NANOTECHNOLOGIES FOR STRUCTURAL COMPOSITE MATERIALS

Review of latest research developments and open challenges towards application

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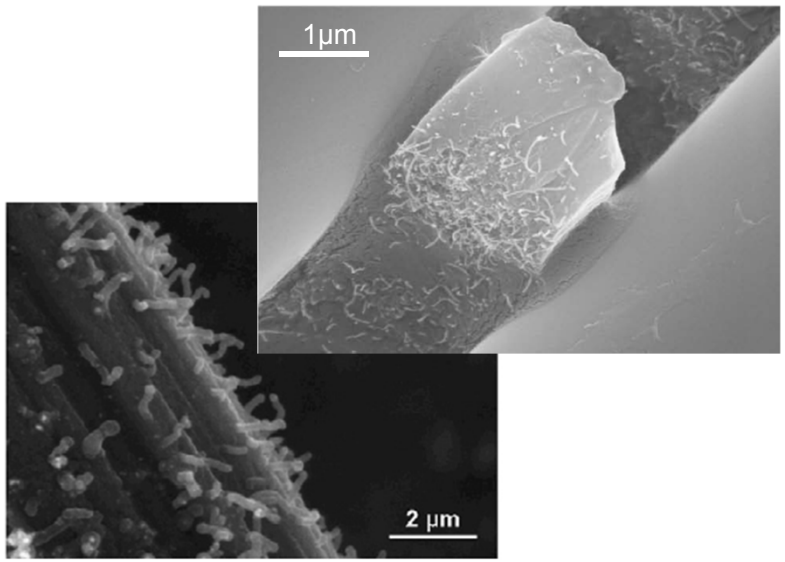


Starting point

- Nano-composites have been around already since the ‘90s (e.g. carbon black)
- CNT gave a boost to research of nano-composites

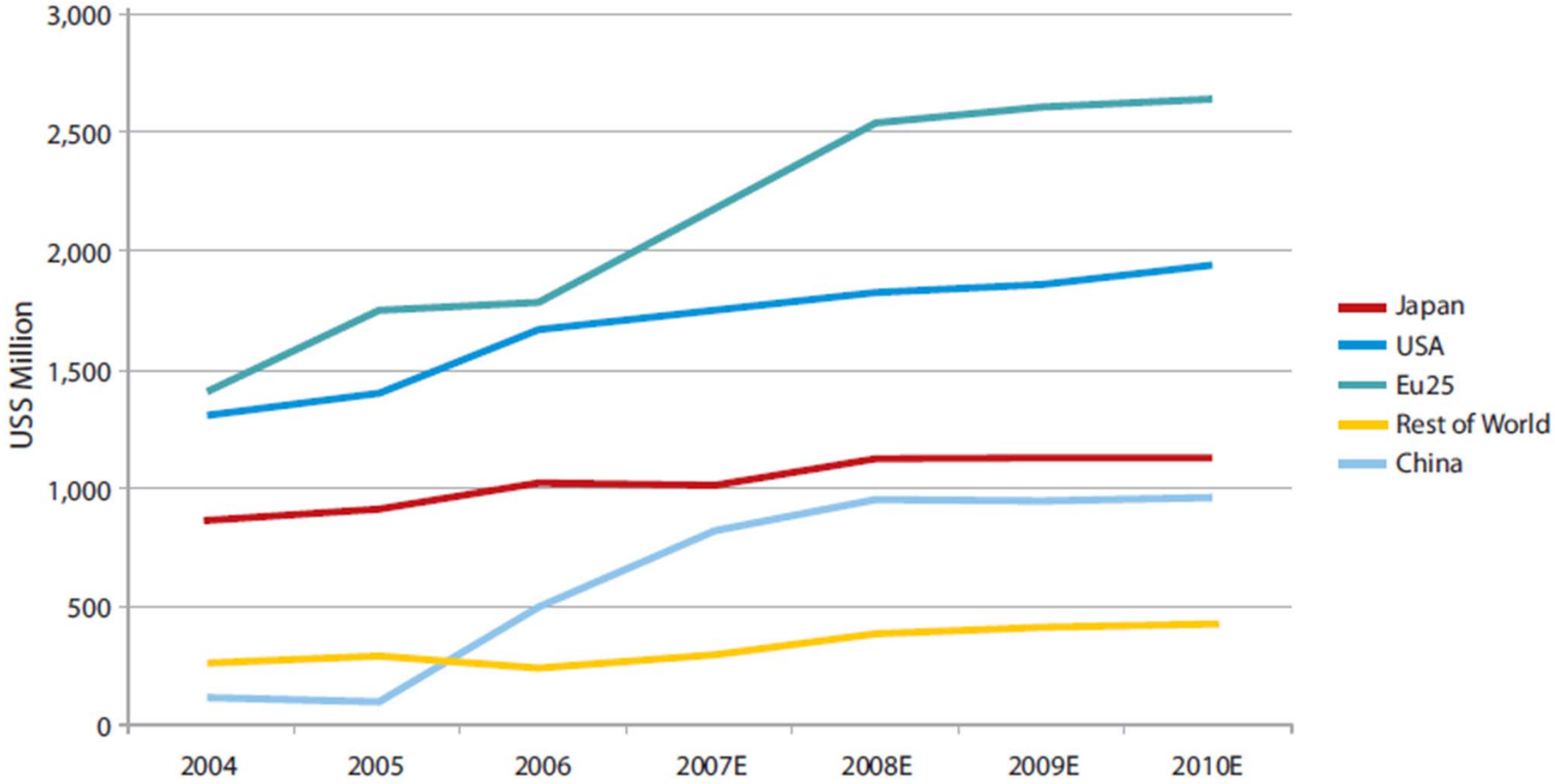
The tipping point

Nano-modification of FRP matrix for hybrid fibrous composite materials

Multi-scale reinforcement

- Initial works related to structural composites:
  - **EU-FP6-AEROSPACE-NOESIS**:Aerospace nanotube hybrid composite structures with sensing and actuating capabilities, 2004-2009

Since then... *Nanotechnology*



Source: Tekes Programme Report 2006 (FI)

Background

- During the past decade:
  - A lot of money (>1b€) (specific to nano-composites)
  - A lot of people (>100 research groups in EU)

  …have been "invested" to investigate nanotechnology for materials

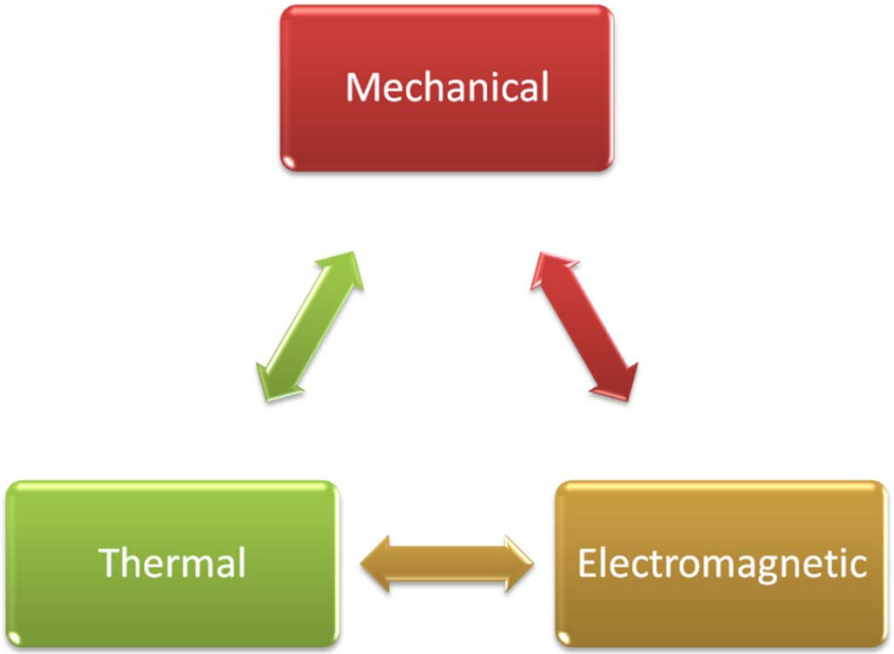
- Progress has been made, but where do we stand after >10 years?
- What do the end-users see and say?
- Our focus is on structural nano-composites

Introduction

- Review of approaches for nano-reinforcement of composites
- Modeling capabilities for nano-reinforced composites
- Up-scaling strategies towards final structures

Framework

- Structural Composites: E > 50GPa, σ > 100MPa
- Fibrous composites → Manufacturing methods
- Multi-functional performance
- Novel functionalities

