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Damage analysis of composite structures: simulation supported by testing

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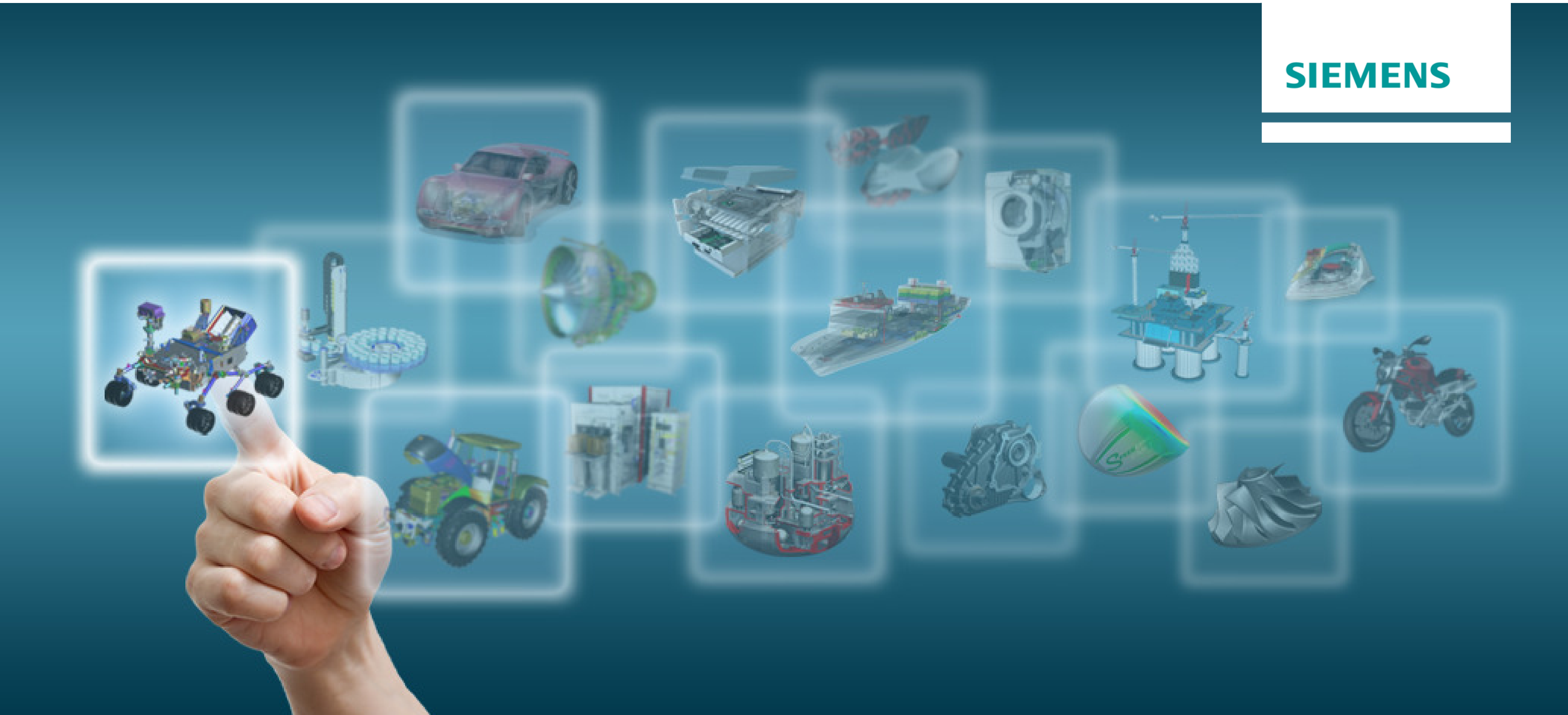
Outline

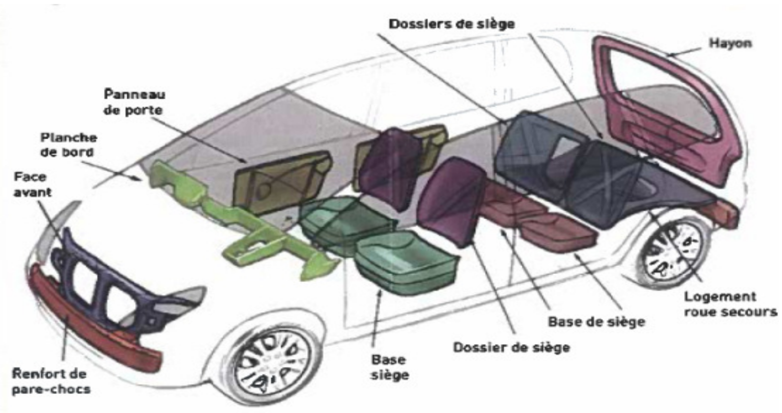
- Which composites are considered in this presentation and why
- The composite structures sizing process
- Challenges for simulation
- Why is it essential to take non linearities (incl. damage) into account?
- SAMCEF capabilities for damage analysis
- Parameter identification process: link between simulation and testing
- Illustrations
- Extensions of the work
- Conclusions

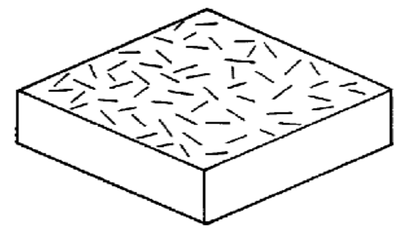


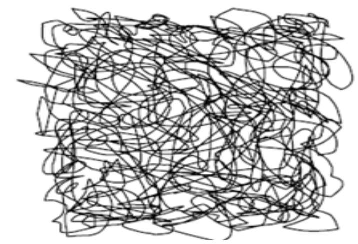
Which composites are considered and why

Which composite materials and why?

- Fibers arrangement and function in the structure
  - Non load carrying structural parts

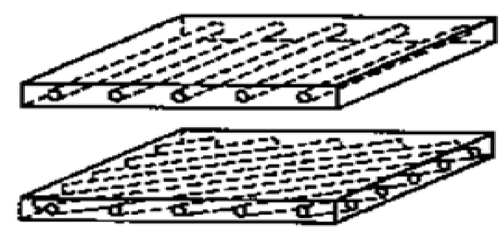






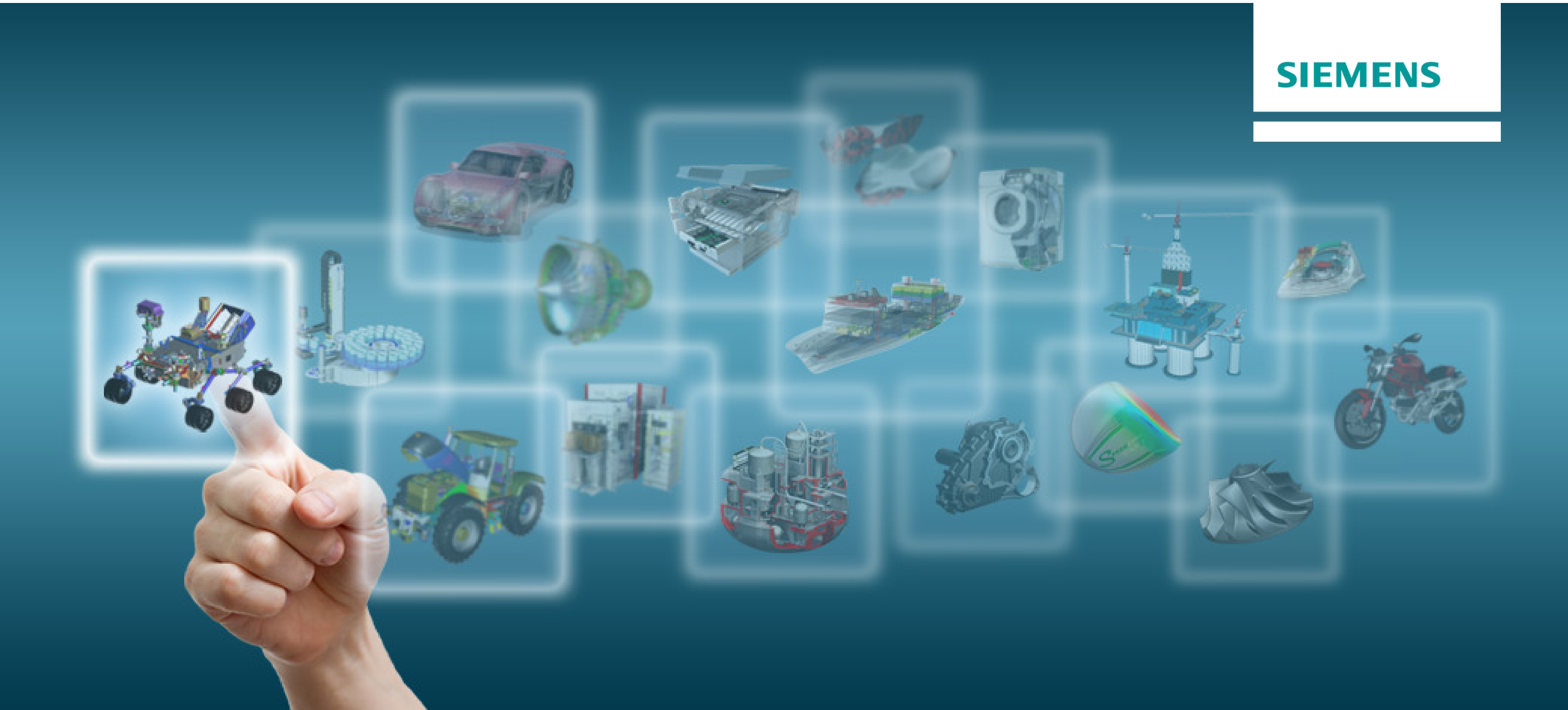
Random short or long fibers composites

  - Load carrying structural parts



Continuous fibers, structured laminated composite

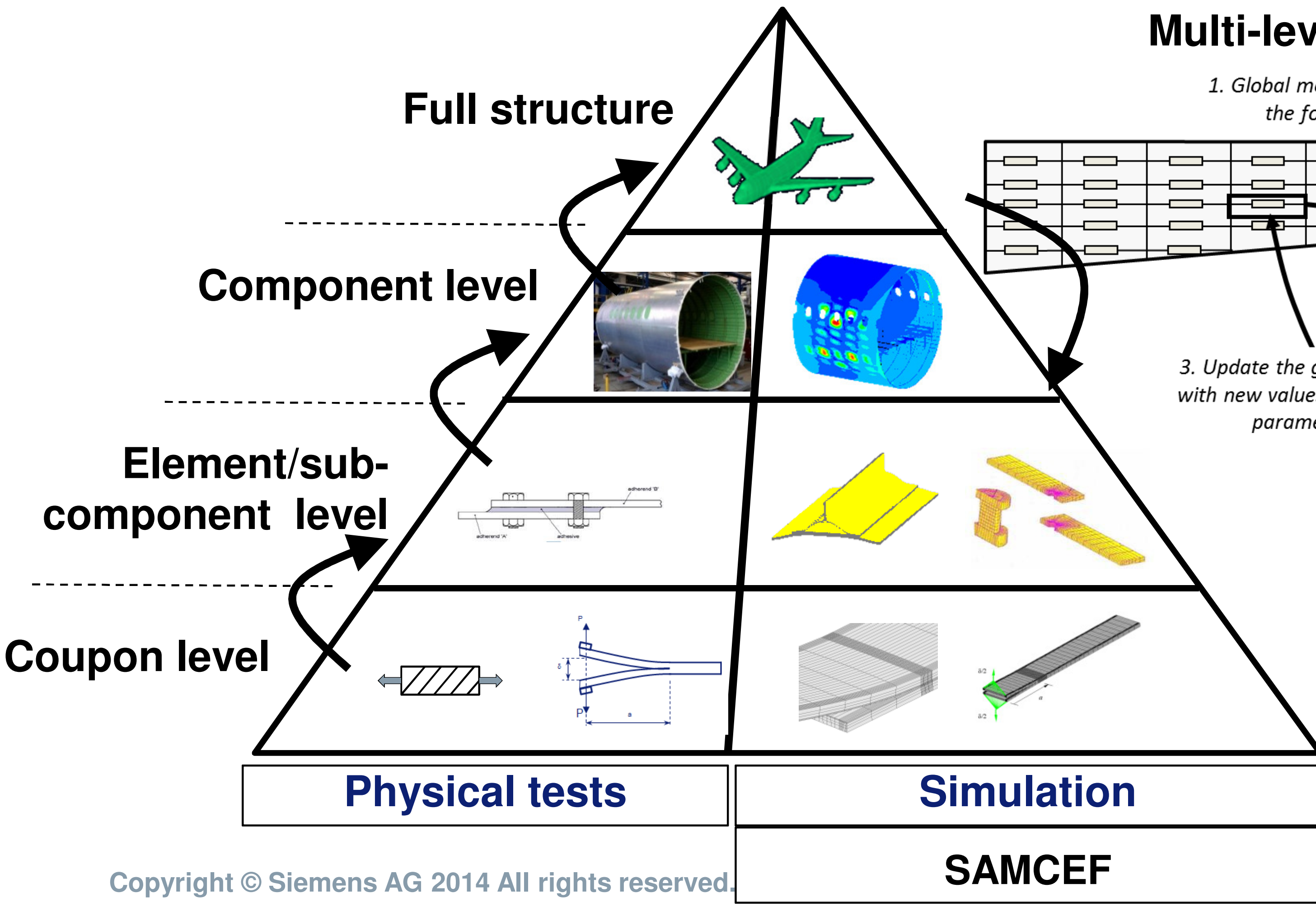
Today's topic: high performance laminated composites



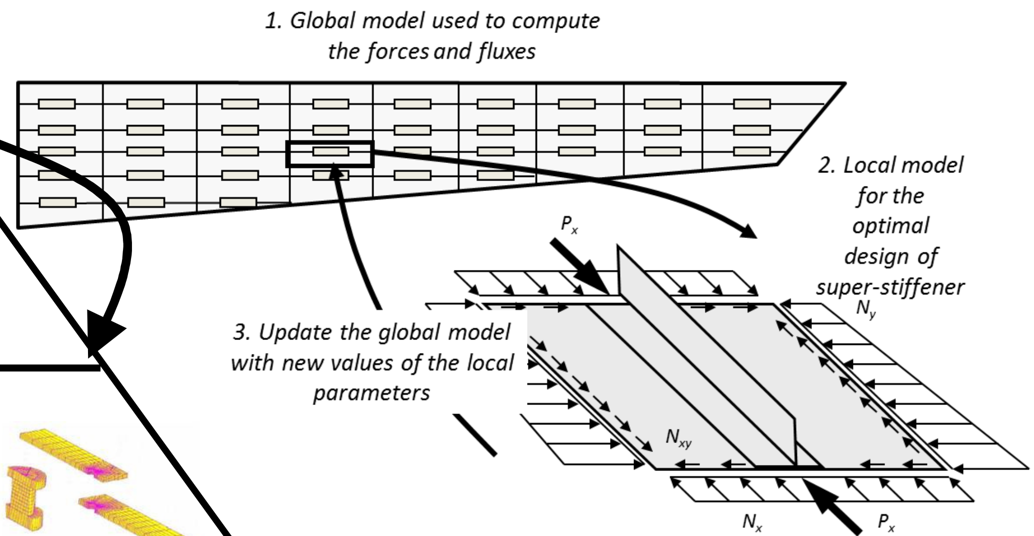
The composite structures sizing process

The composite structures sizing process

- The building block approach
- The pyramid of tests: **real and virtual testing ("virtual twin")**

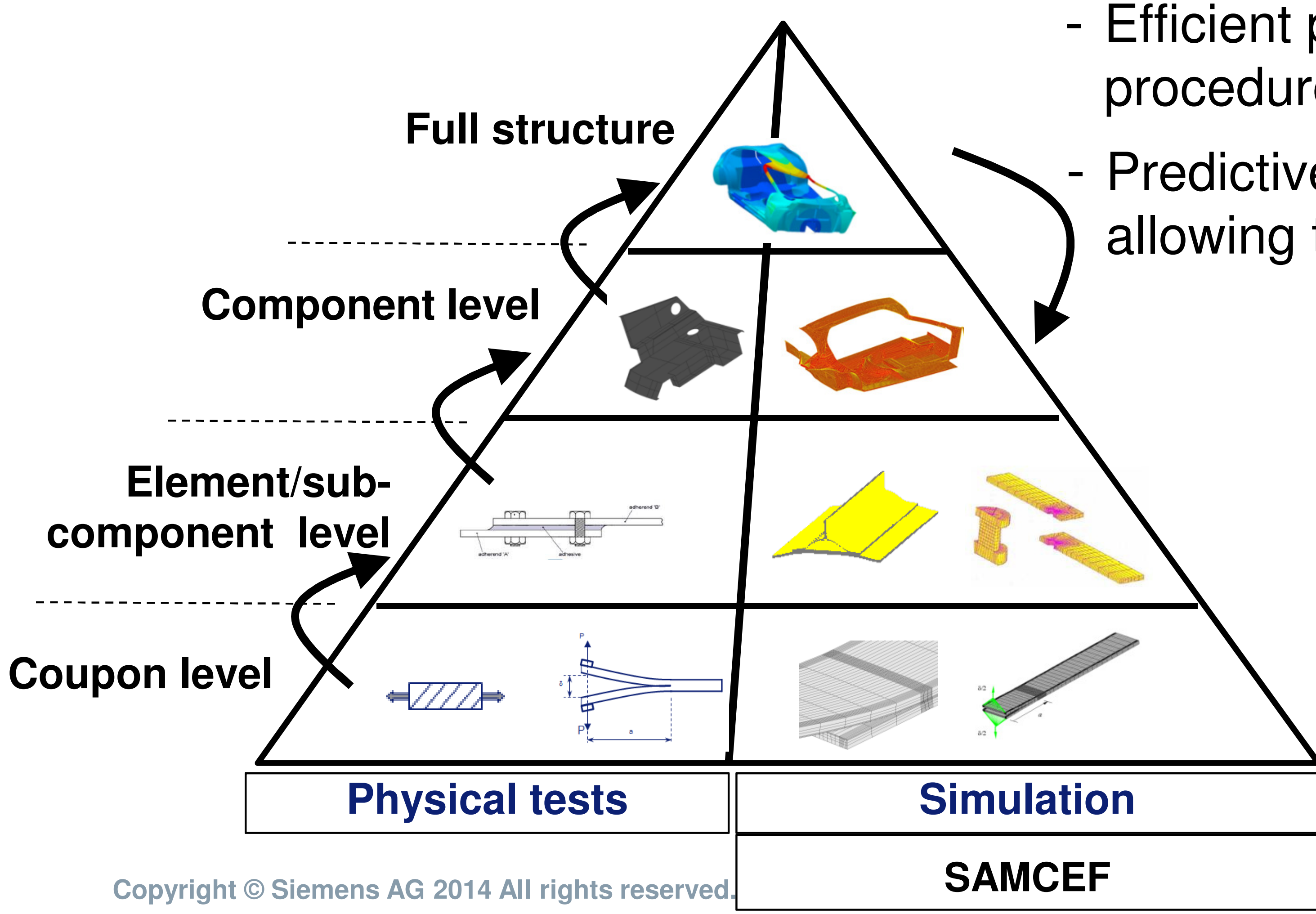


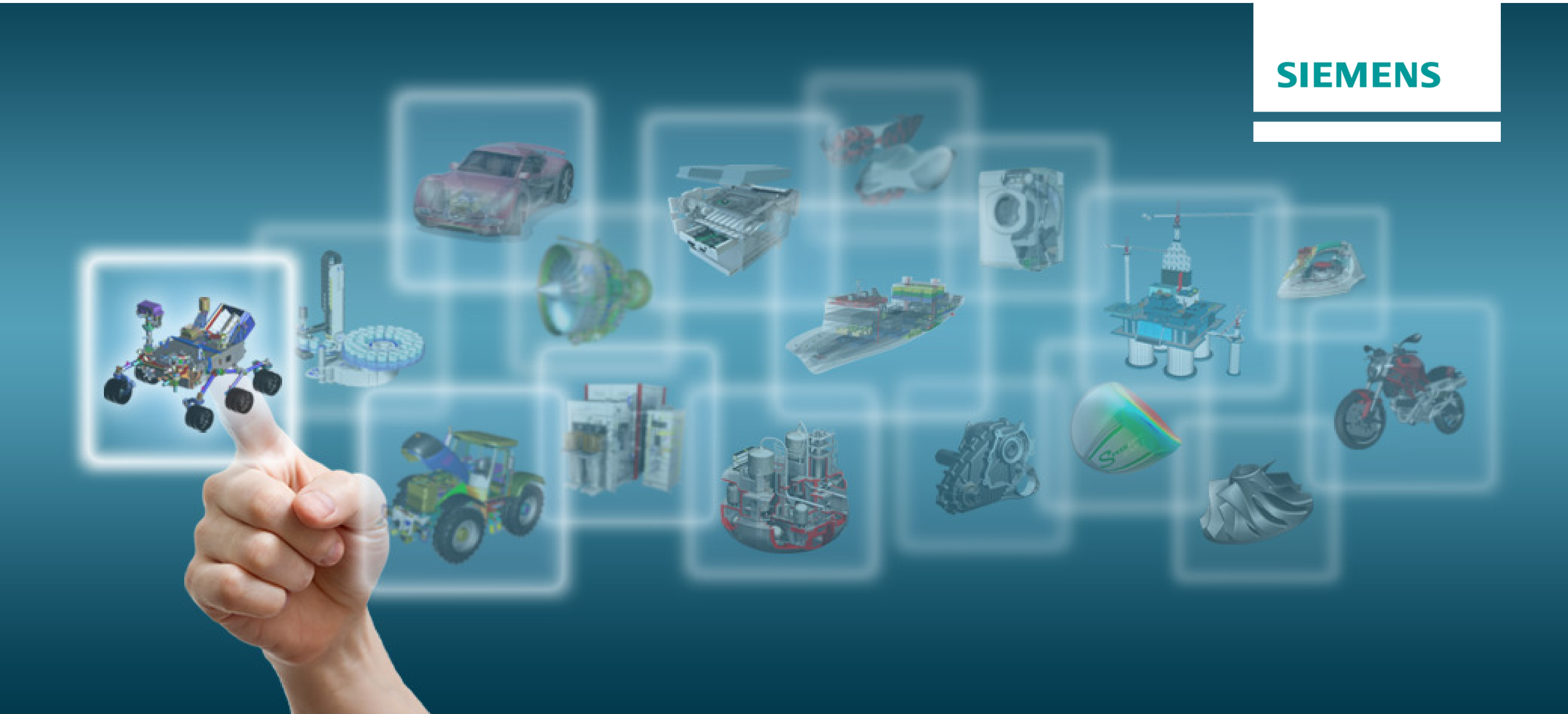
Multi-level (global/local) approach



The composite structures sizing process

- The building block approach
- Replace some tests by simulation…OK if:
  - Accurate material models
  - Efficient parameter identification procedure (at coupon level)
  - Predictive simulation tool, allowing to go up in the pyramid

