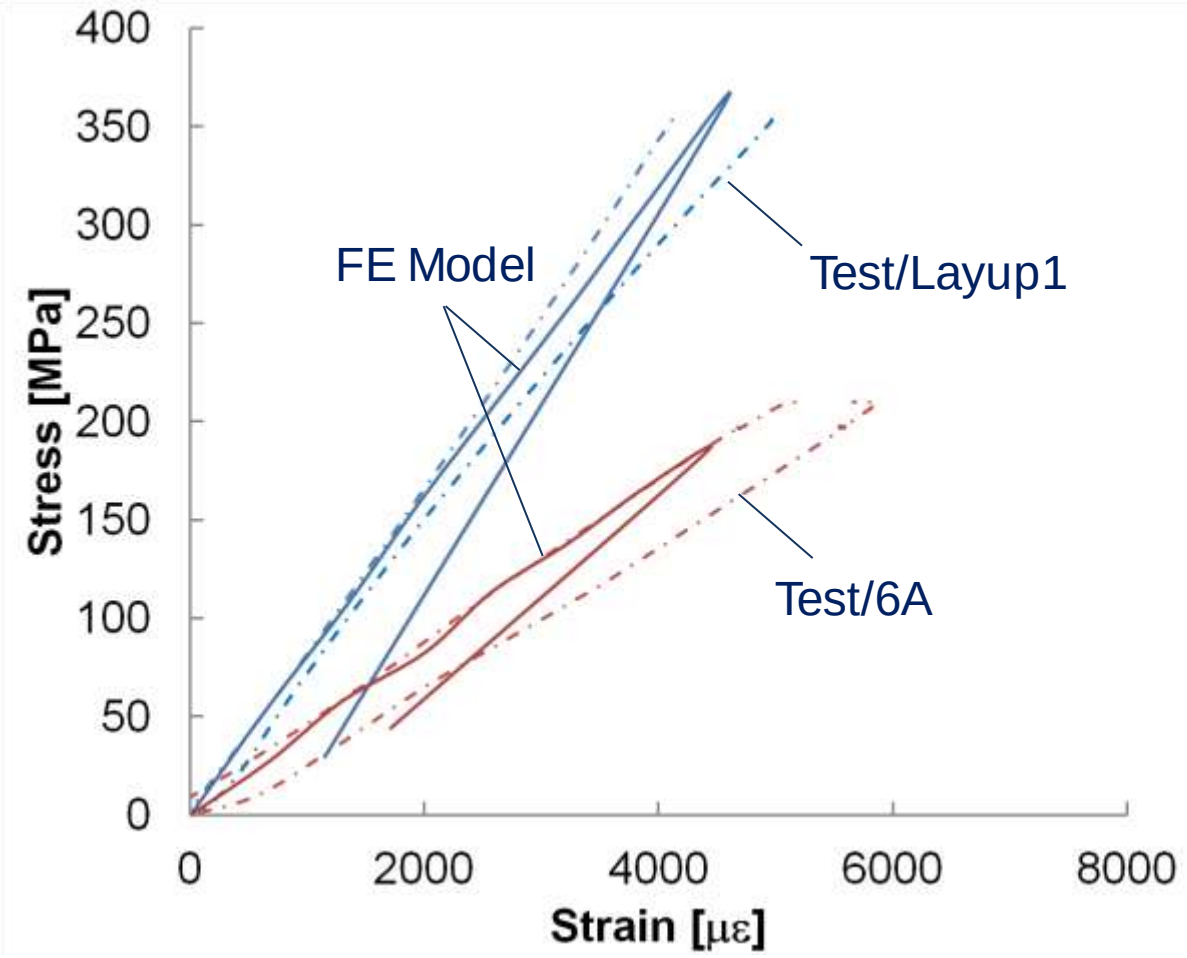




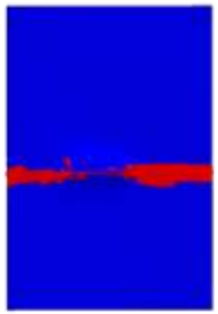
(1) Specimen; (2) anti-buckling fixture; (3) platen to machine crosshead; (4) platen to load cell

