Incidence of the mechanisms of damage in the scale effect of composites involving Ultra Thin Plies

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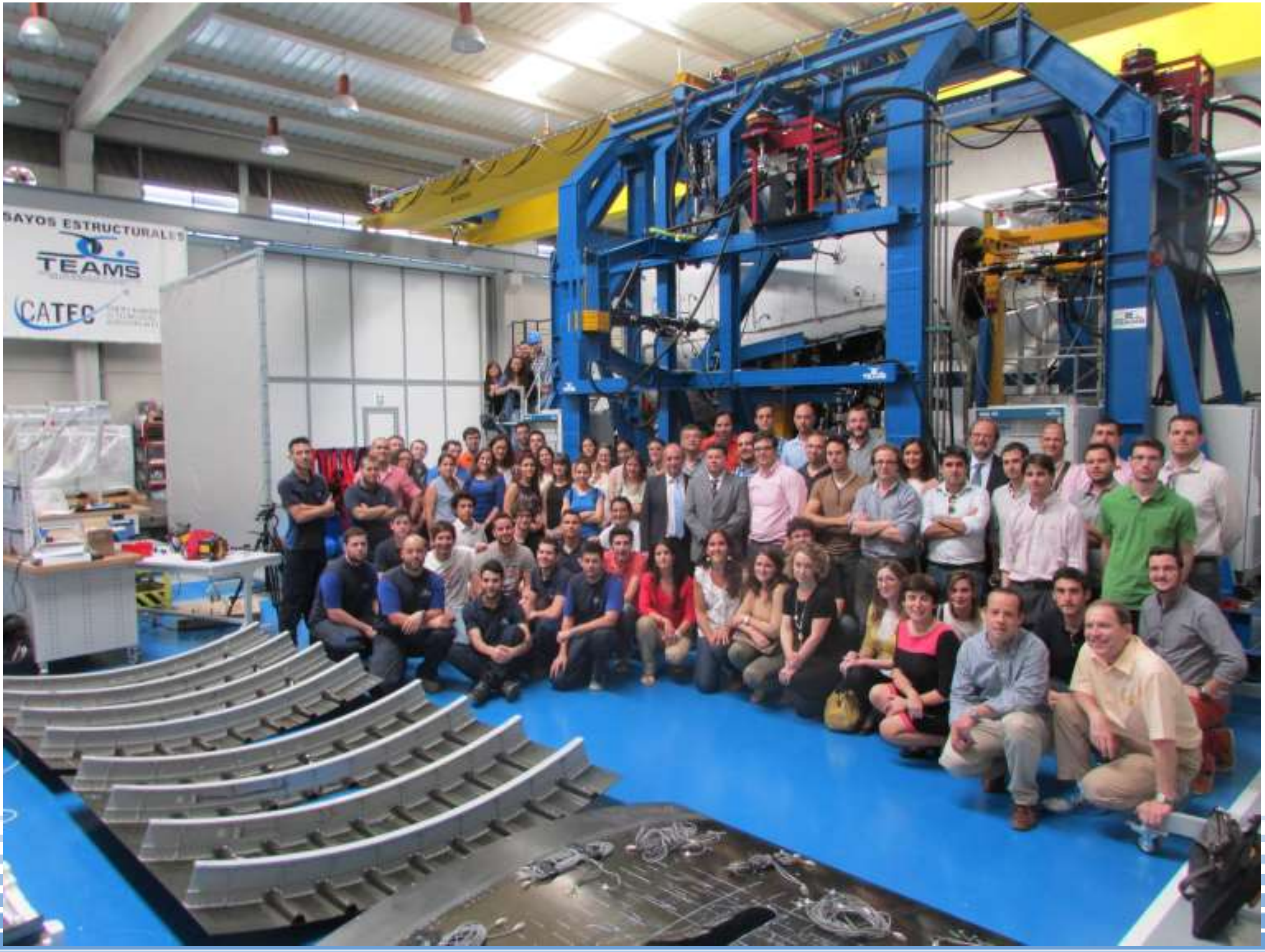
COMPTEST
Girona, May 30-June 2, 2023

THE BACKGROUND
FULL SCALE TEST OF TAIL CONE OF THE A350



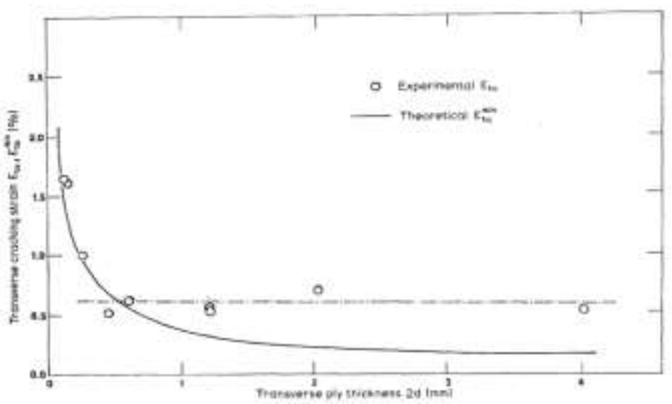
THE ORIGIN

Parvizi et al (1978)

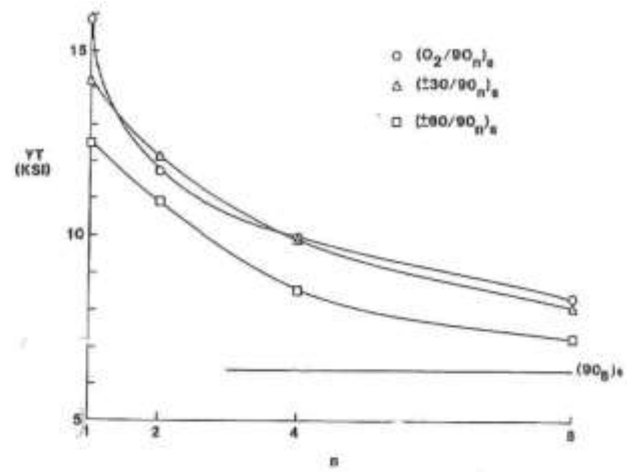
Glass fibre /epoxy resin
Detection Method: visual and acoustic emission

Flaggs and Kural (1981)

Carbon fibre /epoxy resin
Detection Method: x-radiographic inspection



Values of ε_{tu} as a function of ply thickness and experimental values of ε_{tu} for various ply thicknesses



In situ transverse strengths as a function of thickness and the orientations of the adjacent laminae.

The damages that appear were not specified, it was understood that the points in the graphics were associated with the apperance of a transverse crack in the 90 degrees lamina

GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES

THE APPROACH

NASA/CR-2001-210661

A Study of Failure Criteria of Fibrous Composite Materials

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George Washington University
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Langley Research Center
Hampton, Virginia

DAMAGE AND FRACTURE

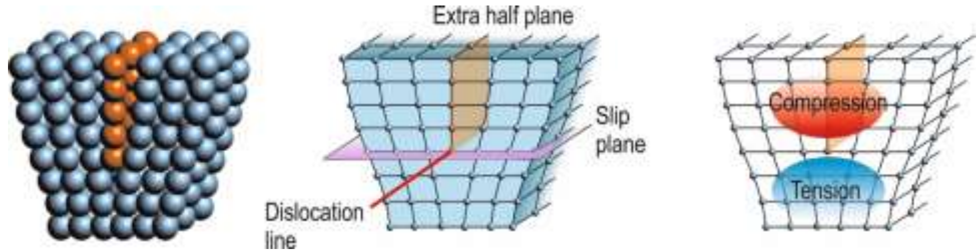
Damage: Alteration of the internal structure of the material abandoning the pristine state.

What is the key factor to predict damage?

Damage usually takes place at micromechanical level and typically we take homogenized models where the variables involved (stresses or strains for instance) are associated with homogenized (macromechanical) models of the material.

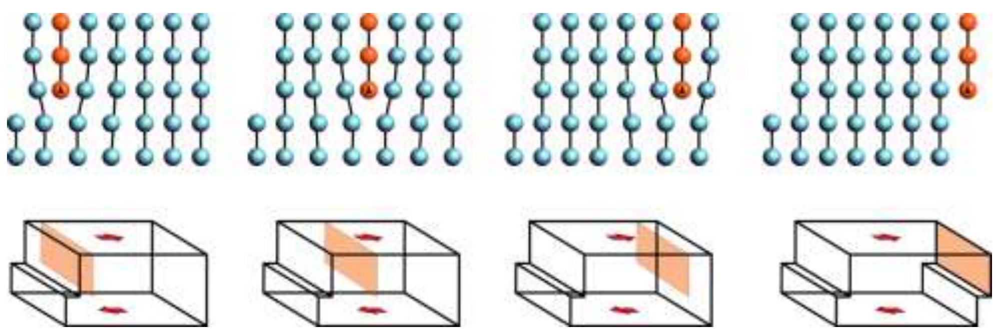
Then, in order to get success in representing the damage by means of variables associated with the homogenized material, we should have a physical connection between the damage at micromechanical level and the variable used to predict the damage at macromechanical level.

PLASTICITY IN METALS



Schematic representation of a dislocation

Movements of a dislocation:
final configuration of the material

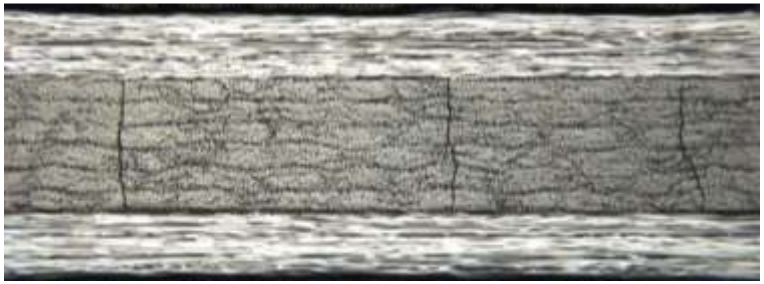


Von Mises criterion: $/s^{d}/ < \sqrt{2/3}\; s_{e}$

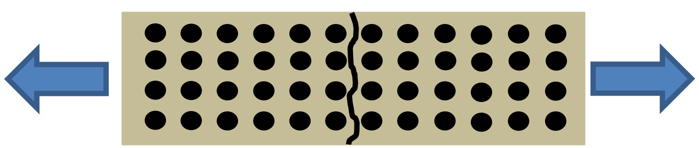
Hencky version: $U\left(s_{ij}^{d}\right) < s_{e}^{2} / 6G$

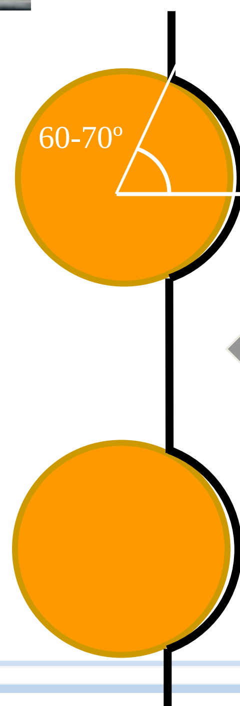
THE TOOL: MICROMECHANICAL STUDY OF TRANSVERSE FAILURE UNDER TENSION

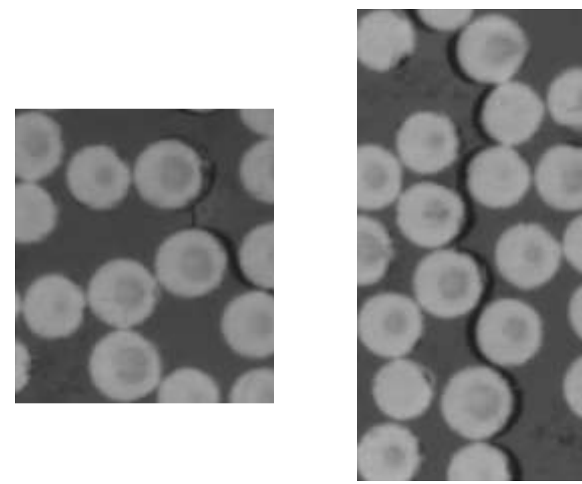
GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES



París, F., Correa, E., Mantič, V. Kinking of transverse interface cracks between fibre and matrix.Journal of Applied Mechanics-Transactions of the ASME74:703-716, 2007.