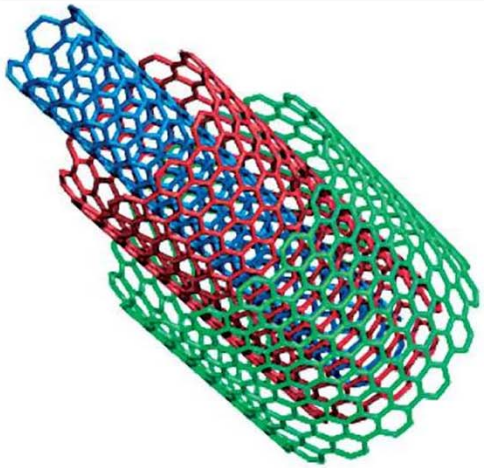


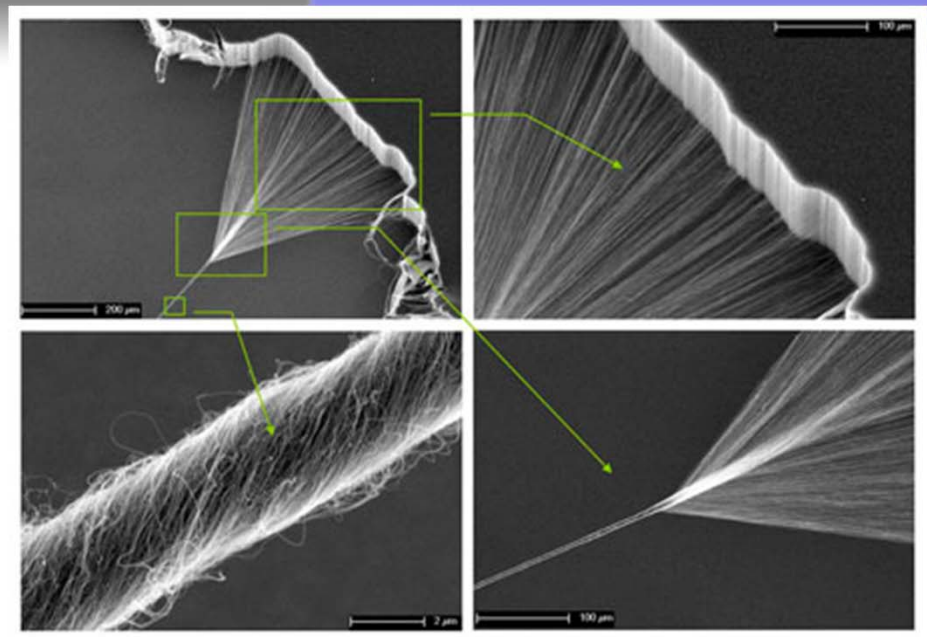
Approaches

Concepts of utilizing nanotechnology in composites

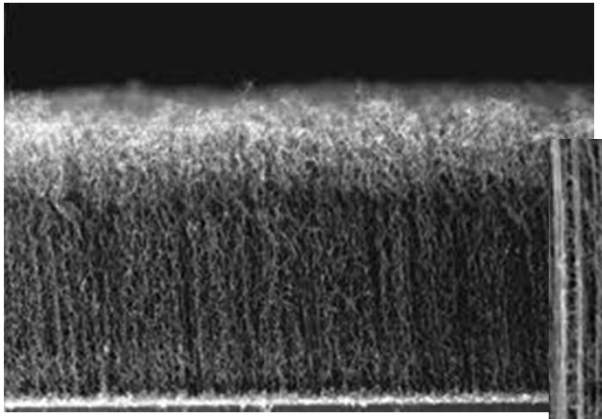
Nano-Augmenting	Nano-Engineering	Nano-Design
•Multifunctional materials	•Organized structures of nano-reinforcements (continuous nanofibers, bucky papers, aligned 2D structures, CNT forests)	•Organized structures of nano-reinforcements (continuous nanofibers, bucky papers, aligned 2D structures, CNT forests)
•Hybrid nanocomposites	•Multifunctional materials	•Multifunctional materials
•Enhancement of Mechanical, Electrical and Thermal Properties	•Hybrid nanocomposites	•Hybrid nanocomposites
•Sensing properties (Damage monitoring, SHM)	•Enhancement of Mechanical, Electrical and Thermal Properties	•Optimization of the enhancement of Mechanical, Electrical and Thermal Properties
	•Sensing properties (Damage monitoring, SHM)	•Sensing properties (Damage monitoring, SHM)
	•Actuating capabilities in various scales and various forms	•Actuating capabilities in various scales and varius forms

Snapshots I *Grown CNT forests and ropes*

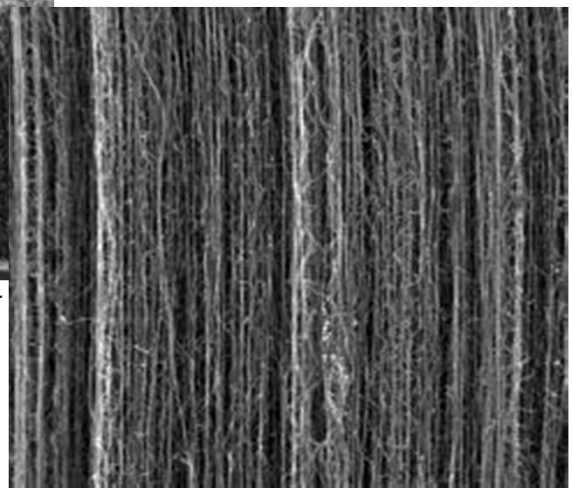


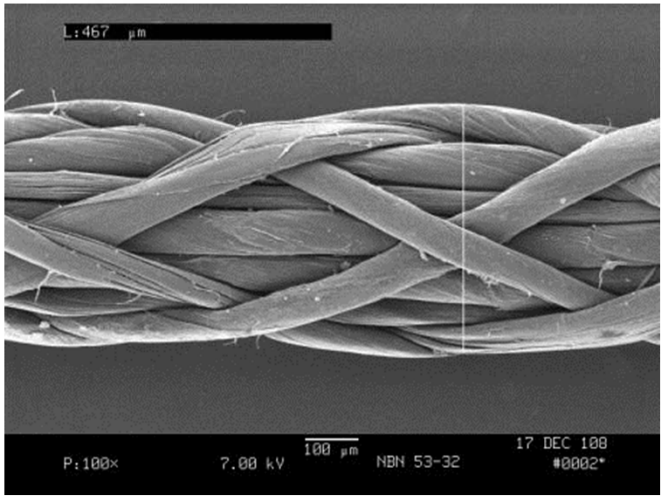


Zhang et al. Science, 306 (2004), pp. 1358–1361



Riccardo Signorelli/MIT

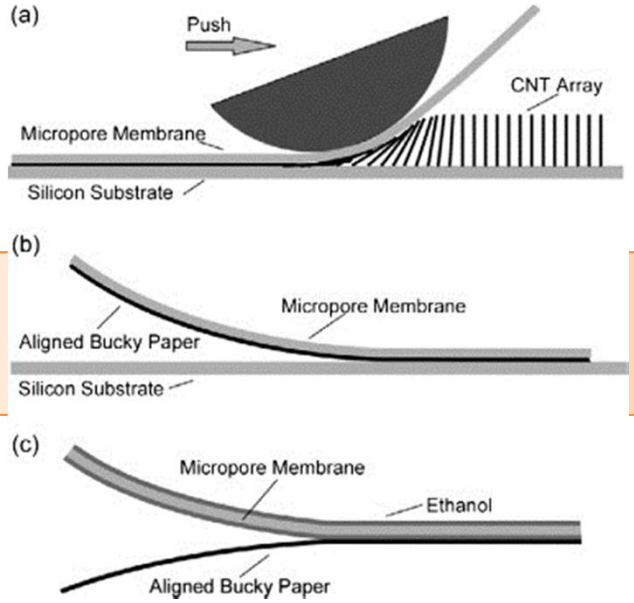




CNT yarn (Nanocomp, USA)

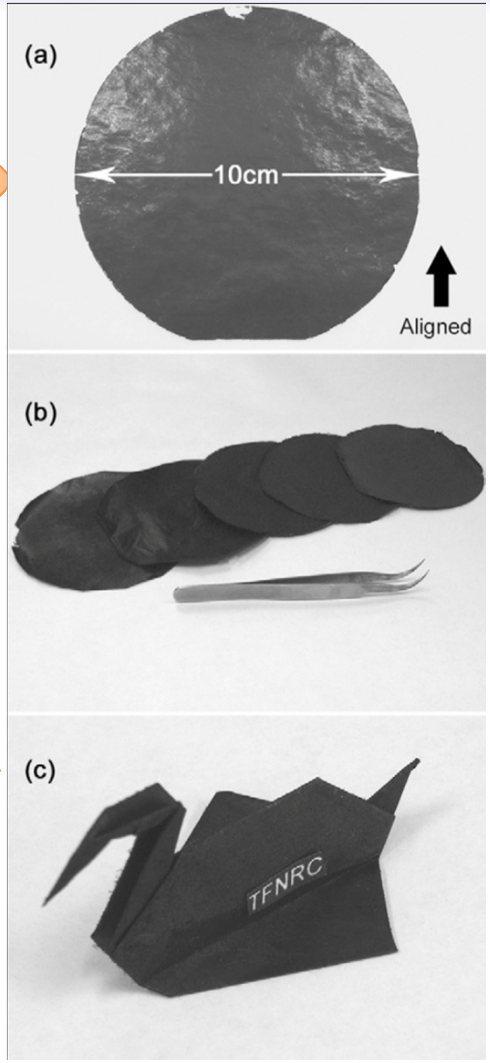
Snapshots II *CNT Buckypaper preforms*

Kostopoulos et al. 14th European Conference on Composite Materials, Budapest, Hungary, June 2010



