Presented by

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Structure Analysis,
Methods and Technologies

Bondline Analysis and Bonded Repairs

CACRC Meeting / Workshop for Composite DT & Maintenance,
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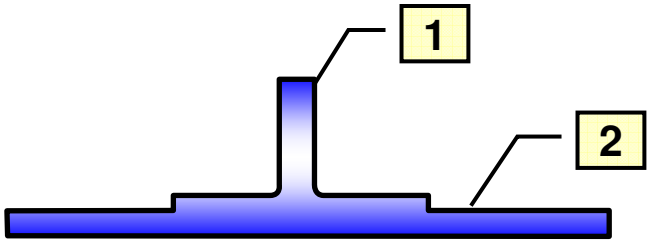
AIRBUS

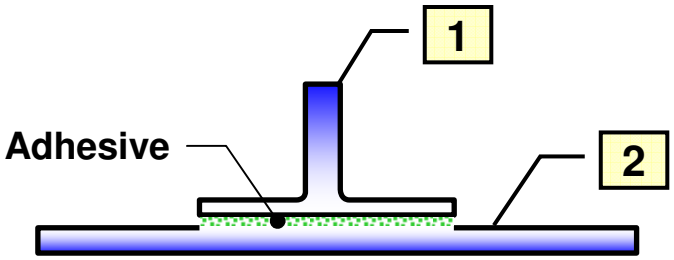
Content

I. Introduction

Bonded Assembly / Interfaces



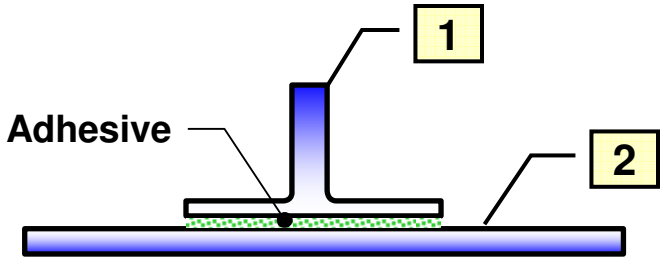
CO-CURING: Components cured together
- Component 1 un-cured
- Component 2 un-cured



CO-BONDING: Components bonded together during cure of one of the components

- Comp. 1 cured
- Comp. 2 un-cured
- Adhesive

- Comp. 2 cured
- Comp. 1 un-cured
- Adhesive



SECONDARY BONDING: Components bonded together with separate bonding operation

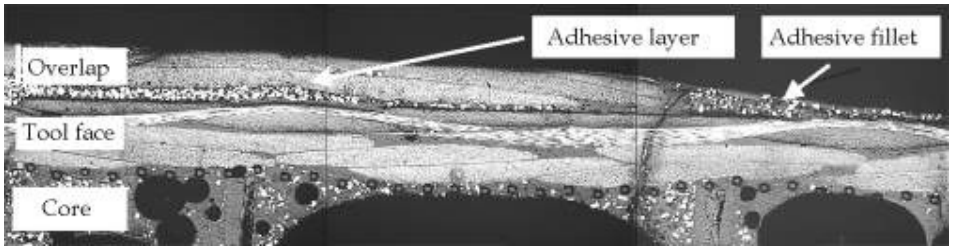
- Component 1 cured
- Component 2 cured
- Adhesive

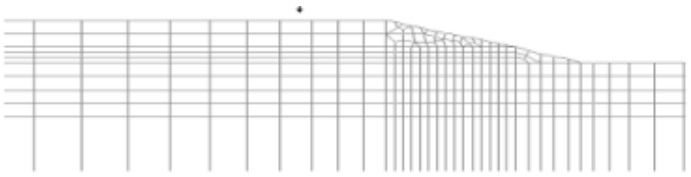
Specificities

- The properties of interface and bonds are difficult to determine.

- Achilles' heel of bonds:
  - Weak in carrying peel and tension loads,
  - There are no generally agreed failure criteria relevant to all loci of failure.
  - Fatigue sensitive items and governed primarily by durability rather than the mere ultimate static strength substantiation,
  - The locus of failure in aged conditions is more important that the determination of the mere ultimate capability of the joint.

- How to handle singularities in calculations (Where are they ?):





  - Local geometry and plasticity/damage are likely to redistribute singular fields,
  - There is a need to simplify and improve the accuracy of calculation methods.

Industrialisation Aspects

- Quality Control of the materials and the process ensures good bonding:
  - Compatibility tests in order to address sensitivity to durability parameters,
  - Controlled surface preparation and Controlled Process, until Bonding is completed, is key (Effect of pre-bond moisture, time between surface preparation and bonding, etc.),
  - Control of bond thickness [Strength and Toughness are *independently* linked with the adhesive thickness],
  - Assessment of F&DT performance and taking into account effect of defects (porosity in bond line, imperfect bonding, etc.) is necessary.

- Kissing bonds. FAR/CS 25.601 prevents the use of questionable design features and precautions in FAR/CS 23.573 applies (now in AC20-107B). Bonded Joints:
  - shall not be used in structural single-load path application,
  - shall not be the weak link fuse by material and design choices,
  - shall sustain Limit Load, assuming no bond between two crack arresting features, and taking into account the repeated application of the loads.