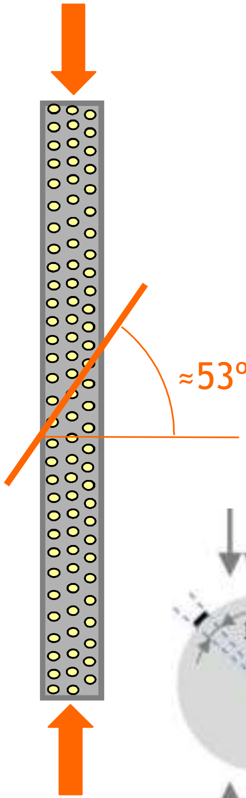


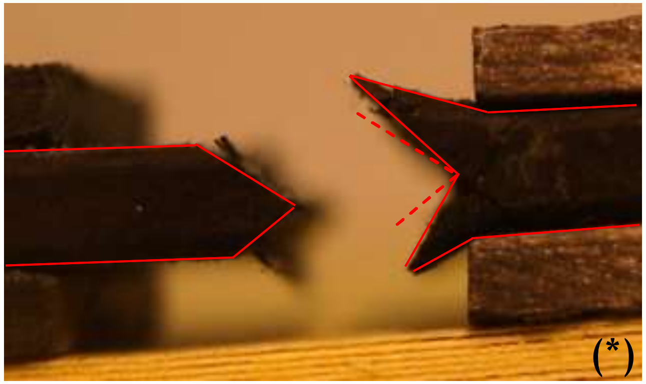


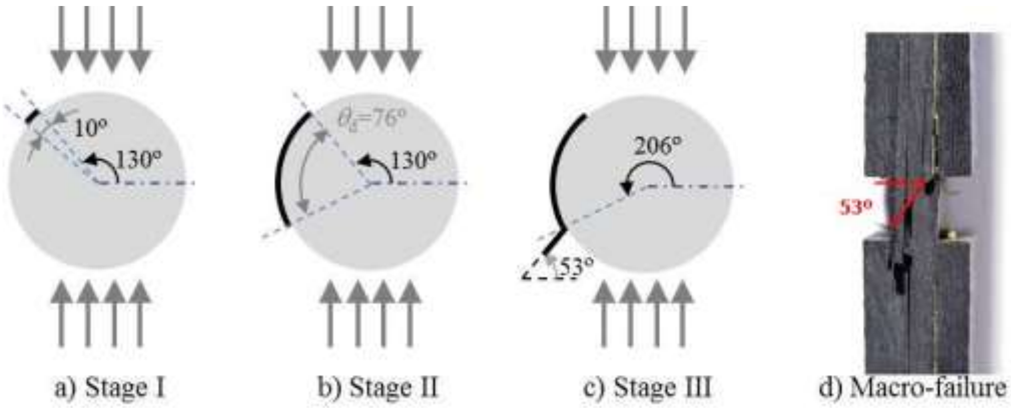
Numerical predictions

Experimental evidence

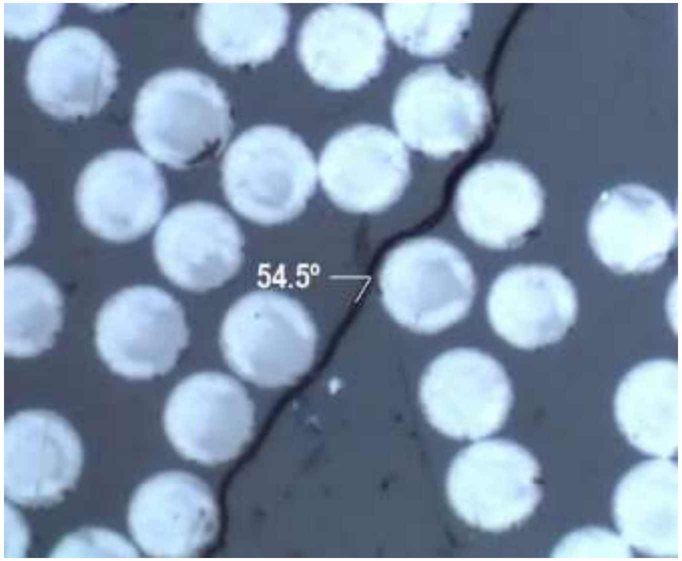
THE TOOL: MICROMECHANICAL STUDY OF TRANSVERSE FAILURE UNDER COMPRESION





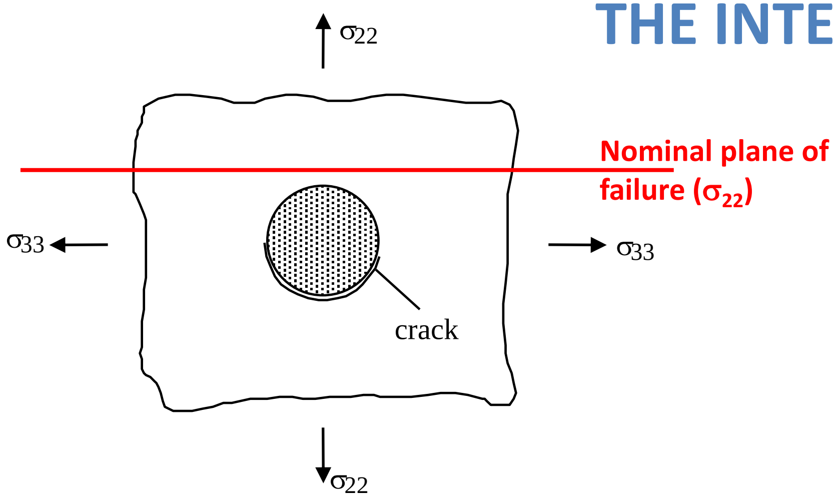


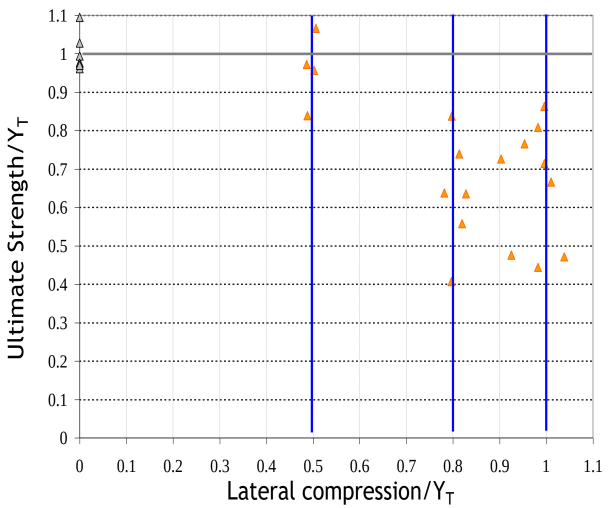
Experimental evidence

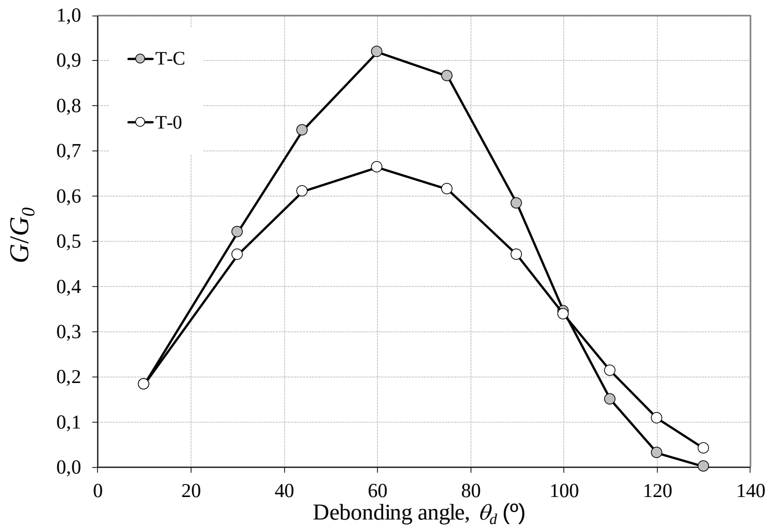


Correa E., Mantič V., París F., A micromechnical view of inter-fibre failure of composite materials under compression transverse to the fibres, Comp. Sci. Tech., 68, pp. 2010-2021, 2008.

THE TOOL: MICROMECHANIC EFFECT OF THE STRESS PARALLEL TO THE PLANE OF FAILURE IN THE INTERFIBRE FAILURE







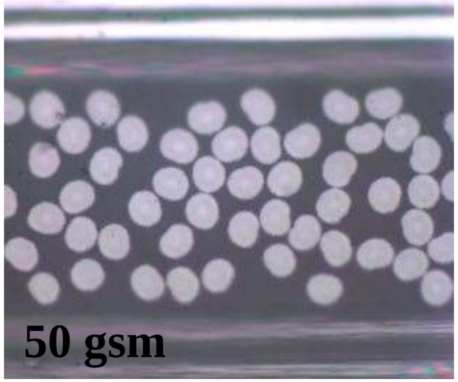
The presence of a lateral compression superimposed on the tension nominally responsible for the failure accelerates the fracture

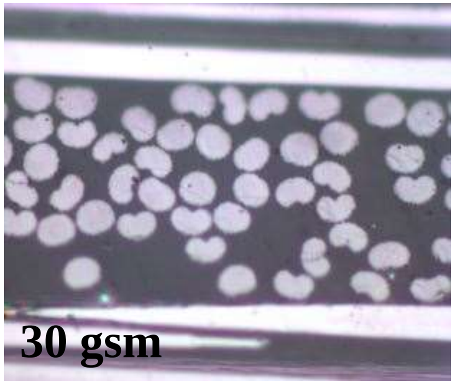
E. Correa, F. París, V. Mantič, Effect of the presence of a secondary transverse load on the inter-fibre failure under tension. Engineering Fracture Mechanics 103: 174-189, 2013.

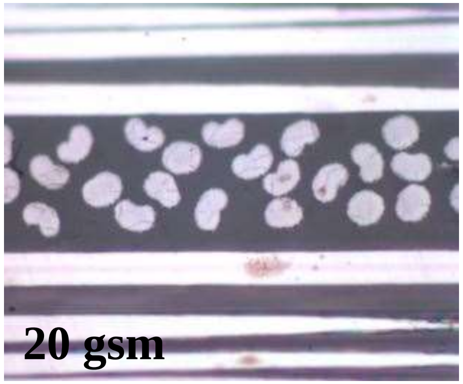
GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES

Ultra thin plies

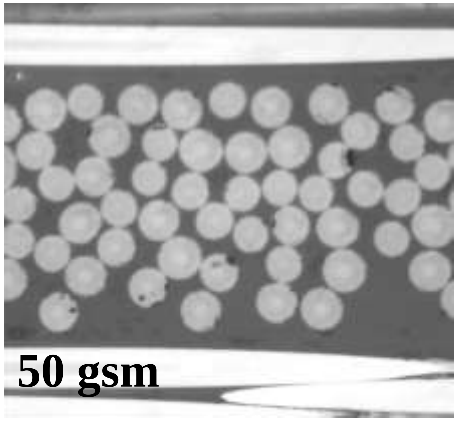
TRIPLE H COMPOSITES
UK SUPPLIER OF
SKYFLEX Carbon Prepreg

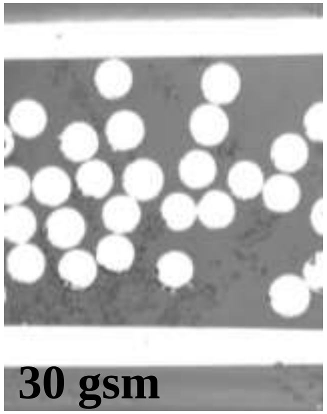




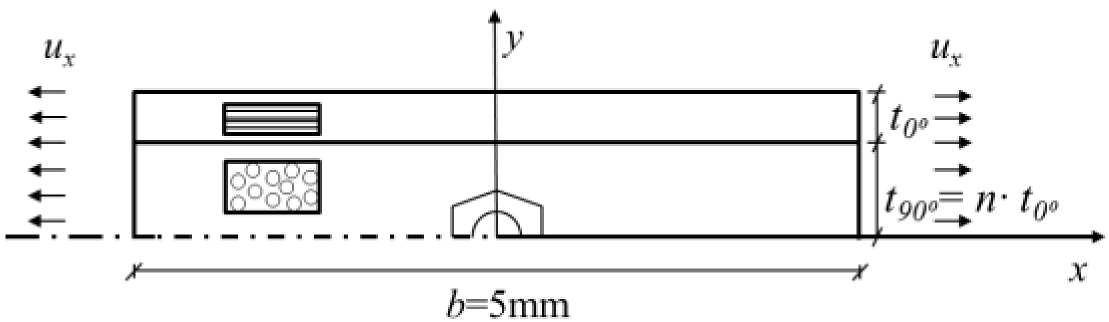


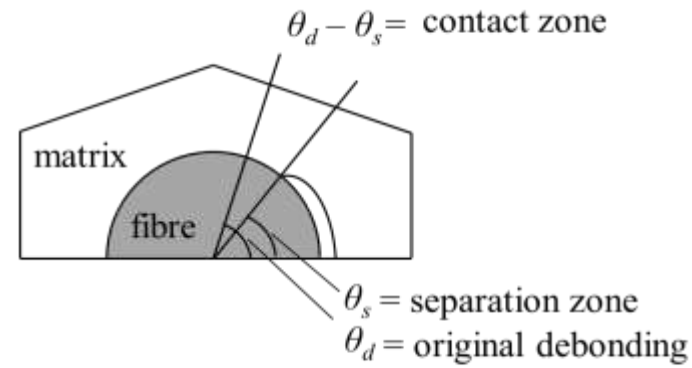
ntpt
North Thin Ply Technology

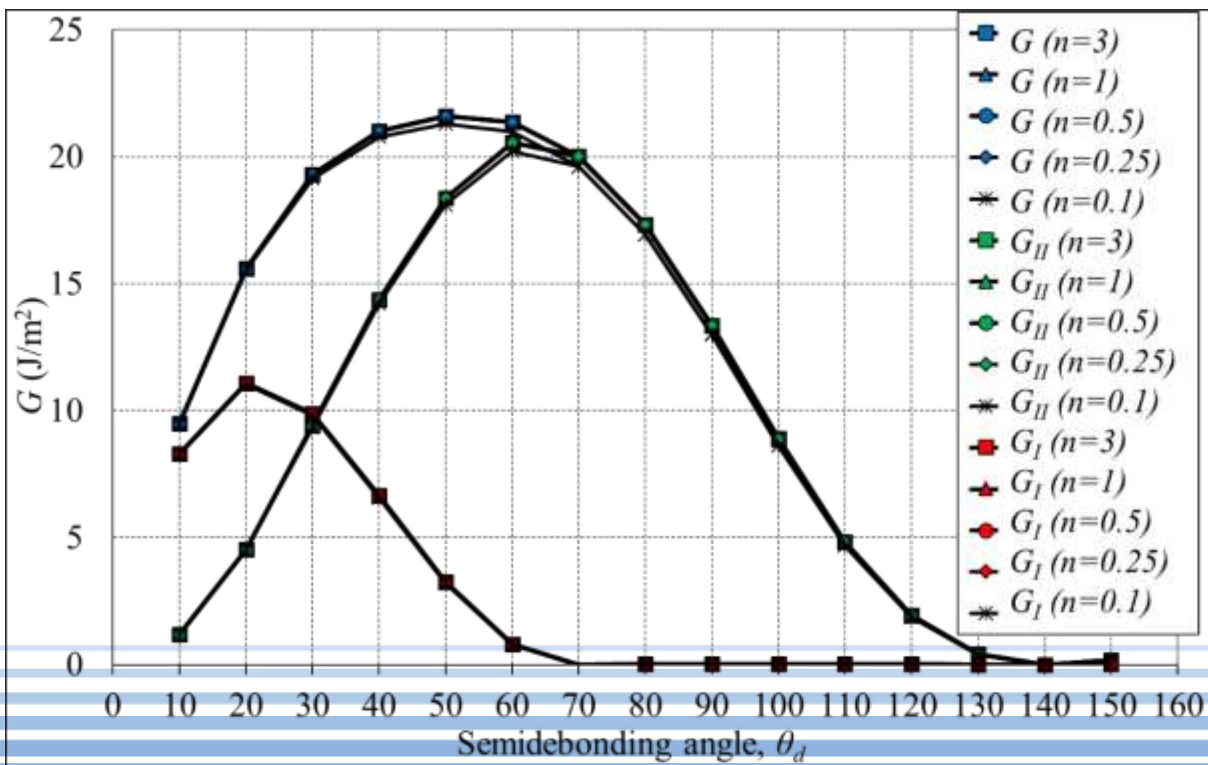




MICROMECHANICAL STUDY OF THE FIRST PHASE OF DAMAGE: DEBONDINGS







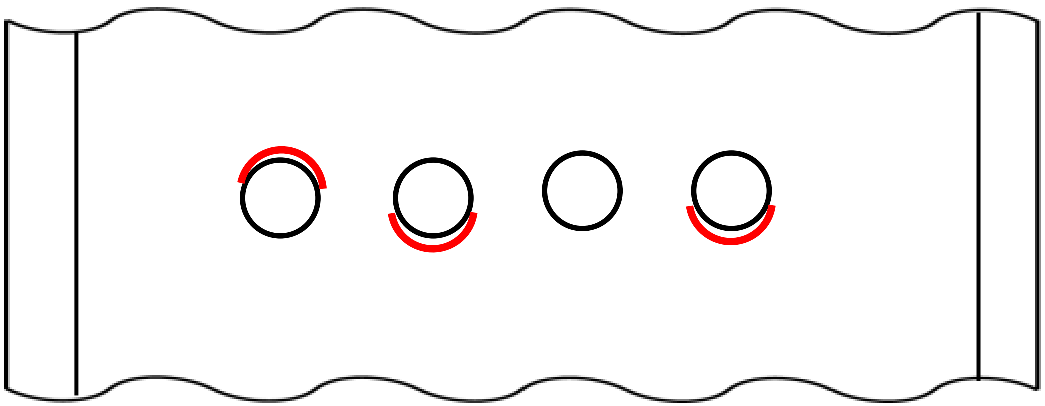
There is the same probability of getting isolated debondings in laminates with thick and thin 90 degrees laminas.

MICROMECHANICAL STUDY OF THE FIRST PHASE OF DAMAGE: DEBONDINGS

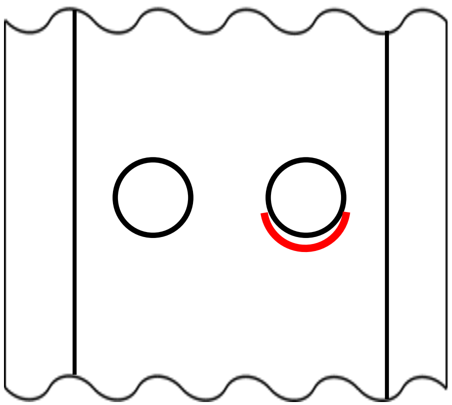
Same probability of getting isolated debondings in laminates with thick and thin 90 degrees laminas,

but it does not imply the same possibility of observing them!

