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Design Analysis of GRP Panels

The Roof of the Haramain High Speed Railway (HHR) Jeddah Station

Foster + Partners · SAUDI OGER LTD. · CALCUL CONCEPTION EXPERT FORMATION Méca · COHMAS · SOCOTEC · CRITT mécanique & composites · Institut Clément Ader

MECA : in short

Material and structural design analysis

Meca's team : 20 engineers and technicians

- 7 structural engineers
- 5 design engineers
- 2 experts (insurance and administration)

CAD and structural software

SolidWorks, Catia V5,Inventor, Pro Eng
Cosmos/M, Nastran, ADINA, HyperMesh

Meca technical skills in composite materials have been accredit by French administration for the research and the industry.

Great Stadium of Lille, France (EIFFAGE Society)

CAD, drawings, design

Structural analysis of composite structures

Assessment of execution methods

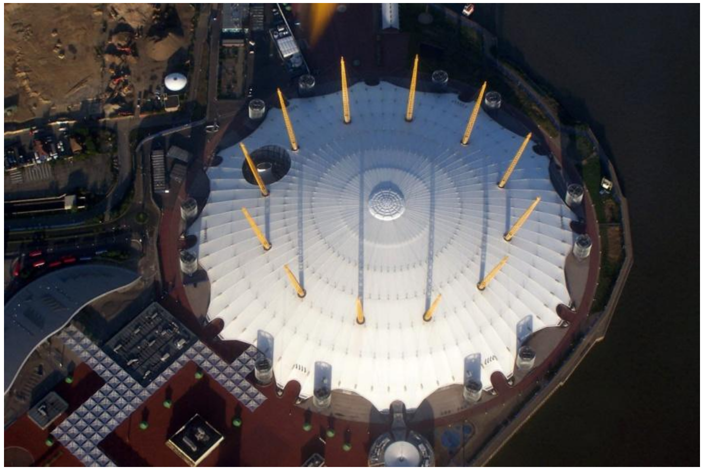
Outline

- HHR Project / The Jeddah station
- Structural Design Guidelines
- Particular aspect of FRP design for buildings structures
  - Material properties prediction
  - Moisture effects
  - Safety factors and failure modes
  - Creep of FRP structures
  - Global / Local method according to failure modes
- Criteria and damage approaches for FRP buildings structures
  - Energetic / Phenomenological failure criteria
  - Progressive damage mechanics
- GRP Panel
  - Mock Up

Sandwich materials in building construction

DXB Airport, Dubai (1972)

Mondial House, London (1975)



Millennium Dome (O_2 Arena), London (2000)

Dome of Central Library PNU, Riyadh (2010)

HHR – Jeddah Station Project

- The Haramain Railway project in figures

  450 km of high-speed track

  60 million passengers each year

  5 train stations

  11.2 Billion USD

  FOSTER + PARTNERS (London, United Kingdom)

  DAR al Handasah (Beyruth, Liban)

- Partners of the HHR Jeddah Station project

  SAUDI OGER (Riyadh, Saudi Arabia)

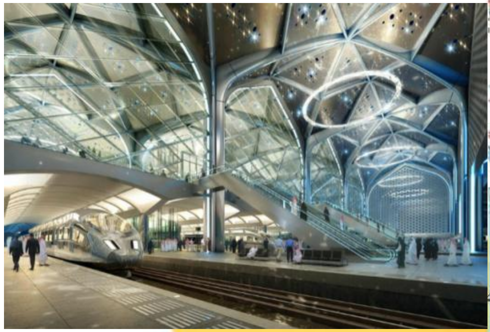
  CALCUL MECA (Nantes, France)

  COHMAS Laboratory (Thuwal, Saudi Arabia)

  SOCOTEC (Paris, France)

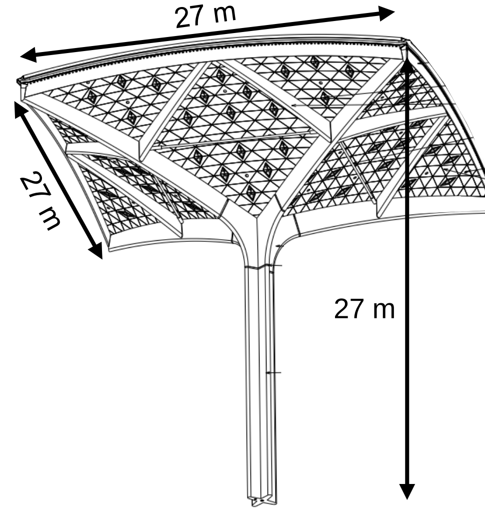
  CRITT (Toulouse, France)

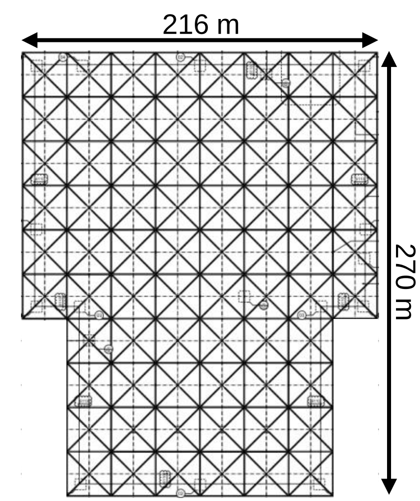
  CLEMENT ADER Institute (Toulouse, France)



