Composites Technology MSE 440

Smart composites

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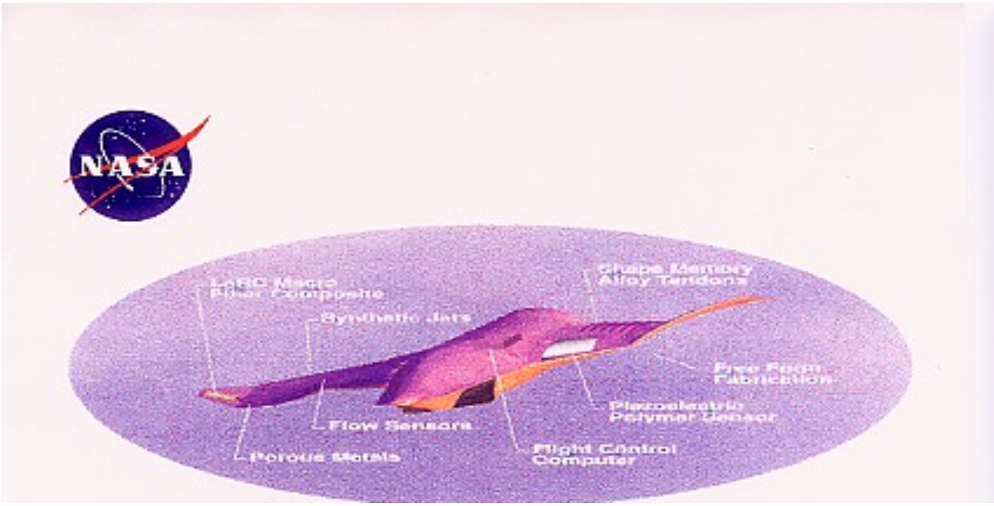


Composite materials evolution

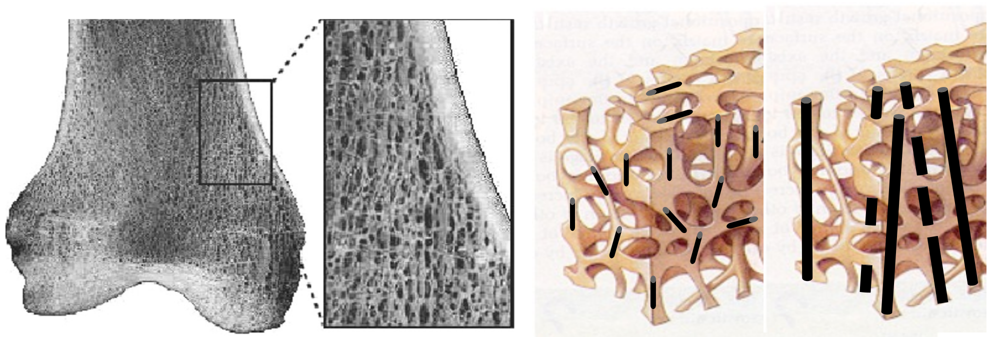
Mechanical properties

Manufacturing costs

Unique performance

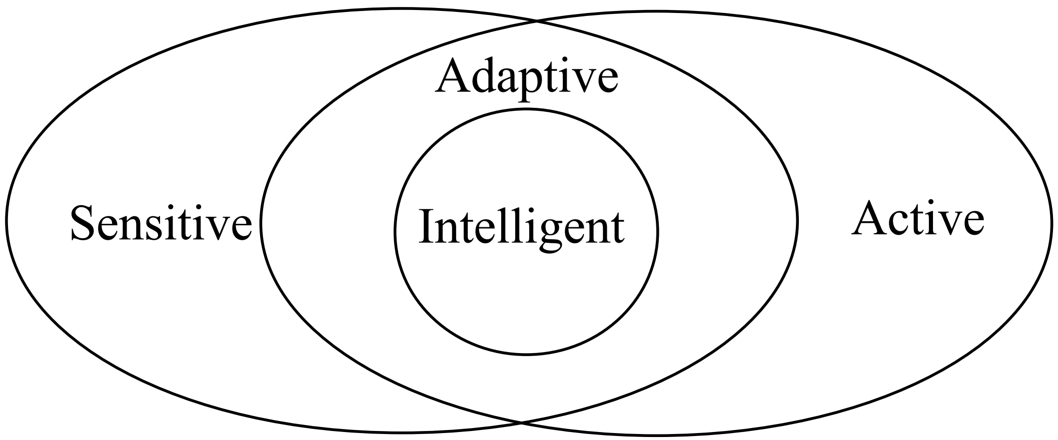
Unique functionality

?



Adaptive, smart composites?

Definition: what are adaptive composites, smart composites, functional composites, intelligent structures???
Basic concept: incorporate sensors and actuators into the composite, or another phase, so that the material is not only structural, but also functional: the material is capable to adapt to its environment, and to modify its properties in response to external stimuli.



Adaptive, smart composites?

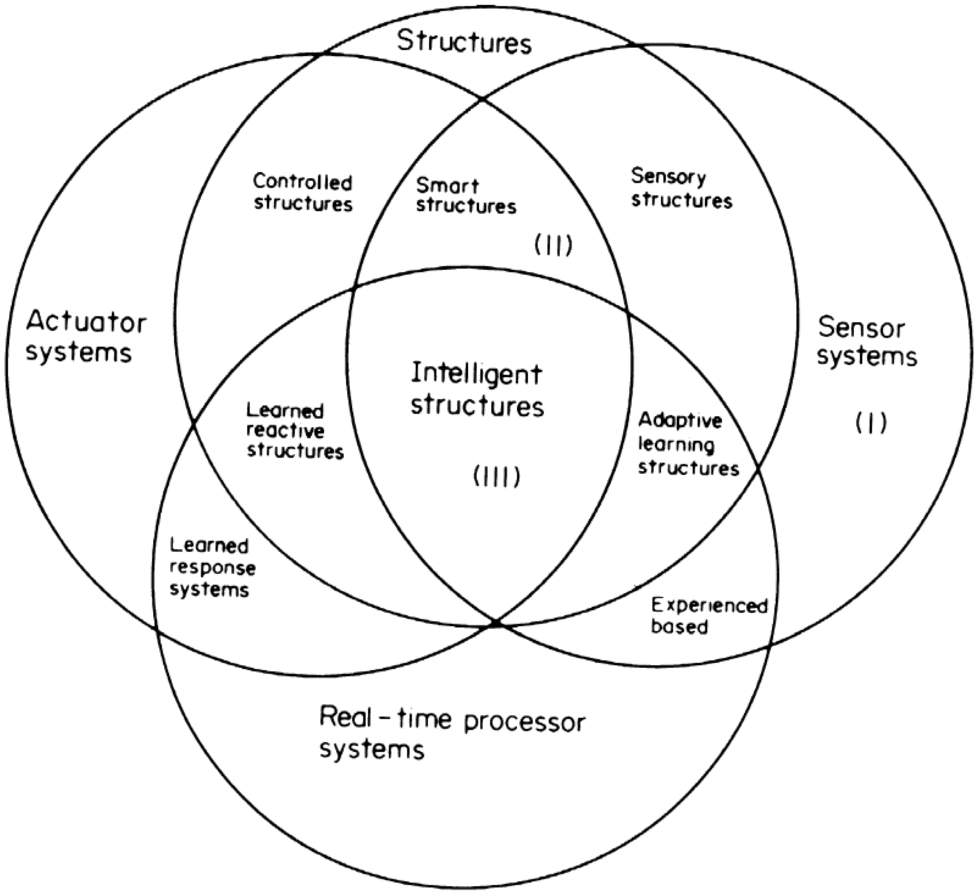


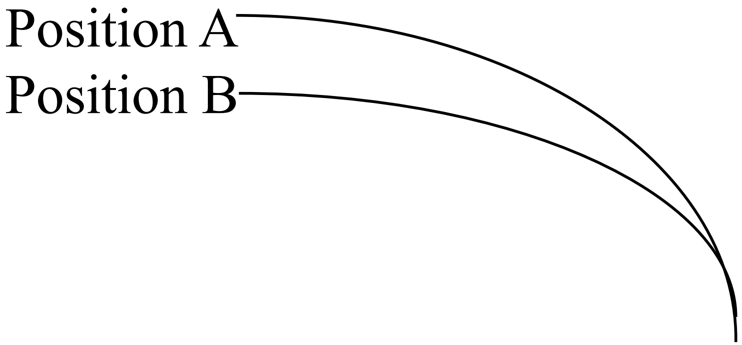
Figure 1 Smart materials classification.

Addition of the third element, real time processing element, “the brain”, for active systems.

Source: smart composite materials systems, Chapter 5.20 encyclopedia of composite materials
DOI: 10.1016/B978-0-12-803581-8.10298-X

Adaptive composites concept

Example:



Adaptive composite concept

Incorporation of several potential materials into the composite to confer sensing or actuating properties:

- Piezo-electric ceramics
- Shape memory alloys
- Electrostrictive, magnetostrictive, magneto-rheologic materials
- Electroactive polymers
- Optical fibers, sensors, MEMS
- Self-healing materials,
- Shear thickening fluids…

- Any third phase that can bring a functionality to the composite (could also be a solar panel film, or some Phase change material, etc.)
- It is also a growing field, with the era of IoT…(Internet of Things), with the possibility to embed electronic circuits to link elements.

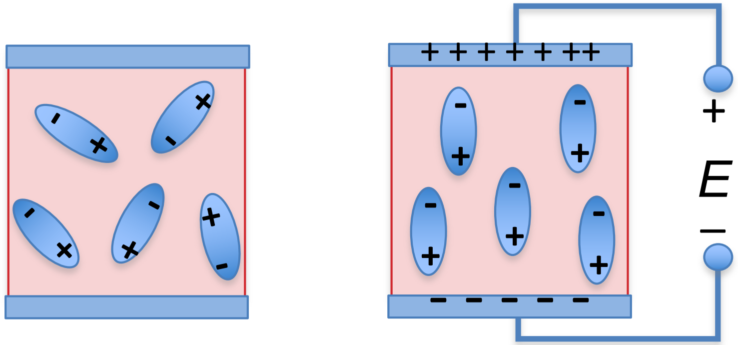
Composites with piezo-electric elements

Under the form of particulates, platelets, or better, fibers.
Basic principle: under strain, the material produces electricty, and vice-versa.
--> shape change applications
--> Active damping applications

- Advantages: high frequency possible (kHz).
- Limitations: low amplitude, need an electric field and electrodes, so a bit difficult to produce.

Dielectricity and piezoelectricity

Dielectric material



Relative permittivity $\varepsilon_r(f)$

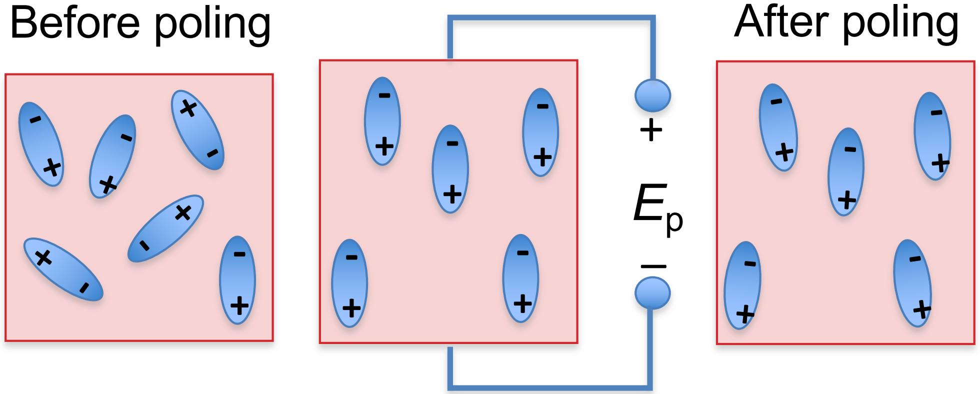
Dielectric loss tangent $\tan\delta(f)$

Breakdown strength E_{max}

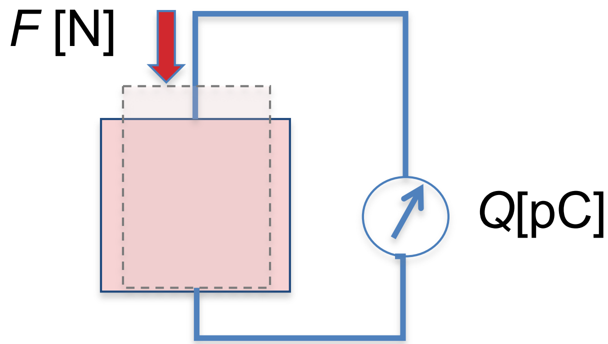
Piezoelectric material

Before poling

After poling



Poled piezoelectric material

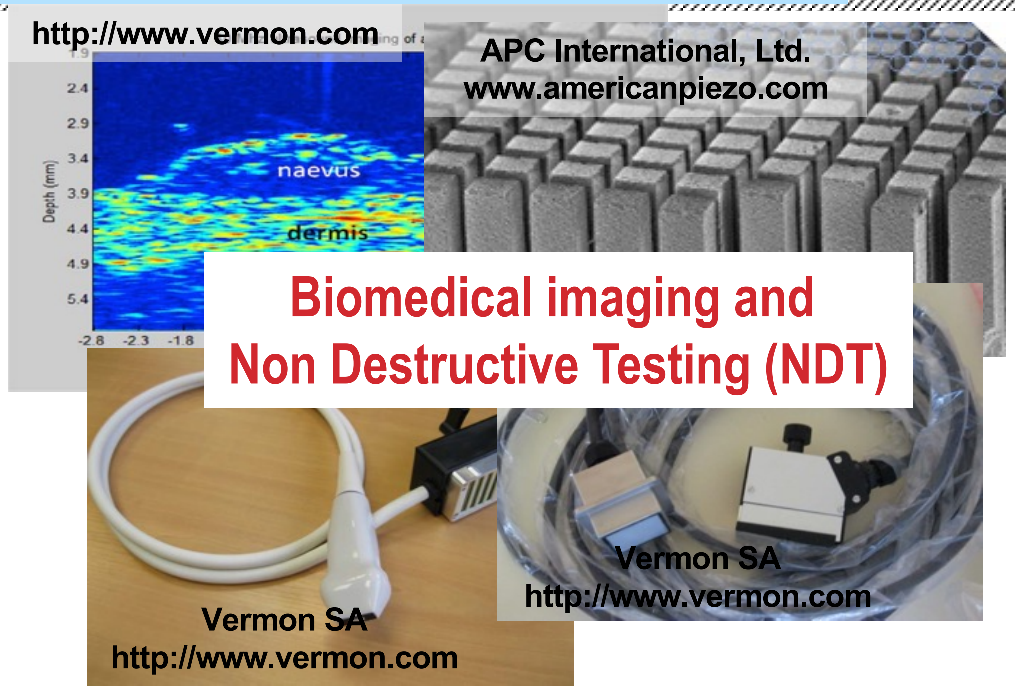


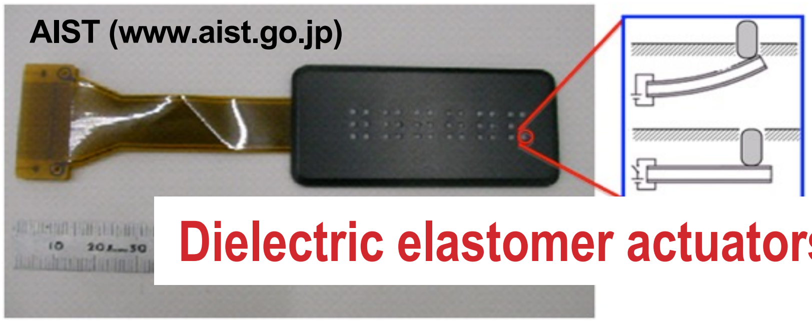
Coercive field E_c ($E_p > E_c$)

Piezoelectric coefficient $d_{33}\left[pC/N\right] = \dfrac{Q\left[pC\right]}{F\left[N\right]}$

S. Dalle Vacche, 2015

Dielectric and piezoelectric composites: applications



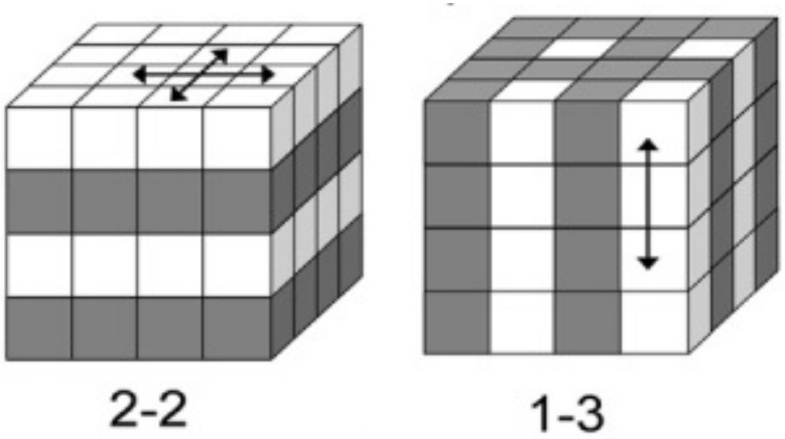


…and more…

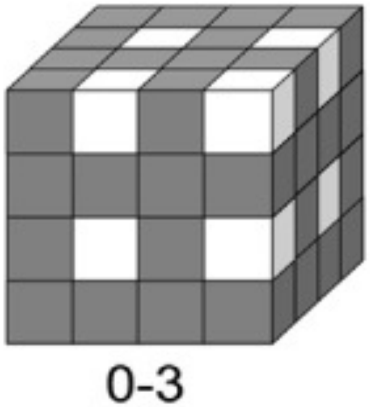
Types of composites

Commercial applications are mainly based on **2-2** and **1-3 composites**

- Fabrication and shaping may be complex (e.g. dice & fill)



0-3 composites allow a cost-effective polymer-like processing and shaping

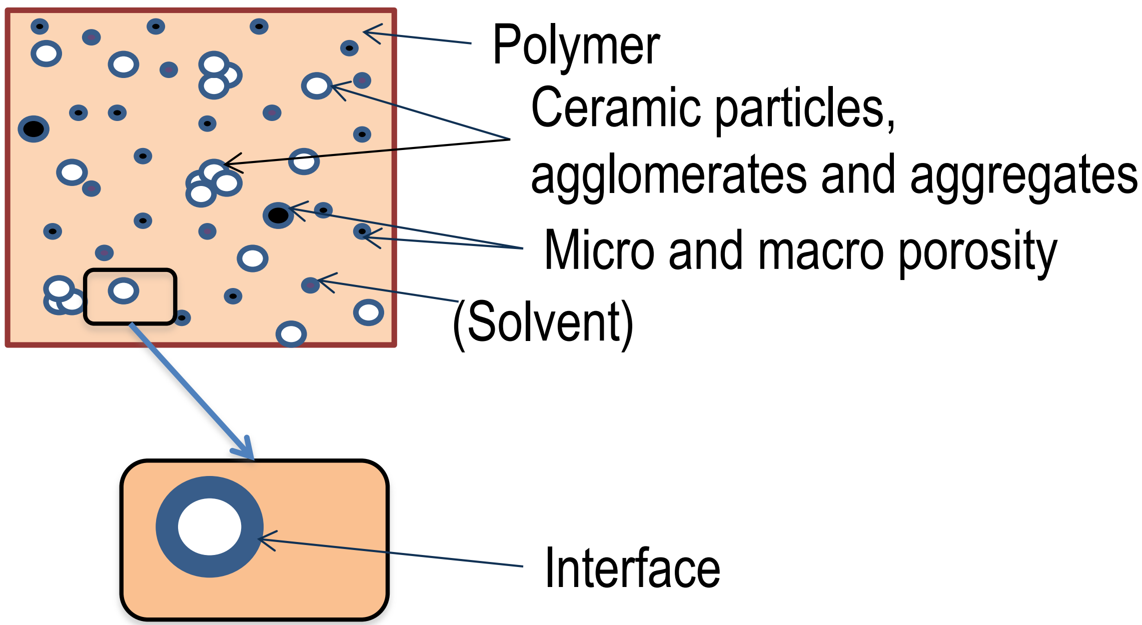


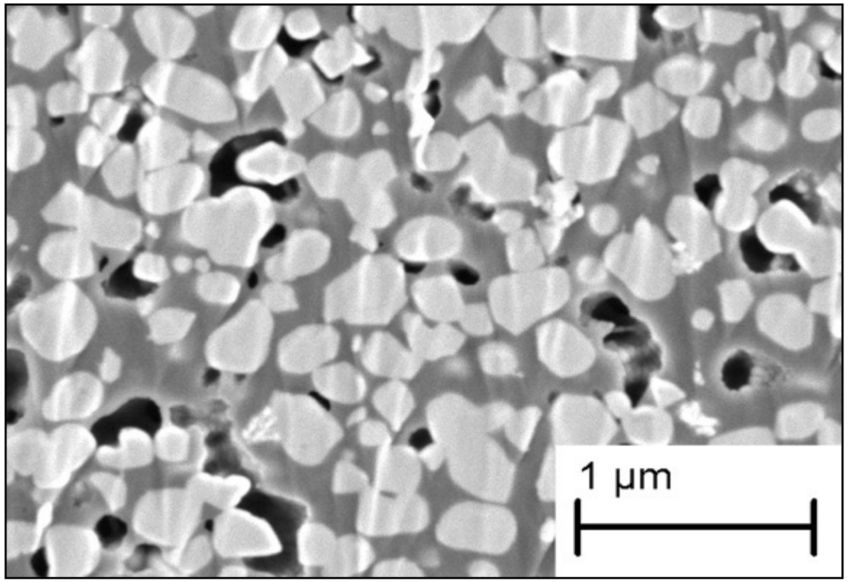
R.E. Newnham (1978)

The challenge of 0-3 composites

Fabrication of fluoropolymer based composites with high inorganic particles volume fractions and/or high aspect ratios:

- great surface energy difference between matrix and filler
- complex morphology due to coexistence of several phases





P(VDF-TrFe)/$BaTiO_3$ composite (Φ=0.6)

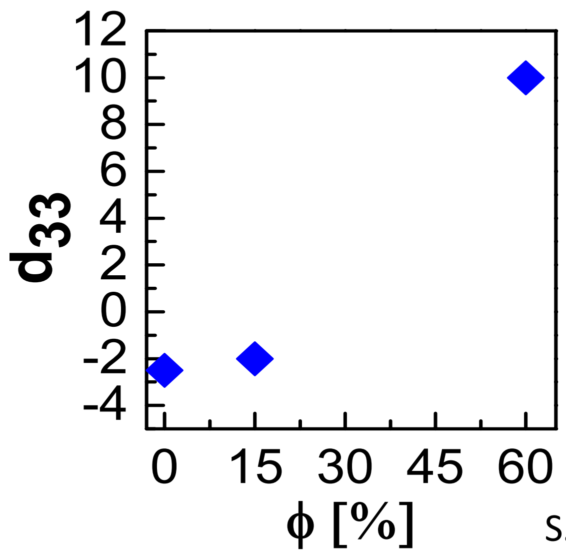
S. Dalle Vacche, 2015

P(VDF-TrFE)/$BaTiO_3$ composites

Piezoelectric composites with 60 vol% well dispersed submicron sized ceramic particles:

- Storage modulus: 7x increase with respect to P(VDF-TrFE)
- Relative permittivity: 8x increase with respect to P(VDF-TrFE)
- Piezoelectric coefficient: 5x increase with respect to P(VDF-TrFE) with poling field of 100 kV/cm
- Particle surface modification increased thermomechanical stability and decreased dielectric loss factor at low frequency

Research is ongoing to further increase dielectric and piezoelectric properties for practical applications



d_{33} of composites poled with E_p = 100 kV/cm, in function of $BaTiO_3$ vol.fraction

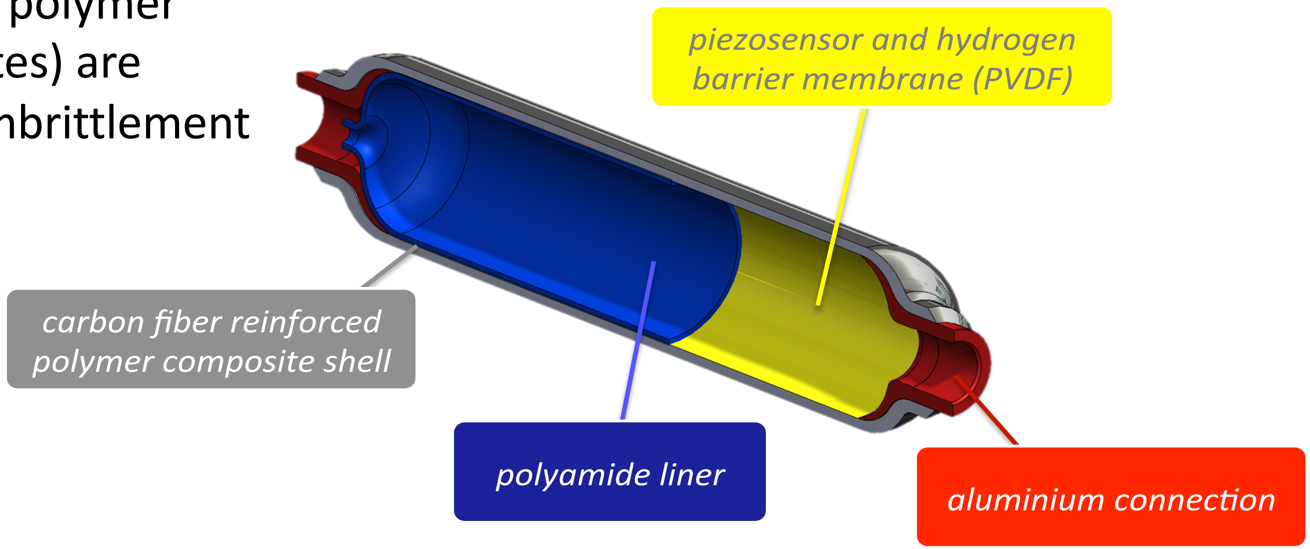
S. Dalle Vacche, 2015

Another example of use: Self-sensing high pressure H_2 storage vessel

4 kg H_2 needed to drive a fuel cell car 400 km (45 m^3 at ambient -> 0.11 m^3 at 400 bar)

Schlapbach, L. Züttel, A. Hydrogen-storage materials for mobile applications, Nature, 414 (2001)

Commercial H_2 storage vessels (thick polymer liner + metal + carbon fiber composites) are expensive and present a risk of H_2 embrittlement



-High barrier properties
-> Low permeability material

-Health monitoring and sensing (safety)
-> "smart structure"

- High pressure to reduce volume
-> High strength without embrittlement

Nanocomposite of PVDF-TrFE (poly-vinylidene fluoride trifluoroethylene copolymer) with **surface modified clay platelet particles**

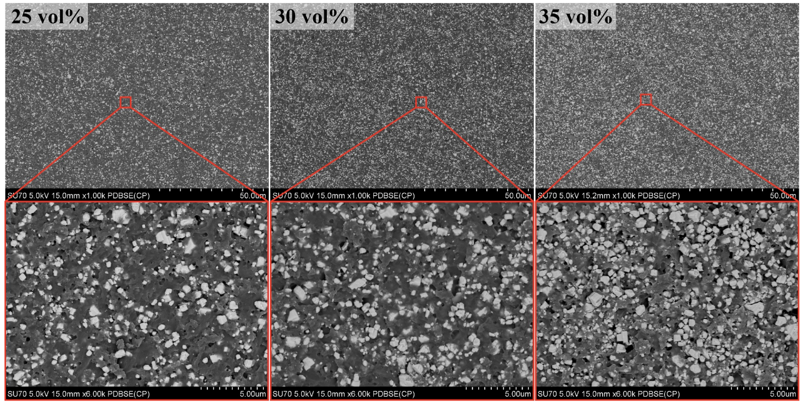
+

High strength carbon fiber reinforced composite

Leterrier et al, 2013

Another example of use: Damage detection and energy harvesting

-$K_{0.5}Na_{0.5}NbO_3$ nanoparticles with epoxy, sandwiched between two CFRP plates



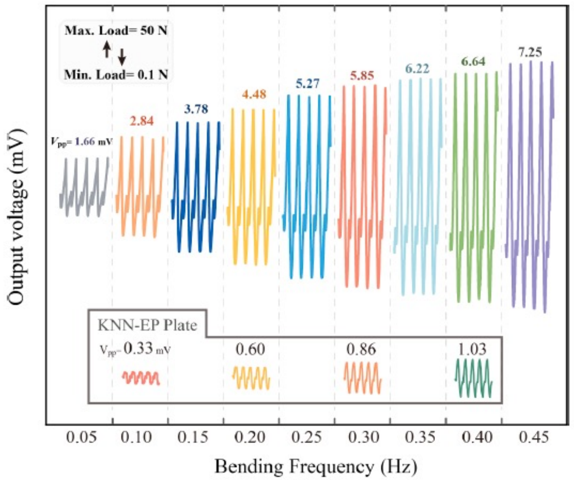


Fig. 12. Output voltage signals generated by CFRP/KNN–EP. The inset represents those generated by the KNN–EP plate.