Wang et al. Nanotechnology 2008;19(7):075609

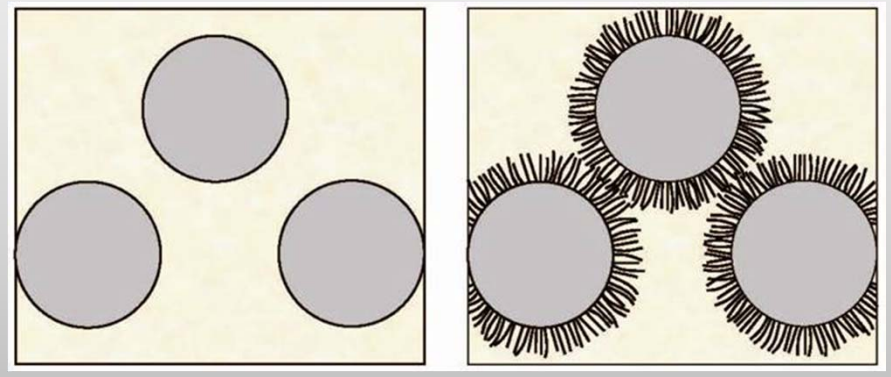
Florida State University

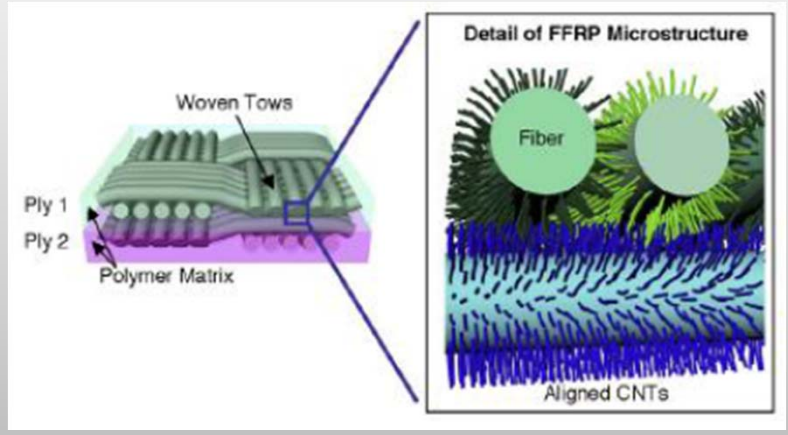


Wang et al. Nanotechnology 2008;19(7):075609

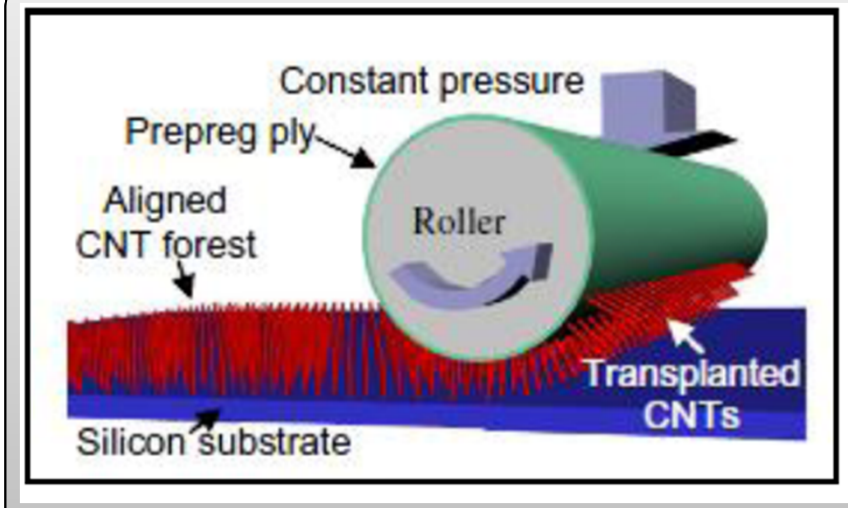
Snapshots III

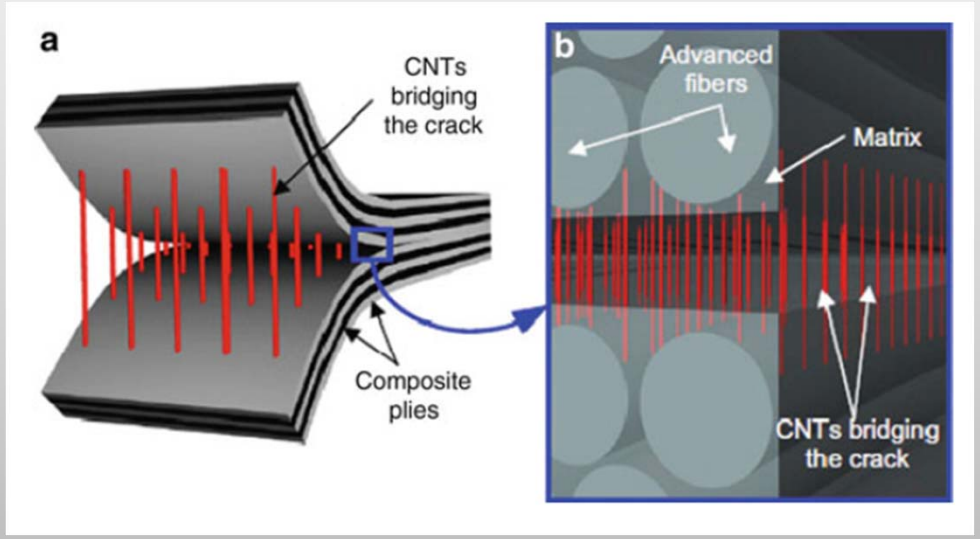
Growth on fibres and transferred forests





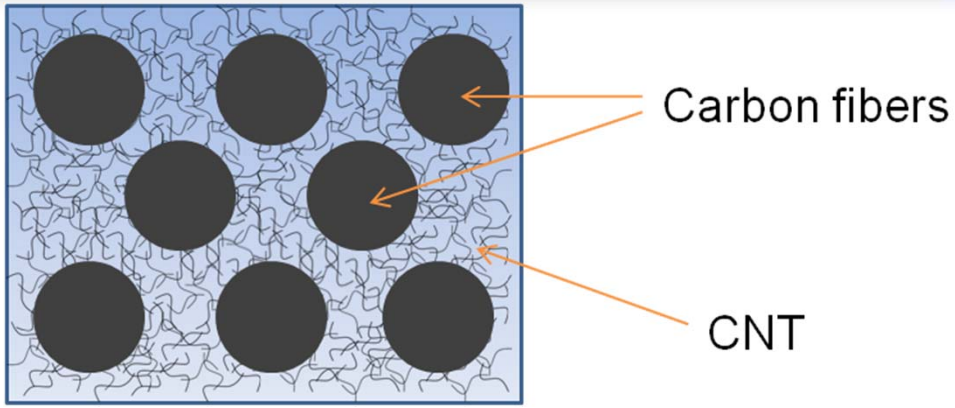
Wicks et al. Composites Science and Technology 70 1 (2010) pp. 20-28.



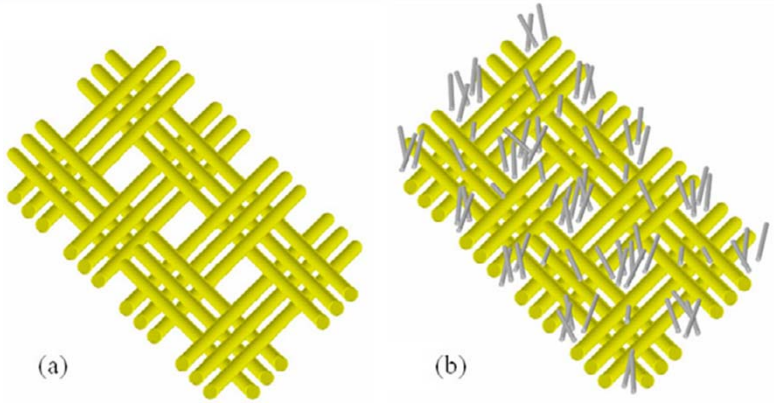


Garcia et al. Compos. Part A: Appl. Sci. Manuf. 39(6), 1065–1070 (2008).

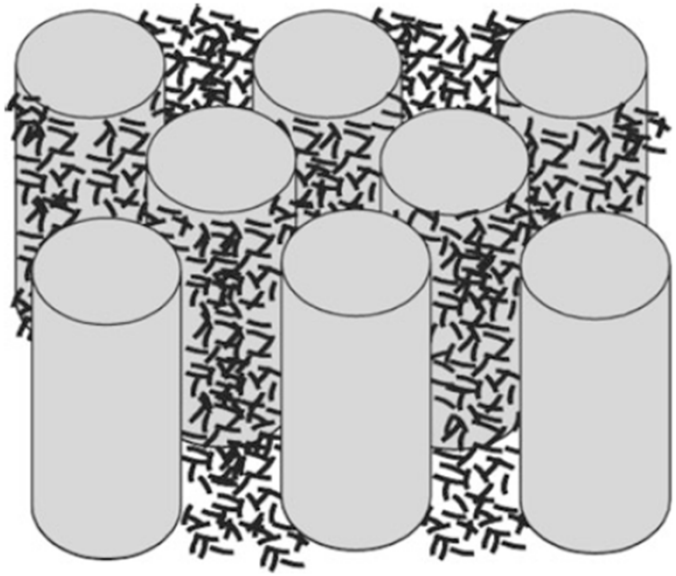
Snapshots IV *CNT doped matrix*



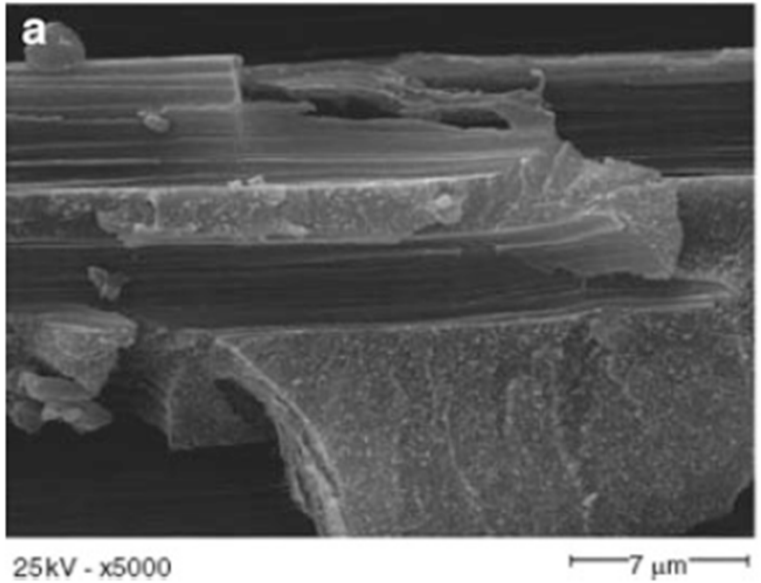
Preferential orientation through thickness



