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

Presented by: E. PAROISSIEN, SOGETI HIGH TECH, Toulouse (FR)

Co-Authors:
A. DA VEIGA, SOGETI HIGH TECH, Toulouse (FR)
S. SCHWARTZ, SOGETI HIGH TECH, Toulouse (FR)
G. LELIAS, SOGETI HIGH TECH, Toulouse (FR)
F. LACHAUD, ISAE-SUPAERO, Toulouse (FR)
P-Y. MEYER, SOGETI HIGH TECH, Toulouse (FR)

Eric Paroissien, eric.paroissien@sogeti.com, +33(0)5.34.46.92.64
1. SOGETI HIGH TECH
2. FRAME
3. MECHANICAL ANALYSIS
4. MACRO-ELEMENT TECHNIQUE
5. CURRENT CAPABILITIES
6. RELEVANCE
7. APPLICATION
Capgemini, founded in 1967, is one of the world foremost providers of consulting, technology and outsourcing services.

**Revenue by industry**
- Financial services: 21.5%
- Manufacturing: 17.1%
- Customer products, retail, distribution & transportation: 14.1%
- Energy, utilities & chemicals: 11.8%
- Telecoms, Media & Entertainment: 8.4%
- Public sector: 22.1%
- Other: 5.0%

**Revenue by business**
- Technology services: 40.6%
- Outsourcing services: 40.1%
- Consulting services (Capgemini Consulting): 4.5%
- Local professional services (Sogeti): 14.8%
- Other: 5.0%
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
  o A 25-year long expertise in services for industrial companies
  o Seven main markets:
    ➢ Aeronautics
    ➢ Energy
    ➢ Life Sciences
    ➢ Railway
    ➢ Space
    ➢ Defense
    ➢ Telecoms & media

• Five business lines
  o Consulting
  o Systems Engineering
  o Physics Engineering
  o Software Engineering
  o 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
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
Partnerships

✓ ISAE (Institut Supérieur de l’Aéronautique et de l’Espace, Toulouse):
  ▪ signed in 2009
  ▪ prolonged in 2012 up to 2017

<table>
<thead>
<tr>
<th>THEMES</th>
<th>WHAT?</th>
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<tr>
<td>COMPOSITE MATERIALS</td>
<td>2 PhD Theses</td>
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<tr>
<td></td>
<td>1 MS Thesis</td>
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<tr>
<td>JOINING TECHNOLOGIES</td>
<td>1 PhD Thesis</td>
</tr>
<tr>
<td></td>
<td>6 MS Theses</td>
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</table>

✓ 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
Stress can support M&P, Manufacturing and Operations

M&P
chemical formulation
material lab testing

OPERATIONS
Repairs
SHM

MANUFACTURING
process reliability
(simulation, monitoring)

MECHANICAL ANALYSIS
experimental characterization
modeling, simulation, optimization

1 PhD Thesis in progress
in building
« SWB » project

Presentation on the 3rd July 2015 at Adhesive Bonding Conference in Porto
Content

MECHANICAL ANALYSIS
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 conduct 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
MACRO-ELEMENT TECHNIQUE
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

From 2004 up to now

MACRO-ELEMENT
new macro-elements
systematization

ANALYSIS
vibration fatigue
non linear 2
non linear 1
thermal
1D-beam unbalanced
1D-beam balanced
1D-bar

ANALYSIS

MATERIAL LAW
visco-plastic hyper-elastic
visco-elastic damage 2
damage 1
bilinear
elastic perfectly plastic
visco-plastic

GEOMETRY

coupled crit. vs CZM
DCB...
stepped, scarfed DLJ
MLR

STRENGTH
coupled crit. damage mech

JoSAT is launched

5 years
2004
2008
04/2008
05/2005
08/2004
1D-bar
1D-bar mechanical
1D-beam balanced
1D-beam unbalanced
thermal
non linear 1
non linear 2
vibration fatigue
07/2009
08/2010
07/2010
08/2011
09/2011
08/2012
09/2012
09/2013
08/2014
09/2014

