POLITECNICO DI MILANO

MEMS modelling and design group

cosm

Centre for Computational Structural and Materials Mechanics

A multiscale approach to the smart deployment of micro-sensors over flexible plates

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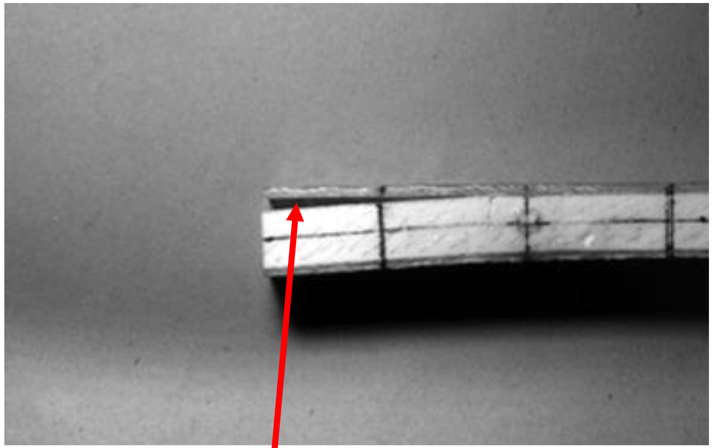
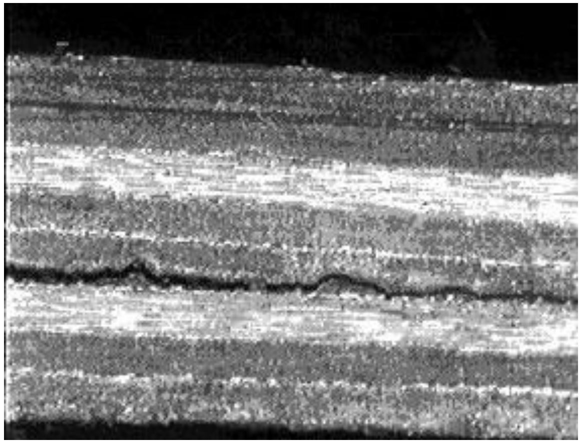
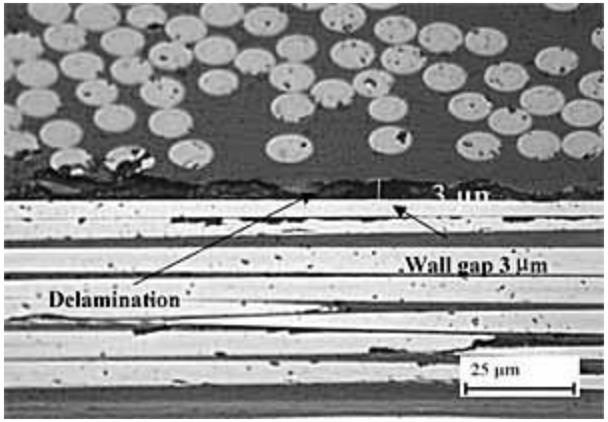
Politecnico di Milano

Syntactic foam/glass fibre composite sandwich

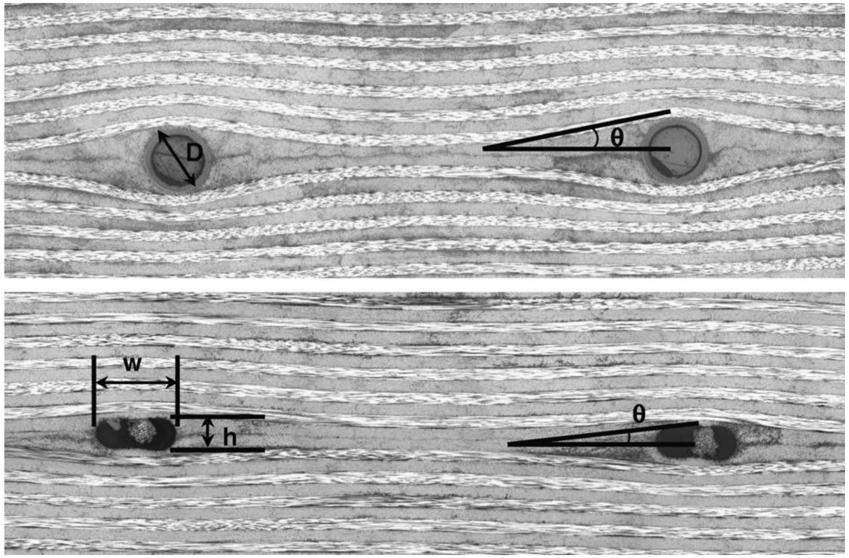


delamination



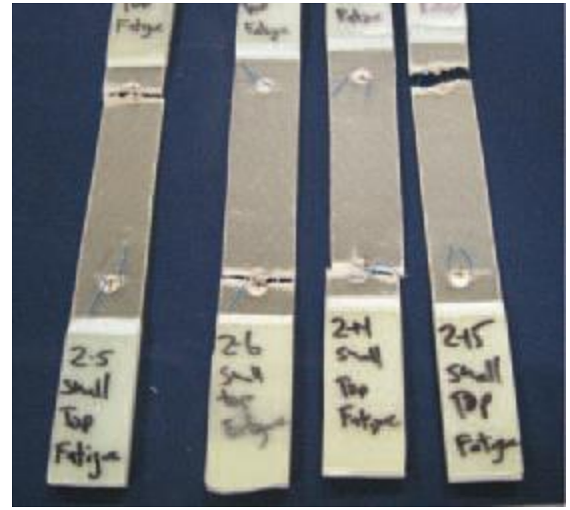


Effects of embedded monitoring systems

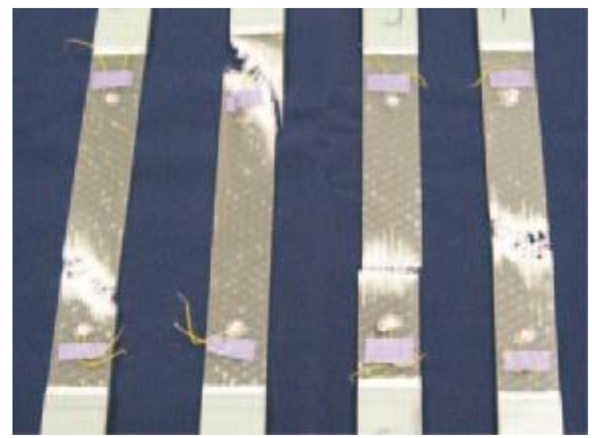


effects of embedded fiber sensors

after Kousourakis et al., Composites (2008)