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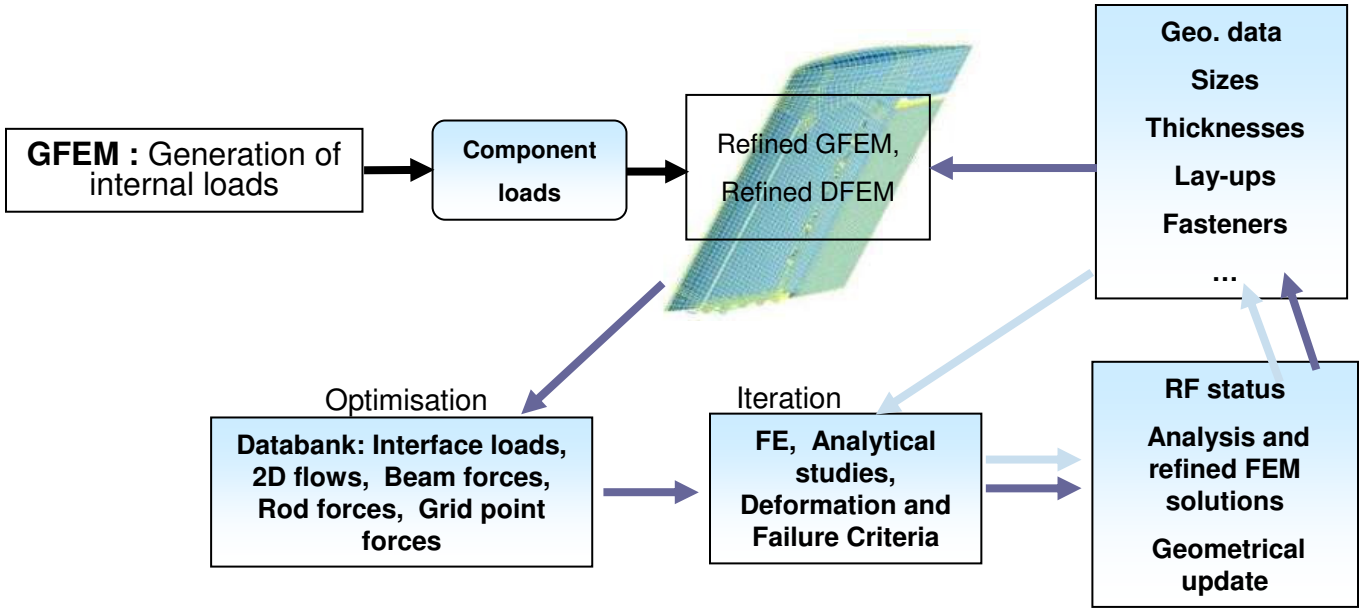
Structure Analysis Stress Process [1,2]

Several Design/Calculation loops taking into account all load configurations.



A Stress Process is required defining different level of analyses, e.g:

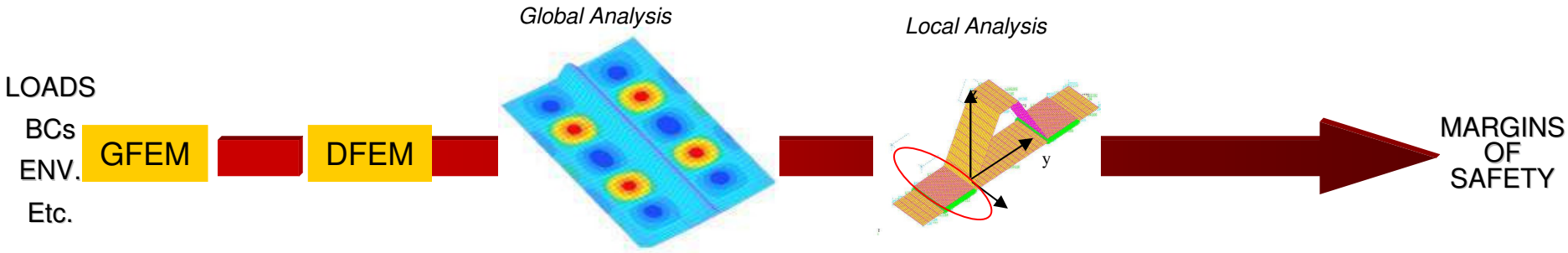
- Pre-sizing: fast evaluation (max. simplifications, gross accuracy),
- Quick Sizing with accuracy in line with simplifications,
- Advanced Sizing for state-of the-art calculations.

1, Integrating Materials Modeling Aspects into the Industrial Analysis of Composite Structures, Stephane Mahdi, CompTest 2008, Dayton, 22-24 Oct. 2008

2, *Application of multi-scale analyses to the sizing of composites structures and bonded assemblies*, Stephane Mahdi, Composites2009, London, 1-3 Apr. 2009

Structure Strength Analyses

- Structure Strength Analysis is, *typically*, a three steps process:
  - Internal load calculation from GFEM,
  - Internal stress calculations from 2D or specific 3D analyses,
  - Optimisation and Calculations of Margins of safety.