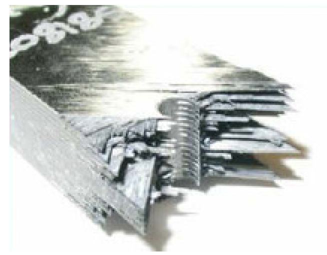


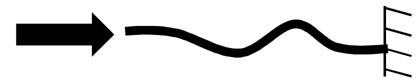


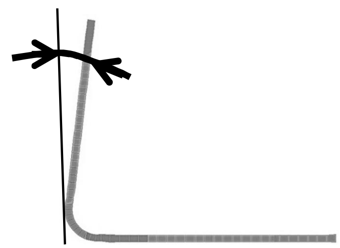
Challenges in the analysis of composites

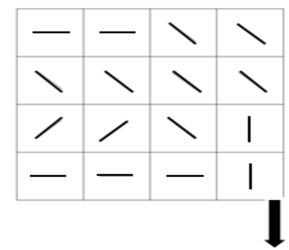
Challenges for analysis of composites

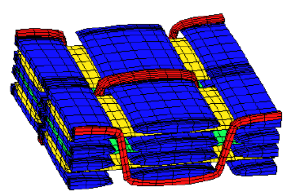
- Predictive simulations, becoming companions of the physical tests
- Some big challenges:
  - Damage analysis
  - Geometric non linearities
  - Manufacturing process simulation
  - Optimization
  - Material modeling
  - Design and link to analysis

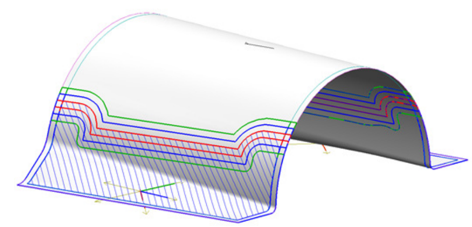












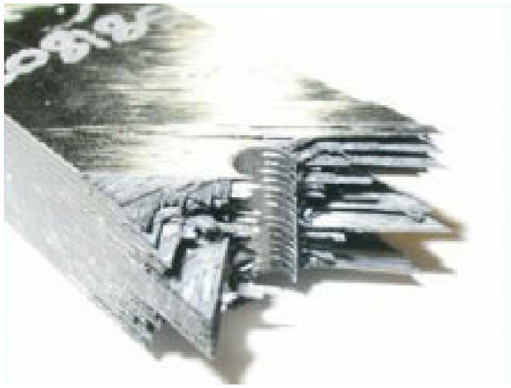
- Attributes for damage:
  - Static, fatigue, crash

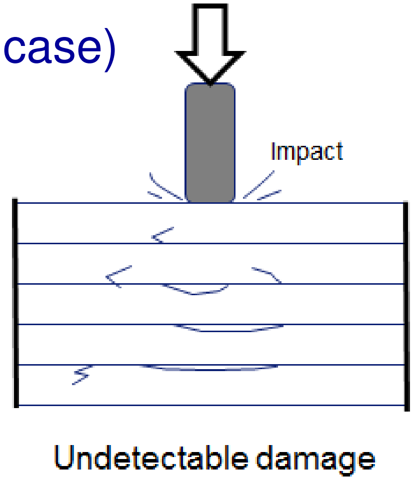
- Requirement for material models: accurate, simple to use, parameter identification available

Challenges in the analysis of composites: damage

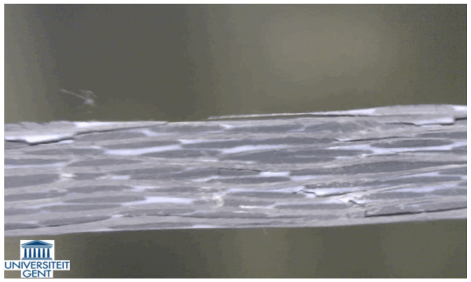
- **Damage** appears in composites, even when unexpected
- Damage may appear for quasi-**static case** (or slow dynamic case)
  - Quasi-static loading
  - Impact (low velocity/low energy)
  - Solutions exist today,

  but still improvements needed

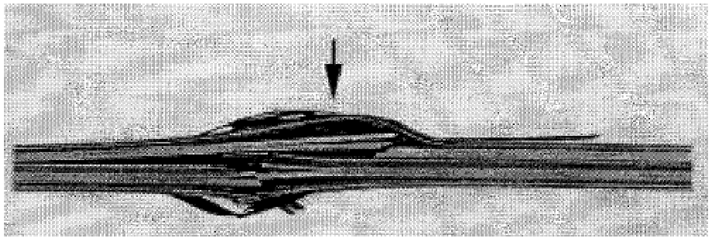


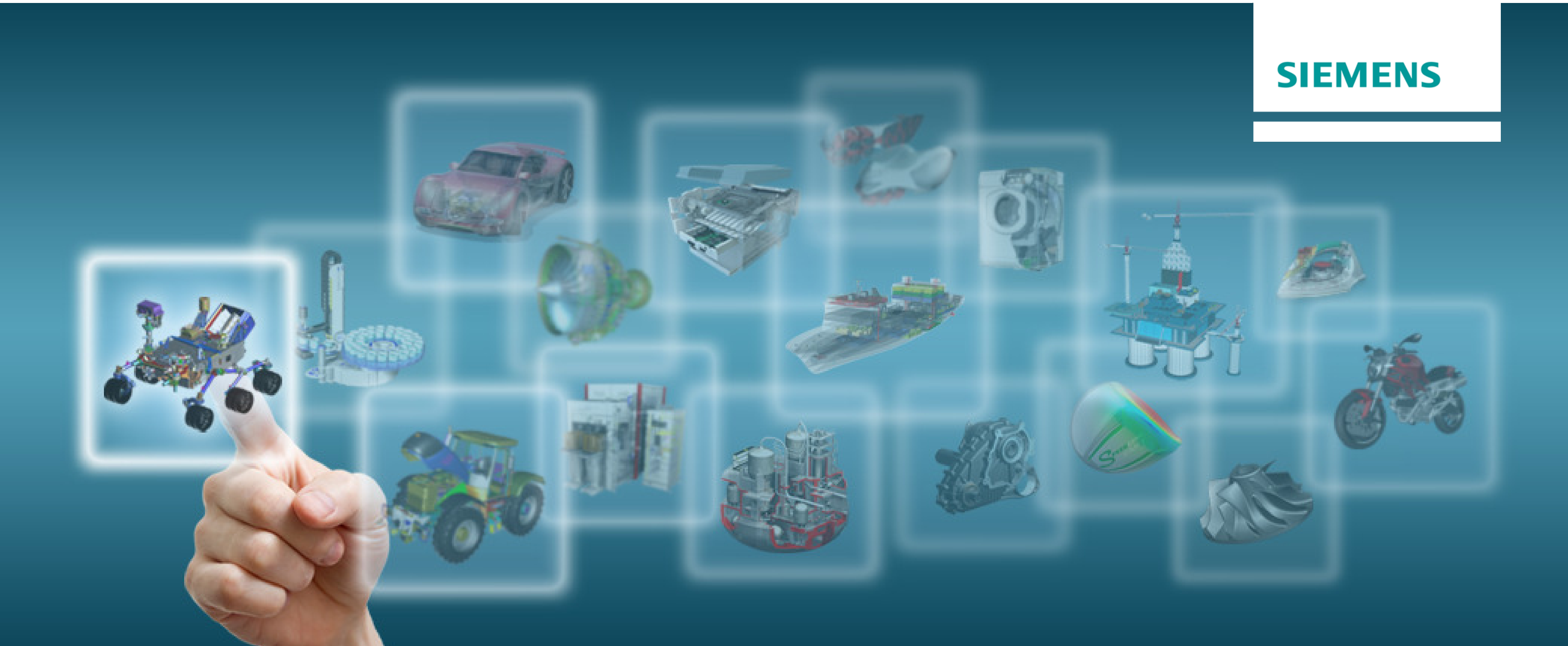


- Damage may appear for **fatigue case**
  - Still lot of things to do…



- Damage in **crash case** (high energy impact/fast dynamics)
  - Still lot of things to do…



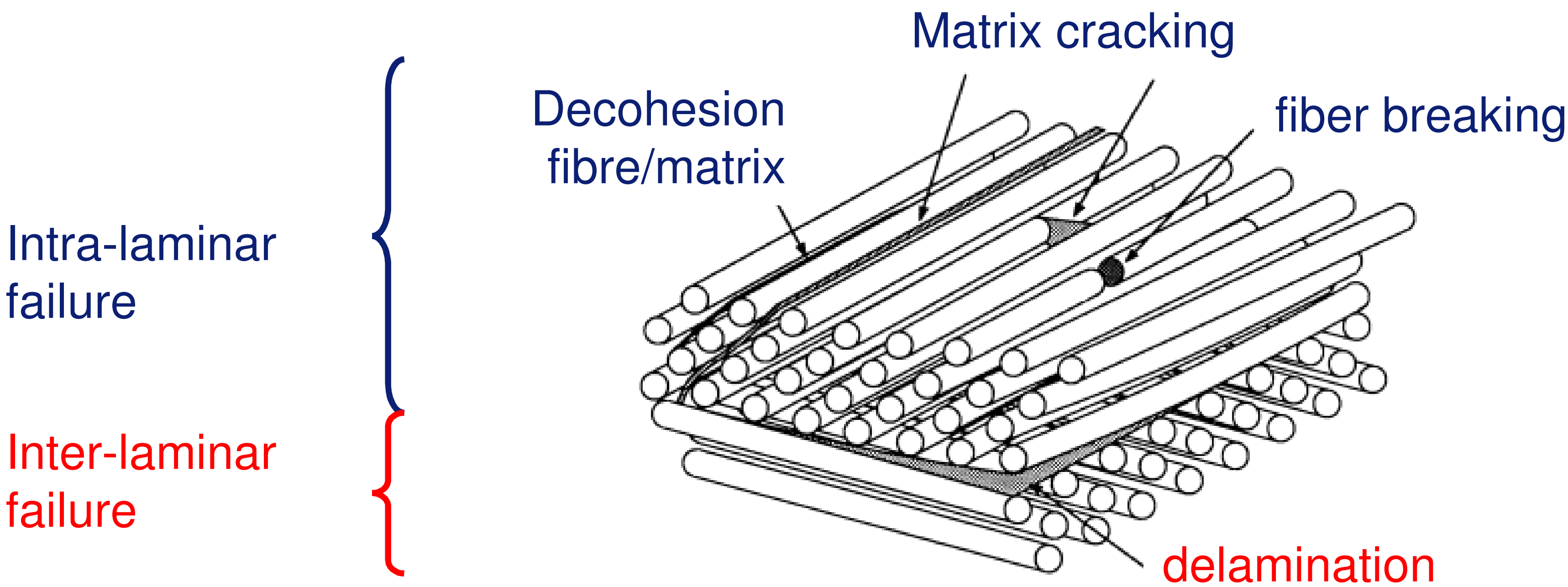


Advanced composites analysis

Why is it essential to take non linearities into account

Why considering damage?

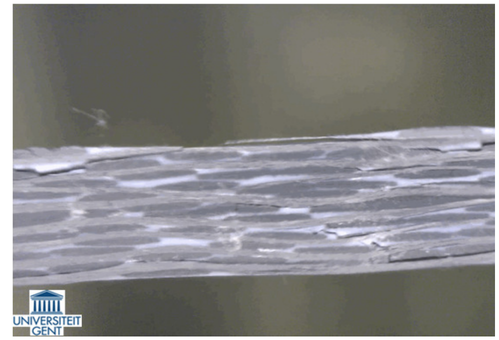
- Failure modes in a laminated composite structure

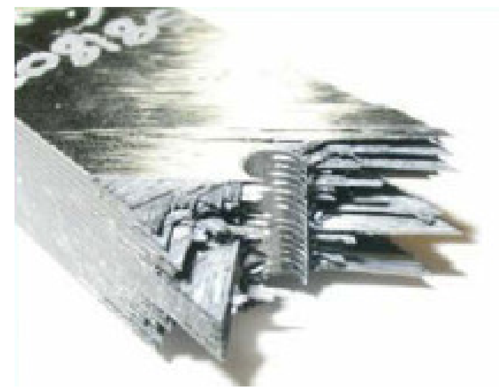


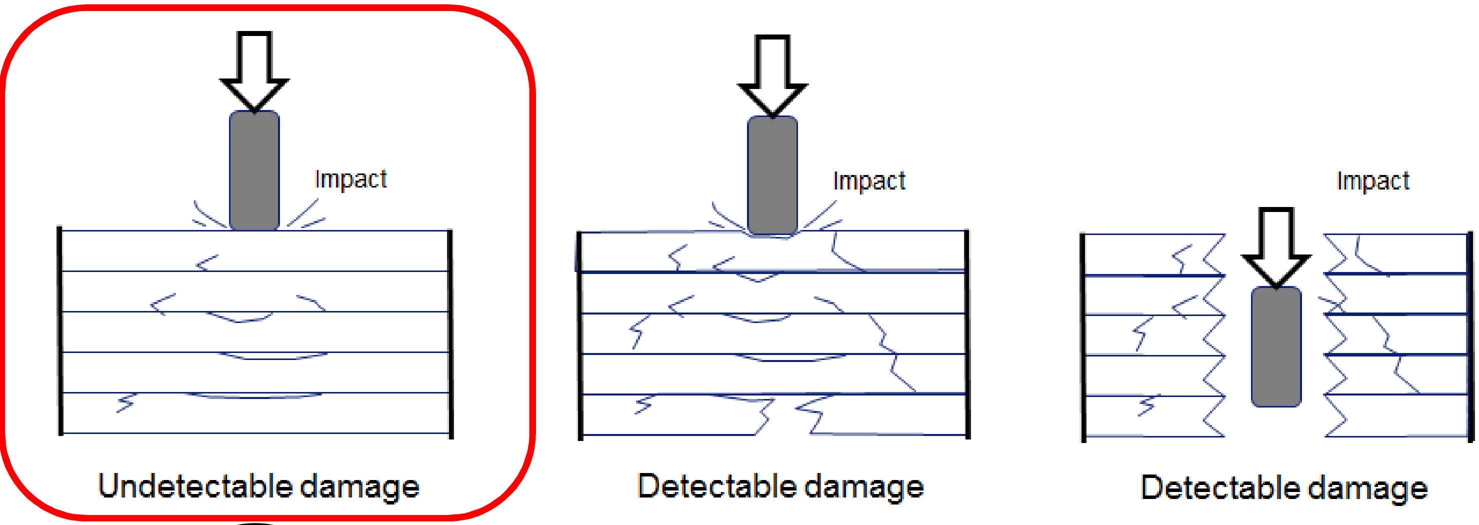
- Both failure modes families must be taken into account in the analysis

Why considering damage?

- **Damage** appears in composites, even when unexpected
- **Damage** may appear for <u>**static cases**</u>, not only for fatigue
- Damage is sometimes invisible, e.g. Barely Visible Impact Damage (**BVID**), so this may be very dangerous if ignored







?

Damage analyses must be conducted (quasi-static cases)
- Even if we don't want to have damage in the final design
- Because damage will anyway certainly appear…

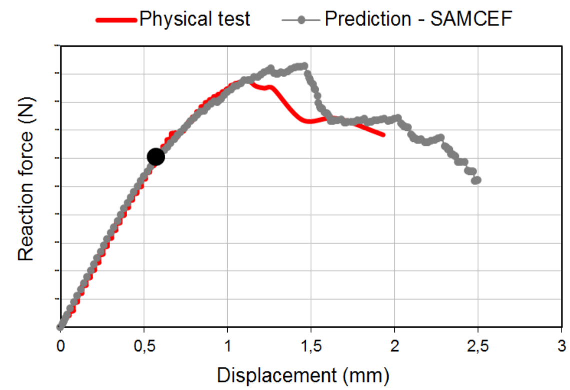
⇒ There is a need for a **damage tolerant approach**

Why considering non linearities?