inner (embedded) piezo

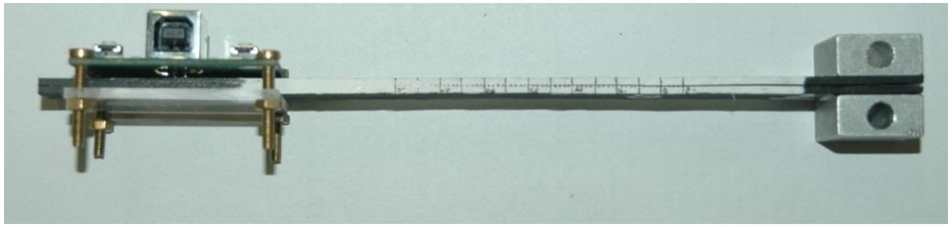


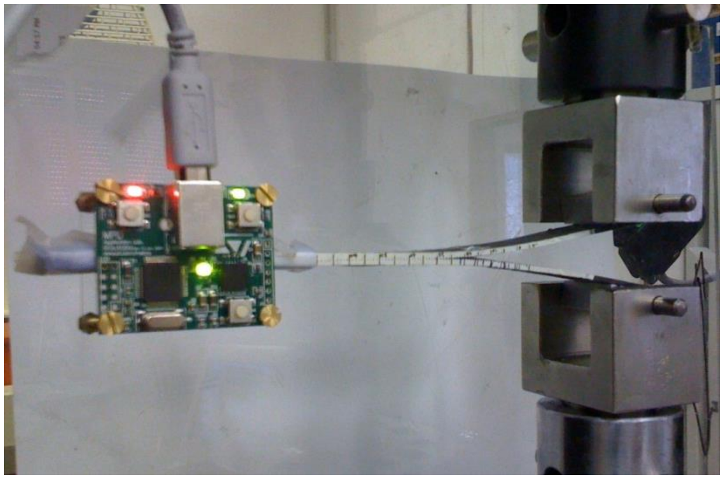
surface mounted piezo

after Tang et al., JIM (2011)

SHM modifies the stress-carrying capacity of the structural component

Surface-mounted MEMS-based sensing





MEMS evaluation board

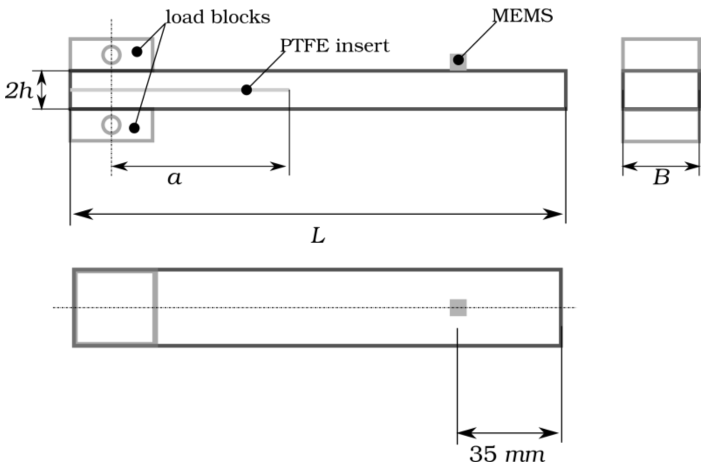
Features of 3-axis, digital output **MEMS** (micro electro-mechanical sensor) accelerometer **LIS3LV02DQ** (STM):

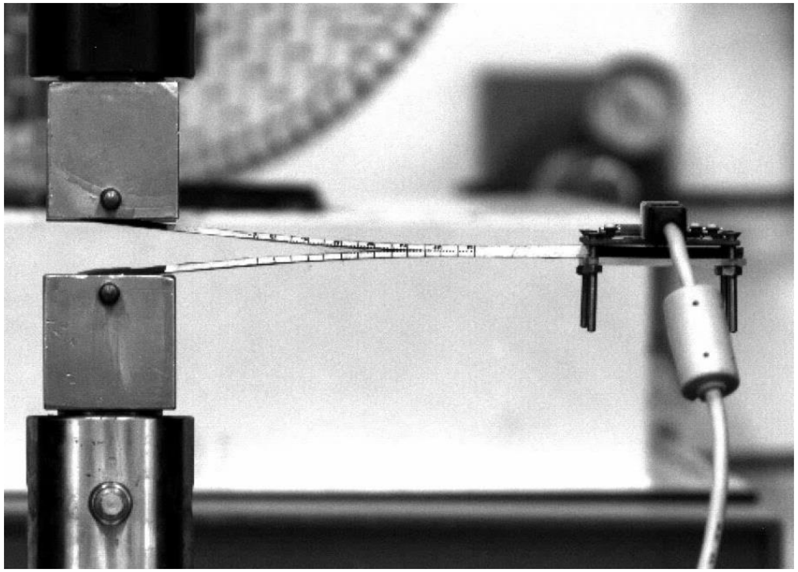
- full scale $\pm 2g$
- bandwidth 640 Hz
- sensitivity 1,000 LSb(Least_Significant_bit)/g
- resolution 1 mg
- weight 0.2 grams