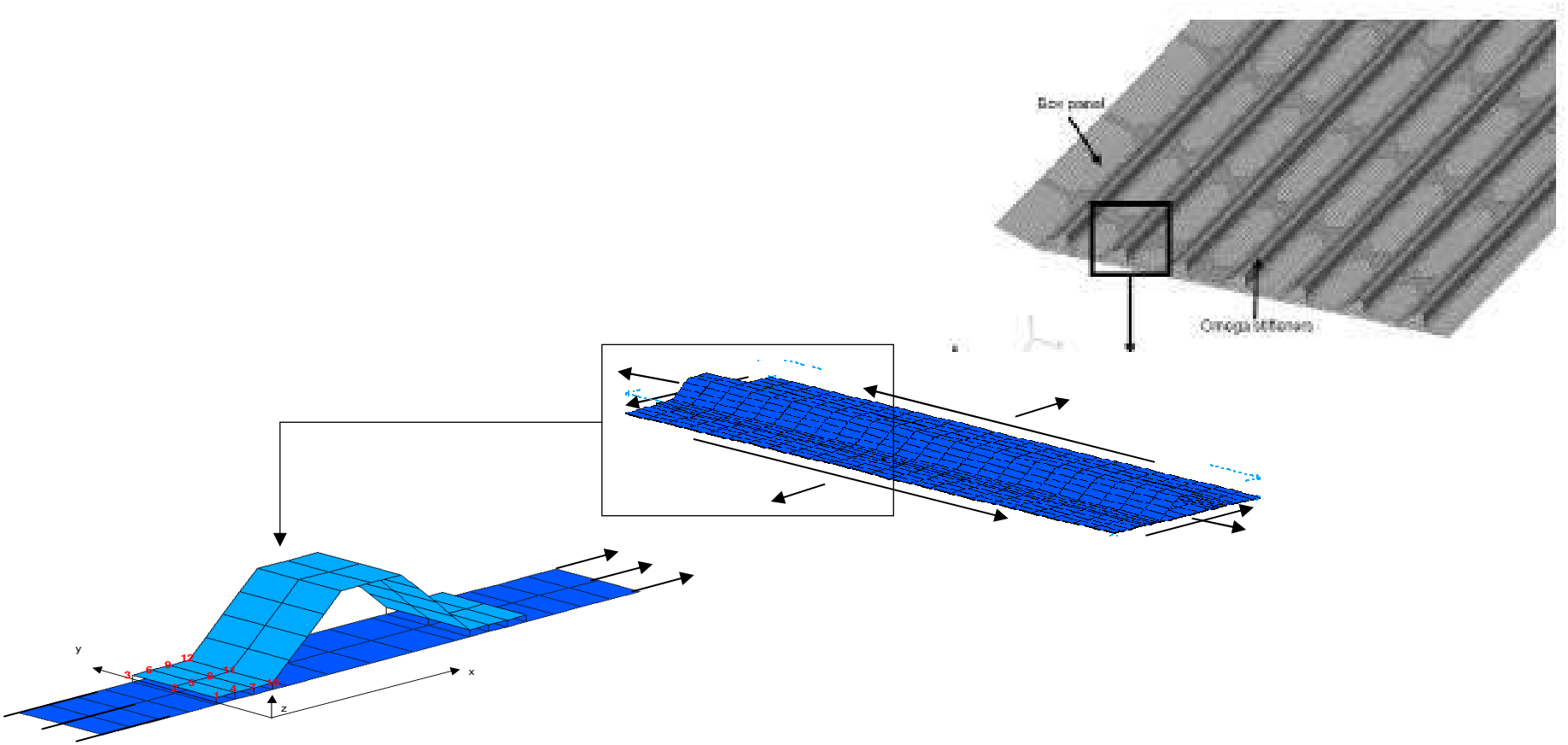


Example for Bonded Joint / Interface analysis

1. Retrieval of panel loads, from GFEM to DFEM,
2. Calculation of Stresses along the Bondline (analytical / FE)
3. Failure assessment, with allowable defined with a Building Block Approach

➔ Dependence on testing for the generation of adequate 'fitting parameters',
➔ Limitation of the structural design space,

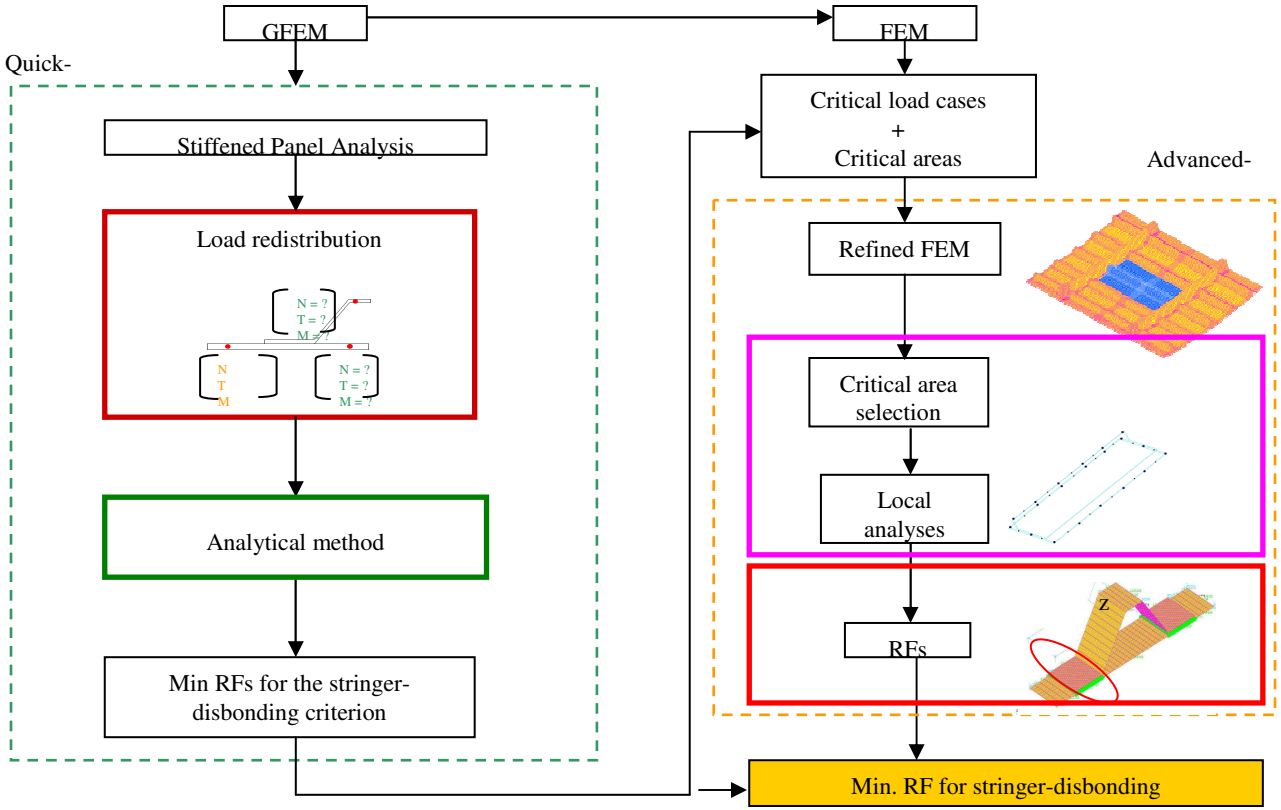
II. Composites Bonded Joints / Interfaces Analysis



