Composite In-Service Damage Assessment

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Outline

1. Damage Tolerance of Composite Structures
2. Damage Survey
3. Damage Survey – Observations
4. Literature Survey
5. Conclusions

IMAGE SOURCE:
http://www.airforce.gov.au

1. Damage Tolerance of Composite Structures

QinetiQ set up a research and development project together with DST Group within a framework of the Strategic Alliance Agreement between the two organisations.

- The project, Delamination, Durability and Damage Tolerance of Composite Structures aims to develop quick analytical methods to assess the integrity of composite structures containing damage sustained in operation of aircraft.
  - The project has two distinctive but dependent/linked parts: damage detection and damage assessment
  - The damage detection is looking at more reliable and precise NDI methods for inspecting composite components during routine inspection of aircraft in service
  - The damage assessment is focused on determination of structural integrity/residual strength of components with detected damage.

1. Damage Tolerance of Composite Structures

Is it possible to accurately assess the residual strength after damage?

(*Do not expect a definite answer – it is a very subjective judgement and case dependent*)

- What affects the residual strength?
  - Manufacturing factors: variations in raw material properties, deviations from ideal process parameters, inherent defects like degree of porosity or ply wrinkles (acceptable!), defects below detectable threshold (microcracking, voids), handling
    - They are unavoidable, unpredictable, un-assessable, unknown (to large extent) but tolerated
  - In-service environmental factors: operating temperature, moisture absorption, exposure to ultraviolet radiation
  - Operational factors – sustained damage due to: internal loads, particularly peak loads, accidental loads (impacts, cuts, wear), installation factors (too much grip, edge damages

1. Damage Tolerance of Composite Structures

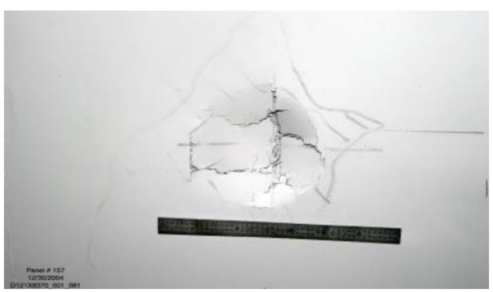
- Did we recognise and appreciate all factors? Are we conservative or unconservative?
  - We tend to reduce the design allowables much below the material allowables to take care of the hidden, unavoidable defects or those small difficult to detect in-service damages (like BVID)
    - This arbitrary reduction is based on ‘B’ basis material properties
    - There is still evidence that it may not be enough, that the manufacturing hidden (missed? ignored?) defects contribute to failures in service, like ‘kissing’ bonds, foreign inclusions in lay-up.
  - Another argument - Environmental factors:
    - “The static test data indicates that the service history including the environmental exposure has not degraded the structural integrity of the bonded stepped-lap joint.” *
    - “The test specimens survived tension-dominant fatigue spectrum for ten lifetimes, and other specimens survived compression-dominant fatigue spectrum for thirty lifetimes.”*
    - But we know that hydration softens the matrix!

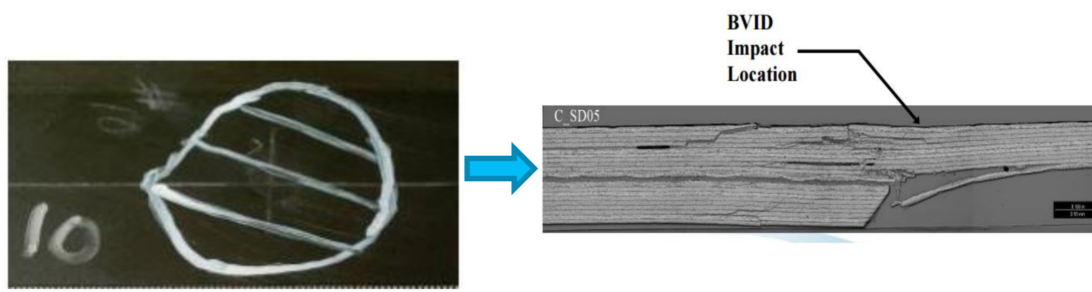
* Durability and Residual Strength Assessment of F/A-18 A-D Wing-Root Stepped-Lap Joint, National Institute for Aviation Research (NIAR), AIAA 2011-7032

1. Damage Tolerance of Composite Structures

It does not matter how difficult it is to determine the effect of manufacturing, environmental and operational factors on the residual strength