Flat Panel I Validation

- Solve FE model using Abaqus™/Explicit



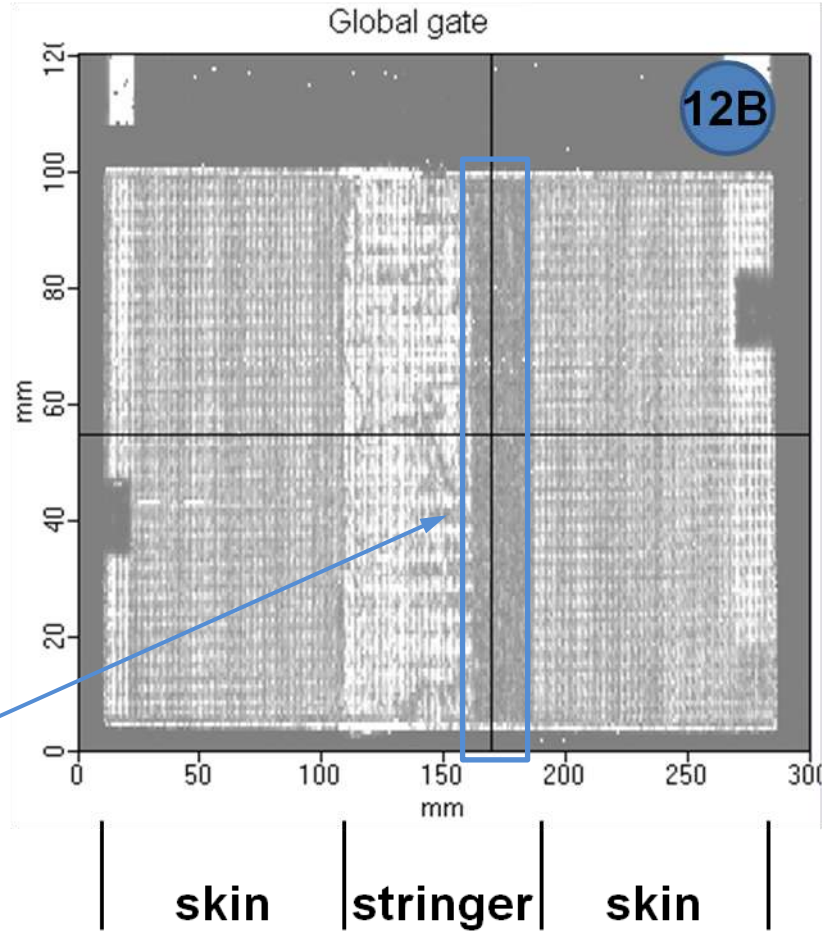
Fibre/matrix compression



Skin/stringer I Understanding the Damage

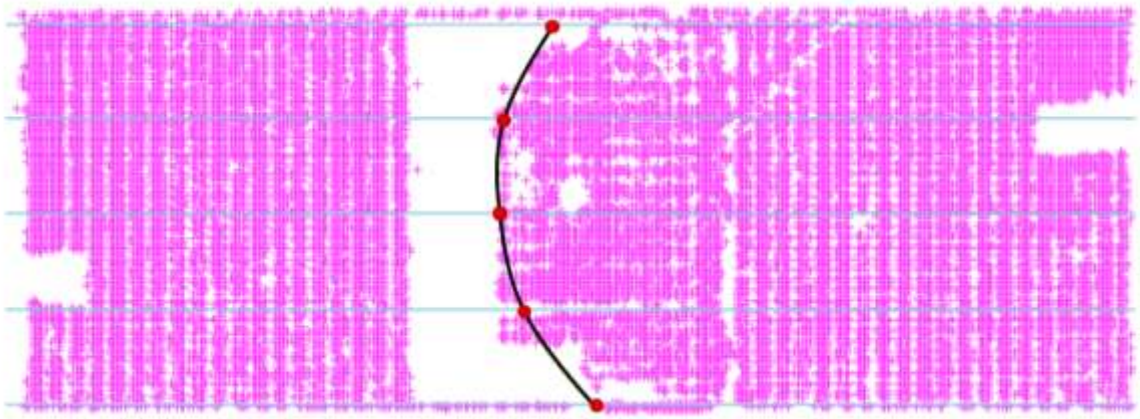
- Low velocity/energy impacts (≤40J) on skin/stringer configurations
- Damage primarily being skin-to-stringer delamination

- Still attached stringer area



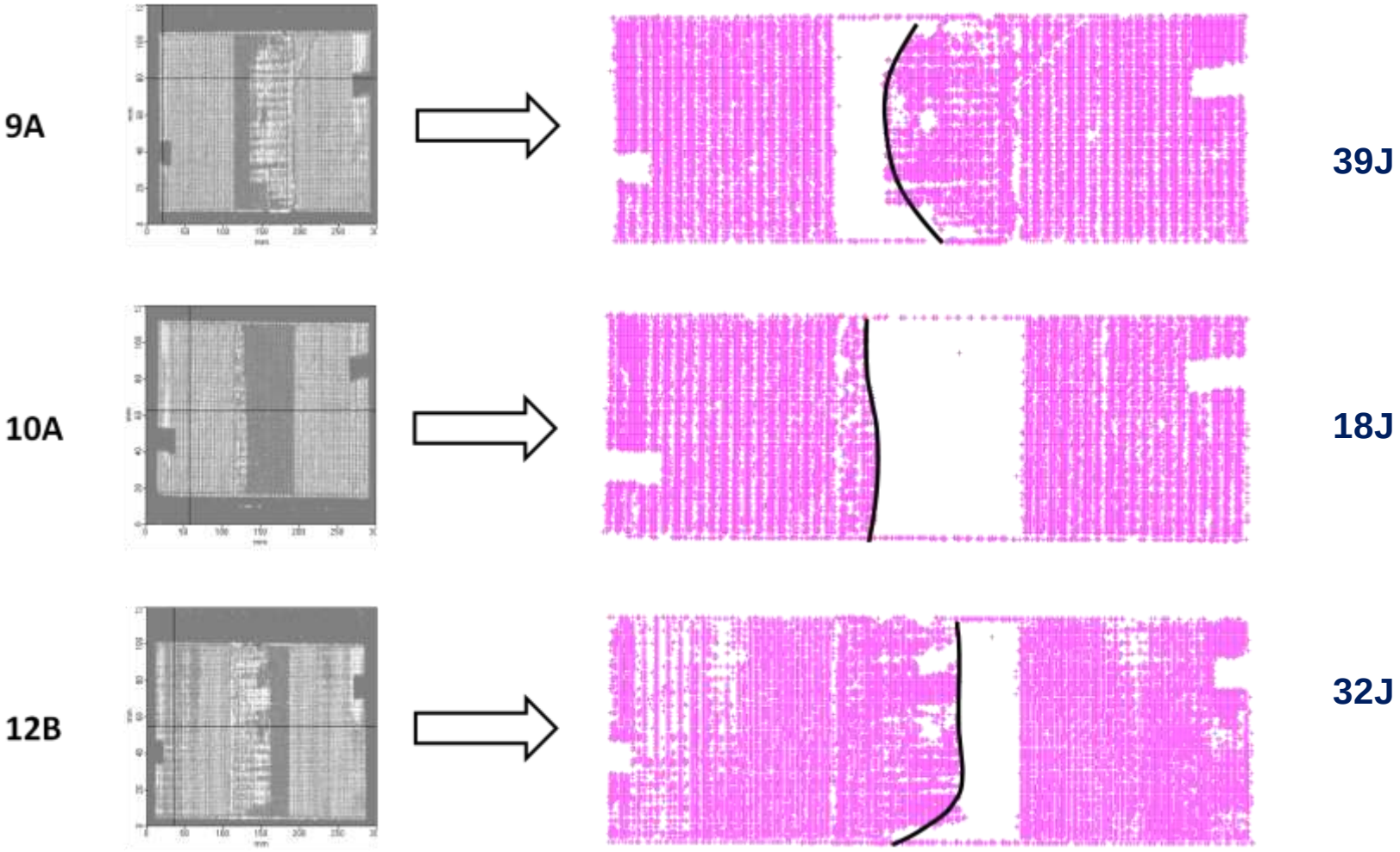
Crack Front Identification

- Analyse the gated signal the same way as with the flat panel
- Single or double independent crack fronts (i.e. not closed loop)
- Create five (or more) reference lines and for each one find the interval, where no data points exist
- Interpolate spline between these points to determine the crack front