Validation of the SHM scheme

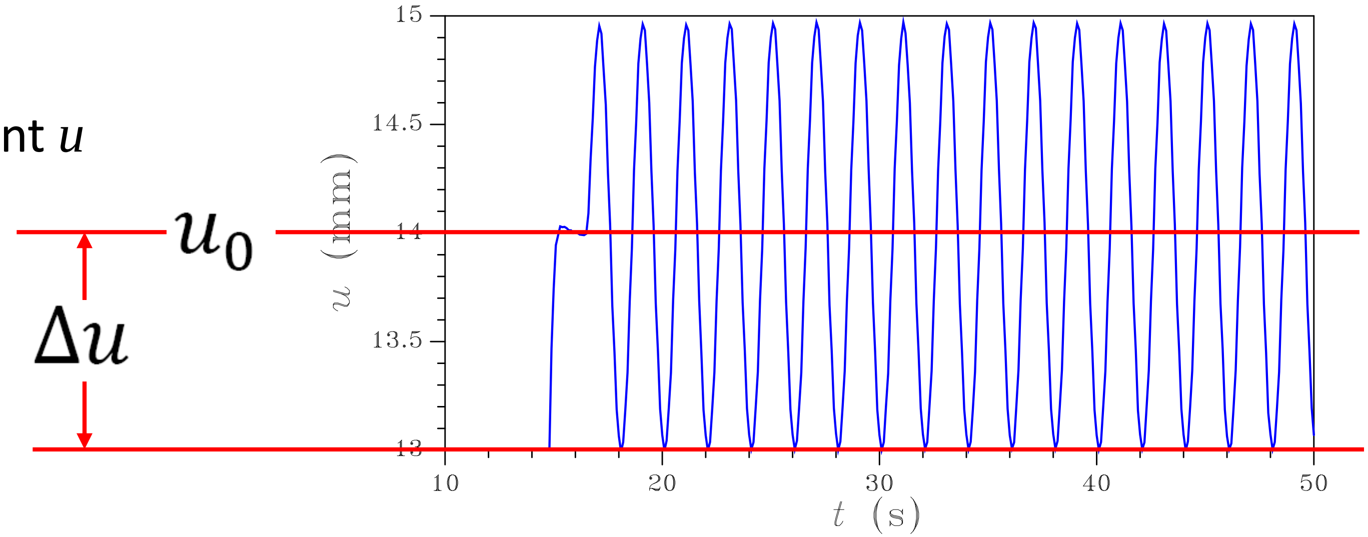
Optimal sensor placement

Validation test: DCB test under cyclic loading



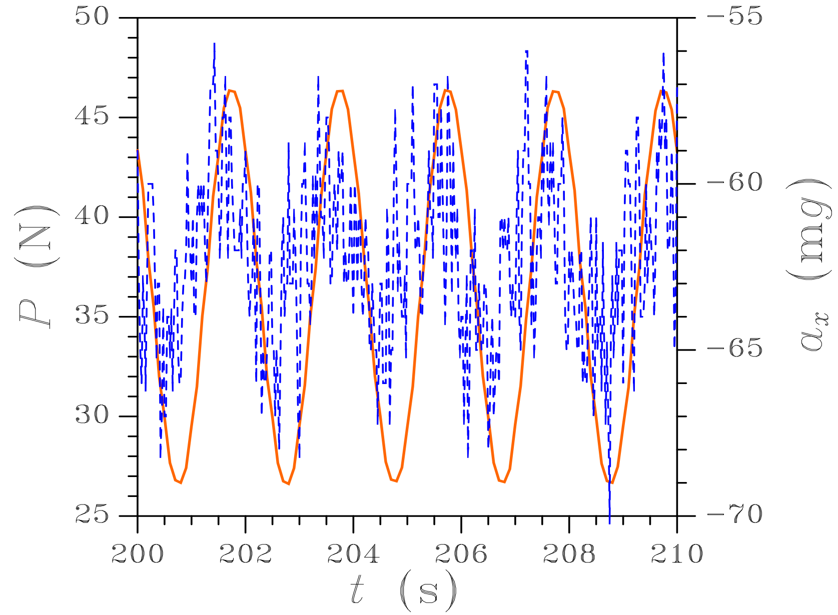


Sinusoidally varying imposed displacement u (at increasing u_0)

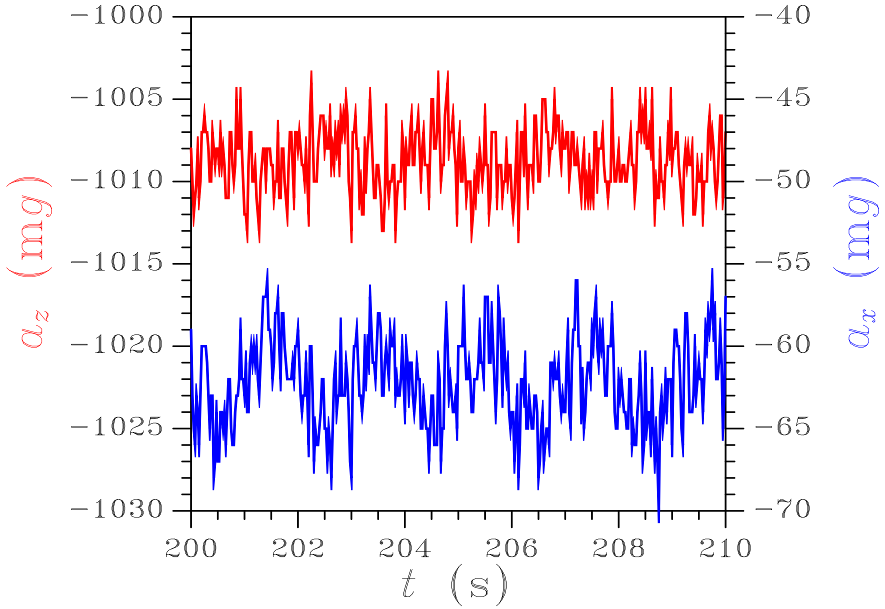


Validation test: test results and MEMS output

Load *P* varies smoothly



MEMS output shows
high-order frequency fluctuation



Validation test: theoretical model (Bernoulli-Euler beam bending)