Qiu et al. Nanotechnology 18 (2007) 275708



Vlasveld et al. Polymer 46(23), 10269–10278 (2005)

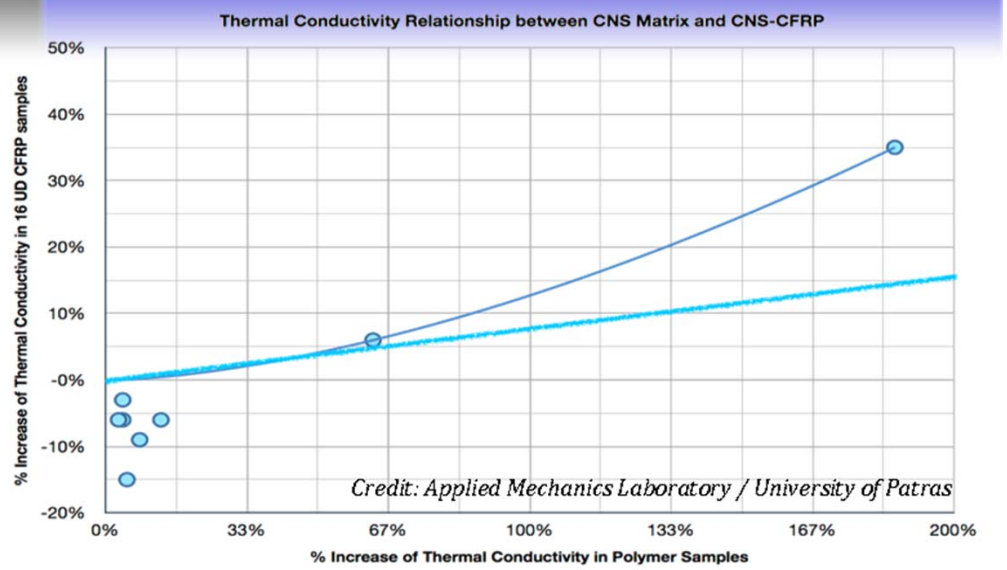


Karapappas et al. J. Compos. Mater. 43(9), 977–985 (2009)

Performance enhancement *CNT doped matrix*

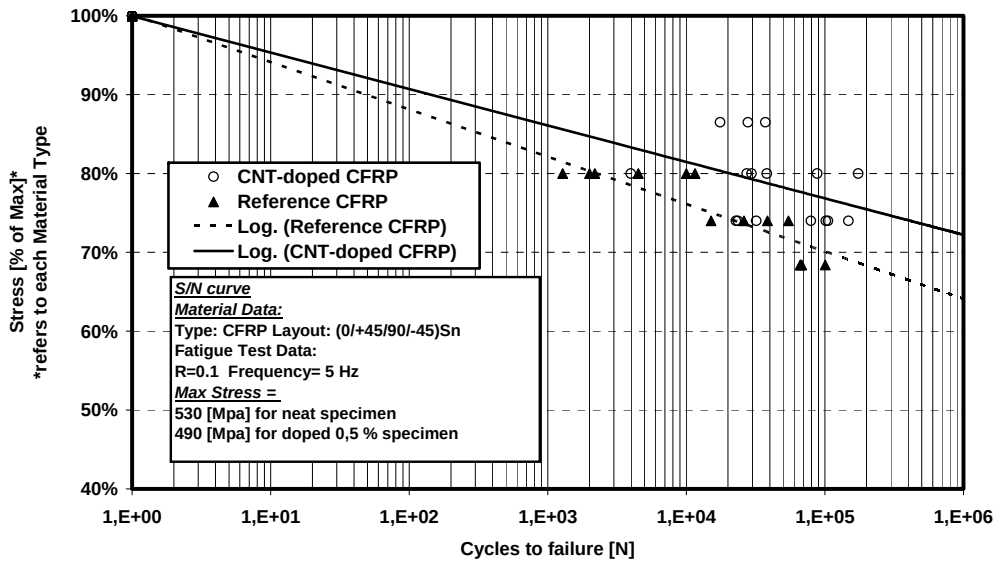
Novel aerospace structures via:

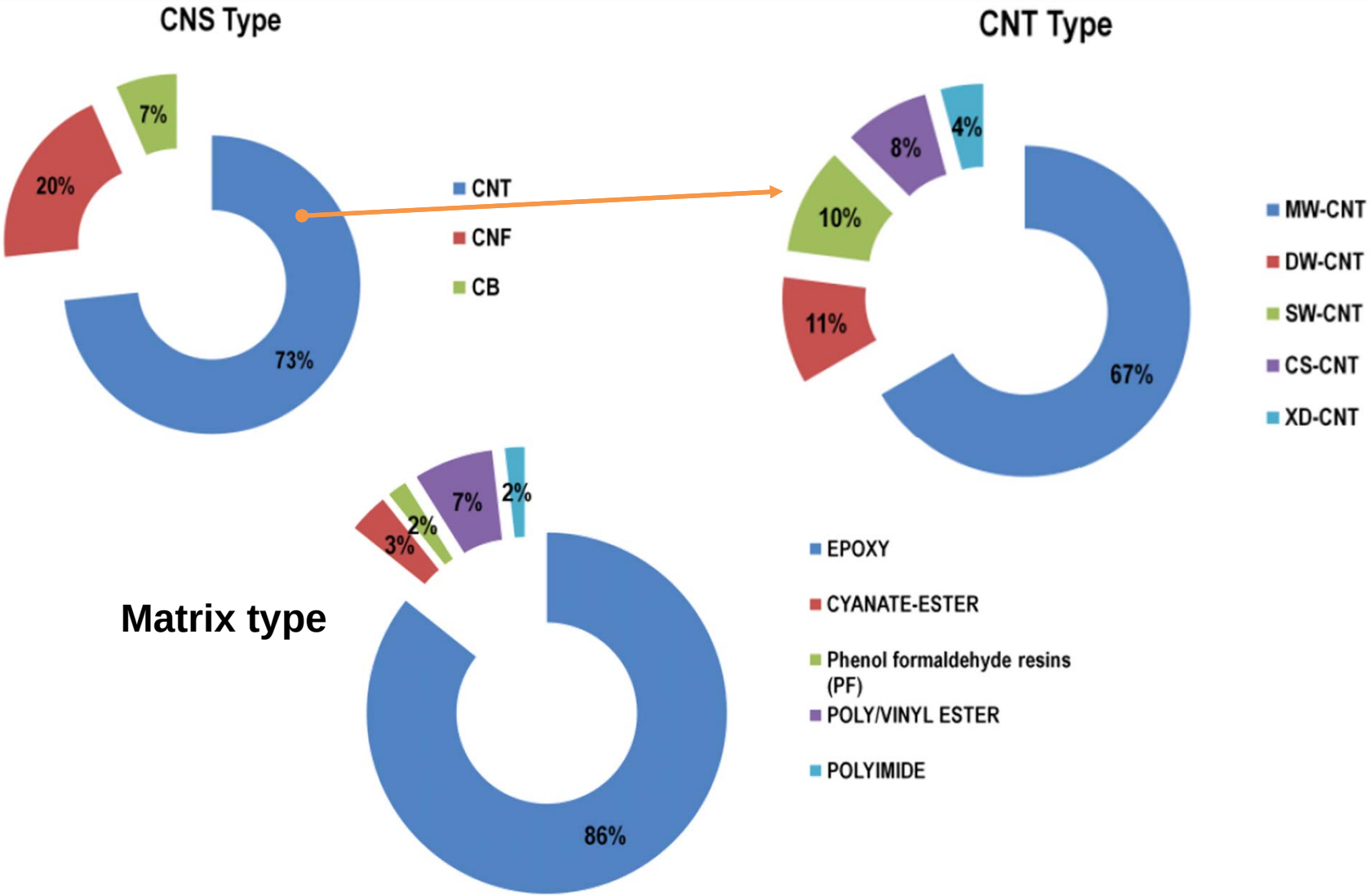
- Improved Fracture Toughness
- Improved Fatigue Life
- Increased electrical conductivity
- Increased thermal conductivity
- Damage Sensing Capabilities