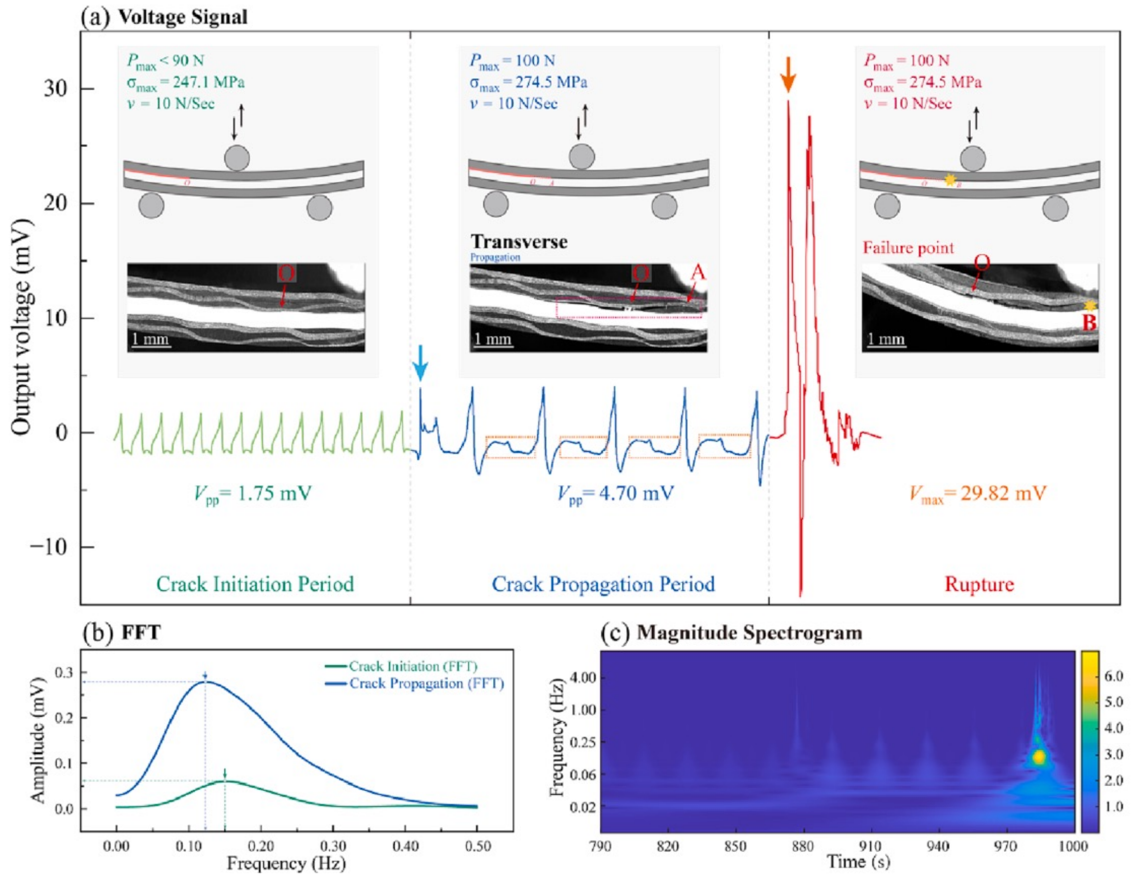
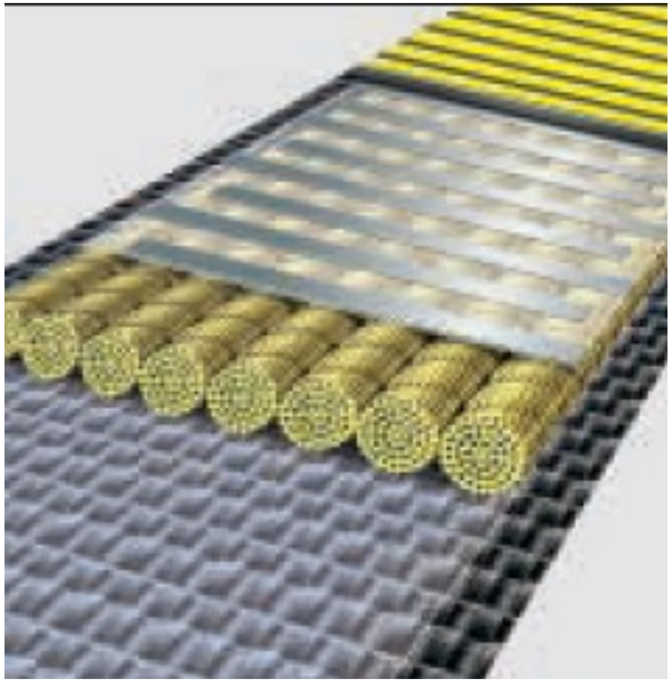


Fig. 14. Case 2: using ENF CFRP/KNN–EP for damage detection in a cyclic 3-point bending test. (a) Voltage signal, the inset is cross-sectional observation. (b) FFT spectrum analysis, and (c) magnitude spectrogram (unit: mV).

Carbon Fiber-Reinforced Piezoelectric Nanocomposites: Design, Fabrication and Evaluation for Damage Detection and Energy Harvesting Yaonan Yu a, Yu Shi b,*, Hiroki Kurita a, Yu Jia c, Zhenjin Wang a, Fumio Narita a,* Composites: Part A 172 (2023) 107587

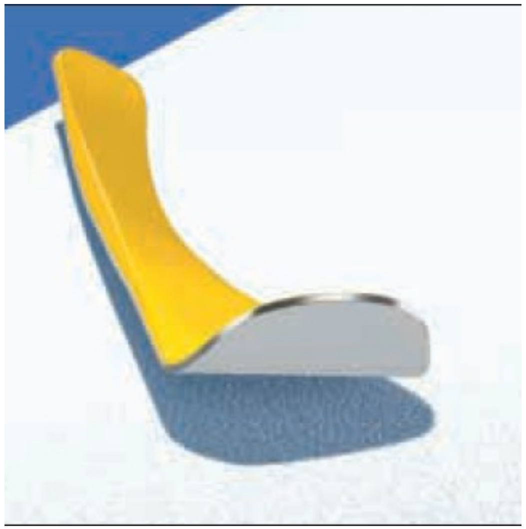
Another example: Active ski - Head intellifiber

Piezo fibers



Smart Ski

Response time, 5ms. The ski twists, creates an electrical currents that is sent to a circuit, which sends it back to the other fiber patch, to bring back the shape to flat.



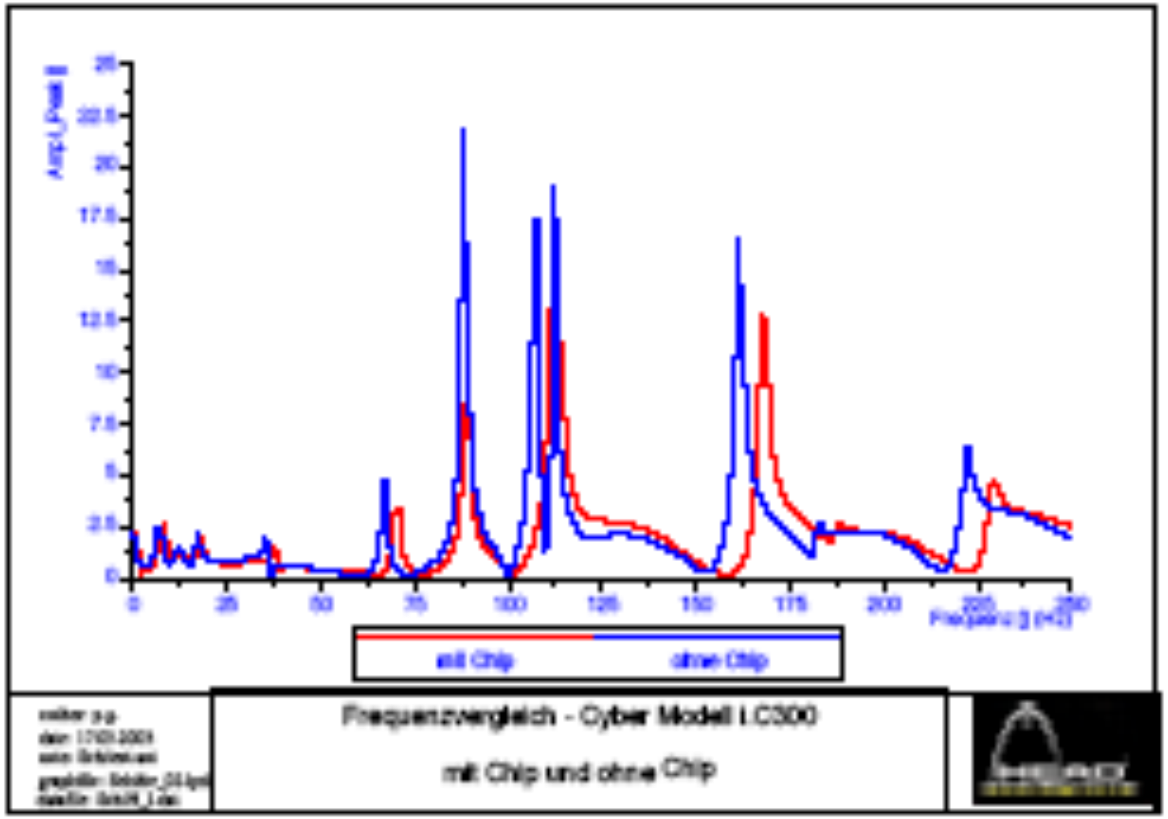
Traditional Ski

Intelligent ski

Position of the fiber patches

Smart Ski

Frequency versus amplitude for the ski, in red with piezo, and in blue without piezo.

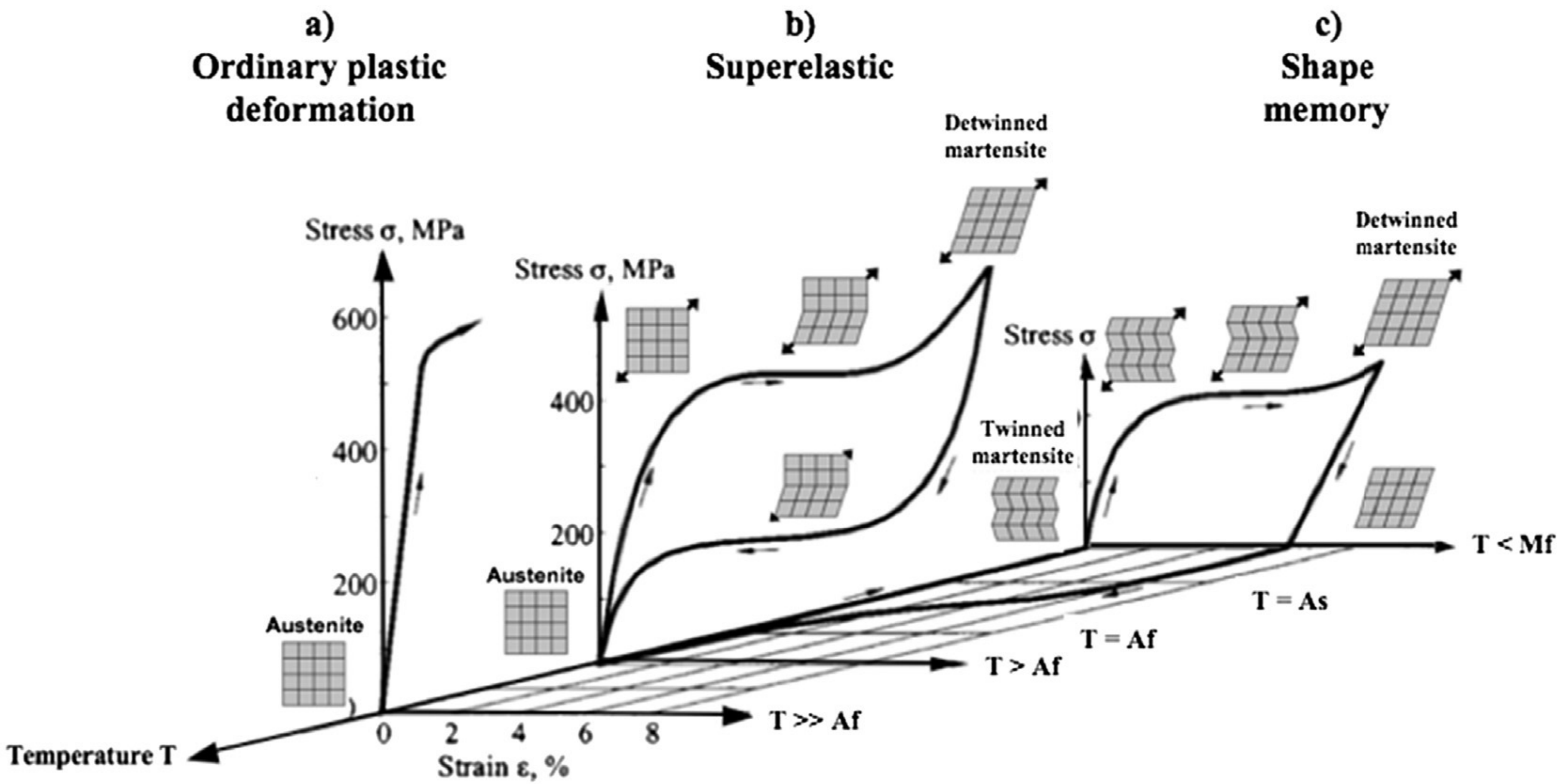


Optimized for torsion resonance frequency, around 90-120Hz

Source: H.Lammer, Head Sport AG, SAMPE Europe, 2005

Composite materials with Shape Memory alloys

Principle of Shape Memory Alloys

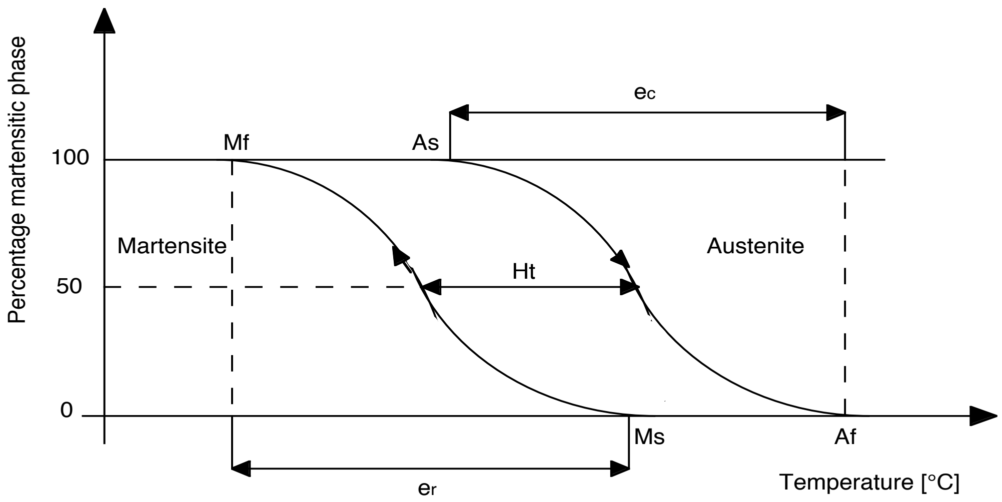


Thermoelastic phase transformation, present in several metallic alloys: NiTi, Cu-based, Fe-Pt, etc…

Principle of Shape Memory Alloys

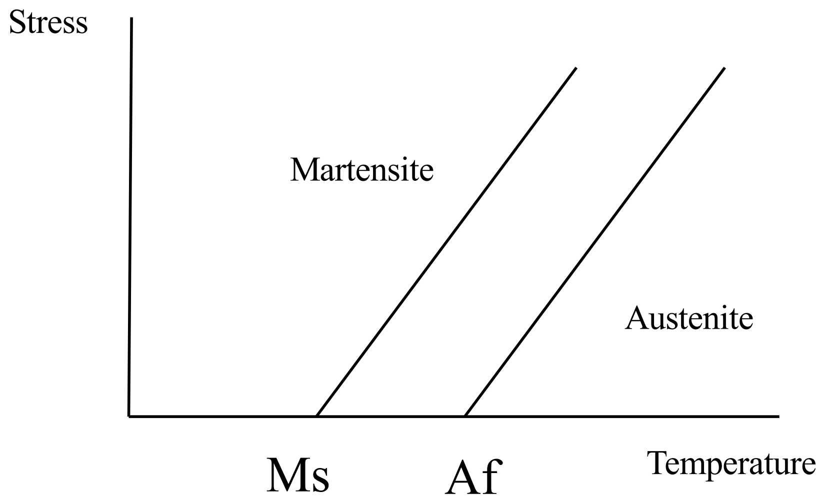
Several interesting features:

- Shape memory effect
- Superelastic effect
- Damping of martensite phase



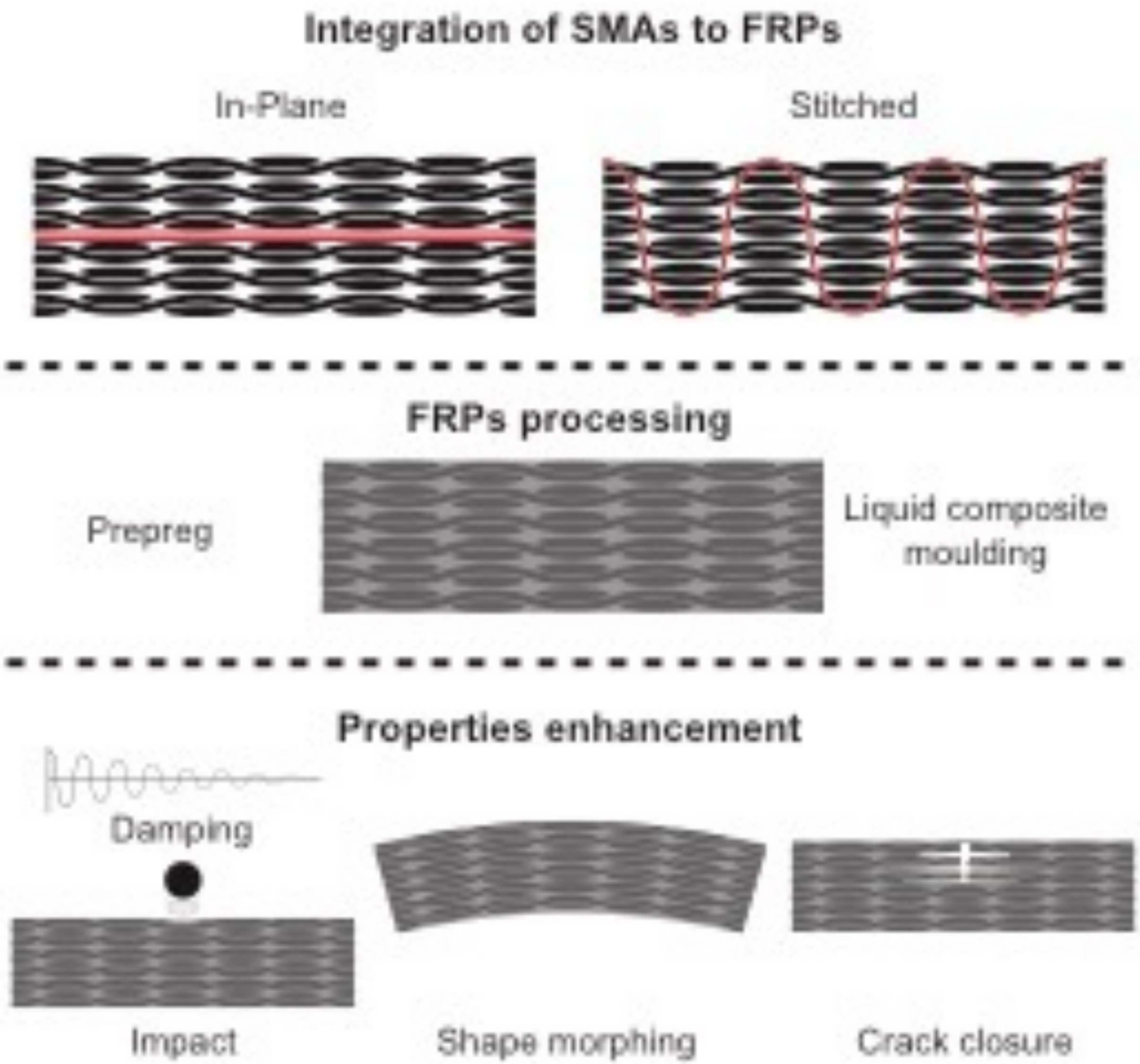
e_c = Af - As
e_r = Ms - Mf
Ht = $A_{50\%}$ - $M_{50\%}$

transformation cycle



		Elastic modulus [GPa]	Strength [MPa]	Recoverable strain [%]	Recovery stress [MPa]
Shape memory alloys	NiTi NiTiCu	10–35 19	800–1100 1200	5–8 5	<500 MPa <800 MPa
Shape memory polymers		0.01–3	0.1–100	<800	1–3

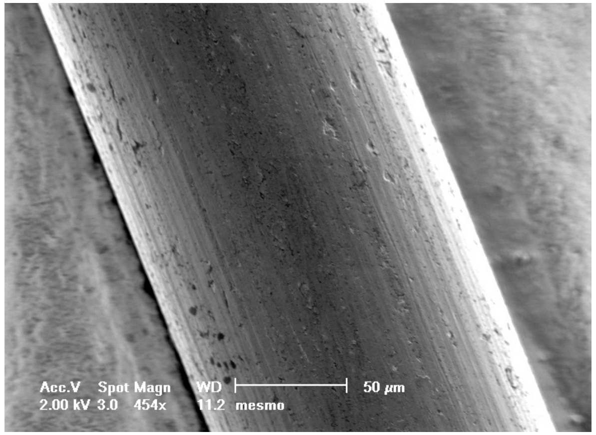
Motivation for composites with SMA



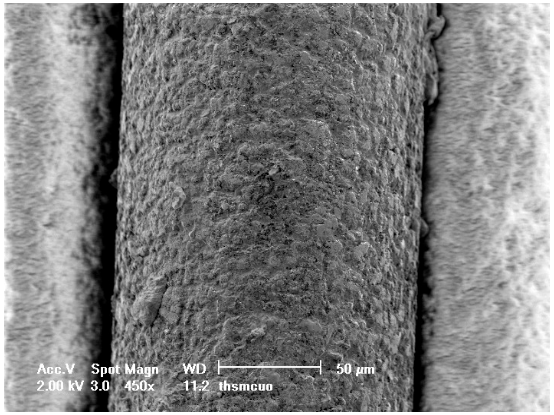
A. Cohades, V. Michaud / Advanced Industrial and Engineering Polymer Research 1 (2018) 66-81

Main challenges

- Thermal actuation…T cycle and slow process (Hz)
- Hysteretic behaviour
- Fatigue life, linked to surface conditions
- Biocompatibility: NiTi OK if TiO_2 at the surface
- Adjust the transformation temperature, possible with alloying
- Need of a bias element if one-way shape memory effect.



