FORUM TERATEC 2015

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SOGETI High Tech

Simplified stress analysis of bonded joints using the macro-element technique

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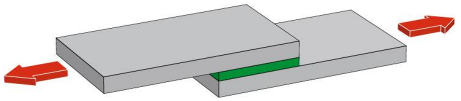
Inspiring TECHNOLOGY

Content



Content

SOGETI HIGH TECH

A Capgemini group subsidiary

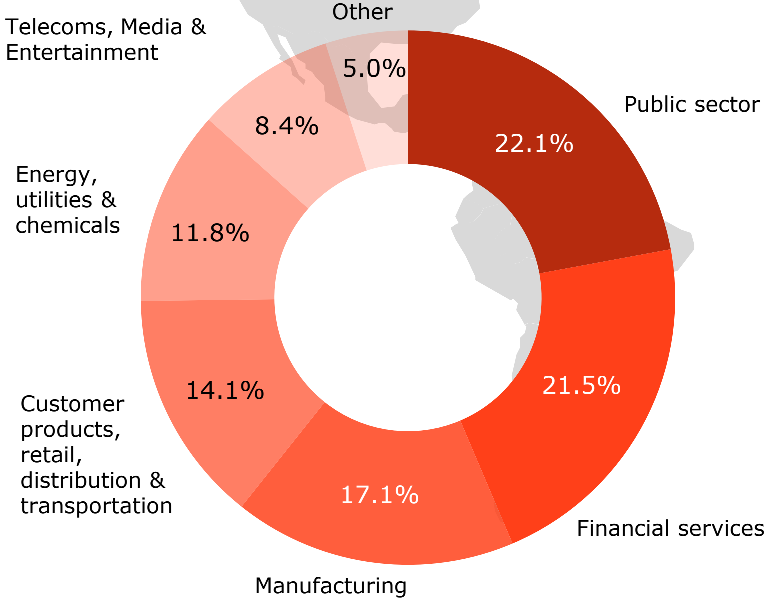
In 44 countries

Revenue of 10.1 billion euros

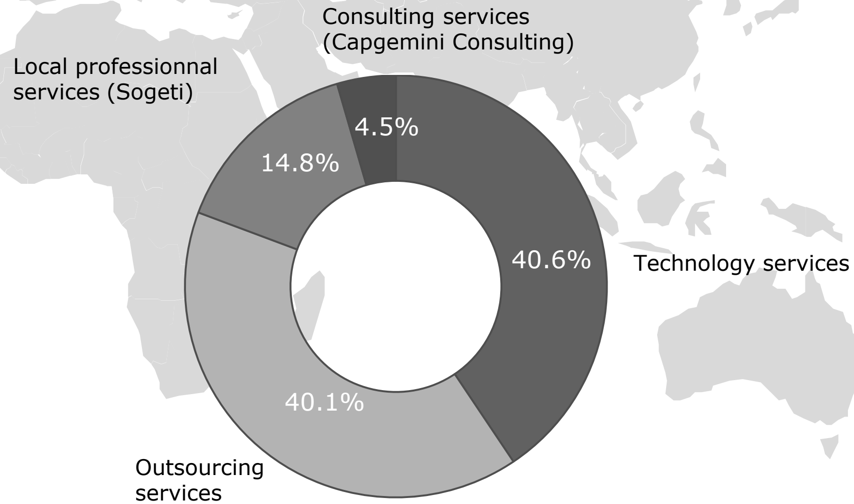
131.000 people with more than 50,000 pin offshore*

Capgemini, founded in 1967, is one of the world foremost providers of consulting, technology and outsourcing services.

Revenue by industry



Revenue by business



Capgemini Consulting | Capgemini CONSULTING.TECHNOLOGY.OUTSOURCING | SOGETI | Prosodie | EURIWARE

*offshore = Inde, Vietnam, Maroc, Guatemala, Pologne,...

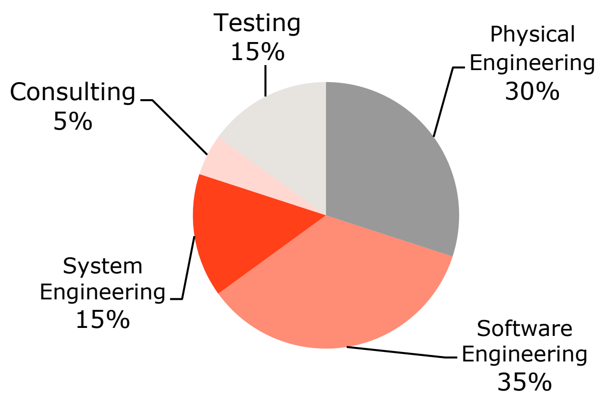
Sogeti : Engineering and Technology Consulting Services in the world

Nearly 20.000 employees on 100 locations in 15 countries

▲ Sogeti High Tech business development

Sogeti High Tech, specialist in Engineering and R&D

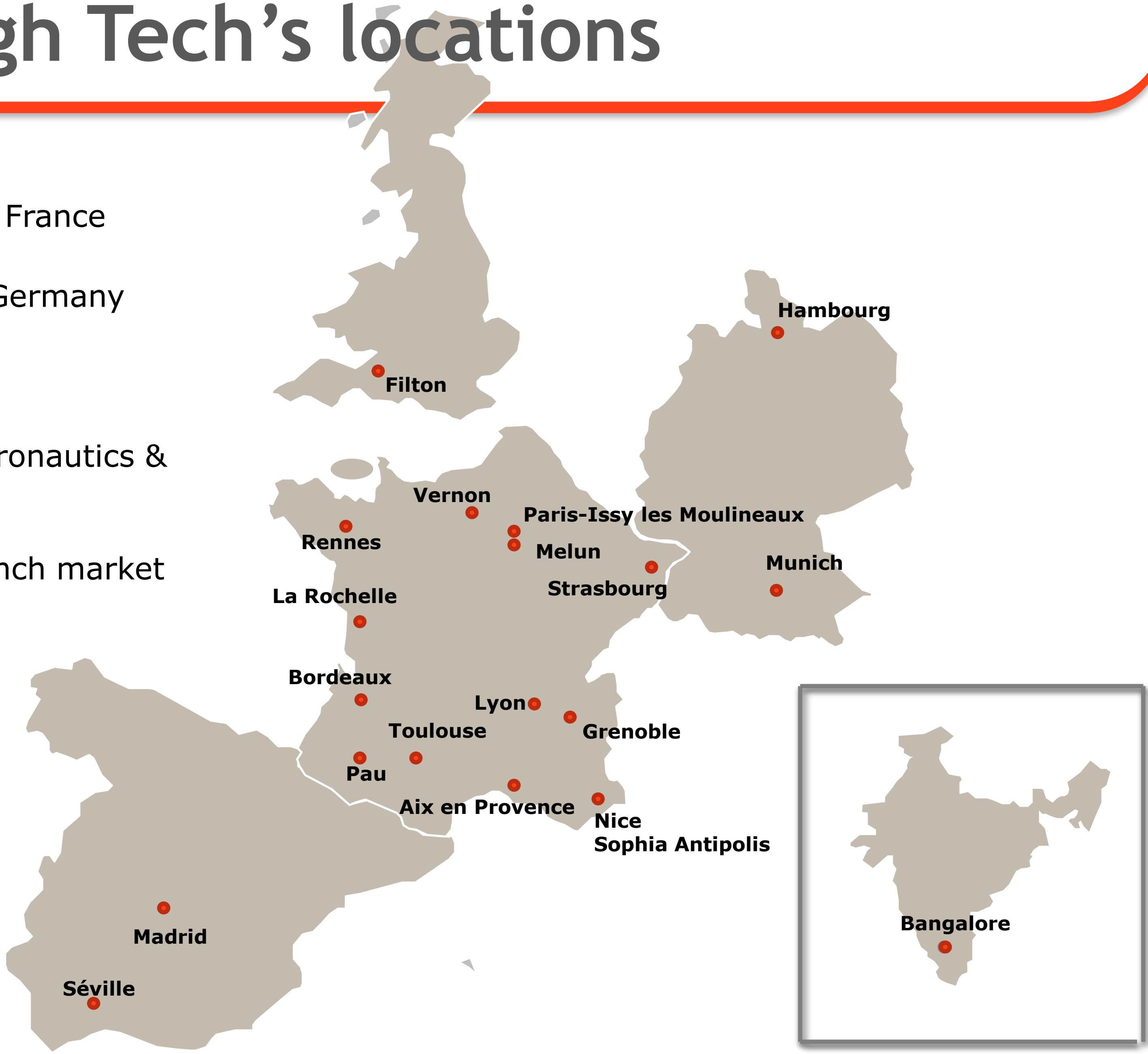
- **Leader in Engineering and Technology Consulting Services**
  - A 25-year long expertise in services for industrial companies
  - Seven main markets :
    - Aeronautics
    - Energy
    - Life Sciences
    - Railway
    - Space
    - Defense
    - Telecoms & media



- **Five business lines**
  - Consulting
  - Systems Engineering
  - Physics Engineering
  - Software Engineering
  - Testing

Sogeti High Tech's locations

- 3000 employees in France
- 300 employees in Germany
- 19 locations
- Rank n°1 in the Aeronautics & Space sectors
- 5th rank in the French market



Content

FRAME

Frame

Internal Research Project

JoSAT (Joint Stress Analysis Tool)

✓ **ID SHEET:**

- internal research project
- started in 2008
- self-funding
- workload: 7400 days at the end of June 2015

✓ **DRIVEN LINE**

- *research theme*: **joining technologies**
- *2 research axes*: axis **bonding** and axis **bolting**
- *objectives*: **better understanding of the mechanical behavior** of bonded joints and bolted joints