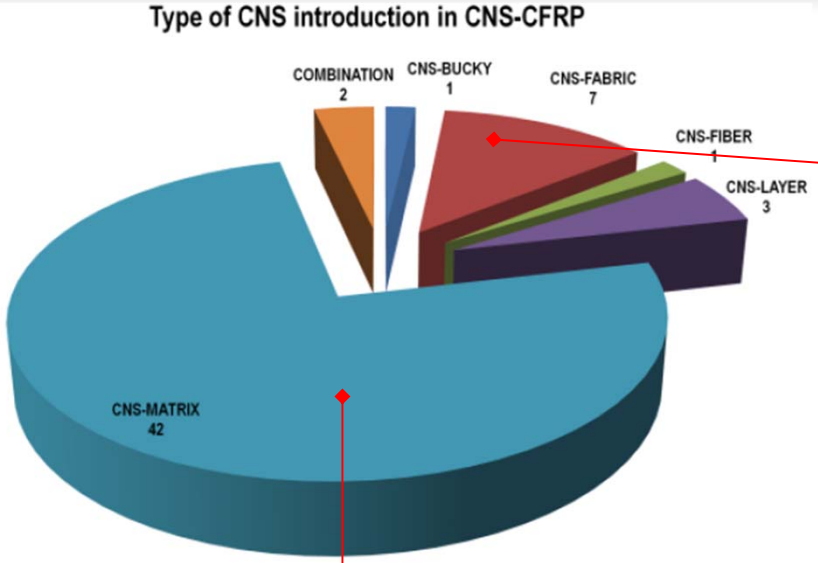
Specific interest for space applications

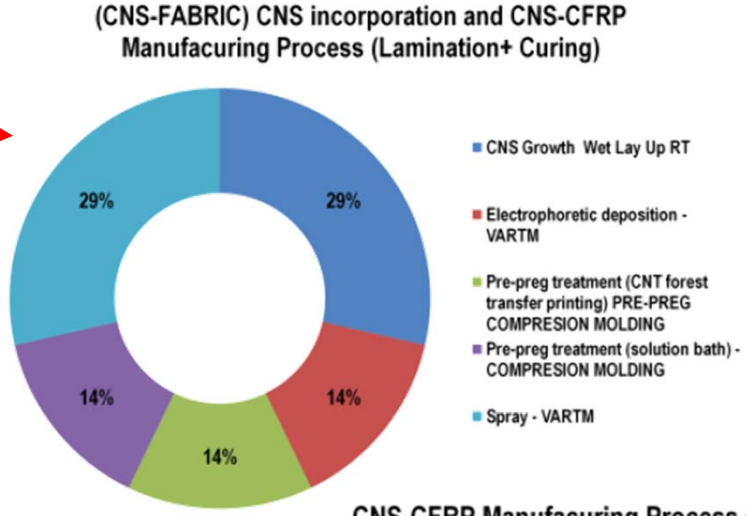
- Stiffness to density
- Thermal Conductivity
- Electrical Conductivity
- CTE

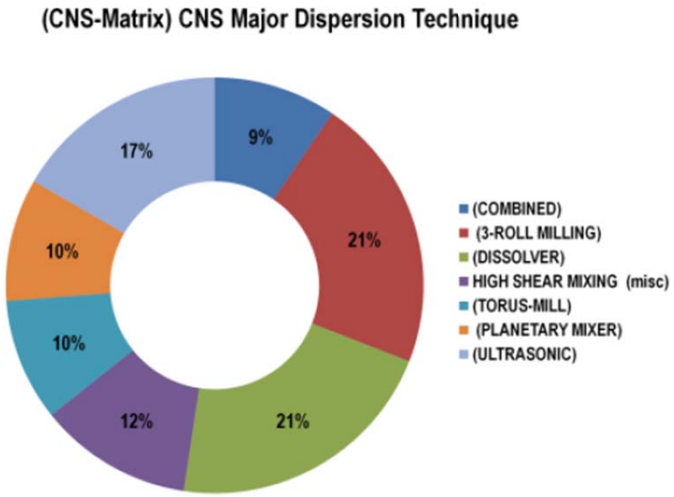


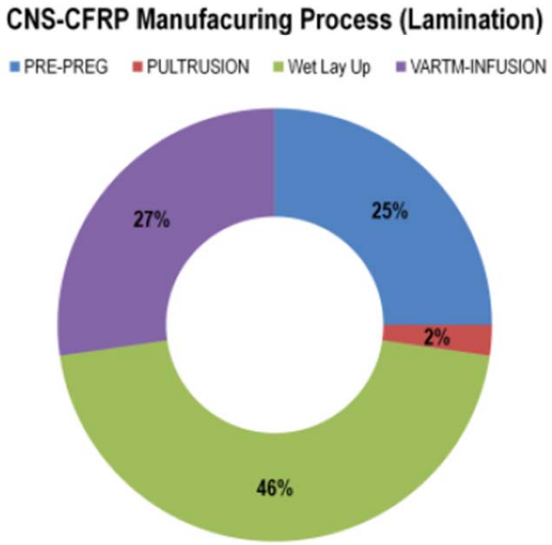

CNS Type
7%
20%
73%
CNT
CNF
CB
CNT Type
4%
8%
10%
11%
67%
MW-CNT
DW-CNT
SW-CNT
CS-CNT
XD-CNT
Matrix type
7%
2%
2%
3%
86%
EPOXY
CYANATE-ESTER
Phenol formaldehyde resins (PF)
POLY/VINYL ESTER
POLYIMIDE

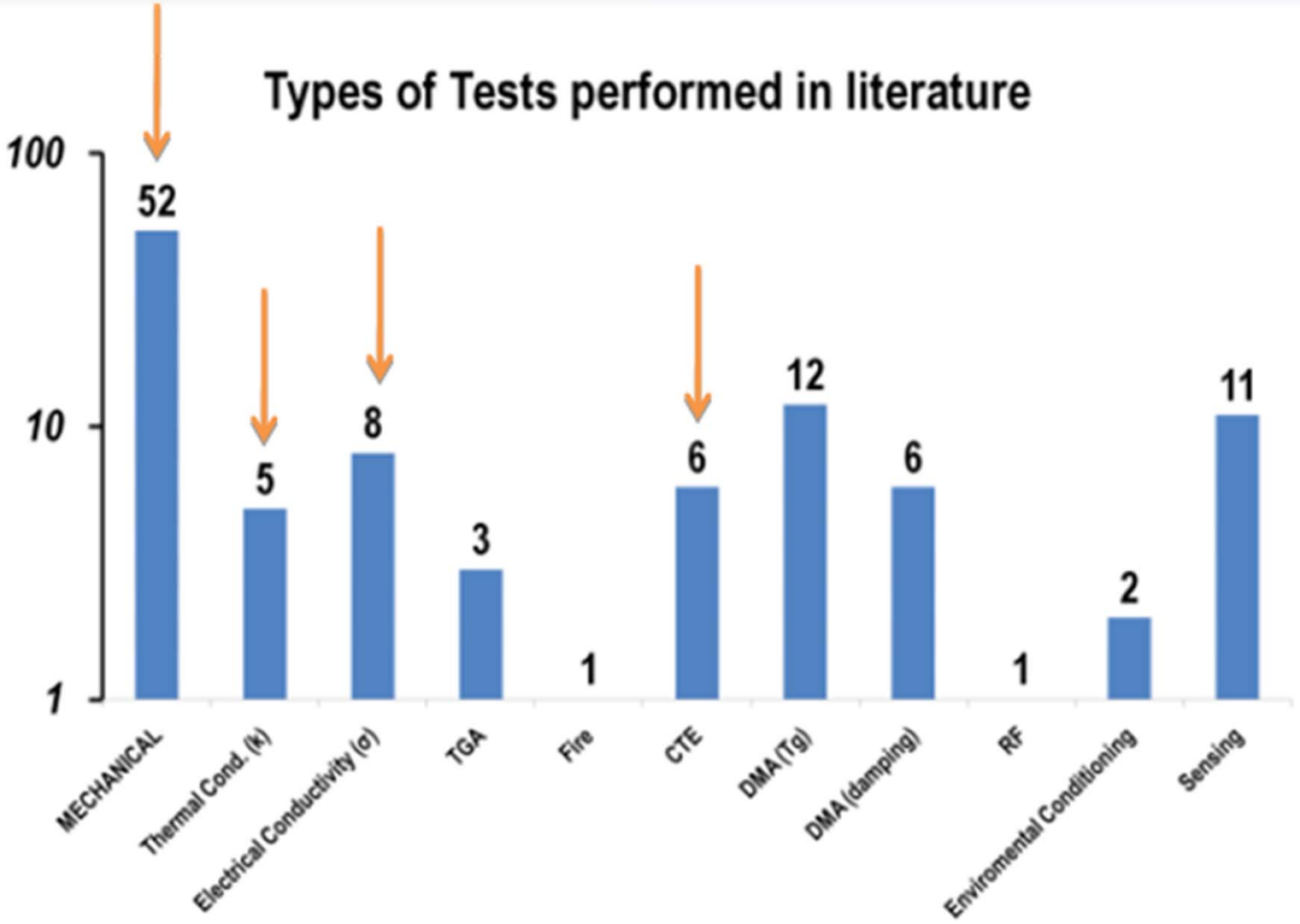
ESA Projects *NAREMA survey*










Types of Tests performed in literature
100
10
1
52
5
8
3
1
6
12
6
1
2
11
MECHANICAL
Thermal Cond. (k)
Electrical Conductivity (σ)
TGA
Fire
CTE
DMA (Tg)
DMA (damping)
RF
Enviromental Conditioning
Sensing