- We need to progress the investigative work to get a better understanding and remove conservatism, if it is there
  - It is unrealistic to expect manufacturing to be flawless or composite material to have perfectly identical properties every time
  - We need to limit rather than eliminate manufacturing defects through more consistent automated manufacturing techniques and more efficient NDI methods
- But we can’t avoid in-service damages
  - We need to find an efficient way to assess damages and to determine an actual effect on strength



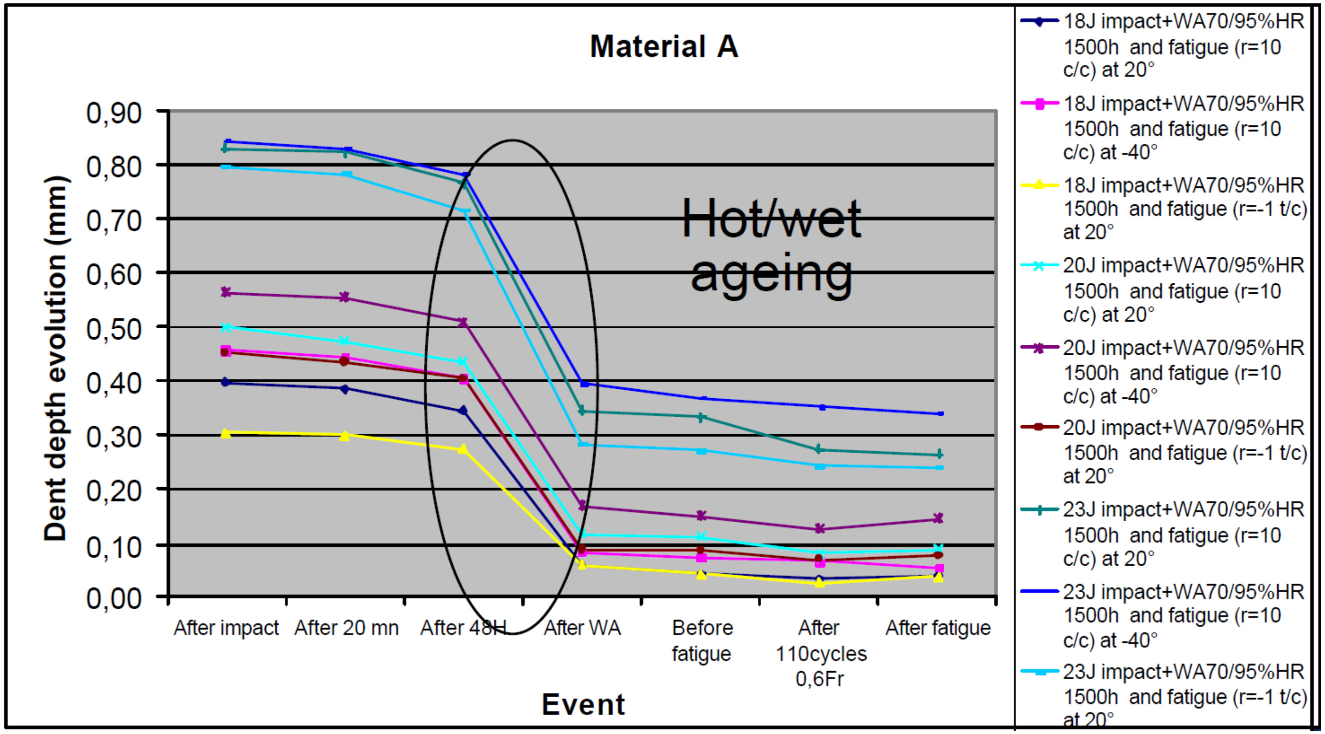


SOURCE: servidor-da.aero.upm.es/wip/apuntes/quinto/materiales-compuestos/Airbus.pdf

1. Damage Tolerance of Composite Structures

Relaxation Behaviour – An interesting phenomenon that leads to damages becoming less detectable over time.

- A damage being detectable at time of impact, can become undetectable after an interval of inspection due to mechanical, thermal cycling, wet and ambient ageing and temperature.