Bonded Joints / Interfaces Stress Process

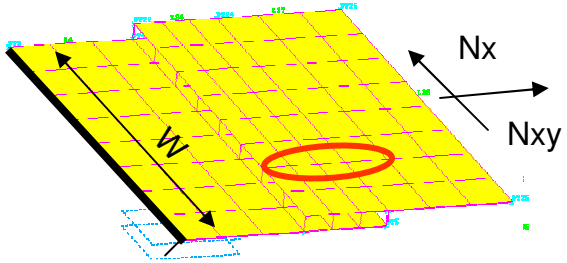
- Secure the Internal Loads and Stresses, from the GFEM down to the Local Analyses, with the aim to predict Failure load levels and Failure loci.

Example for Disbonding Analysis in Stiffened Panel Stress Process

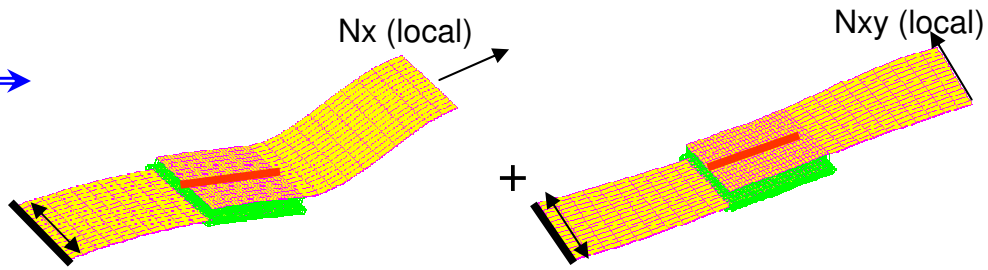


Global-Local Analyses / Securing Internal Stresses

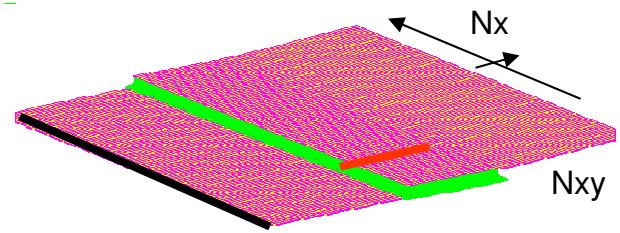
Global Model (refined)



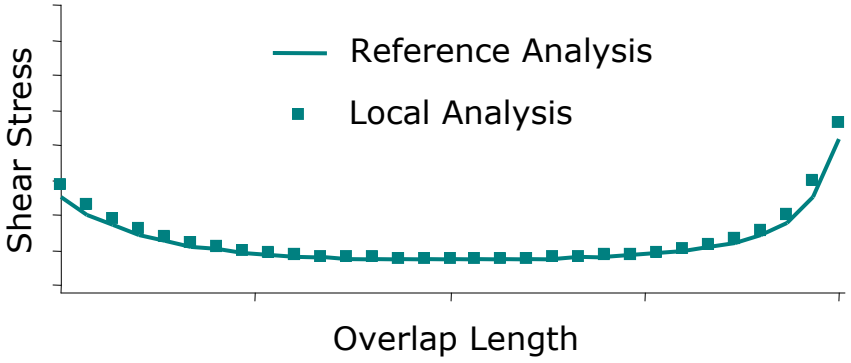
Local model



Reference Model



Global / Local Bondline Analysis



Similar Results

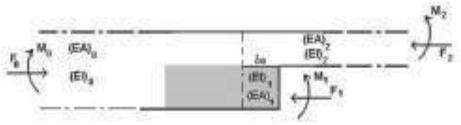
Local Analyses for Strength

QUICK-

ADVANCED-

Analytical Fracture mechanics /

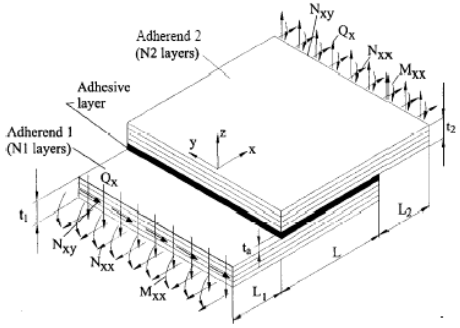
Damage Mechanics



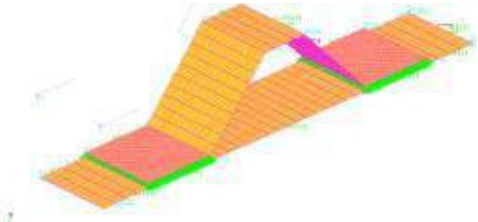
FE Fracture mechanics /

Damage Mechanics

Analytical Stress approach

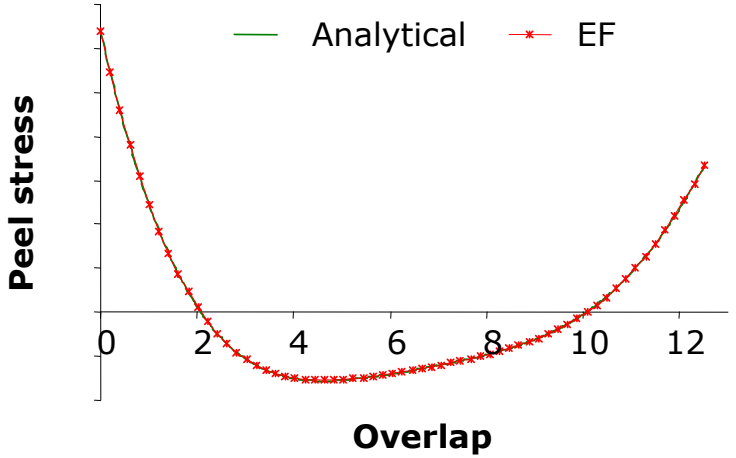


FE Stress approach



Strength of Materials Approach

- Calculation of Shear / Peel Stresses from analytical or parametric-FE models
  - Linear / NL bond properties.
  - Simplified or Detailed Geometry,
  - – Peak Stress/Strain varies with the (local) design,
  - + Good agreement between analytical and numerical calculations. Good Predictive Capability.