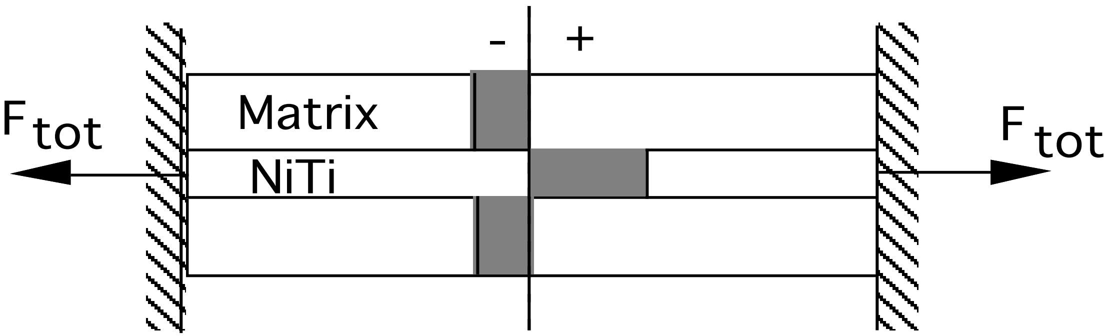
NiTiCu
Cold worked



NiTiCu
Straight annealed

Principle of SMA-Hybrid active Composites

When heated

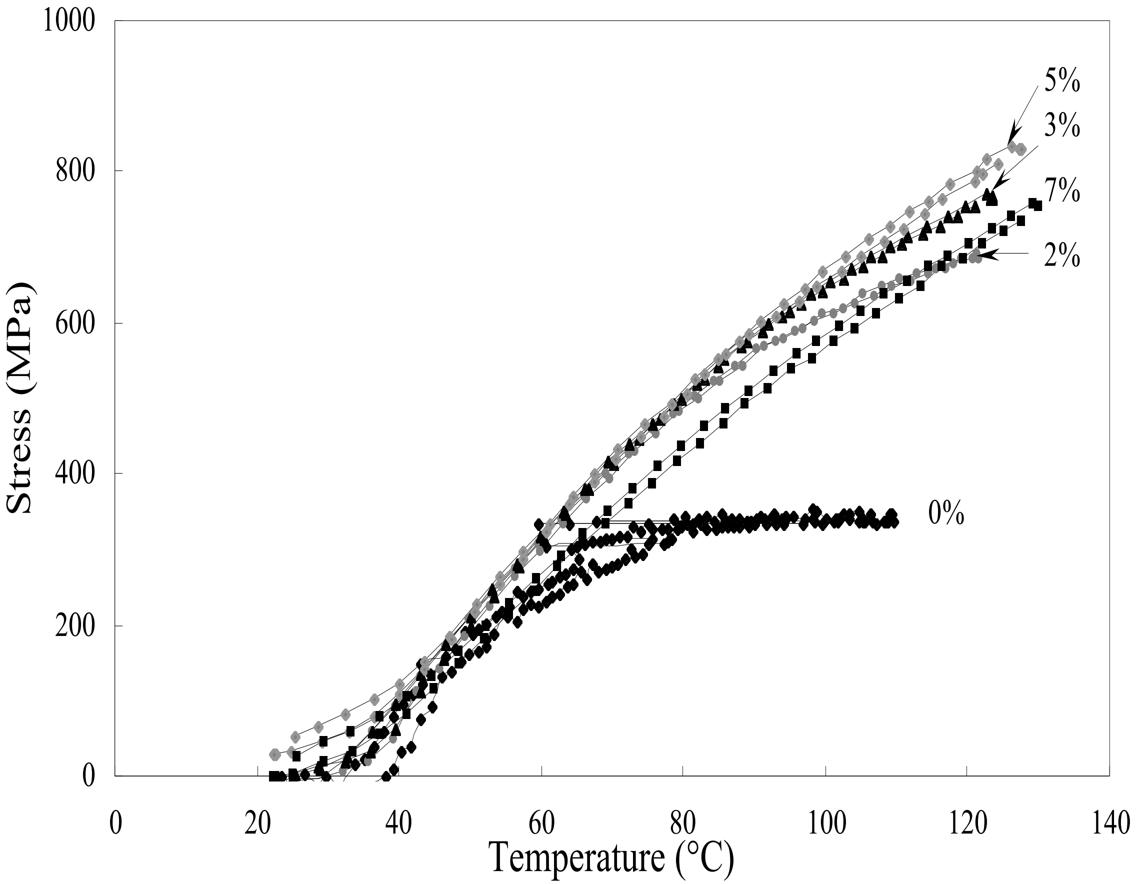


thermal forces

transf. forces

$$F_{tot} = F_0 - \alpha_m (T - T_0)\, E_m\, S_m + F_{NiTi}$$

Example: Recovery stress versus temperature for NiTi12%Cu wire



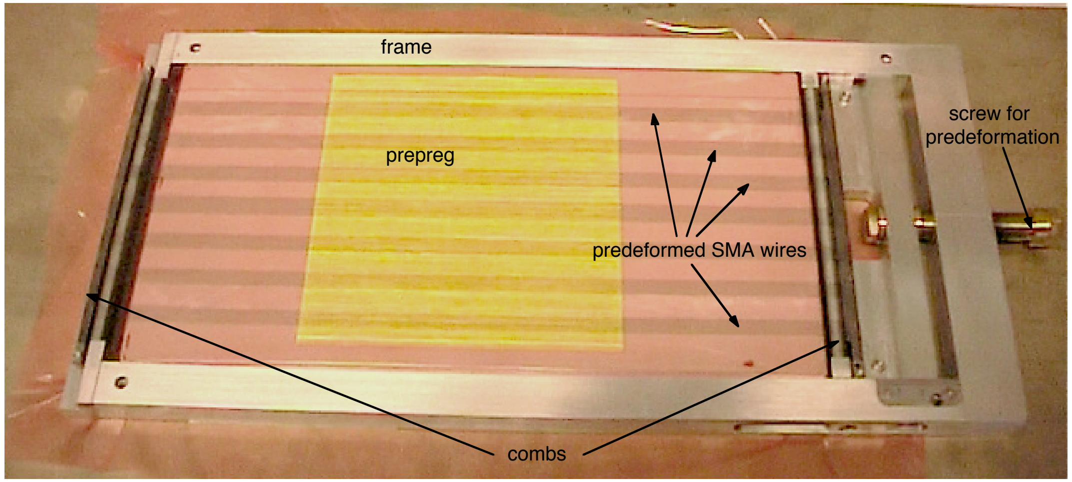
- Very low hysteresis
- Recovery stress of 600 MPa at 100° C
- Beyond 3% pre-strain no significant change is observed
- MT between -20 and 35° C and AT between 52 and 77° C

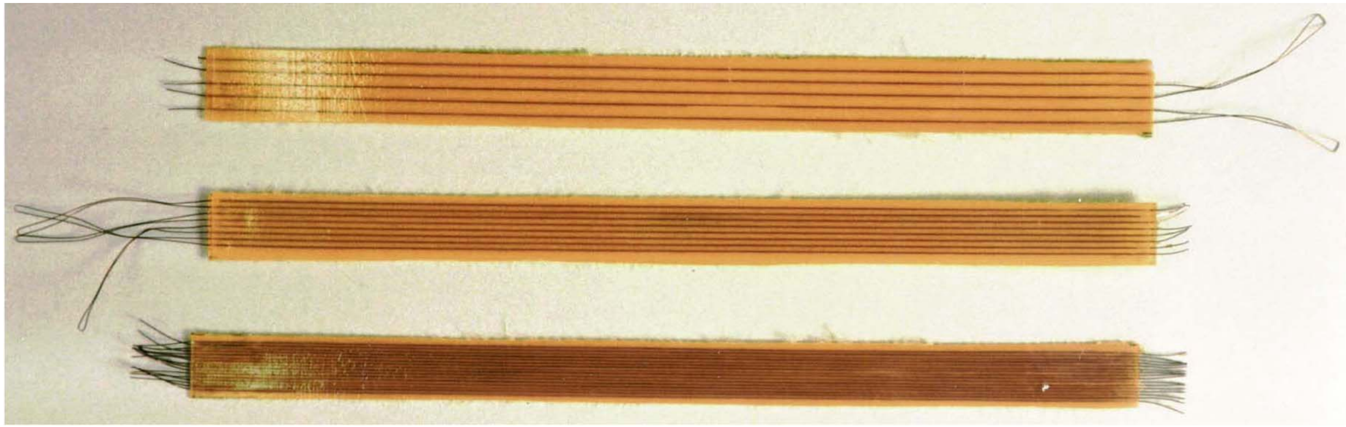
Design with SMA composites

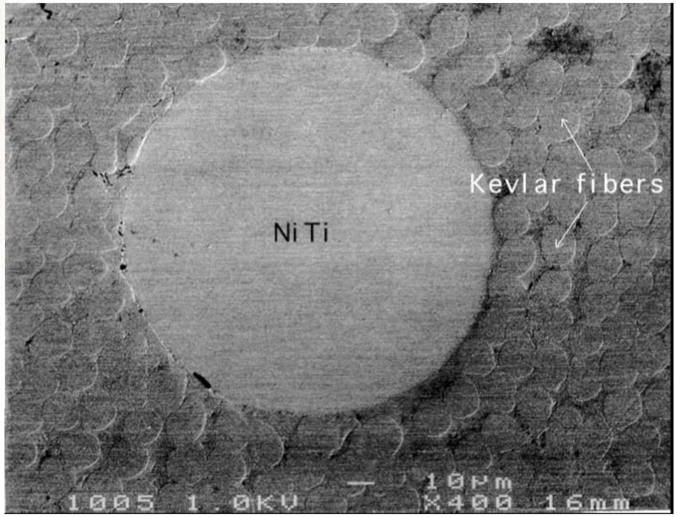
Necessary volume fraction wires, level of pre-strain, wire arrangement, etc… to achieve the desired activation level.

- Model the wire behavior
- Model the composite recovery stress
- Model the composite resonance vibration frequency

Example of Kevlar/epoxy composites with SMA NiTi or NiTiCu wires

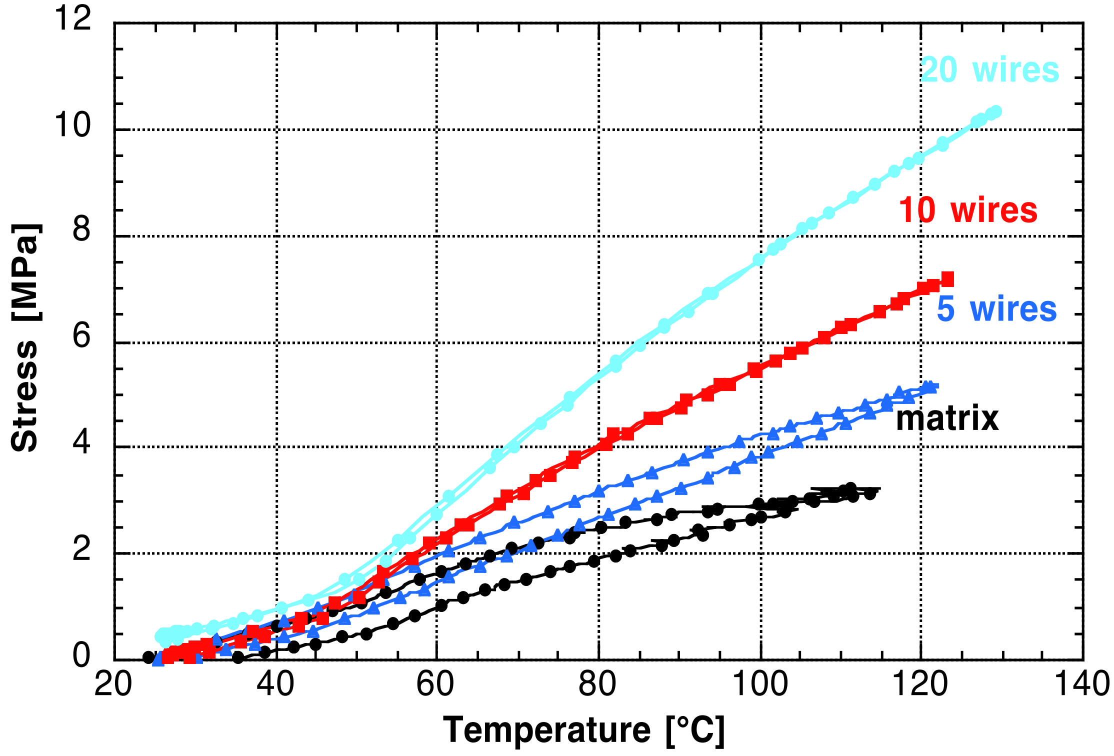




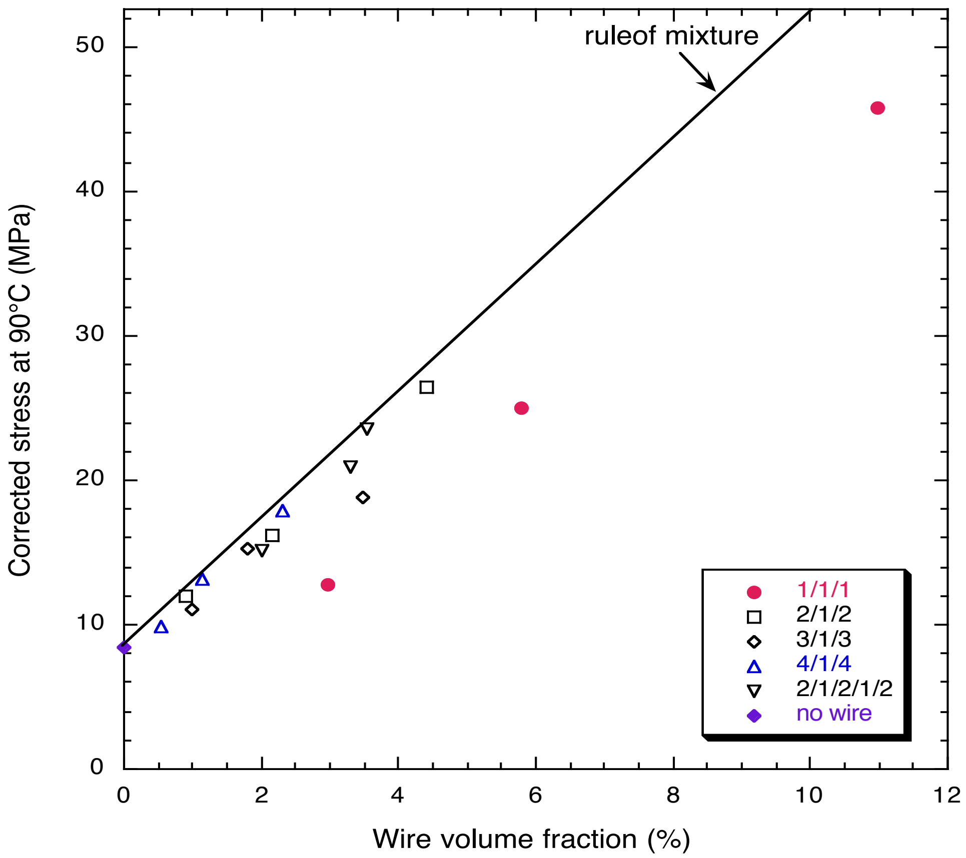


Recovery stress response of the composites

Composite with Kevlar-epoxy and SMA wires between 6 layers of pre-preg with 3% pre-strain.



Recovery stress at 90° C as a function of V_f



Taking into account the compliance of the frame

$$\sigma_{total} = \sigma_{meas.}\left(1 + \frac{E_c S_c}{k\,l}\right)$$

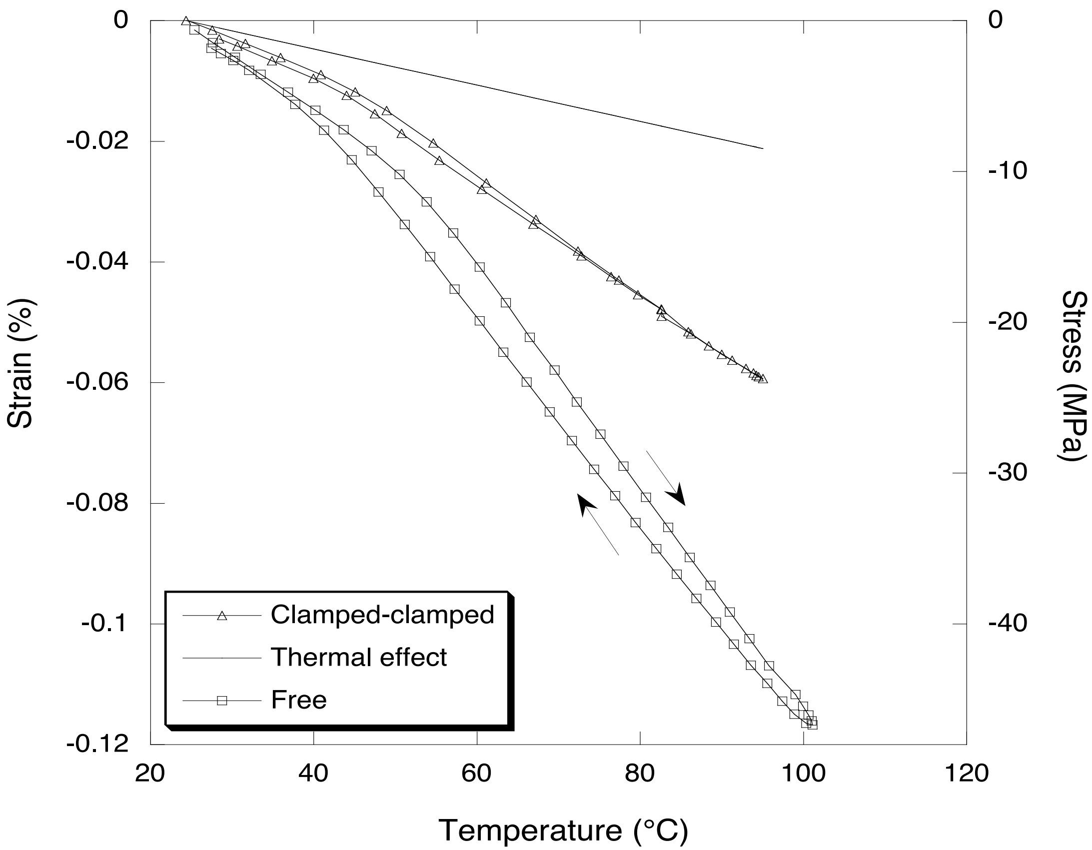
$$\sigma_{total} = -E_c \alpha_c \Delta T + V_f^{SMA} \sigma^{SMA}$$

A simple rule of mixtures provides a good first estimate of the response.

Michaud, Scripta Materialia, 50 (2004), 249-253

Strain measurement during activation

Sample with 5 vol% SMA, free and clamped

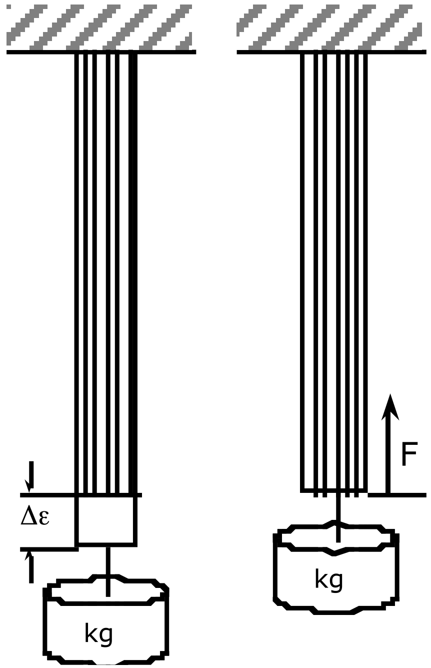


- *strain measured from the FBG sensor, stress in the matrix deduced from it.*

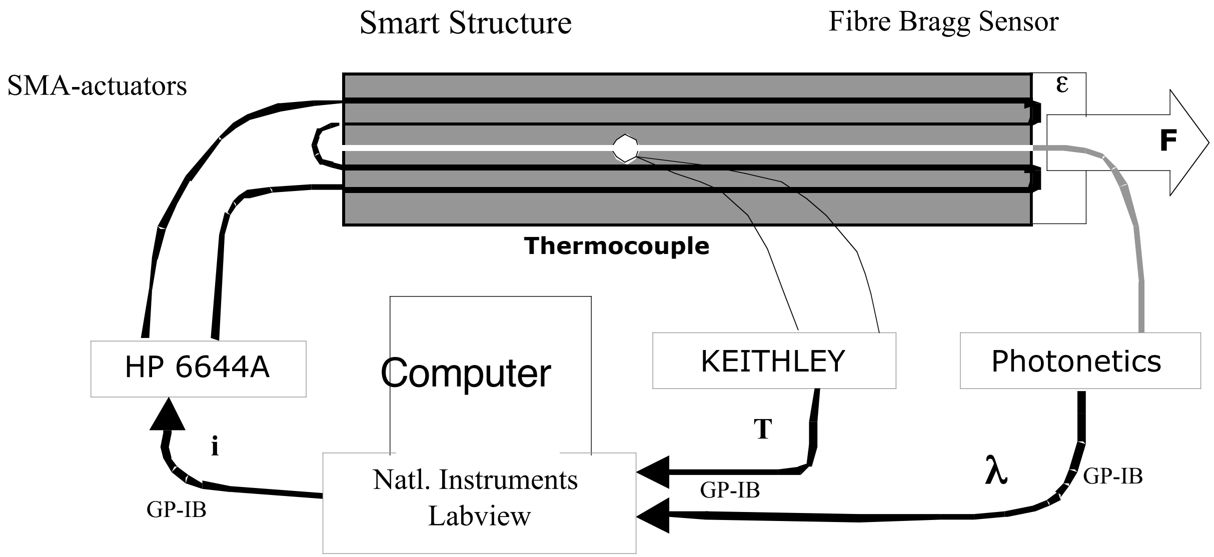
- *large strain in the free configuration compared to the thermal contraction alone.*

H.J.Yoon, D. Costantini, H.G. Limberger, R. Salathé, C.G. Kim and V. Michaud, "In-situ strain and temperature monitoring of adaptive composite materials", *Journal of Intelligent Materials and Structures,* vol.17, pp.1059-1067, Dec. 2006.

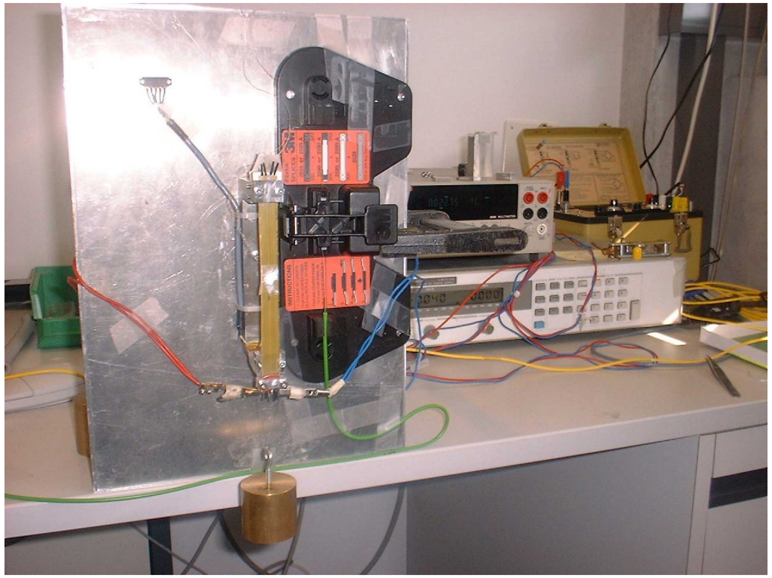
Closed loop control of adaptive composites

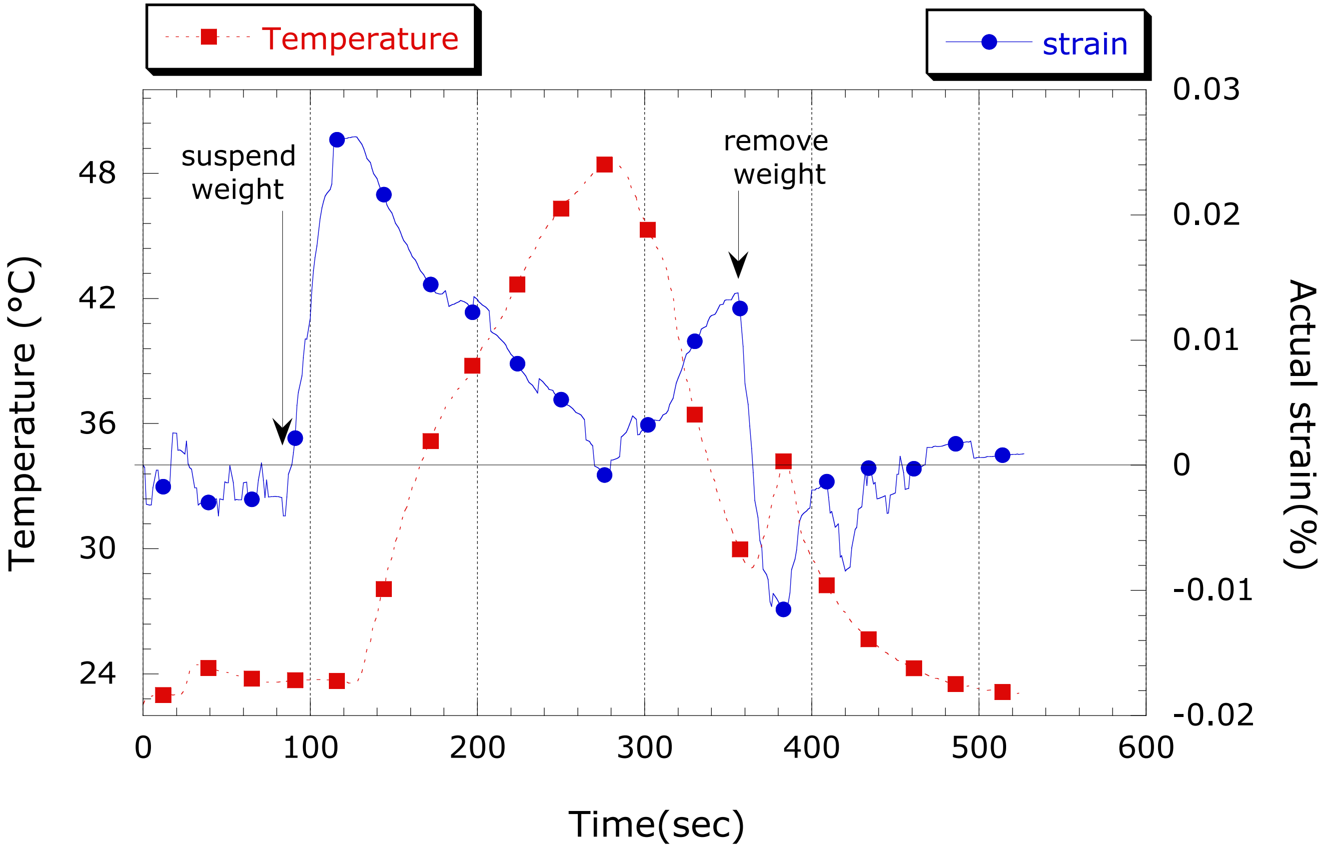


Reinforced composite with SMA actuators and Bragg fibre gratings sensors ⇒ Closed loop control system