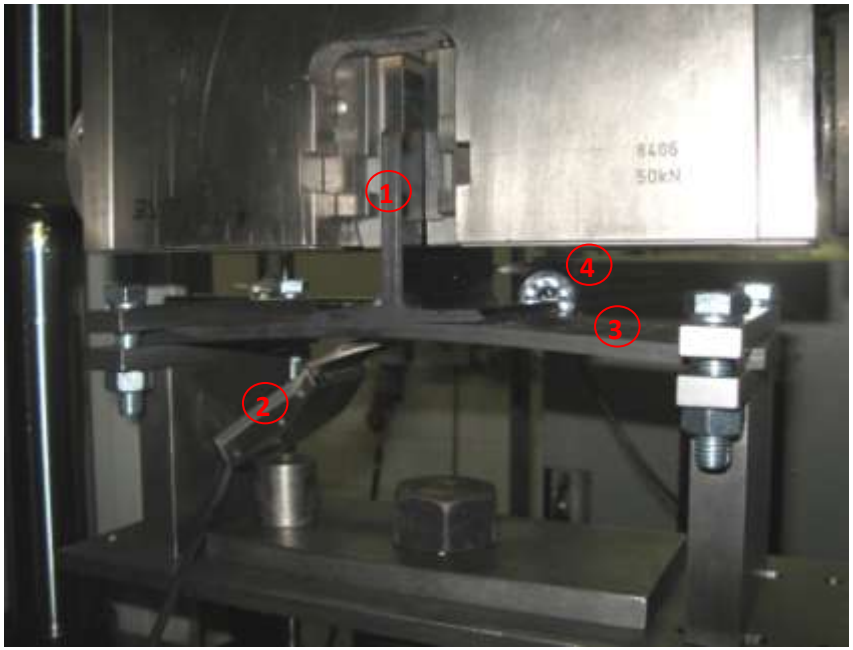
Skin/stringer Damage Patterns

- Delamination/de-bond considered only in skin/stringer interface

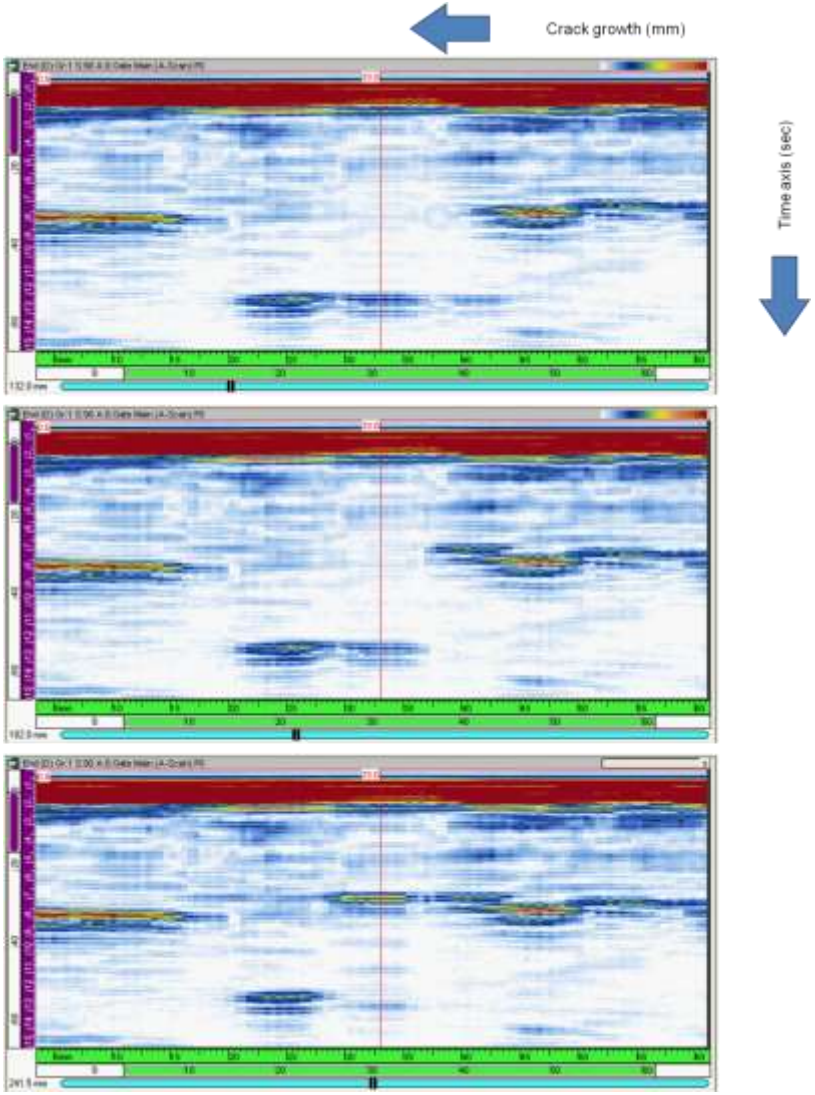


Skin/stringer | Experiments

- In-situ ultrasonic scanning enabled visualising the damage evolution

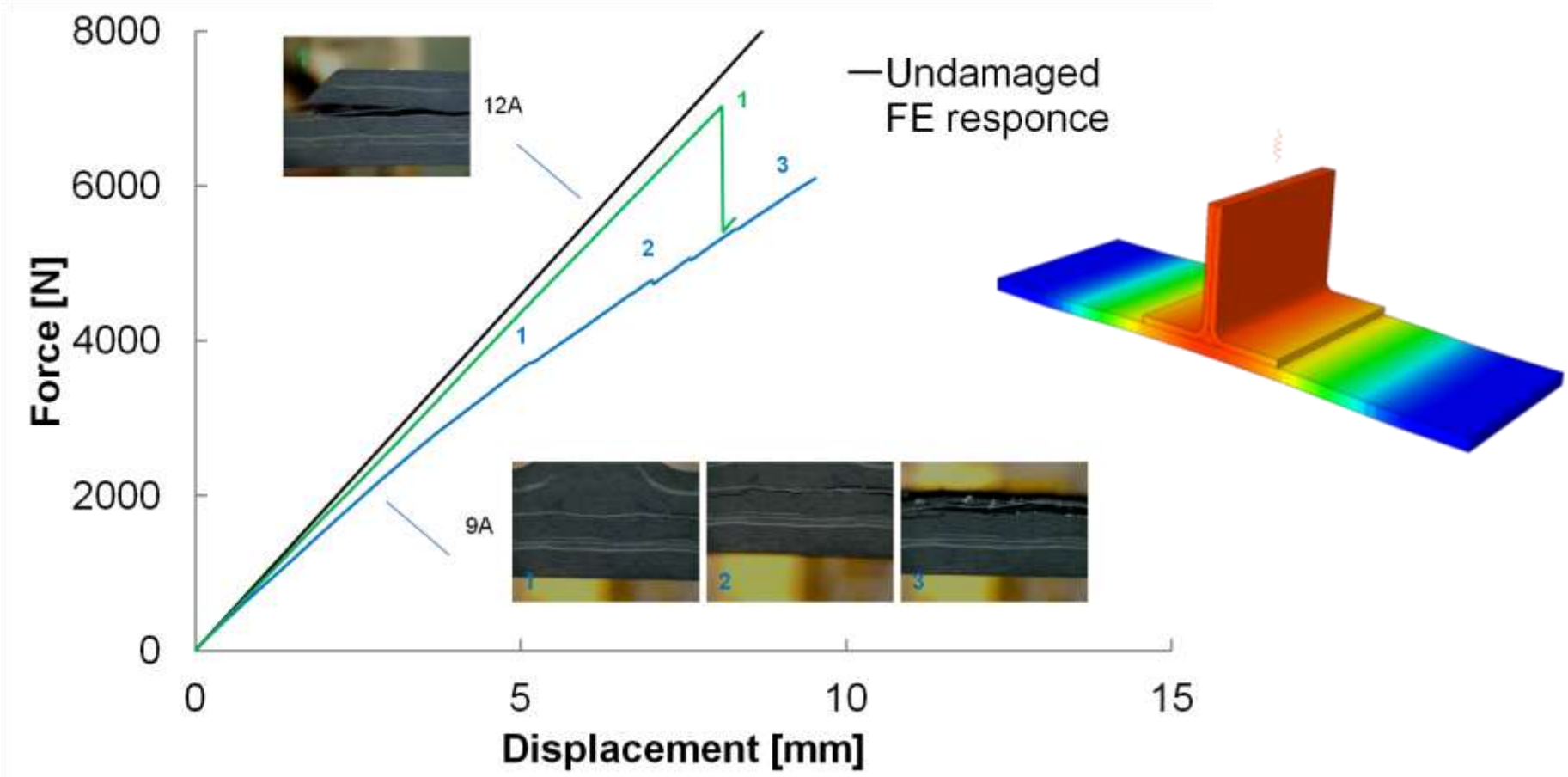


(1) Specimen stringer; (2) flexible ultrasonic phased array; (3) specimen skin; (4) microscope