SOURCE:
servidor-da.aero.upm.es/wip/apuntes/quinto/materiales-compuestos/Airbus.pdf

2. Damage Survey

This Composite In-Service Damage Assessment project aimed first to survey and identify actual typical damages in military aircraft – their form and location:

- Review all available maintenance records related to representative composite parts:
  - Identify the relevant maintenance events
  - Reduce the investigated damages to one most common type of damage to limit scope of the project
  - Idealise/simplify the damage to a suitable form for analysis
  - The survey covered about 10 years of operational records for a military transport and fighter aircraft

2. Damage Survey

The survey results were interesting but not surprising:

- The survey demonstrated that delamination was the most frequently reported damage regardless its location and cause of damage
- Delaminations were very challenging form of composite structure damage in terms of detection, assessment and disposition
  - Spread through the laminate thickness – extent difficult to assess
- Obvious differences in damage location, type and cause, which could be attributed to aircraft configuration – high wing vs. low wing, role – transport vs. fighter, or to aircraft specific manufacturing or design issues
- Fewer than expected reported cases of delamination after impact
- The entries were not precise in many cases
  - Generally it was difficult to ascertain what the actual damage was and what cause it was.

2. Damage Survey

The relevant maintenance composite damage records for selected components were evaluated and categorized as shown:

- Fighter aircraft – wing skins, T/E flaps, horizontal tailplane:

Description	Number
Total damages	111
Relevant damages (delams, disbonds, dents, fiber breaks)	85
Delaminations	56
Delaminations after impact	14
Delaminations around fastener holes	17

2. Damage Survey

The relevant maintenance composite damage records for selected components were evaluated and categorized as shown:

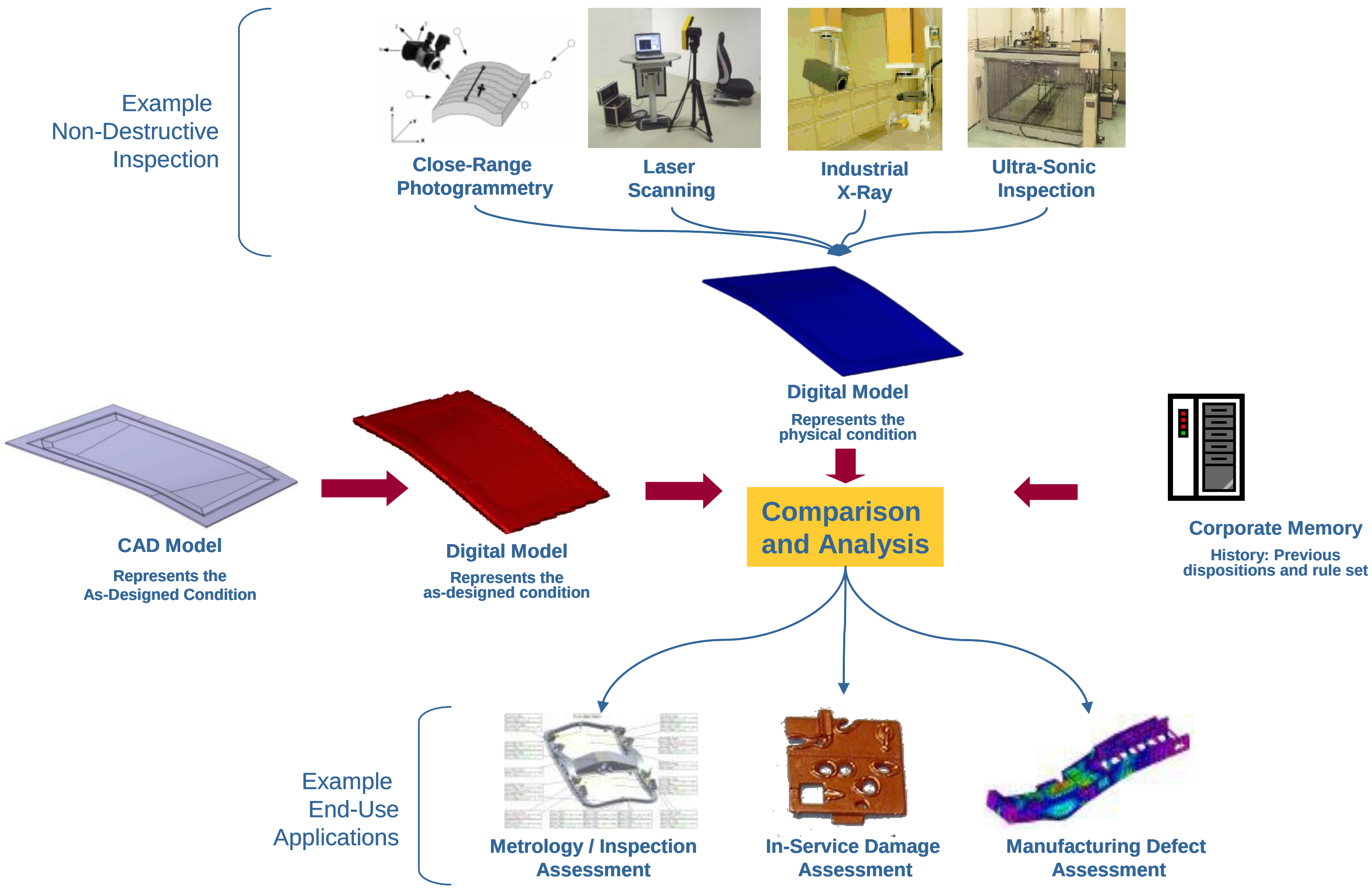
- Transport aircraft – wing T/E panels, T/E flaps:

Description	Number
Total damages	234
Relevant damages (delams, disbonds, dents, fiber breaks)	74
Delaminations	54
Delaminations, clean and away from attachments	25

3. Damage Survey - Observations

- Lack of clarity in the maintenance records may result from inaccurate/inconclusive NDT inspections
- It is clear that the damage detection methods need more attention and improvement:
  - Methods to determine an accurate through thickness extent of damage and possibly a nature of the damage
  - Automated methods with suitable algorithms for the return signal processing to eliminate human factor in the interpretation
- Manufacturing inspection records could assist in understanding of origin of the damage and progression
  - The concept was voiced by Airbus CTO: “At the end you have a digital functional model of your airplane, unique to the tail number, that can live with that airplane for the rest of its life giving tremendous benefits in the maintenance”
- The survey confirmed our presumption that delamination is a most frequent form of damage in composite structures and the one which was difficult to detect and characterise
  - This is the damage which should be a focus of analytical phase of our Damage Assessment project.

3. Damage Survey – Observations
Integrated Engineering Concept



4. Literature Survey – Assessment of Damage in Composite Structures

Purpose of the literature survey in this project was to investigate the published research approaches, analytical methods and FE modelling applicable to the damage in composite structure analysis

- Compare features and capabilities of each method
- Focus on delamination damage following the damage survey findings
- Identify most popular methods used by other research organisations
- Identify methods considered by us as most suitable in our investigation

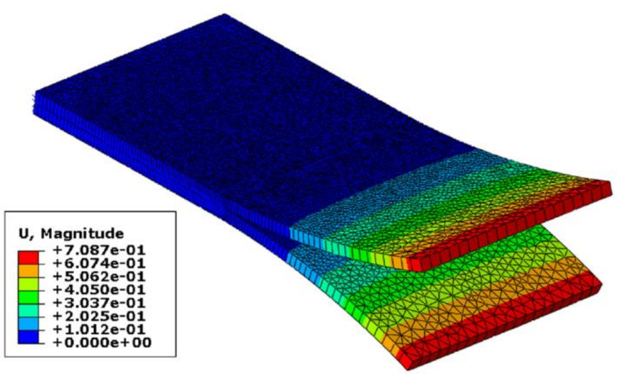
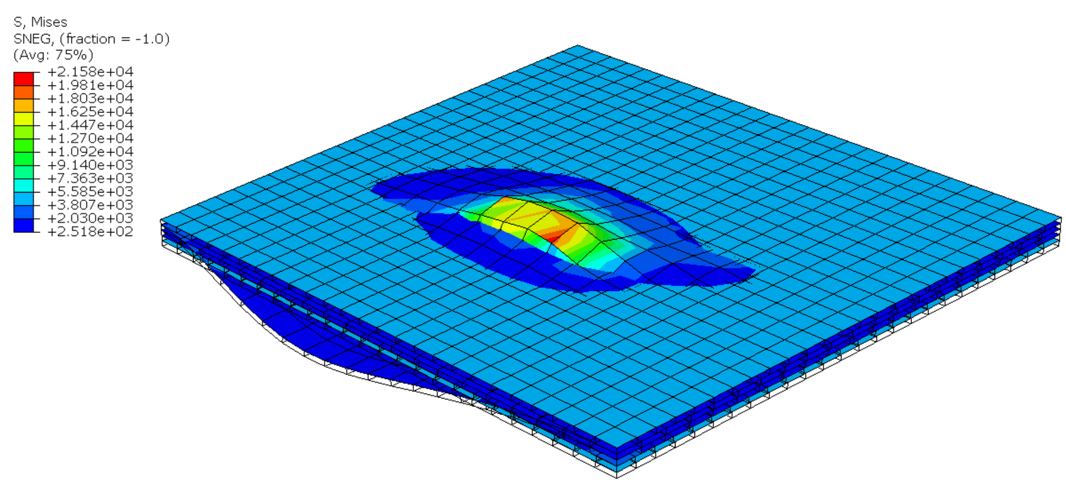