Trade-off *Routes Vs. Applicability*

	Nano-integration Process			Manufacturing Process		
	Safety	Handling	Scalability	Resin Infusion	Autoclave	Quality Control
Resin Doping	− +	+	+	− +	+	− +
Growth	− −	−	−	+	+	− +
Buckypaper preform	−	− +	− +	+	− +	− +
Prepreg	+	+ +	+ +	N.A.	+ +	+

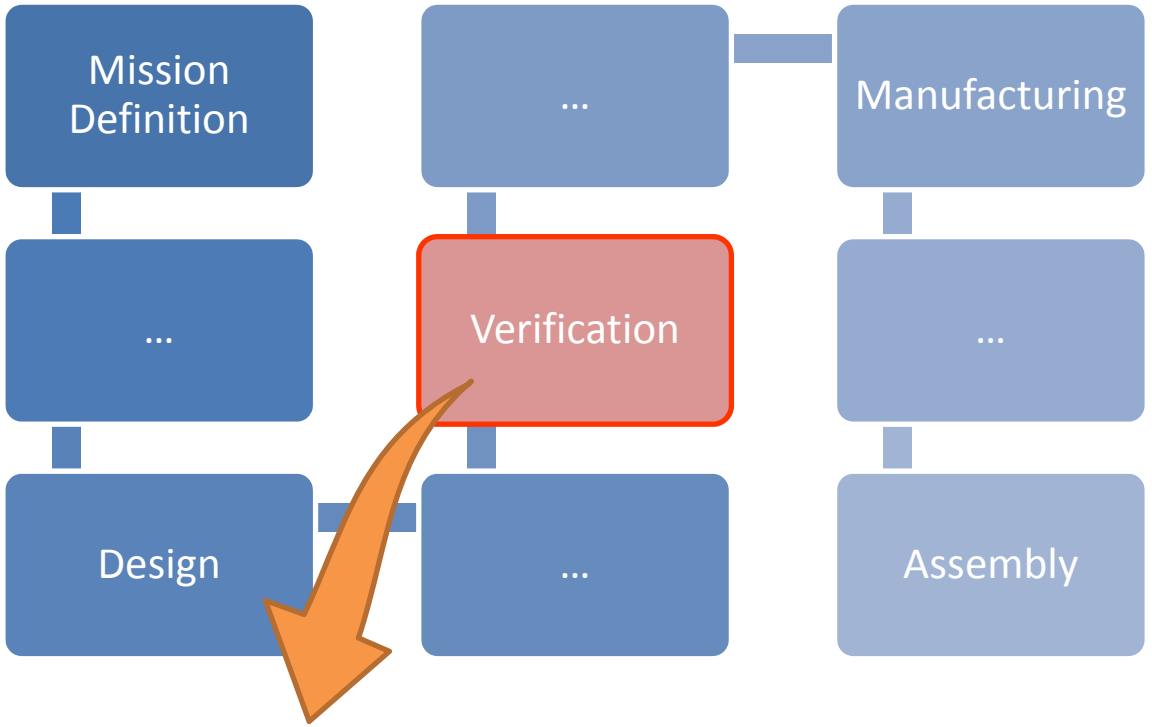
Incorporation of nano-phase *Challenges*

- Agglomerations
  - Effective use of nano-species
- High nano-phase content may be needed
  - Depending on the process different levels can be achieved
- Modification routes may alter the host material
  - It is usual to employ solvents in such processes
- IP Rights

Why modeling?

Importance of modelling @NANO-scale

- The road to the launch



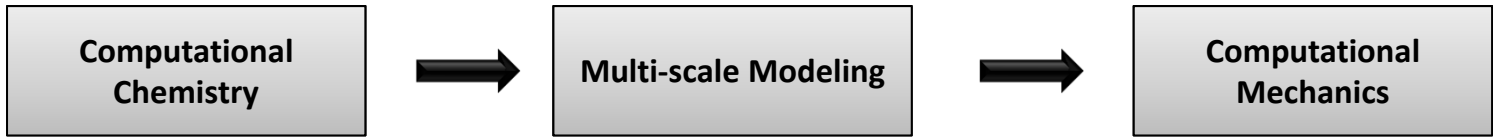
Modeling

"If you cannot model it, you can't fly it"

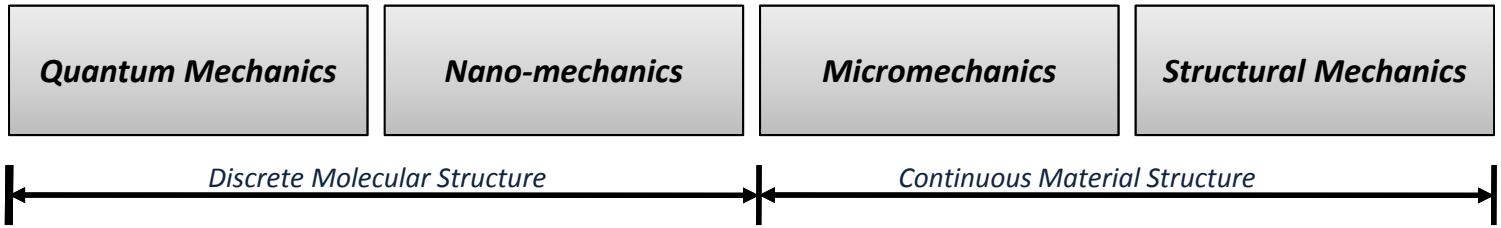
- Based on physical and chemical principles, predict material properties
- Understand trends and capabilities of materials
- To predict the performance of the materials under service conditions
- To design materials according to application needs

Nano-modeling capabilities *Available approaches*

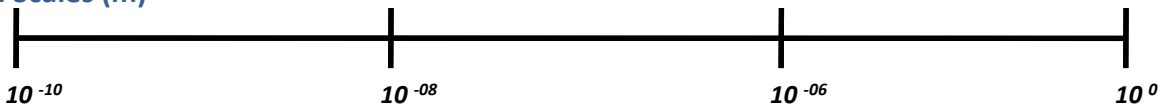
Modeling Methods



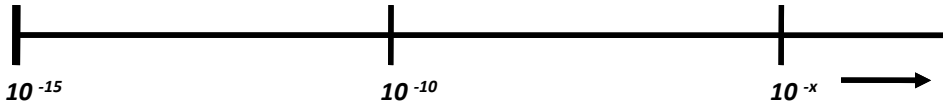
Modeling Tools



Spatial Scales (m)

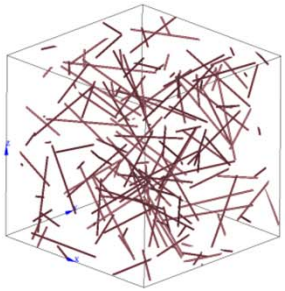


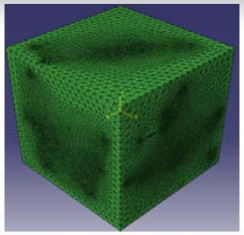
Time Scales (sec)