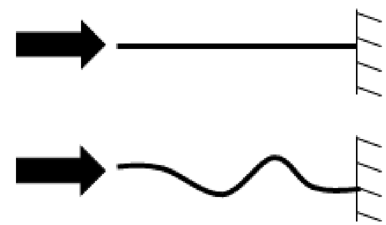
- Weight saving…

  ⇒ Use the full capacity of the material

  ⇒ Clever use of composites



  ⇒ Minimum weight ⇒ Thin structures sensitive to geometric instabilities

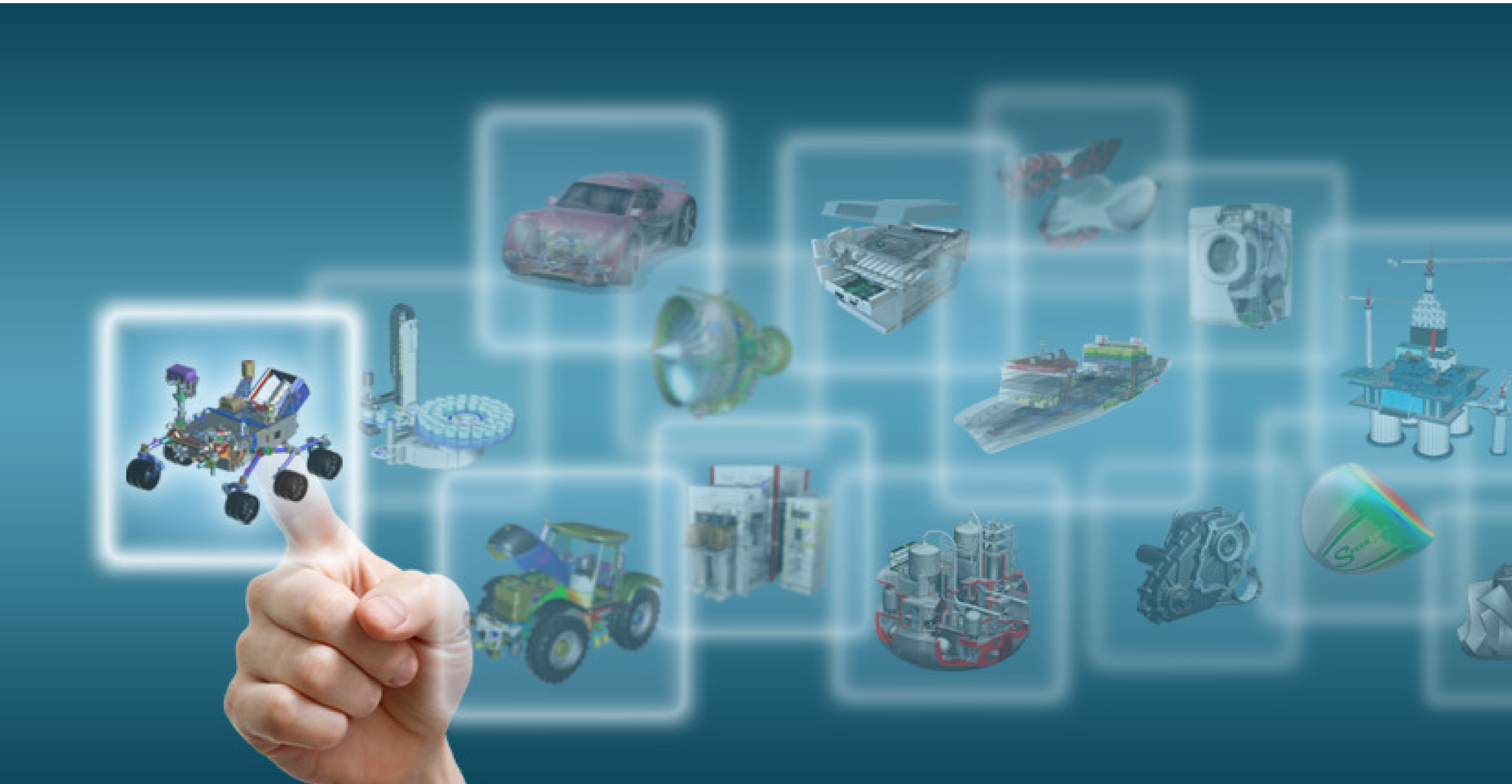


  ⇒ We can live with damage in composites

  ⇒ Size in order to limit the probability of its occurence

  ⇒ Size in order to avoid its propagation

  ⇒ There is a need for sizing composites, having these points in mind, and simulation can help

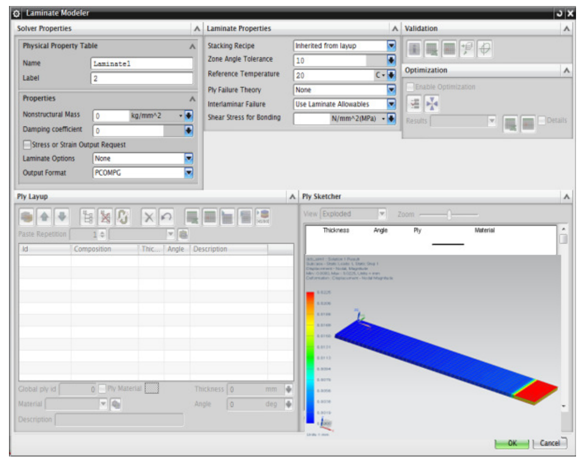


Advanced composites analysis

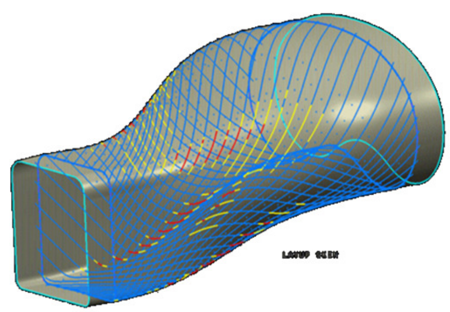
SAMCEF capabilities for damage analysis

Siemens ecosystem for composites analysis

- Today’s topic: SAMTECH solutions for composites analysis
  - ⇒ **LMS Samtech Samcef**: general non linear finite element solution (static, dynamic, damage, buckling, post-buckling, curing simuation, …)
  - ⇒ Specific algorithms for structural optimization of composites



- Other elements of the SIEMENS ecosystem for composite simulation
  - ⇒ **NX CAE**:
    - pre-post environment (define the problem, launch the analysis, results);
    - **NXLC** laminate modeler
    - **NX NASTRAN, SAMCEF**
  - ⇒ **Fibersim**:
    - advanced draping simulation
    - link to manufacturing
  - ⇒ **LMS Virtual Lab** suite
    - Reference solution for NVH, acoustics, durability



All the ingredients of a global and reliable solution for composite simulation

LMS Samtech Samcef =

- A general (non linear) finite element code (implicit => static and dynamic cases)
- More than 35 years of experience in modeling composites
- Lots of industrial references (here are some of them for the aero sector)

Capabilities for composite analysis

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- A general (non linear) finite element code (implicit => static and dynamic cases)
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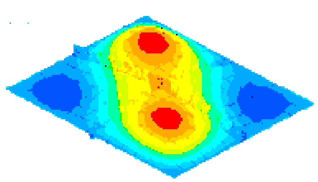
- A comprehensive library of finite elements for multi-layer composites

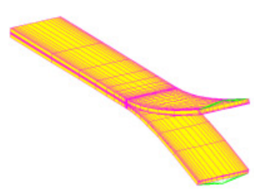
Capabilities for composite analysis

LMS Samtech Samcef =

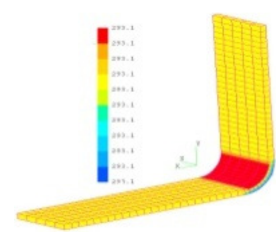
- A general (non linear) finite element code (implicit => static and dynamic cases)
- More than 35 years of experience in modeling composites
- Lots of industrial references (here are some of them for the aero sector)
- A comprehensive library of finite elements for multi-layer composites
- A large range of structural analysis methods for composite structures
- Advanced models for progressive damage in composites
- Specific tools for composite structures optimization



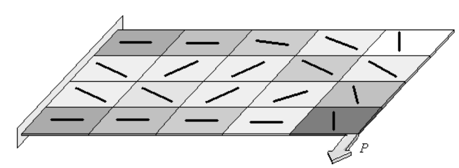
Linear analysis (static, modal, buckling, Harmonic/time response)



Non linear analysis (static, dynamic, rotor dynamic)



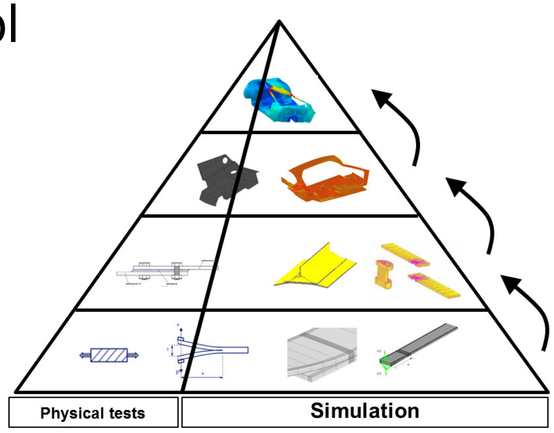
Thermo-mechanical analysis



Structural optimization

Damage analysis of composites

- Capabilities of the LMS Samtech Samcef damage models
  - Sophisticated material models for:
    - **Ply progressive damage** (strengths, non linearities, plasticity, coupling effects in the matrix): continuum damage mechanics.
    - **Delamination** (possibly coupled to damage in surrounding plies): cohesive elements
  - Comprehensively implemented in LMS Samtech Samcef
    - No need for sef-programming (difficult, prone to errors; little support)
    - No need for additional plug-in/add-on (not free!)
  - Validated on lots of industrial use cases (as illustrated in the following)
  - The parameter identification procedure for these damage models exists:
    - We can provide the test protocol
    - Few physical tests needed
  - Predictive models



Overview of the SAMCEF capabilities for damage

- Damage models available in SAMCEF

Native in SAMCEF

- **No need for additional plug-ins/add-on**
- **No need for self-programming**

Intra-laminar failure

- Progressive failure of general orthotropic ply
- Damage model for the **UD** ply – Cachan (Ladevèze)
- Damage model for **woven fabrics** – Marseille (Hochard)
- User material

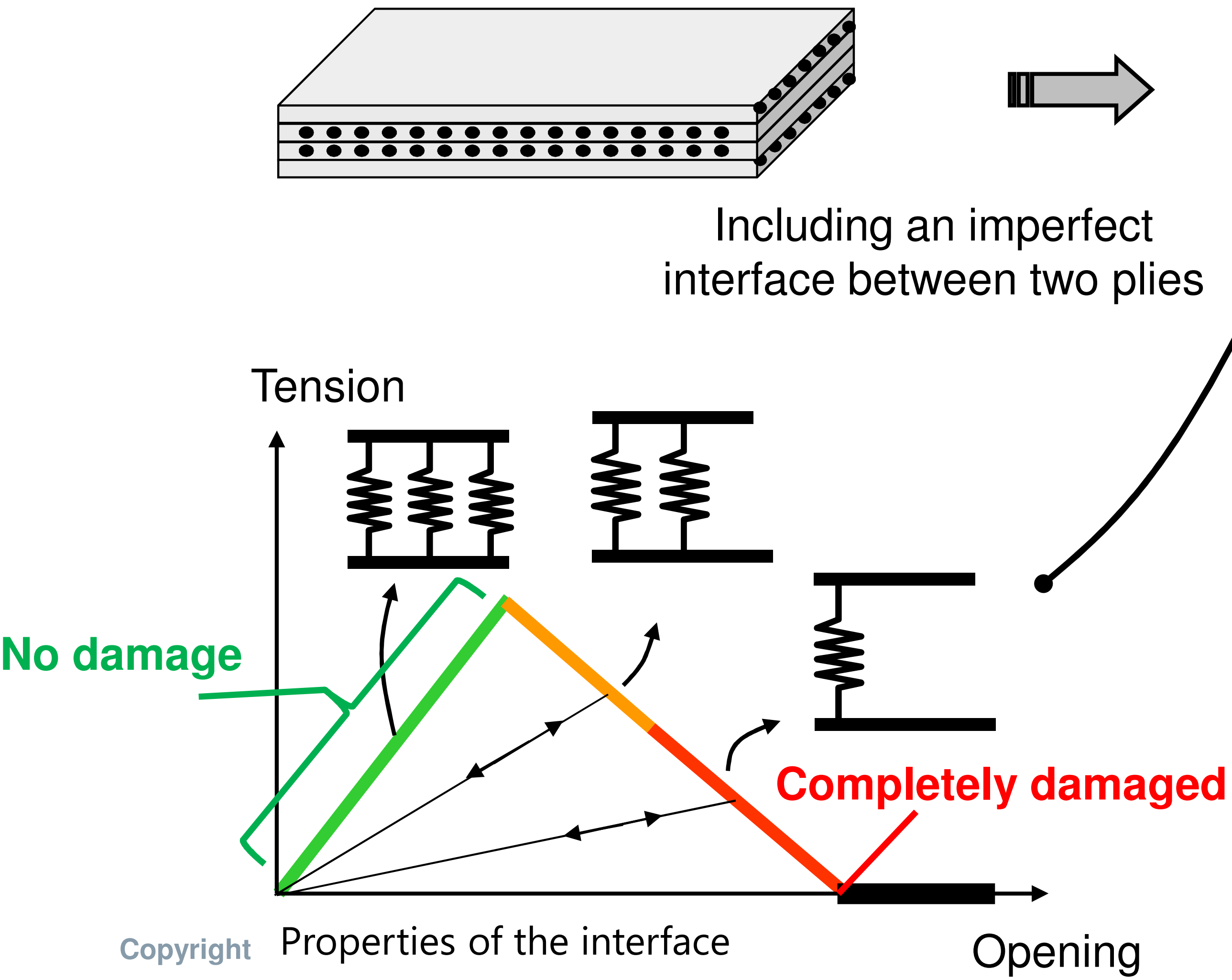
Inter-laminar failure

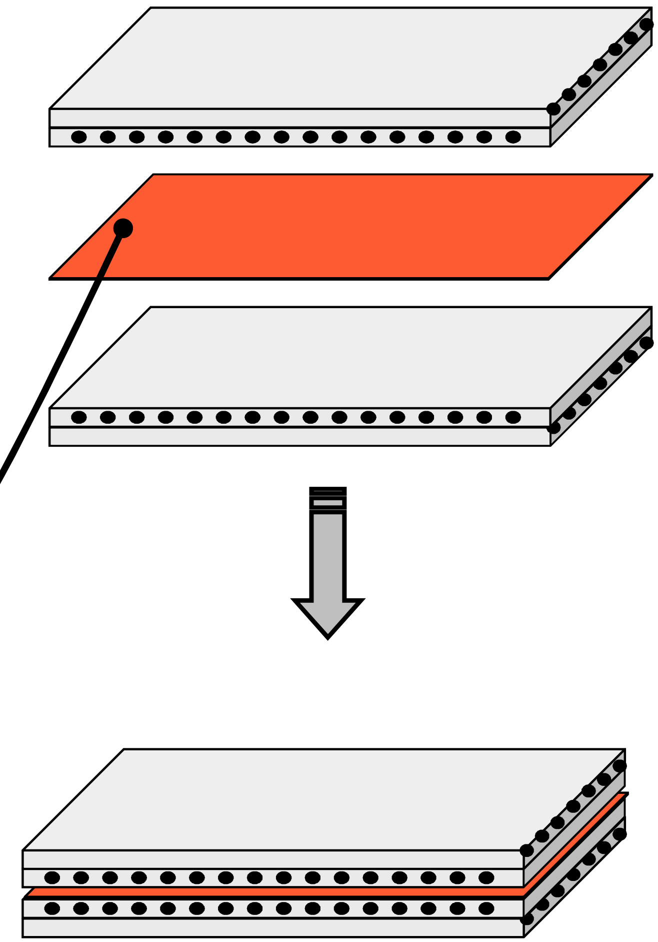
- Virtual Crack Extension (**VCE**)
- **Cohesive elements** approach (Cachan model, Allix & Ladevèze)
- User material

Model with coupling available – Cachan model

Progressive inter-laminar damage: delamination

- Inter-laminar failure – delamination (cohesive elements)
- Continuum Damage Mechanics



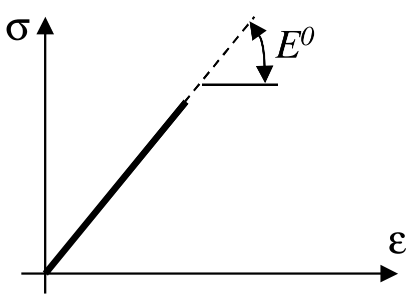


Damage analysis of composites

- Principle of the continuum damage mechanics

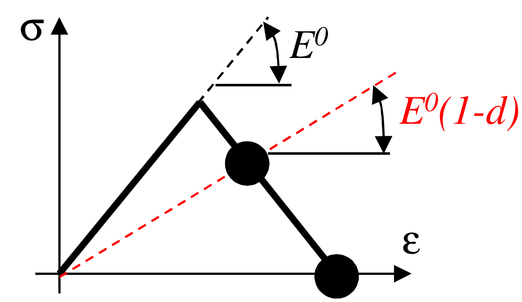
Potential without damage

$$\sigma = E^0 \varepsilon \qquad e = \frac{\sigma^2}{2E^0}$$



Potential with damage variable

$$e_d = \frac{\sigma^2}{2(1-\boxed{d})E^0} \qquad Y = \frac{\partial e_d}{\partial d} = \frac{\sigma^2}{2(1-d)^2 E^0}$$

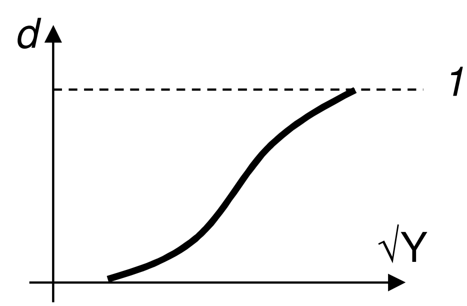


d = 1 => completely failed

d = damage associated to the (isotropic) material

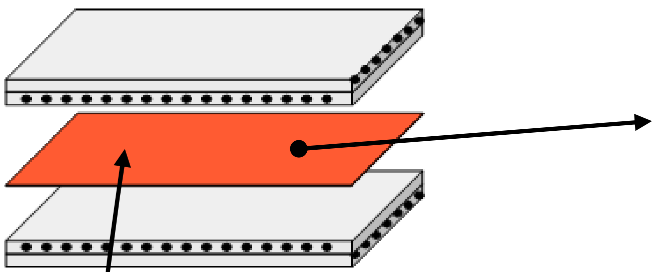
d ∈ [0 1]

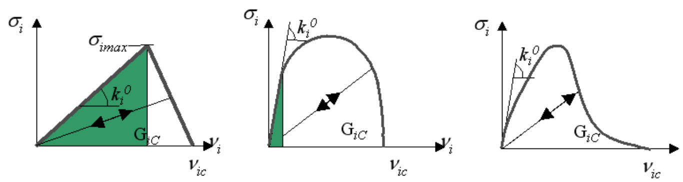
d increases as the loading increases



Progressive inter-laminar damage: delamination

- Inter-laminar failure – delamination (cohesive elements – Cachan model)





1. Potential in the interface elements

$$e_d = \frac{1}{2}\left[k_I^0 \langle \varepsilon_{33} \rangle_-^2 + k_I^0 (1-d_I) \langle \varepsilon_{33} \rangle_+^2 + k_{II}^0 (1-d_{II}) \gamma_{31}^2 + k_{III}^0 (1-d_{III}) \gamma_{32}^2\right]$$

2. Thermodynamic forces ("forces in the interface")

$$Y_{d_I} = \frac{1}{2} k_I^0 \langle \varepsilon_{33} \rangle_+^2 \qquad Y_{d_{II}} = \frac{1}{2} k_{II}^0 \gamma_{31}^2 \qquad Y_{d_{III}} = \frac{1}{2} k_{III}^0 \gamma_{32}^2$$

3. Equivalent thermodynamic force (with the 3 modes effects)

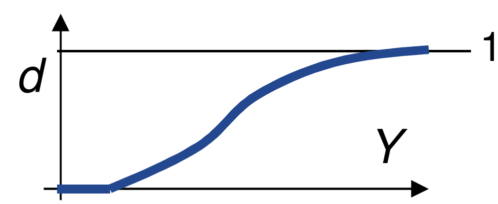
$$Y = \sup_{\tau \le t} G_{IC} \left\{ \left(\frac{Y_I}{G_{IC}}\right)^{\alpha} + \left(\frac{Y_{II}}{G_{IIC}}\right)^{\alpha} + \left(\frac{Y_{III}}{G_{IIIC}}\right)^{\alpha} \right\}^{1/\alpha}$$