HHR roof

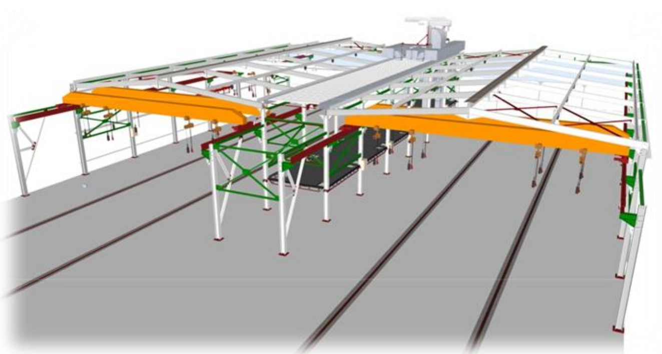
- One station: 58000m²
- Characteristics
  - Self supported roof, span 27m,
  - Insulated panels: structural foam act as thermal foam U < 0.25W/m²K
  - Fire specifications (ASTM E84): Flame index < 250
    Smoke index < 450
  - Erected with false ceilings, mosaic tiles and equipments (erection benefits)
  - Only 56 kg/m² with equipments (naked panel: 24 kg/m²)
- 2 panels manufactured and erected per day
  - Industrial process for building construction
  - 288 composite panels
  - 72 modules
  - Factory built close to the station





HHR drawings (Foster+Partners, 09)

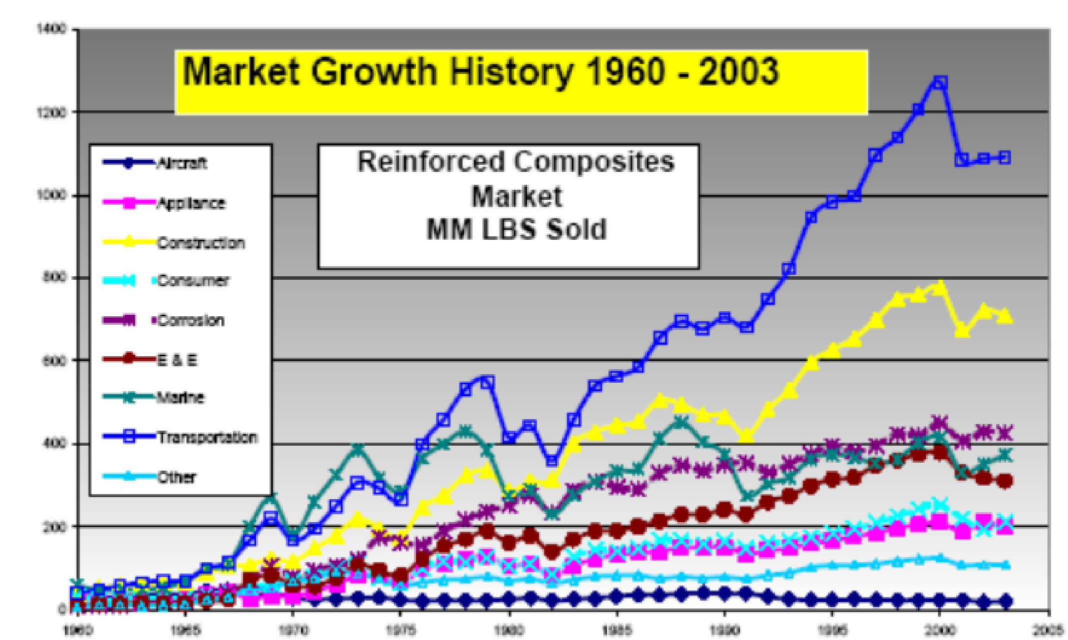
Top of the Jeddah Station



Standards

- European civil engineering standards
  - Eurocode 2: Concrete structures
  - Eurocode 3: Steel structures
  - Eurocode 5: Timber structures
  - Eurocode 9: Aluminum structures

- Example of standards for composite materials
  - EN 13121: GRP pressure vessels
  - ISO 14692: GRP piping offshore



Evolution of FRP market share (American Composite Manufacturing Association)

- Lack of GRP standard for building structures
  - EuroComp book – Design Guide
  - JRC (European commission)

Purpose and justification for new design standards regarding the use or FRP in civil engineering

Design comparison between metallic and composite structures

	Metallic structure	Composite structure (FRP)
Standards or references	Eurocodes	EuroComp book / Eurocodes
Behavior	Isotropic	Anisotropic lamina & Stacking
Failure analysis, stress criteria	Von Mises / Tresca	Tsaï-Wu / Puck
Effect on material properties	Thermal	Thermal, Moisture
Long term effect	Fatigue, corrosion	Creep

Structural Design Guidelines

- Materials characteristics
  - Orthotropic behavior (fiber ratio, void content, stacking)

Stiffness and Strength prediction prior manufacturing and tests

Micromechanics (Halpin-Tsaï model)

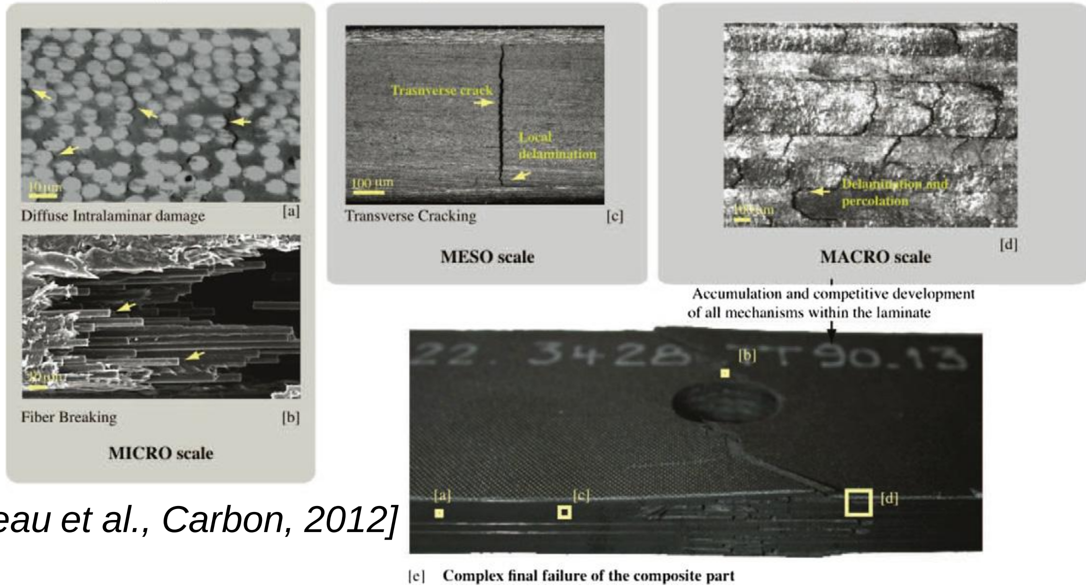
  - Influence of temperature on mechanical properties and thermal expansion
  - Influence of moisture on mechanical properties and moisture expansion