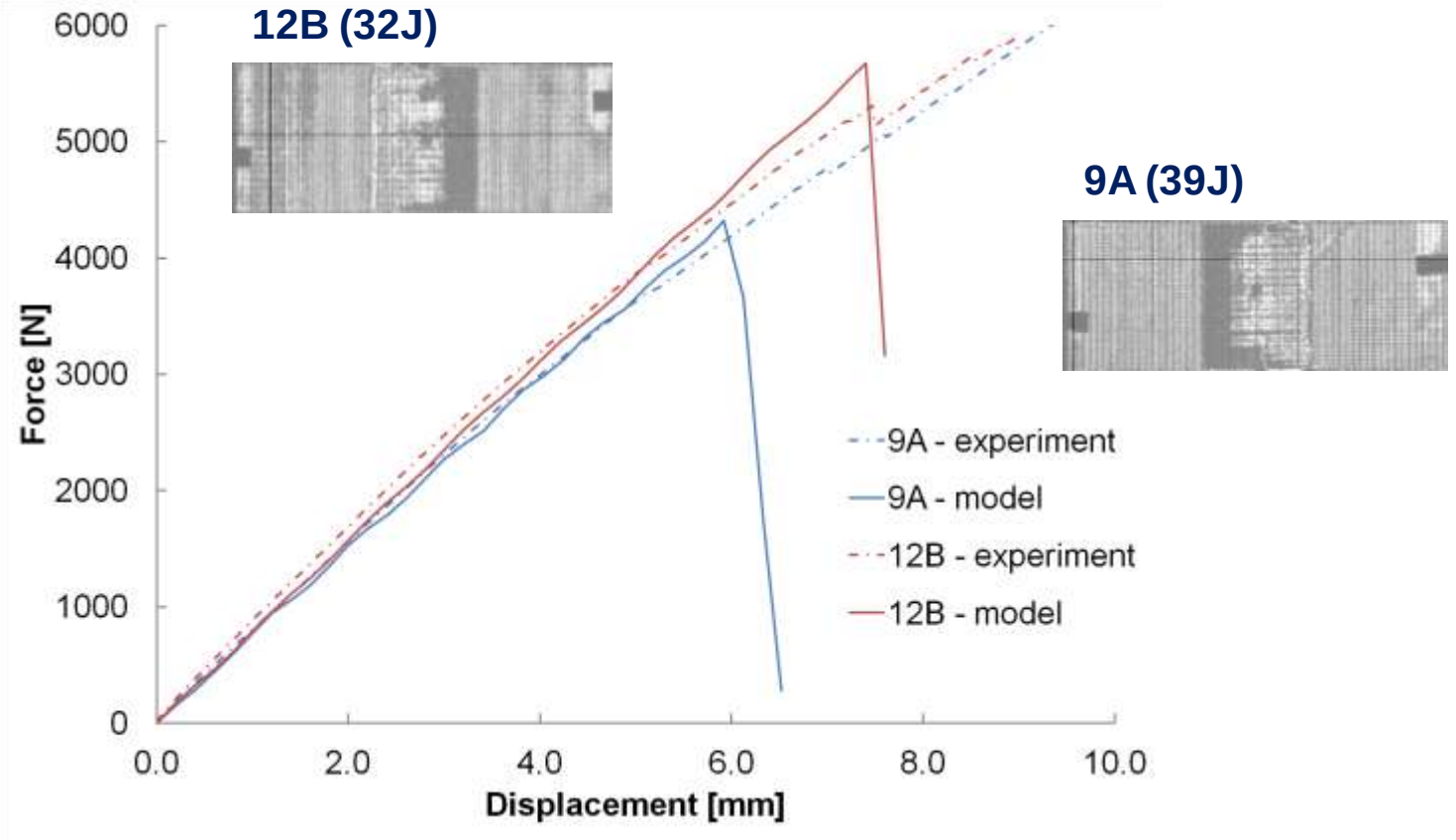
Skin/stringer | Undamaged Response

- Machine compliance modelled by spring element



Skin/stringer | Validation

- Shape and length of the impact induced crack determines the mixed-mode ratio and consequently the failure load
  - Analysis was found to be very sensitive to that shape



Flange I Damage Mapping

- Generate algorithm that considers the geometry of the flange and maps the sliced NDT data (i.e. Defect) on the corner of the flange

[Axis Lengths]
107 54
[X Axis Range]
0 0.071 m
[Y Axis Range]
0 0.036 m
[Data Range]
-100 100
[Data]

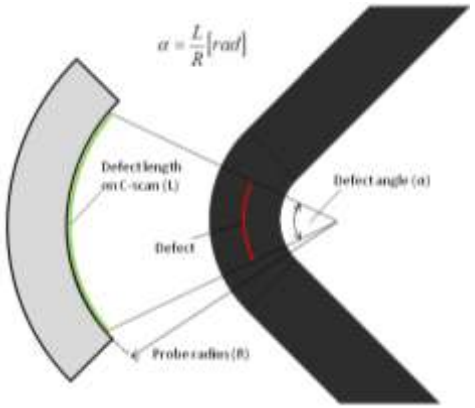
Defect width

x

Defect length

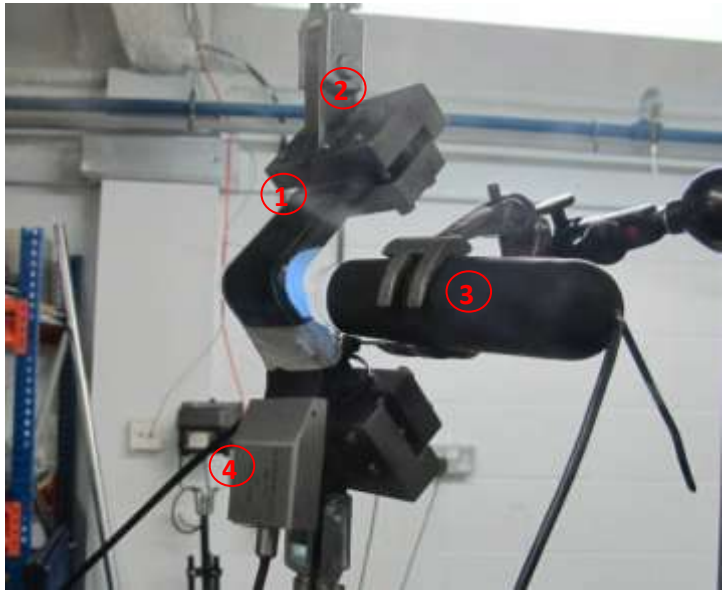
2.344	3.906	5.469	5.469	5.469	7.031	6.25	5.469	3.906	2.344	3.125	7.813	6.25	...
1.563	3.125	4.688	4.688	6.25	5.469	4.688	4.688	3.906	3.125	3.906	7.813	6.25	...
1.563	3.906	6.25	7.813	7.813	8.594	6.25	6.25	5.469	3.906	3.906	8.594	7.813	...
1.563	3.906	7.031	7.813	8.594	8.594	6.25	6.25	6.25	3.906	3.125	6.25	7.813	...
2.344	6.25	10.156	13.281	14.063	14.063	12.5	12.5	10.938	6.25	6.25	10.156	10.938	...
2.344	7.813	10.938	14.844	15.625	15.625	15.625	14.063	11.719	6.25	7.813	10.938	12.5	...