1. to develop a **simplified mechanical analysis tool**
2. to **better control** these joining technologies

Frame

Network Development

Partnerships

✓ **ISAE (Institut Supérieur de l'Aéronautique et de l'Espace, Toulouse):**

- signed in 2009
- prolongated in 2012 up to 2017

THEMES	WHAT?
COMPOSITE MATERIALS	2 PhD Theses 1 MS Thesis
JOINING TECHNOLOGIES	1 PhD Thesis 6 MS Theses

✓ **BORDEAUX INP / ENSEIRB-MATMECA**

- our Center of Competences is trusted to teach their students the Mechanics of Assemblies (https://www.enseirb-matmeca.fr/syllabus1415/index.php?&module=MS312&langage=EN)

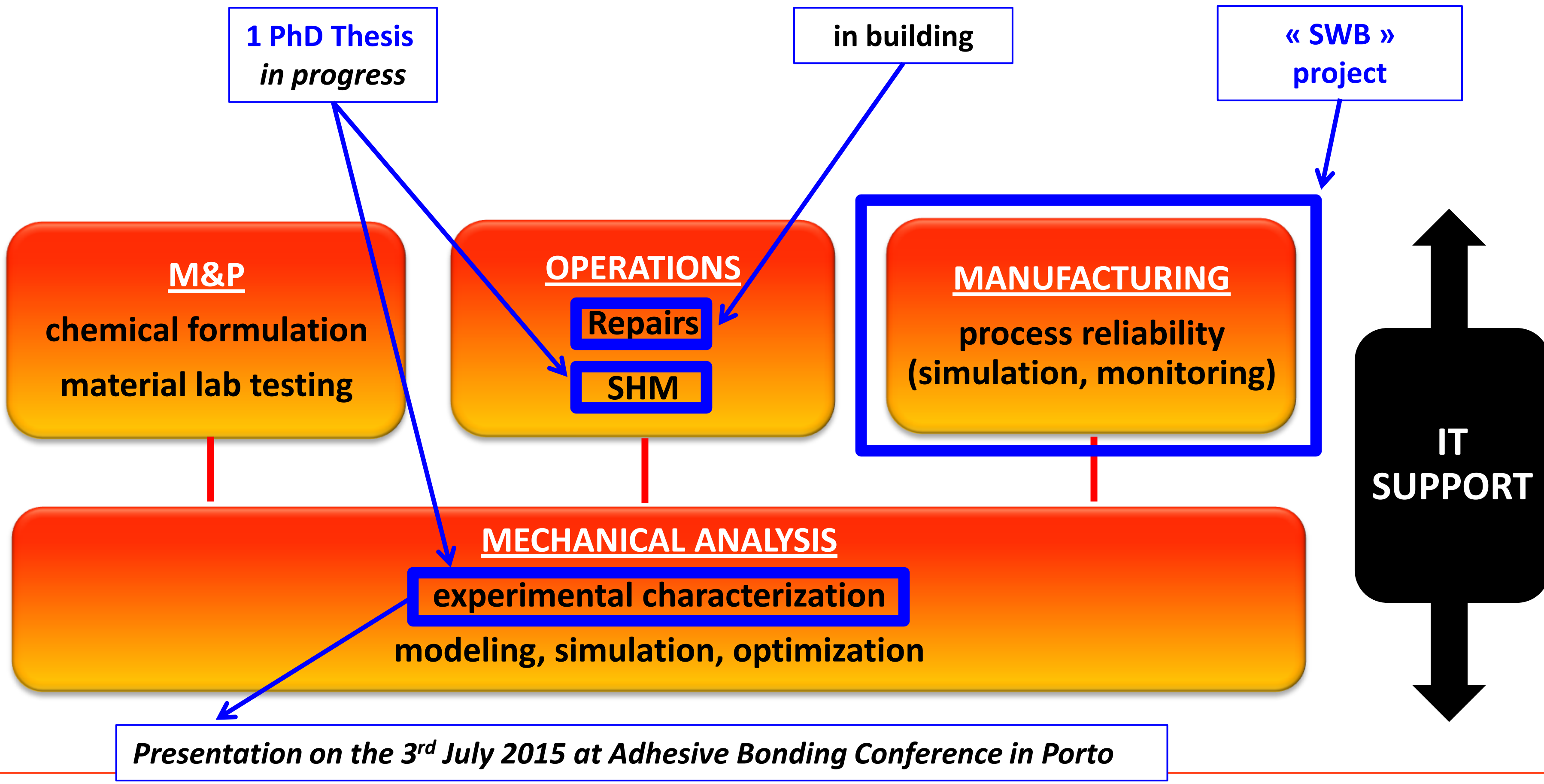
✓ **AN ADHESIVE SUPPLIER**

- to be signed but collaborative activities already in progress

Frame

Rationale of Development

Stress can support M&P, Manufacturing and Operations



Content

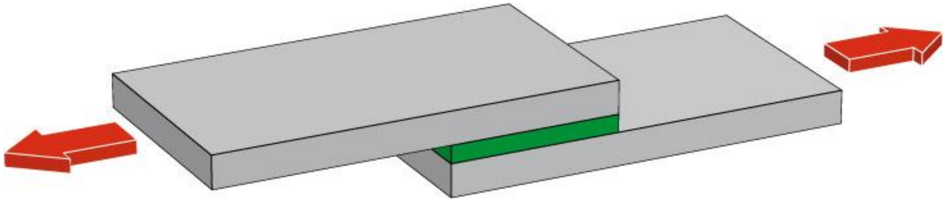
MECHANICAL ANALYSIS

Mechanical Analysis

Why?

Strength Prediction

- ✓ Strength prediction consists in comparing computed criteria with allowable.
- ✓ The definition of criteria can be based on:
  - experimental and theoretical investigations on the failure mechanisms
  - in-service feedbacks
- ✓ Criteria requires input data , provided by mechanical analysis.
- ✓ Allowable are obtained from experimental characterization.



Mechanical Analysis

How?

Finite Element (FE) Analysis

✓ FE method can address the mechanical analysis of bonded joints, to provide input data to criteria.

✓ Nevertheless, FE analysis:

- is time consuming
- and demands highly skilled engineers to be suitably applied

✓ The relative difference in thickness between the adhesive and the adherends, and the mesh requirements conducts to develop models with a very high number of degrees of freedom

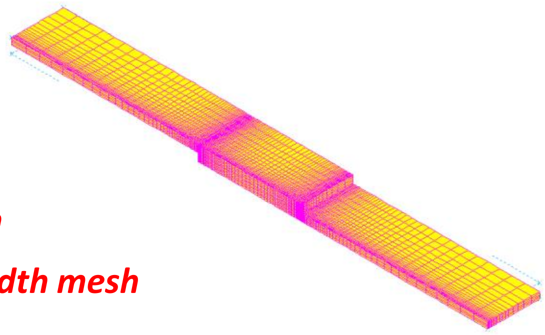
Example of single-lap bonded joint in 3D:

- adherend thickness: 2 mm / adhesive thickness: 0.2 mm

- 10 cubic elements in adhesive thickness = 0.02 mm each

- transition ratio of 1 imposed at the adhesive interface, an element size of 0.02 mm

⇒potentially 100 elements in the adherend thickness, to be multiplied by length, width mesh parameters



Mechanical Analysis

Simplified Analysis

A Mathematical Issue

✓ Various analytical closed-form solutions exist, based on simplifying hypotheses on the kinematics and the number of adhesive stress tendon components to be considered, leading to accurate mechanical behavior approximation.

✓ But **the application field appears as restricted**, even for practical problems (ex: steel to aluminium joint including bending and normal displacement)

✓ To enlarge the application field, **mathematical procedures** shall be used to solve the set of governing differential equations (deduced from hypotheses taken)