- Creep analysis
  - Long term effects: Temperature / Permanent loading
  - Bending creep analysis: measurement of the deflection

Structural Design Guidelines

- Laminates Failure modes
  - Fiber Failure
  - Inter Fiber Failure

Associated Safety Factors



[Lubineau et al., Carbon, 2012]

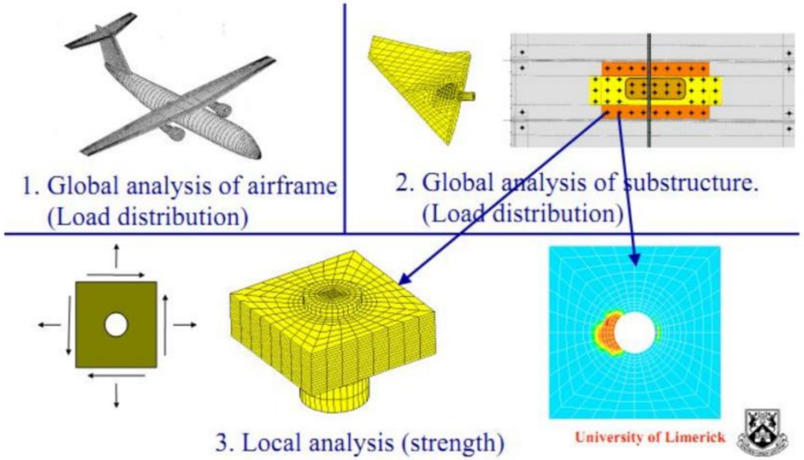
- Materials Safety Factors (according to EuroComp book)

Safety factor	Description
γ_{m1}	Derivation of material properties from test values
γ_{m2}	Material and production process
γ_{m3}	Environmental effect and duration of loading
$\gamma_m = \Pi\gamma_{mi}$	Safety factor for materials properties at ULS

Global-Local Method

<u>Series approach:</u>

Global analysis first, then transfer BCs to local model

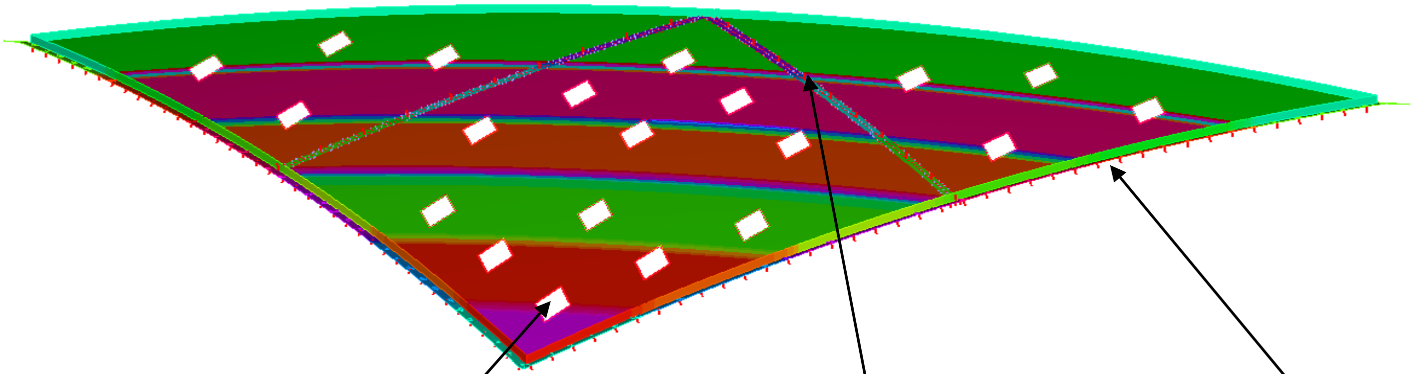


Global and local analysis (McCarthy, 03)

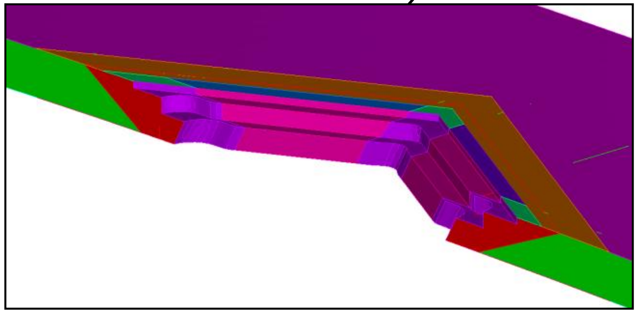
Global Analysis (multi-Layer 2D FEA)	Local Analysis (3D FEA)
Overall panel behavior	Boundary Conditions from ULS global model
SLS: Deflection criterion ULS: In-plane failure criteria (Layerwise)	3D stress state -> In-plane failure criteria (Classical Laminate Theory, CLT)
Lack of accuracy: discontinuity, through thickness stresses	ILSS calculation