- Measurement of Constitutive Properties
  - Shear Stress-Strain (ASTMD5656),
  - Peel Stress-Strain(Measured / Estimated)
  - Definition of Interactive Failure Criteria (mostly empirical),
  - Derivation of Design Values.

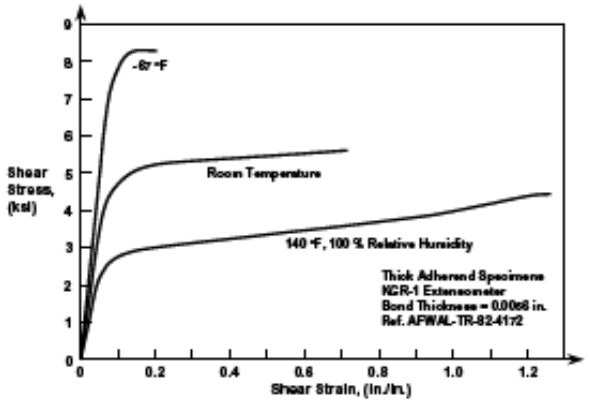


Fig. 2 Effect of Temperature on Stress-Strain Curves for Adhesive Layers in Shear

[e.g. *Recent Advanced in Structural joints and Repairs for composite materials*, Hart-Smith, Proceedings of SAMPE, Seattle, 2003]

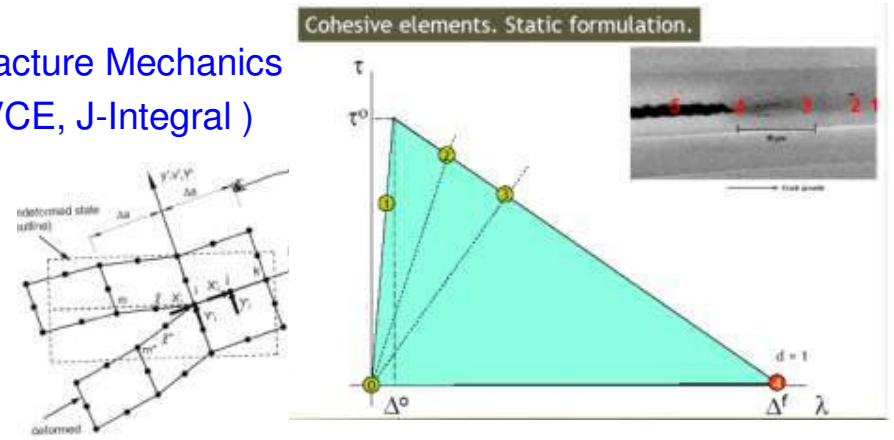
Fracture / Damage Mechanics Approach

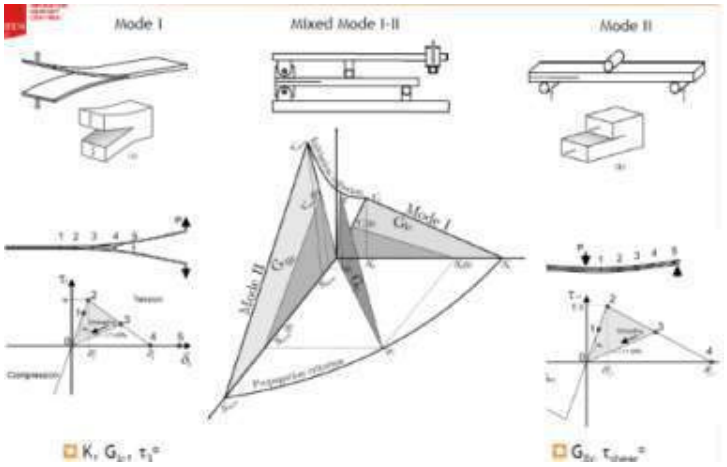
- Analytical / Numerical Calculations of SERR
  - Typically linear interface properties,
  - Simplified or Detailed Geometry
  - – Numerical Stability is difficult to ensure → Advanced User.
  - \+ Good agreement with experimental results is demonstrated.

- Measurement of Strain Energy Release Rates
  - Mode I, Mode II and Mixed-Modes SERR,
  - Definition of Mixed-Mode Failure Criteria,
  - Derivation of Design Values.

Damage Mechanics (CZM)

Fracture Mechanics
(VCE, J-Integral)





Simulation of delamination under mixed-mode loading conditions, A.Turon, J.Costa, J. Renart, P.P.Camanho, Composites2009, London, 1-3 April 2009).

Bonded Joints / Interfaces Strength Analyses

SoM

- Traditional approach for <u>design</u> (strength also possible),

+ Failure criteria easy to set-up,

- Measurement of constitutive properties costly and difficult.