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.
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
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)

\[
\begin{align*}
\frac{dN_j}{dx} &= (-1)^j T \\
\frac{dV_j}{dx} &= (-1)^{j-1} S \\
\frac{dM_j}{dx} + V_j + \frac{1}{2}(e_j + e_b)T &= 0
\end{align*}
\]

Constitutive equations
Shear springs, peel springs

\[
\begin{align*}
T &= \frac{G}{e} \left( u_2 - u_1 - \frac{1}{2} e_1 \theta_1 - \frac{1}{2} e_2 \theta_2 \right) \\
S &= \frac{E}{e} \left( w_1 - w_2 \right)
\end{align*}
\]

Constitutive equations
Euler-Bernoulli laminated beam

\[
\begin{align*}
N_j &= A_j \frac{du_j}{dx} - B_j \frac{d^2w_j}{dx^2} \\
M_j &= -B_j \frac{du_j}{dx} + D_j \frac{d^2w_j}{dx^2}, \quad j = 1, 2 \\
\theta_j &= \frac{dw_j}{dx}
\end{align*}
\]

System of coupled differential equations

Resolution

Expression for displacements then for internal forces
**Macro-Element Technique**

**1D-Beam Stiffness Matrix (Bonding)**

**Equations (2)**

Computation of nodal forces and nodal displacements

\[
U = \begin{pmatrix}
    u_i \\
    u_j \\
    u_k \\
    u_l \\
    w_i \\
    w_j \\
    w_k \\
    w_l \\
    \theta_i \\
    \theta_j \\
    \theta_k \\
    \theta_l
\end{pmatrix} = MC \quad \text{and} \quad F = \begin{pmatrix}
    Q_i \\
    Q_j \\
    Q_k \\
    Q_l \\
    R_i \\
    R_j \\
    R_k \\
    R_l \\
    S_i \\
    S_j \\
    S_k \\
    S_l
\end{pmatrix} = NC
\]

Stiffness Matrix

\[
K = NM^{-1}
\]
CURRENT CAPABILITIES
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 stiffened configuration **[POSSIBLE]**
- etc.... + including fasteners
Current Capabilities

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

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
Results Directly Available

✓ DISTRIBUTION AT ANY POINTS:

- displacements in the adherends \((u, v, \theta)\)
- 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
Relevance

Against Available Literature [6]

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

![Graph showing shear and peeling stress analysis](image-url)

- shear by Tsai et al. model
- shear by present model
- peeling by Tsai et al. model
- peeling by present model
Relevance

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

![Graphs showing comparison between model predictions and experimental results.](image-url)
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

With SCILAB Code

✓ Clamped single-lap bonded joint:
  - bilinear elasto-plastic
  - kinematic, isotropic and mixed hardening
  - mechanically loaded
  - loading then unloading
Relevance

Early IHM

- Clamped single-lap bonded joint in-plane loaded:
  - bilinear damage evolution
  - mixed mode I/II
  - loading then unloading

DEMO
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
Application

Hybrid (Bolted / Bonded) Joints

- Identification of material parameters [IN PROGRESS]
  - through an optimization platform
  - to analyze failure mechanisms

![Graphs showing experimental results and 1D-beam predictions for adhesive layer thicknesses of 110 µm and 50 µm.](image)
Application

Process Reliability

- Simulation of the reliability of the manufacturing process
  - Considering manufacturing knowledge
  - Simulation with Monte-Carlo analysis

![Histogram of endommax occurrences](chart.png)

<table>
<thead>
<tr>
<th>Moments</th>
<th>Values</th>
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<tbody>
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<td>Mean</td>
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<tr>
<td>St. Dev.</td>
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<td>St. Err. Mean</td>
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<td>Upper 95% Mean</td>
<td>0.0951</td>
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<td>Lower 95% Mean</td>
<td>0.09282</td>
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<tr>
<td>N</td>
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<table>
<thead>
<tr>
<th>Quantiles</th>
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<td>0.16232</td>
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<td>97.5%</td>
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<tr>
<td>75% quantile</td>
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<tr>
<td>50% median</td>
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<table>
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List of References