Global-Local Method

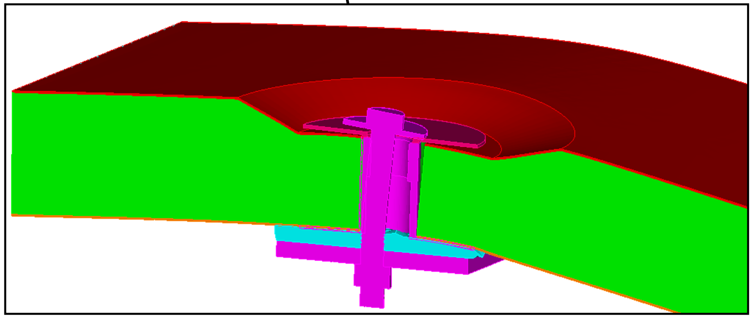
- Multi-Layer shells model



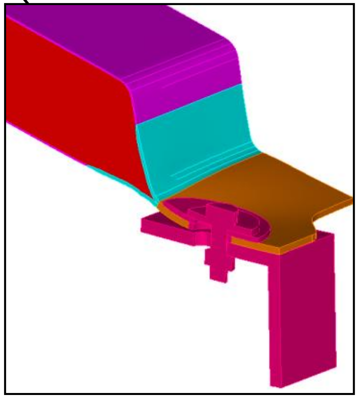
- 3D local models



Antiglare frame



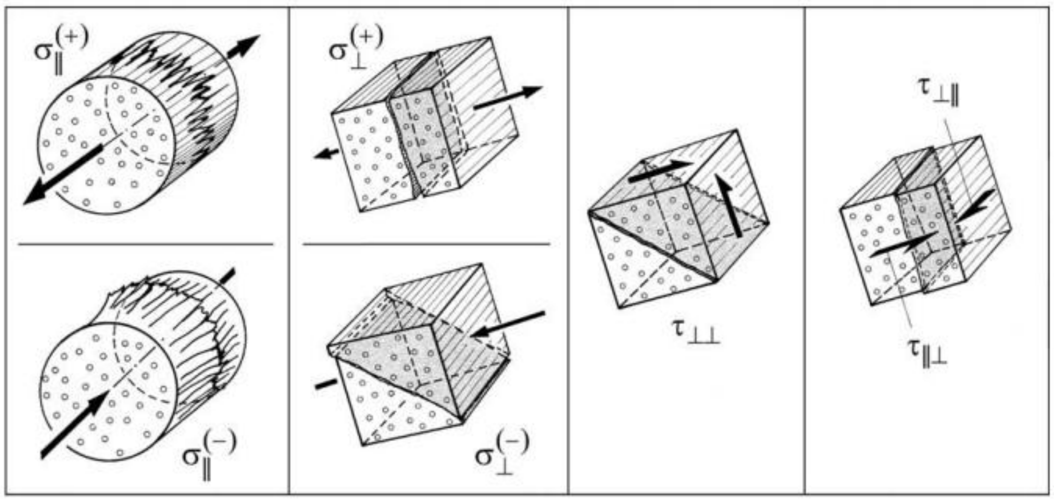
Supports on secondary beams



Supports on primary beams

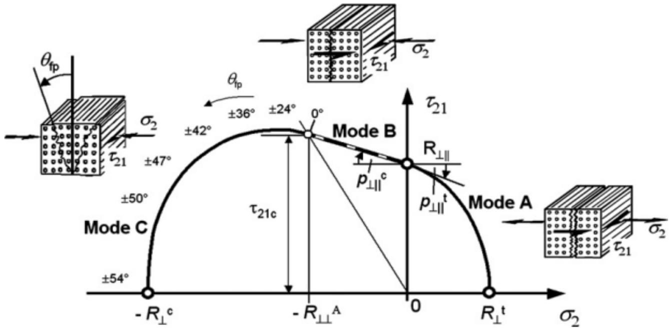
GRP skins: Failure criteria

Energetic criteria	Phenomenological criteria
Do not distinguish the failure mode	Criterion for each lamina failure
Quadratic formulation of the stress tensor	Interactive: Interaction between stresses/strains acting on a lamina
First ply failure criterion	Failure associated to mechanisms
Tsaï-Wu, Tsaï-Hill	Puck, Cuntze , Zinoviev

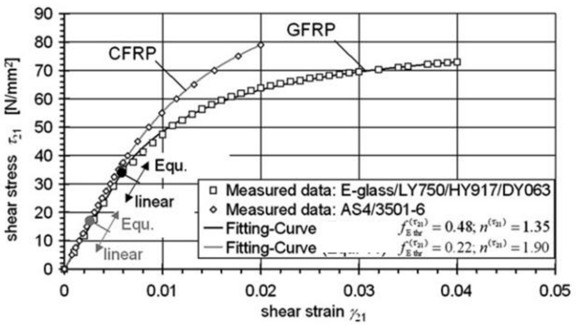


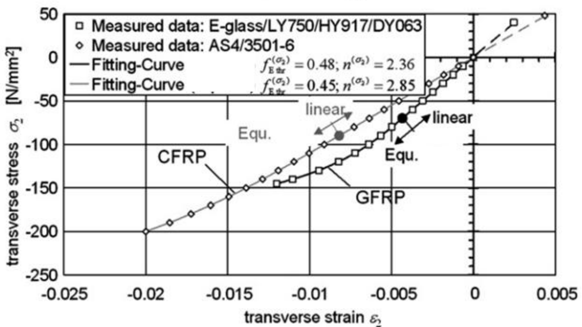
Basic stressing of the UD-Lamina and corresponding fracture planes (Knops, 06)