Fig. 7. 3D double cantilever beam specimen.

SOURCE: Cohesive zone and level set method for simulation of high cycle fatigue delamination in composite materials, Ahmad Amiri-Rad, Mohammad Mashayekhi, Frans P. van der Meer, 2017



SOURCE: QINETIQ AUSTRALIA

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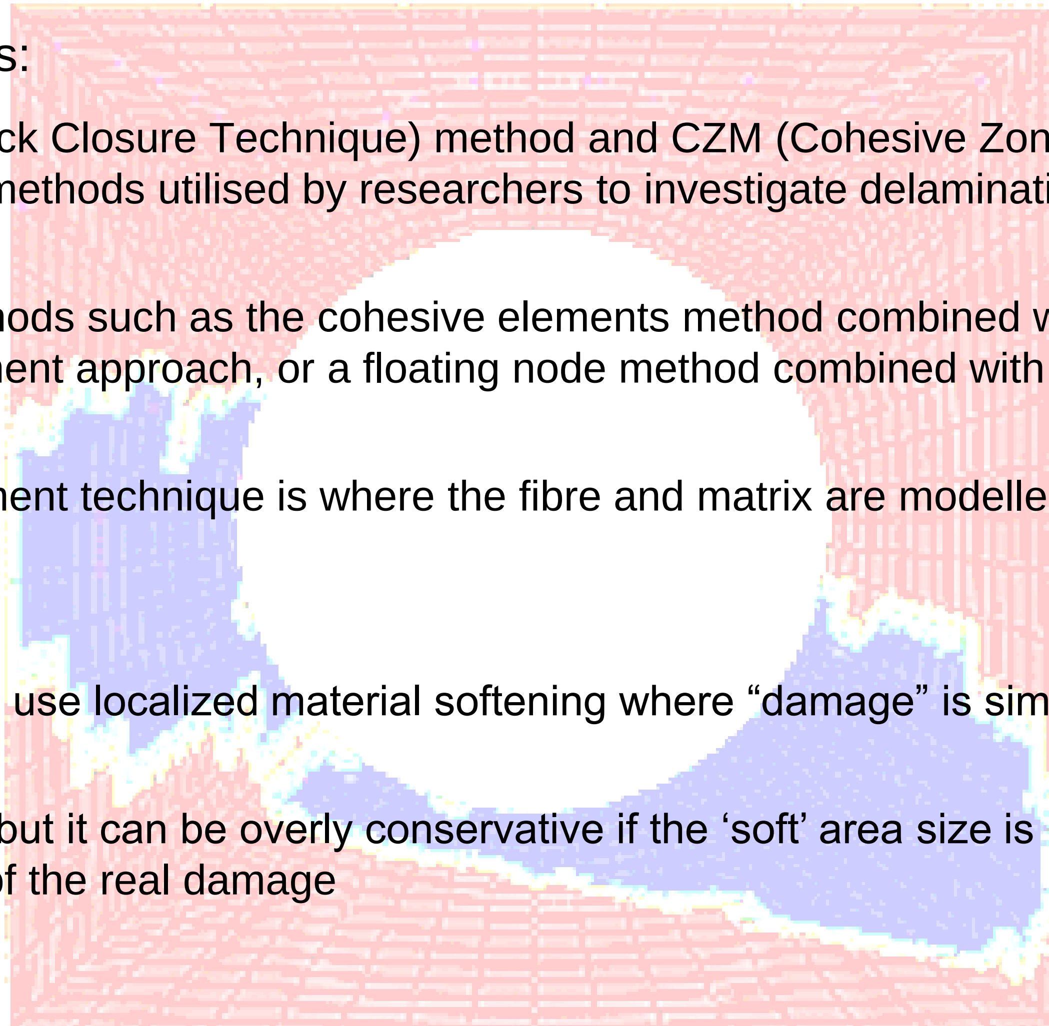
4. Literature Survey - damage modeling in composites

The survey findings:

- VCCT (Virtual Crack Closure Technique) method and CZM (Cohesive Zone Modeling) are the most popular methods utilised by researchers to investigate delamination in composites.
  - Hybridised methods such as the cohesive elements method combined with the embedded element approach, or a floating node method combined with VCCT are also used
  - Embedded element technique is where the fibre and matrix are modelled and meshed independently.