4. Only one resulting damage variable

$$d_I = d_{II} = d_{III} = d$$

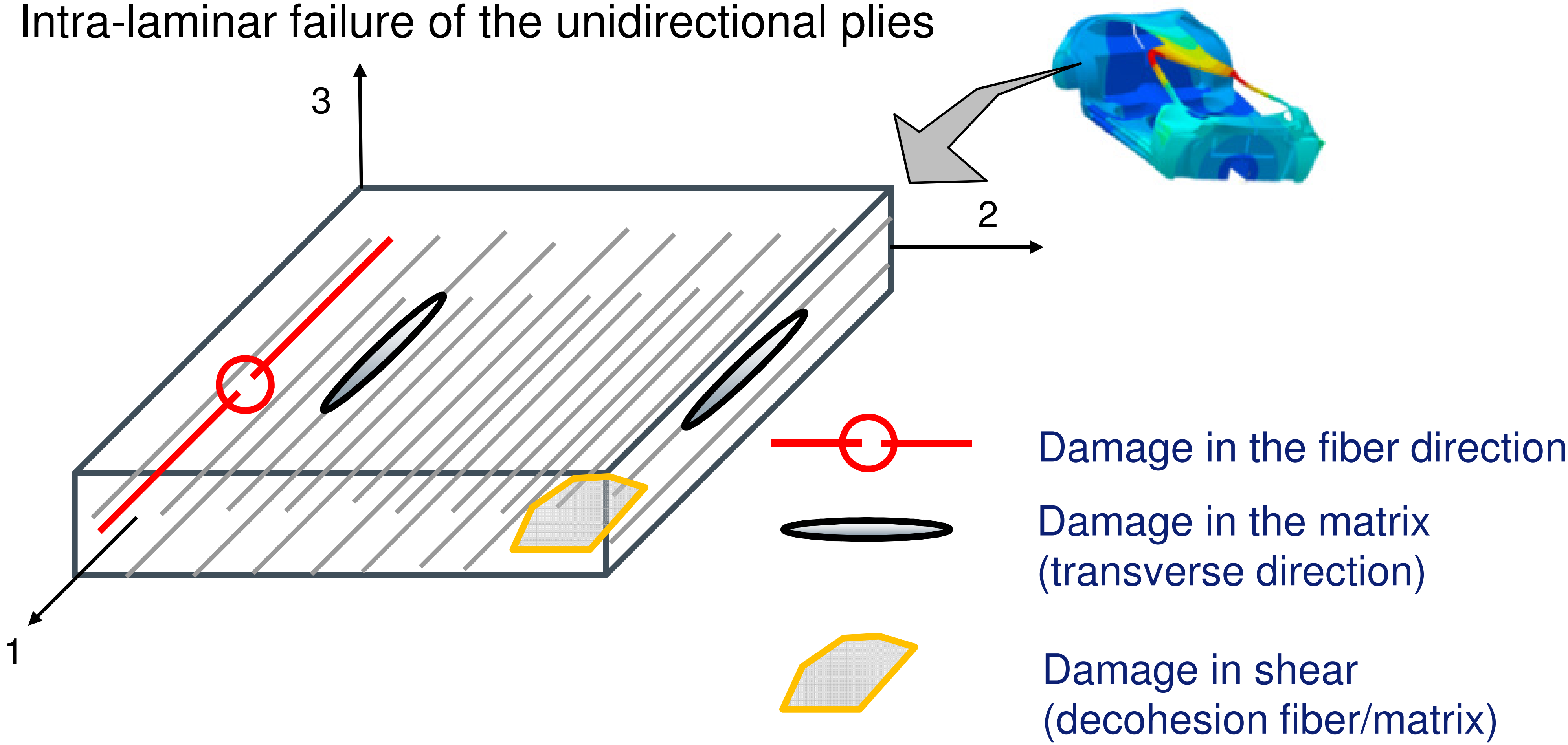
5. Evolution of the damage wrt the thermodynamic force

$$d = h(Y)$$



Progressive intra-laminar damage: inside the plies

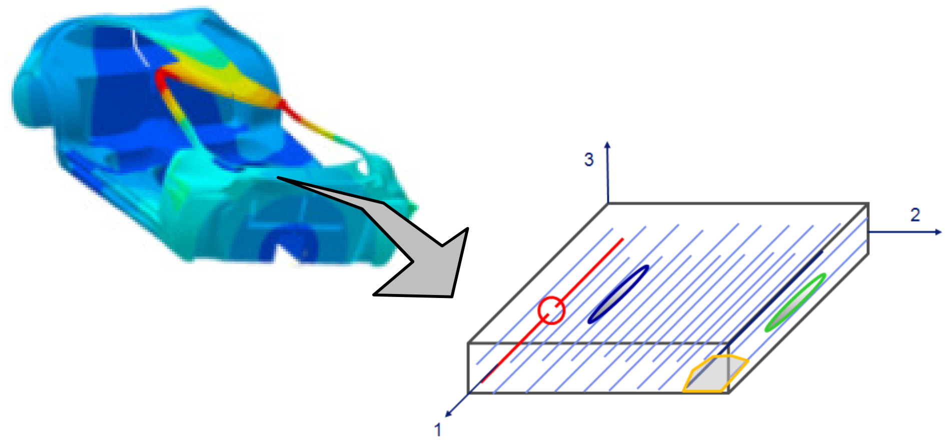
- Intra-laminar failure of the unidirectional plies



- The approach is based on the **Continuum Damage Mechanics**
- **Homogenized approach (meso-model):** we work at the ply level (homogeneous ply)

Progressive intra-laminar damage: inside the plies

- Intra-laminar failure of the unidirectional plies



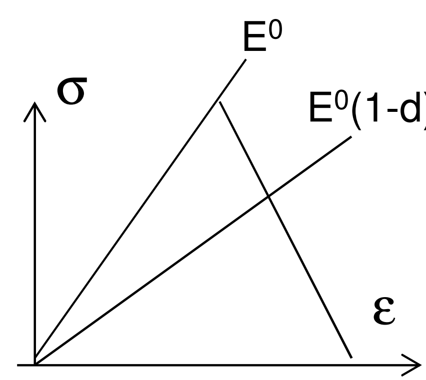
Strain energy without damage

$$e = \frac{\sigma_{11}^2}{2E_1^0} + \frac{\sigma_{22}^2}{2E_2^0} - \frac{\nu_{12}^0}{E_1^0}\sigma_{11}\sigma_{22} + \frac{\sigma_{12}^2}{2G_{12}^0}$$

$\Downarrow$

Strain energy with damage variables for fiber breaking, matrix cracking and decohesion between fiber/matrix

$$e_d = \frac{\sigma_{11}^2}{2(1-\boxed{d_{11}})E_1^0} + \frac{\langle\sigma_{22}\rangle_+^2}{2(1-\boxed{d_{22}})E_2^0} + \frac{\langle\sigma_{22}\rangle_-^2}{2E_2^0} - \frac{\nu_{12}^0}{E_1^0}\sigma_{11}\sigma_{22} + \frac{\sigma_{12}^2}{2(1-\boxed{d_{12}})G_{12}^0}$$



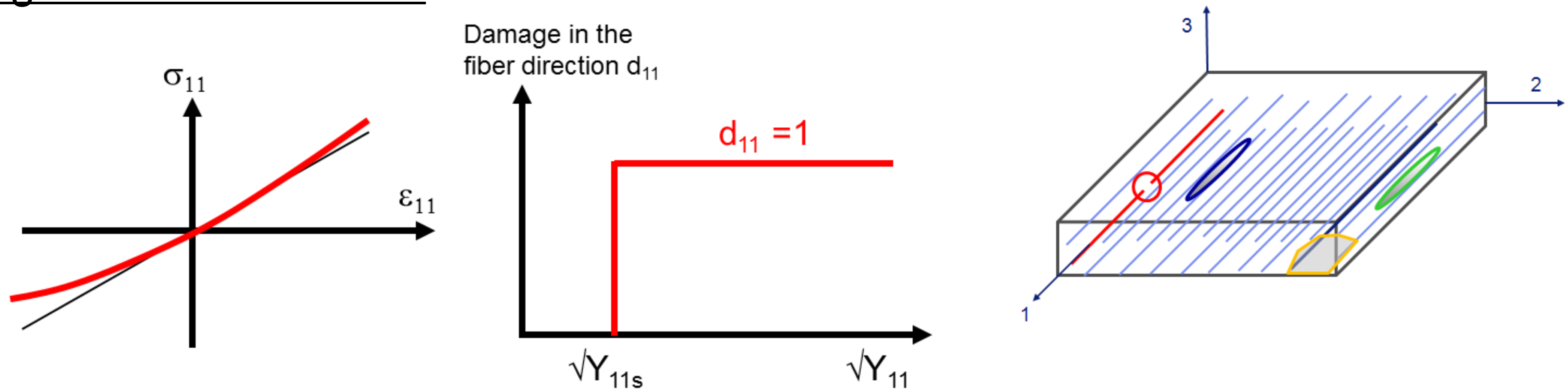
d_{ij} depending on the physics of the problem (observed from physical tests)

Progressive intra-laminar damage: inside the plies

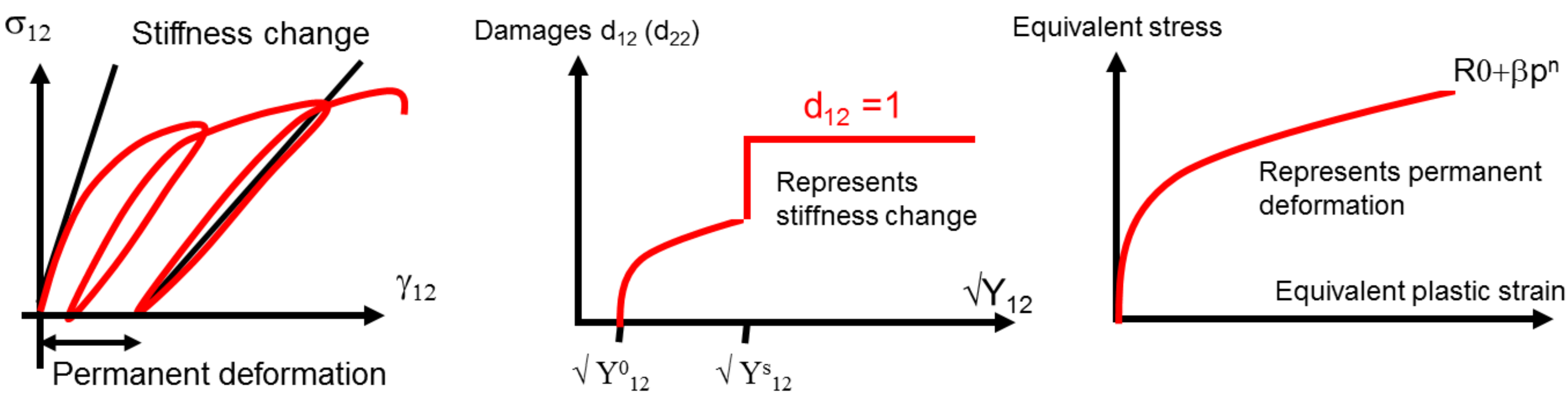
- Intra-laminar failure of the unidirectional plies: Cachan model (Ladevèze)

The parameters: E_1, E_2, ν_{12}, G_{12}, Y_{11s}, Y_{12S}, R_0, β, …

Along the **fiber direction**

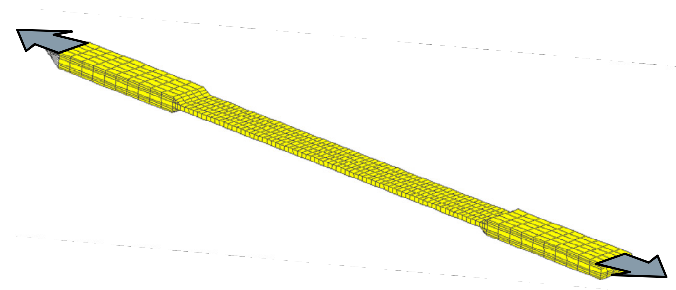


In the **matrix**

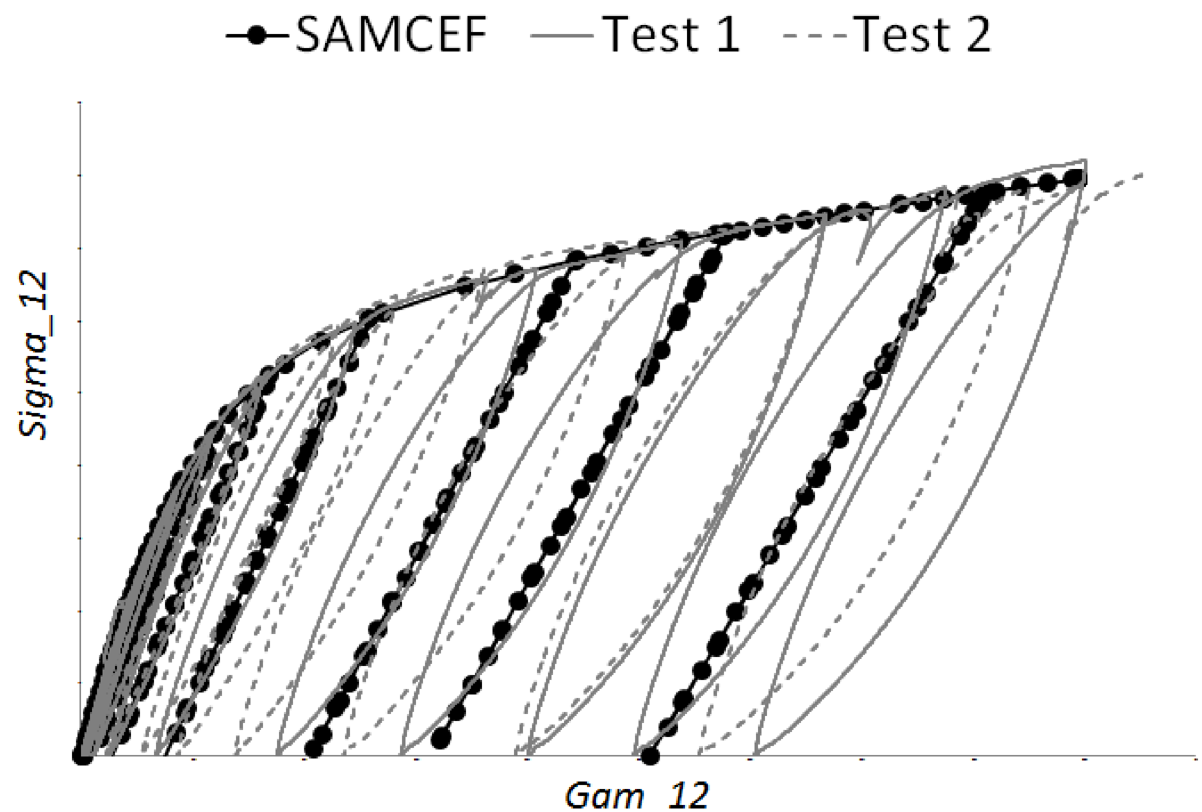


Progressive intra-laminar damage: inside the plies

- Intra-laminar failure of the unidirectional plies



Parameter identification at the coupon level
(Here **[45/-45]$_{2s}$**)

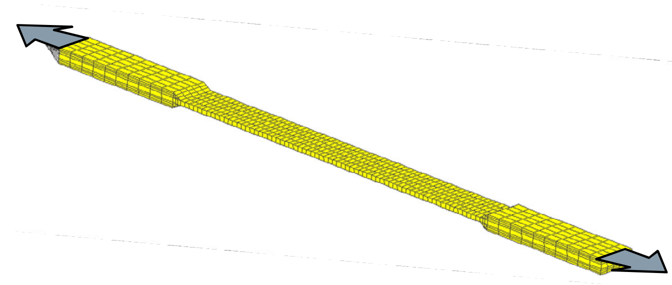


With the well-identified parameters

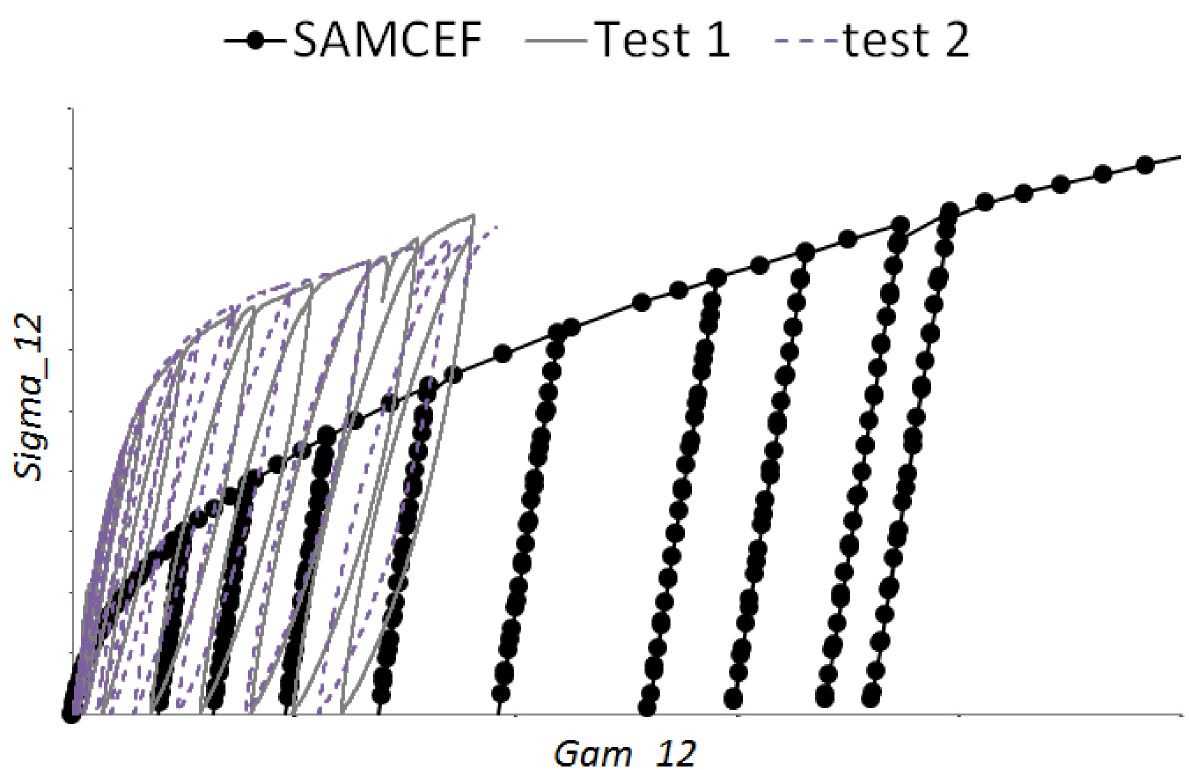
Source : Bruyneel, Urushiyama, Naito, ASC Conference, 2014

Progressive intra-laminar damage: inside the plies

- Intra-laminar failure of the unidirectional plies



Parameter identification at the coupon level
(Here **[45/-45]$_{2s}$**)



With other values for the parameters

Source : Bruyneel, Urushiyama, Naito, ASC Conference, 2014

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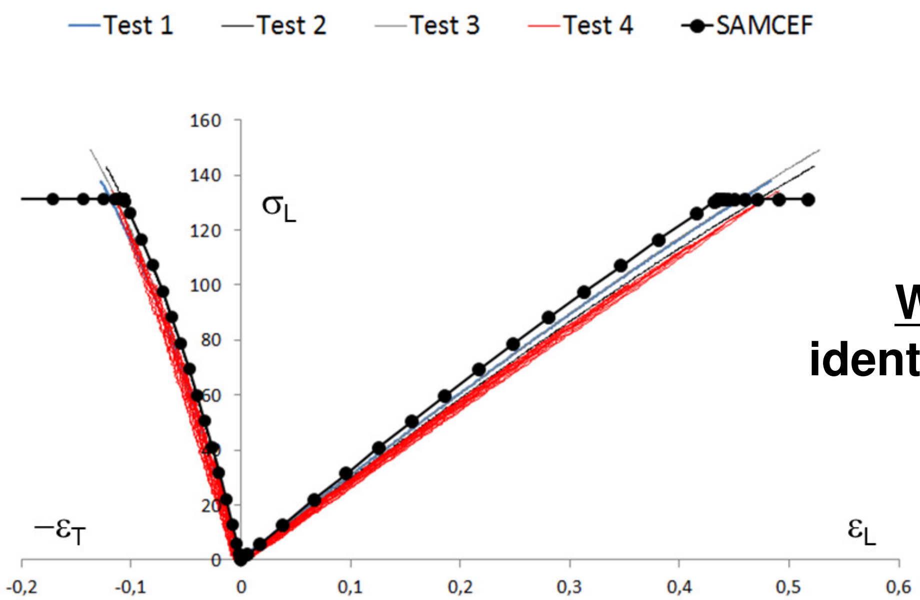
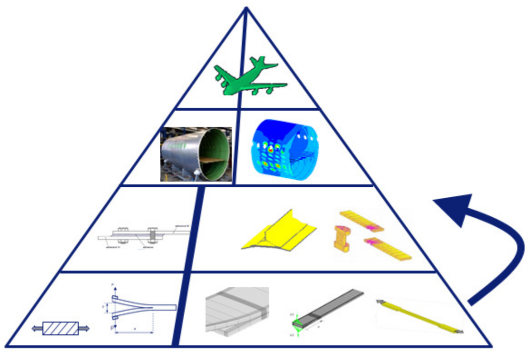
Progressive intra-laminar damage: inside the plies

- Intra-laminar failure of the unidirectional plies
- **Predictive models** at the coupon level
  - ⇒ Still Ok if change stacking sequence, number of plies in the coupon
- Example: blind test on a **$[67,5/22,5]_{2s}$**