In fact, we had never observed isolated debondings, as a first manifestation of damage using plies of conventional thickness.

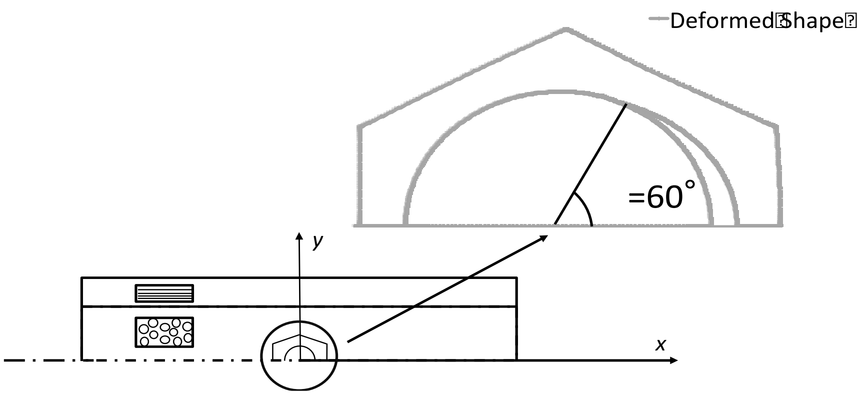


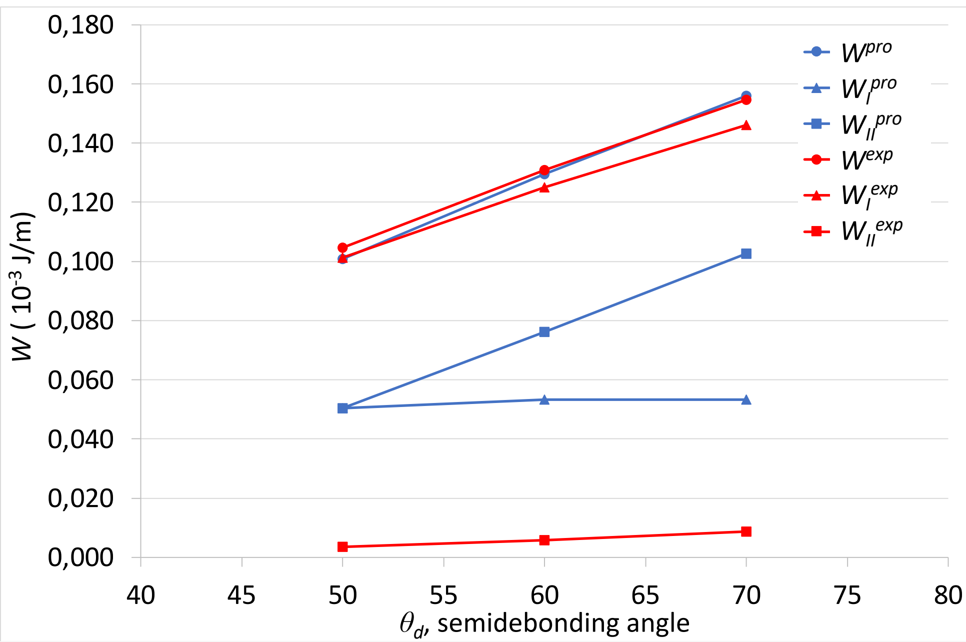
Thick (90º) laminates



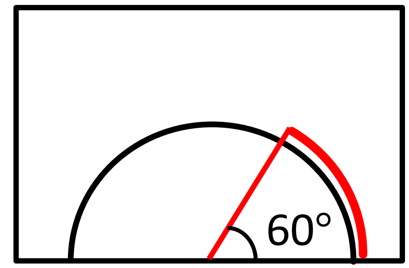
Thin (90º) laminates

EXPLOSIVE AND PROGRESSIVE MECHANISMS OF DAMAGE

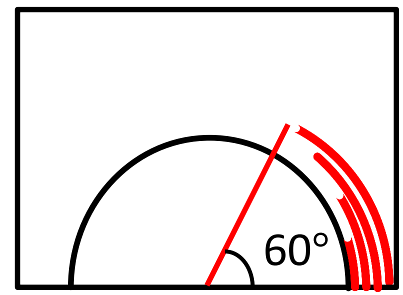




Explossive Mechanism



Progressive Mechanism

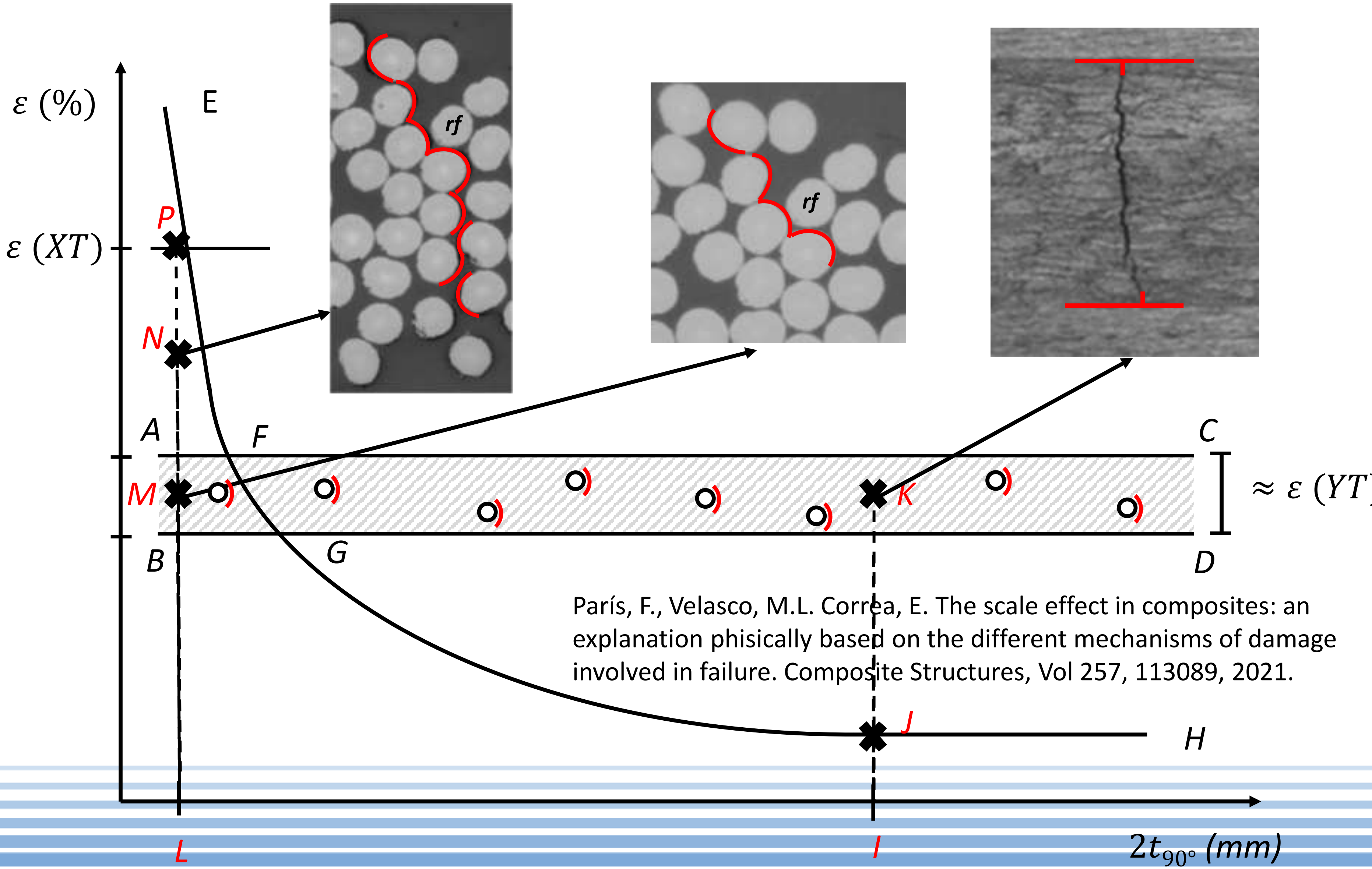


Isolated debonding between fibre and matrix which appears in an explosive or progressive way.

A micromechanical analysis using FEM with a cohesive approach, for instance, may condition the detection of one particular mechanism of damage

A PHISICALLY BASED EXPLANATION OF THE SCALE EFFECT, [0,90n,0] LAMINATES

GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES

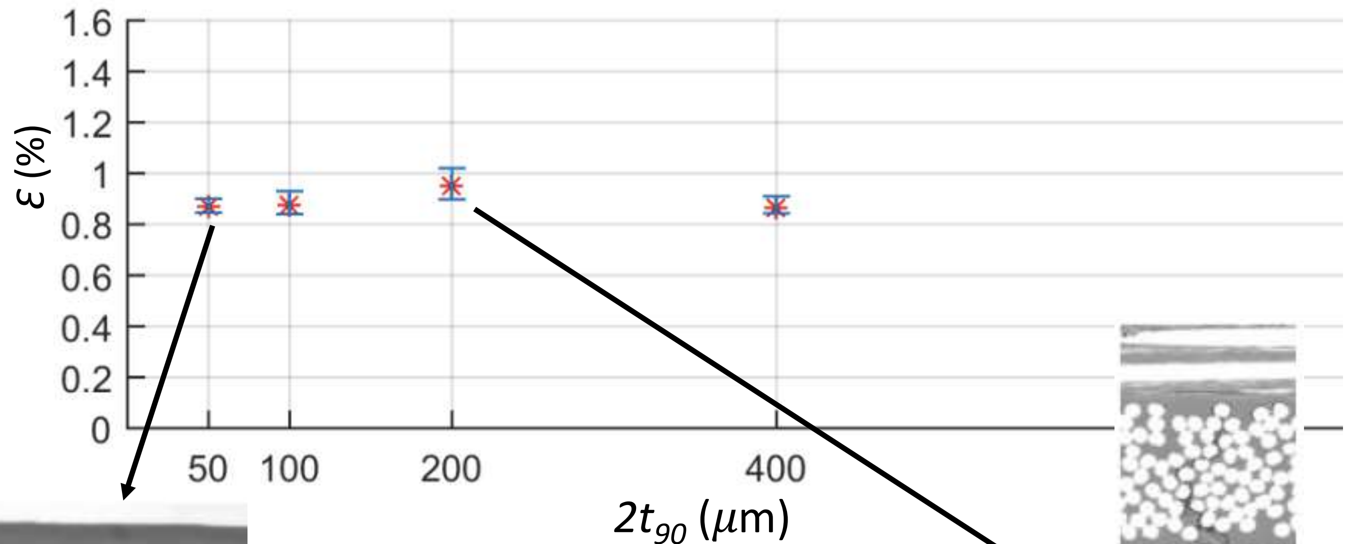


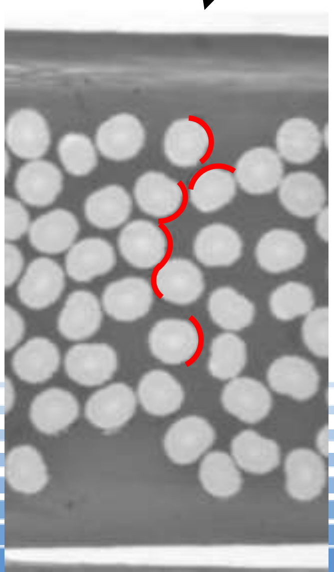
París, F., Velasco, M.L. Correa, E. The scale effect in composites: an explanation phisically based on the different mechanisms of damage involved in failure. Composite Structures, Vol 257, 113089, 2021.

EXPERIMENTAL CONFIRMATION OF THE EXPLANATION

Detection of the FIRST damage

$[0_{12}, 90_n, 0_{12}]$ LAMINATES MADE OF UTPS OF USN50

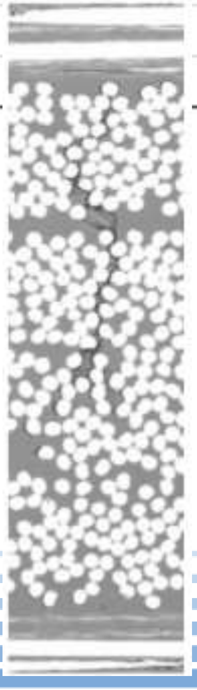




No possibility of checking it till the appearance of UTPs

$[0_{12},90,0_{12}]$
$2t_{90}$=50gsm

$[0_{12},90,0_{12}]$
$2t_{90}$=200gsm



PRACTICAL APPLICATION OF THE KNOWLEDGE ACQUIRED

-Verification of the pattern of damage associated with the failure of the 90 degrees lamina as a function of the thickness

PRACTICAL APPLICATION OF THE KNOWLEDGE ACQUIRED

-Verification of the pattern of damage associated with the failure of the 90 degrees lamina as a function of the thickness

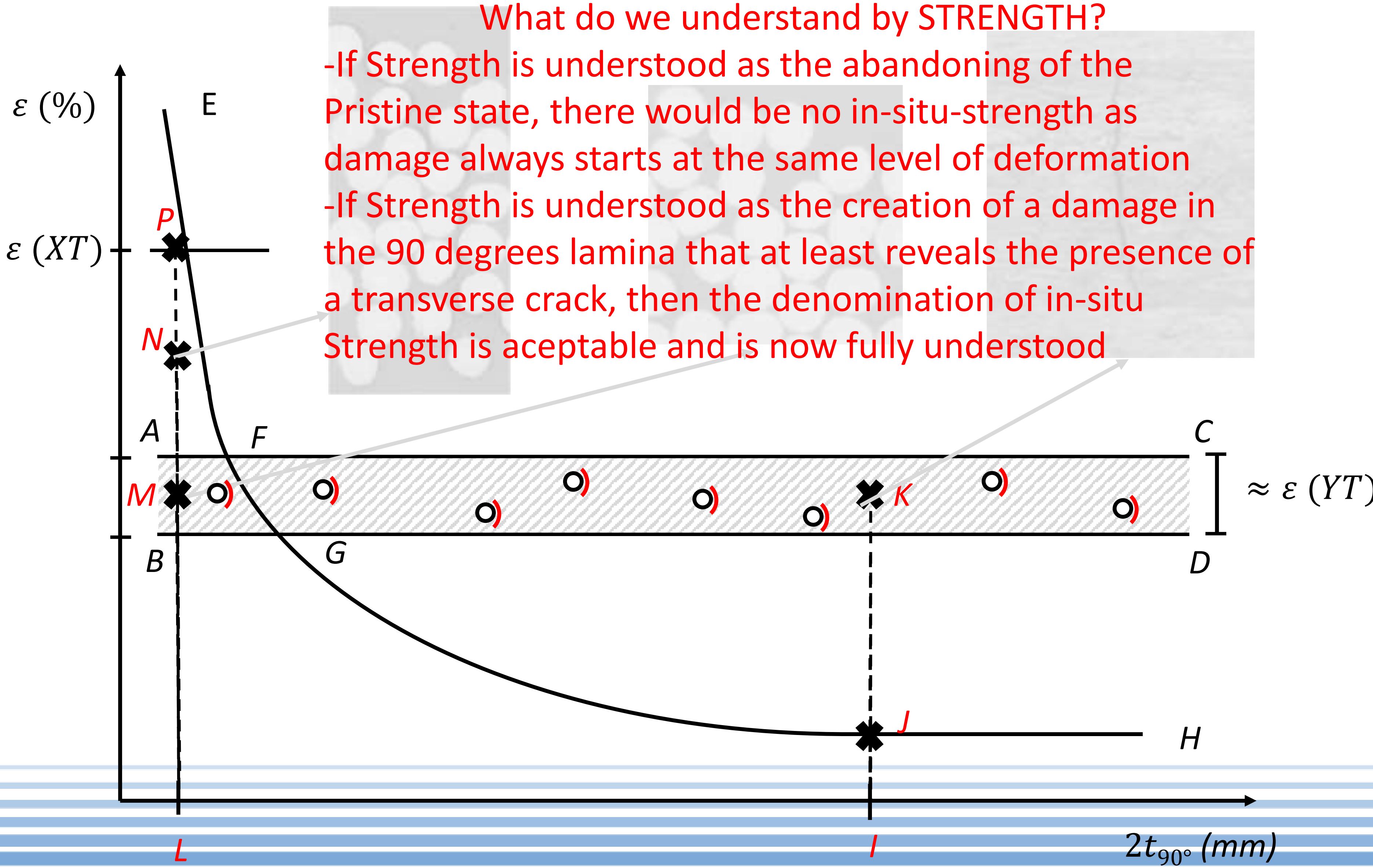
-On the concept of “in-situ Strength”

A PHISICALLY BASED EXPLANATION OF THE SCALE EFFECT, [0,90n,0] LAMINATES

What do we understand by STRENGTH?