Specimen compliance: $C = \frac{u}{P} = 8\frac{a^3}{E_l B h^3}$ — a: delamination length

Acceleration-load relation: $\ddot{u} = \varphi P$ — φ: assumed constant (geometry dependent)

In case of sinusoidal load:

$$\ddot{u} = \varphi \frac{u}{C} = \frac{\varphi}{C}\left[u_0 + \Delta u \ \sin(2\pi f_u t)\right]$$

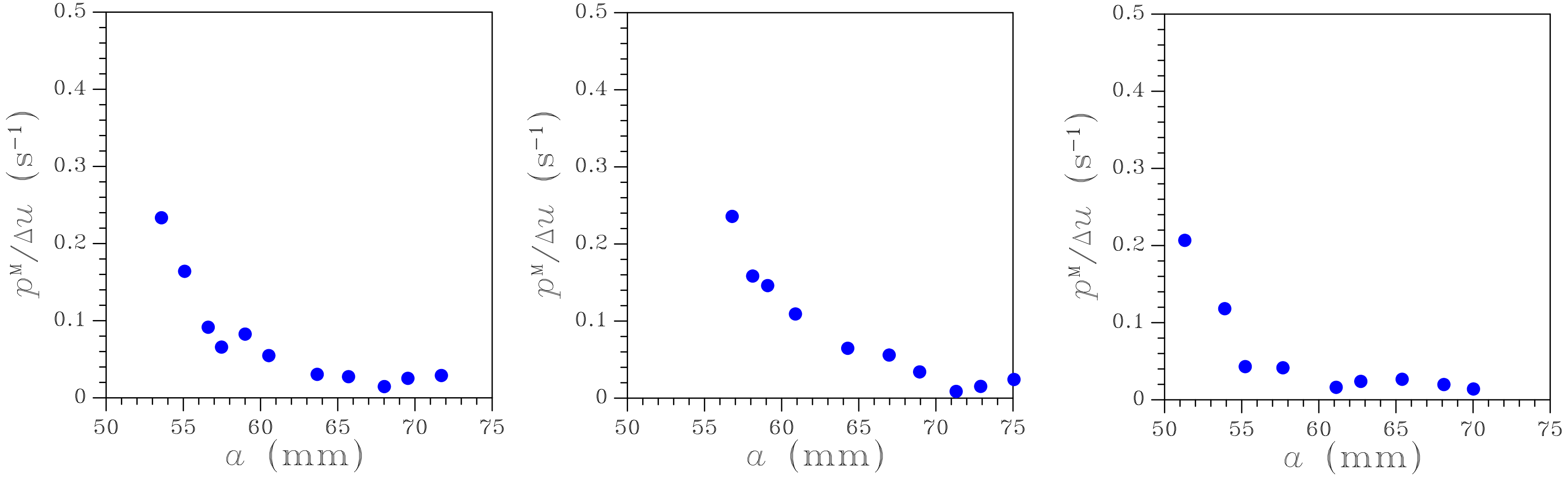
Moving to the frequency domain, through FFT:

$$|\hat{\ddot{u}}| = \frac{\varphi}{C}\left[u_0 \delta(f) + \frac{\Delta u}{2}\delta(f \pm f_u)\right]$$

At the driving frequency:

$$\frac{|\hat{\ddot{u}}|}{\Delta u} = \frac{\varphi}{2C}\delta(f - f_u)$$

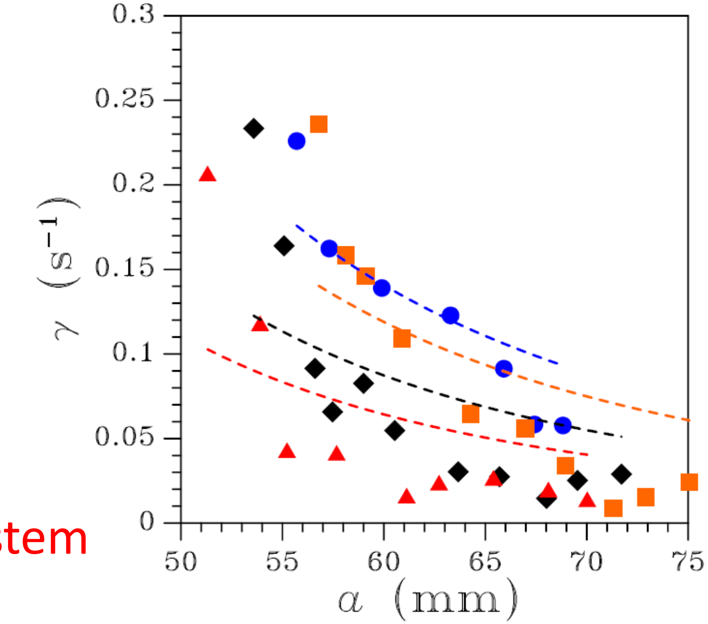
Validation test: theoretical model (Bernoulli-Euler beam bending)



$$\gamma = \frac{|\hat{\hat{u}}|}{\Delta u} = \frac{\varphi}{2C}\delta(f - f_u)$$

$$C = \frac{u}{P} = 8\frac{a^3}{E_l B h^3}$$

$$= \frac{\mu}{a^3}\delta(f - f_u)$$



We obtained a delamination length-sensing SHM system

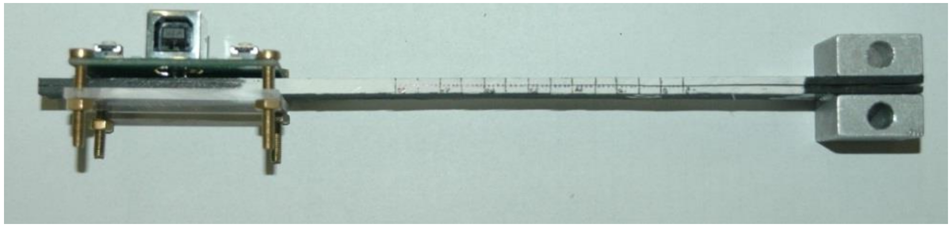
(Mariani et al., MEJ 2013, IEEE Sensors 2014)