- Some researchers use localized material softening where “damage” is simulated as a soft material
  - Simple method but it can be overly conservative if the ‘soft’ area size is not representative of the real damage



4. Literature Survey

Brief comparison of VCCT and CZM capabilities:

- Cohesive zone modeling (CZM) is able to predict the growth and initiation of a delamination without a predefined point of crack initiation.
  - CZM can be used in complex structures with complex loading scenarios.
  - Input data to define traction separation laws are extensive and can be hard to get, and there is a dependency on mesh characteristics
- VCCT technique has the benefit of being a fracture mechanics based method with a large body of work where the crack growth criteria is based on strain energy release rate.
  - The VCCT method requires a predefined crack front (like a single pair of unattached nodes)
  - Can be difficult to incorporate into large and complex structures in a modeling environment
- Both methods require robust data in the way of material properties, especially for the CZM method.
  - Both methods show capability to include multiple crack fronts.
  - Both methods are promising but require test validation to gain confidence in accuracy.

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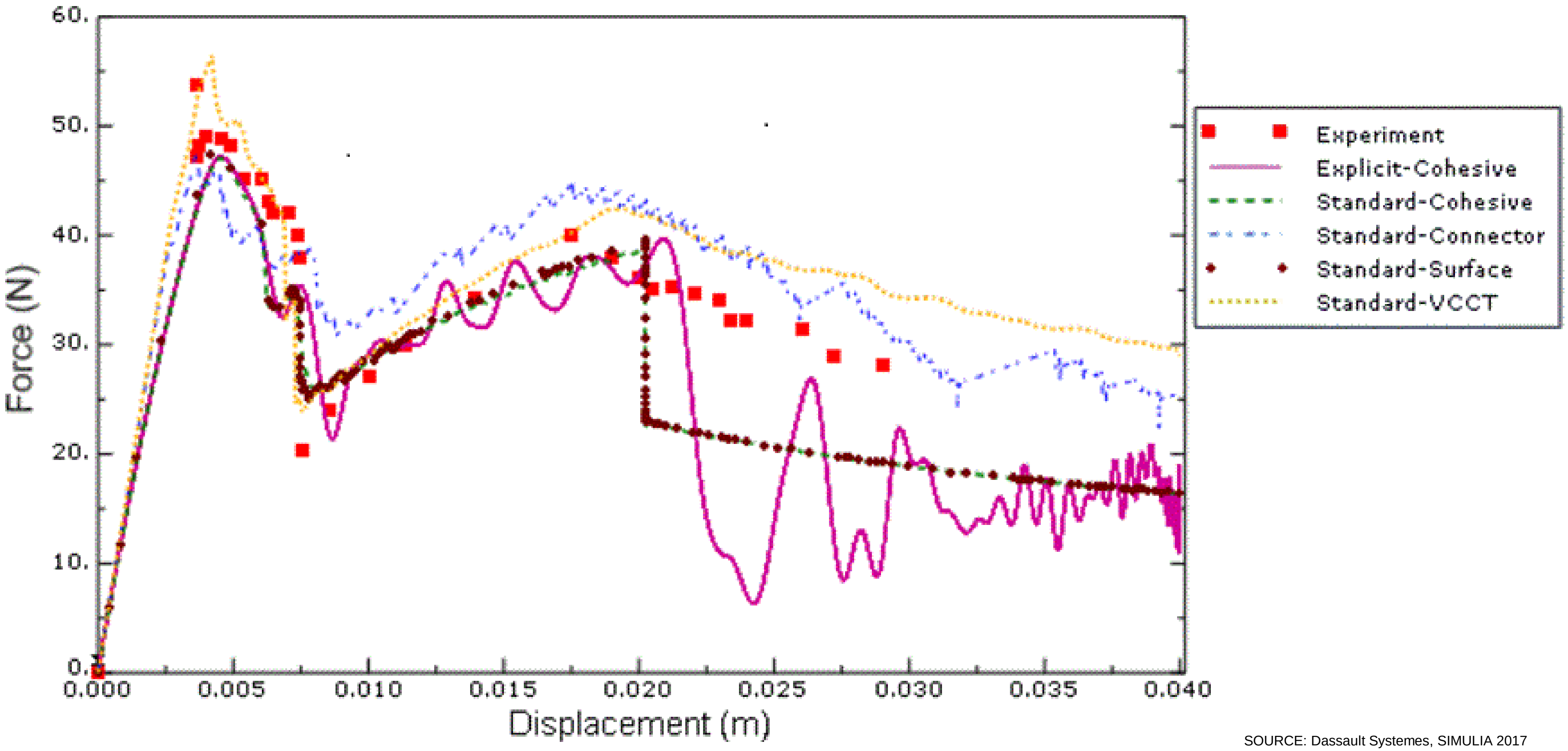
4. Literature Survey – Modified Methods