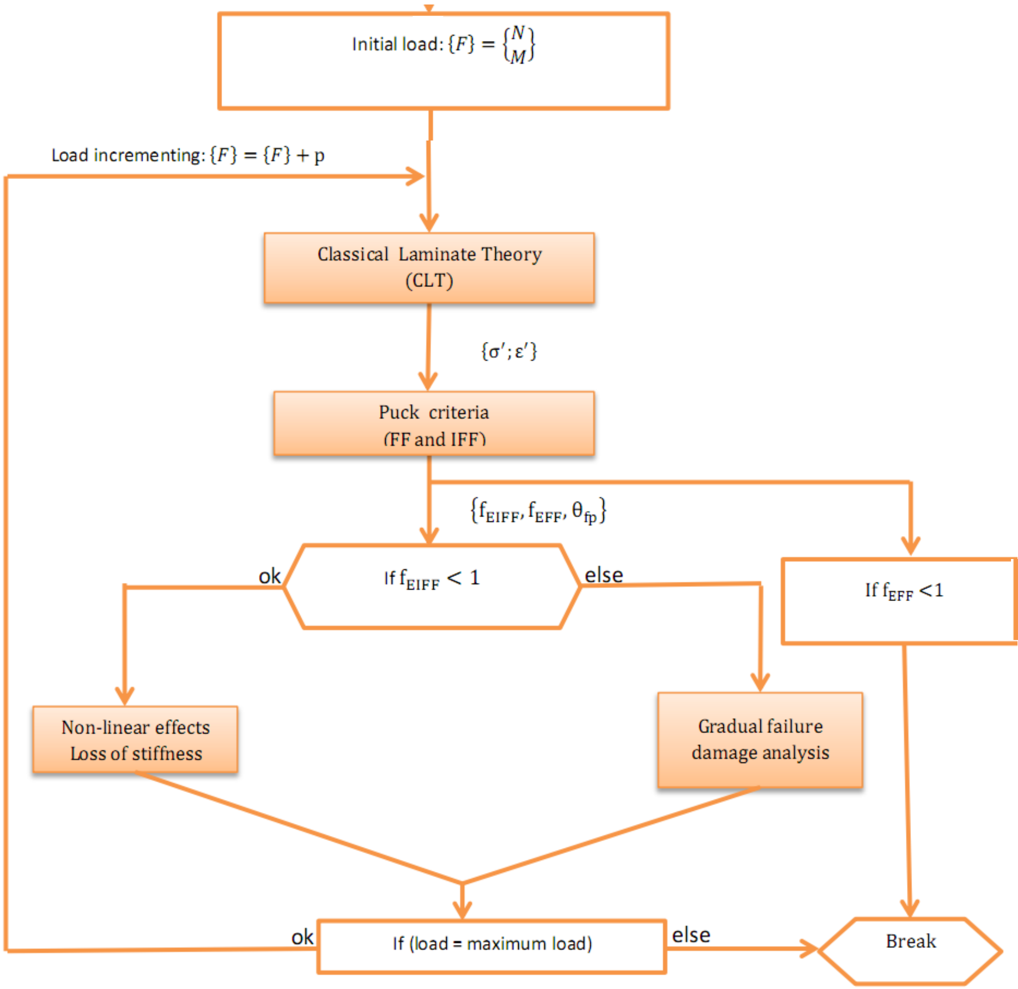
Puck's Failure Theory
Progressive Behavior up to Final Failure



Predicted fracture curve from Puck's IFF criterion (Puck & Mannigel, 07)





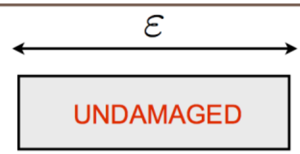


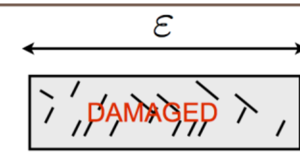
Progressive damage mechanics

- Alternative approach capable of predicting the nature (mechanism) of the degradation and its evolution **beyond the first ply failure**
- Concept **initially developed for isotropic damage**:

  - Describing every single crack in the laminate is impossible (two complex, two many uncertainties).

  - Damage mechanics GLOBALIZES everything (the degradation is quantified using a representative “internal” variable).





Initial strain energy density e_d^0

Damage strain energy density e_d

$$e_d^0 = \frac{1}{2}\sigma \cdot \varepsilon = \frac{1}{2}\sigma \cdot \frac{\sigma}{E_0}$$

$$e_d = \frac{1}{2}\sigma \cdot \varepsilon = \frac{1}{2}\sigma \cdot \frac{\sigma}{E}$$