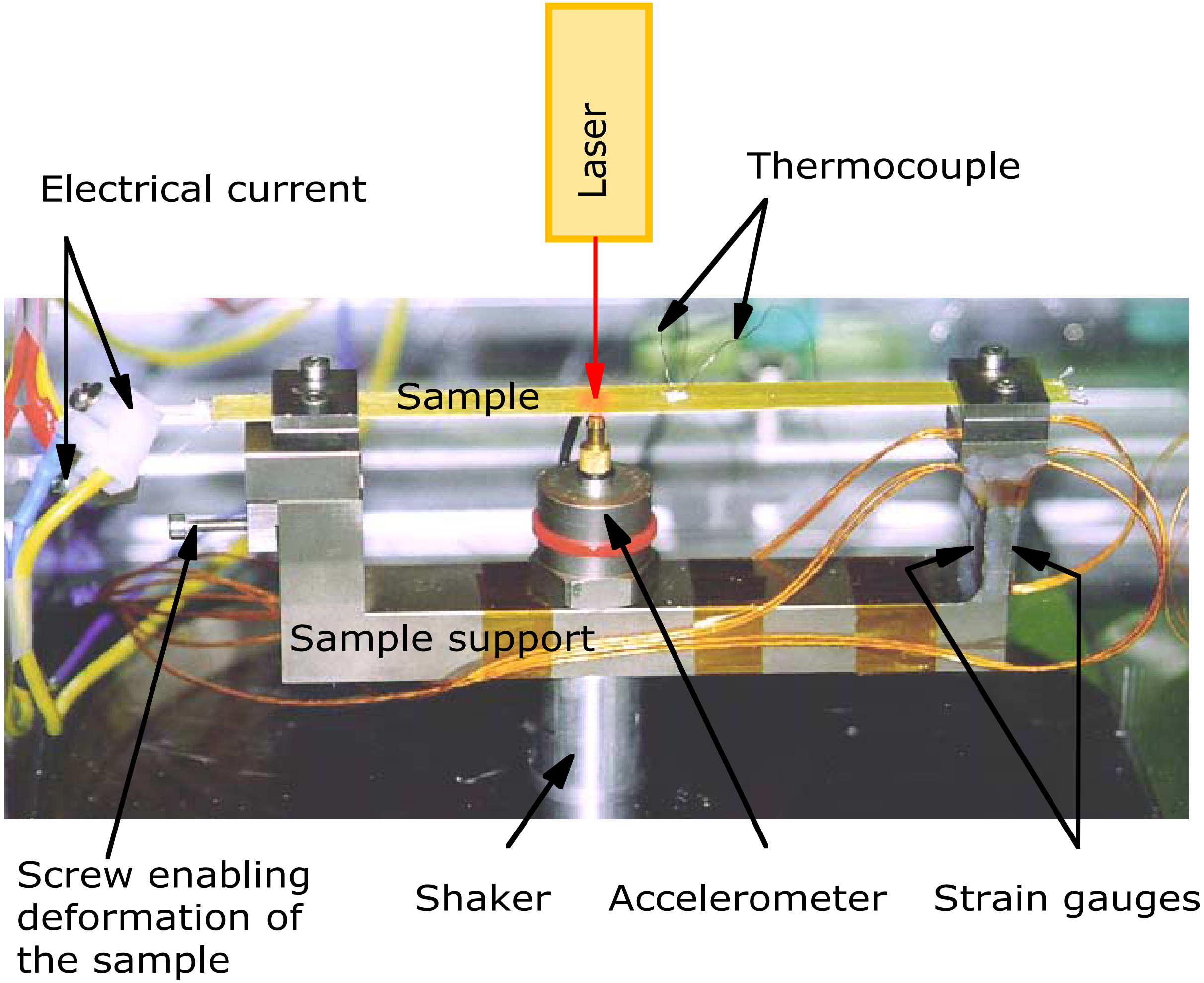
Closed loop control of adaptive composites



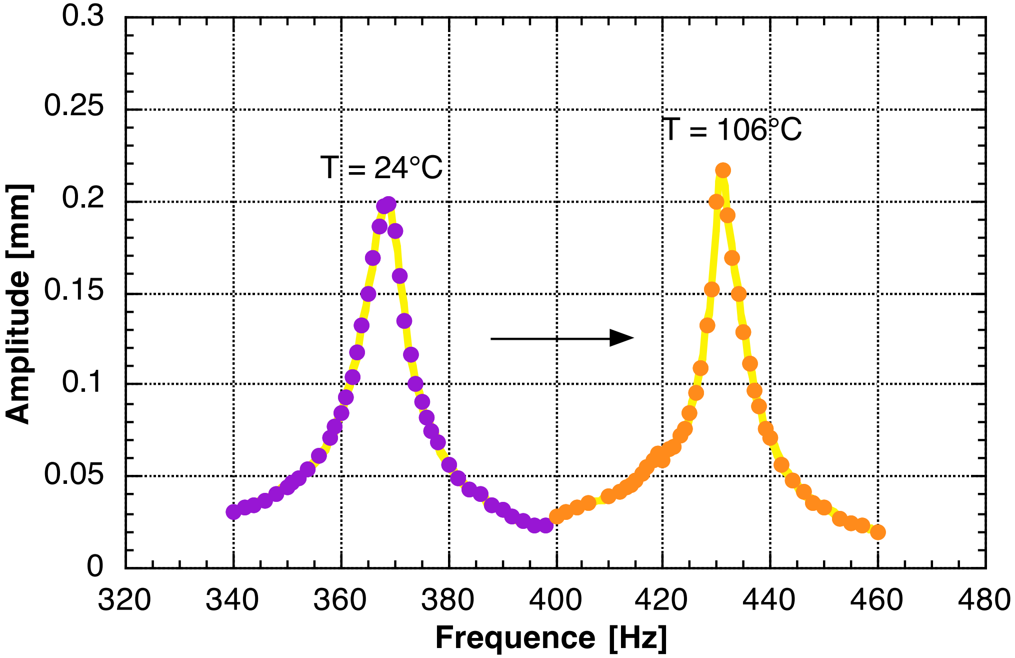


Preliminary results show that it is possible to control displacement by inducing Joule effect in the wires

Vibration response of the composites

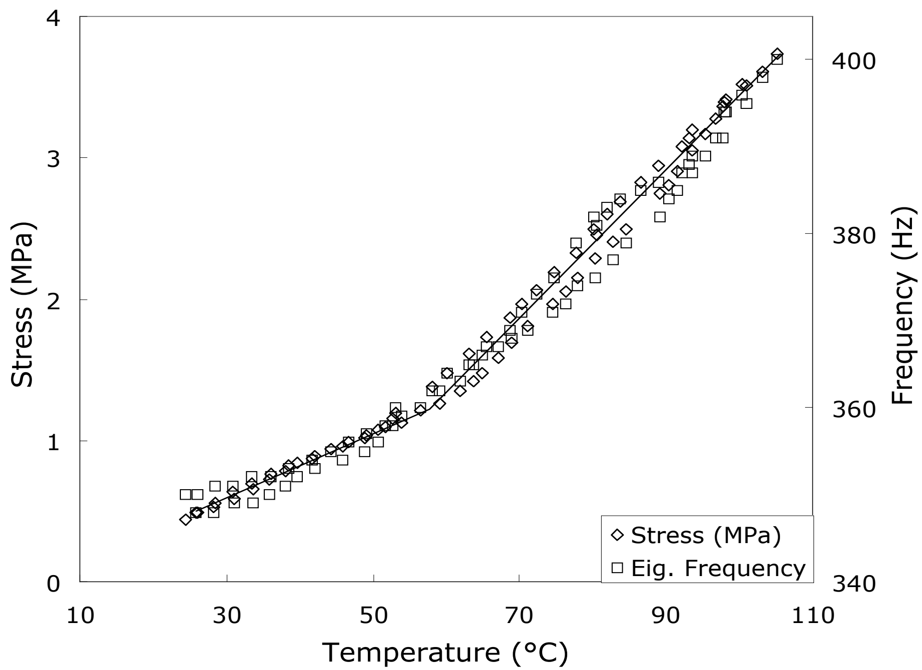


Vibration response of the composites



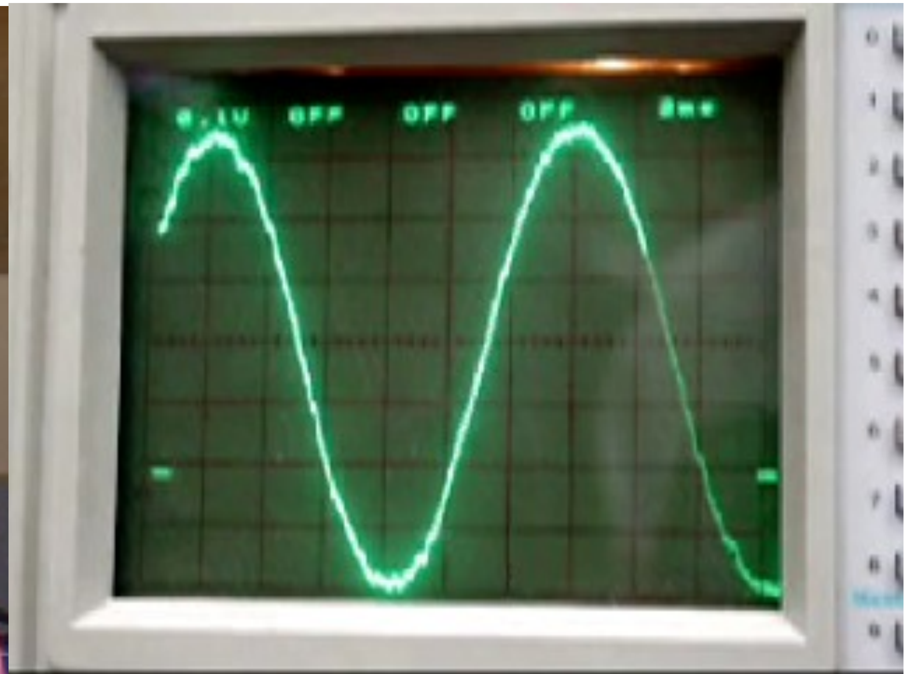
Composite with Kevlar-epoxy
5 SMA wires between 6 layers of pre-preg with 3% pre-strain.

Resonance frequency and recovery stress vs. temperature.



J. A. Balta, F. Bosia, G. Dunkel, V. Michaud , J. Botsis , J.-A. Månson, "Smart composites with embedded SMA actuators and fibre Bragg grating sensors: activation and control", *Smart Materials and Structures,* vol.14, pp457-465, 2005

Towards real structures with adaptive composites?



Demonstrator manufactured in the ADAPT project

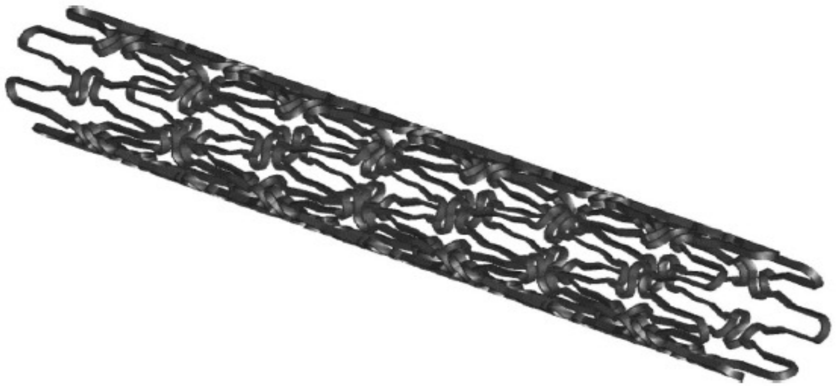
Other applications…

- Morphing,
-impact resistance improvement, etc.,, etc..

Bio-medical applications of NiTi alloys

Many « passive » applications already on the market

- Orthodontic wires, tools, stents, grafts
- Some thermal activation under investigation: anal sphincter, urethral valve (T.Yambe, Japan)
- A good alternative to stainless steel (more immune to NMR)



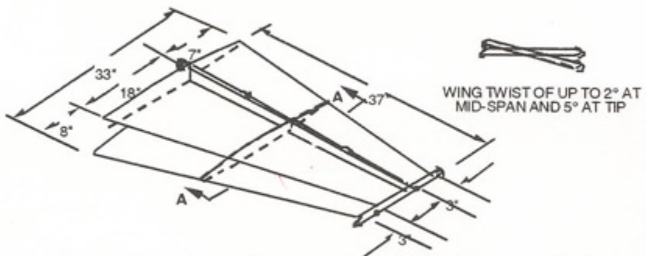
N.B. Morgan, Materials Science and Engineering A 378 (2004) 16–23

Other applications…morphing in aircrafts

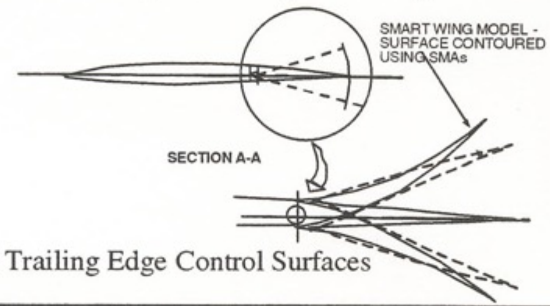
Demonstrate Improvements in Aerodynamic (L/D, Maneuver and Aeroelastic) Performance of Military Aircraft Using Smart Materials and Structures Based Actuation Systems:

- *Design, Fabricate and Test Scaled Semi-Span and Full-Span Models*
- *Address System Integration Issues*
- *Lay the Ground Work for Technology Transition Via a Flight Test in a Potential Follow-on Program*

Phase 1



Spanwise Wing Twist using SMA Torque Tube



Contoured Trailing Edge Control Surfaces

Phase 2

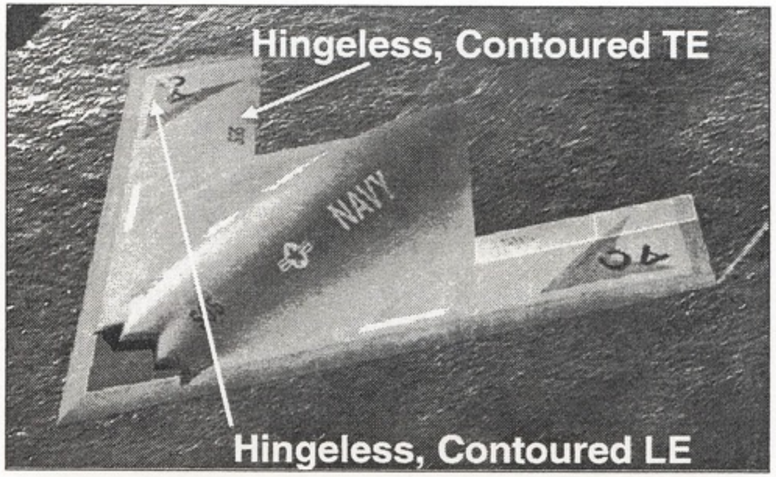
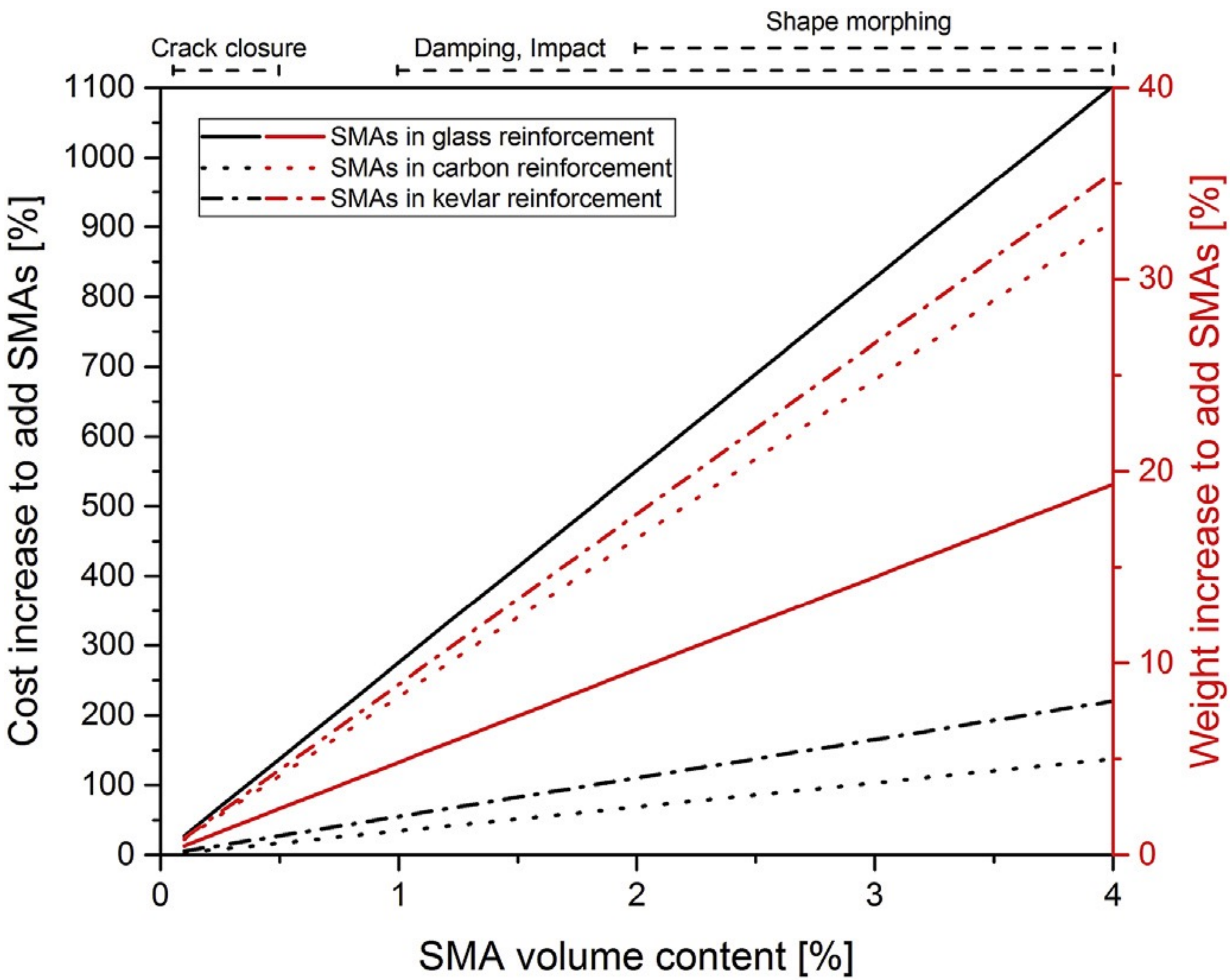


Figure 1. Smart Wing Program Objectives

Resulting cost and weight penalty



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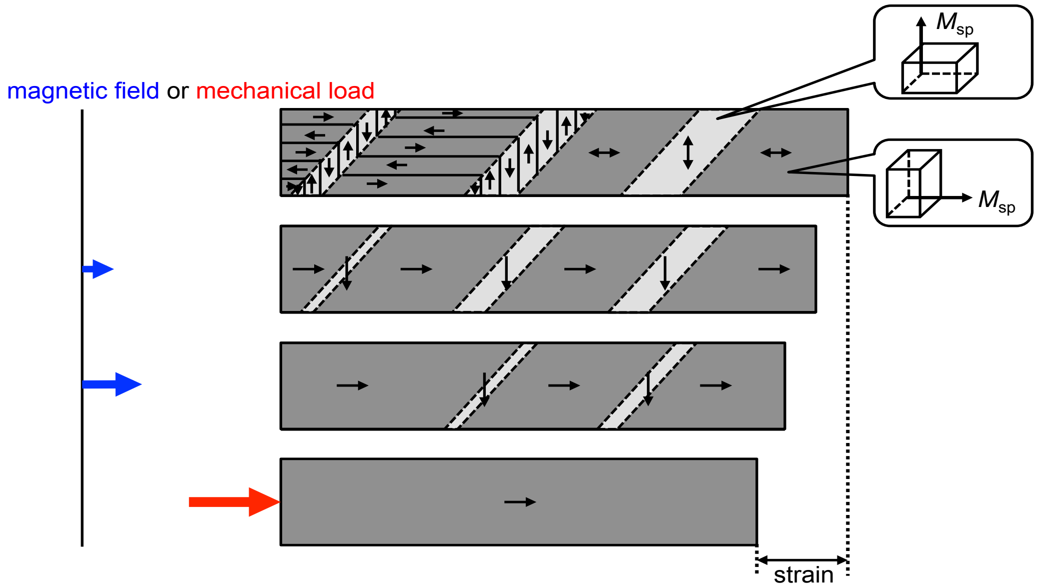
Principle of magnetic SMA

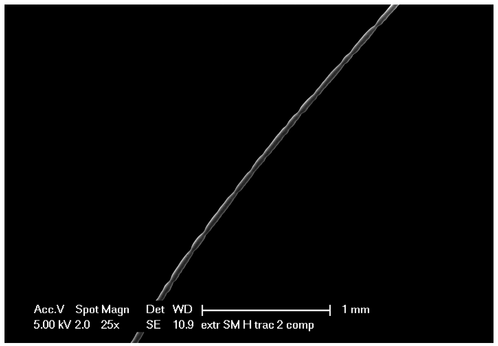
In general, NiMnGa:

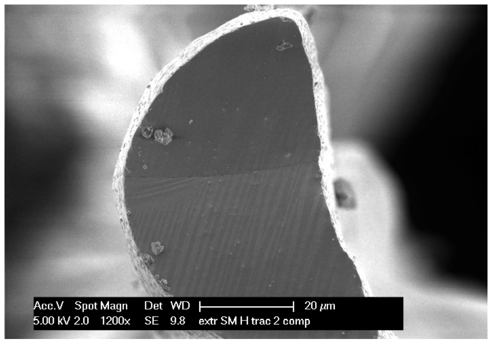
- Conventional Shape Memory Effect
- Magnetic field induced Autenite-Martensite transformation
- Magnetic field induced motion of mobile twin interfaces (martensite variants). In single crystals, high strain (up to 10%), frequency up to 1kHz, but expensive and brittle.

-> Solution:

Use thin wires, forming a succession of crystals, into a composite host, evaluate damping and actuation strain



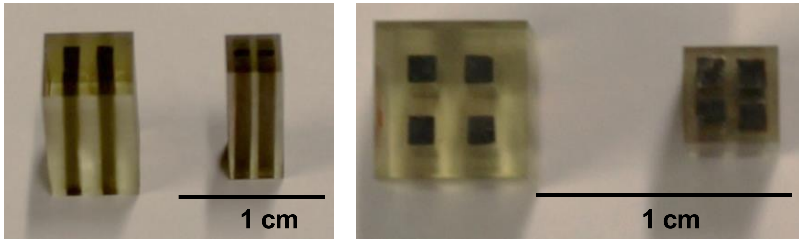


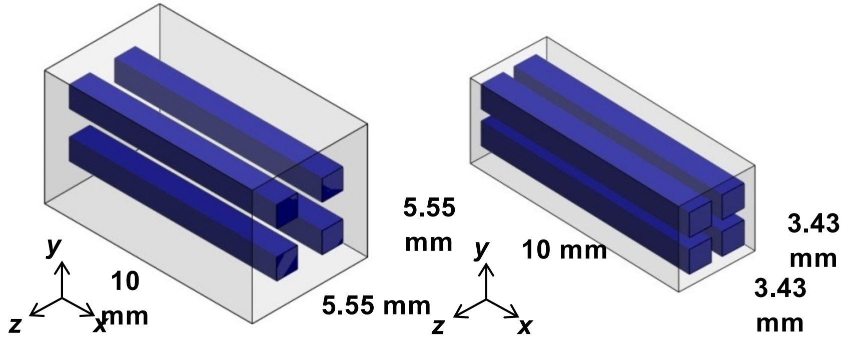


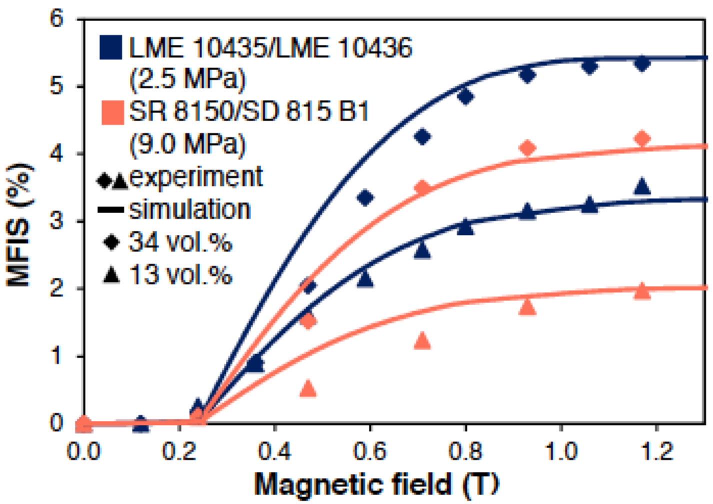
Magnetic SMA

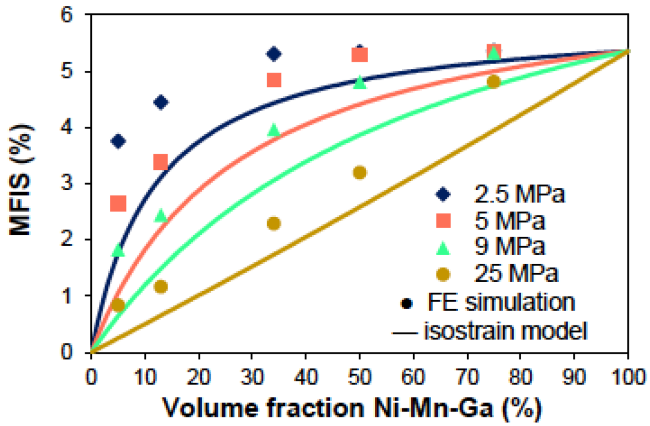
Example of a NiMnGa (single crystals)/ epoxy composite:

Up to 5% actuation is achieved, but the matrix modulus needs to be very low to reach this level with a low volume fraction of SMA.