-If Strength is understood as the abandoning of the Pristine state, there would be no in-situ-strength as damage always starts at the same level of deformation

-If Strength is understood as the creation of a damage in the 90 degrees lamina that at least reveals the presence of a transverse crack, then the denomination of in-situ Strength is aceptable and is now fully understood



PRACTICAL APPLICATION OF THE KNOWLEDGE ACQUIRED

-Verification of the pattern of damage associated with the failure of the 90 degrees lamina as a function of the thickness

-On the concept of "in-situ Strength"

-Optimization of the thickness of the 90 degrees laminas

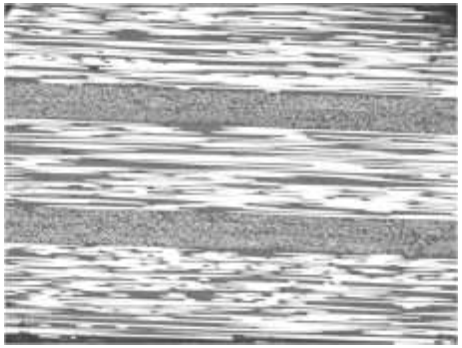
GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES

OPTIMIZATION OF THE MATERIAL

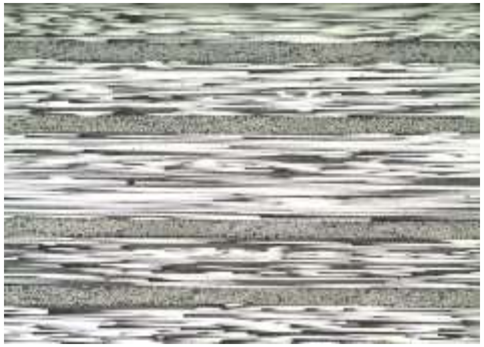
0° laminae	USN150
90° laminae	USN50

Total thickness of the laminates = 1,1mm

$[0_3, 90_4, 0_3]$



$[0_2, 90_2, 0_2, 90_2, 0_2]$



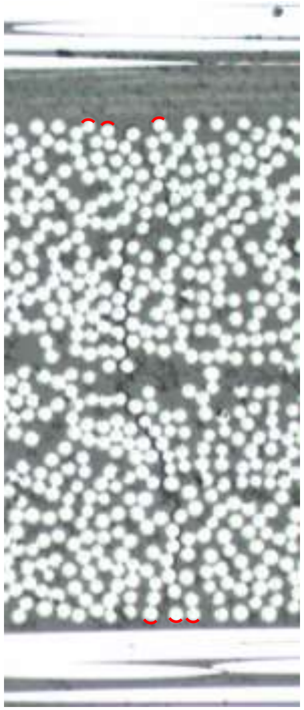
$[0, 90, 0, 90, 0, 0, 90, 0, 90, 0]$

OPTIMIZATION OF THE MATERIAL

PROGRESSION OF DAMAGE IN LAMINAS ORIENTED 90°

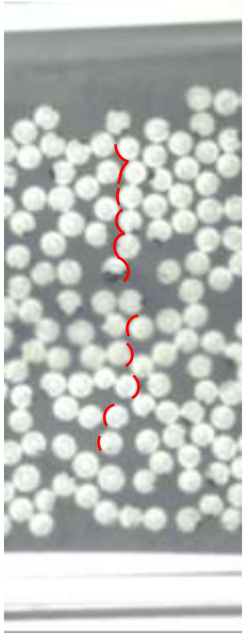
12000N-13000N
ε~0.5%

$[0_3, 90_4, 0_3]$



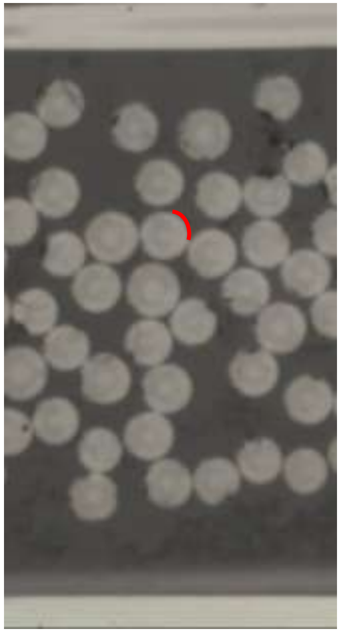
TRANSVERSE DAMAGE WITH ADDITIONAL DAMAGE INDICATING FUTURE DELAMINATION

$[0_2, 90_2, 0_2, 90_2, 0_2]$



DEBONDINGS ISOLATED/CONECTED

$[0, 90, 0, 90, 0, 0, 90, 0, 90, 0]$



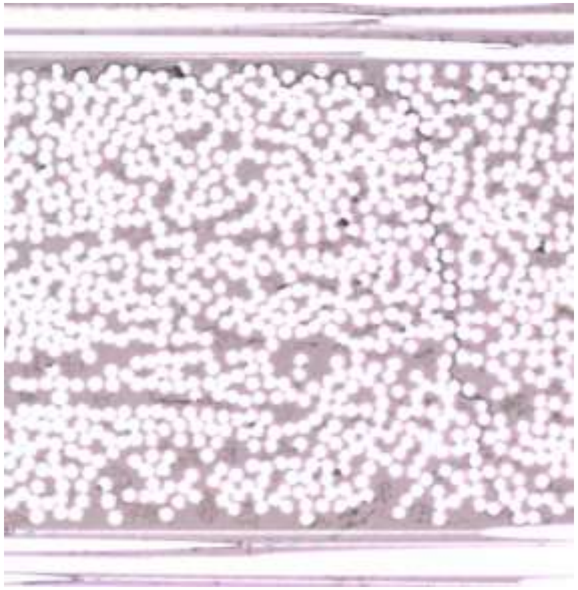
ISOLATED DEBONDINGS

OPTIMIZATION OF THE MATERIAL

PROGRESSION OF DAMAGE IN LAMINAS ORIENTED 90°

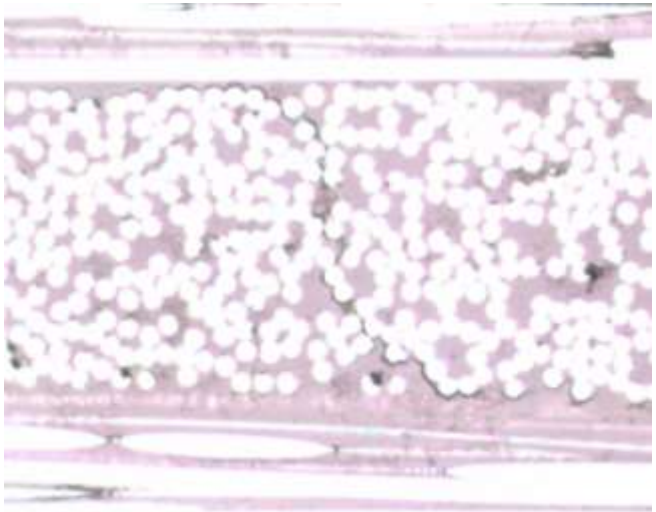
29000N-30000N
ε~1.15%

$[0_3, 90_4, 0_3]$



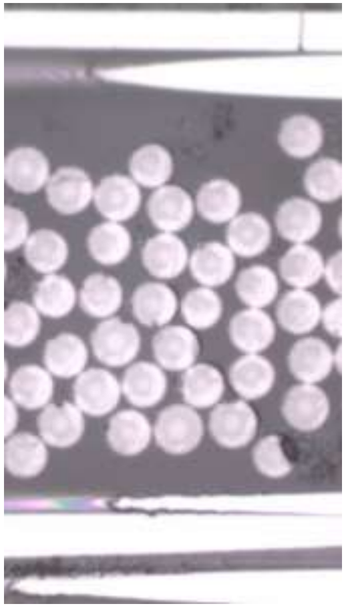
TRANSVERSE CRACK WITH DELAMINATION

$[0_2, 90_2, 0_2, 90_2, 0_2]$



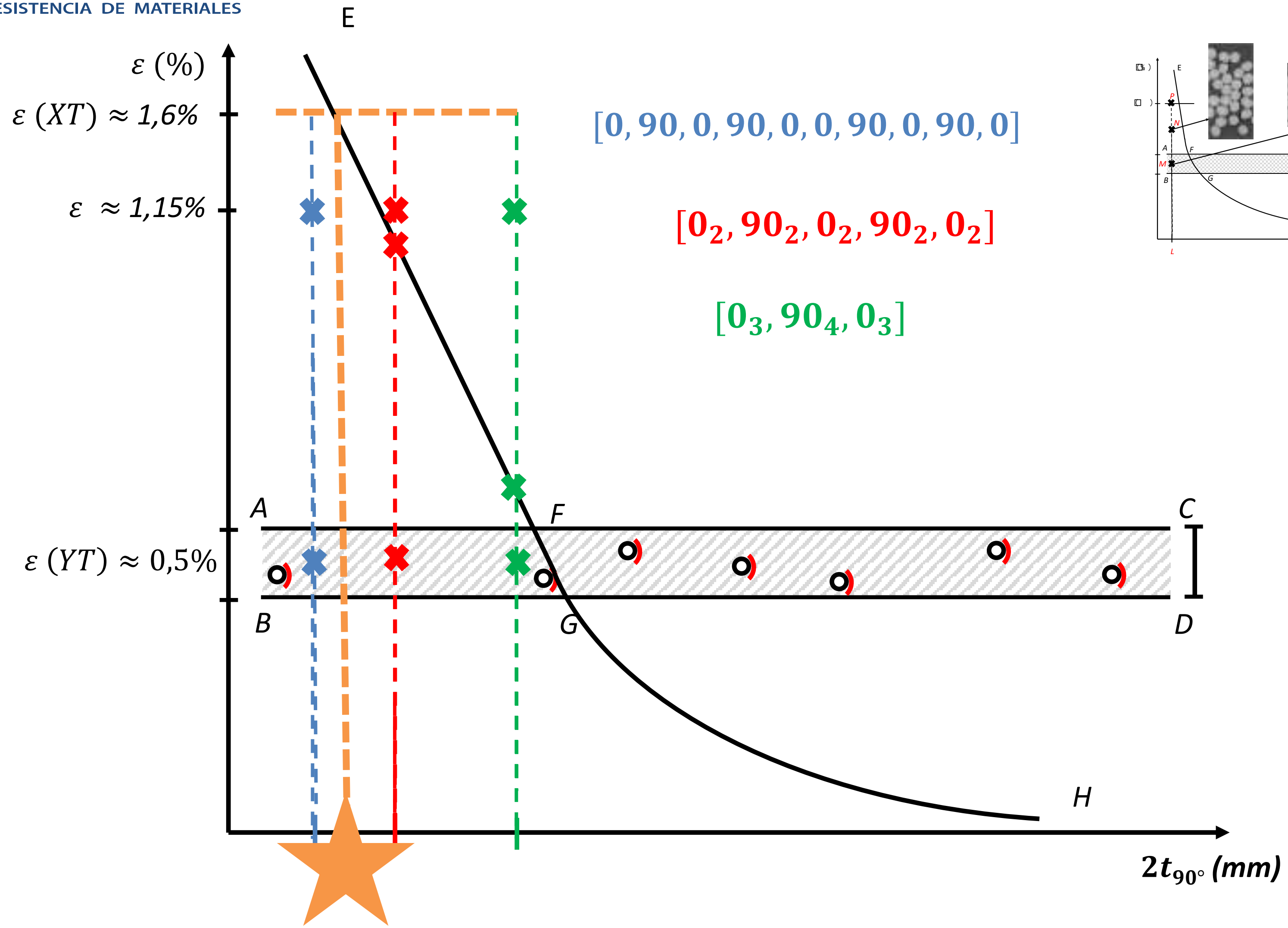
TRANSVERSE CRACK WITH DELAMINATION

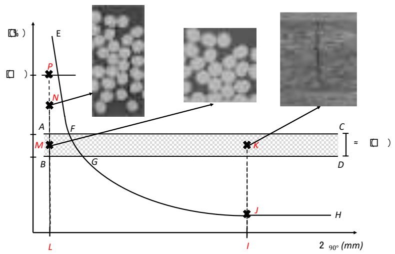
$[0, 90, 0, 90, 0, 0, 90, 0, 90, 0]$



DEBONDINGS ISOLATED/CONECTED

OPTIMIZATION OF THE MATERIAL





PRACTICAL APPLICATION OF THE KNOWLEDGE ACQUIRED

-Verification of the pattern of damage associated with the failure of the 90 degrees lamina as a function of the thickness

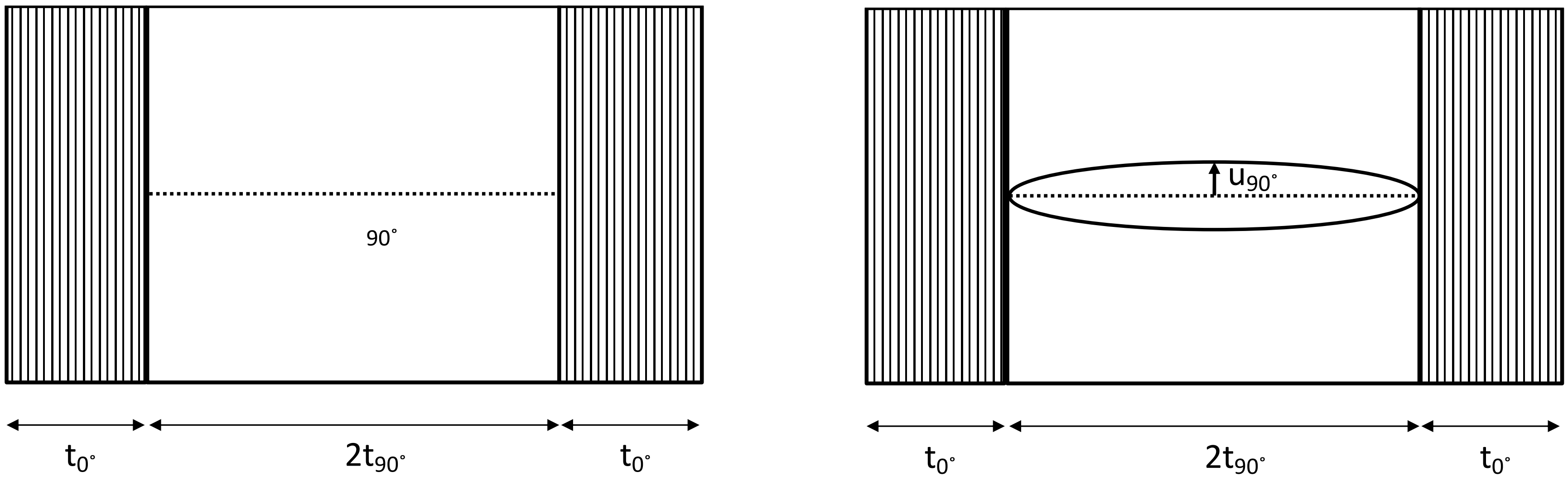
-On the concept of “in-situ Strength”