<u>With</u> **the well-identified parameters**

- Parameters used at the upper stages of the pyramid of tests
  - ⇒ Replace physical tests by simulation

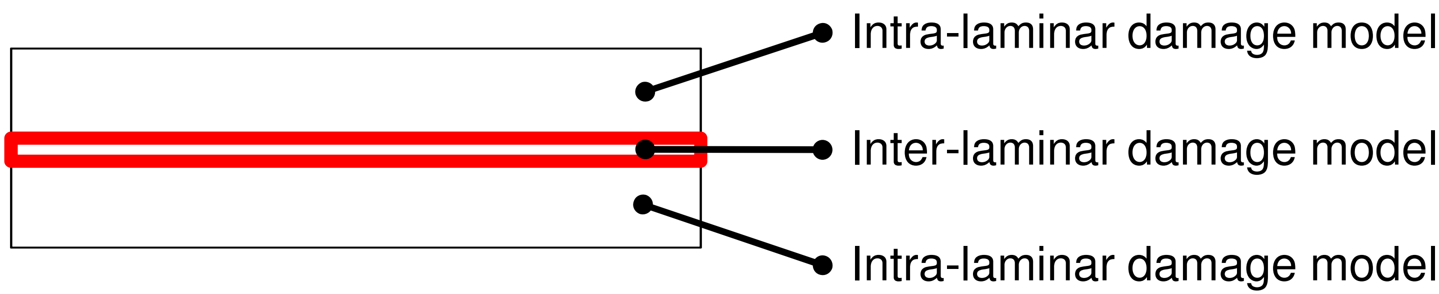


Coupling inter and intra-laminar damages

- Inter and intra-laminar damage models used **independently but simultaneously** in the FE model

- Progressive damage model in the plies
- Progressive damage model in the interfaces

No communication between the material models



- Most of the time, this is **enough** to represent the physics of the composite degradation

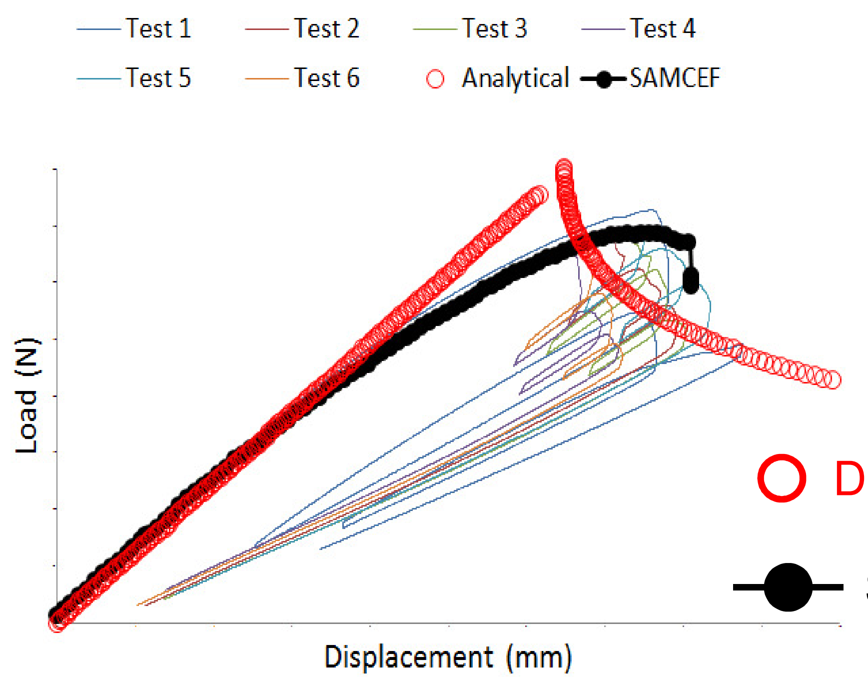
Coupling inter and intra-laminar damages

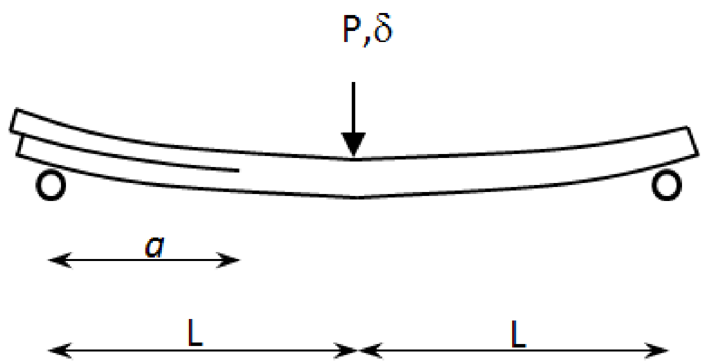
- Inter and intra-laminar damage models

  ⇒ Inter-laminar damage law alone may be not enough

  ⇒ Intra-laminar damage law alone may be not enough

  ⇒ Simple example: ENF coupon with delamination at a 45/-45 interface





Delamination only (intra-laminar): analytical solution

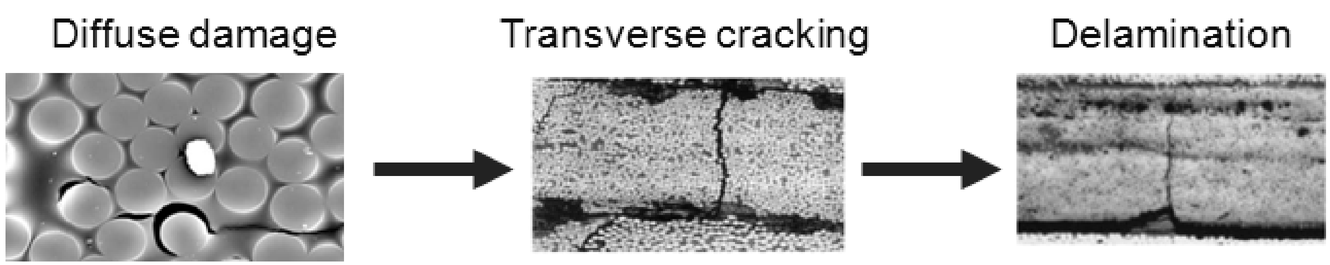
SAMCEF (simulation: inter- and intra-laminar damage)

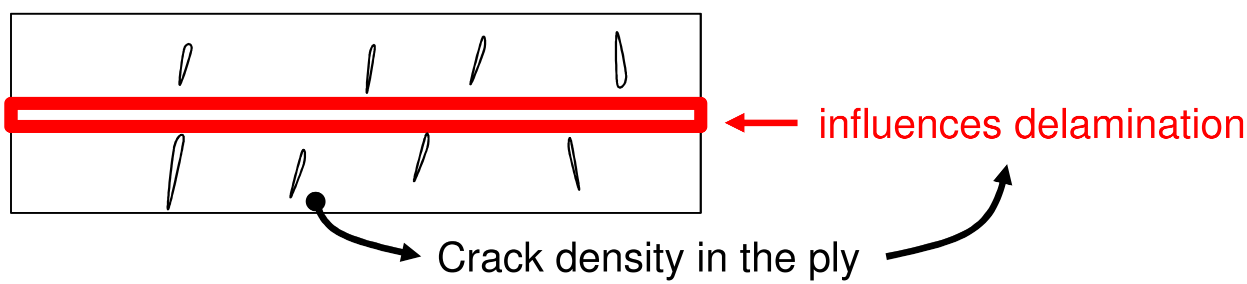
Coupling inter and intra-laminar damages

- Inter and intra-laminar **damage models coupled** in the FE model

  - In case of large stress concentrations in the problem, a **coupling** may be necessary
  - Influence of the crack density on the ply on delamination
  - The cohesive element must see the crack density in the adjacent solid elements

⇒ **Non local aspect of the material law (Cachan model, implemented in SAMCEF)**

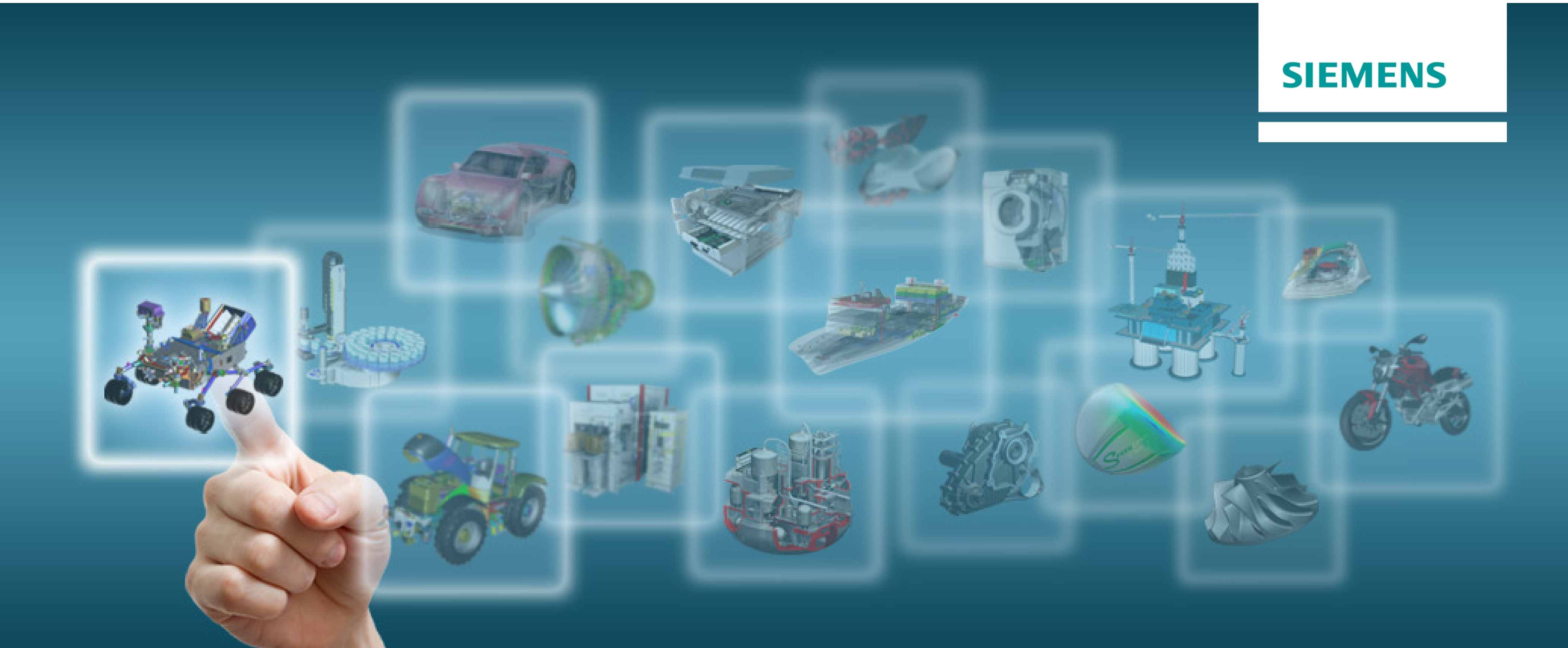




} Communication between the material models

⇒ Simulation results even closer to reality

⇒ Interesting for e.g. **plates with hole**



Advanced composites analysis

Parameter identification process: link between simulation and testing

Progressive damage models: parameter identification

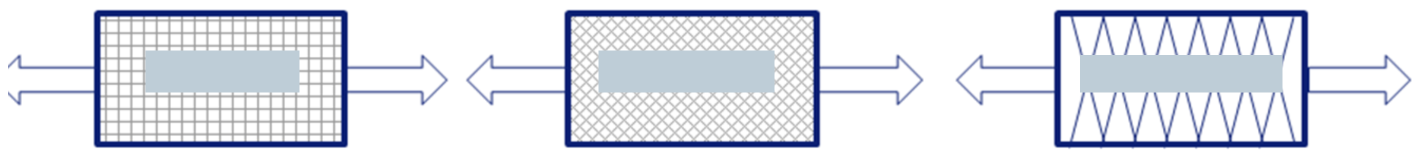
- Parameter identification procedure: a comprehensive test protocol exists (via Engineering Service)

- Tests needed
- Number of tests
- Associated standards
- Test output requested

Test protocol
Intralaminar elastic and damage identification

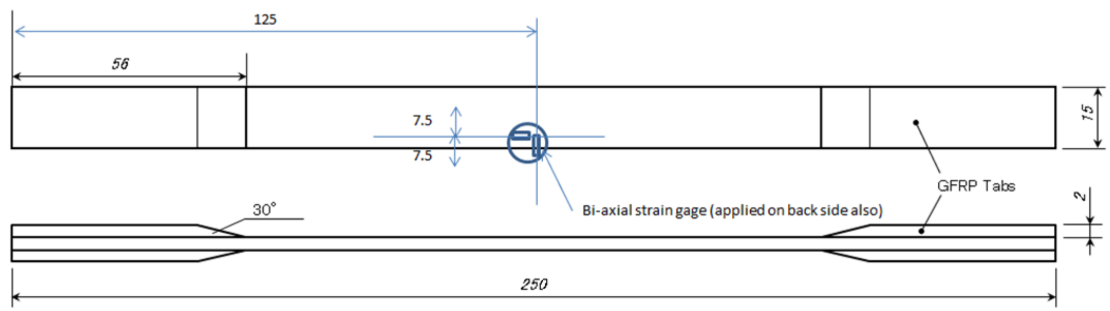
Elastic properties: Coupons under tensile strength

- 3 layups



5 successful tests *2 successful tests* *2 successful tests*

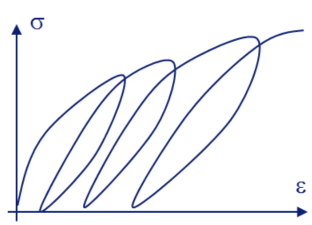
- Norm: **ASTM D3039** for coupon under tensile strength

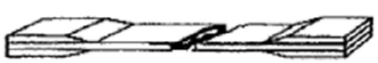


ASTM D3039 Test piece with GFRP Tabs for **UD** Material

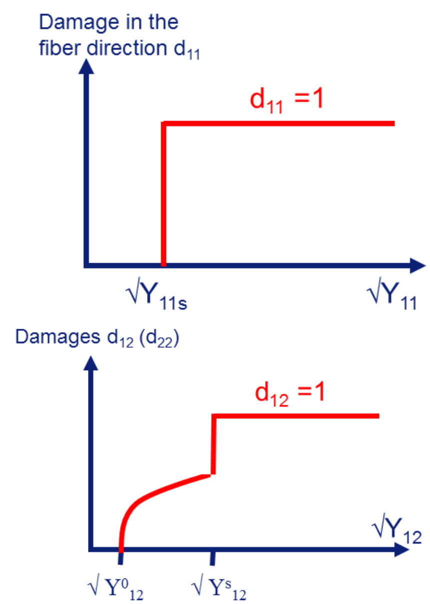
Progressive intra-laminar damage: inside the plies

- Intra-laminar failure of the unidirectional plies
  - The parameter identification procedure exists (coupon level)
  - The test protocole is known
    ⇒ for UD, **standard tests on 4 stacking sequences are needed** (**very few tests**)
    ⇒ only few simulations needed / procedure mainly based on EXCEL sheets
  - It results that the damage laws available in LMS Samtech Samcef can be used





Loading/unloading the coupon (physical test on standard machine)



- ✓ Identification of the elastic properties E_1, E_2, ν_{12}, G_{12}, …
- ✓ Identification of damage/plasticity laws
- ✓ Identification of strengths

Progressive intra-laminar damage: inside the plies

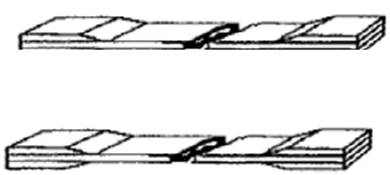
- Parameter identification procedure: a comprehensive test protocol exists (more information via Engineering Service)

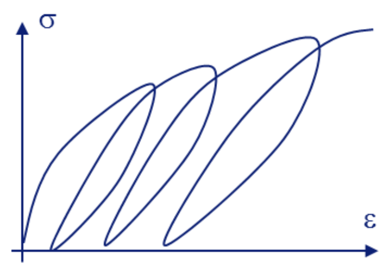
Tests needed to identify the parameters (E_1, E_2, ν_{12}, G_{12}, Y_{11s}, Y_{12S}, R_0, β, …)

⇒ Test on a **$[x/y]_{ns}$** laminate; tension and compression

⇒ Test on a **$[45/-45]_{ns}$** laminate, in tension with loading/unloading

⇒ Test on a $[\alpha_n/\beta_m]$ laminate, in tension with loading/unloading



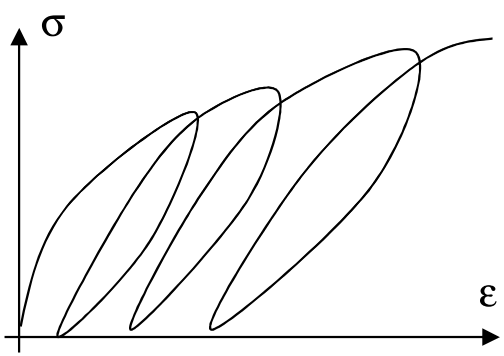


Tests on 4 configurations only!!

Very small number of tests

Progressive intra-laminar damage: inside the plies

- Parameter identification procedure: a comprehensive test protocol exists

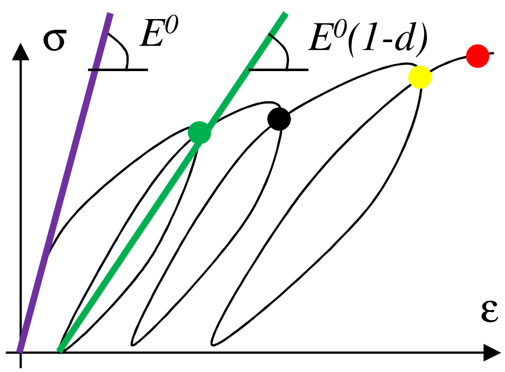


Loading/unloading

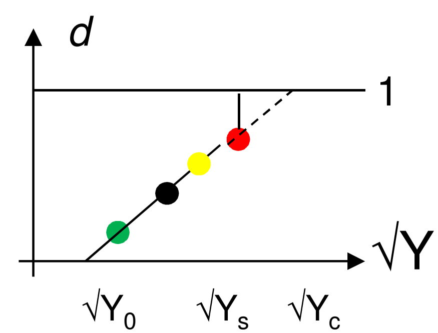
$$e_d = \frac{\sigma^2}{2E^0(1-d)}$$

$$\epsilon = \frac{\partial e_d}{\partial \sigma} = \frac{\sigma}{E^0(1-d)}$$

$$Y = \frac{\partial e_d}{\partial d} = \frac{\sigma^2}{2E^0(1-d)^2}$$

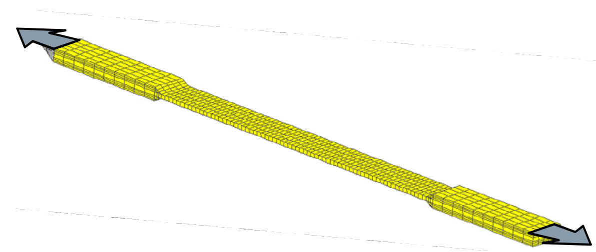


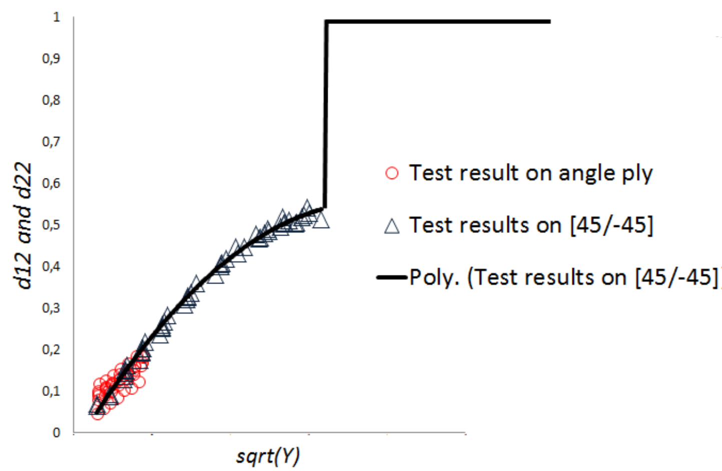
1. Determine *d* by comparing $E^0(1\text{-}d)$ and E^0
2. Calculate Y, and √Y
3. Plot *d* as a function of √Y
4. Determine the parameters