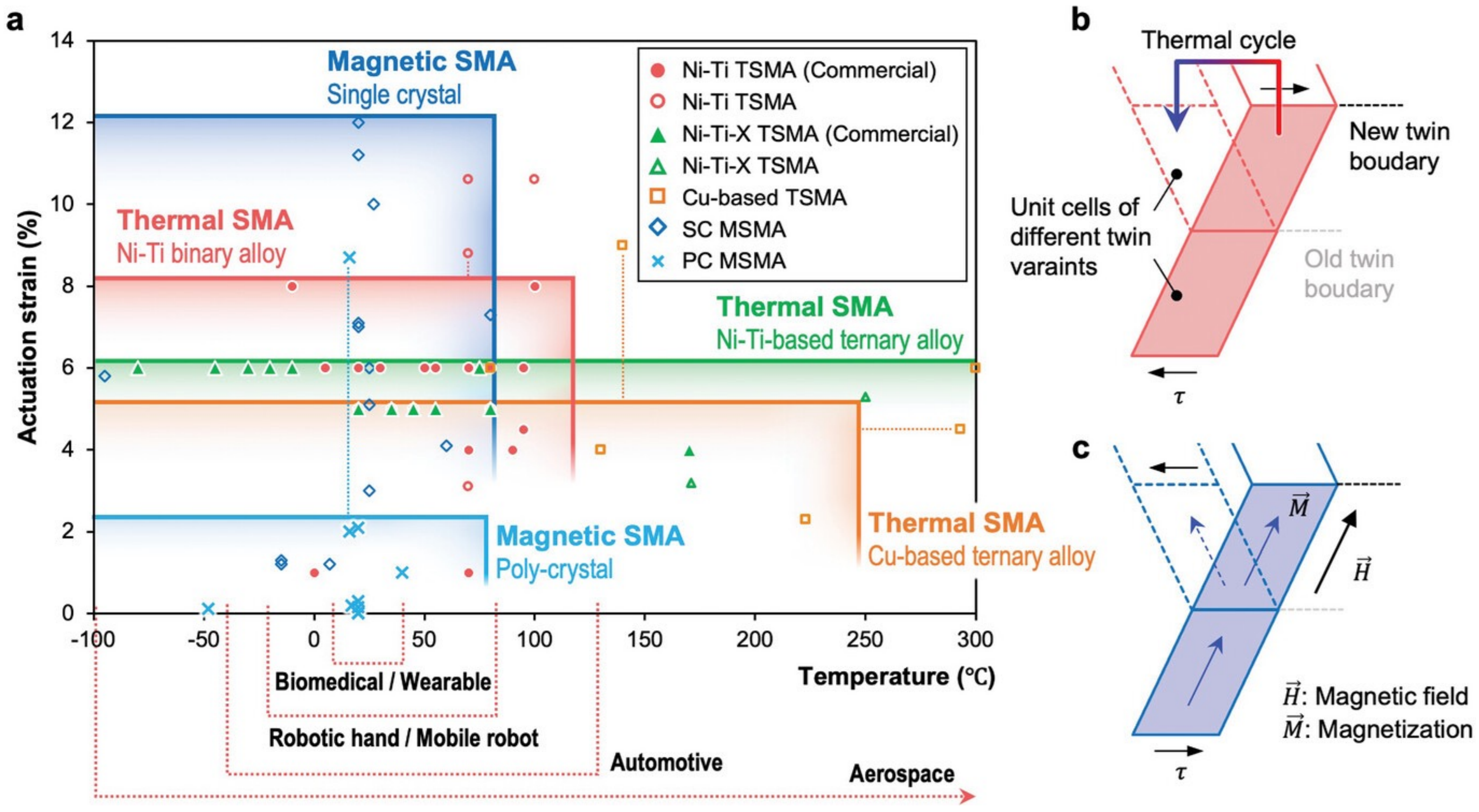






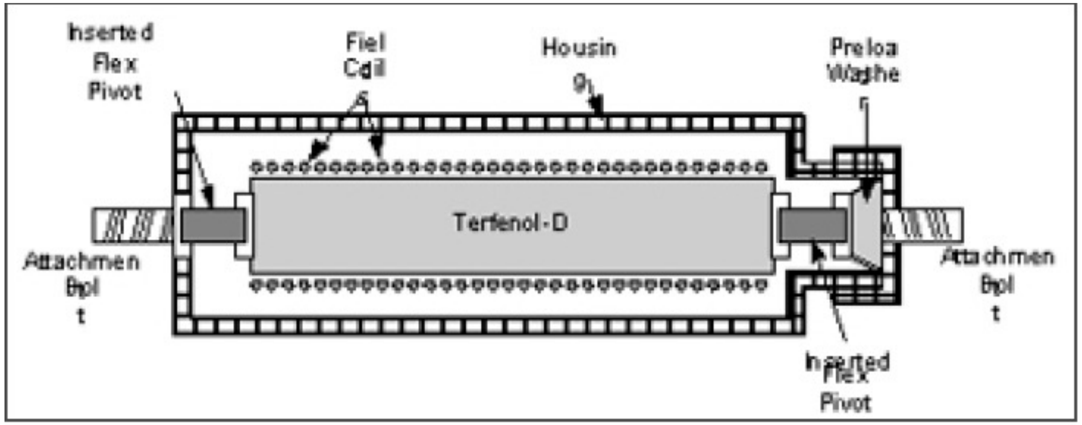
Glock, 2014, PhD EPFL

Comparison of various SMA actuators



https://doi.org/10.1002/adma.202208517

Magneto-strictive materials

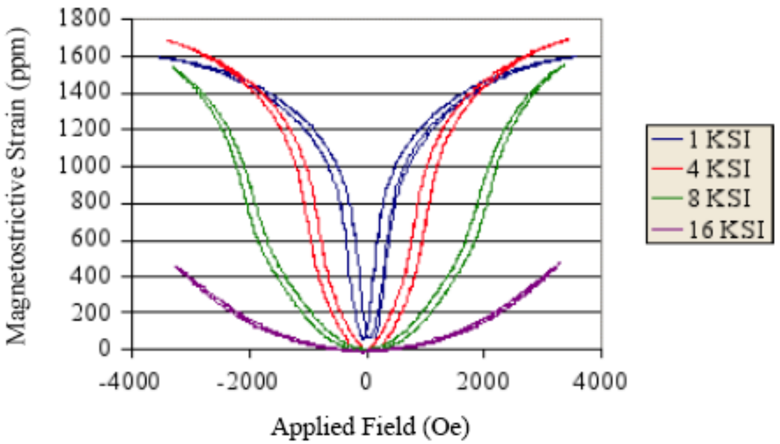


Magnetostriction: material strain in a magnetic field in general, or to produce elctromagnetic field when strained-> sensing and actuation

- Terfenol D is one example
- A coil is wrapped around the material and the material is actuated by driving the coil.

Magneto-strictive materials

Le Terfenol-D is an alloy of Fe and rare earths $Tb_{0.3}Dy_{0.7}Fe_{1.9}$, and is short forTerbium Fe Naval Ordnance Laboratory Dysprosium, from the name of the lab in US which developped this material around 1950. First idea was to use this as acoustic transducer in sonars.



TERFENOL-D PHYSICAL PROPERTIES

Nominal Composition	$Tb_{0.3}Dy_{0.7}Fe_{1.92}$
Mechanical Properties	
Young's Modulus	25-35 GPA
Sound Speed	1640-1940 m/s
Tensile Strength	28 Mpa
Compressive Strength	700 Mpa
Thermal Properties	
Coefficient of Thermal Expansion	12ppm/°C
Specific Heat	0.35kJ/kg-K
Thermal Conductivity	13.5 W/m-k
Electrical Properties	
Resistivity	58 x 10-8 O-m
Curie Temperature	380 °C
Magnetostrictive Properties	
Strain (estimated linear)	800-1200ppm
Energy Density	14-25 kJ/ m^3
Magnetomechanical Properties	
Relative Permeability	3-10
Coupling Factor	0.75

Electro-active polymers

-Ionic polymer /metal composites
Nafion (Dupont) , PTFE plus active ion-exchange sites

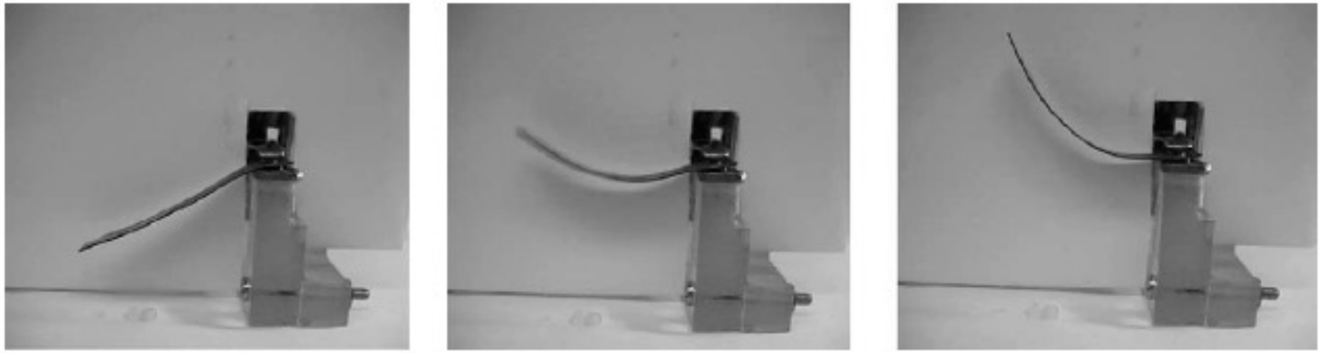


Fig. 1. Successive photographs of an IPMC strip that shows very large deformation (up to 4 cm) in the presence of low voltage. Note that $\Delta\tau = 0.5$ s, 2 V applied. The sample is 1 cm wide, 4 cm long, and 0.2 mm thick.

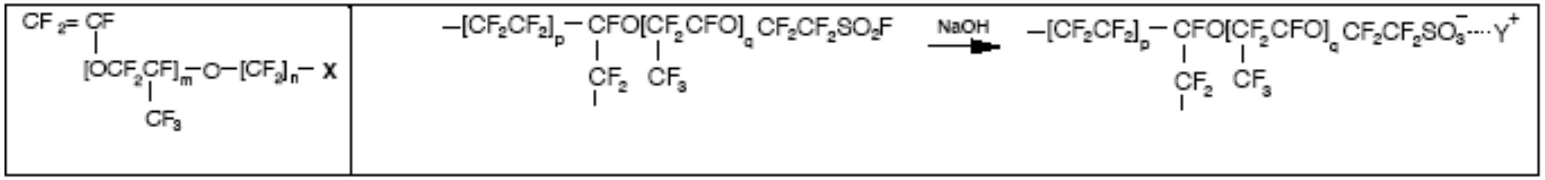


Fig. 1. The monomer (left) and the synthesis of Nafion™ (right). Note that $X = SO_3^-$ or COO^-, $m = 0$–2, $n = 1$–4, $p = 5$–11, and $q = 1$.

http://ndeaa.jpl.nasa.gov

http://www.unm.edu/~amri/

Electro-active polymers

-Operating principle

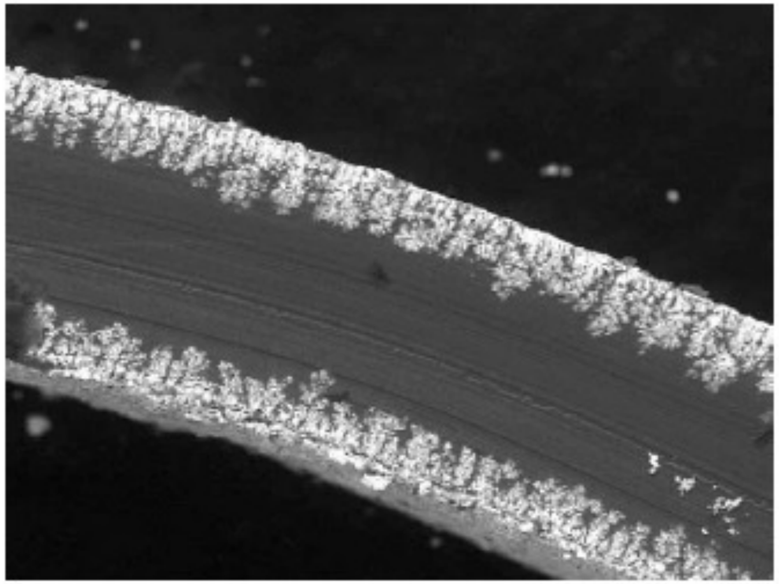


Fig. 7. Penetration of reduced metal in the polyelectrolyte membrane due to chemical plating.

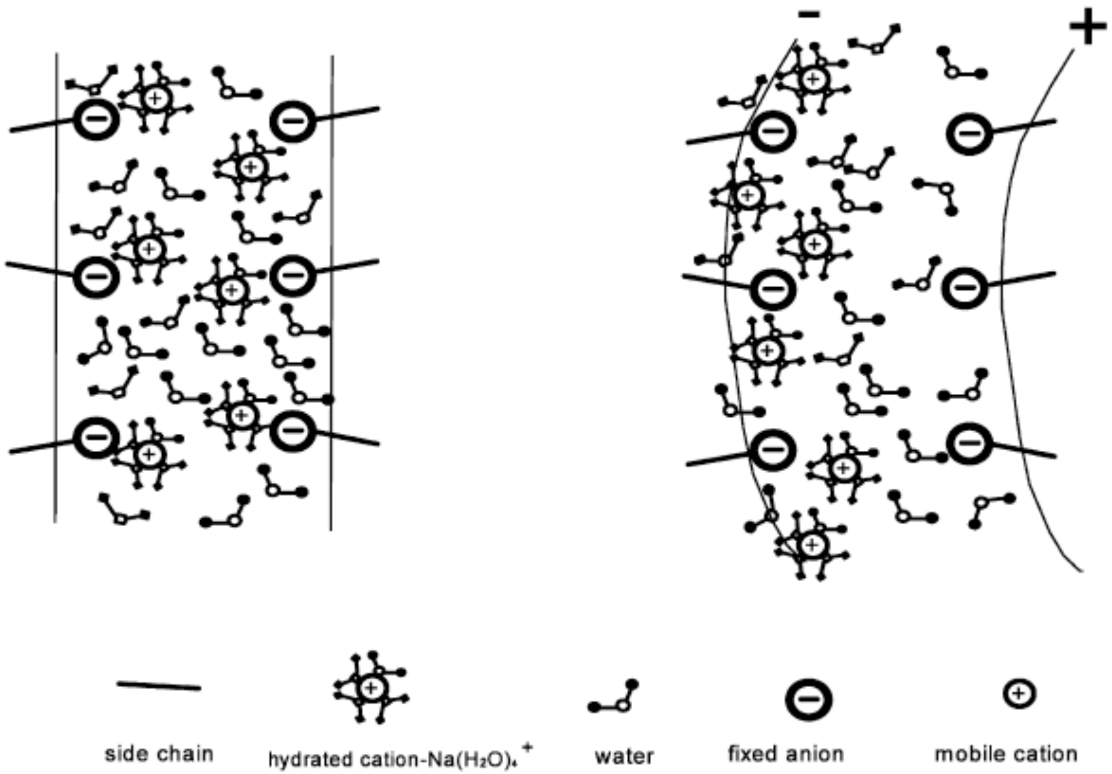


Fig. 10. Schematics of the electrophoretic migration of counter ions within IPMC network.

http://www.unm.edu/~amri/

Electro-active polymers

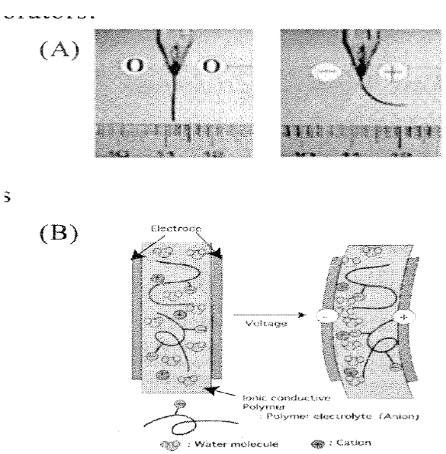


Fig.1 (A) Photograph of the bending motion of the Flemion®/gold composite driven by 2V voltage in water. (B) Schematic representation of the electromechanical model of the IPMC based on the stress due to electro-osmotic flow.

Works in wet conditions

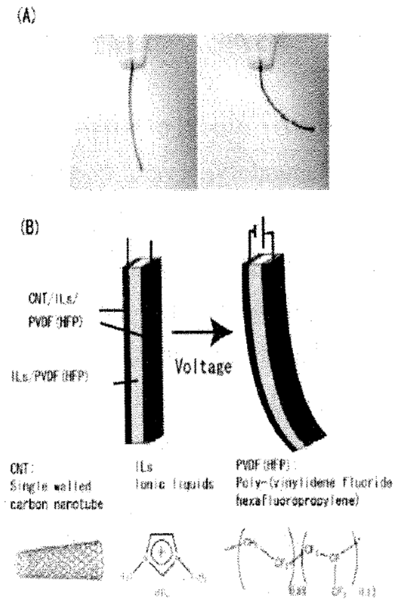


Fig.2 (A) Performances of a bucky-gel actuator (15 mm in length, 0.28 mm in thickness) in response to 3.5V voltage. (B) Schematic representation of the structure of the actuator.

Works in dry conditions

Comparison of various actuators

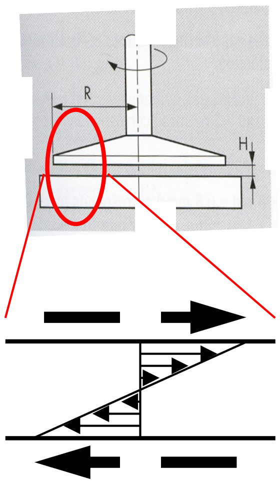
Actuator type	Stress (MPa)	Strain (%)	Efficiency (%)	Bandwidth (Hz)	Work per Volume (J/cm^3)	Power per Volume (W/cm^3)
NiTi SMA	200	10	3	3	10	30
Piezoceramic	35	0.2	50	5000	0.035	175
Single crystal piezoelectric	300	1.7	90	5800	2.55	15,000
Human Muscle	0.007–0.8	1–100	35	2–173	0.035	0.35
Hydraulic	20	50	80	4	5	20
Pneumatic	0.7	50	90	20	0.175	3.5
NiMgGa (magnetic)		5-10		1-5000		
Shape memory polymer	1-3	400		1		

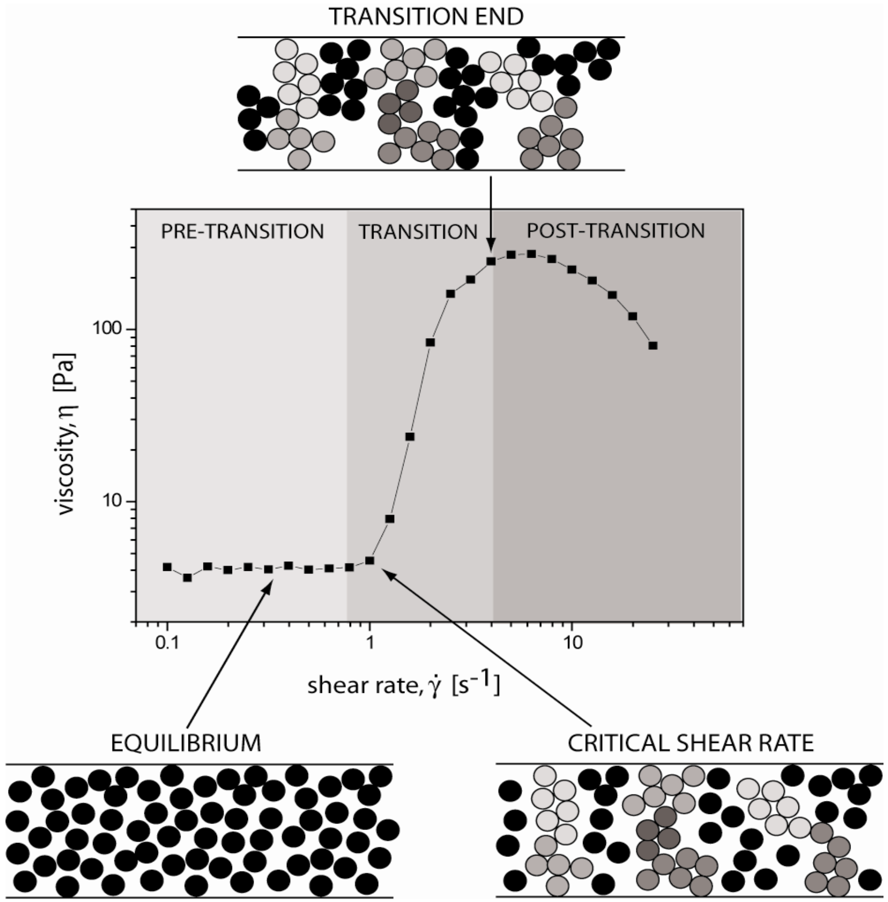
Jaronie Mohd Jani, Martin Leary, Aleksandar Subic, Mark A. Gibson, A review of shape memory alloy research, applications and opportunities, Materials & Design (1980-2015), Volume 56, 2014, Pages 1078-1113,

Other elements, fluids?

Introduction of shear thickening fluids, or of microcapsules containing resin or other elements

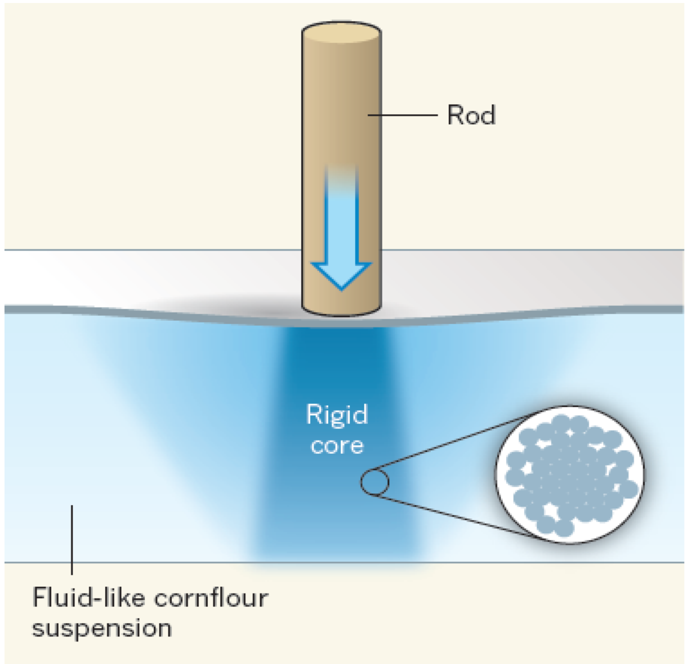
Shear thickening fluids





STF potential for energy dissipation

- These materials dissipate large amounts of energy during the transition, and this is also true in high speed compression conditions, through solidification via dynamic jamming fronts (H. Jaeger, work on corn starch)



Waitukaitis and Jaeger, Nature, 2012

Impact protection using STF

Can we use STF for impact protection of composite structures?

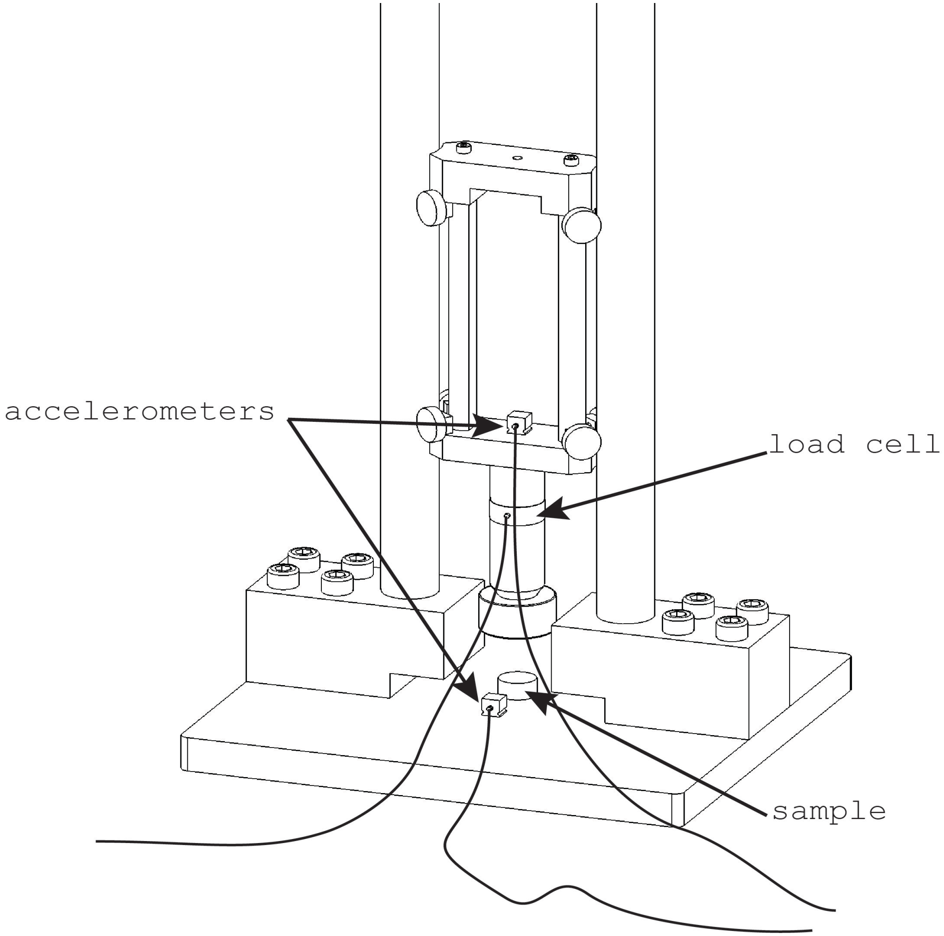
Challenges:

- Select adequate STF composition and processing,
- Provide a scaffold for the liquid at rest,
- Make sure the material is stable over time, and does not degas in vacuum,
- Compare impact absorption to that of commercial materials.

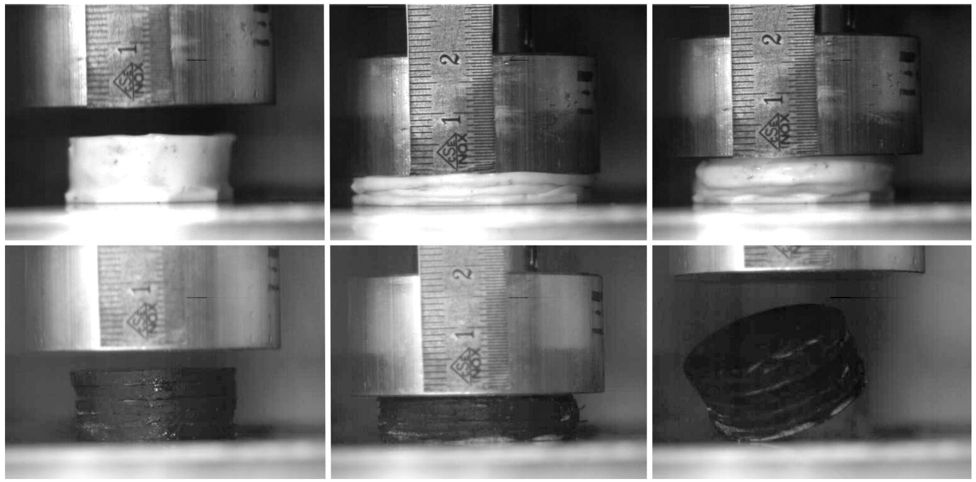
-> Proposed solution: infiltrate the STF into a foam, then encapsulate with silicone for handling and protection.