3.125	8.594	14.063	17.188	17.188	17.188	17.188	15.625	10.938	5.469	10.938	14.844	14.063	...
3.906	8.594	12.5	15.625	14.844	15.625	14.844	13.281	8.594	6.25	12.5	15.625	14.063	...
3.125	9.375	12.5	15.625	15.625	15.625	14.844	14.063	8.594	8.594	14.844	17.969	15.625	...
3.125	7.031	9.375	10.938	10.938	10.156	9.375	7.813	4.688	7.031	11.719	13.281	11.719	...
3.125	6.25	8.594	9.375	10.156	10.156	7.813	5.469	4.688	8.594	12.5	13.281	11.719	...
2.344	3.906	4.688	4.688	5.469	4.688	4.688	4.688	4.688	7.031	9.375	8.594	7.813	...
1.563	2.344	3.125	3.125	3.906	3.906	6.25	4.688	3.906	6.25	7.031	8.594	8.594	...
2.344	0.781	1.563	2.344	1.563	2.344	4.688	4.688	3.906	5.469	5.469	6.25	4.688	...
1.563	0.781	0.781	1.563	0.781	2.344	3.125	3.906	4.688	6.25	7.031	6.25	5.469	...
1.563	0.781	0.781	1.563	3.125	1.563	3.125	4.688	4.688	3.906	4.688	4.688	4.688	...
1.563	0.781	1.563	2.344	3.906	3.125	7.813	10.156	10.156	10.156	11.719	10.156	7.031	...
0.781	1.563	3.125	3.125	4.688	5.469	11.719	11.719	10.156	9.375	10.938	10.938	6.25	...
1.563	3.125	3.906	3.906	5.469	7.813	14.063	14.844	12.5	12.5	14.063	14.063	10.156	...
2.344	3.906	3.906	4.688	6.25	9.375	12.5	13.281	13.281	13.281	14.844	14.063	10.938	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...