It is important to recognize that any developed method must be accurate and robust as well as simple to execute.

- Recent studies use the VCCT combined with FNM (floating node method) to computationally produce accurate results comparable to a DCB delamination growth test benchmark
  - FNM allows multiple cracks having an arbitrary orientation and their connections to be accommodated within an element
  - FNM allows sub-elements within an original element to share information
- Other studies use cohesive elements in conjunction with the Embedded Element Technique
  - EET allows the polymer matrix and fibre reinforcement to be meshed separately – model accurately represents stiffness of the composite structure
  - It is computationally is very intensive but shows good agreement with experimental work

4. Literature Survey

Comparison of selected solutions with experimental results:



SOURCE: Dassault Systemes, SIMULIA 2017

5. Conclusions

At the present state of knowledge it is not yet possible to develop a generic (one-fits-all) tool for damage assessment in aircraft composite structures:

- Many factors affecting the structural integrity which we do not control or we have insufficient information about
  - Manufacturing process variations and deviations (pressure, temperature, material shelf life)
  - Manufacturing defects: accepted “as is” or repaired
  - Raw material properties variation (next slide); standard deviation over 10% in some cases
  - Changes in material properties in time due to environmental factors
- The impact of the above factors on the structure integrity is appraised by application of conservative reduction factors in the design process
  - Effectively the structure is damage tolerant and it ensures safety of flight
  - Introduces weight and cost penalty

5. Conclusions

Difficulties with material data input

Material	Elastic Constants				Strengths		Publication
Fibre / Resin	E_{11}	E_{22}	υ_{12}	G_{12}	Y_t	Y_c	
	MPa	MPa	N/A	MPa	MPa	MPa	
IM7/977-3	164000	8977	0.32	5020	100	247	Journal of Composite Mat'ls
IM7/977-3	162000	N/A	N/A	N/A	N/A	N/A	Cycom TDS
IM7/977-2	168922	8687	N/A	4757	N/A	N/A	CMH 17 Vol 2,
IM7/8552	162027	N/A	0.311	5033	N/A	N/A	CMH-17 Vol 2,
IM7/8552	157000	8960	0.32	5080	N/A	N/A	Composites Science &Tech. 89,
IM7/8552	192300	10600	0.31	6100	2715	1400	(POSICOSS)
IM7/8552	164100	8700	0.28	5100	1741	854	(COCOMAT)
IM7/8552	175300	8600	N/A	5300	2440	1322	(ESA STUDY)
IM7/8552	163000	12000	N/A	N/A	2724	1690	(HEXCEL DATA SHEET)
AS-4/3501-6	126000	11000	0.28	6600	48	200	DSTG
AS-4/3501-6	138000	8960	0.3	7100	N/A	N/A	Composite Structures 92,

5. Conclusions

We are positive about the potential to develop an engineering tool to assess integrity of composite structure with damages.

It is possible to develop an unique tool for specific structure configurations, loading conditions and specific lay-ups

- VCCT and CZM are the most prevalent methods used in the damage analysis and QinetiQ adopts similar approach
- Corrections to the algorithm based on empirical data and verification tests may be necessary to gain sufficient confidence in the engineering assessment tool accuracy.
- Significant amount of work is required to develop reliable methods for damage progression predictions
- We can’t afford to loose sight of the ultimate goal – gaining as much knowledge and confidence in composite structures as we have with metallic structures.

QUESTIONS
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