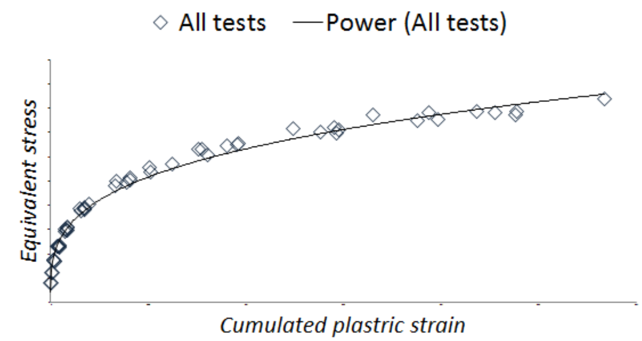


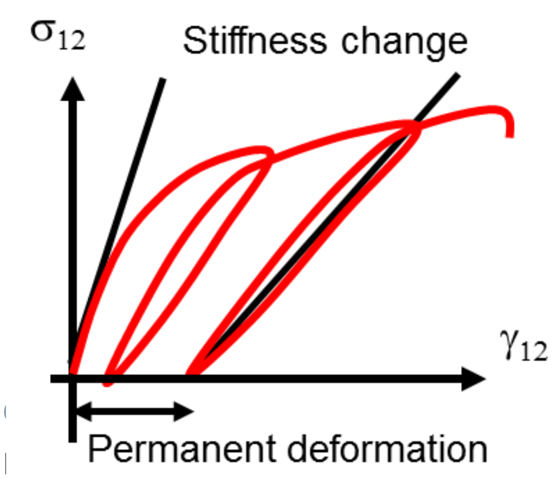
Progressive intra-laminar damage: inside the plies

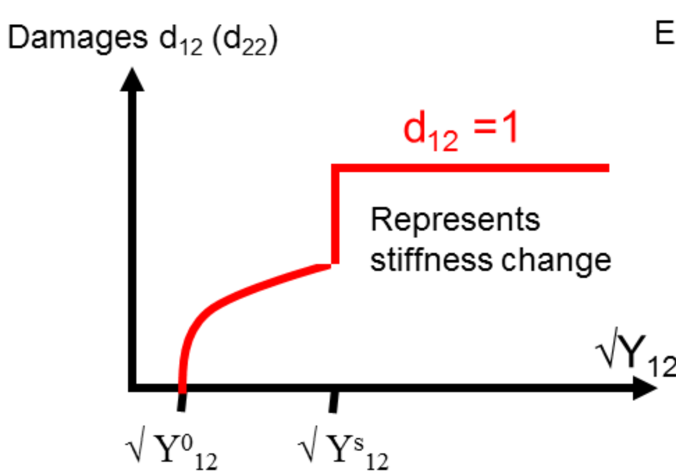
- Parameter identification procedure

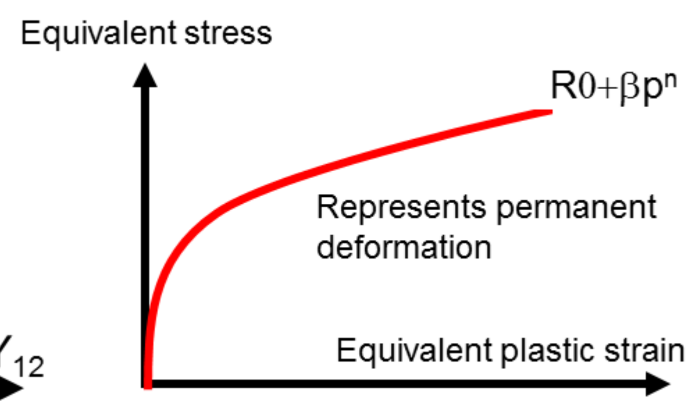






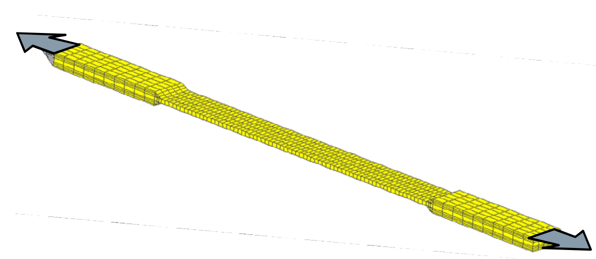


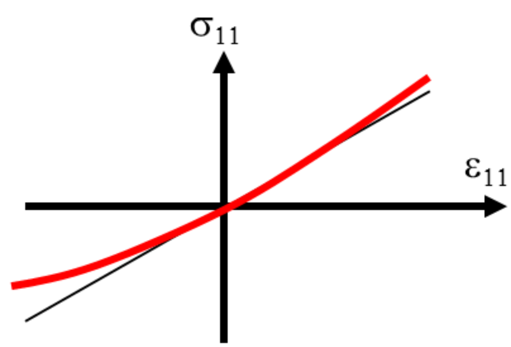


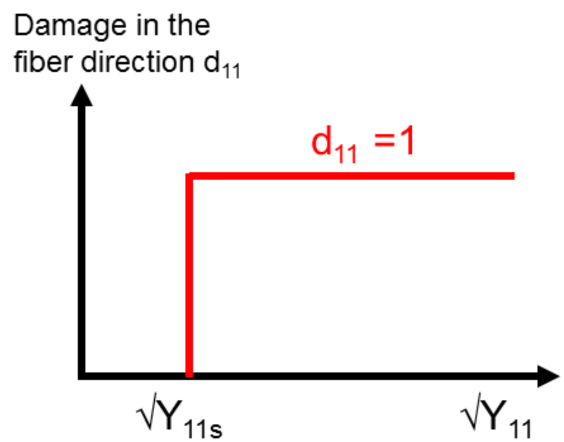


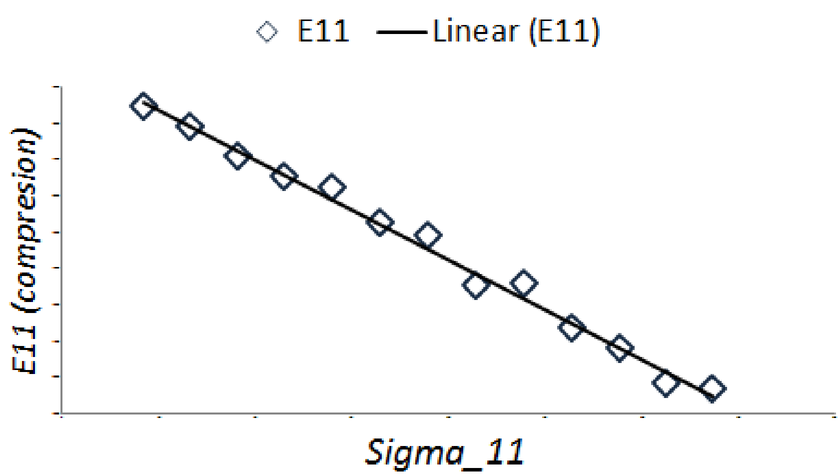
Progressive intra-laminar damage: inside the plies

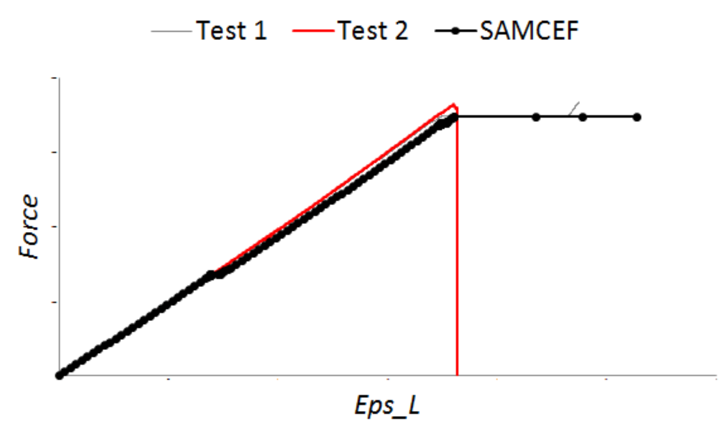
- Parameter identification procedure







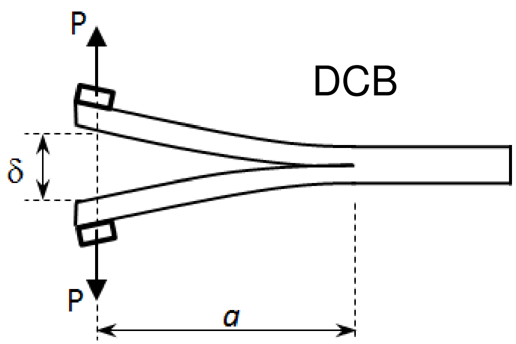


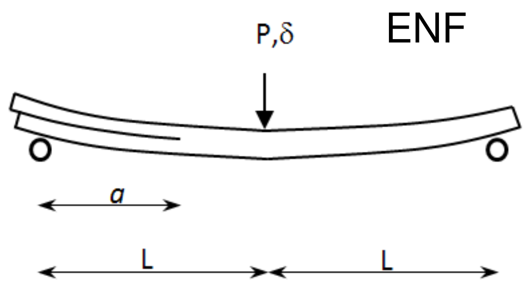


Progressive inter-laminar damage: delamination

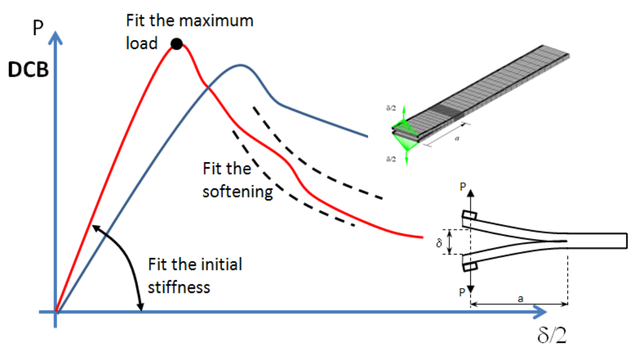
- Inter-laminar failure: parameter identification

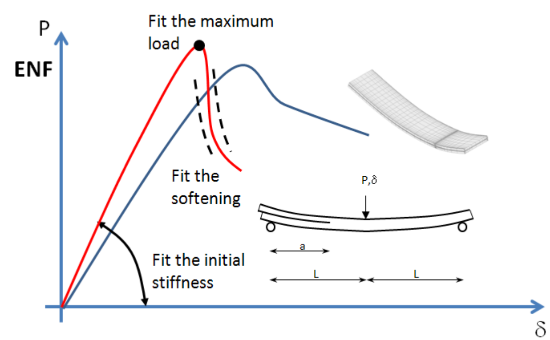
Conduct physical tests



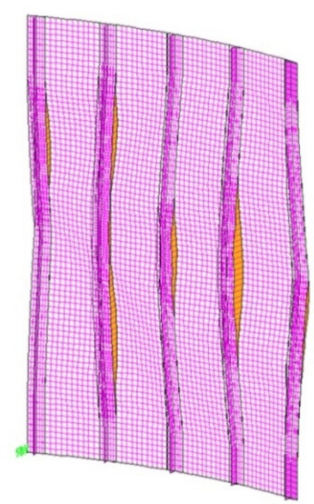


Fit simulation with tests results





Value of the interface parameters → Used to study delamination on larger structures

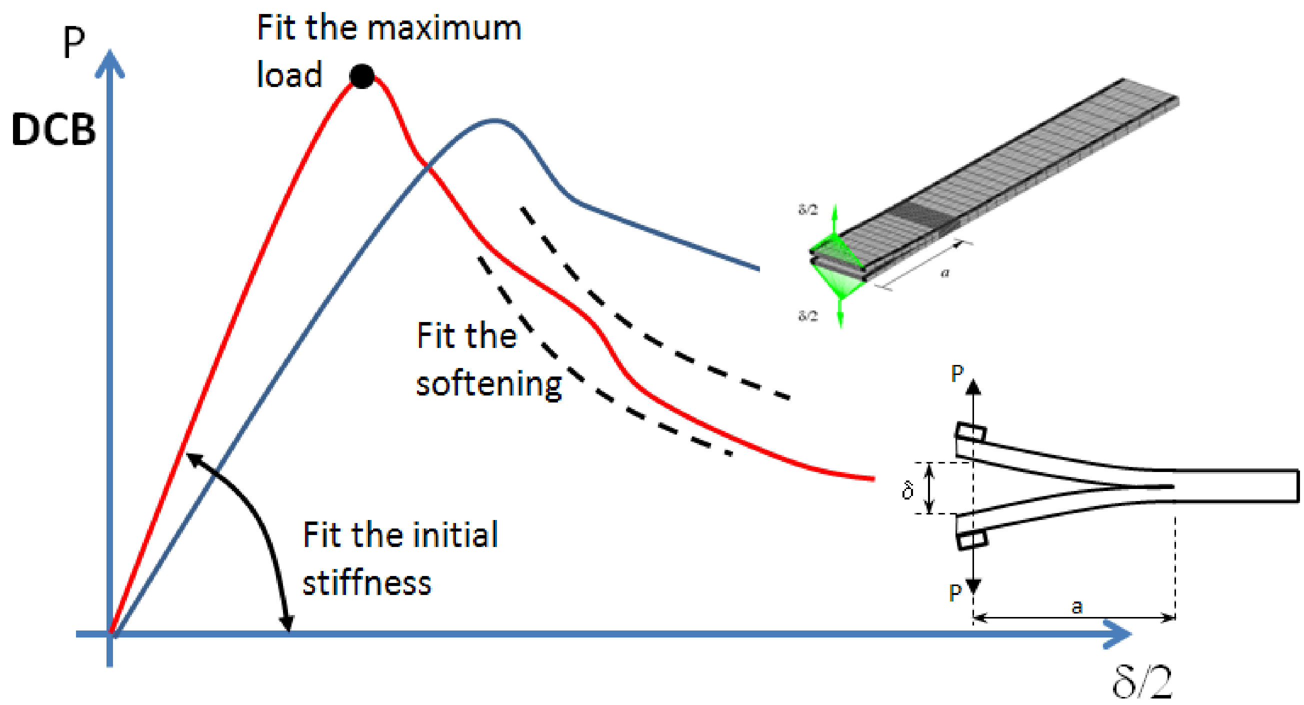


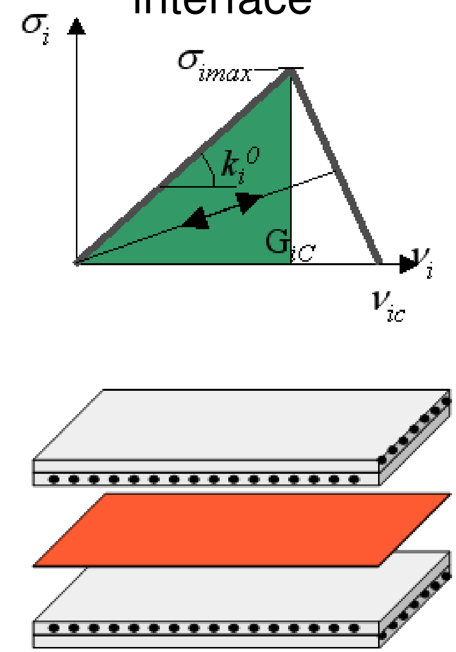
Progressive inter-laminar damage: delamination

- Inter-laminar failure: parameter identification

Structural response

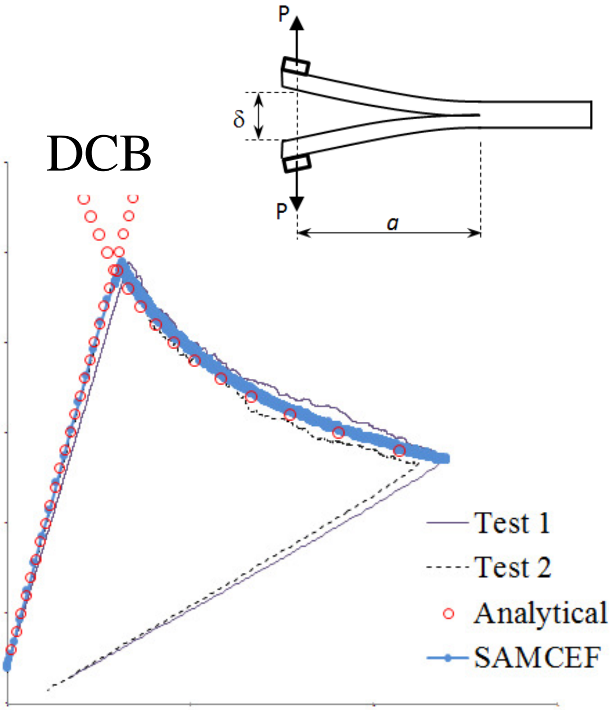
Constitutive model in the interface

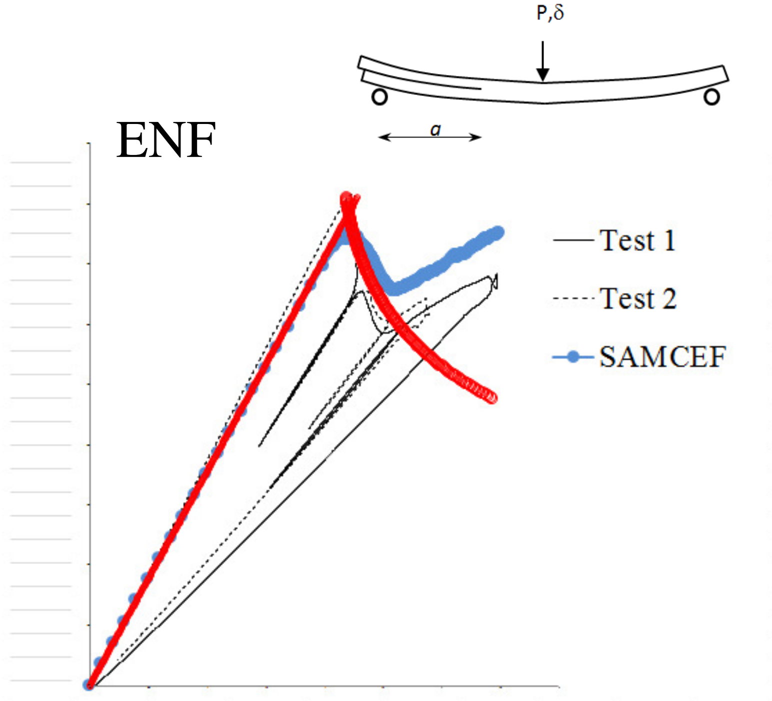


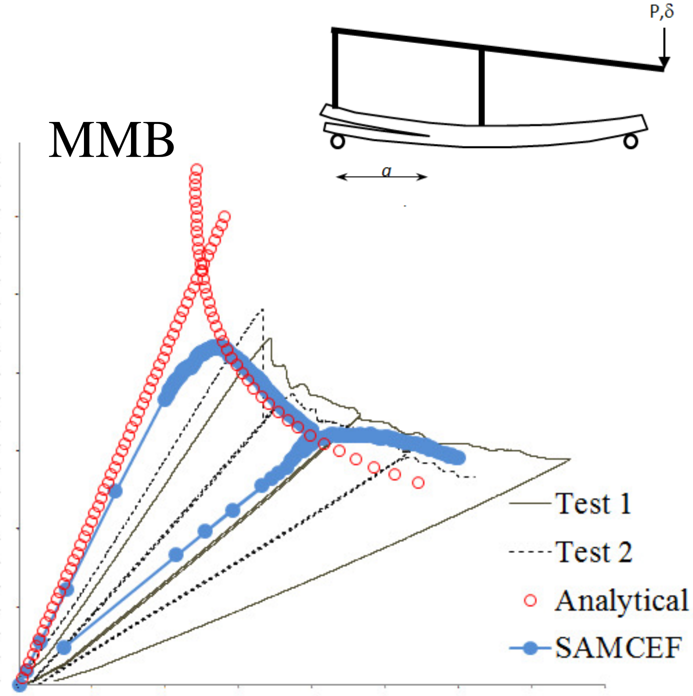


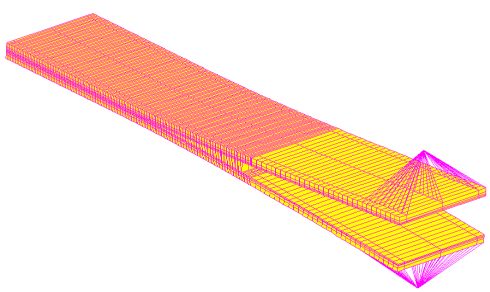
Progressive inter-laminar damage: delamination