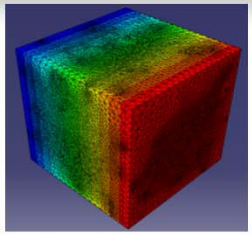


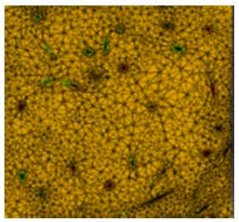
Nano-modeling capabilities

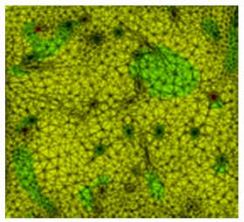
Electrical and Thermal properties

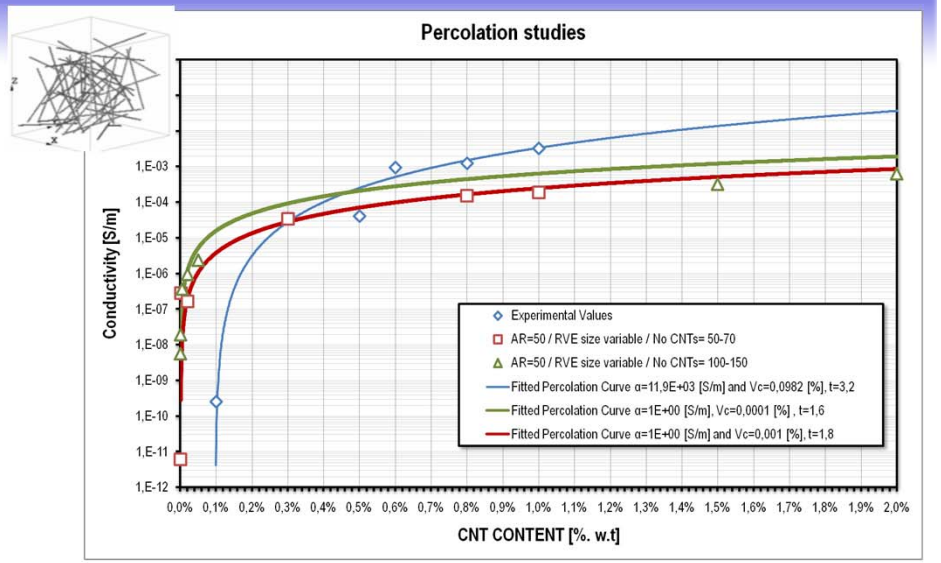


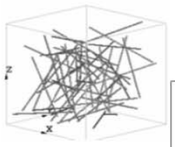


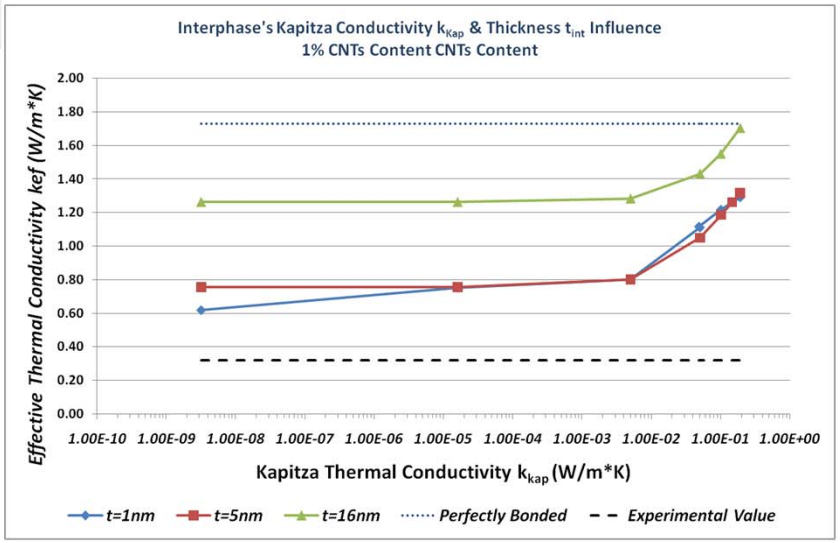










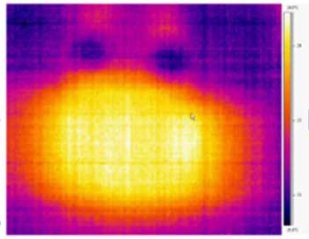


Nano-modeling capabilities *Multi-physics problems*

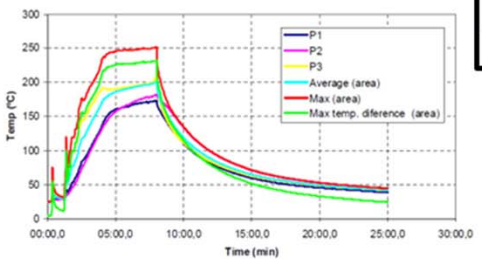
Experiment

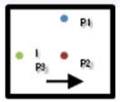
Experimental Layer Set Up

Application of Electrical Power Pe At RT



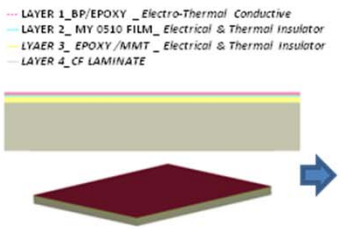
Heat of Top Specimen Surface due to Joule Phenomenon





1st Modelling Approach

FEA Model



Computational Layer Set Up

Material Model Variables

$\rho, \sigma, k, c_p, \eta$, hair

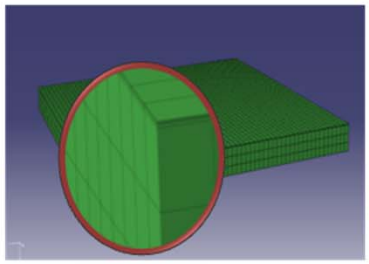
Where:

$\sigma \rightarrow$ *derived by the NrPM_RVE*

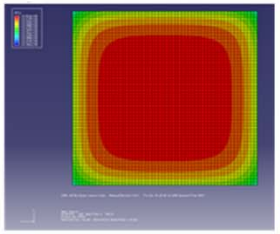
developed for the Electrical Analysis

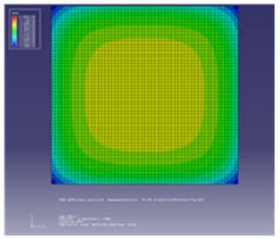
$k, c_p \rightarrow$ *derived by the NrPM_RVE*

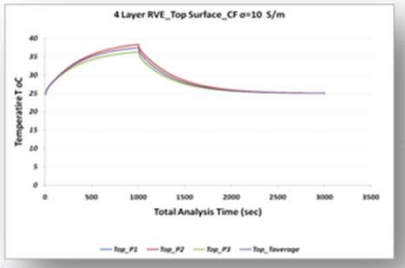
developed for the Thermal Analysis

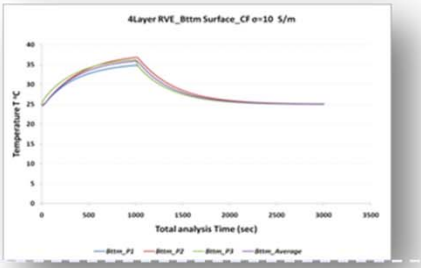


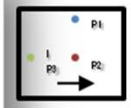
Application of Electrical Power Pe At RT







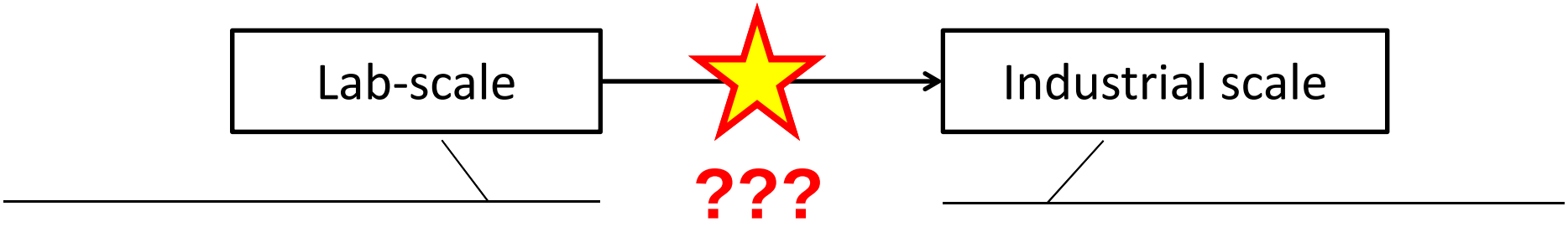




....the other side

Large scale applications *The scale gap*

- When it comes to real and large structures, what is the strategy there?



Small scale up to prototype
Batched production
Loose quality control
Basic performance assessment

Large dimensions
Continuous production
Strict quality control
Performance validation
Material qualification

Large scale applications

- Quality Control System
- Performance validation (…B-values?)
- Quantity requirement
- Continuous processes
- Safety issues in production (*"The European Commission envisages modifications in some of the REACH Annexes and encourages ECHA to further develop guidance for registrations after 2013."*)

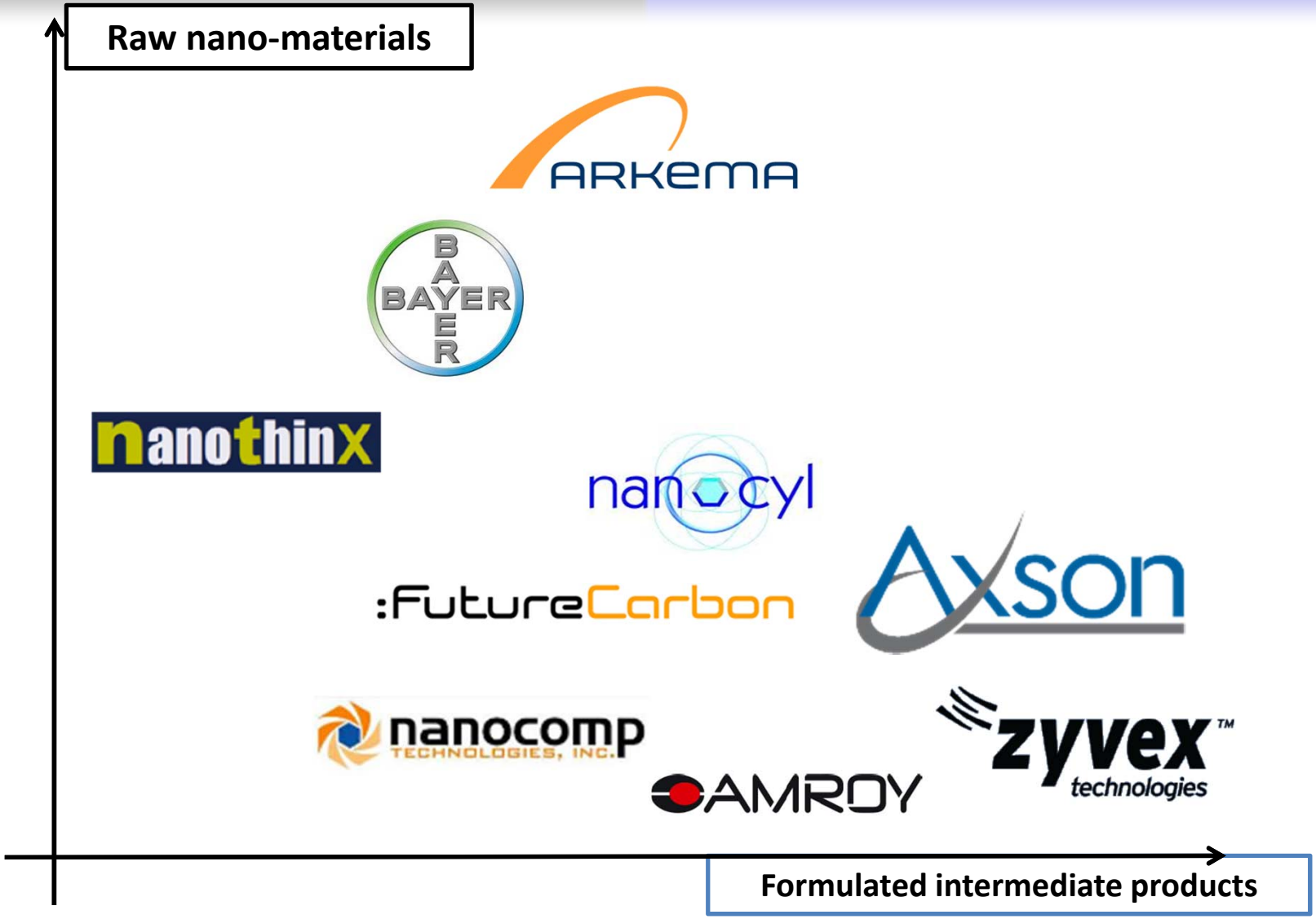
**European Commission, Press release 3-10-2012, IP/12/1050*