Validation of the SHM scheme

Optimal sensor placement

Optimal sensor placement

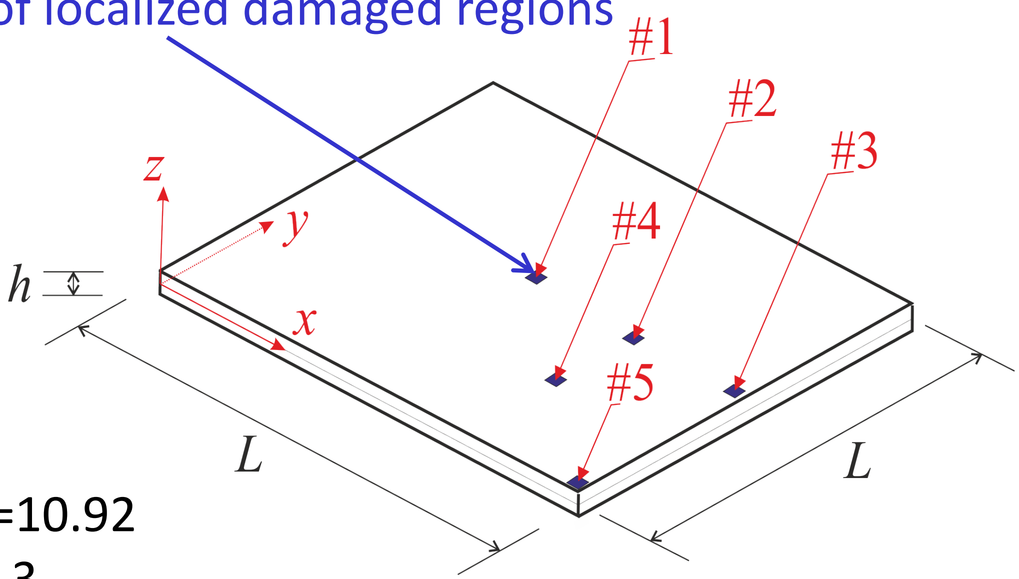
DCB test



Thin square,
simply supported plate:

$$\frac{L}{h} = 1000$$

Isotropic material:
(dimensionless) Young modulus E=10.92
Poisson ratio ν=0.3



Optimization approach (coupling FEA and MMA)

In case of a **single damaged region** (of known position), to maximize the sensitivity to the effects of damage:

$$\begin{cases} \max_x \sum_{i=1}^{n} x_i^p (u_i - \hat{u}_i)^2 \\ \text{s. t.} \\ \quad \sum_{i=1}^{n} x_i \leq \bar{N} \\ \quad 0 \leq x_i \leq 1 \qquad i = 1, \dots, n \end{cases}$$

- u_i: undamaged plate solution
- $\hat{u}_i$: damaged plate solution
- x_i^p: penalization term to approach pure 0-1 distributions (p>1)
- x_i: "sensor density" at the i-th position
- $\bar{N}$: max allowed number of sensors
- n: number of possible sensor locations (FE)

(Mariani-Bruggi et al., EO, JIM 2013)

number of damaged areas

In case of a **multiple damaged regions** (of known positions), to maximize the sensitivity to the magnitude of the effects of damage [FORM-1]:

$$\begin{cases} \max_x \sum_{k=1}^{s} \left[\sum_{i=1}^{n} x_i^p (u_{ki} - \hat{u}_i)^2 \right] \\ \text{s.t.} \\ \sum_{i=1}^{n} x_i \leq \bar{N} \\ 0 \leq x_i \leq 1 \qquad i = 1, \dots, n \end{cases}$$

or, to maximize the sensitivity to damage [FORM-2]:

$$\begin{cases} \max_x \sum_{k=1}^{s} \left[\frac{\sum_{i=1}^{n} x_i^p (u_{ki} - \hat{u}_i)^2}{\max_i x_i^p (u_{ki} - \hat{u}_i)^2} \right] \\ \text{s.t.} \\ \sum_{i=1}^{n} x_i \leq \bar{N} \\ 0 \leq x_i \leq 1 \qquad i = 1, \dots, n \end{cases}$$

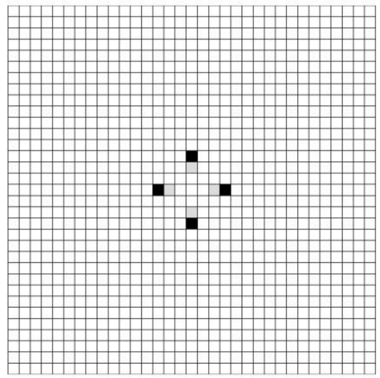
To be adopted at **each length-scale** (two concatenated analyses in the cases to follow)

Square plate: optimal sensor placement – damage anywhere at the macroscale
simply supported plate

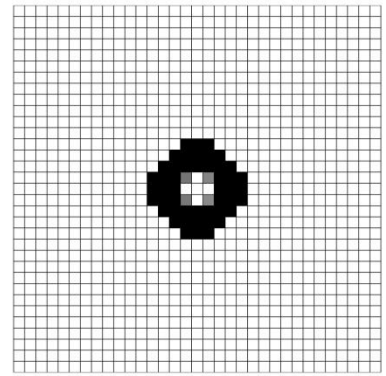
$$\theta = \sqrt{\theta_x^2 + \theta_y^2}$$

[FORM-1]