y

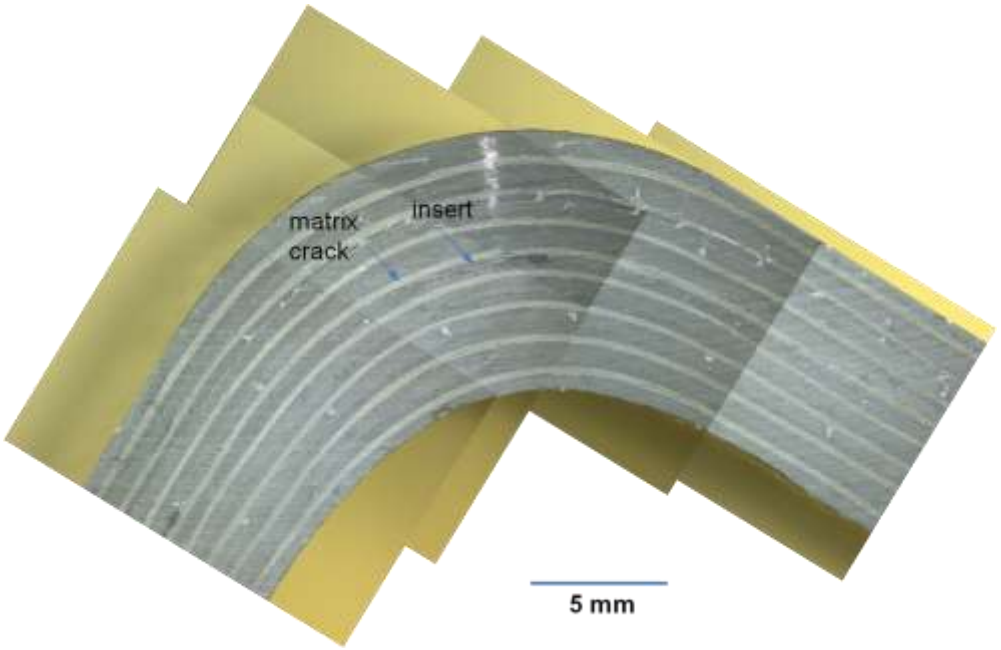


Flange I Damage Tolerance Evaluation

- Interlaminar strength testing and in-situ monitoring of damage evolution

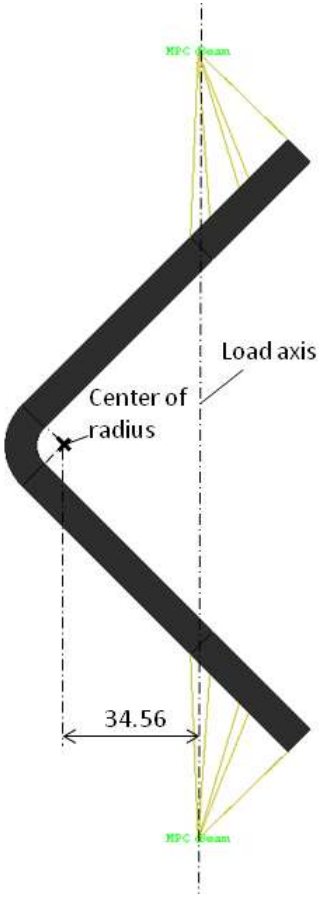


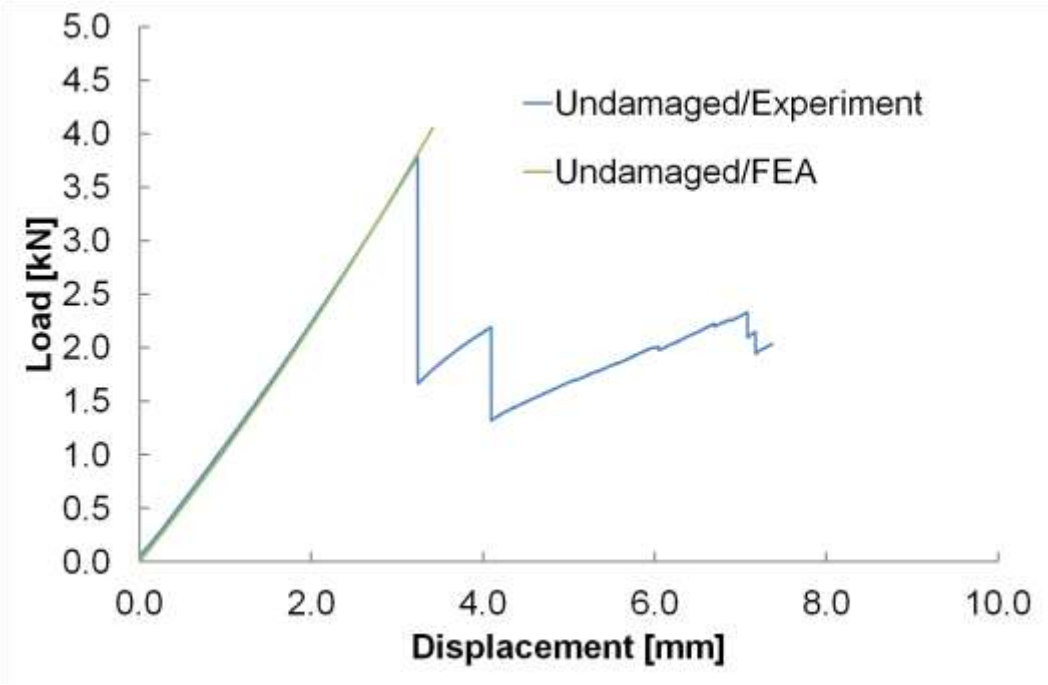
(1) Specimen; (2) microscope; (3) loading fixture; (4) flexible ultrasonic phased array