Initial stiffness

$$\boxed{E = E_0(1-d)}$$

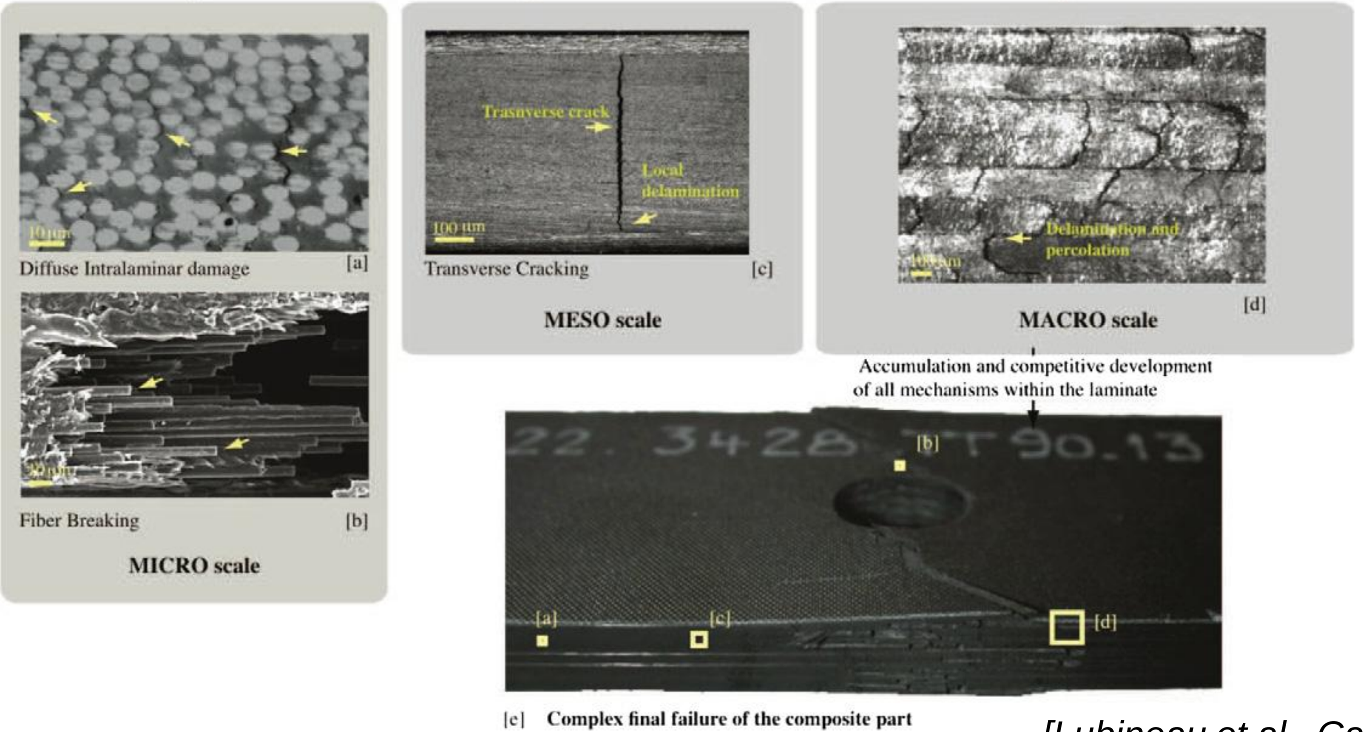
Damaged stiffness

Progressive damage mechanics

- **Application to the composite skins: challenge?**

- complexity/multiplicity of damage mechanisms in laminated composites

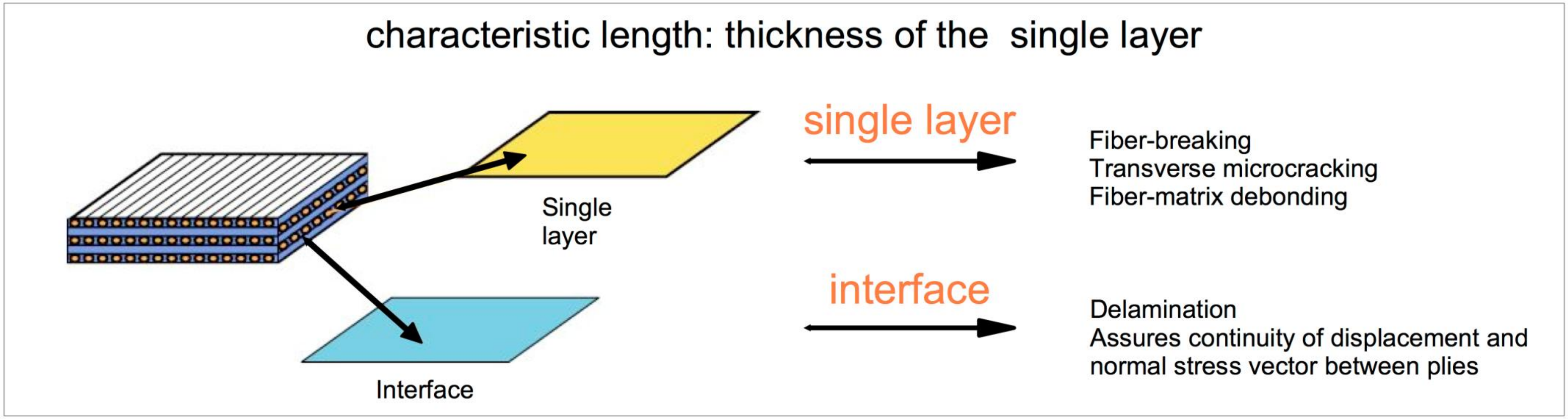
- highly induced anisotropy.



[Lubineau et al., Carbon, 2012]

Progressive damage mechanics

- **A pragmatical model:** meso scale damage mechanics



Hyp 1: the behavior of any structure up to he final failure can be predicted from the behavior of two “mesoconstituents” which are continuum media: the single layer and the interface

Keypoint: the damage behavior of each mesoconstituent is “intrinsic”. It does not depends on the exact stacking sequence and can be identified on reference laminates.

[Ladeveze, 86; Ladeveze and Le Dantec, 92]

Intralaminar model

- **Elastic energy (plane stresses)**

$$e_d = \frac{1-d_f}{2}\left[\frac{\langle\tilde{\sigma}_{11}\rangle_+^2}{E_1^0} + \frac{\phi\left(\langle\tilde{\sigma}_{11}\rangle_-^2\right)}{E_1^0} - \left(\frac{\nu_{12}^0}{E_1^0} + \frac{\nu_{21}^0}{E_2^0}\right)\tilde{\sigma}_{11}\tilde{\sigma}_{22}\right] + \frac{1-d'}{2}\left[\frac{\langle\tilde{\sigma}_{22}\rangle_+^2}{E_2^0}\right] + \frac{1}{2}\left[\frac{\langle\tilde{\sigma}_{22}\rangle_-^2}{E_2^0}\right] + \frac{1-d}{2}\left[\frac{\tilde{\sigma}_{12}^{\,2}}{G_{12}^0}\right]$$

- **Damage kinematics:**

  d_f: fracture of the fiber
  d, d': microcraking of the matrix and matrix/fiber debonding

- **Damage forces and evollution laws:**

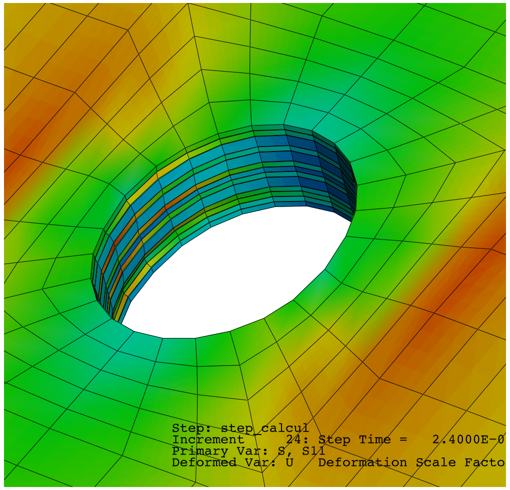
$$Y_d = -\rho\frac{\partial}{\partial d}\left[\text{free energy}\right]\Big|_{\tilde{\sigma}=\text{cst}} = \frac{1}{2}\left[\frac{\left[\!\left[\tilde{\sigma}_{12}^{\,2}\right]\!\right]}{G_{12}^0}\right]$$