$\bar{N} = 5$

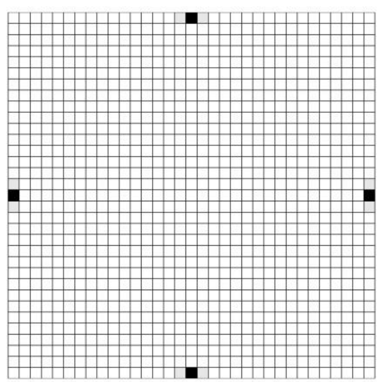


$\bar{N} = 50$

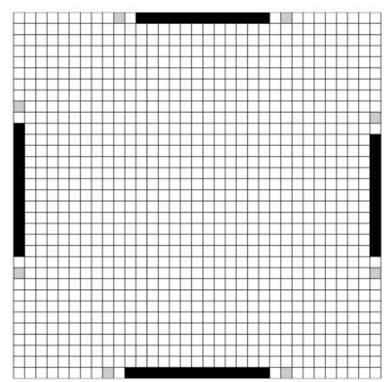


[FORM-2]

$\bar{N} = 5$



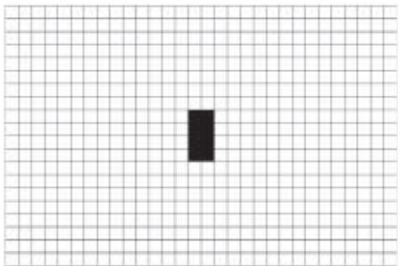
$\bar{N} = 50$

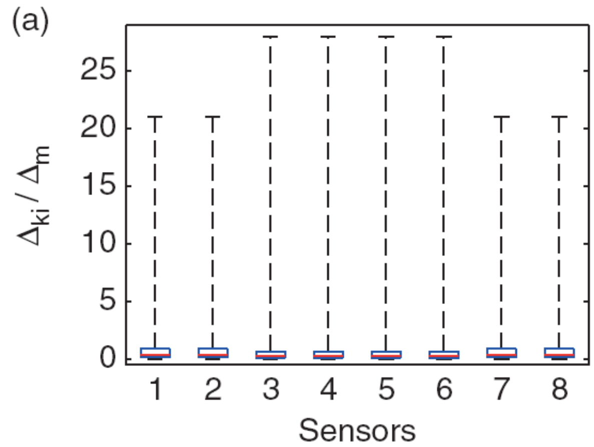


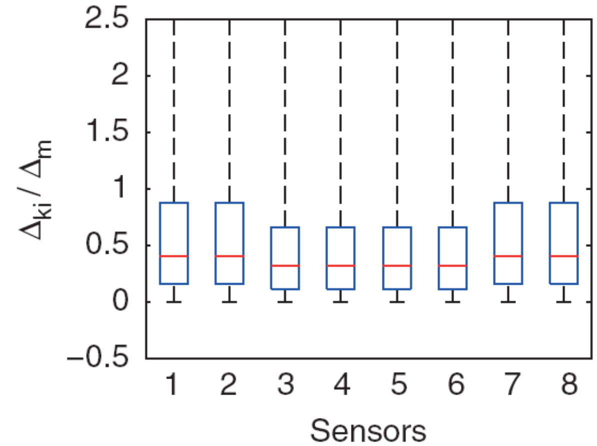
Rectangular plate: optimal sensor placement – damage anywhere at the macroscale simply supported plate

$$\theta = \sqrt{\theta_x^2 + \theta_y^2}$$

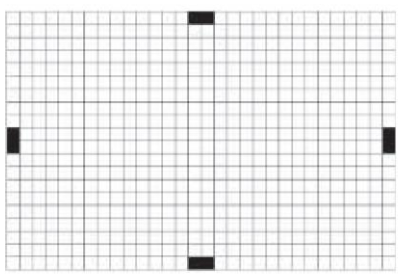
[FORM-1]

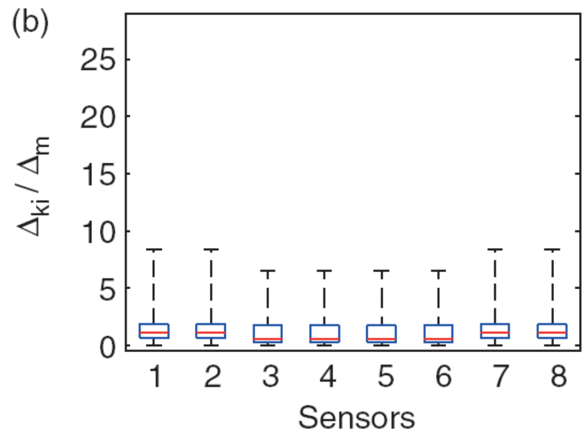


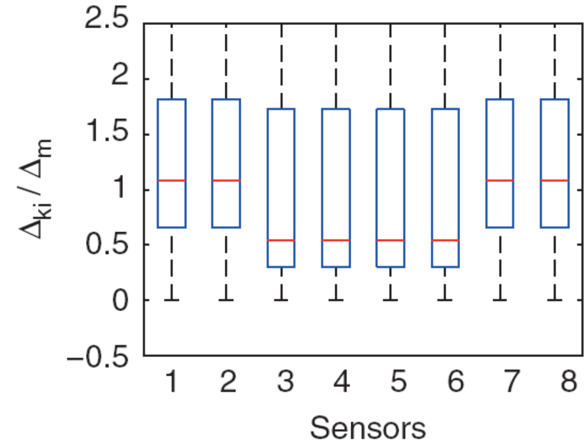




[FORM-2]