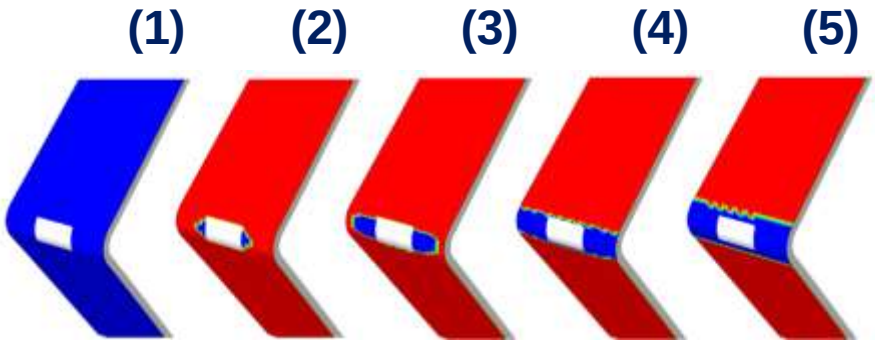
Flange I Undamaged Response

- Good practice to confirm the undamaged response of 3D model
- FEA model successfully predicts the stiffness of the undamaged flange

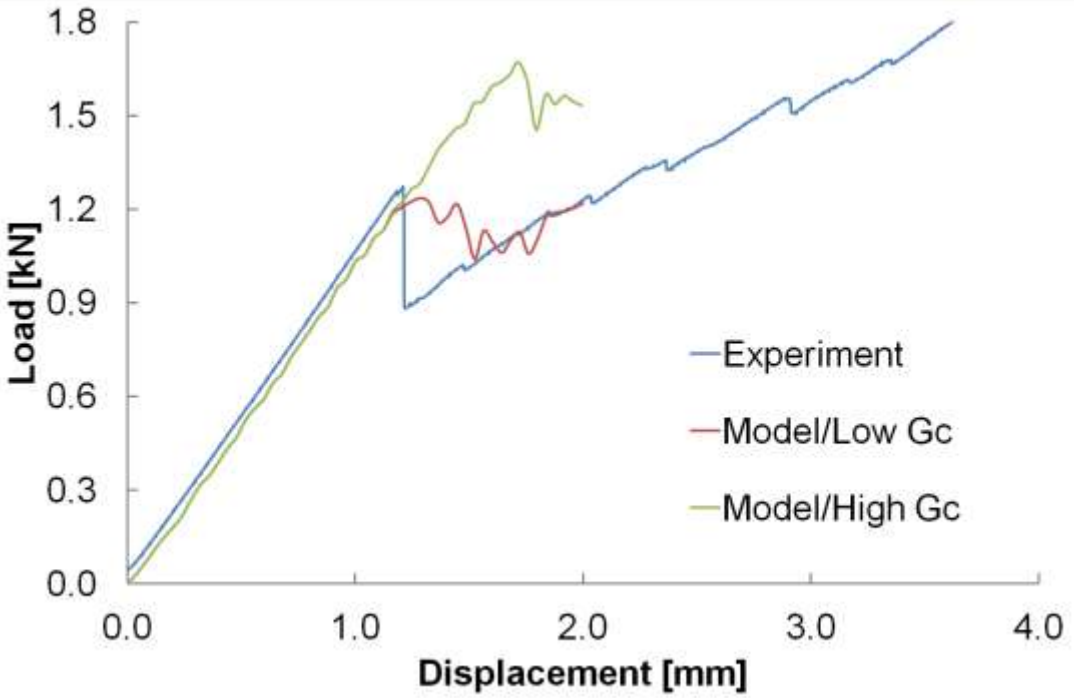




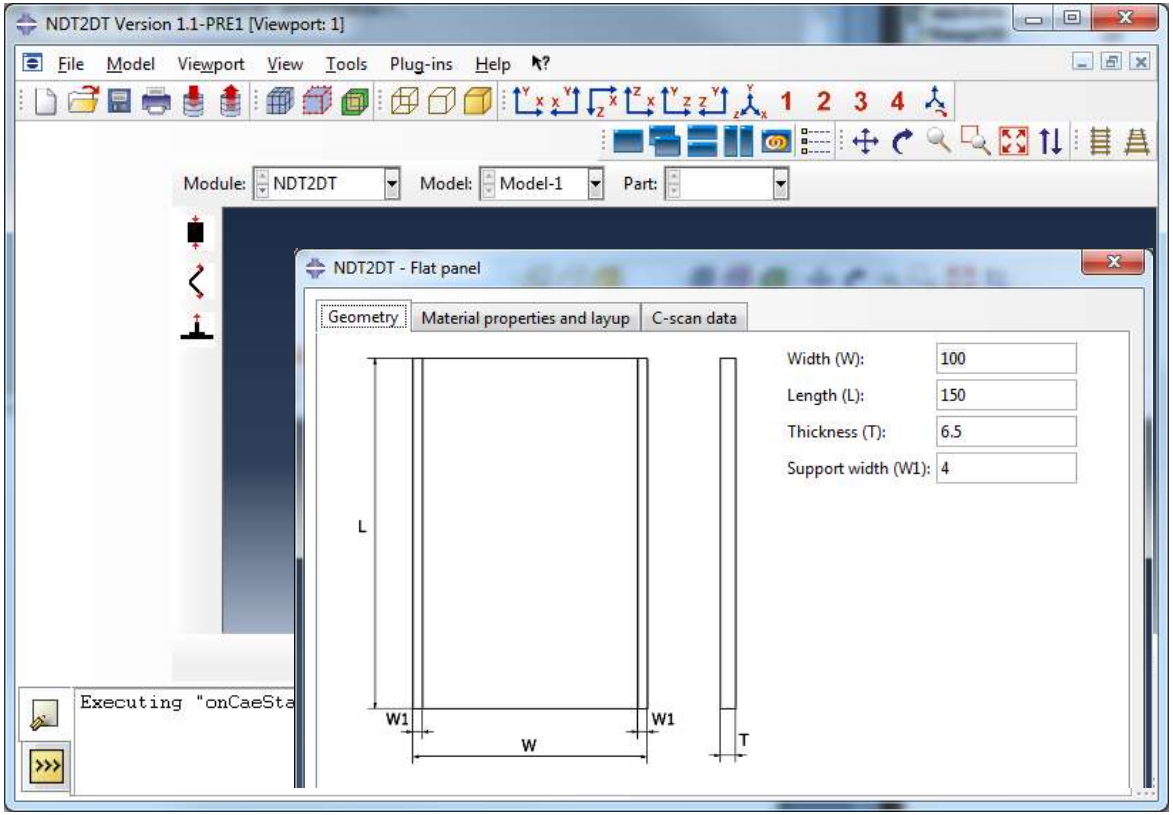
Flange I Damage Tolerance Evaluation

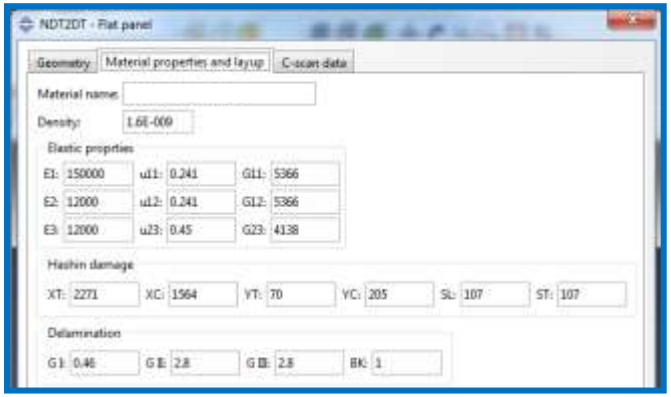


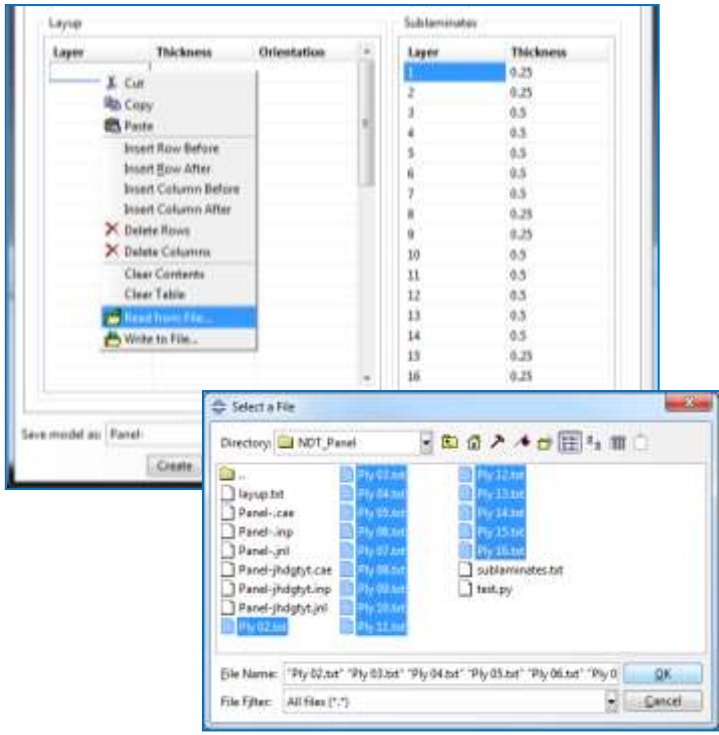
- Good prediction of the initial stiffness of the damaged flange
- Predicted failure load 1.29 kN
- Experimental failure load 1.33±0.16 kN
- Material data sensitivity analysis



Graphical User Interface







Concluding Remarks

- Did we do what we set to do?
  - Proved that the concept works
  - Obvious limitations associated with finite element tools and capabilities
  - Once NDI detects a delamination/de-bond this can be translated across the FE numerical model
- What is the level of confidence in the process?
  - Medium/Low confidence due to the limited cases studied
  - This was a platform to prove the concept, with more comprehensive studies needed to increase confidence (e.g. larger components, fatigue)
  - Damage tolerance evaluation depends a lot on the material (i.e. NCFs vs. Prepregs vs. bonded joints). Can one generic algorithm of damage translation and damage material model be used across all cases?
- Where can this fit in the current framework?
  - Local damaged models driven by global models and general load cases
  - Validated simulation approaches to help reduce the number of tests during development

Acknowledgments

- The presenter would like to acknowledge the support from the UK Technology Strategy Board under the project *New ICT Approach to Automate Non-destructive Testing and Inspections with Evaluation of Damage Tolerance in Composite Structures* (NDT2DT) with project No. 101014
- Special thanks to my colleagues at Element Materials Technology Vladimir Matěják, Dr. Sabine Frenz and Anastasios Toulitsis
- Richard Freemantle (richard@wavelength-ndt.com) is responsible for the all the NDT work and developments within this project