-Optimization of the thickness of the 90 degrees laminas

- Characterization of the material: Fracture toughness of the 90 degrees lamina

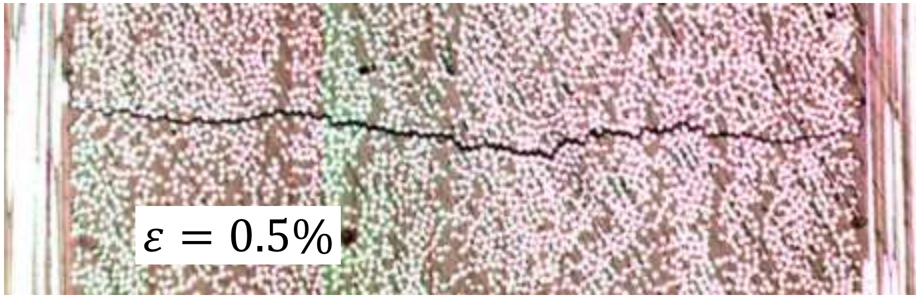
Fracture Toughness of the 90 degrees lamina

To identify Properties of AS4/8552 (thickness of one lamina 0.190 mm)



$[0_4, 90_n, 0_4]$ $\quad n = 4\ (2t_{90^\circ})$

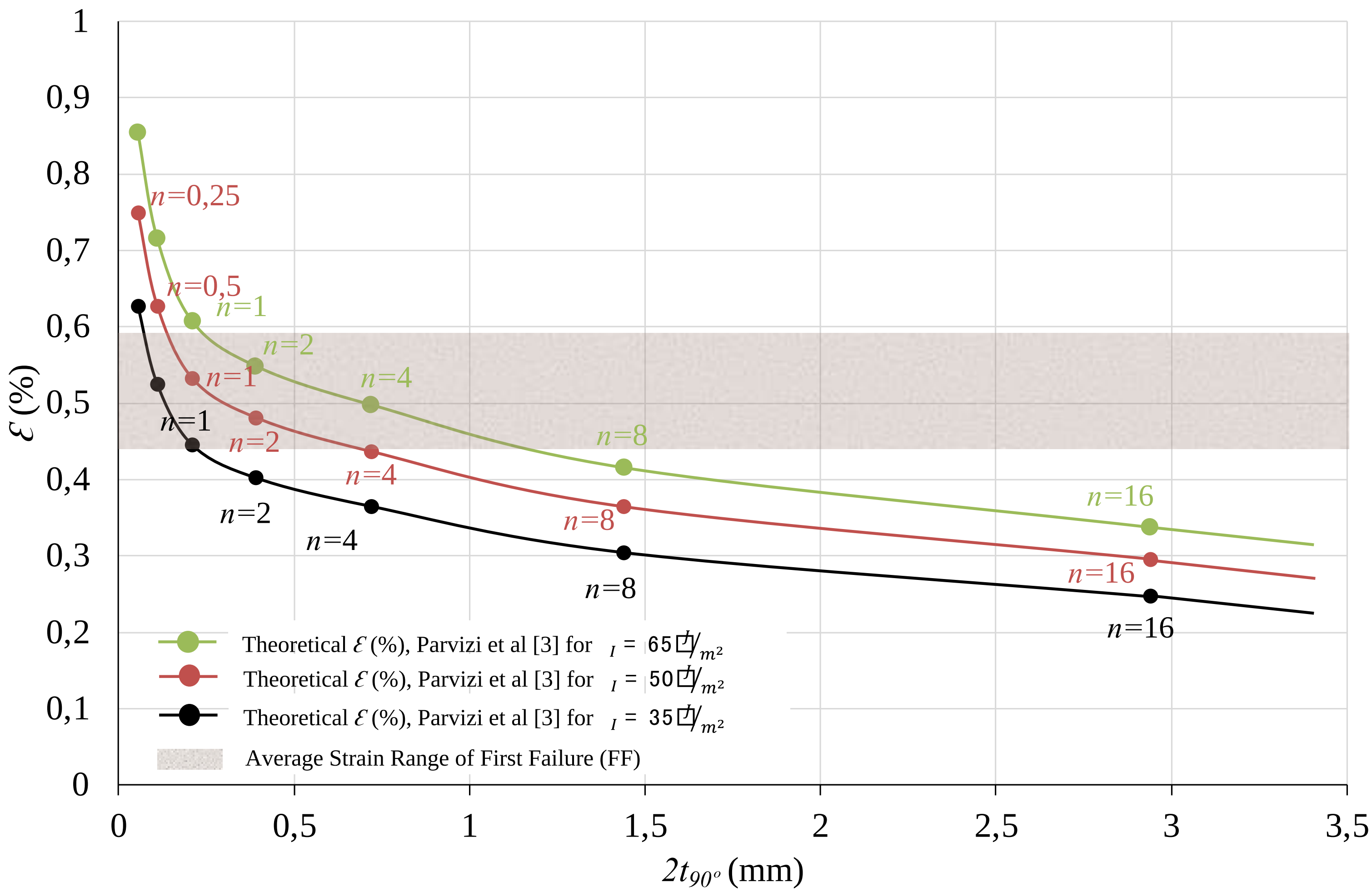
$$\int_0^{t_{90^\circ}} \left(\frac{1}{2}\cdot\sigma_{90^\circ}\cdot u_{90^\circ}\right)\cdot 2\cdot 2\ ds = G_{IC}^{90^\circ}\cdot 2\cdot t_{90^\circ}$$



$$\boldsymbol{G_{IC}^{90^\circ} \approx 100\ J/m^2}$$

Fracture Toughness of the 90 degrees lamina

To identify Properties of AS4/8552 $[0_4, 90_n, 0_4]$



GERM
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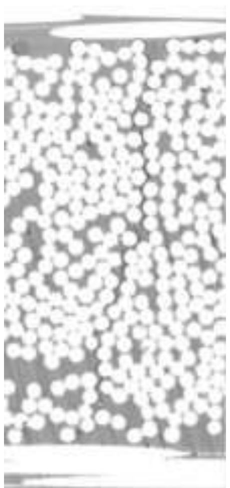
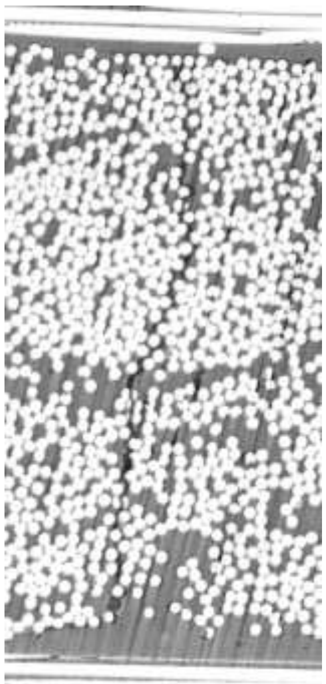
Fracture Toughness of the 90 degrees lamina

To identify Properties of AS4/8552 $[0_4, 90_n, 0_4]$

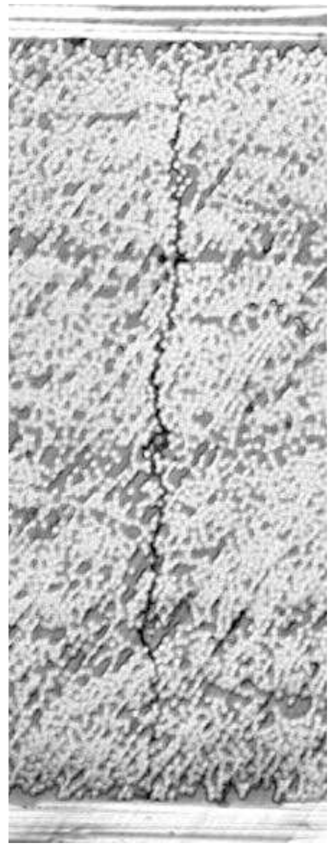
Damage patterns corresponding to the range of $\varepsilon(Y_T)$



n=1

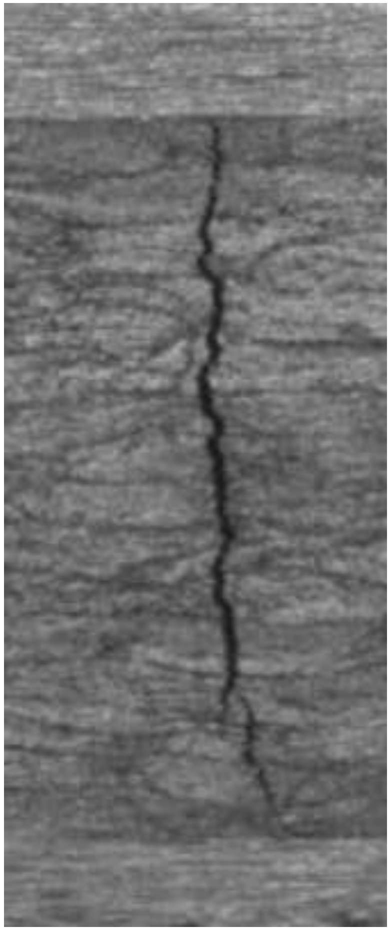


n=2



n=4

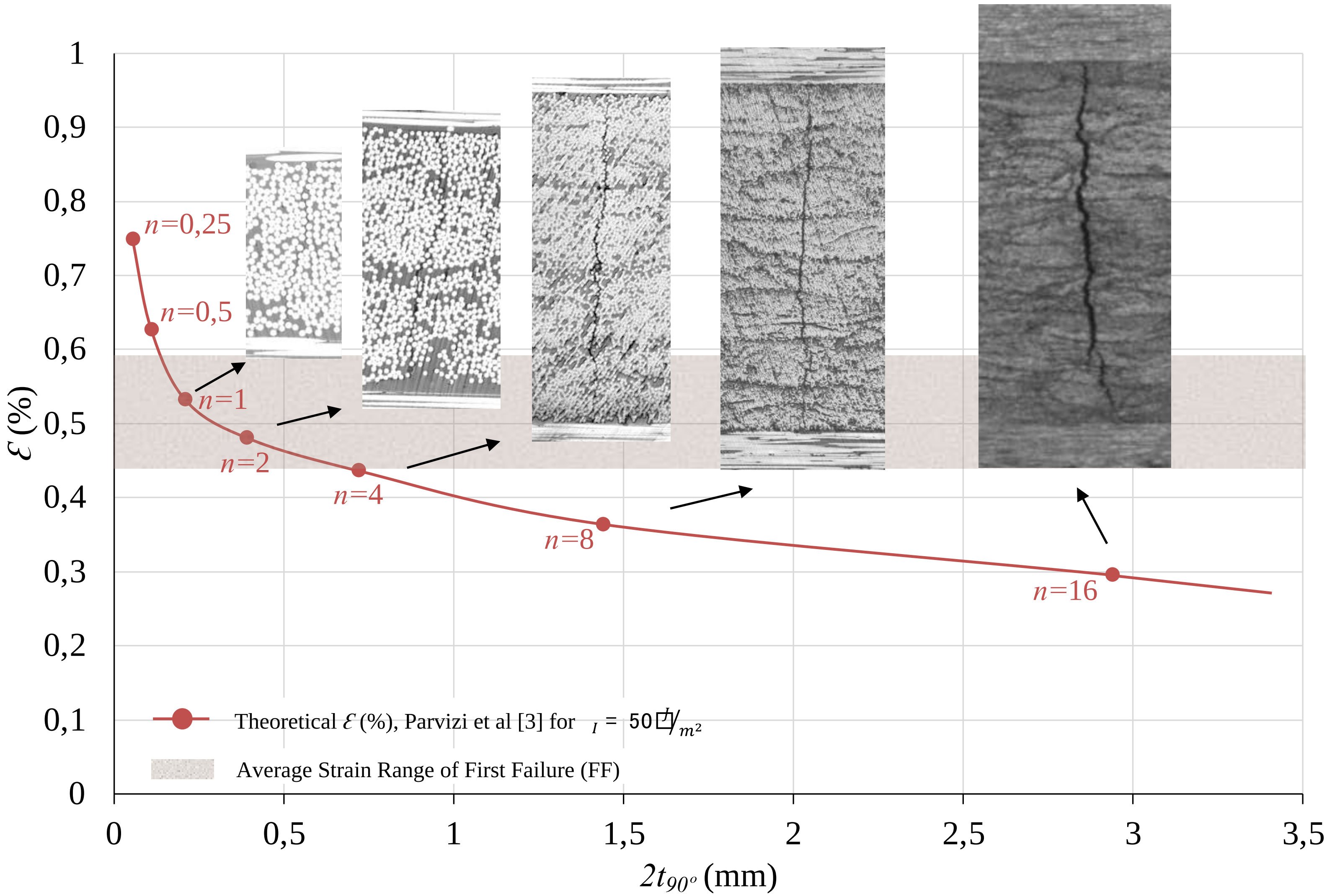
n=8



n=16

Fracture Toughness of the 90 degrees lamina

To identify Properties of AS4/8552



PRACTICAL APPLICATION OF THE KNOWLEDGE ACQUIRED

-Verification of the pattern of damage associated with the failure of a “thick” 90 degrees lamina

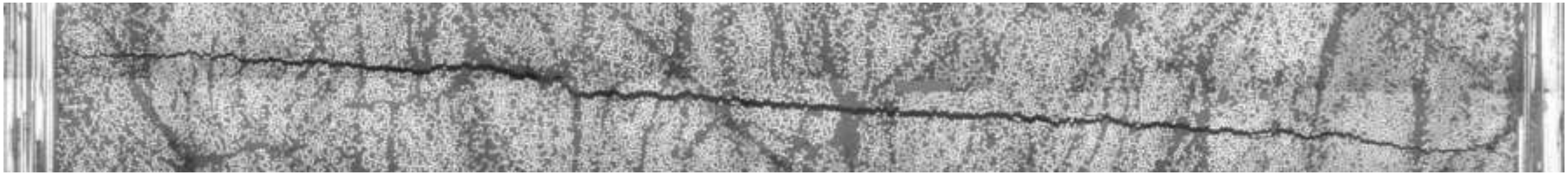
-On the concept of “in-situ Strength”