The macro-element technique is a mathematical procedure

Content

MACRO-ELEMENT TECHNIQUE

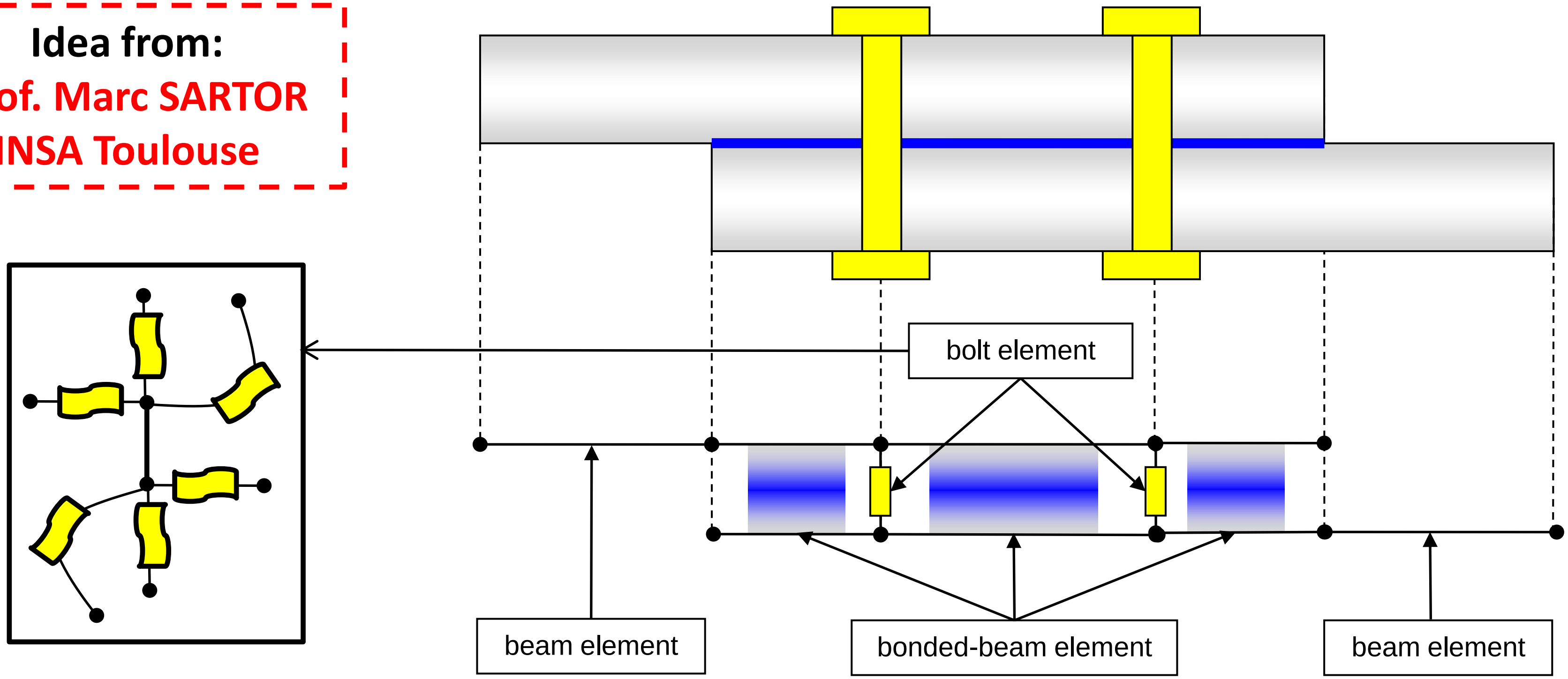
Macro-Element Technique

Origin

Simplified Analysis of Hybrid Joints

- First developments between 2004 and 2006 in the frame of PAROISSIEN's PhD **[1]**, to simplify the stress analysis of **hybrid (bolted/bonded) joints**
- **Significant extension of the application field** since 2008 by SOGETI HIGH TECH in the frame of JoSAT

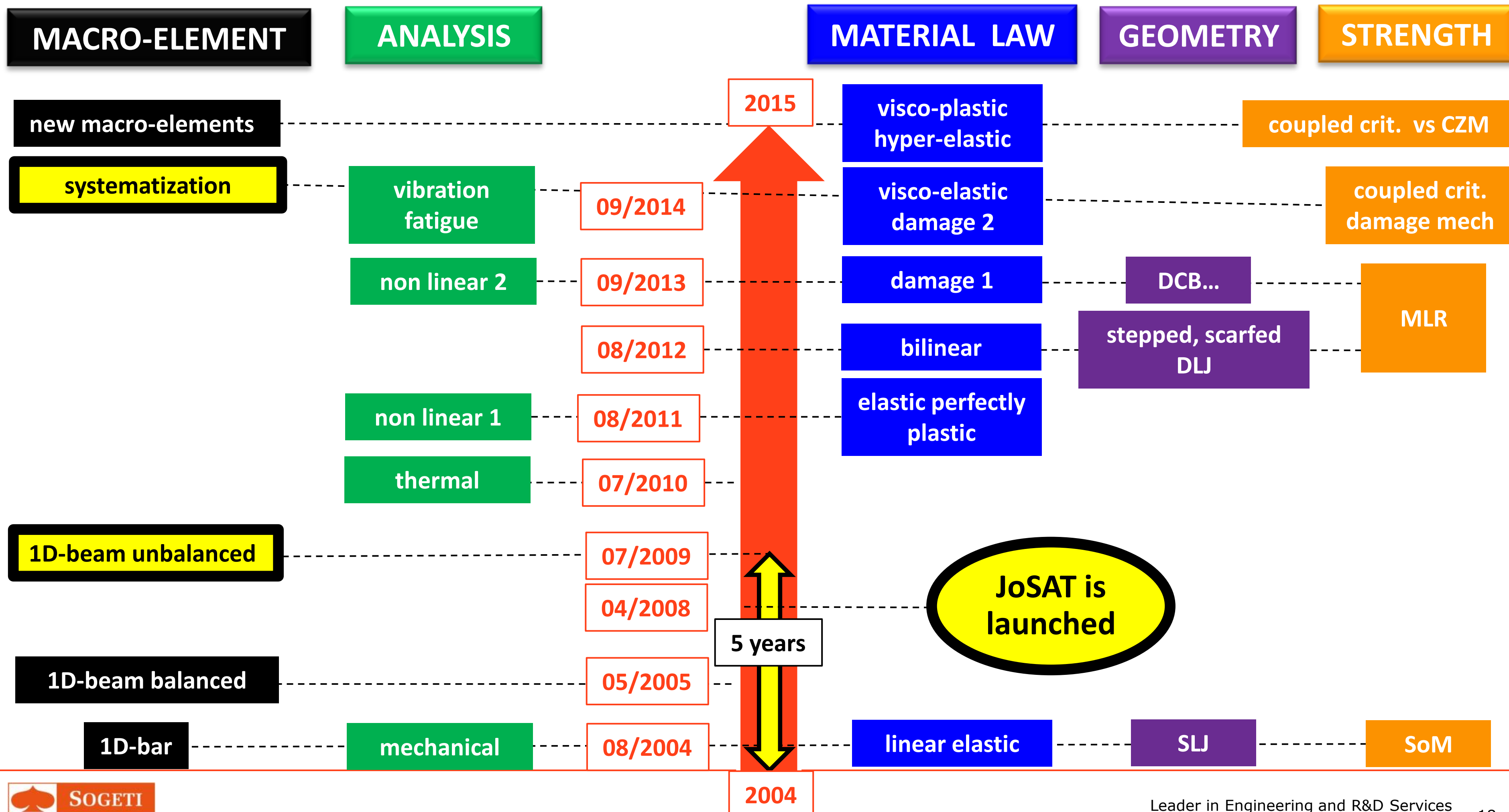
Idea from:
Prof. Marc SARTOR
INSA Toulouse



Macro-Element Technique

Chronology

From 2004 up to now

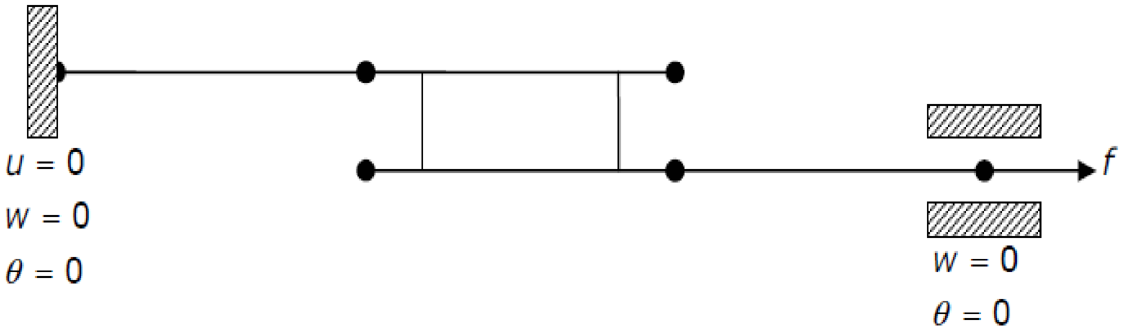


Macro-Element Technique

How?

Inspired by FE Method

- ✓ **1st STEP: MESHING THE JOINT**, in beam (or bar) elements and macro-element.
  - **Only 1 macro-element** is needed **for 1 entire overlap**
- ✓ **2nd STEP: ASSEMBLY OF THE STIFFNESS MATRIX (K)** for the joint
  - **KEY POINT**: the stiffness matrix of the macro-element (see next slide)
- ✓ **3rd STEP: APPLICATION OF BOUNDARY CONDITIONS** (load and prescribed displacement)
- ✓ **4th STEP: MINIMIZATION OF POTENTIAL ENERGY**
  - leading to a linear system to be solved: **F=KU**



Example:
single-lap bonded joint in-plane loaded membrane + bending

=> the solution consists in inverting a 13x13 linear system only!

Macro-Element Technique

Stiffness Matrix (Bonding)

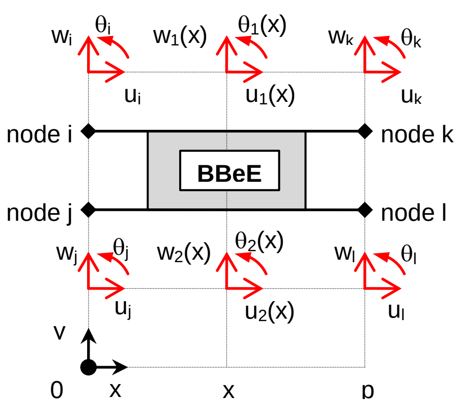
Principle

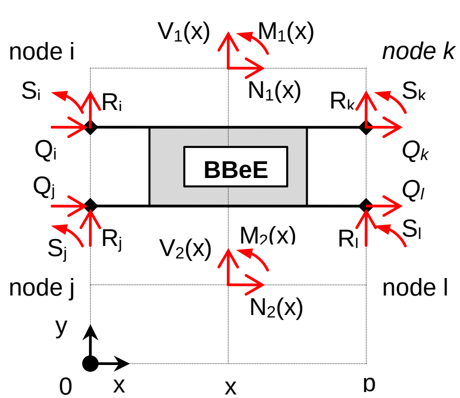
✓ **(semi-)analytical formulation** based on the set of governing differential equations:

- **local equilibrium equations**
- **constitutive equations**

There is **not any hypotheses on the shape of interpolation functions.**

The shape of interpolation functions is the shape of solutions of the system of governing differential equations