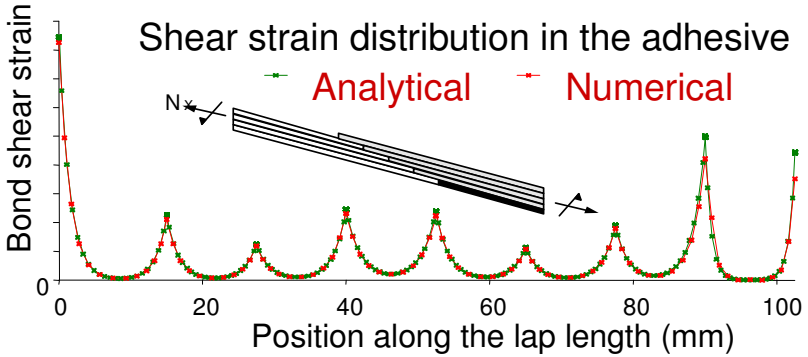
LEFM/CZM

- Suited for <u>strength, durability</u> analysis (also allow assessment of realistic damage scenario),

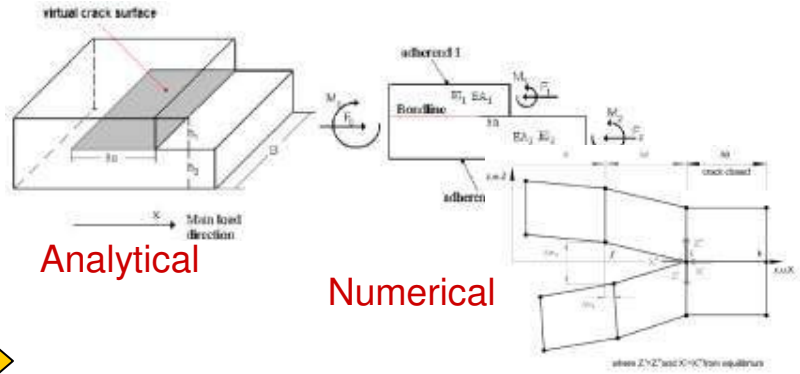
+ Measurement of SERR easier

(despite some difficulties for standardisation …)

- Numerical analysis not yet stable & robust



Calculation of σ-ε /τ–γ



Calculation of SERR

One problem to solve, *several* approaches to solve it …

Results from one analysis should not invalid results from another.

Deformation & Fracture Criteria

✓Ensure Robust Stress Process

✓Secure Global/Local Analysis

- Define Bond Constitutive properties – Strain Energy Release Rates:
  - ✓*Stress-Strain: e.g., ASTMD5656, Butt joints, modified-Arcan, etc.*
  - ✓*Fracture Mechanics: e.g., ASTMD5528/ISO15024, C-ELS, MMB, etc.*

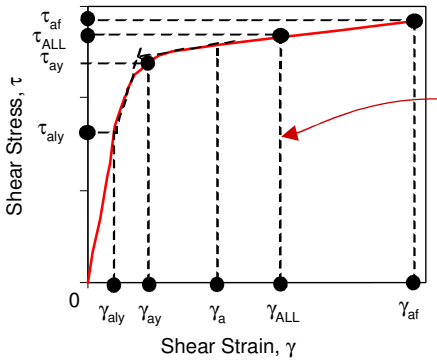
✗ *Industry standards for Bond Deformation and Fracture properties.*

- Failure Criteria
  - ✓A plethora of criteria has been proposed in the literature, e.g., Point Stress, Point Strain, Plasticity, Strain Invariant, B-K and Hart-Smith Failure Criteria, to name but a few. These are largely Semi-Empirical.
  - ✓Test–Analysis correlation is necessary.

✗ *Definition of a (Physically-Based) Mixed-Mode Failure Criteria*

Duality Strength / Fracture Mechanics Approaches

- Design of the joint in terms of stress / strain distribution
- Calculate failure in terms of energetic fracture criteria



$$P = 4\sqrt{E_s t_s h_a W_c}$$

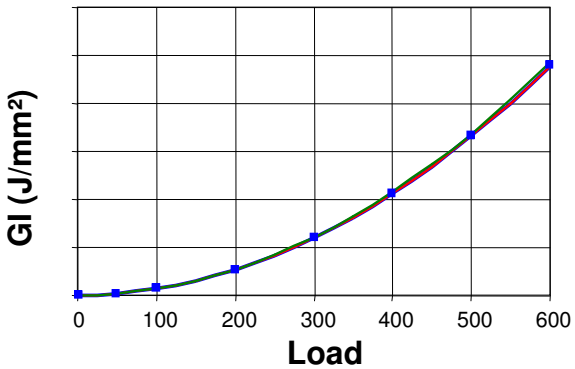
$$W_c = \sigma_{ay}(\gamma_{af} + \frac{\gamma_{ay}}{2})$$

- Strength is related to the area under the Stress-Strain curve
- *Wc* is related to Material Properties,
- *Wc* is also related Mode II SERR.

e.g., see Fernlund and Spelt (1994)

$$GI = ha\frac{\sigma^2}{2Ea} \qquad GII = ha\frac{\tau^2}{2Ga}$$

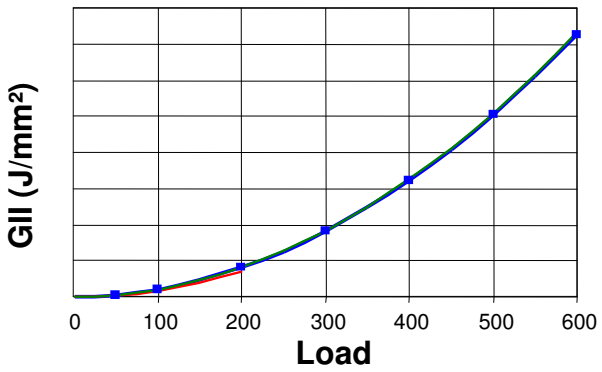
- Ex : Assessment of SERR at the overlap end - SLJ



Analytical (LEFM)

Analytical (SoM)