- Interest from major players pushes viable scenarios to the surface
- Alternative routes for adoption of nanotechnologies in existing production lines
- IP rights and availability of materials & formulations**

Standardization of Nanotechnology *Latest addition...*

- ISO/TS 27687:2008
  - Nanotechnologies -- Terminology and definitions for nano-objects -- Nanoparticle, nanofibre and nanoplate
- ISO/TS 80004-1:2010
  - Nanotechnologies -- Vocabulary -- Part 1: Core terms
- ISO/TS 80004-3:2010
  - Nanotechnologies -- Vocabulary -- Part 3: Carbon nano-objects
- ISO/TS 12805:2011
  - Nanotechnologies -- Materials specifications -- Guidance on specifying nano-objects
- ISO/TS 80004-4:2011
  - Nanotechnologies -- Vocabulary -- Part 4: Nanostructured materials
- ISO/TR 11360:2010
  - Nanotechnologies -- Methodology for the classification and categorization of nanomaterials
- ISO/TR 10929:2012
  - Nanotechnologies -- Characterization of multiwall carbon nanotube (MWCNT) samples
- ...

The Market *Commercial products*



Products

Indicative nano-enabled products for composites

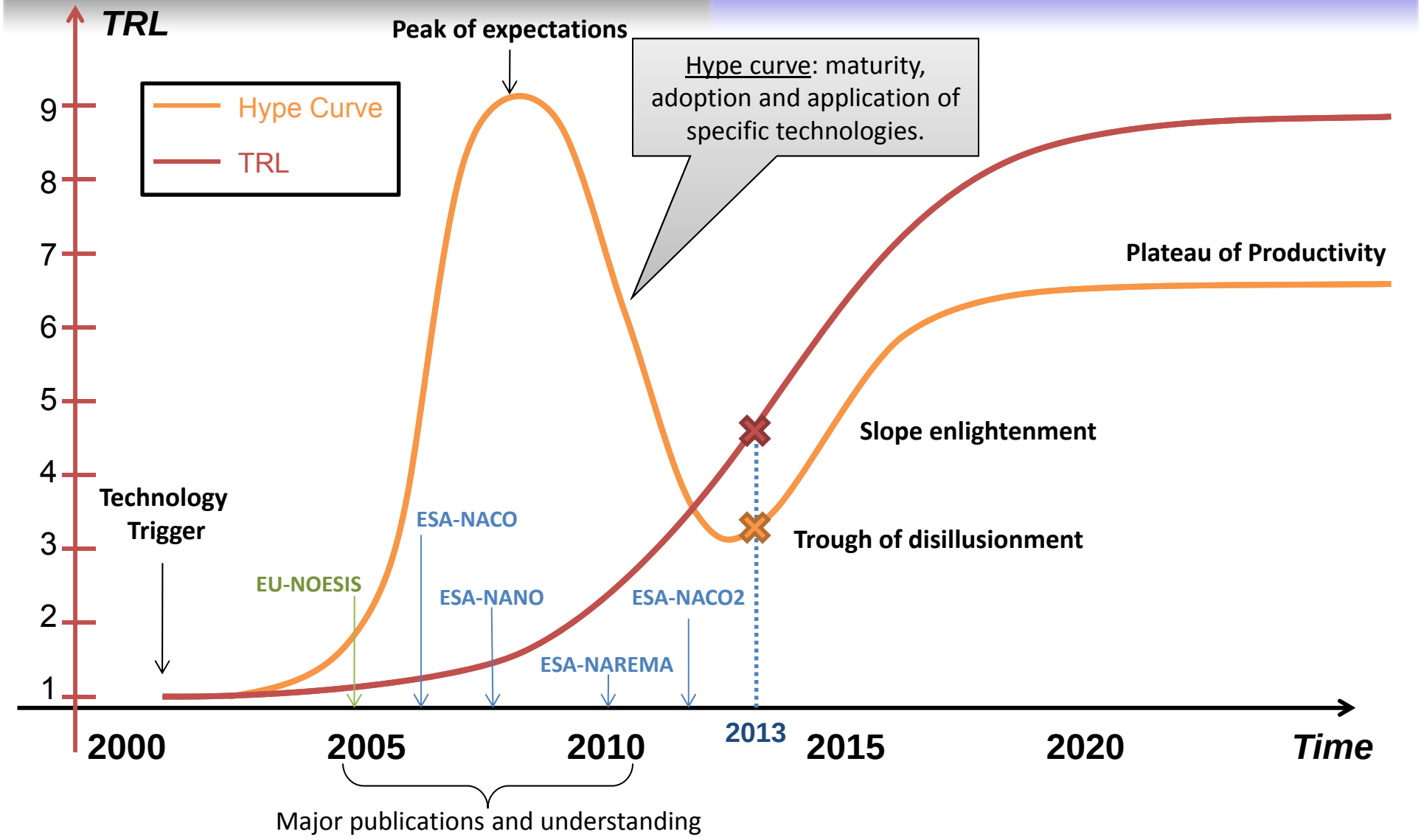
Baytubes (Bayer Materialscience, D)

BuckyShield (Buckeye Composites, USA)

Raw MWCNT & Epocyl (Nanocyl, BE)

TRL & Gartner chart

Structural nano-composites: Hype curve



European Union

For the future of nano-materials (overall)

- Nano-materials is a key enabling technology
- The global market for nano-materials is estimated at 11 million tons at a market value of €20 billion
- 300,000 to 400,000 employed in Europe
- Presently dominated by carbon black, amorphous silica etc.
- Products underpinned by nanotechnology are forecast to grow from a global volume of €200 billion in 2009 to €2 trillion by 2015

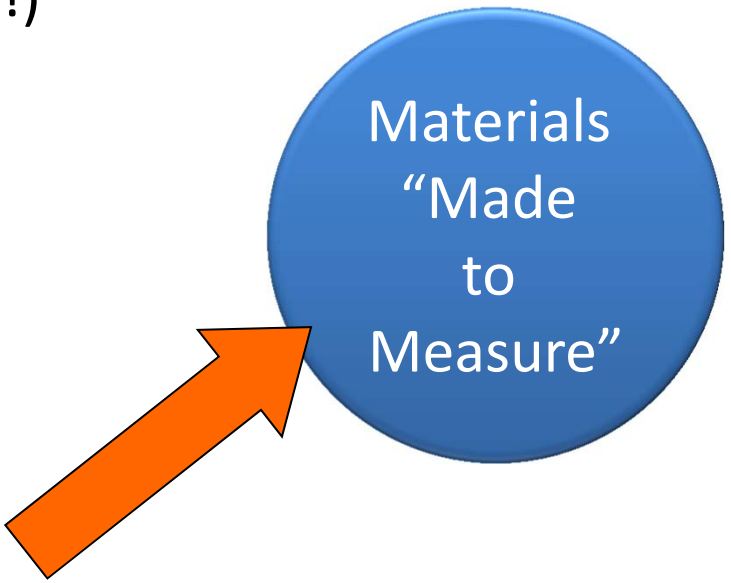
**European Commission, Press release 3-10-2012, IP/12/1050*

- ...nano-materials for Structural applications is a rather small piece of the pie

Conclusions

- Targets to be achieved still remain:
  - Reduce mass and improve stiffness (!)

  Steps to reach the target:
  - Processing
  - Tune specific properties
    - Thermal conductivity
    - Electrical conductivity
    - EM compatibility
  - Tune combination of properties



- What should be expected the coming years?
  - Integration of nano-enabled products in commercial portfolios

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ESA-NANO

EU-FP6-NOESIS Project

ESA-NACO1 & NACO2

EU-FP7-ELECTRICAL Project

EU-FP7-LAYSA Project

EU-FP7-SARISTU Project

EU-FP7-IAPETUS Project

Applied Mechanics Laboratory Internal Projects