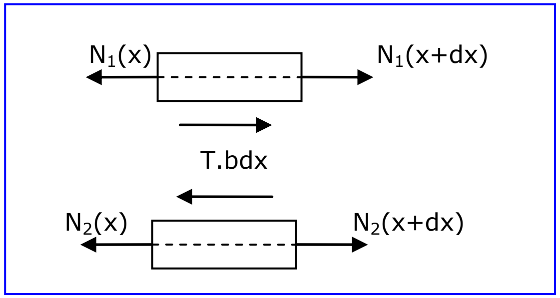
$$K_{BBe} = \begin{pmatrix} \left[\frac{\partial Q_\sigma}{\partial u_\tau}\right] & \left[\frac{\partial Q_\sigma}{\partial w_\tau}\right] & \left[\frac{\partial Q_\sigma}{\partial \theta_\tau}\right] \\ \left[\frac{\partial R_\sigma}{\partial u_\tau}\right] & \left[\frac{\partial R_\sigma}{\partial w_\tau}\right] & \left[\frac{\partial R_\sigma}{\partial \theta_\tau}\right] \\ \left[\frac{\partial S_\sigma}{\partial u_\tau}\right] & \left[\frac{\partial S_\sigma}{\partial w_\tau}\right] & \left[\frac{\partial S_\sigma}{\partial \theta_\tau}\right] \end{pmatrix}, \sigma, \tau = i, j, k, l$$

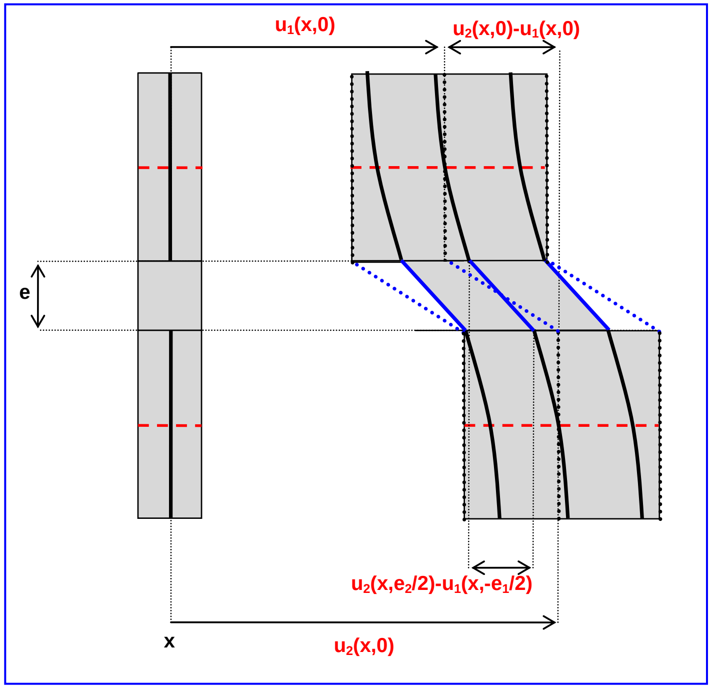
Macro-Element Technique

1D-Bar Stiffness Matrix (Bonding)

Hypotheses

- ✓ linear local equilibrium :
  - VOLKERSEN **[2]**





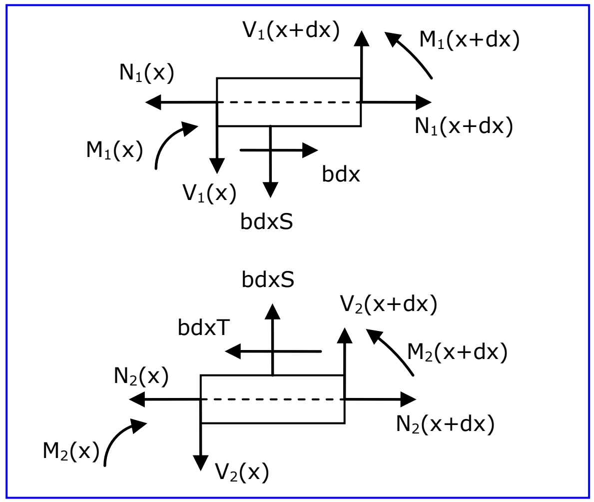
- ✓ adherend as linear bars:
  - including thermal expansion
  - linear variation of the adherend shear stress with the thickness as TSAÏ, OPLINGER and MORTON **[3]**
- ✓ adhesive layer as shear springs continuously distributed:
  - adhesive thickness constant along the overlap
  - adhesive shear stress and shear stress supposed constant in the adhesive thickness

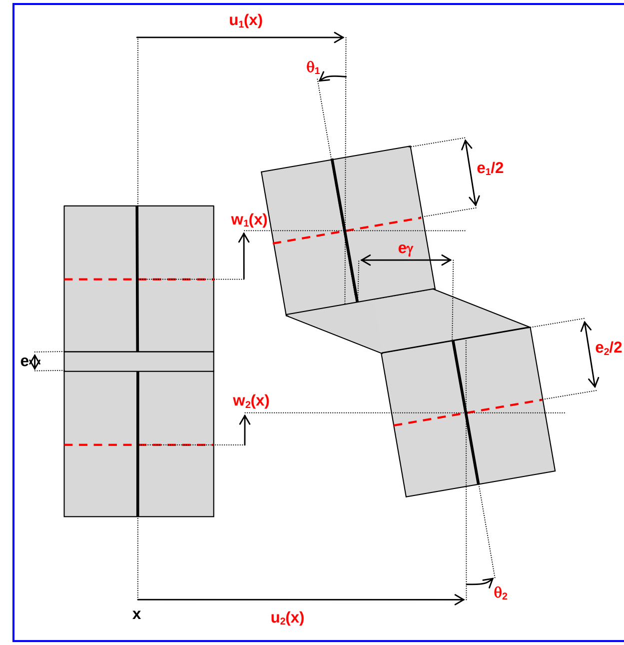
Macro-Element Technique

1D-Beam Stiffness Matrix (Bonding)

Hypotheses

- ✓ linear local equilibrium available:
  - GOLAND & REISSNER **[4]**
  - HART-SMITH **[5]**





- ✓ adherend as linear Euler-Bernoulli beam:
  - in the classical laminated theory
  - including thermal expansion
  - linear variation of the adherend shear stress with the thickness as TSAÏ, OPLINGER and MORTON **[3]**
- ✓ adhesive layer as shear and peel springs continuously distributed:
  - adhesive thickness constant along the overlap
  - adhesive shear stress and shear stress supposed constant in the adhesive thickness

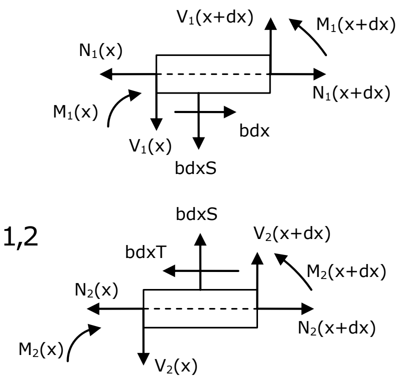
Macro-Element Technique

1D-Beam Stiffness Matrix (Bonding)

Equations (1)

local equilibrium (GOLAND & REISSNER)

$$\begin{cases} \dfrac{dN_j}{bdx} = (-1)^j T \\ \dfrac{dV_j}{bdx} = (-1)^{j+1} S \qquad , \qquad j = 1,2 \\ \dfrac{dM_j}{dx} + V_j + \dfrac{1}{2}(e_j + e)bT = 0 \end{cases}$$



constitutive equations shear springs, peel springs

$$\begin{cases} T = \dfrac{G}{e}\left(u_2 - u_1 - \dfrac{1}{2}e_1\theta_1 - \dfrac{1}{2}e_2\theta_2\right) \\ S = \dfrac{E}{e}(w_1 - w_2) \end{cases}$$

constitutive equations Euler-Bernoulli laminated beam

$$\begin{cases} N_j = A_j \dfrac{du_j}{dx} - B_j \dfrac{d^2 w_j}{dx^2} \\ M_j = -B_j \dfrac{du_j}{dx} + D_j \dfrac{d^2 w_j}{dx^2}, \qquad j = 1,2 \\ \theta_j = \dfrac{dw_j}{dx} \end{cases}$$

SYSTEM OF COUPLED DIFFERENTIAL EQUATIONS

resolution

Expression for displacements then for internal forces

HARD WORK

Macro-Element Technique

1D-Beam Stiffness Matrix (Bonding)

Equations (2)

Computation of nodal forces and nodal displacements

$$\mathbf{U}=\begin{pmatrix} u_i \\ u_j \\ u_k \\ u_l \\ w_i \\ w_j \\ w_k \\ w_l \\ \theta_i \\ \theta_j \\ \theta_k \\ \theta_l \end{pmatrix}=\begin{pmatrix} u_1(0) \\ u_2(0) \\ u_1(\Delta) \\ u_2(\Delta) \\ w_1(0) \\ w_2(0) \\ w_1(\Delta) \\ w_2(\Delta) \\ \theta_1(0) \\ \theta_2(0) \\ \theta_1(\Delta) \\ \theta_2(\Delta) \end{pmatrix}=\mathbf{MC} \quad \textit{and} \quad \mathbf{F}=\begin{pmatrix} Q_i \\ Q_j \\ Q_k \\ Q_l \\ R_i \\ R_j \\ R_k \\ R_l \\ S_i \\ S_j \\ S_k \\ S_l \end{pmatrix}=\begin{pmatrix} -N_1(0) \\ -N_2(0) \\ N_1(\Delta) \\ N_2(\Delta) \\ -V_1(0) \\ -V_2(0) \\ V_1(\Delta) \\ V_2(\Delta) \\ -M_1(0) \\ -M_2(0) \\ M_1(\Delta) \\ M_2(\Delta) \end{pmatrix}=\mathbf{NC}$$