(PhD thesis M. Soutrenon, EPFL 2014)

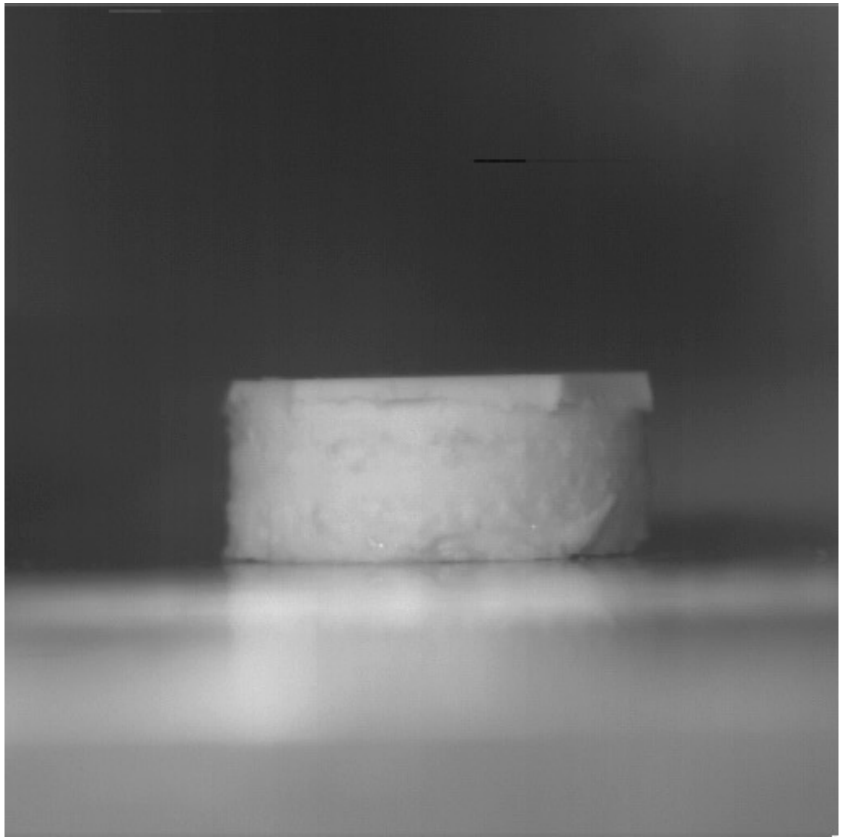
Impact testing



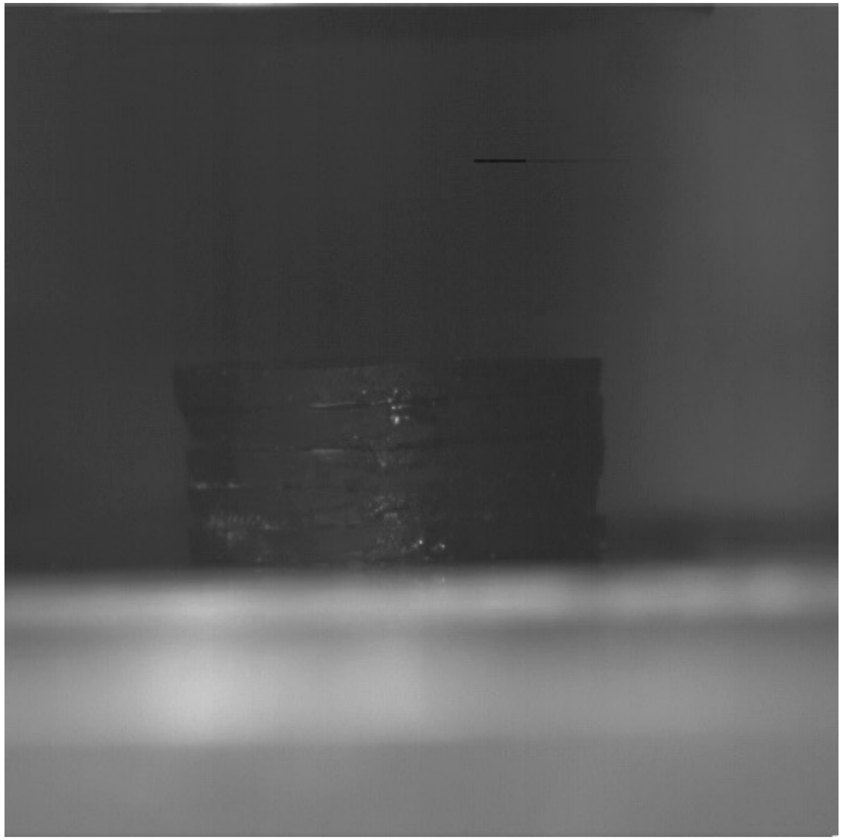
Conditions: V=3.92m/s, corresponding to an energy of 5J
Displacement measured by high-speed camera, 4000 fps



Impact testing

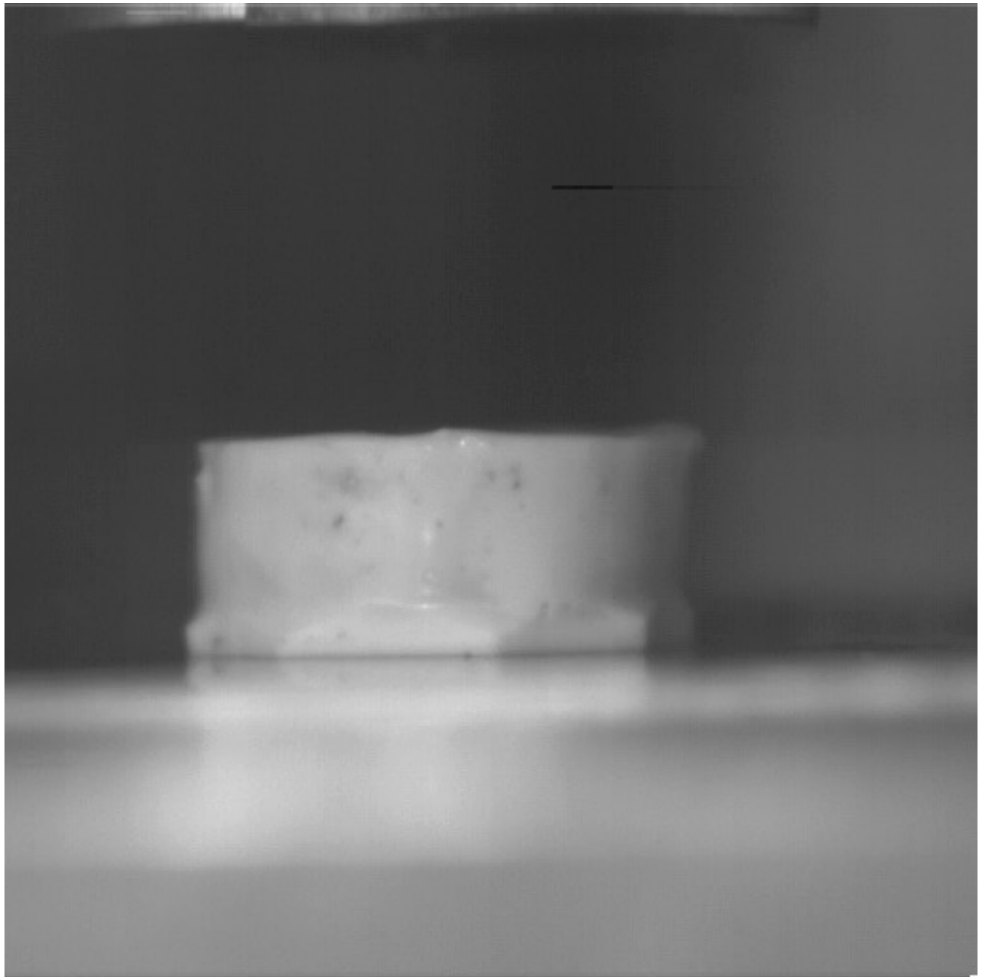


Silicone
RTV



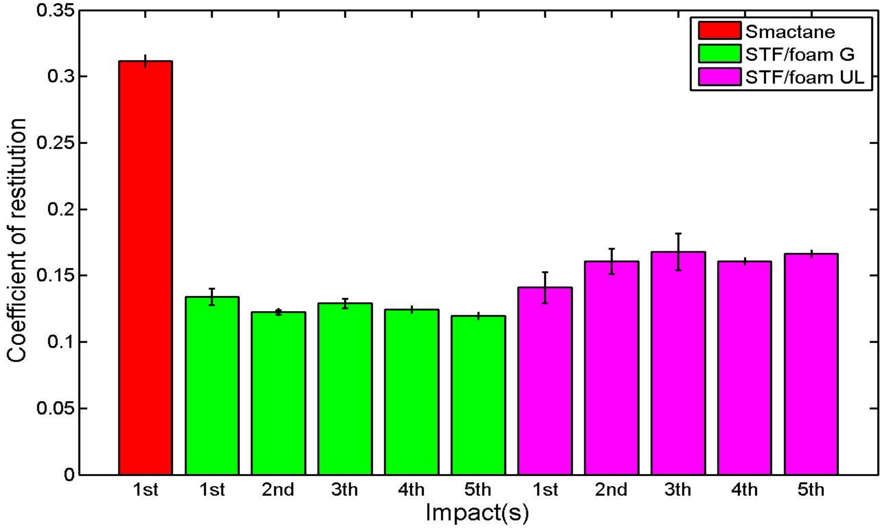
Rubber (Smactane)

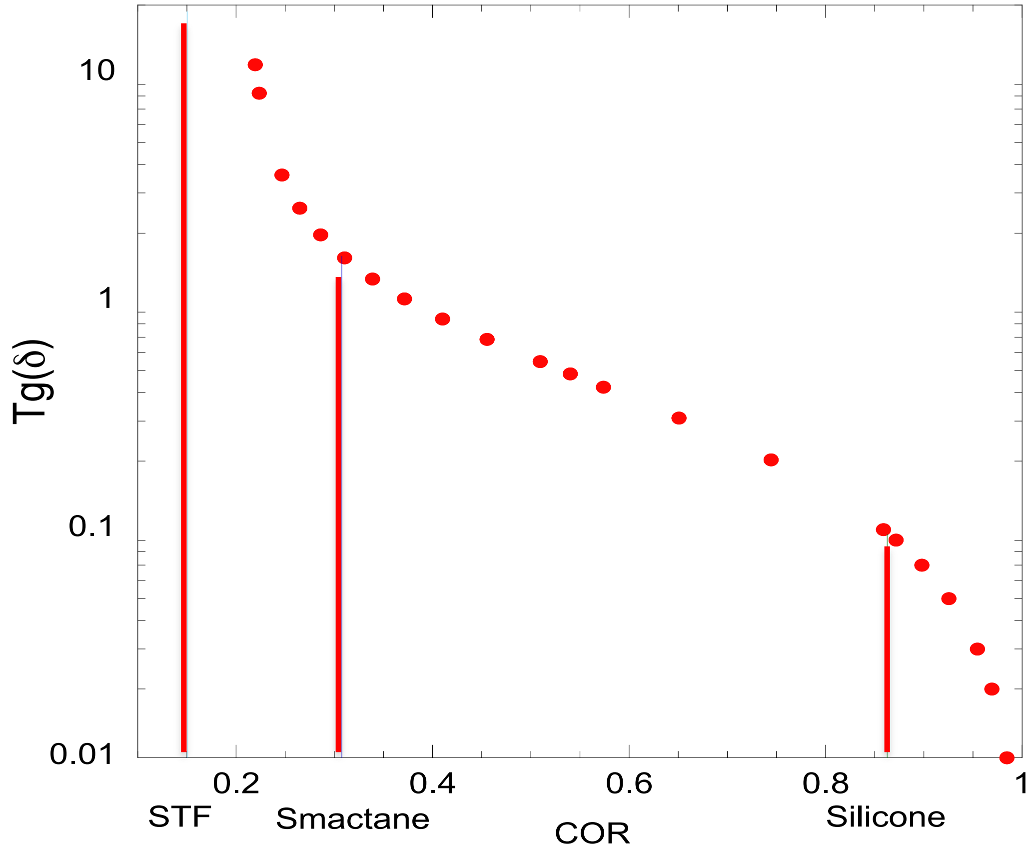
Impact testing



STF/Foam G

Coefficient of restitution





$$COR = \sqrt{\frac{H_1}{H_0}} = \sqrt{(\cos\delta + tg(\delta/2)\sin\delta)\exp(-2tg(\delta/2)(\pi - \delta))}$$

From Chen and Lakes, Int. J .Solid Structures, 1990

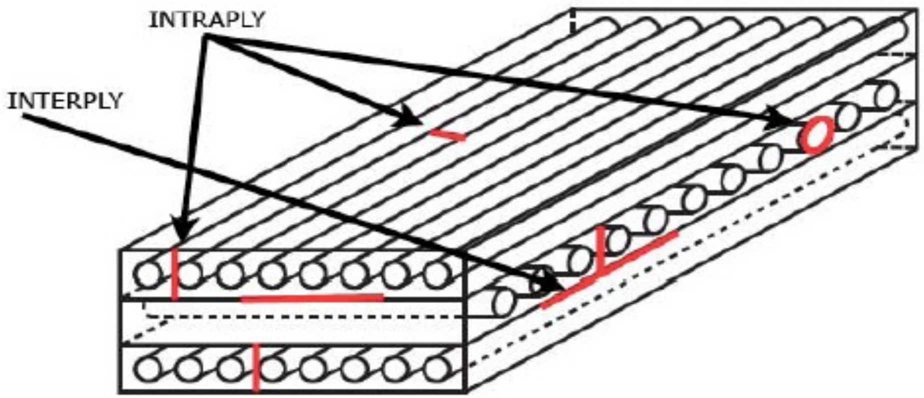
Next step, healing?

Finite life-time of composites
-damage propagation
-risk of catastrophic failure

Current strategies:
-design with safety margins
-regular maintenance
-repair costly and time consuming

Possibility of healing cracks in the matrix

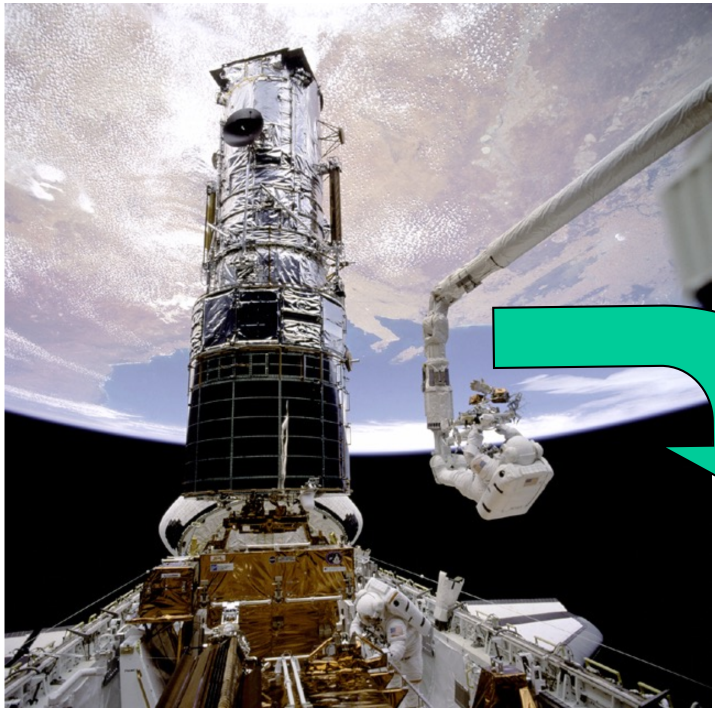
Failure of:
-Matrix
-Interface
-Reinforcement



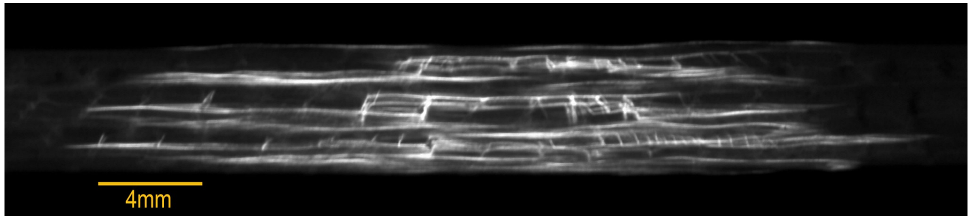
In a laminate: interply or intraply failure.

Progressive failure: in general, accumulation of small fracture events that finally lead to part failure.
Failure modes depend quite strongly on:
•the type of lay-up or textile, ply thickness, etc,
•the defects: from processing, from added phases
•the loading case (impact, fatigue, bending, shear modes…)

Repair in remote places?



Damage in zone F5

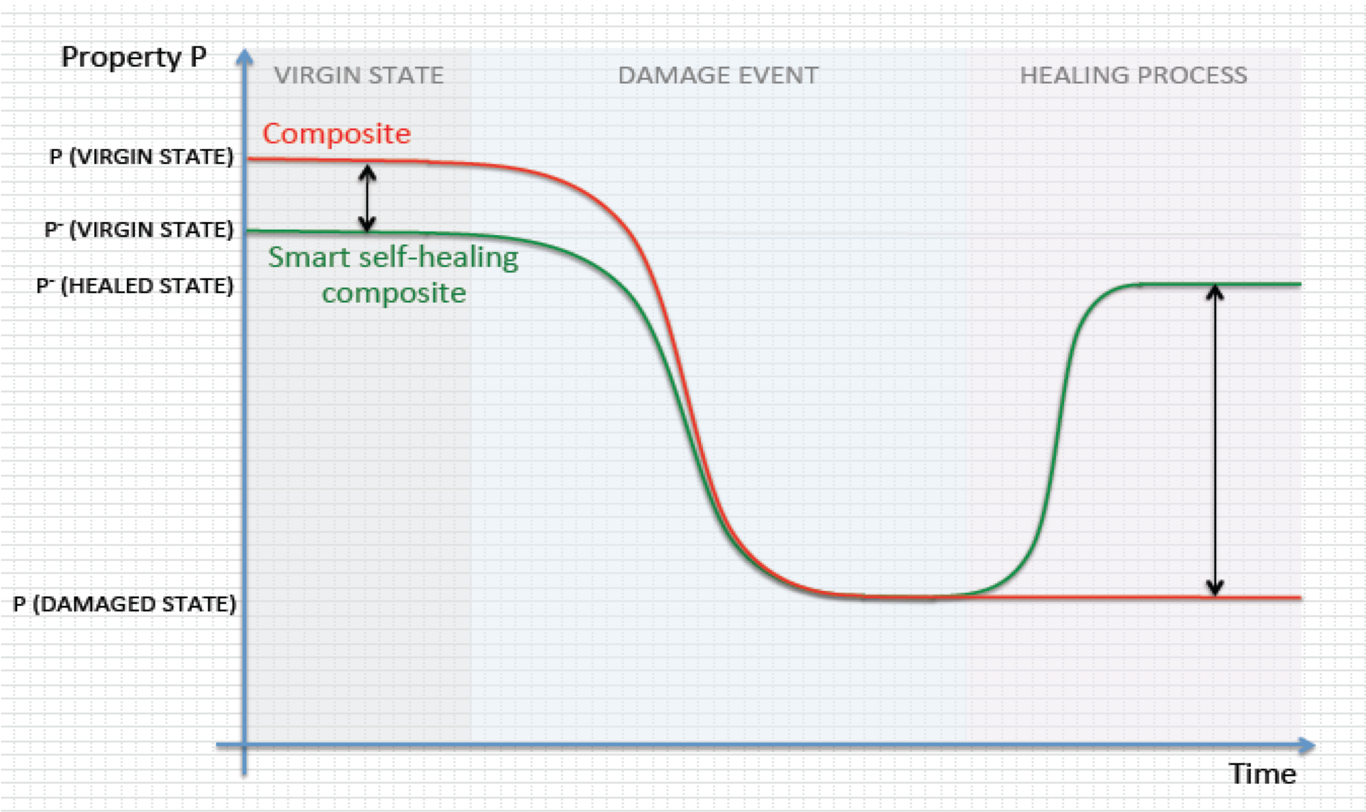


5J impact, from Gaille 2005

➡ It would be great to have a structure that detects damage, localises it and fixes it!

Healing strategies = trade-off

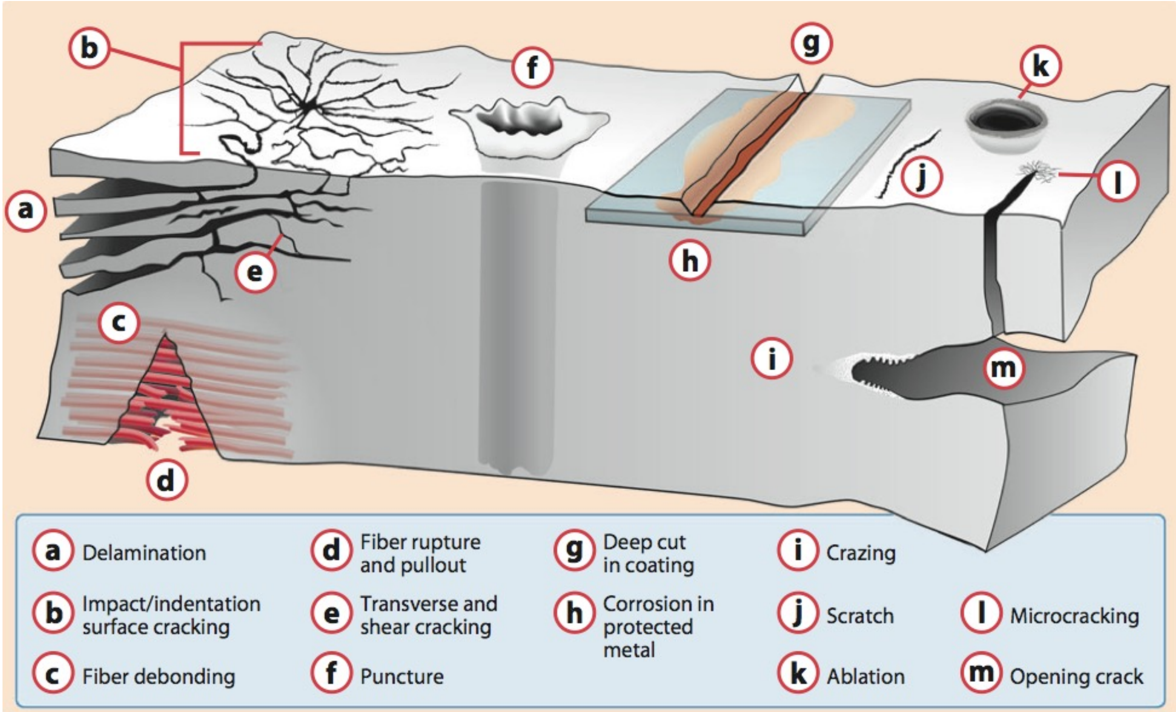
Propose a composite material, that can repair damage, most realistically to prevent catastrophic failures, and to allow continued use, before bringing the part back for repair if necessary.



Manfredi 2012

Self-repairing materials

First concepts in 1980, with the idea to include a repair fiber in concrete, then in polymer composites



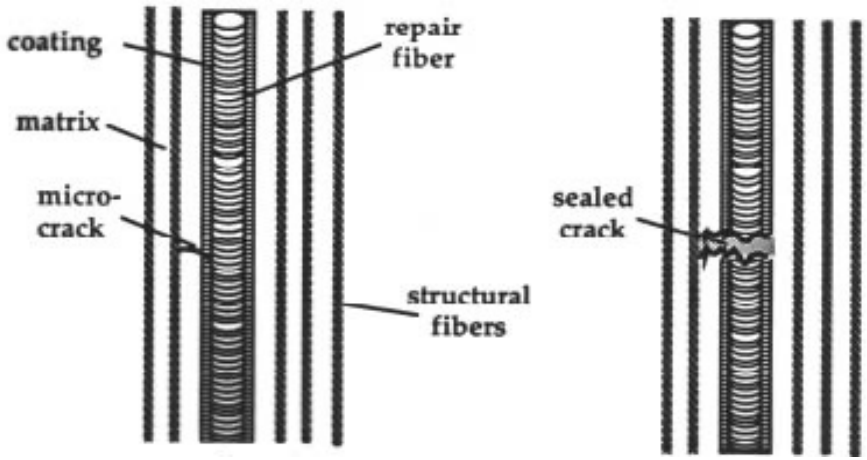


Figure 1. Schematic of Repair Mechanism [8]

C. Dry: Proc. JSME/ASME Intl. Conf. on Materials and Processing, 1, (2002), 343-351.

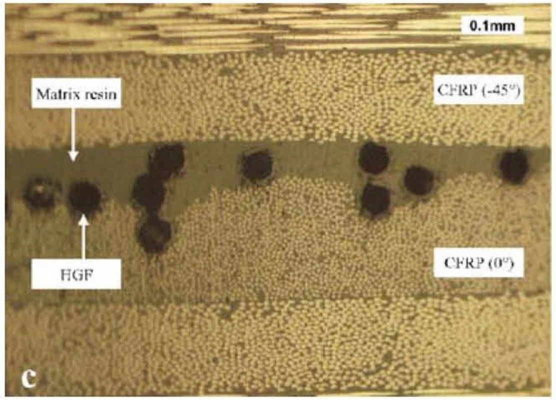
C. Dry and N. Sottos: "Passive Smart Self-Repair In Polymer Matrix Composite Materials," Proc. 1993 North American Conf. on Smart Structures and Materials, SPIE Vol. 1588, (1993).

C. Dry: "Concept Study for Military Port Design Using Natural Processes," Report to Office of Naval Research, August 5, 1980.