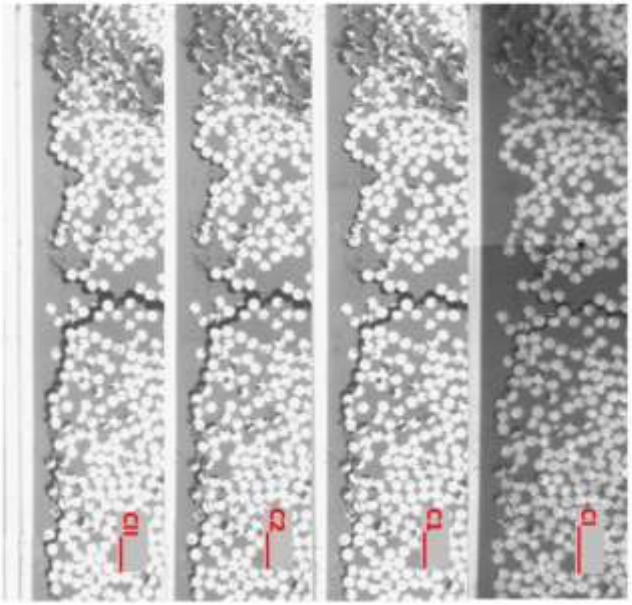
-Optimization of the thickness of the 90 degrees laminas

- Characterization of the material: Fracture toughness of the 90 degrees lamina

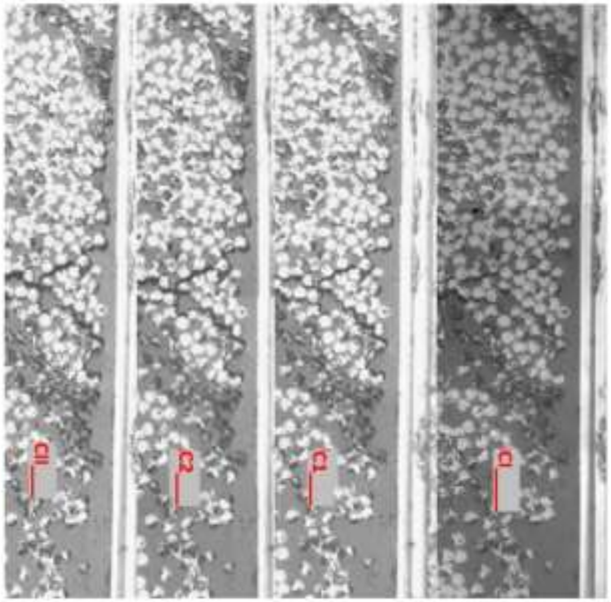
- Future extension of the knowledge acquired
  - -Fracture toughness of the interface between 0 and 90 plies

Tests with thick plies involving significant damage between 0 and 90 degrees laminas





CI: Appearance of the first transverse crack
C1: First Strain Increase
C2: Second Strain Increase
CII: Appearance of the second transverse crack



PRACTICAL APPLICATION OF THE KNOWLEDGE ACQUIRED

-Verification of the pattern of damage associated with the failure of a “thick” 90 degrees lamina

-On the concept of “in-situ Strength”

-Optimization of the thickness of the 90 degrees laminas

- Characterization of the material: Fracture toughness of the 90 degrees lamina

- Present extension of the knowledge acquired
  - -Fracture toughness of the interface between 0 and 90 plies
  - -Effect of the different patterns of damage found with UTPs, conventional and thick plies in presence of other loadings (bending, shear, compression, fatigue,….)
  - -Behaviour of a composite under biaxial loading transverse to the direction of the fibres
  - -Fatigue: effect of the use of Ultra Thin Plies

CONCLUSSIONS

1.- A physically based explanation, not involving Fitting Parameters, has been given about the “scale effect” in composites.

2.- A revision on the “in-situ strength” concept has been given.

3.-The explanation gives a new insight into the necessity of having a failure criterion based on a stress and an energy, as the damage is always controlled by energy, which may be different depending on the mechanism of damage activated.

4.- The understanding of the mechanisms of damage and failure in composites opens a discussion about the capacity of actual tools of modelling damage to represent these mechanisms. These tools have to be used once the mechanisms have been verified.

5.- The use of thick laminae generates more “advanced” damage in the laminate. They may unchain catastrophic failure in the laminate in presence of other loading cases (bending, torsion, fatigue,…).

Incidence of the mechanisms of damage in the scale effect of composites involving Ultra Thin Plies

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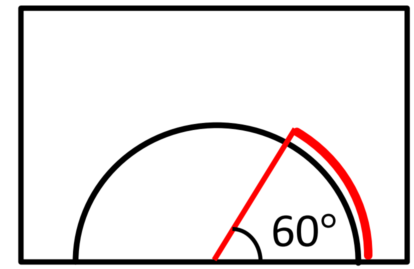
Department of Continuum Mechanics
School of Engineering, University of Seville, Spain

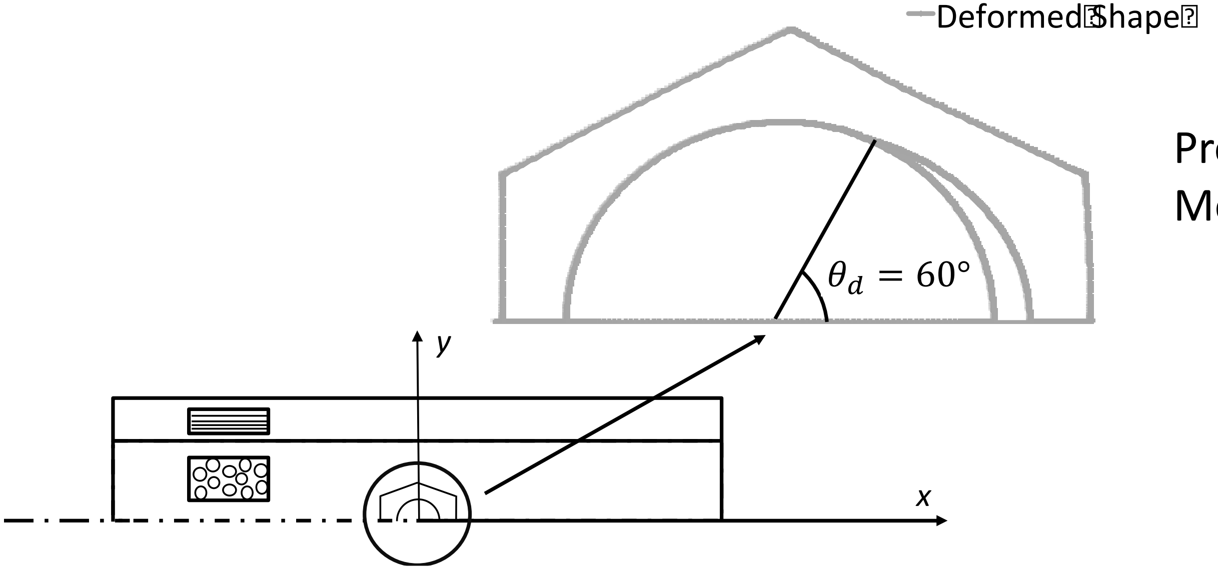
COMPTEST
Girona, May 30-June 2, 2023

DIFFERENT WAYS OF GENERATION OF A DEBONDING

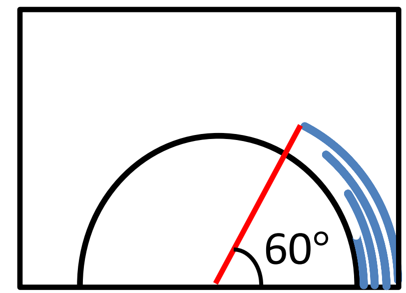
Isolated debonding between fibre and matrix which can appear in an explosive or in a progressive way.

Explossive Mechanism



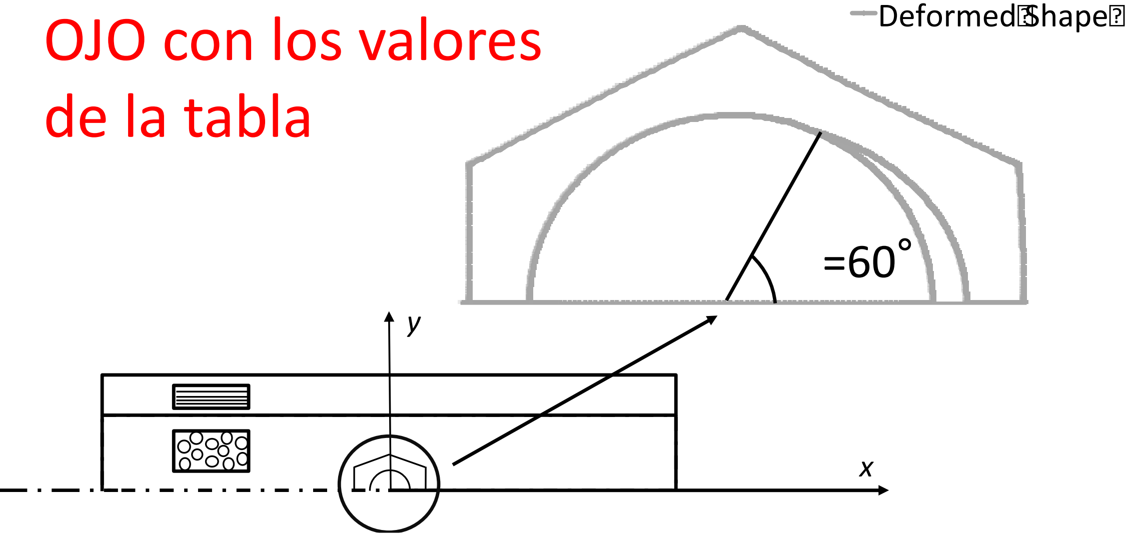


Progressive Mechanism

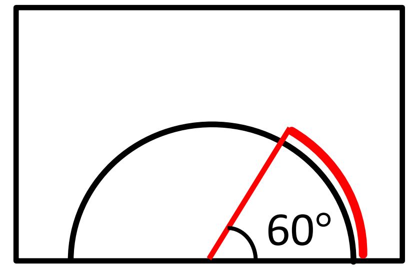


Non-equivalent situations

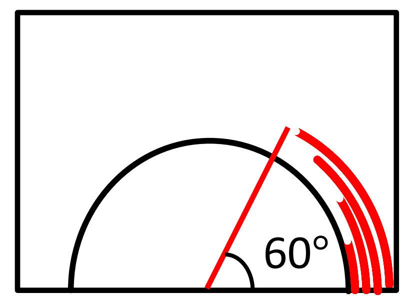
OJO con los valores de la tabla



Explossive Mechanism



Progressive Mechanism

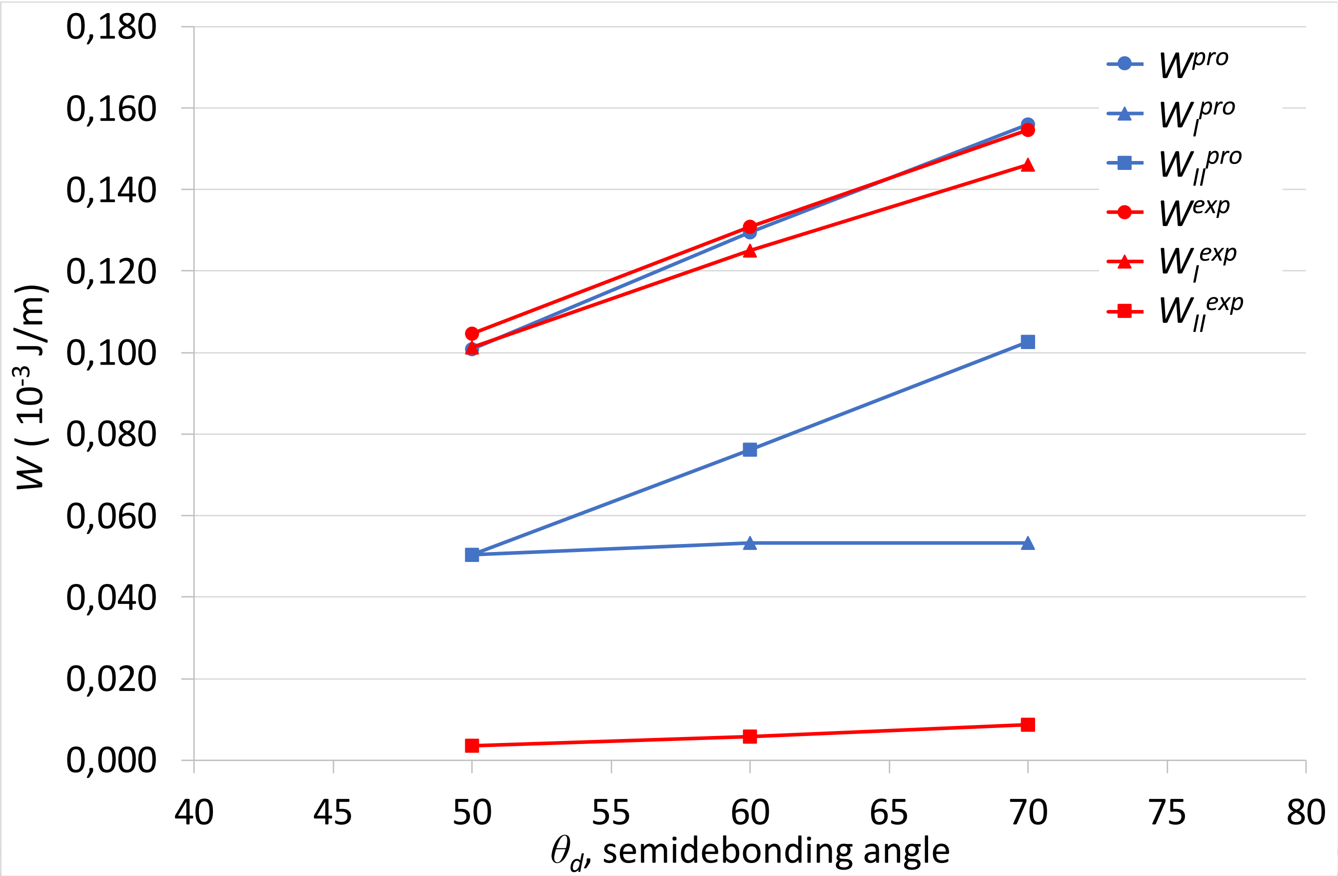


Isolated debonding between the fibre and matrix which appears in an explosive or progressive way.