Stiffness Matrix

$$K=NM^{-1}$$

Content

CURRENT CAPABILITIES

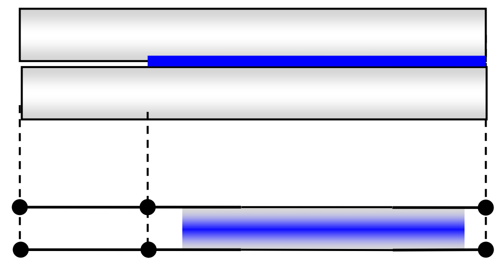
Current Capabilities

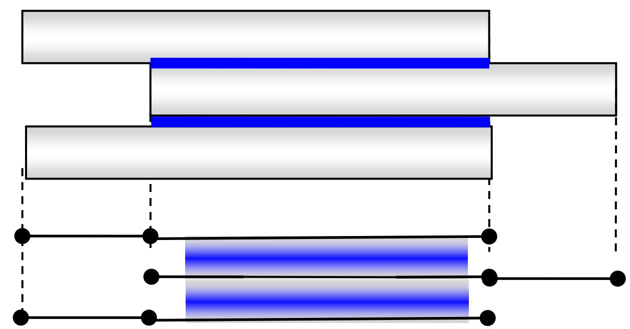
Input

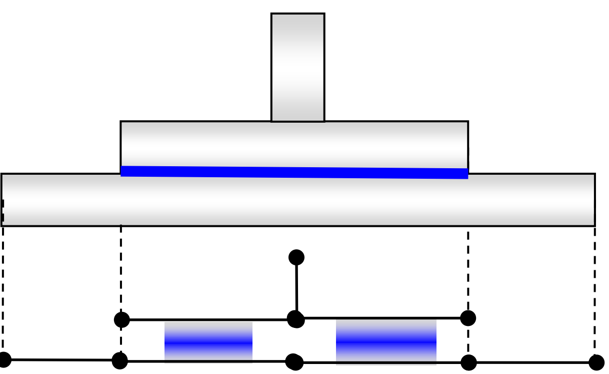
Geometry

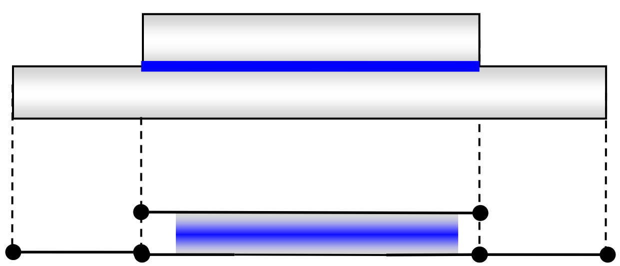
✓ **AS A "LEGO GAME",** **various geometrical configurations** can be modeled:

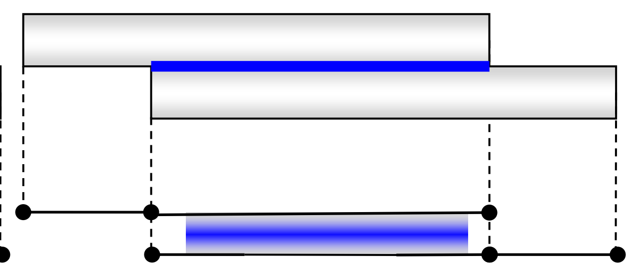
- squared-end single-lap as the nominal configuration
- tapered-end single-lap configuration
- double-lap configuration
- fracture mechanics coupons (ENF, DCB, MMB)
- patch or stiffned configuration **[POSSIBLE]**
- etc…. + including fasteners











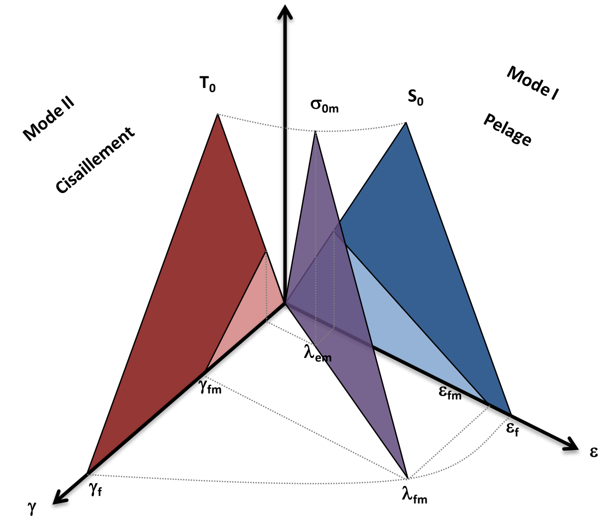
Current Capabilities

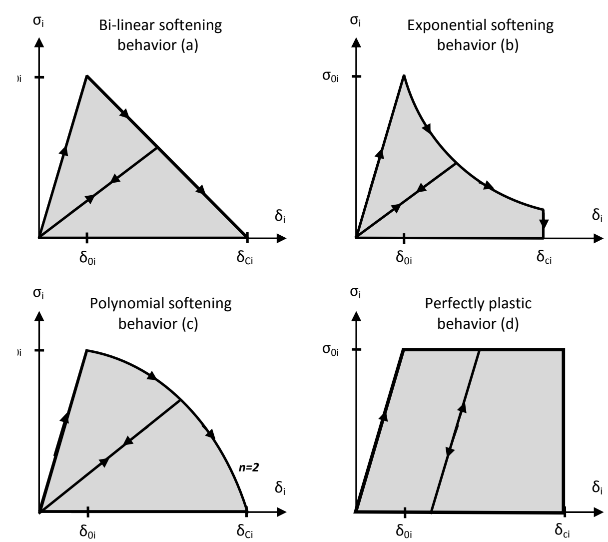
Input

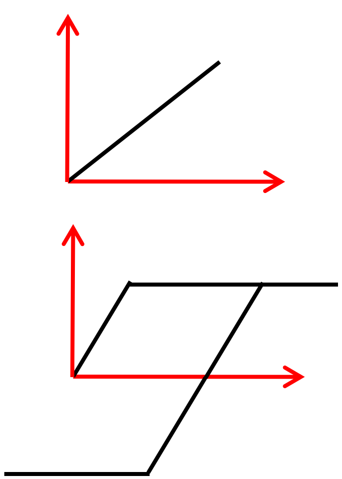
Adhesive Material

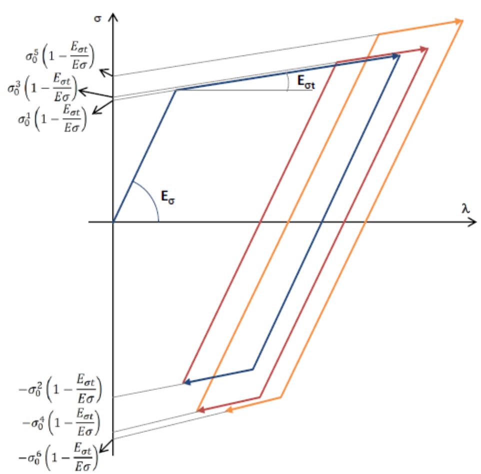
✓ **VARIOUS ADHESIVE MATERIAL CAN BE SUPPORTED:**

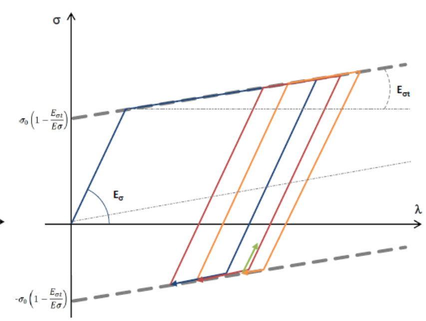
- linear elastic
- elastic perfectly plastic **[6, 8]**
- bilinear (isotropic, kinematic, mixed hardening) **[6, 8]**
- damage evolution law with various shapes and mixed mode **[9]**
- visco-elastic including time-temperature dependency











Current Capabilities

Input

Adherend Material

- ✓ **EULER-BERNOULLI BEAM**
  - in the frame of the classical laminated theory
  - balanced and unbalanced cases
  - linear elastic

- ✓ **LINEAR ELASTIC BEHAVIOR IS NOT A RESTRICTION**
  - the non-linear algorithm already developed to support non-linear adhesive material
  - non linear adherend material could be then implemented

Current Capabilities

Input

Loading

✓ **STATIC [6-9]**

- loading in force or in displacement

✓ **HYDRO-THERMAL**

- uniform variation of temperatures [7] and/or of moisture rate

✓ **FATIGUE**

- basing on progressive damage approach [10, 11] [algo ok, approach under assessment]

✓ **VIBRATION**

- mass matrix implemented
- free modes assessment

Current Capabilities

Output

Results Directly Available

✓ **DISTRIBUTION AT ANY POINTS:**

- displacements in the adherends (u, v, θ)
- internal forces in the adherends (normal force, shear force, bending moment)
- forces in the fasteners (bolt transfer rate)
- shear stress and peel stress along the overlap
- **[EASILY FAISABLE]** stress and strain in the adherends can be easily computed from internal forces