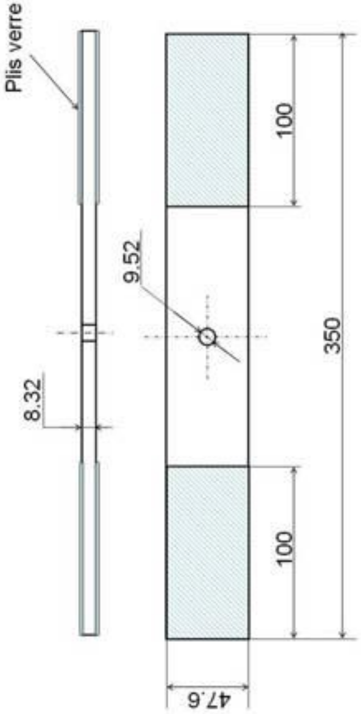
$$Y_{d'} = -\rho\frac{\partial}{\partial d'}\left[\text{free energy}\right]\Big|_{\tilde{\sigma}=\text{cst}} = \frac{1}{2}\left[\frac{\left[\!\left[\langle\tilde{\sigma}_{22}\rangle_+^2\right]\!\right]}{E_2^0}\right]$$

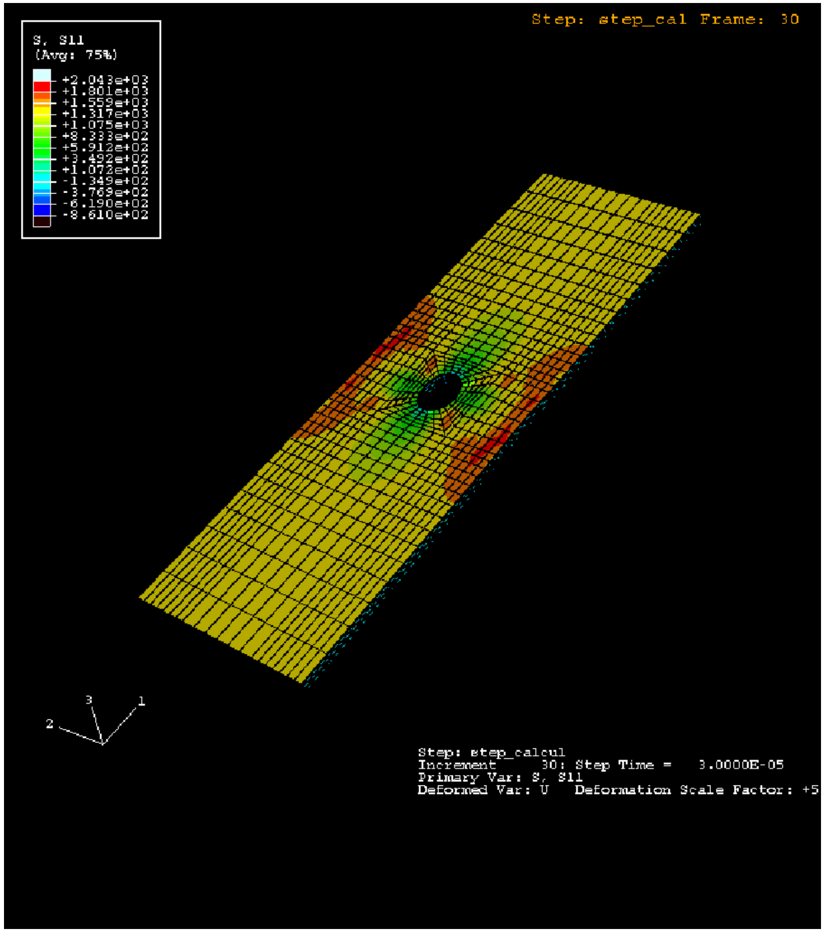
$$Y_f = -\rho\frac{\partial}{\partial d_f}\left[\text{free energy}\right]\Big|_{\tilde{\sigma}=\text{cst}}$$

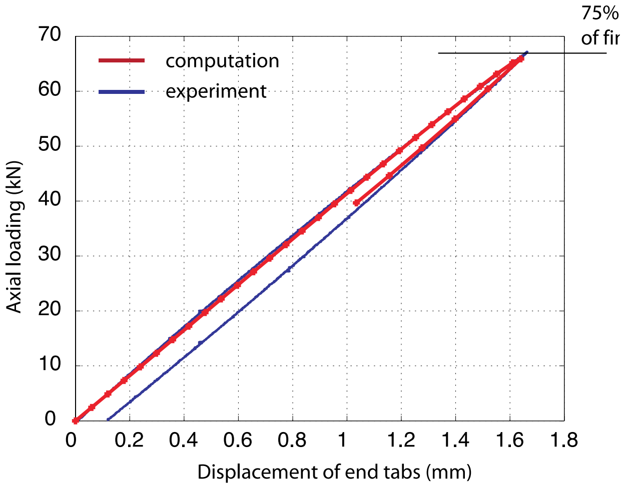
$d_f \longleftrightarrow (Y_f, Yd)$
$d \longleftrightarrow (Yd, Yd')$
$d' \longleftrightarrow (Yd', Yd)$