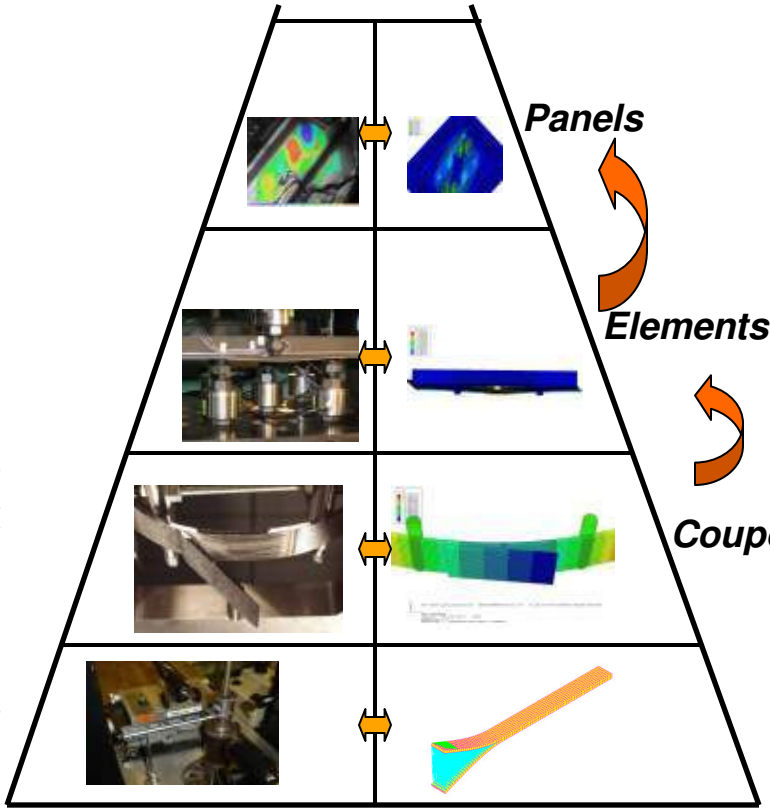
FE



Mixed-Mode Failure Criteria

Verification and Validation

- Demonstration by Analysis supported by Tests, at all levels of the Test Pyramid:
  - Lower level of test pyramid used to determine material Deformation & Fracture properties and Design Values, sensitivity to thermal, moisture effects, etc.
  - Middle part of test pyramid used to validate analysis for design features.
  - Details / Elements / Full scale tests used to validate internal load distribution.



→V&V

→Global / Local Approach

Selection of critical area

→ Verification of mode partitioning

→ Set-up of mixed-mode failure criteria

Characterisation (Coupons) { Mechanical Properties : E, ν, … , G_{IC}, G_{IIC}, G_{I-II}

⇨ Methods and Tools are validated with a Building-Block Approach

⇨This means we cannot just use any calculation methods combined with any material data.

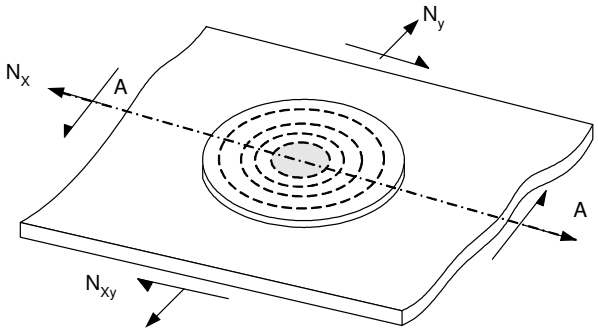
III. Bonded Repairs Analysis

Bonded Repairs Analysis [3]

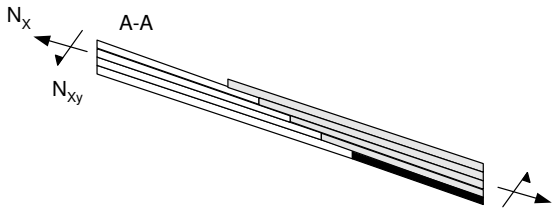
- Bonded Repair Analysis is a simplification of the Bonded Joints Analysis
- Stress/Strain Approach + Sound Design Principles (alleviating Peel Stresses):
  - Averaged Bond properties (Linear / Non-Linear shear),
  - Building-Block approach for static and fatigue validation,
  - \+ Conservative allowable accounts for durability parameters,
  - – Does not capture physics of delamination growth.

- The approach is semi-empirical and work with conservative assumptions :
  - Quick approach: 1D analytical for fast calculations
  - Advanced approach: Quasi-3D parametric-FE for detailed calculations.

(a) 2D Parametric-FE (here circular) repair patch to a monolithic panel



(b) 1D Analytical repair patch to a monolithic panel

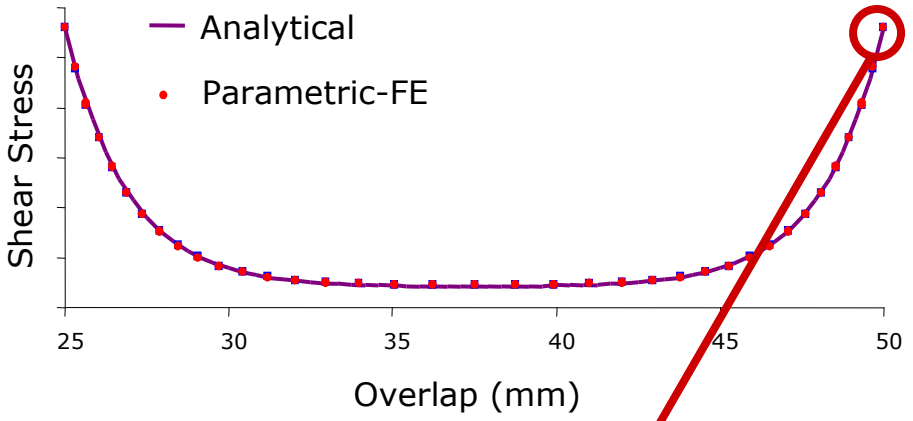


3, Composites Repair Analysis, Stephane Mahdi, Spring 2007 CACRC Meeting, Amsterdam, 2007