The tool provides input for the computation of strength criteria

Content

RELEVANCE

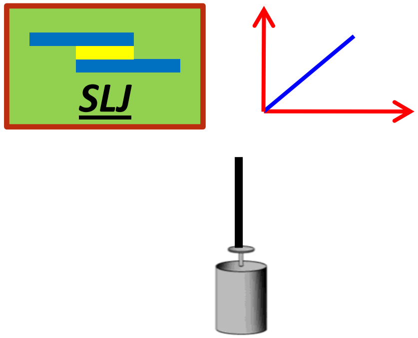
Relevance

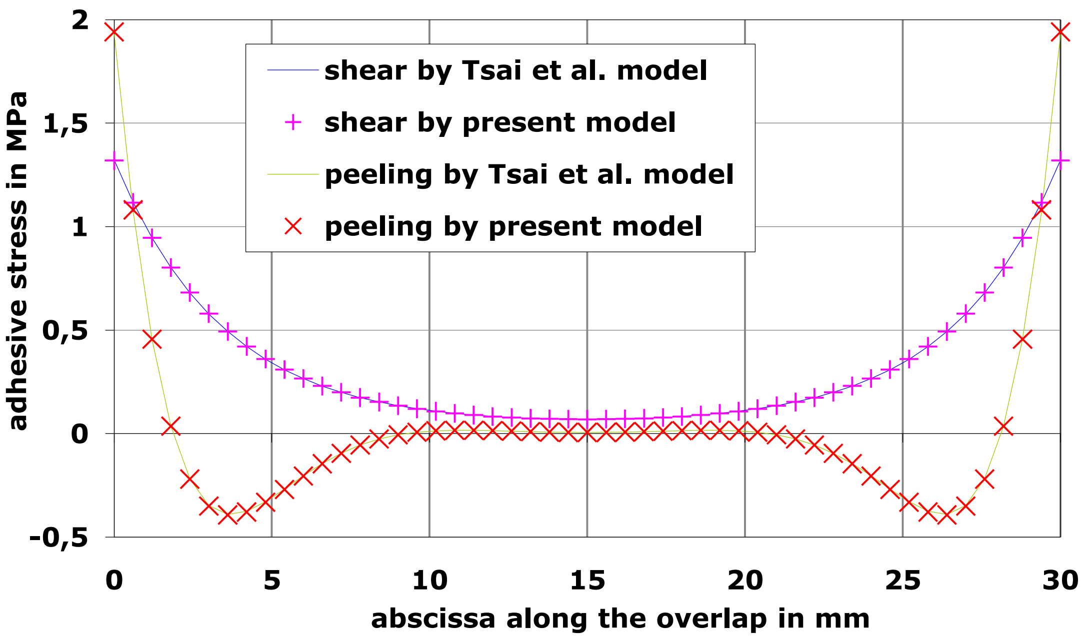
Validation

Against Available Literature [6]

✓ GOLAND & REISSNER [4] stress analysis improved by TSAI et al. [3]

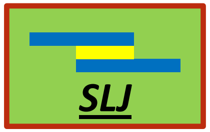
- linear elastic adhesive
- 1D-beam kinematics, simply supported, in-plane mechanically loaded

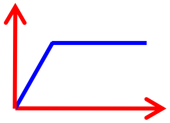




Relevance

Validation

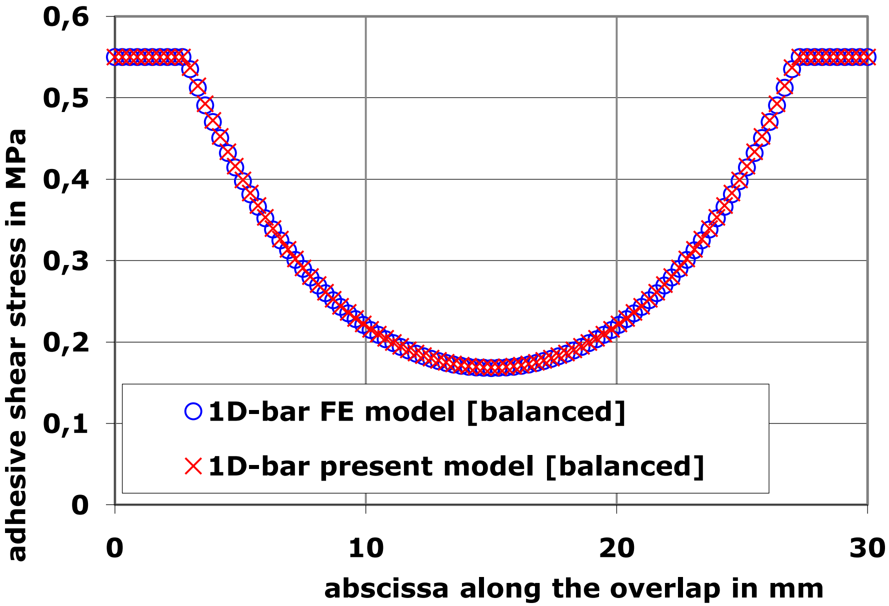


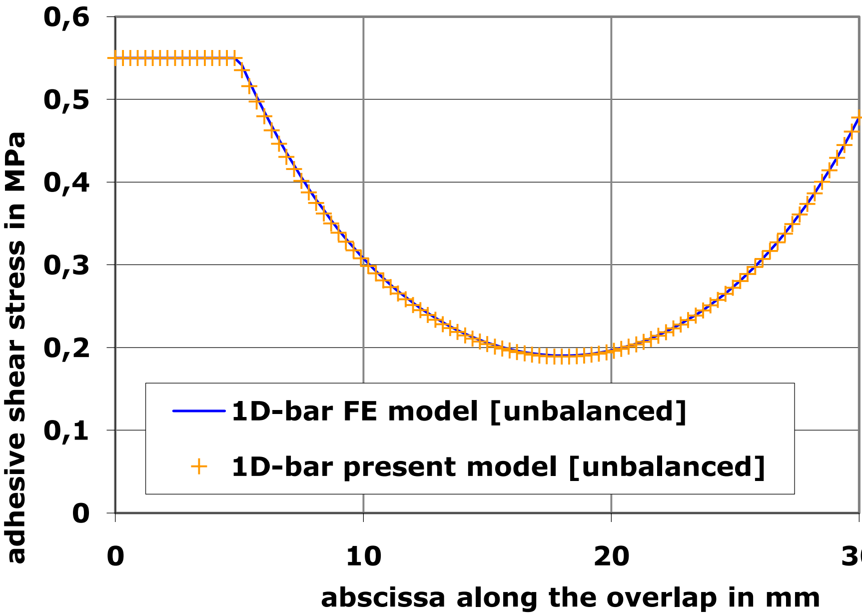


Against Degraded FE Model [6]

✓ Degraded FE model, composed by bars and springs

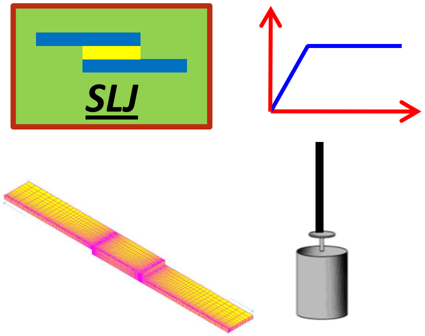
- elastic perfectly plastic adhesive, after maximal stress yield criterion
- 1D-bar kinematics, in-plane mechanically loaded





Relevance

Assessment

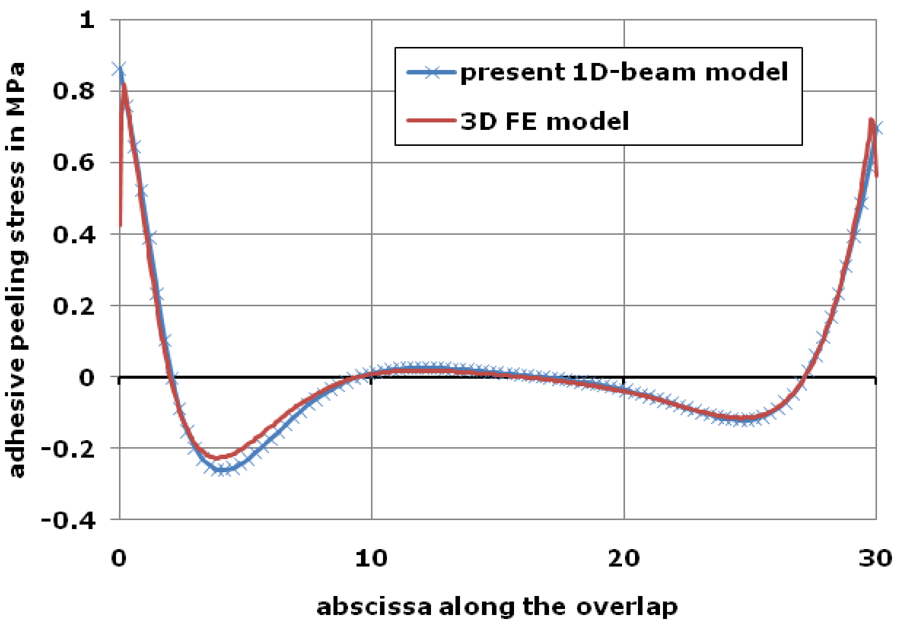


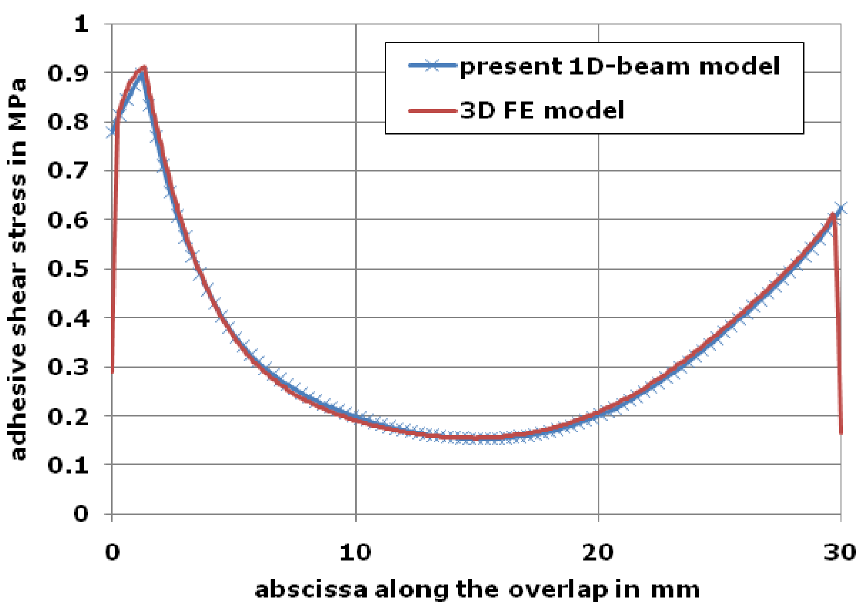
Against Refined FE Model [6,8]