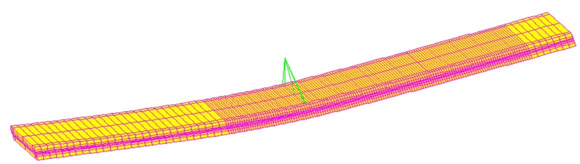
- Inter-laminar failure: parameter identification

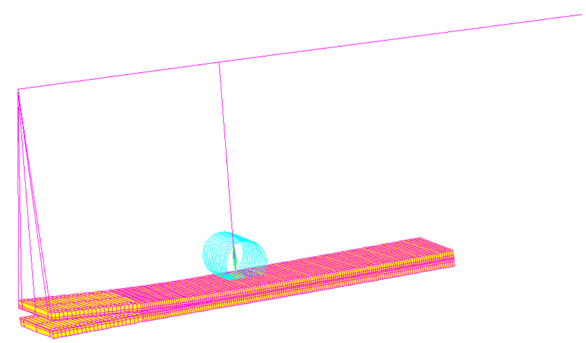


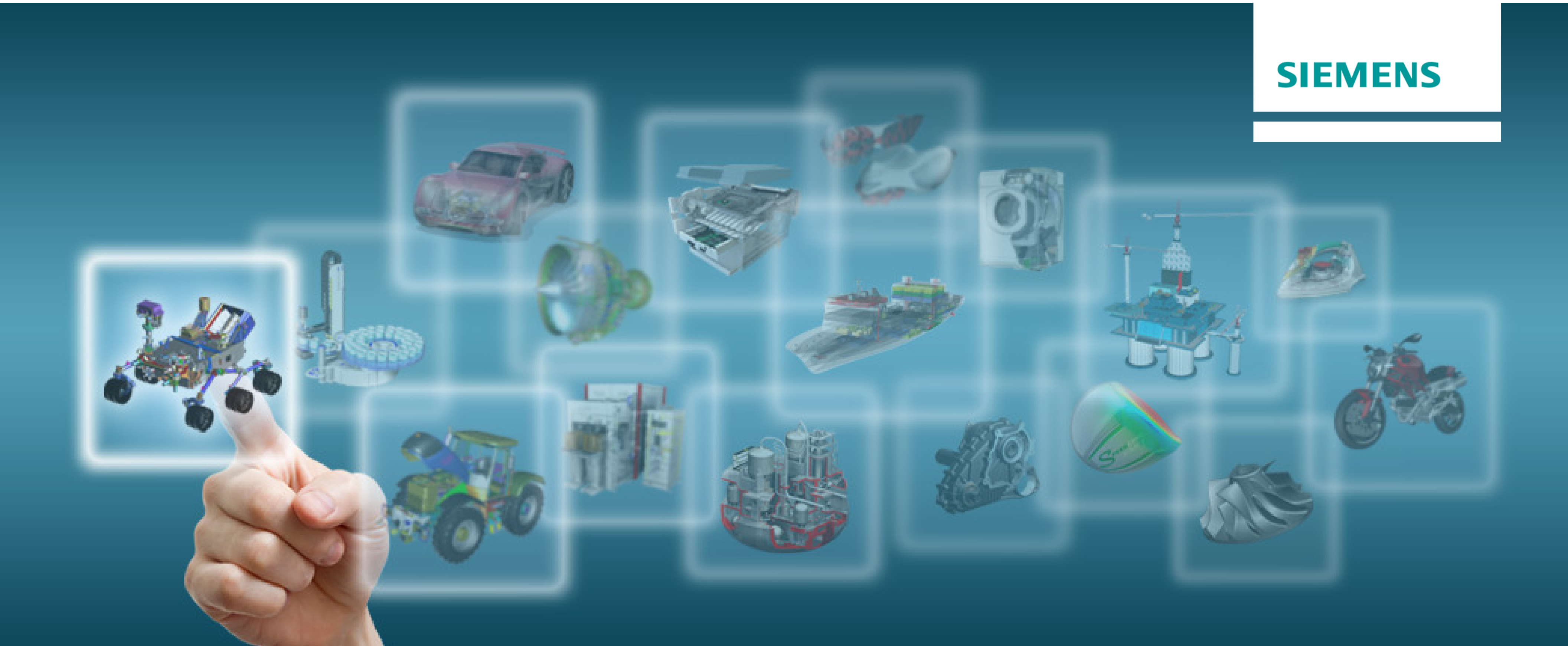












Advanced composites analysis

Illustrations

Illustration 1
Honda R&D Co., Ltd.

SIEMENS

Source : Bruyneel, Urushiyama, Naito, ECCM Conference, 2014

Source : Bruyneel, Urushiyama, Naito, WCCM Conference, 2014

Challenges

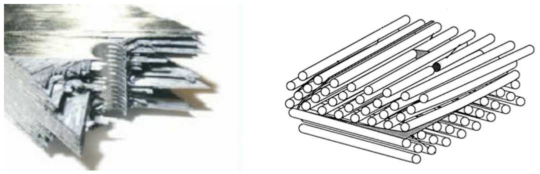
- Innovative methodology for progressive damage analysis in composite car design (weight saving requirements)
- Complex non-linear behavior of composites
- Need for development of material models, characterization and parameter identification procedures for progressive damage analysis and body performance evaluation

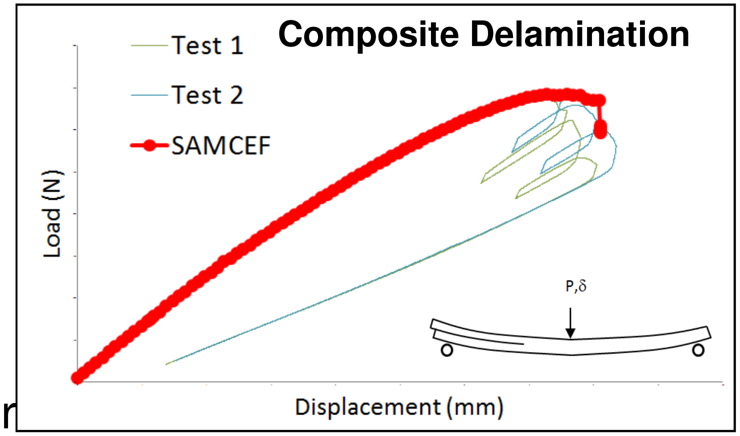
Solution

- LMS Samtech Samcef Mecano non-linear finite element solver
- LMS Engineering Services for composite damage model identification

Results

- Sophisticated material models implemented for:
  - Progressive ply damage; delamination ; coupling of both
- Development of the parameter identification procedure, based on a limited amount of physical tests on coupons
- Predictive damage models





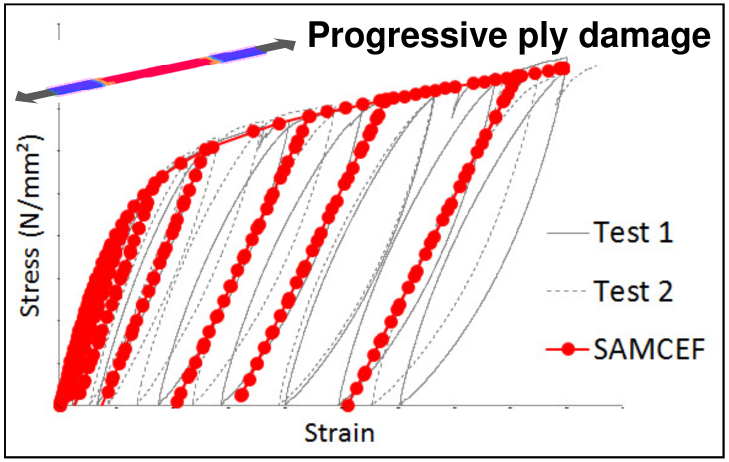


Illustration 1
Honda R&D Co., Ltd.

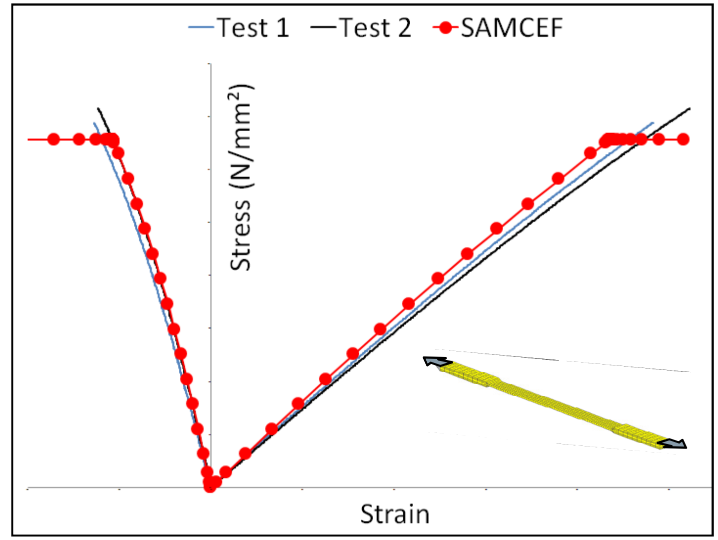
Source : Urushiyama, Naito, JSAE Spring Conference, 2014 52 05

Source : Bruyneel et al., NAFEMS WC, San Diego, June 2015

Exploitation of the methodology

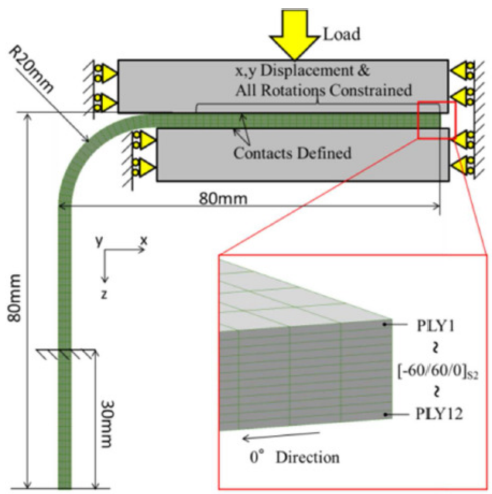
- **Validation of damage models at coupon level**

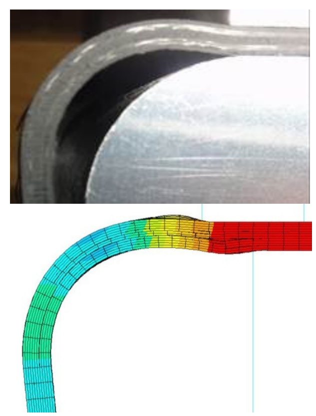
Starting from identified material parameters, the damage model is used to predict the mechanical behavior at the coupon level for evaluation of the behaviour for other stacking sequences and hence replacing physical tests



- **Application of damage models for predictive delamination behavior at component level**

The damage models are supporting the prediction of the progressive damage and delamination inside the plies and at their interface at component level





Progressive ply damage
Progressive delamination

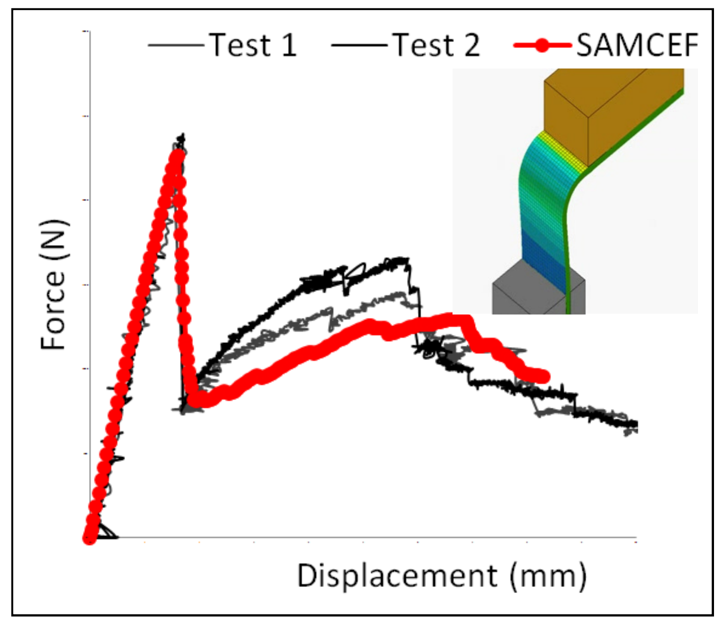
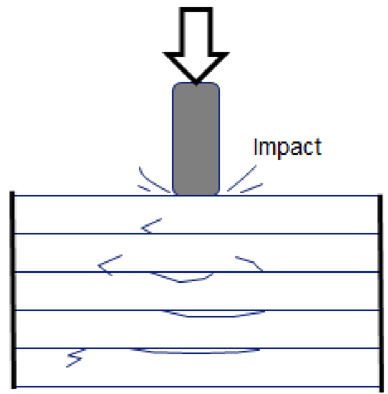


Illustration 1
Honda R&D Co., Ltd.

Source : Bruyneel, Urushiyama, Naito, NAFEMS Benchmark Magazine, July 2015

Exploitation of the methodology

- **Application of damage tolerant approach for composite design**
  - Barely visible impact damage (BVID)
  - Damage induced by a low energy impact
  - Delamination appears at the interfaces between the plies
  - Very good agreement between simulation and C-scan test results



Undetectable damage

The stains represent the level of delamination

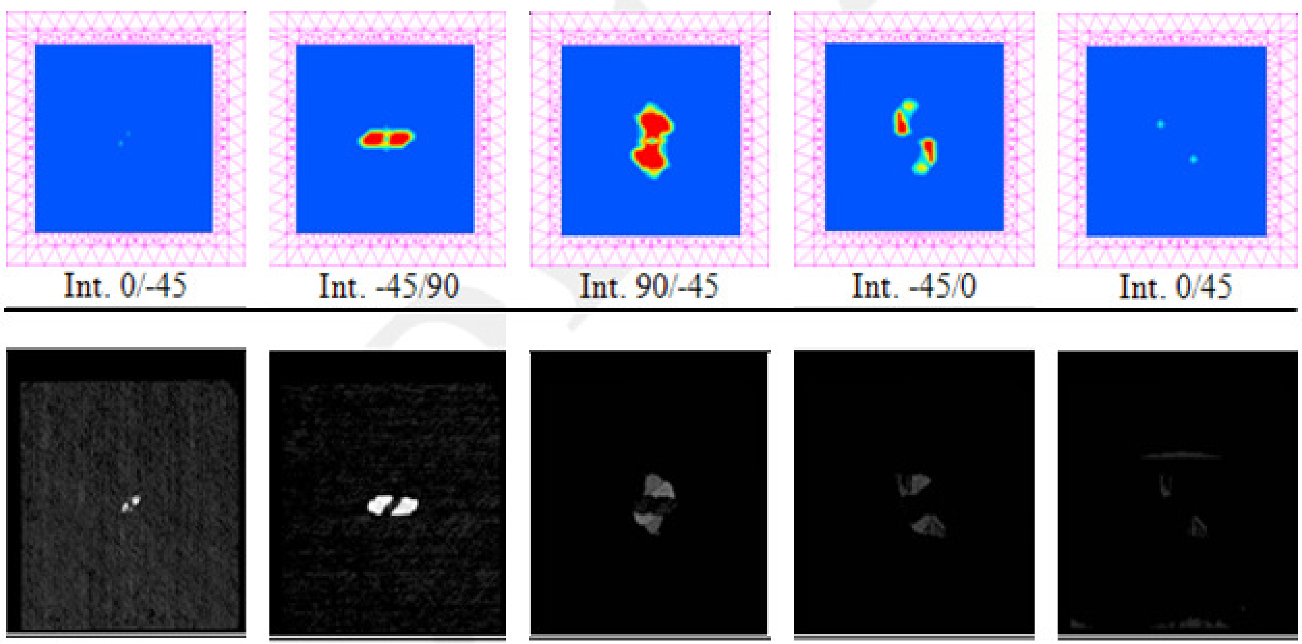
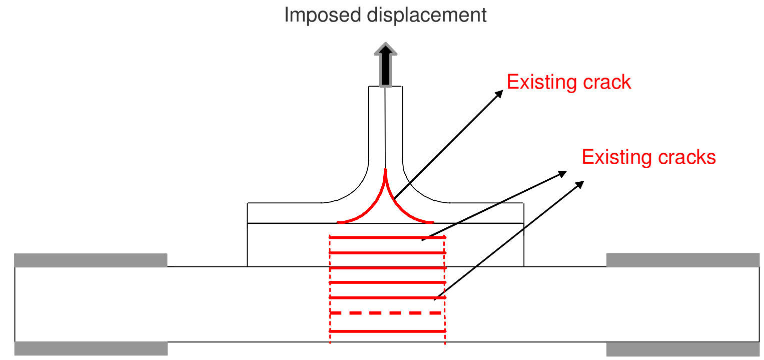


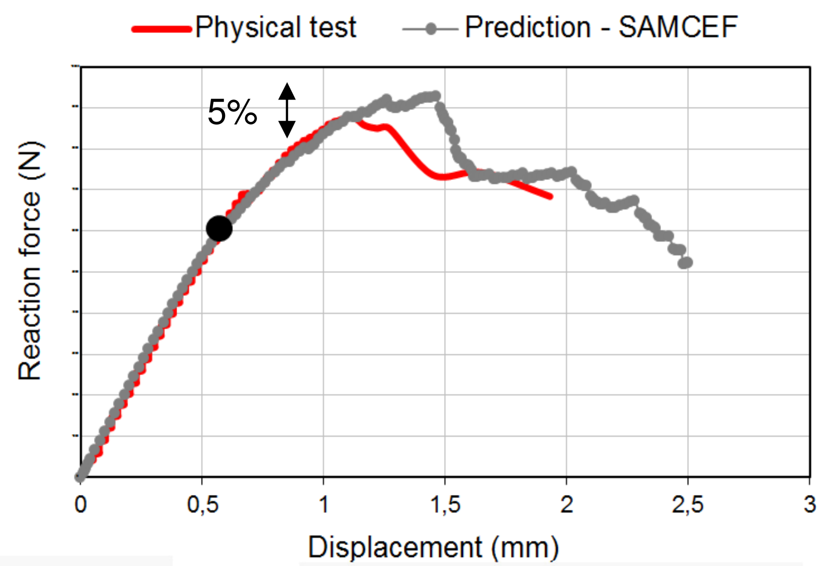
Illustration 2
Latecoere

Source : Bruyneel et al., JEC Composite Magazine 80, 2014



Challenges

- Investigate the damage propagation at the interface of plies of a laminated composite (damage tolerant approach – weight saving)
- Multi-delaminated composite material
- Need for a fast solution procedure

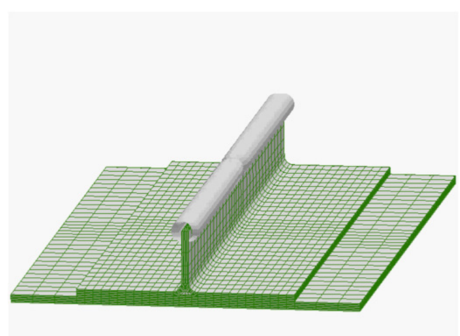


Solution

- LMS Samtech Samcef Mecano, non-linear finite element solver
- LMS Engineering Services

Results

- Better knowledge of the composite structure performance
- Determination of tighter safety margins for
  - A safer design
  - A lighter design