Bonded Repairs Analysis

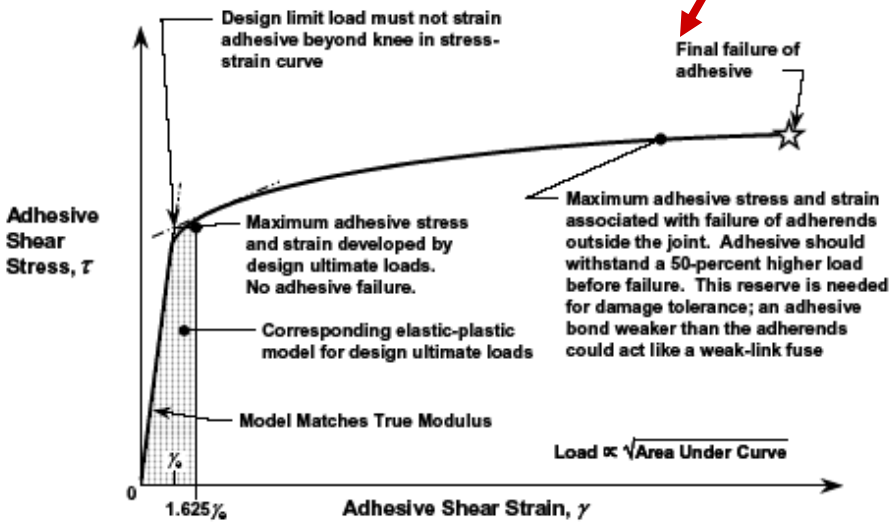
I- Robust Internal Stress Calculation

Shear stress distribution in the adhesive



II- Strength Analysis: (e.g., Hart-Smith's)

[Hart-Smith, *Recent Advanced in Structural joints and Repairs for composite materials*, Proceedings of SAMPE, Seattle,2003]



Note that design process must account for nonlinear adhesive behavior, but a precise stress-strain curve is not mandatory. An approximation, based on a similar adhesive, will usually suffice.

Fig. 23 New Design Procedure to Limit Strains in the Adhesive Layer

IV. Perspectives and Conclusions

Examples of On-going AIRBUS R&D

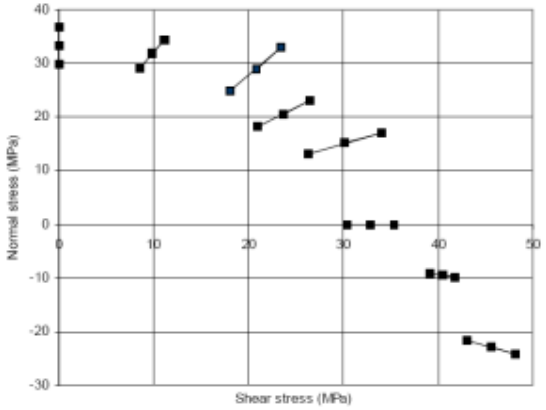
Development of Multi-Axial Constitutive Deformation & Fracture Properties

together with IFREMER / ENSIETA / UBO

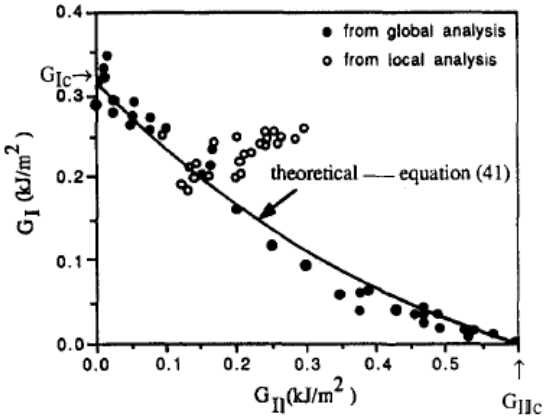
Development of Fracture Mechanics/Damage Mechanics and Durability

together with IMPERIAL COLLEGE LONDON

- Dual SoM / Fracture-Damage Mechanics Developments:
  - Measurement of constitutive behaviour under mixed-mode loadings and realistic environment (durability), Establish failure criteria,
  - Measurement of SERR for Mode I, Mode II and Mixed-Mode loadings, taking into account durability and Establish a physically-based mixed-mode delamination criteria,
  - Evaluate competition between interface / bond failure modes.



Development of an improved adhesive test method for composite assembly design, Cognard, Davies, Ginested and Sohier, Composites Science and Technology, 65(3-4) : 359-368, March 2005



On the analysis of mixed-mode failure, M.Charalambides, AJ.Kinloch, Y.Wang and JG Williams, International Journal of Fracture 54: 269-291, 1992.

Conclusions

INCREASED PERFORMANCE

REDUCED DEVELOPMENT CYCLE

CONTROLLED STRUCTURAL INTEGRITY

CONTROLED MATURITY FOR NEW MATERIALS AND TECHNOLOGIES

REDUCTION OF DIRECT AND INDIRECT (repair, maintainability) COSTS

Understanding of D&F properties of materials

Physical understanding (failure modes, fibre/resin functions)

Calculation methods adapted to the need : from Pre-Design to Advanced Calculations.
Trade off between Complexity ↔ Accuracy

Robust Validation by testing and analysis at all levels of the test pyramid
Predictive ⇔ cost savings
Accurate ⇔ weight savings

Tool development and deployment to extended enterprise
Control of design/stress space

Aircraft Development

Enable Virtual Testing