✓ **Against refined 3D FE models**

- elastic perfectly plastic adhesive after Von Mises yield criterion
- 1D-beam kinematics, unbalanced, in-plane mechanically loaded

CPU TIME SAVINGS: 50 times faster than FE model





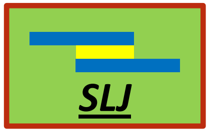
Relevance

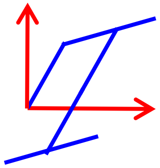
Demonstration

With SCILAB Code

✓ **Clamped single-lap bonded joint:**

- bilinear elasto-plastic
- kinematic, isotropic and mixed hardening
- mechanically loaded
- loading then unloading





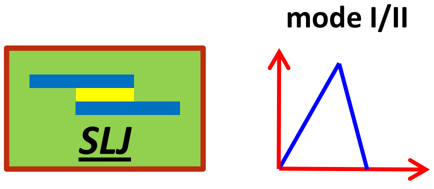
Relevance

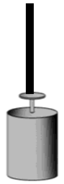
Demonstration

Early IHM

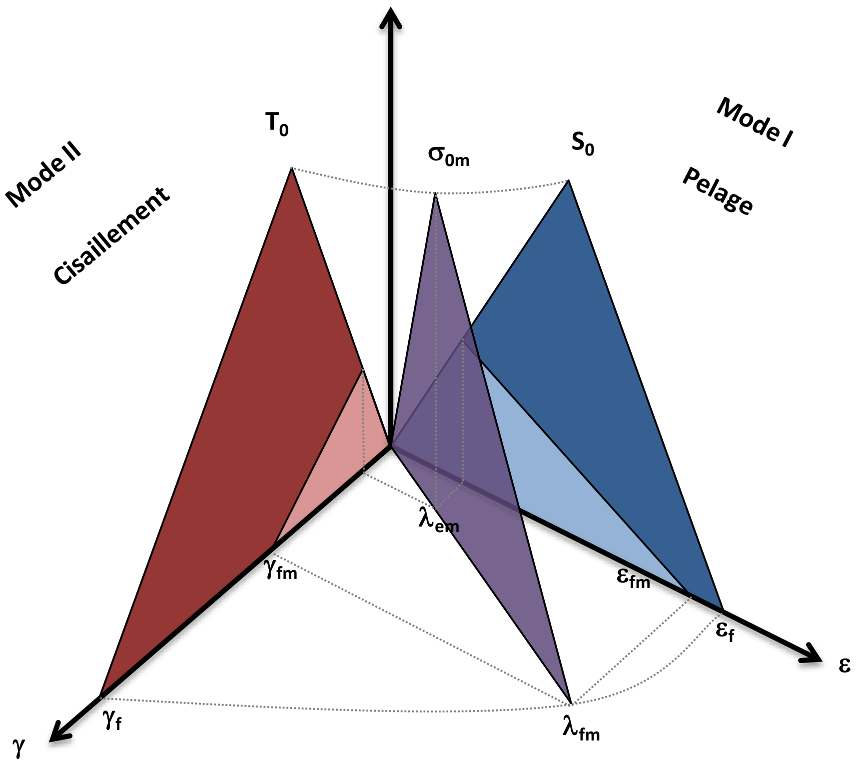
✓ **Clamped single-lap bonded joint in-plane loaded:**

- bilinear damage evolution
- mixed mode I/II
- loading then unloading





DEMO



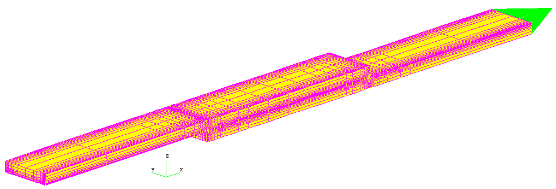
Relevance

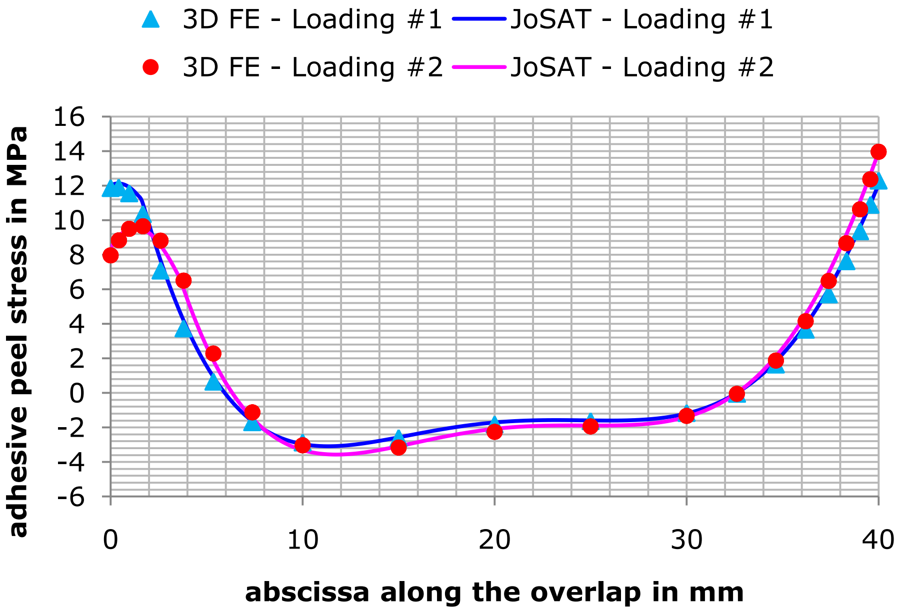
Demonstration

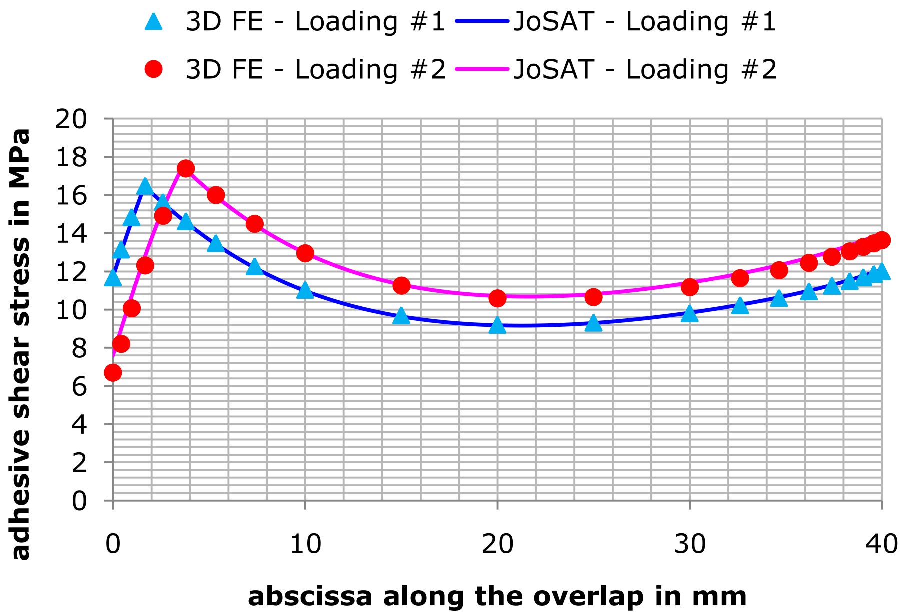
Against Refined FE models

✓ **Against refined 3D FE models**

- bilinear adhesive damaging evolution law
- 1D-beam kinematics, unbalanced, in-plane mechanically loaded







VERY GOOD AGREEMENT WITH 3D FE PREDICTIONS

Content

APPLICATION

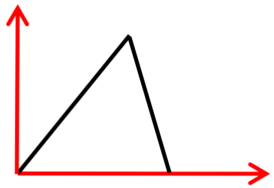
Application

Experimental Test

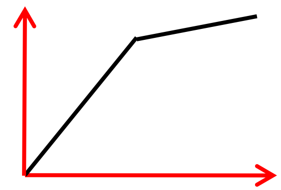
Hybrid (Bolted / Bonded) Joints

✓ **Identification of material parameters** **[IN PROGRESS]**

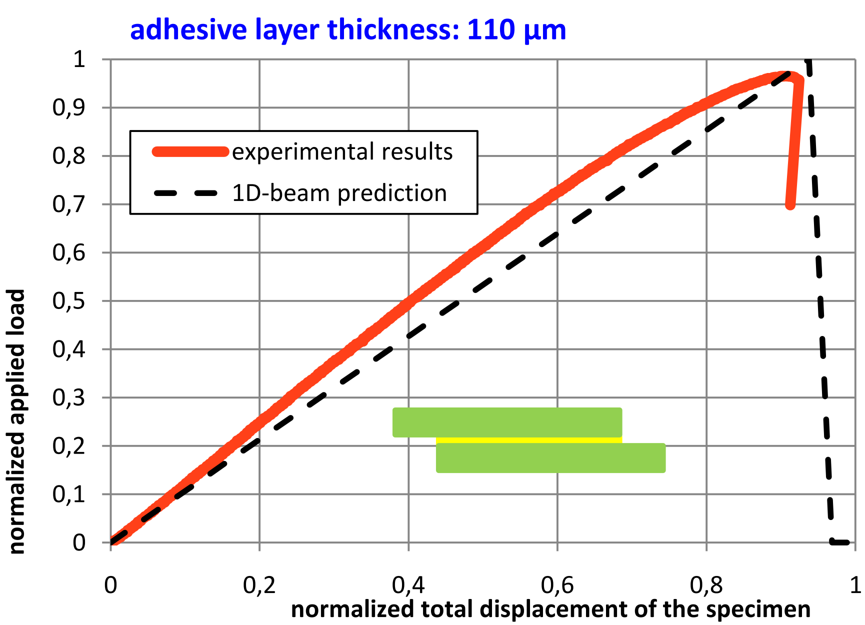
- through an optimization platform
- to analyze failure mechanisms