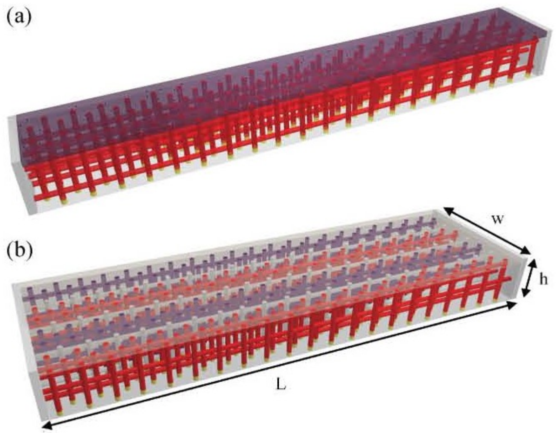
B.J. Blaiszik Self-Healing Polymers and Composites - Annu. Rev. Mater. Res. 2010:179-211

Extrinsic healing systems for composites

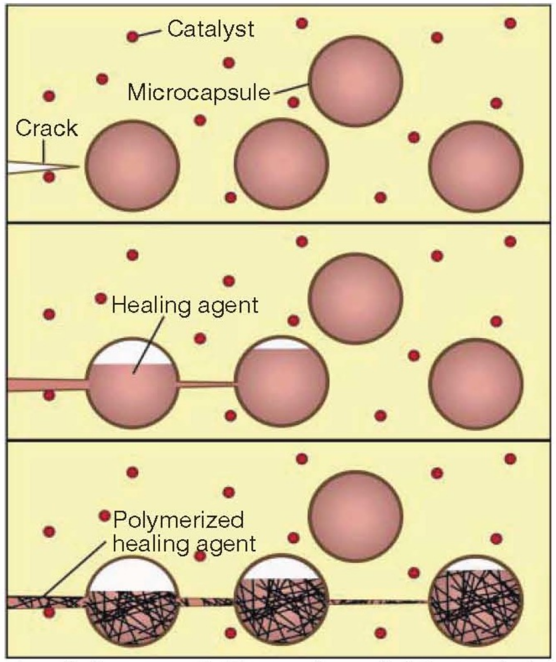
Microtubes



Microvascular



Microcapsules

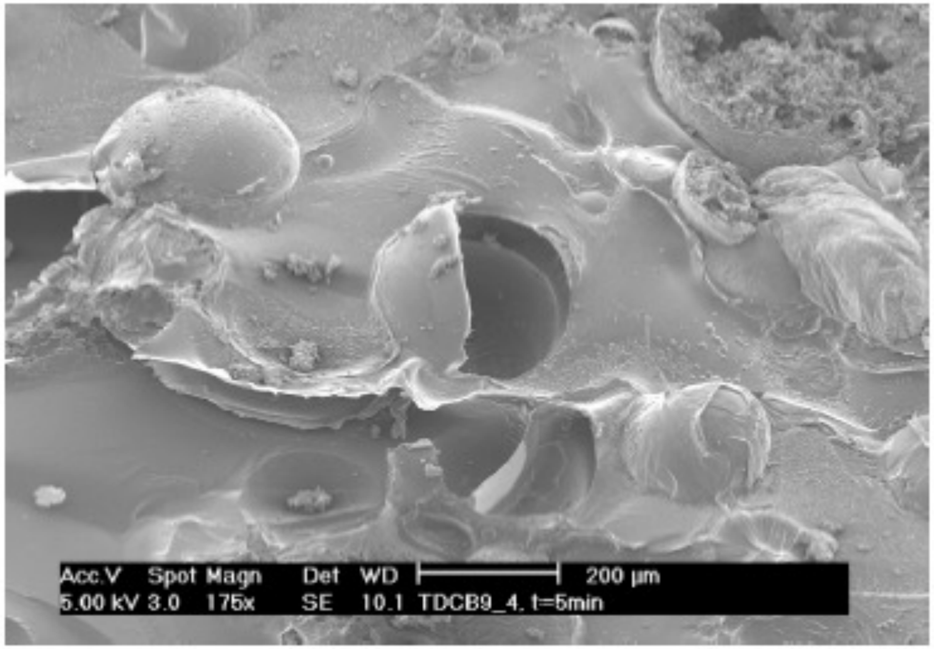


G. Williams et al. *Applied Science and Manufacturing*, 2007. K. S. Toohey et al. *Advanced Functional Materials*, 2009. S. White et al. *Nature*, 2001

Neuser, 2010

self-healing concept

- Crack healing:
  - Microcapsules: dicyclopentadiene (liquid monomer)
  - Matrix: Grubbs' catalyst



Kirkby, 2005

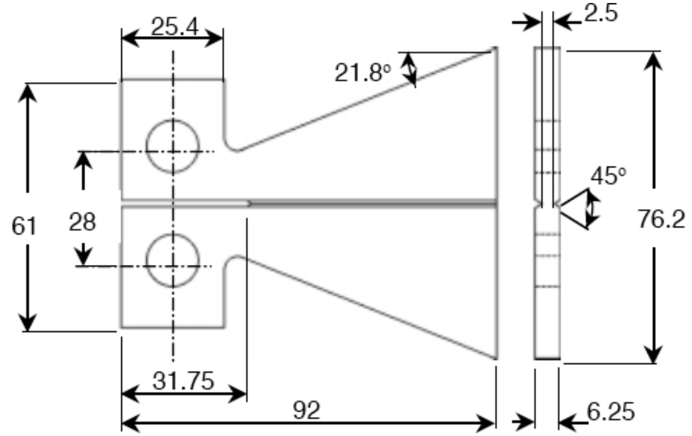
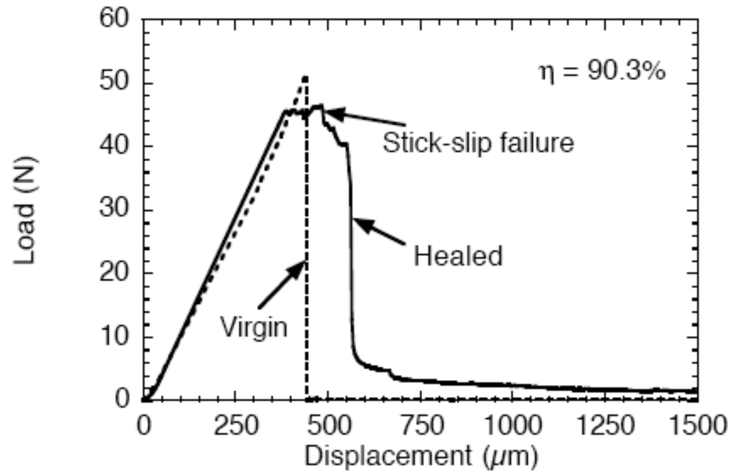


Fig. 3–Tapered double-cantilever beam (TDCB) geometry (dimensions in mm)

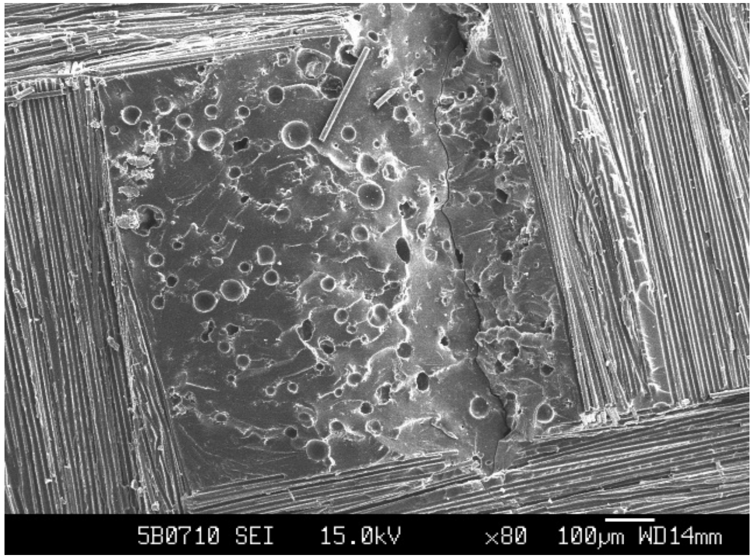


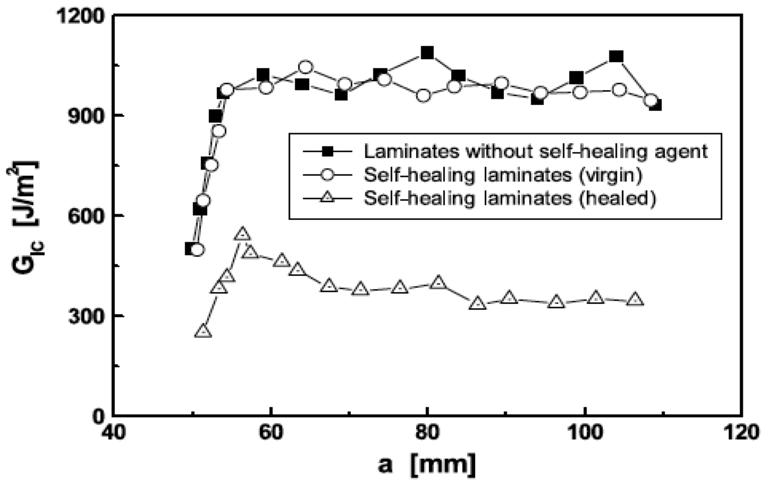
Representative load–displacement curve for an *in situ* sample with 2.5 wt% Grubbs and 5 wt% capsules

Sottos, White et al, 2001

Capsule-based systems in composites?

- Kessler et al (2003), first tests with capsules (DCPD) and Mode I DCB testing, indicated 40% healing in hand lay-up composites, but strong reduction in virgin G1c. Pointed the effect of thermal mass of the fiber bed.
- Yin et al. (2007-2009) with latent curing agent, hand lay-up, V_f=27% glass. 45% healing efficiency

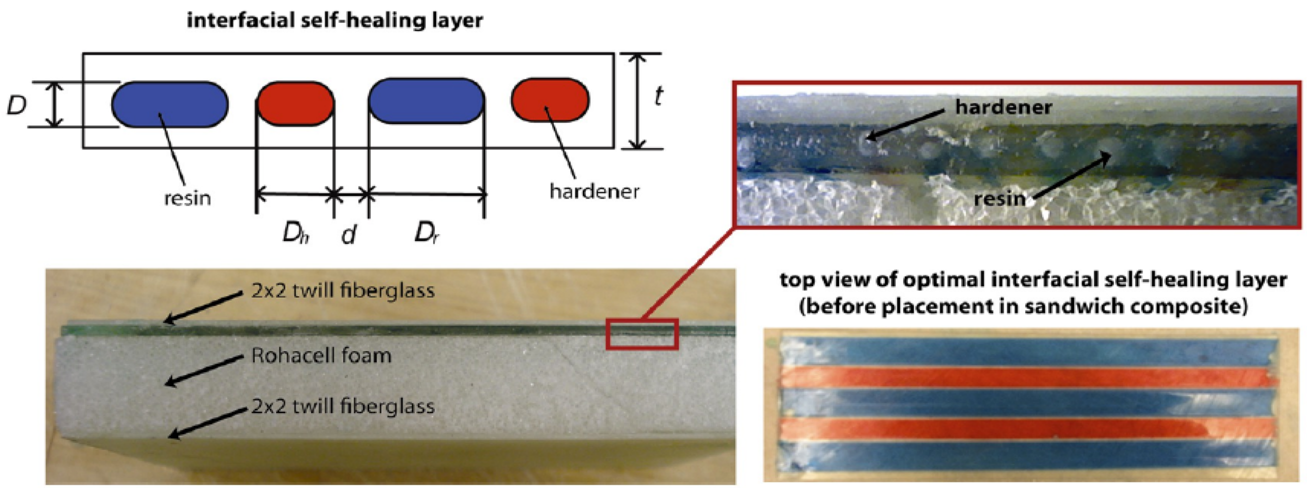


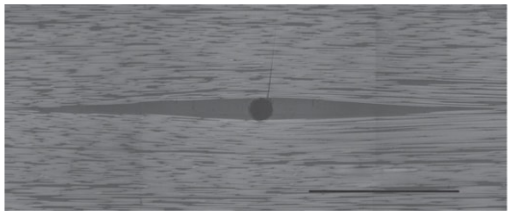


Kessler, et al., Comp. Part A, 2003 , Yin Smart mat and Struct, 2008

Vascular systems

- The idea here is to introduce an array of connected channels, to distribute healing agents, and this is quite similar to « human composite » systems, with load bearing elements (fibers) and a porous matrix.
- Demonstrated in sandwich structures (Wiliams et al, 2007, Chen et al, 2013) , minor reduction of initial properties, fixes some damage but not significant core-skin debonding,
- Potential in plain composites, but issues of processing method (additive manufacturing, fugitive materials)

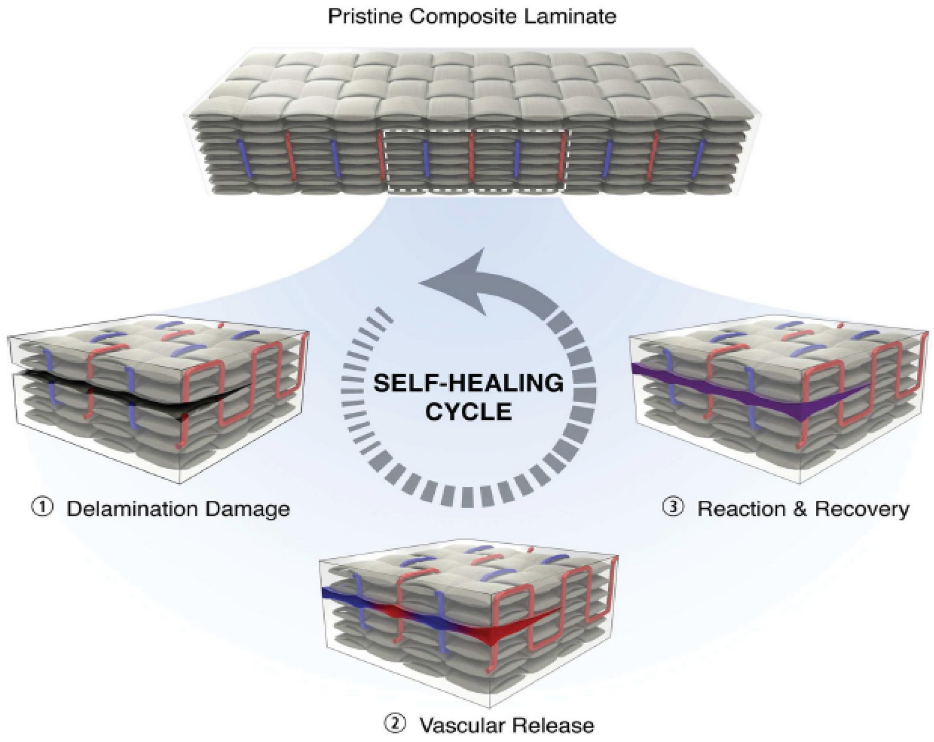


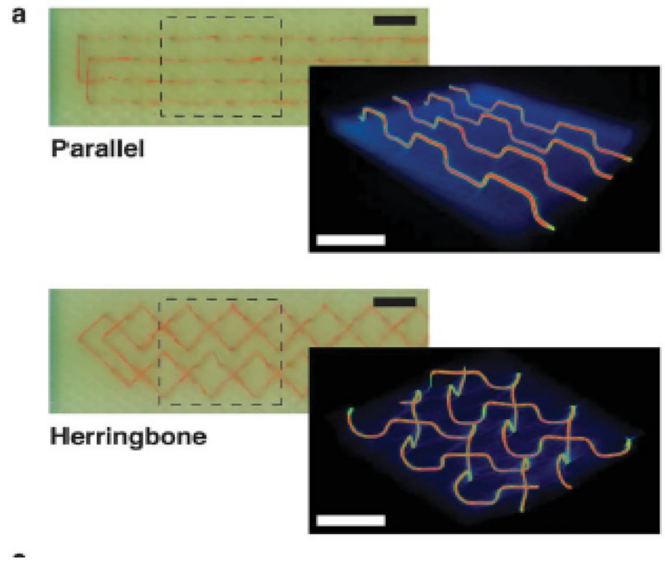


Chen, Smart Mat Struct, 2013, Huang, J Roy Soc Interf. 2010

Vascular systems

- Recent paper by Illinois group, PLA fibers woven into the composite fabric, then VARTM, then PLA is removed by vaporisation to leave a network of capillaries that can be filled with resin and hardener to fill cracks.
  - Nice concept, but reduction of mechanical properties in transverse direction, and need to devise a pumping system for these fluids.
    - Future: 3D printing of complex vascular system…



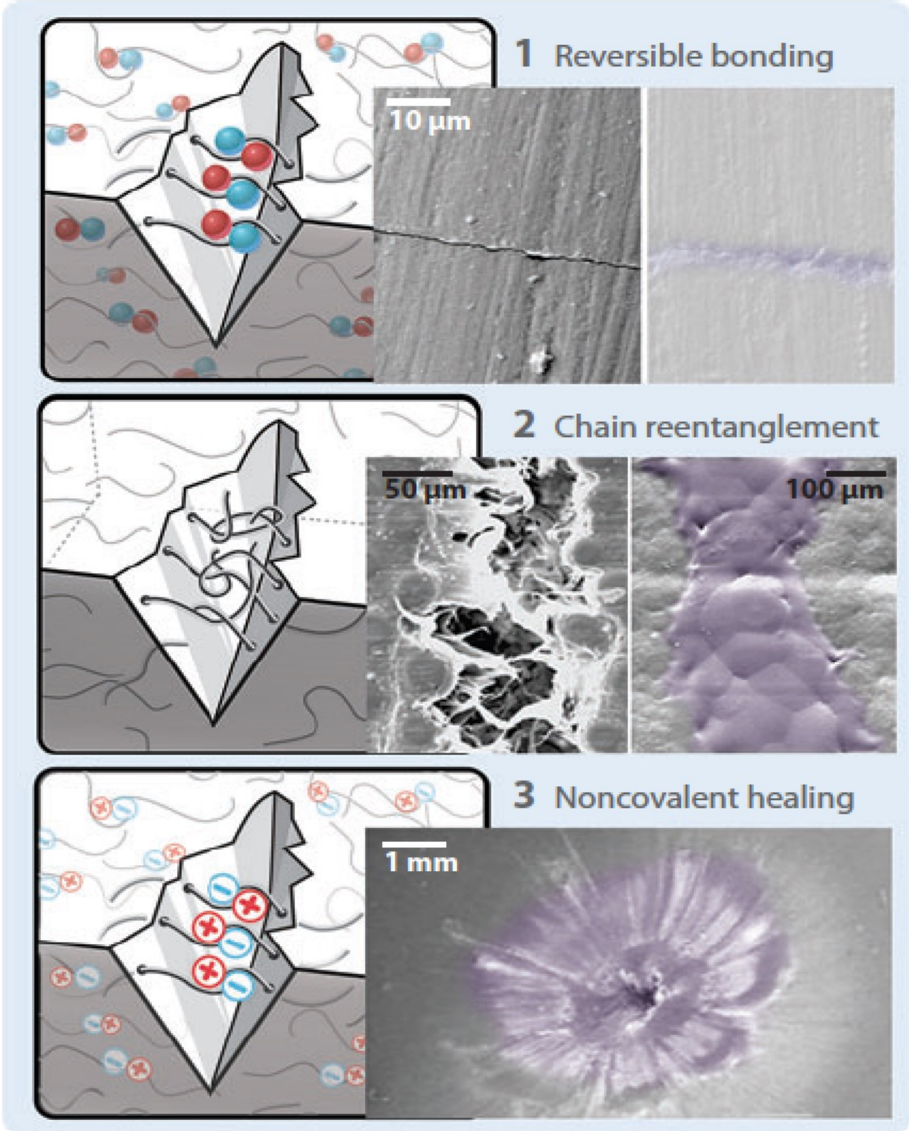


Patrick, Adv. Mat. 2014

Intrinsic systems

Self-healing polymer matrix:
-Supramolecular matrices
-Polymers with reversible bonds (Diels Alder reaction)
-Blends of epoxy and a healing phase
-Many systems…

In that case, no issue of fiber/extrinsic system interaction, but only that of producing composites with these matrices, and getting interesting properties.



B.J. Blaiszik elf-Healing Polymers and Composites - Annu. Rev. Mater. Res. 2010:179-211

Intrinsic systems as matrices for composites

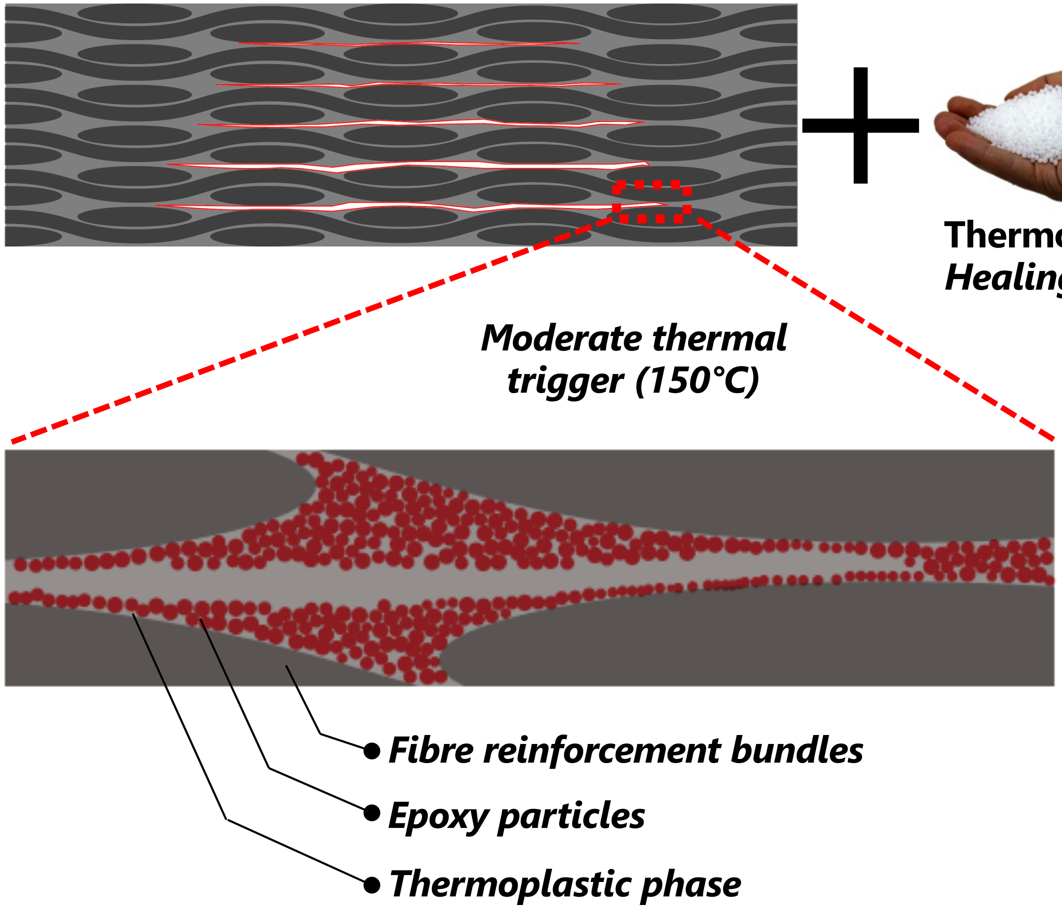
From a composite engineer perspective, two main types of systems:

-Low Tg, high species mobility materials: poor mechanical properties, elastomers or gels, do not damage like thermoset materials, may creep at room T, but could make interesting composite materials,

-Higher Tg, less mobility but better mechanical properties and nicely brittle…but they need some external action to heal, heat (Diels Alder, Thermoplastic blended in, …) or a solvent, or UV.

Polymer blend approach

A new polymer matrix material allowing crack healing

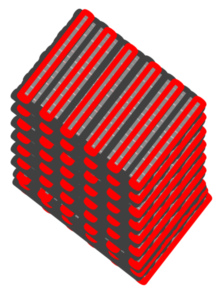


+

Thermoplastic
Healing agent

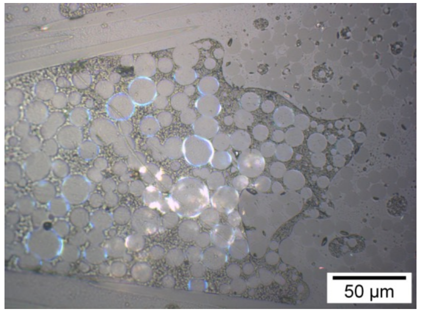
ADVANTAGES

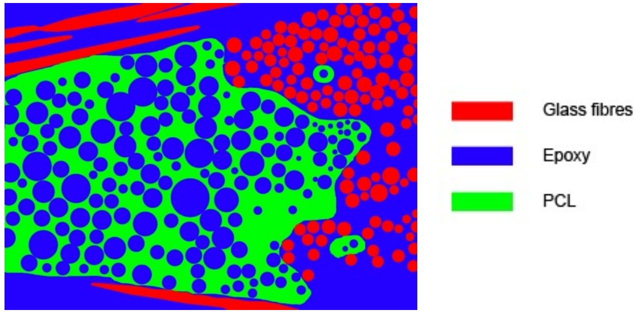
- ***Autonomous regeneration***
- ***Minimum manual intervention***
- ***Mechanical properties preserved***
- ***Processing compatibility***

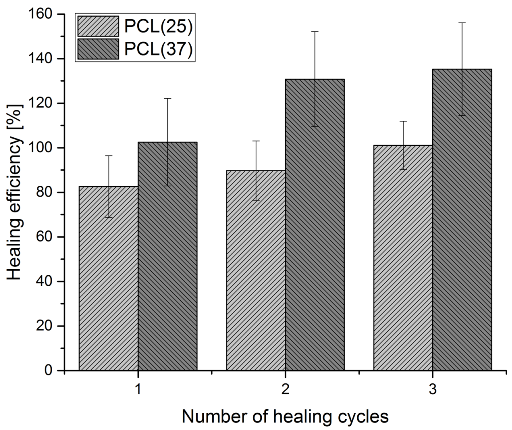


Autonomous composite regeneration upon damage, at low cost and with compatible manufacturing

Epoxy-PCL blend matrix into twill glass fibre reinforcement





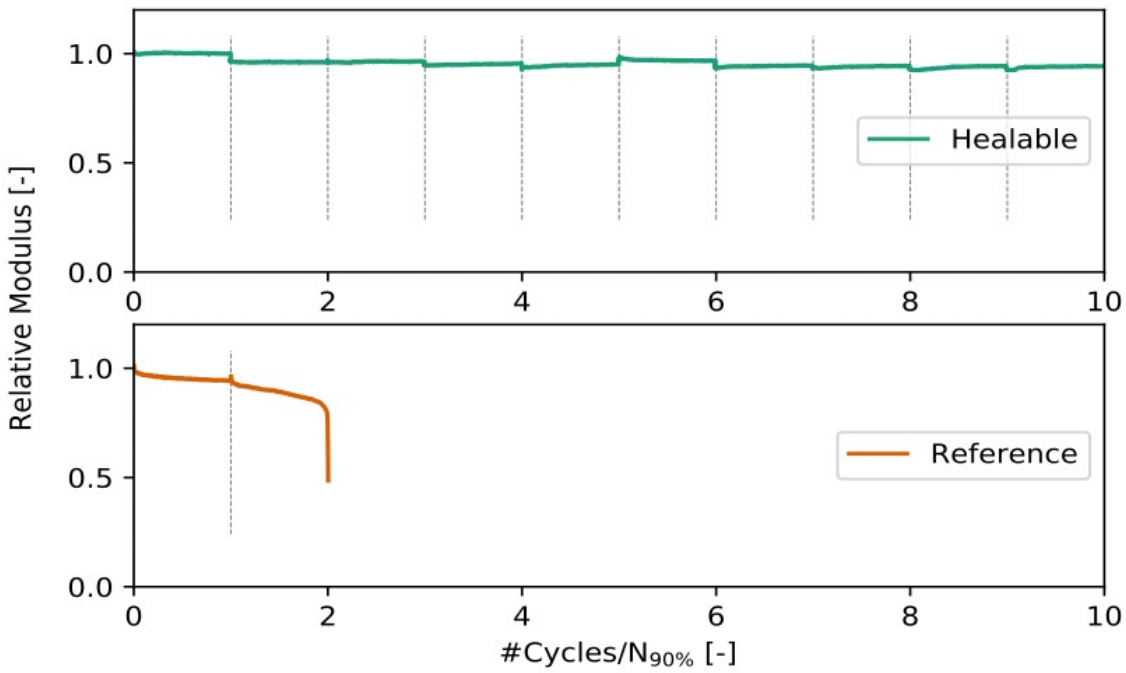


- **No loss in modulus compared to pure epoxy composites**
- **Full stiffness recovery over several cycles**
- **Toughness decrease of 35%**
- **Moderate toughness recovery: incomplete crack filling**