Example of meso scale predictions









Design of an identification and validation campaign

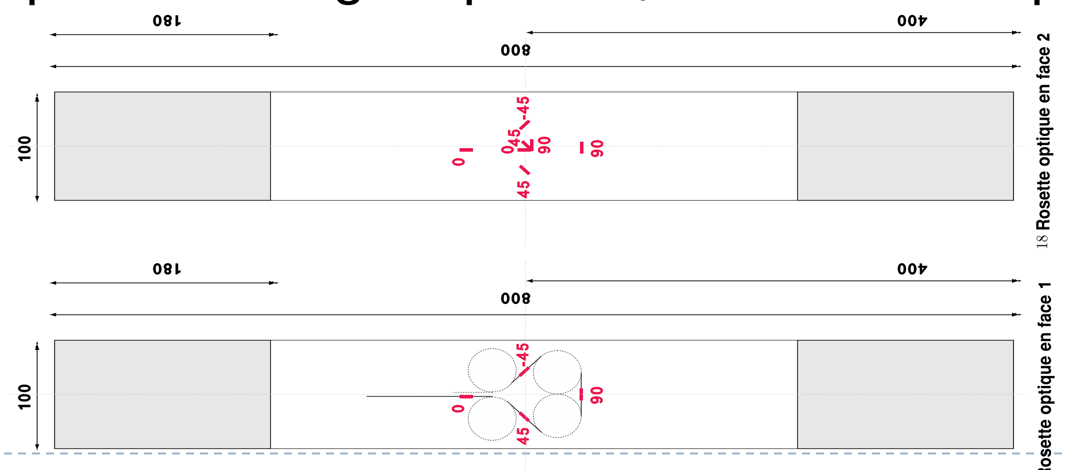
- **<u>Identification campaign currently running at the CRITT:</u> macroscopic stress/strain curves + NDT evaluation (acoustic emission and Xray-2D)**

    - shear:[45/-45]ns, shear/transverse behavior: [67.5/-67.5]ns

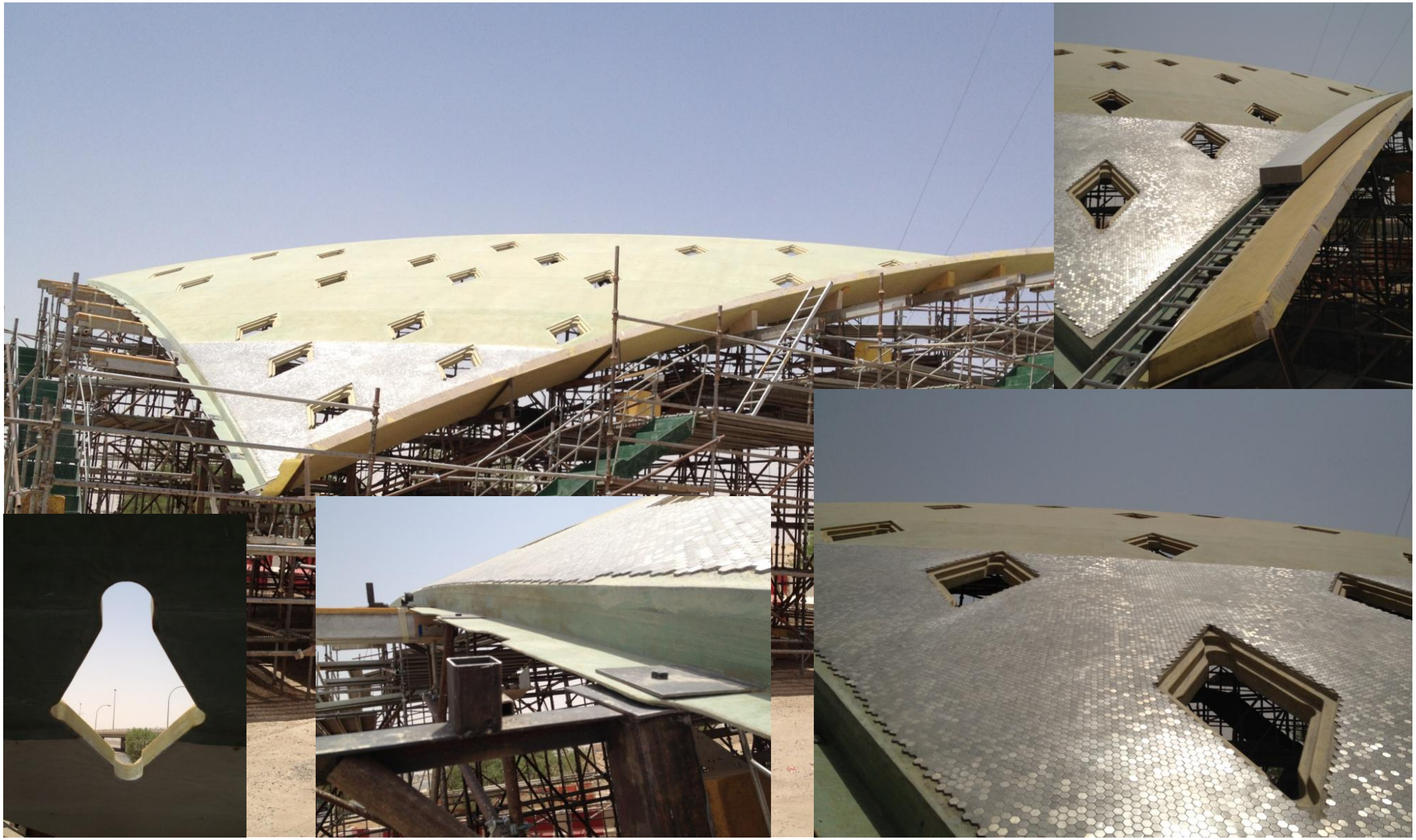
    - fiber behavior: [0]n

- **<u>Mechanical testing of the industrial lay up for validation:</u>**

    - Complex stacking sequence, validation of optical fibber



GRP Panel Mock-Up



THANKS FOR YOUR ATTENTION !