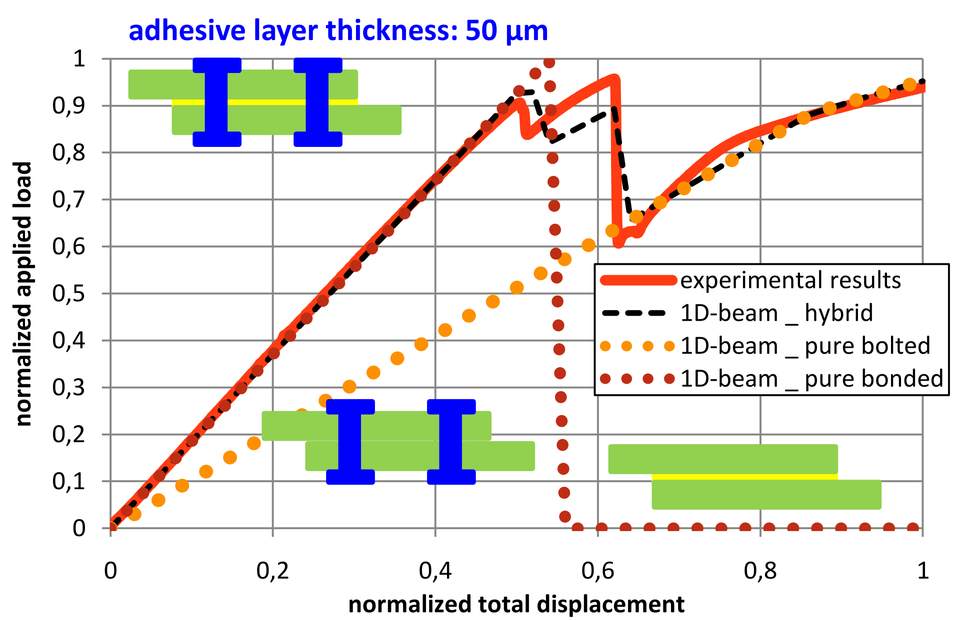


adhesive layer



fastener





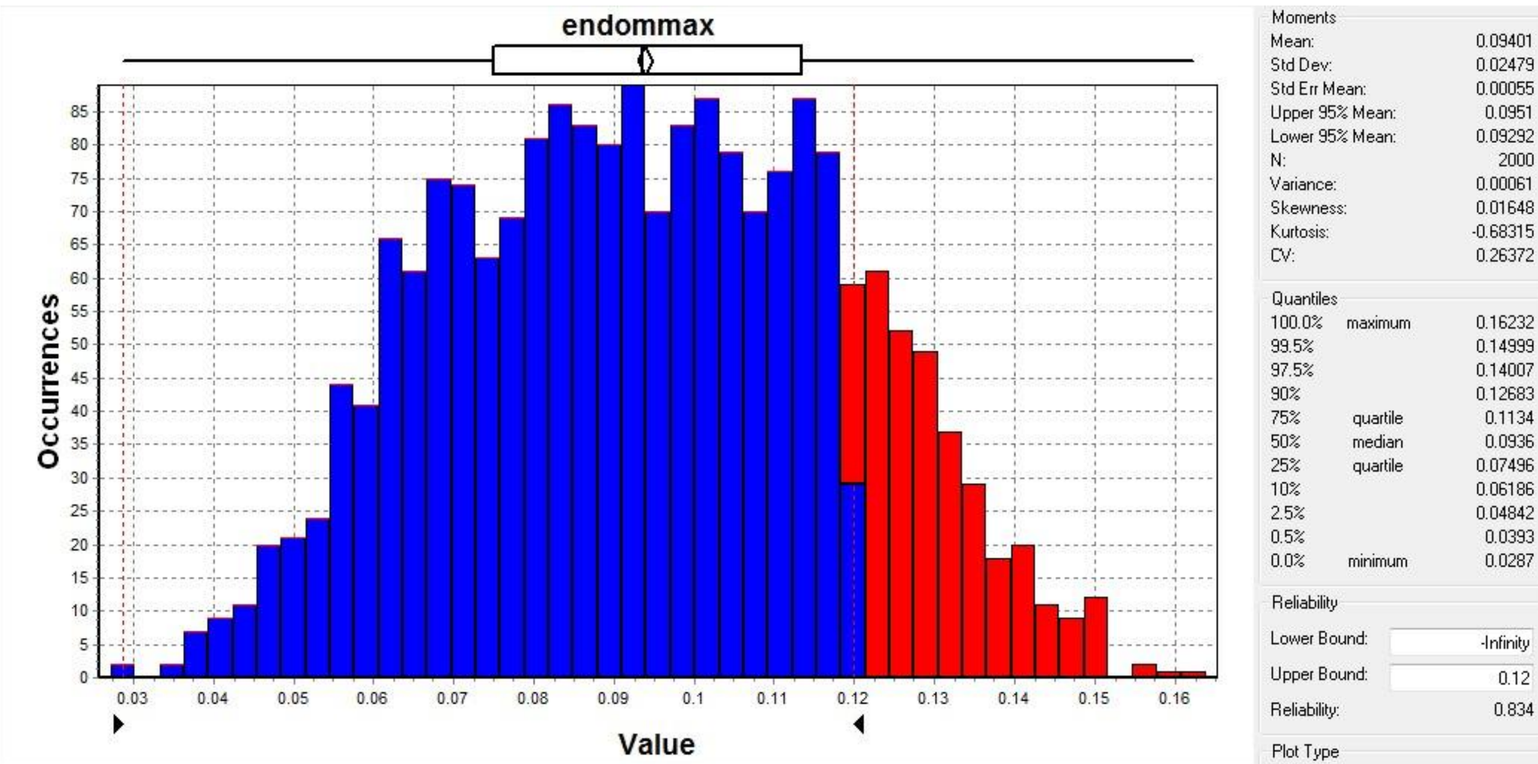
Application

Optimization

Process Reliability

✓**Simulation of the reliability of the manufacturing process**

- Considering manufacturing knowledge
- Simulation with Monte-Carlo analysis



List of References

[1] PAROISSIEN, E. *Contribution aux Assemblages Hybrides (Boulonnés/Collés). Application aux Jonctions Aéronautiques.* PhD Thesis, Paul Sabatier University (Toulouse 3), FR, (2006) . http://thesesups.ups-tlse.fr/3/1/Paroissien_Eric.pdf

[2] VOLKERSEN, O. *Die Nietkraftverteilung in Zugbeanspruchten Nietverbindungen mit konstanten* Laschenquerschnitten Luftfahrtforschung, Vol. 15, pp. 41-47 (1938)

[3] TSAI, M.Y., OPLINGER, D.W., MORTON, J. *Improved theoretical solutions for adhesive lap joints. International Journal of Solids and Structures,* Vol. 35, n°12, pp. 1163-1185 (1998)

[4] GOLAND, M., REISSNER, E. *The stresses in cemented joints*. Journal of Applied Mechanics, Vol. 11, pp. A17-27 (1944)

[5] HART-SMITH, LJ. *Adhesive-bonded single-lap joints*. NASA, Technical Report CR-112235 (1973)

[6] PAROISSIEN, E., GAUBERT, F., DA VEIGA, A., LACHAUD, F. *Elasto-Plastic Analysis of Bonded Joints with Macro-Elements*. Journal of Adhesion Science and Technology. Vol. 27, Issue 13, pp. 1464-1498 (July 2013)

[7] PAROISSIEN, E., DA VEIGA, A., LABORDE, A. *An 1D-Beam Approach for Both Stress Analysis and Fatigue Life Predictions of Bonded Joints*. Book of Proceedings of the 26th ICAF Symposium, Montréal (QC), 1-3 June 2011, DOI 10.1007/978-94-007-1664-3, pp. 359-374 (2011)

[8] PAROISSIEN, E., LACHAUD, F., JACOBS, T. *A Simplified Stress Analysis of Bonded Joints using Macro-Elements*. Chapter 4 of the book: Advances in Modeling and Design of Adhesively Bonded Systems, Editors K.L. MITTAL and S. KUMAR, Scrivener and Wiley Eds, pp. 93-147 (2013)

[9] LELIAS, G., PAROISSIEN E., LACHAUD, F., MORLIER, J., SCHWARTZ, S., GAVOILLE, C. *An extended semi-analytical formulation for fast and reliable stress analysis of adhesively bonded joints* . Accepted on the 29th December of 2014 for publication to International Journal of Solids and Structures.

[10] LACHAUD, F. *Contribution à l'analyse multi échelle du comportement mécanique non linéaire matériau des structures composites.* HDR ISAE, Université de Toulouse 3 (2011)

[11] KHORAMISHAD, H., CROCMOBE, A.D., KATNAM, K. B., ASHCROFT, I.A. *Fatigue damage modelling of adhesively bonded joints under variable amplitude loading using a cohesive zone model. Preprint Eng Fract Mech, Vol. 78, Issue 18, pp. 3212-3225 (2011)*