Cohades *et al.*, Comp. Part A. 99 (2017) 129-138

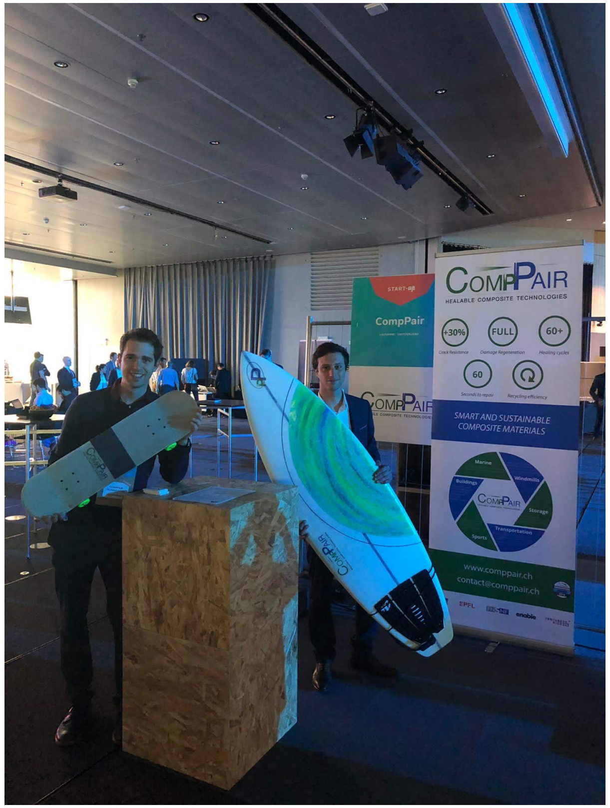
Fatigue performance

Three point bending following ASTM D7264



- **Healing (30 minutes at 150°C) was performed at 90% survival probability**
- **Life-time of the composites can be extended “indefinitely”**

Additional demonstrators

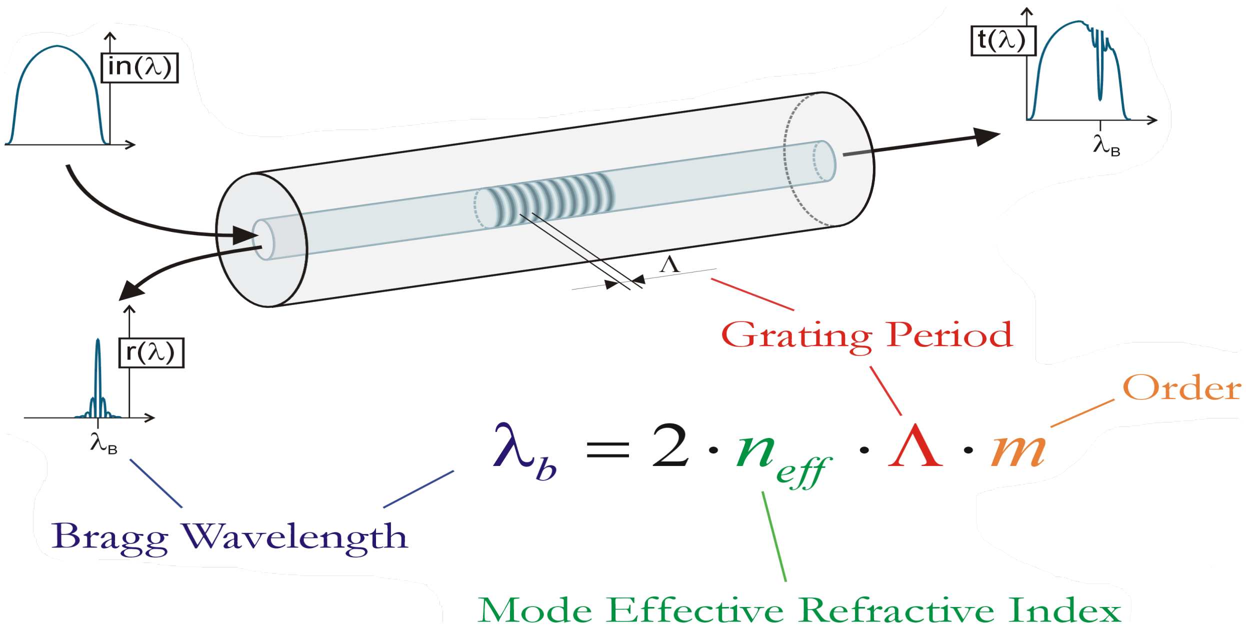


- **Composites with carbon fibers and flax fibers**
- **Real and laboratory life extension tests**

Motivation for sensing in composites

When structures are built with low safety factors….some monitoring may be of use!

One example of sensor: Optical fiber with Bragg gratings



$$\lambda_b = 2 \cdot n_{eff} \cdot \Lambda \cdot m$$

Optical Fiber Bragg Grating sensor.

FBG sensors

Sensitive to strain and temperature

$$\frac{\Delta\lambda_B}{\lambda_B} = K_\varepsilon \varepsilon_{11} + K_T \Delta T$$

$$K_\varepsilon = 1 - \frac{n_{eff}^2}{2}\left((1-\nu)P_{12} - \nu P_{11}\right)$$

$$K_T = \alpha + \xi$$

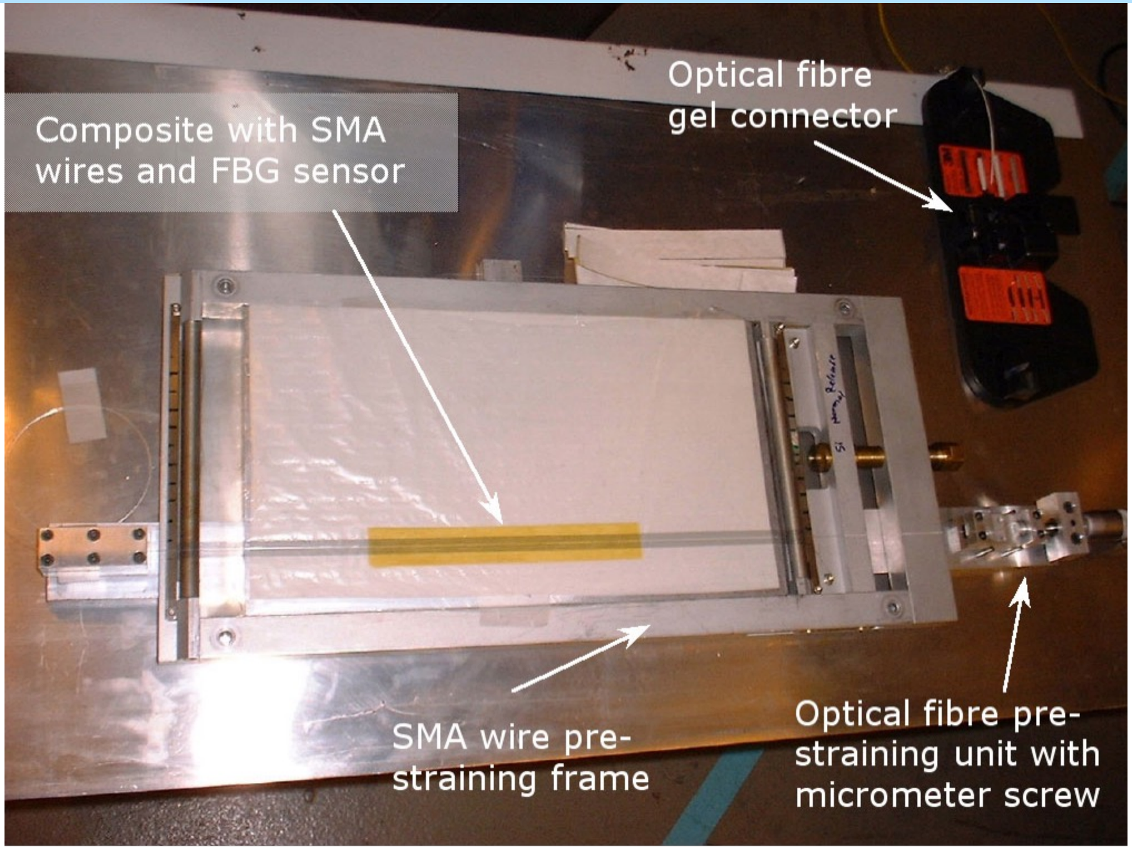
Advantages:

- small size and low weight
- ease of embedding into composite structures
- immunity to electromagnetic interference
- multiplexing capability
- remote sensing
- point sensing
- wavelength-encoded absolute measurement

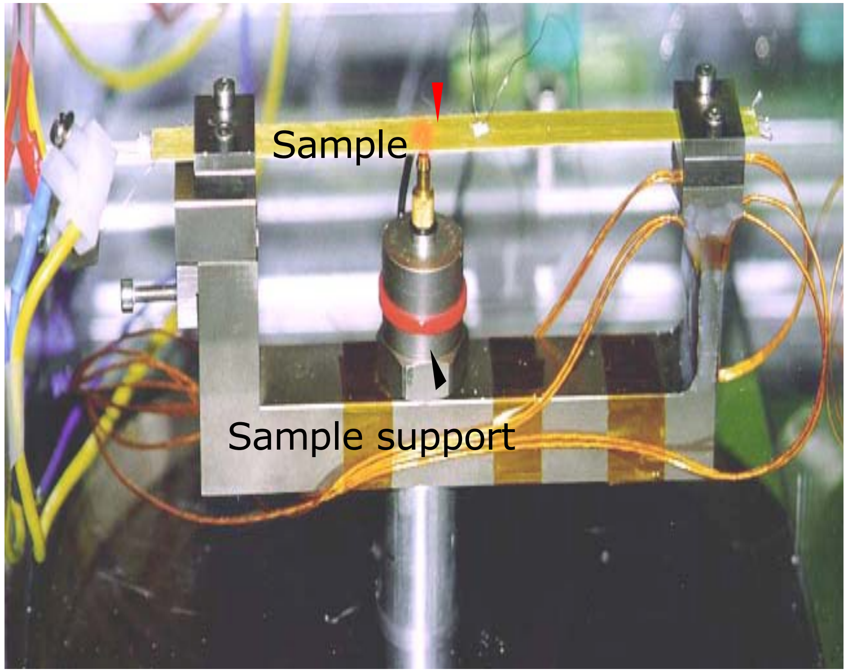
Disadvantages:

- brittleness
- sensitivity to both ε and T
- complex technology

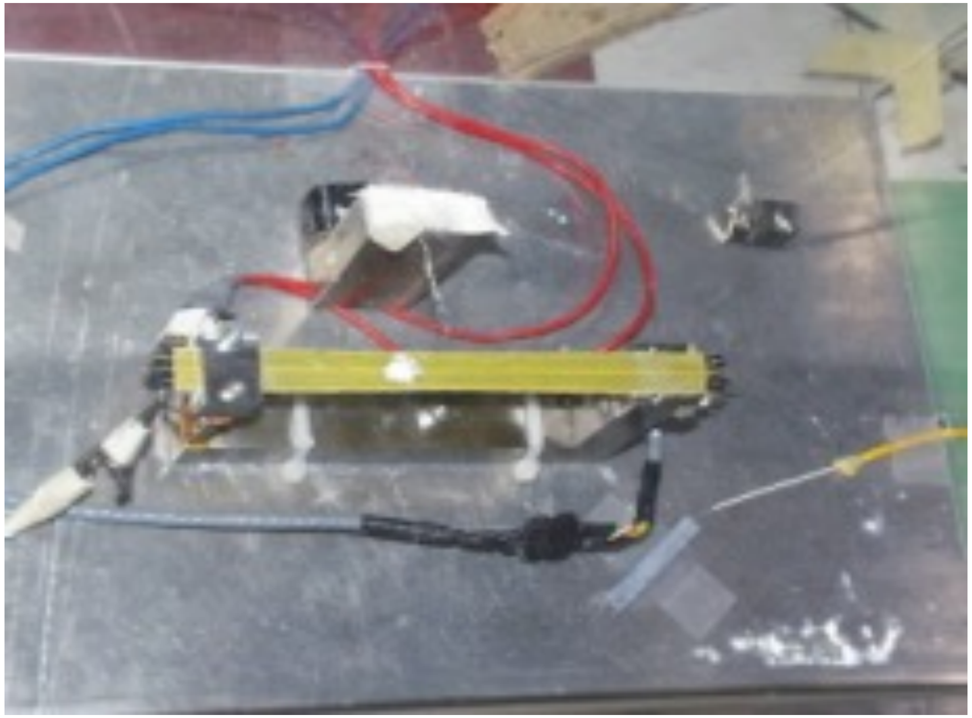
Composite manufacturing with FBG



Strain measurement during activation

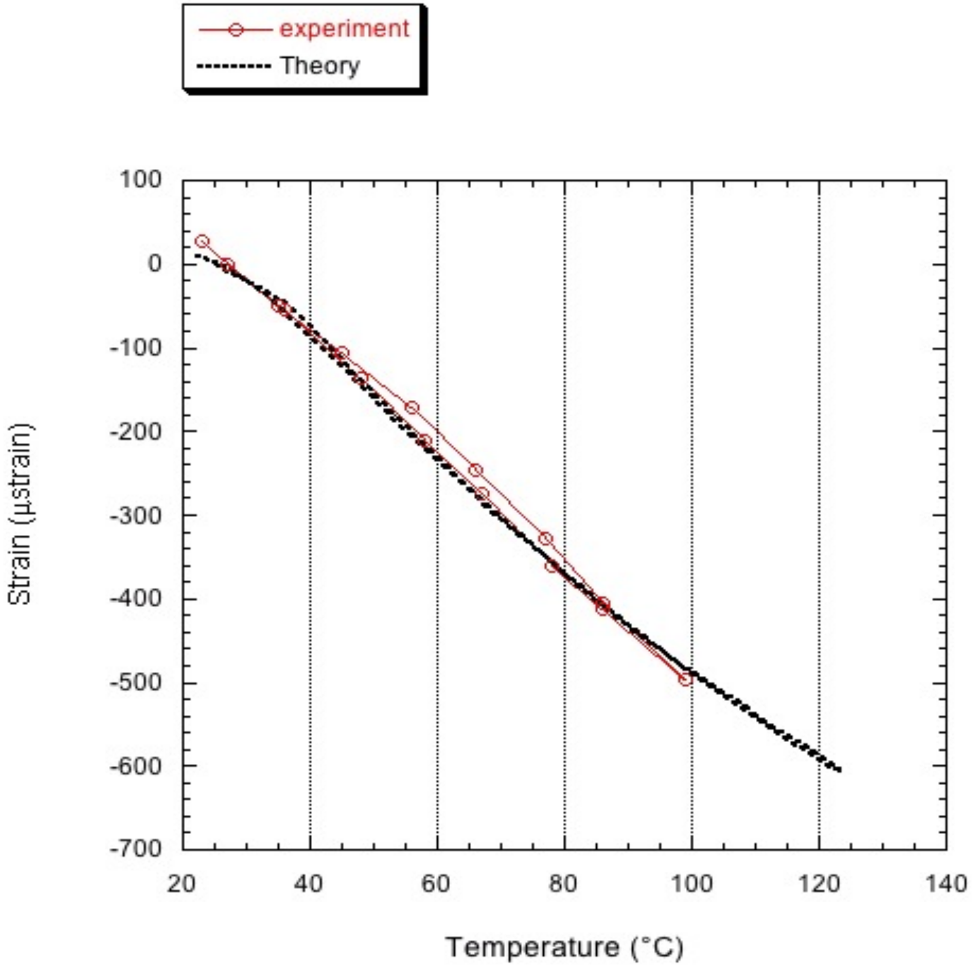


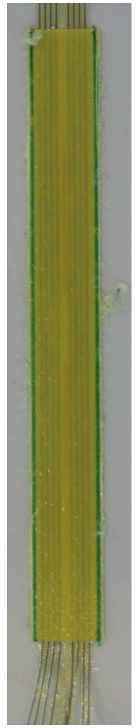
Clamped



Free

Example of strain measurement with temperature





- The composite contracted upon heating due to the recovery of the SMA wires above the transformation temperature. The FBG sensor measures strain and temperature (if two fibers are placed, and one is protected from strain, for example).

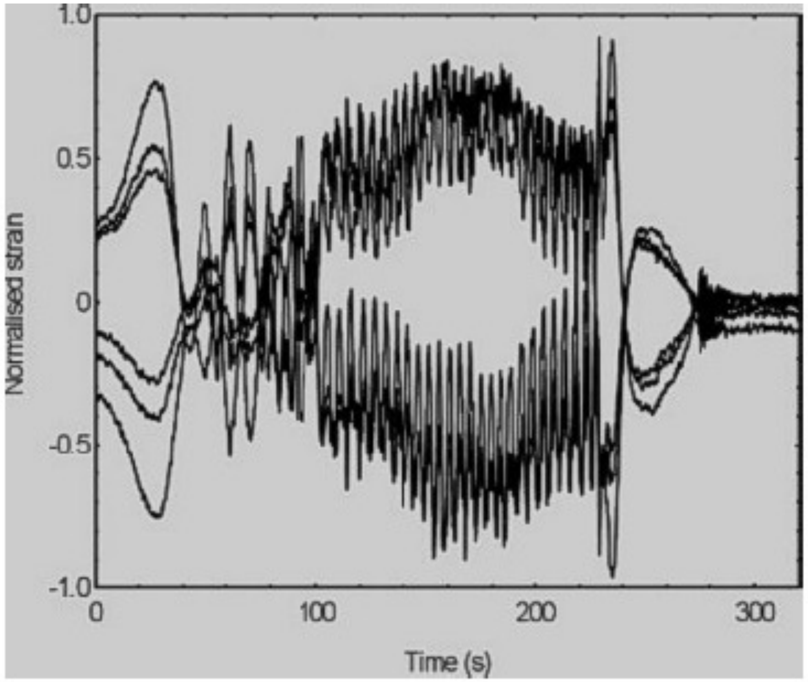
Some applications

Jacquelina Complete with 38 metre AeroRig

Sensor embedment within carbon composite mast

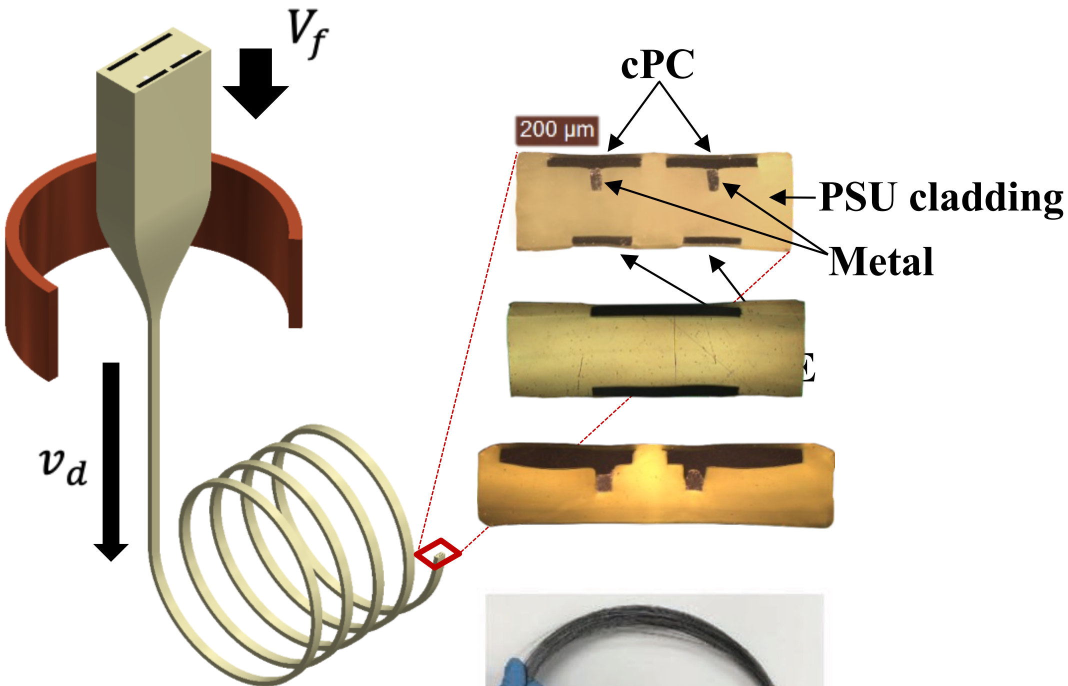
www.smartfibres.com

Some applications: wind turbine blade monitoring



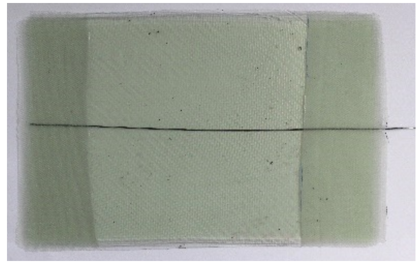
Strains recorded from six FBG sensors in an operational wind turbine blade.

Other sensing fibers…

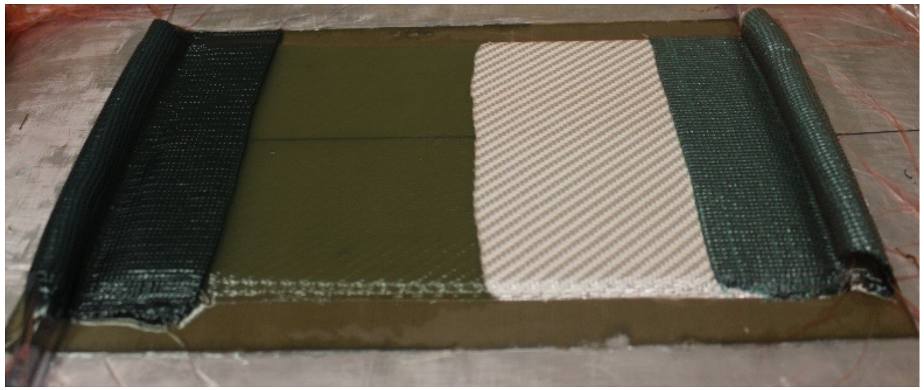


Placed fiber

Cured plate



Vacuum Infusion



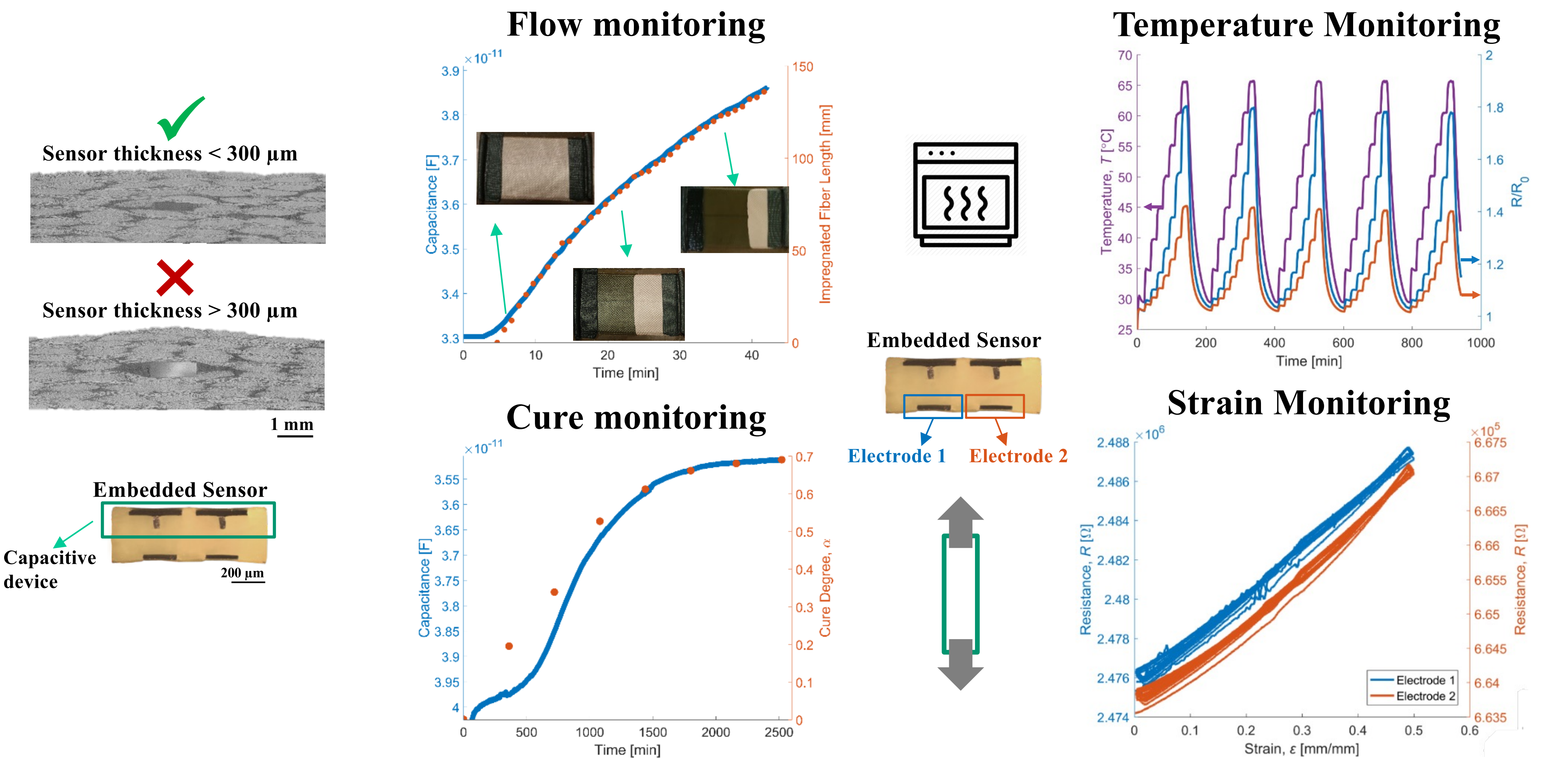
Vacuum Infusion: RTM variant

- **Upper mold half is a plastic bag**
- **Vacuum pulled to compact the fabric and pull the resin into the cavities**

European Patent Pending - EP19193949

<u>Caglar</u> et al. Advanced Materials Technologies, 2021

Process and structure monitoring



Conclusions

• A wide variety of combinations can be made according to the needs of the structure…

-> necessity to combined many various engineering fields.

-> possibility to use these sensing or actuating features during processing as well.

-> lots of marketing, but not so many commercial applications yet.

-> It is a strong research field in composites.

Exercices

1- Consider the integration of SMA wires, with properties given as in slide 22, into a glass-epoxy UD composite material, along the direction of the fibers, with a volume fraction of 5% SMA wires, that have been pre-strained by 3%. The modulus of the host composite is E=35GPa and its thermal expansion is $\alpha=11\ 10^{-6}$.

If the material is fully clamped, calculate the stress exerted on the clamps if the composite is heated at 60° C? What should be the volume fraction SMA in the composite if we would like to have a zero deformation (as compared to the value at room temperature 20° C) at 60° C, if the material is not clamped?

2- What solution could you propose if you were to design a smart composite which could possibly harvest vibration energy?