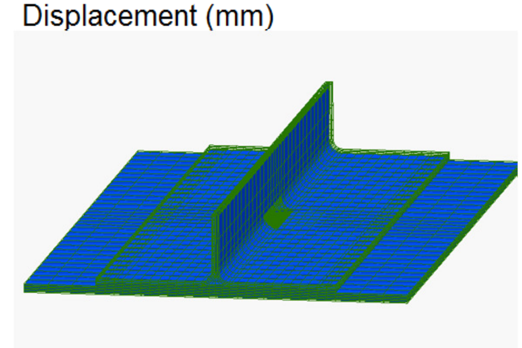
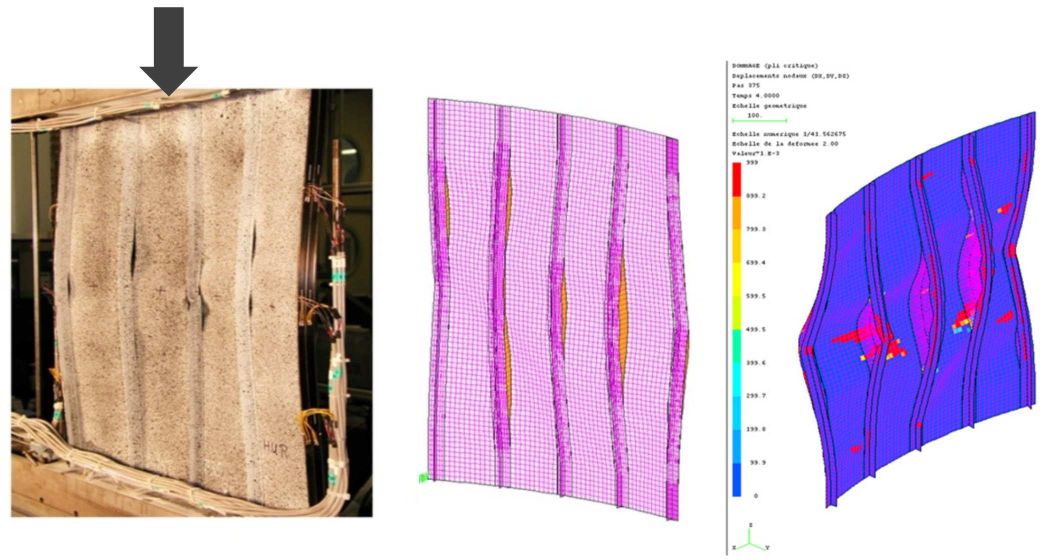


Illustration3
DLR

Source : Bruyneel et al., JEC Composite Magazine 48, 2009

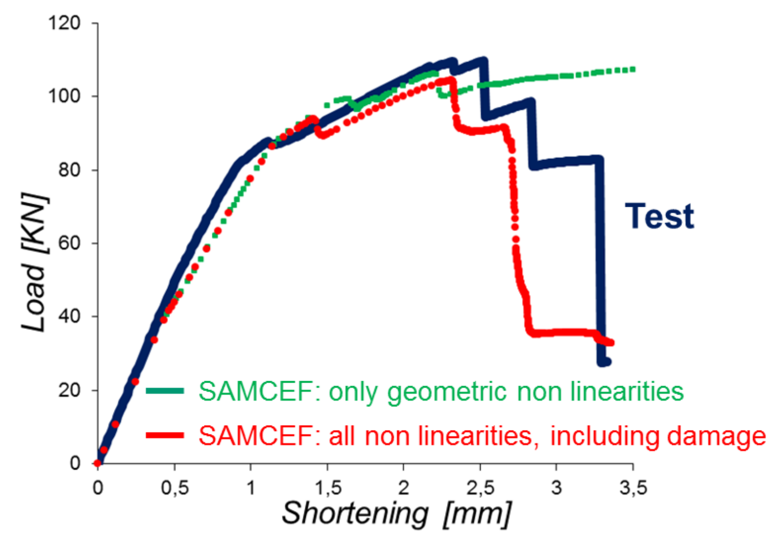
Challenges

- Investigate the non-linear behavior of thon-walled composite structures
- Damage, buckling, post-buckling, collapse
- Develop a predictive model to further optimize the design



Solution

- LMS Samtech Samcef Mecano, non-linear finite element solver



Results

- Better knowledge of the composite structure performance
- Virtual prototype, then used to develop:
  - A safer design
  - A lighter design

Skin/stiffener separation

Damage inside the ply

Illustration 4
Airbus Helicopters
Airbus Group Innovations

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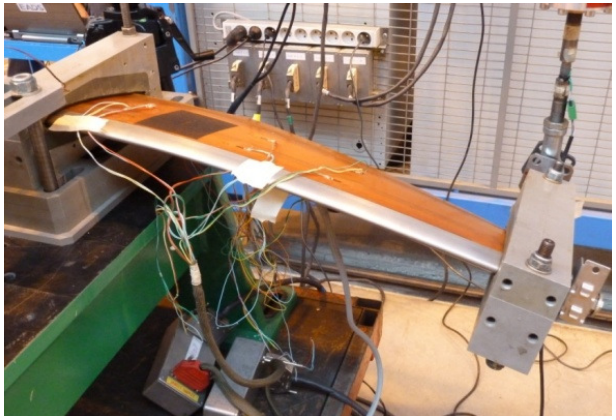
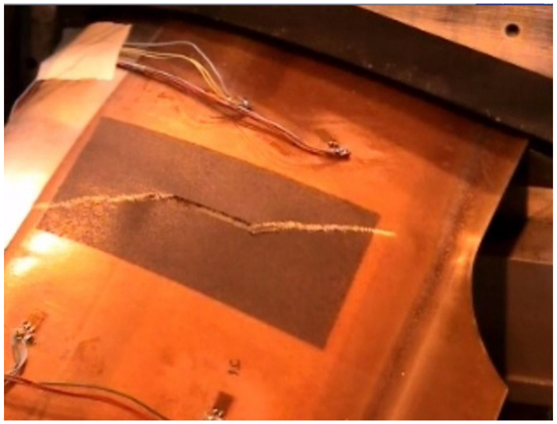
Source : Galucio et al., ECCOMAS Composite Conference, 2011

Challenges

- Reliable solution procedure for damage analysis at the component level
- Developmet of predictive damage models
- Specific case of a pre-craked helicopter blade



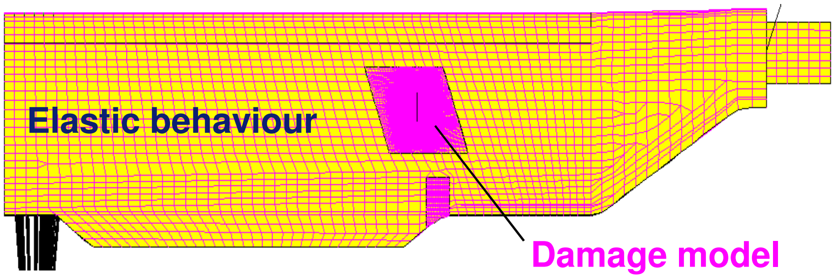


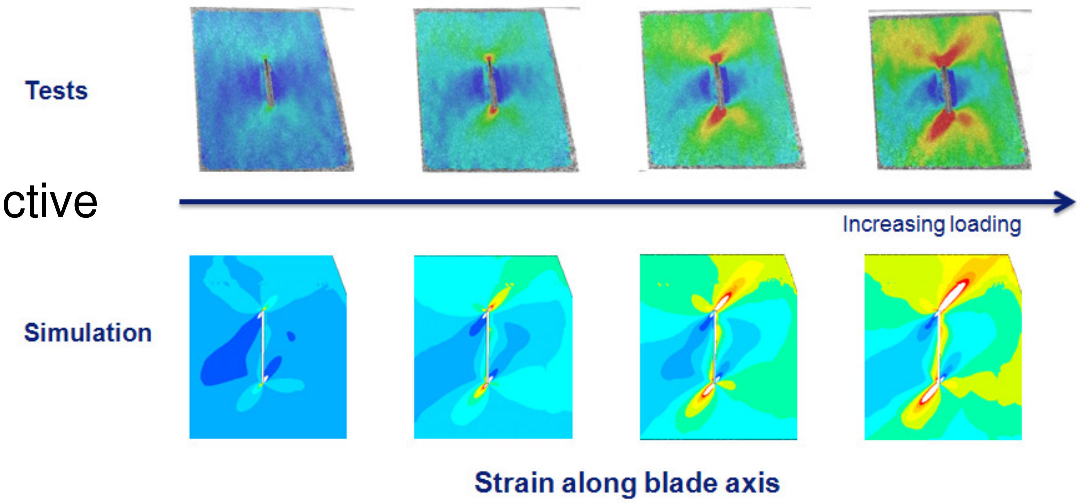
Solution

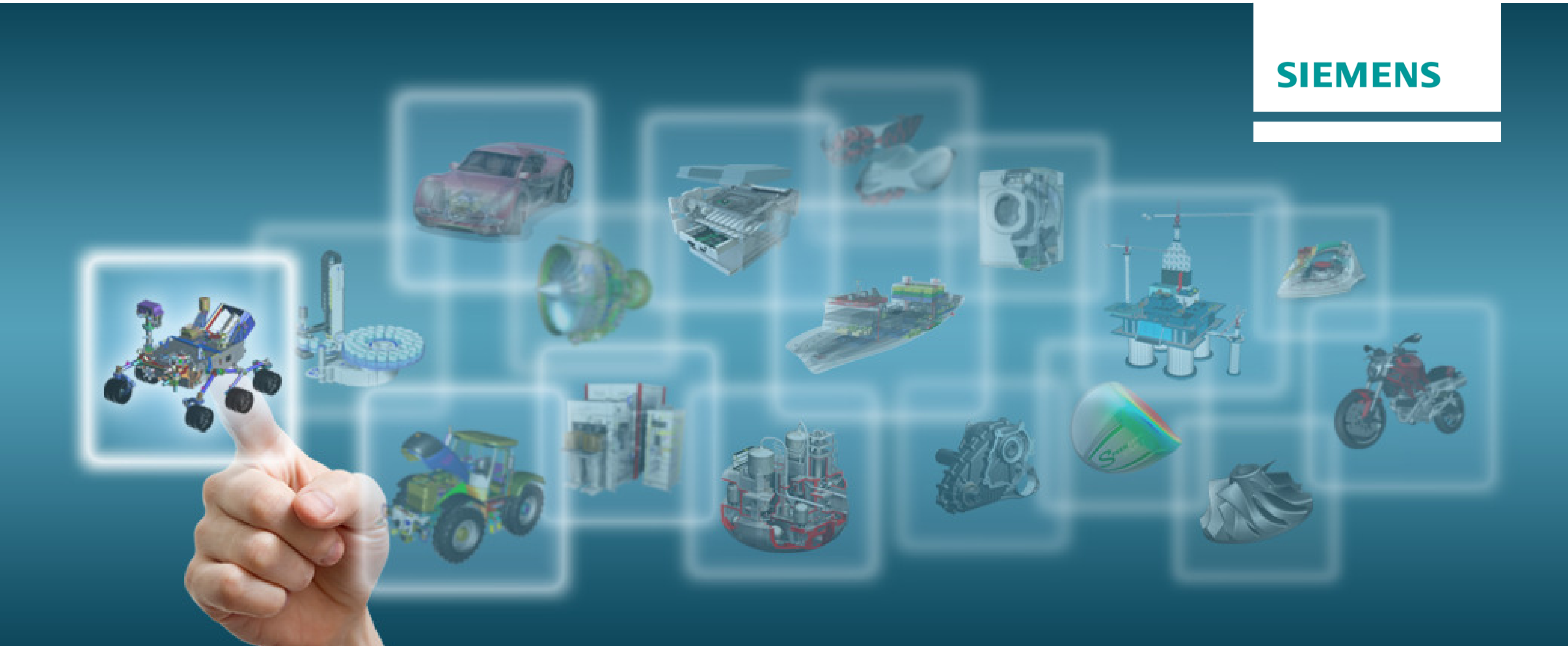
- LMS Samtech Samcef Mecano, non-linear finite element solver

Results

- Validation at the component level of the predictive damage models of LMS Samtech Samcef







Advanced composites analysis

Extensions of the work

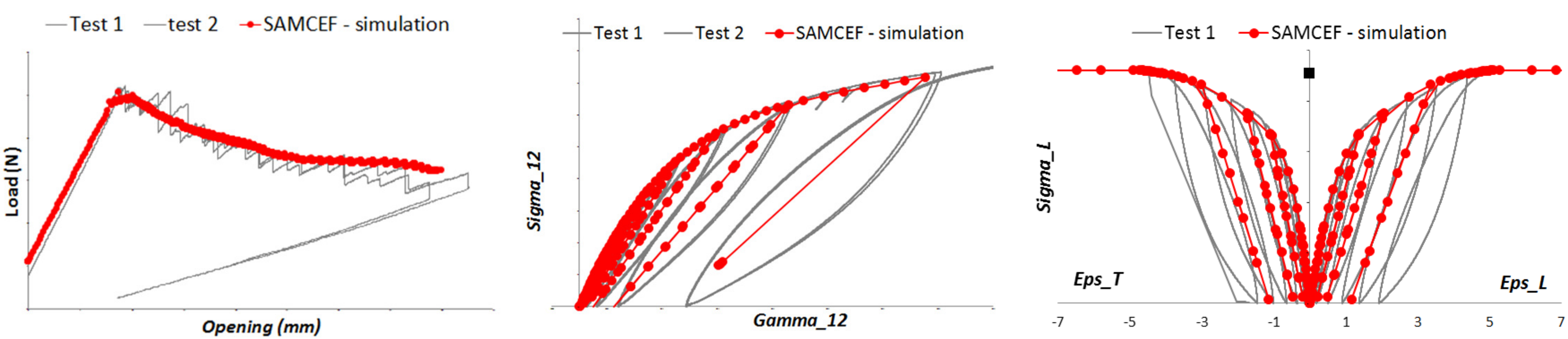
Extensions of the work

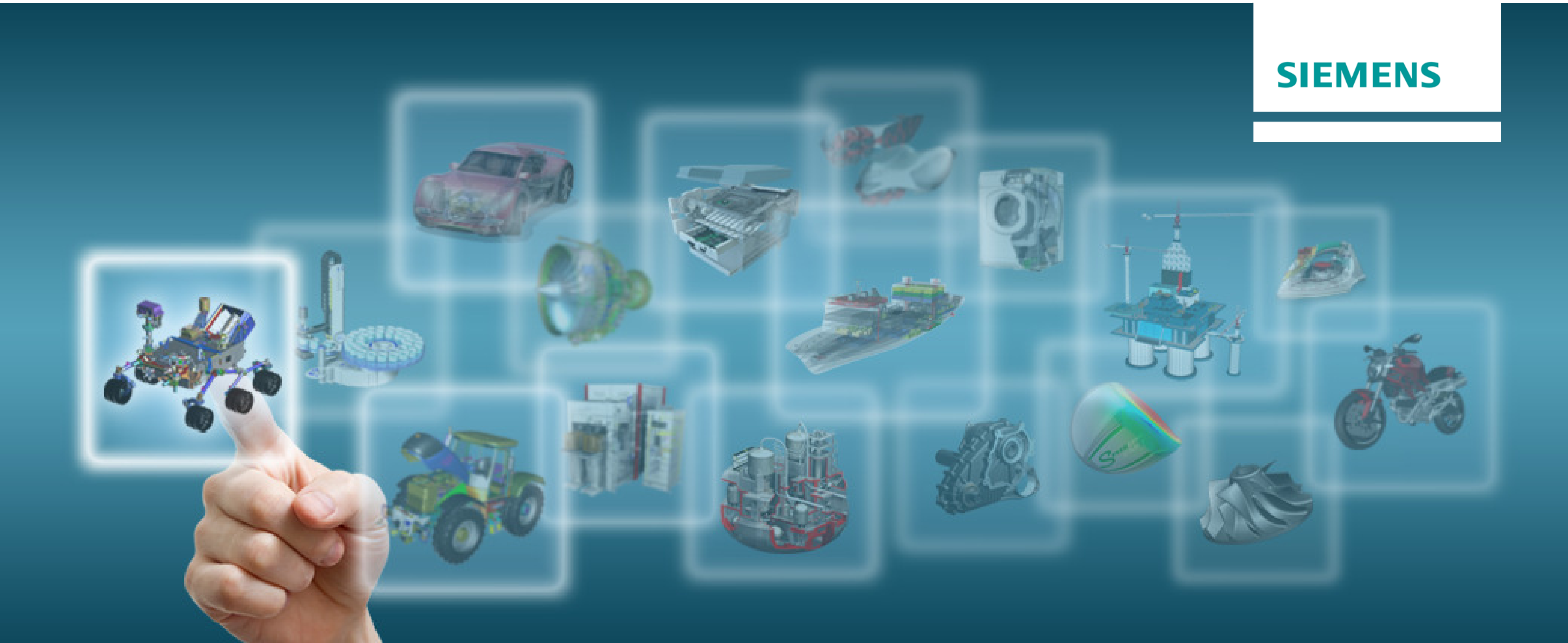
Source : Bruyneel et al., ACOMEN Conference, Ghent, 2014

- The solution procedure was applied to NCF and woven fabrics
- Here, an illustration for woven fabrics

⇒ Inter-laminar damage (model: Cachan, Allix & Ladevèze)

⇒ Intra-laminar damage (model: Marseille, Hochard)





Advanced composites analysis

Conclusions

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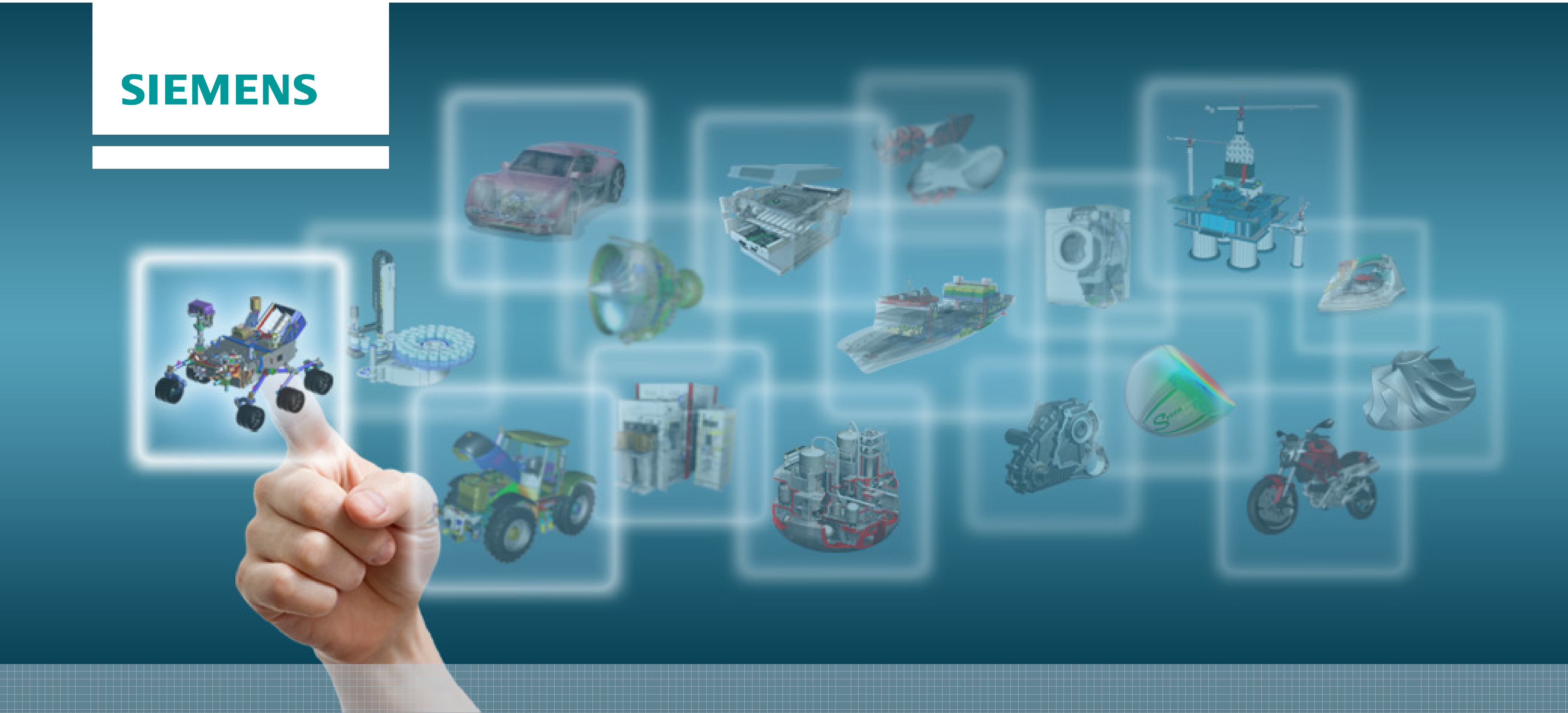
Conclusions

- Minimum weight ⇔ use of the full capacity of the composite materials
- Damage appears and should be controlled in the sizing process
- Simulation can help => need for predictive models becoming companions of the physical tests (virtual twin)
- Physical testing + virtual testing: need to define the material models parameter identification
- Today, the simulation tools for composite structures have reached a certain level of maturity, and can be predictive
    - For static analysis
    - Not yet for fatigue analysis; not yet for crash analysis
- Even if good results can be obtained today for the static case, research is still necessary for these 3 attributes



Thank you for your attention

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