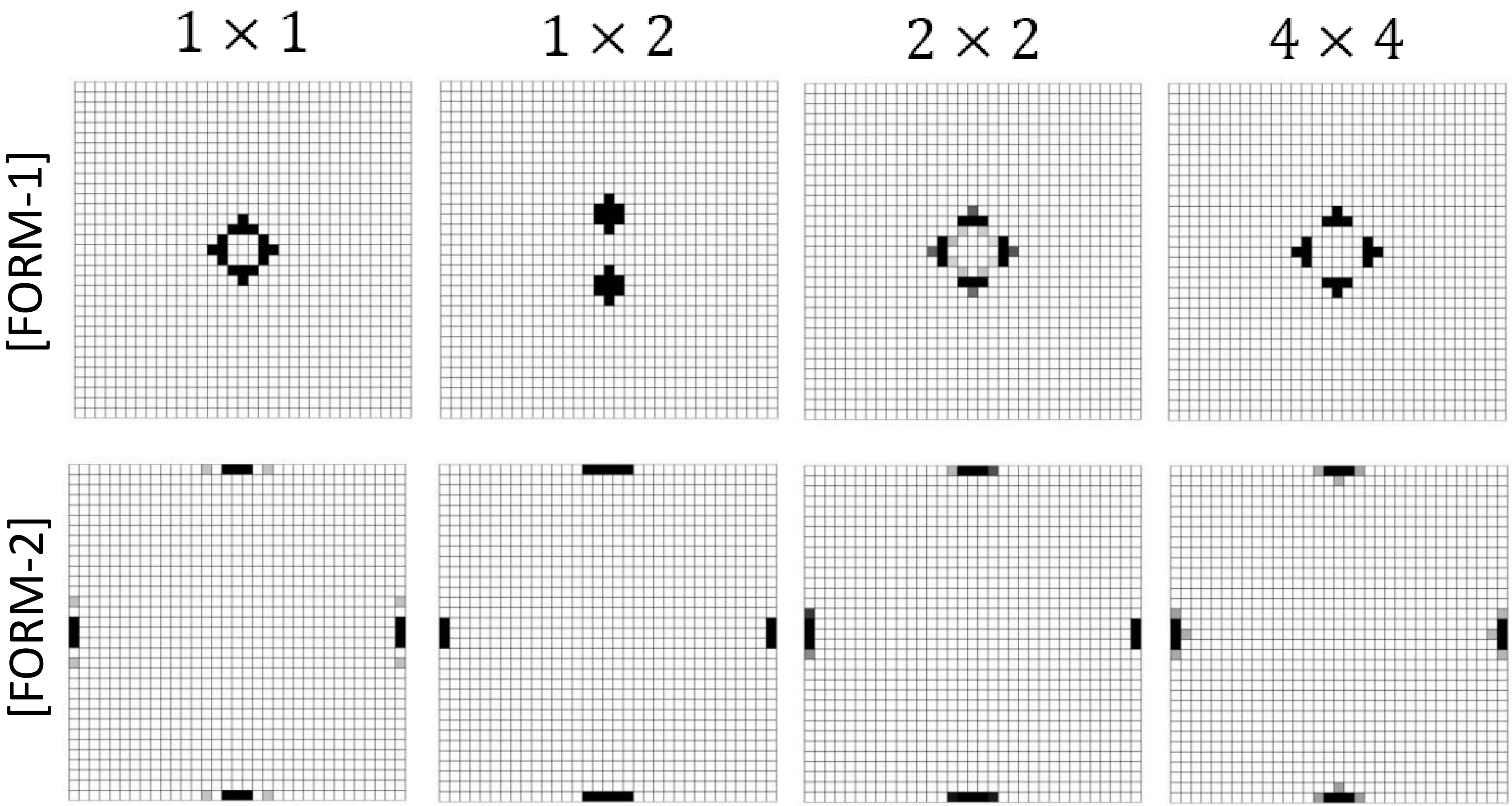




Square plate: optimal sensor placement – damage anywhere at the macroscale simply supported plate

$$\theta = \sqrt{\theta_x^2 + \theta_y^2} \qquad \bar{N} = 16$$

damaged area



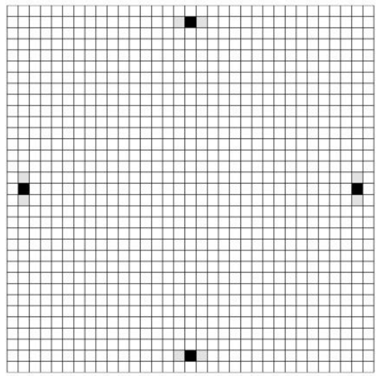
Square plate: optimal sensor placement – damage anywhere at the macroscale clamped plate

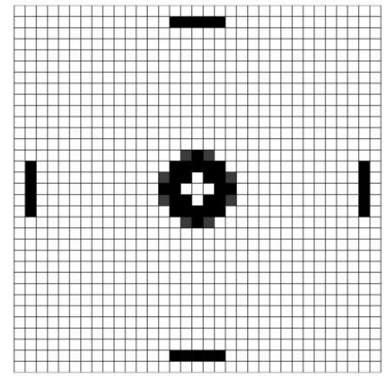
$$\theta = \sqrt{\theta_x^2 + \theta_y^2}$$

$\bar{N} = 5$

$\bar{N} = 50$

[FORM-1]

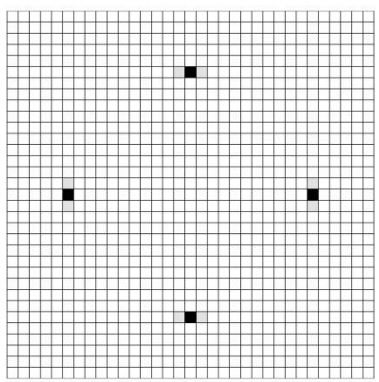


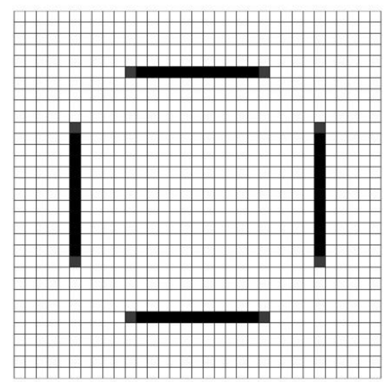


$\bar{N} = 5$

$\bar{N} = 50$

[FORM-2]