If we perform in this case a micromechanical analysis with a cohesive approach we are conditionning the mechanism of damage

$\theta_d = 60°$	PROGRESSIVE MECHANISM	EXPLOSIVE MECHANISM
W_I (10^{-3} J/m)	0,006667	0,031100
W_{II} (10^{-3} J/m)	0,009520	0,001470
W (10^{-3} J/m)	0,016187	0,032570

EVOLUTION OF W, W_I AND W_{II} FOR THE PROGRESSIVE AND EXPLOSIVE MECHANISMS OF GENERATION OF A DEBONDING



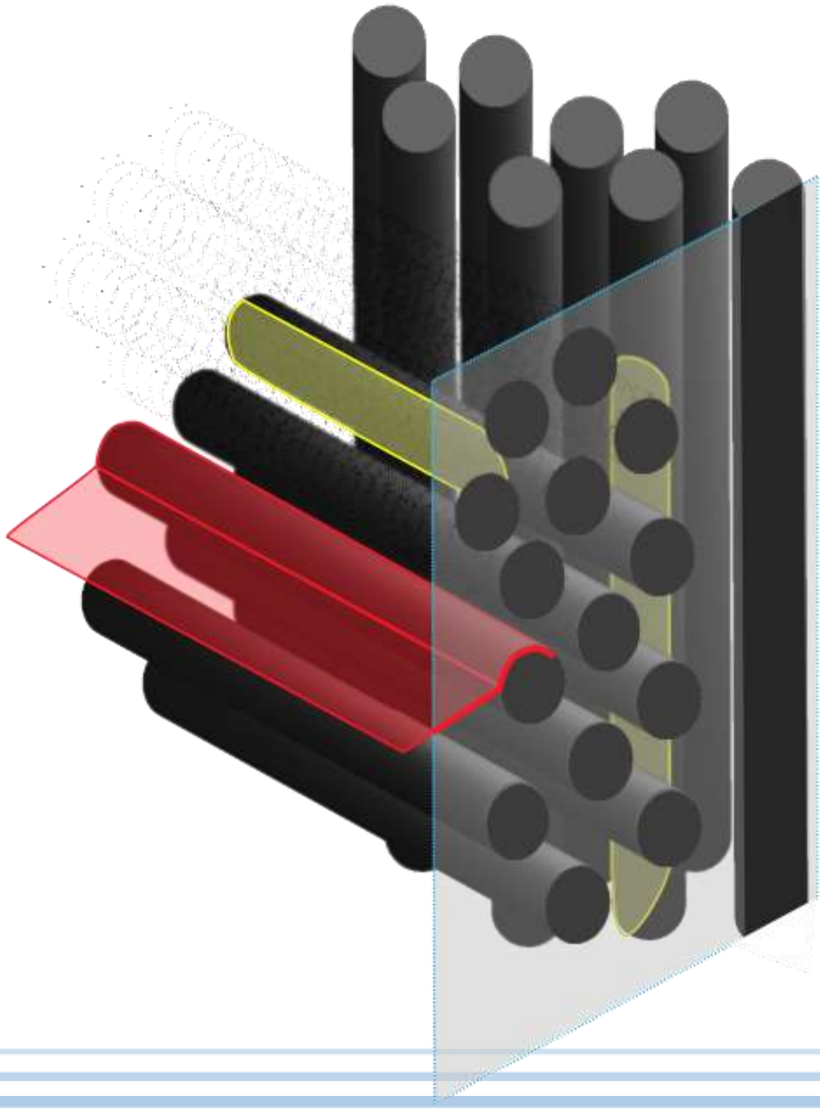
Thick-thin laminae: Tests carried out

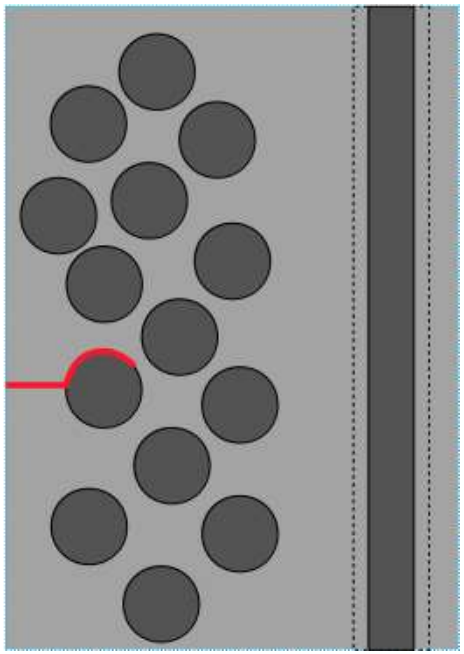
First set

RUPTURE LOAD OF THE LAMINATES

	VALUES OF THE RUPTURE LOADS (N)		
	$[0_3, 90_4, 0_3]$	$[0_2, 90_2, 0_2, 90_2, 0_2]$	$[0, 90, 0, 90, 0, 0, 90, 0, 90, 0]$
Specimen 1	41898	56143	51235
Specimen 2	45381	54671	51748
Specimen 3	42369	49541	56230
Specimen 4	48565	54000	56829
Average	**44553**	**53589**	**54010**
Standard Dev.	3087	2843	2927
C.V.(%)	6,9	5,3	5,4

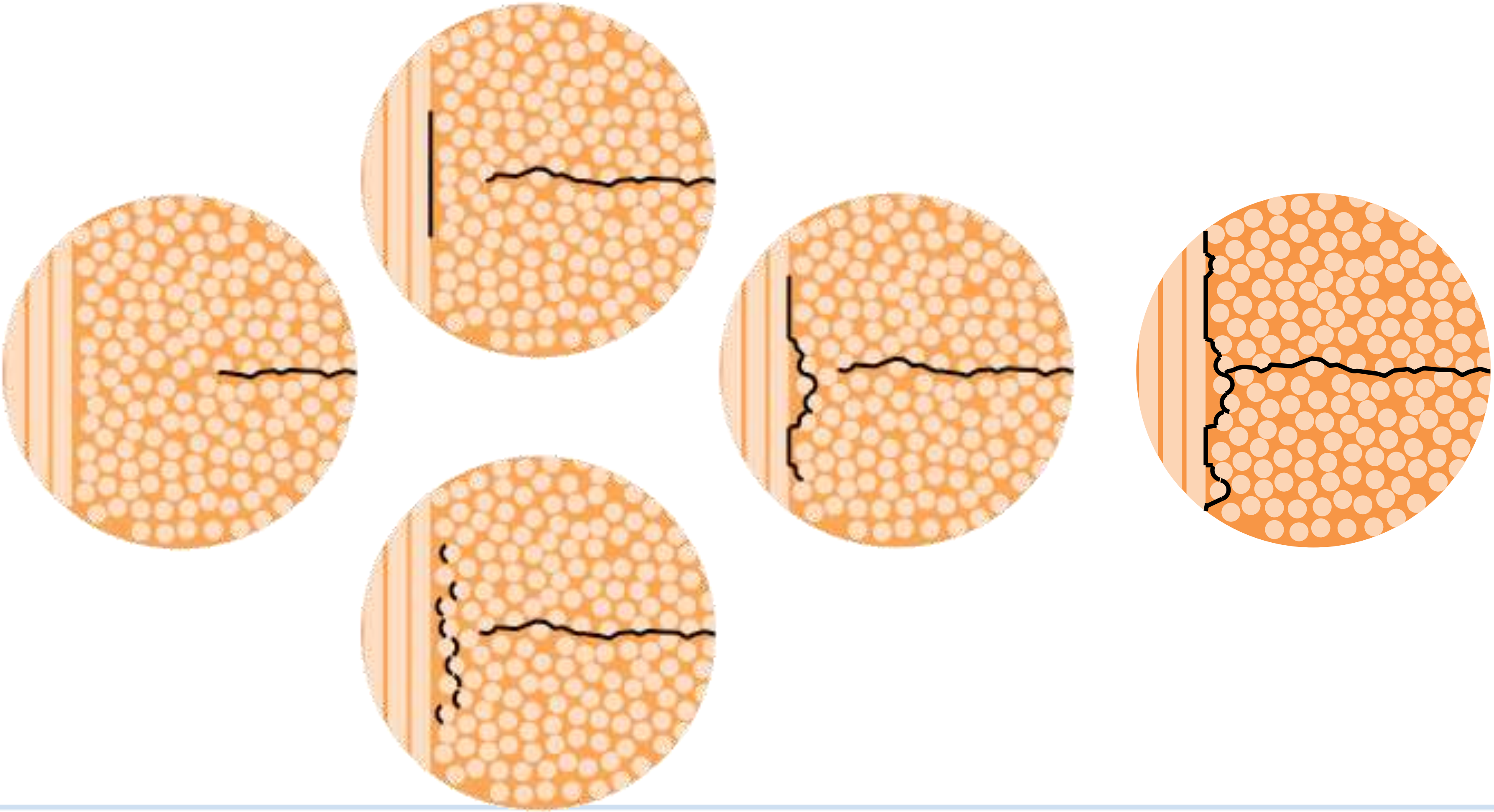
Polishing plane





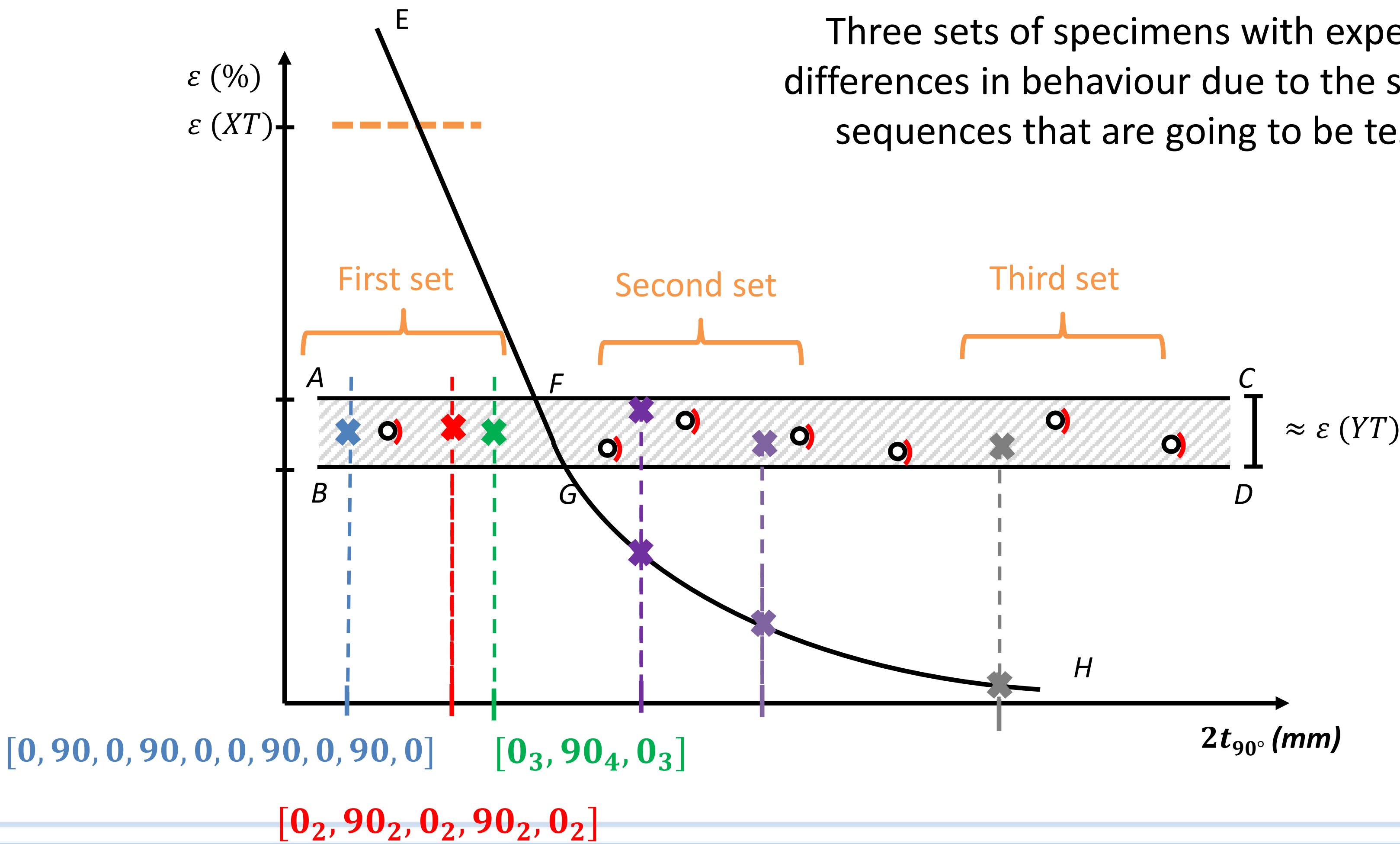
No observed damage like delamination

2D SCHEMATIC REPRESENTATION of the GROWTH of the DAMAGE



Thick-thin laminae: Tests carried out

Three sets of specimens with expected differences in behaviour due to the stacking sequences that are going to be tested

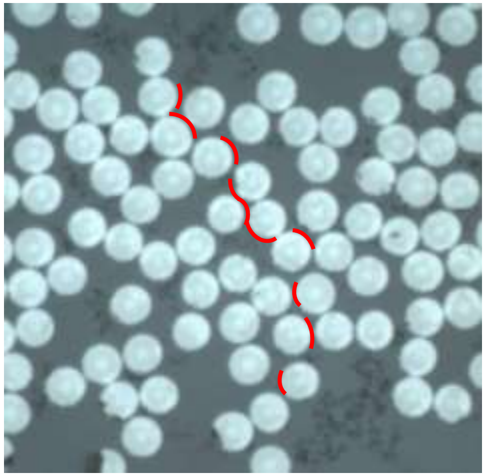


OPTIMIZATION OF THE MATERIAL

DETECTION OF FIRST DAMAGE IN LAMINAS ORIENTED 90°

$[0_3, 90_4, 0_3]$

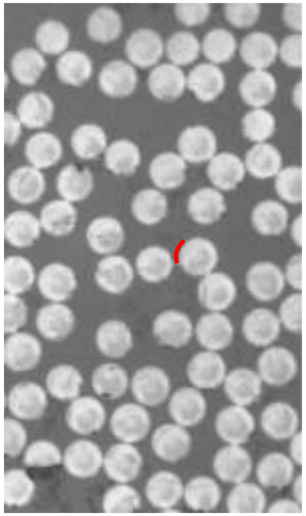
7000N-8000N



DEBONDINGS ISOLATED/CONECTED

$[0_2, 90_2, 0_2, 90_2, 0_2]$

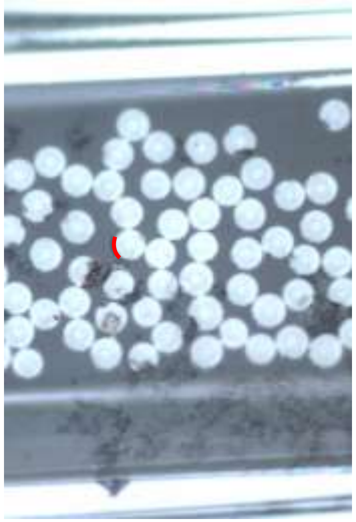
5000N-6000N



ISOLATED DEBONDINGS

$[0, 90, 0, 90, 0, 0, 90, 0, 90, 0]$

4000N-5000N



ISOLATED DEBONDINGS

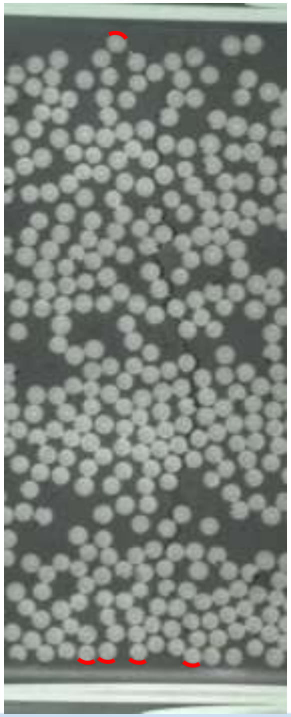
Thick-thin laminae: Tests carried out

GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES

PROGRESSION OF DAMAGE IN LAMINAS ORIENTED 90° IN THE FIRST SET OF SPECIMENS

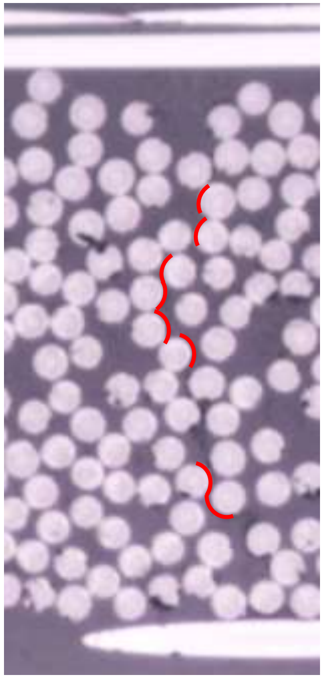
20000N-21000N

$[0_3, 90_4, 0_3]$



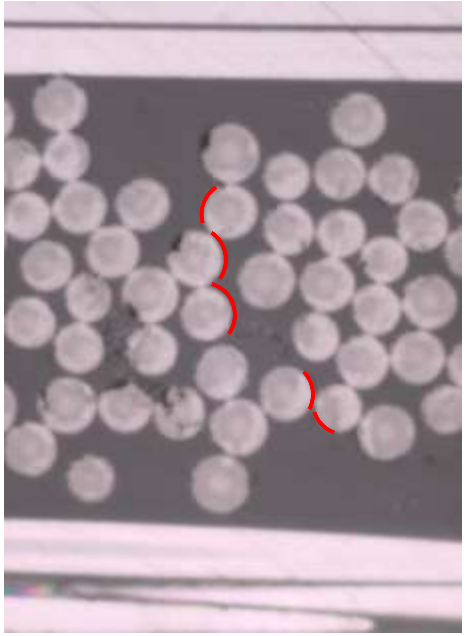
TRANSVERSE DAMAGE WITH ADDITIONAL DAMAGE INDICATING FUTURE DELAMINATION

$[0_2, 90_2, 0_2, 90_2, 0_2]$



DEBONDINGS ISOLATED/CONECTED

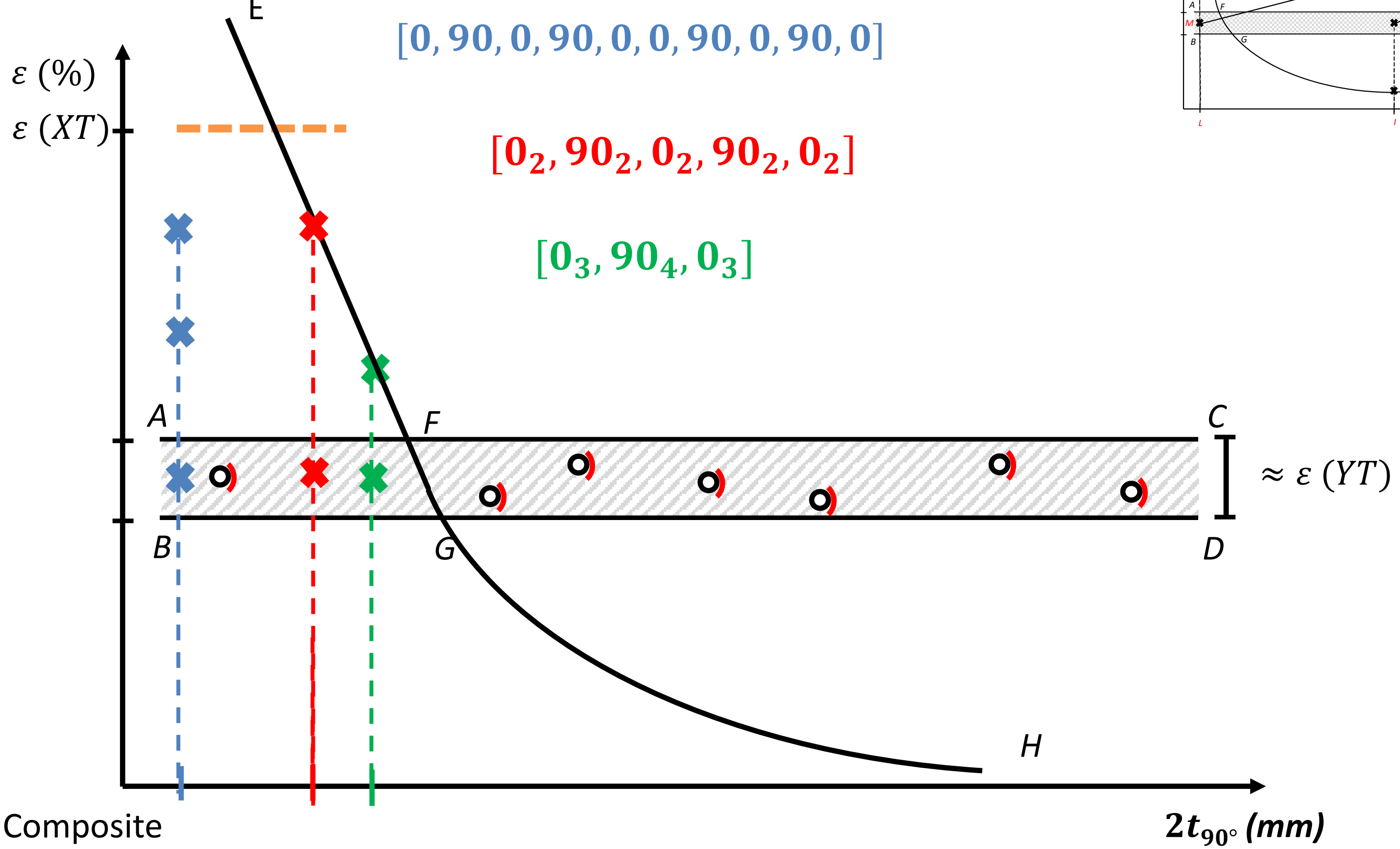
$[0, 90, 0, 90, 0, 0, 90, 0, 90, 0]$

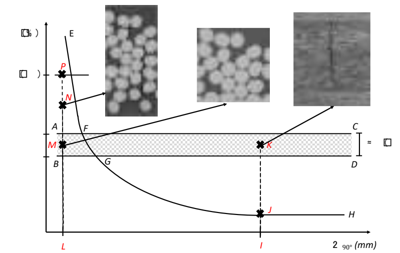


DEBONDINGS ISOLATED/CONECTED

Thick-thin laminae: Tests carried out

First set





París et al. Composite Structures, 2020.

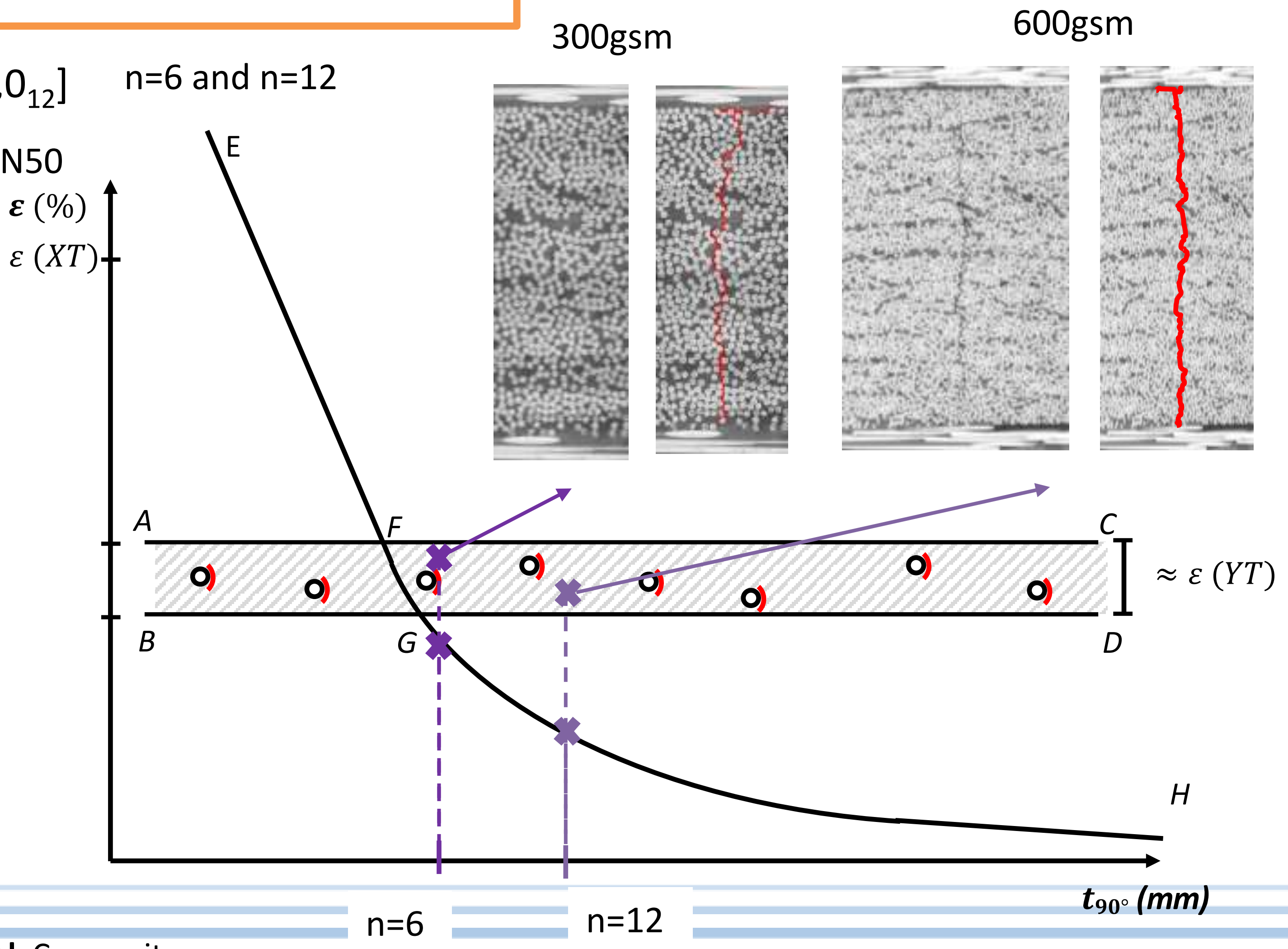
The observations of this experimental work plenary support the explanation phisically based given on the scale effect

Thick-thin laminae: Tests carried out

Second set with UTPs

$[0_{12},90_n,0_{12}]$ n=6 and n=12

NTPT: USN50



París et al. Composite Structures, 2020.

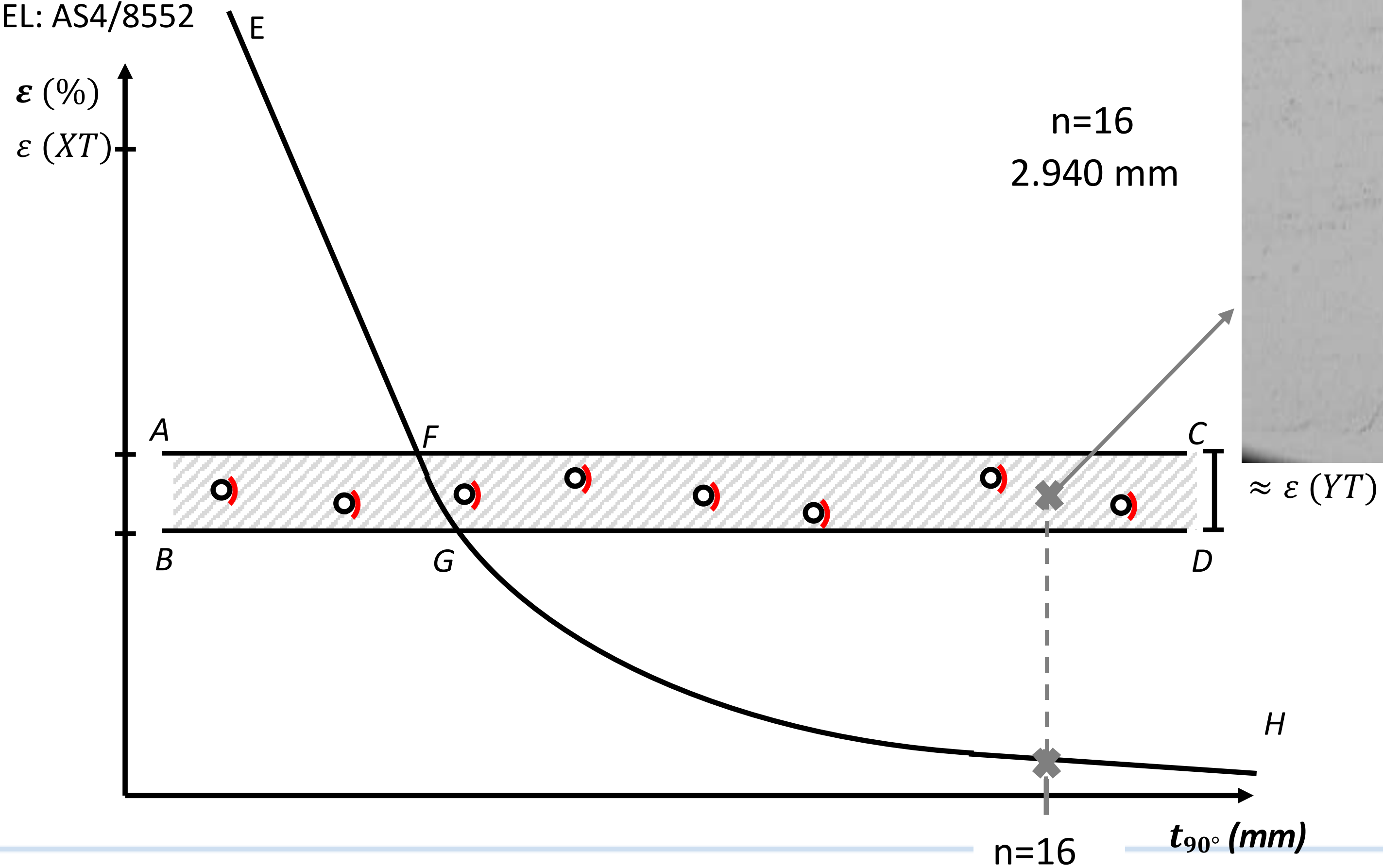
Thick-thin laminae: Tests carried out

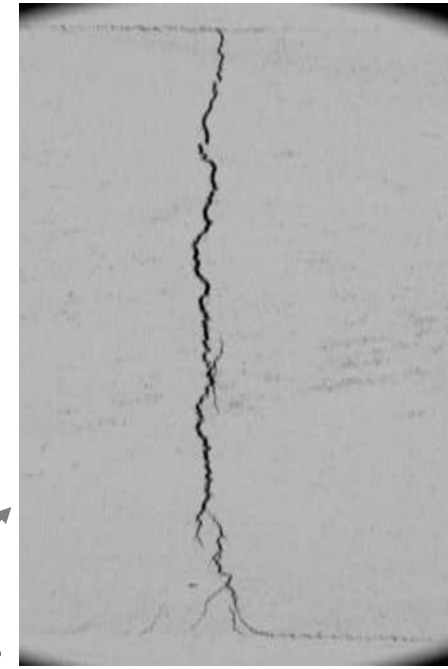
GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES

Third set

$[0_4,90_n,0_4]$

HEXCEL: AS4/8552





París et al. Composite Structures, 2020.

GRUPO DE ELASTICIDAD Y RESISTENCIA DE MATERIALES

The purpose of this presentation is to ilustrate:

1.-How Fracture Mechanics and Interfacial Fracture Mechanics may help engineers to understand Mechanisms of Damage of composite and its consequences in the performance of a composite

2.- The capacity of numerical tools to represent actual mechanisms of damage

3rd question: Why do we need a double criteria, one based on energy and another based on stress?

There is no need of having two failure criteria one based on energy and another based on stress. There are two mechanisms of failure controlled by energy and we need two criteria, one of them being easily expresed by means of a stress

The similarity with other damage scenarios is clear: the start of plastic behaviour is controlled by energy (distortion energy) but there is a very convenient stress (shear octaedric stress or even the modulus of the deviator stress tensor) that represents exactly the same

4th question: Is it adequate the in-situ strength concept?

The full understanding of the damage process explaining the Scale effect has meant a reconciliation with the in-situ strength concept, leading to questioning the concept of Strength in itself