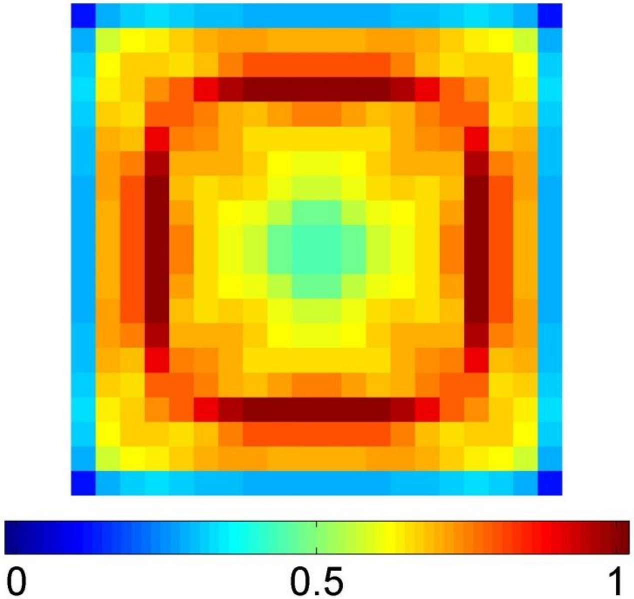
Square plate: optimal sensor placement – damage anywhere clamped plate, distributed load

$$\theta = \sqrt{\theta_x^2 + \theta_y^2}$$

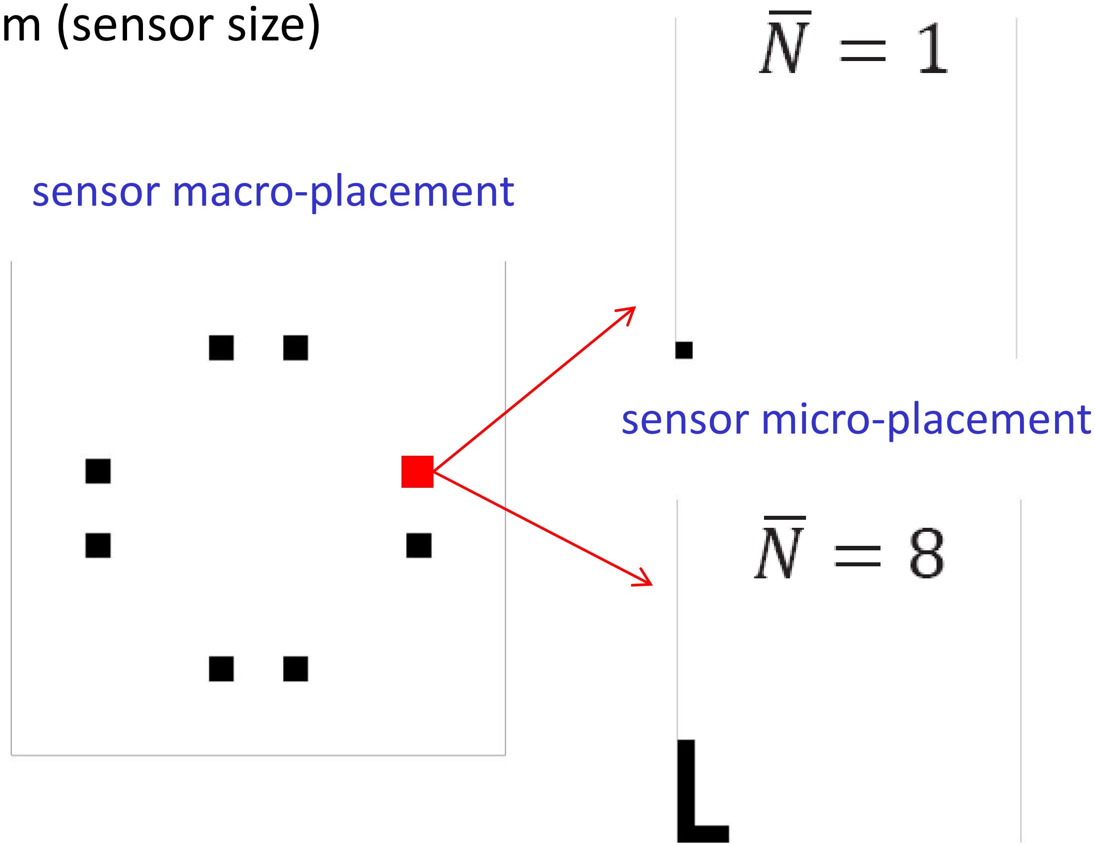
[FORM-2], $\overline{N} = 8$

Multi-scale analysis: *L*=1 m (side length, or structural size)
s=5 cm (element, or damaged area size)
l=2.5 mm (sensor size)

objective function



sensor macro-placement



Square plate: optimal sensor placement – damage anywhere clamped plate, concentrated load

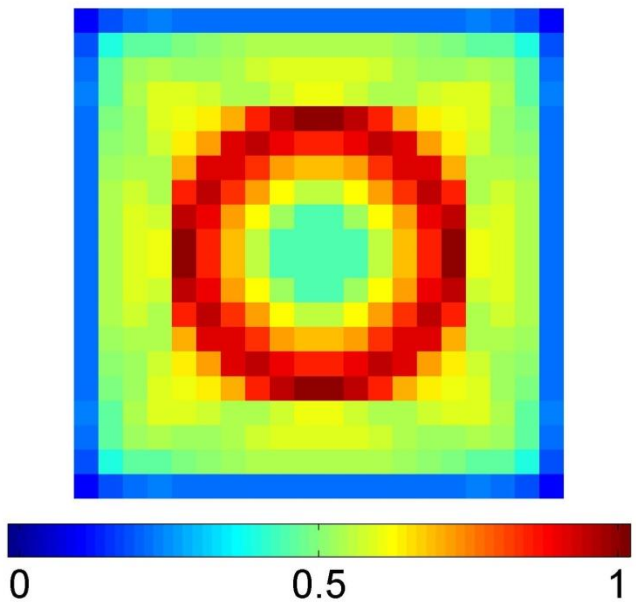
$$\theta = \sqrt{\theta_x^2 + \theta_y^2}$$

[FORM-2], $\bar{N} = 8$

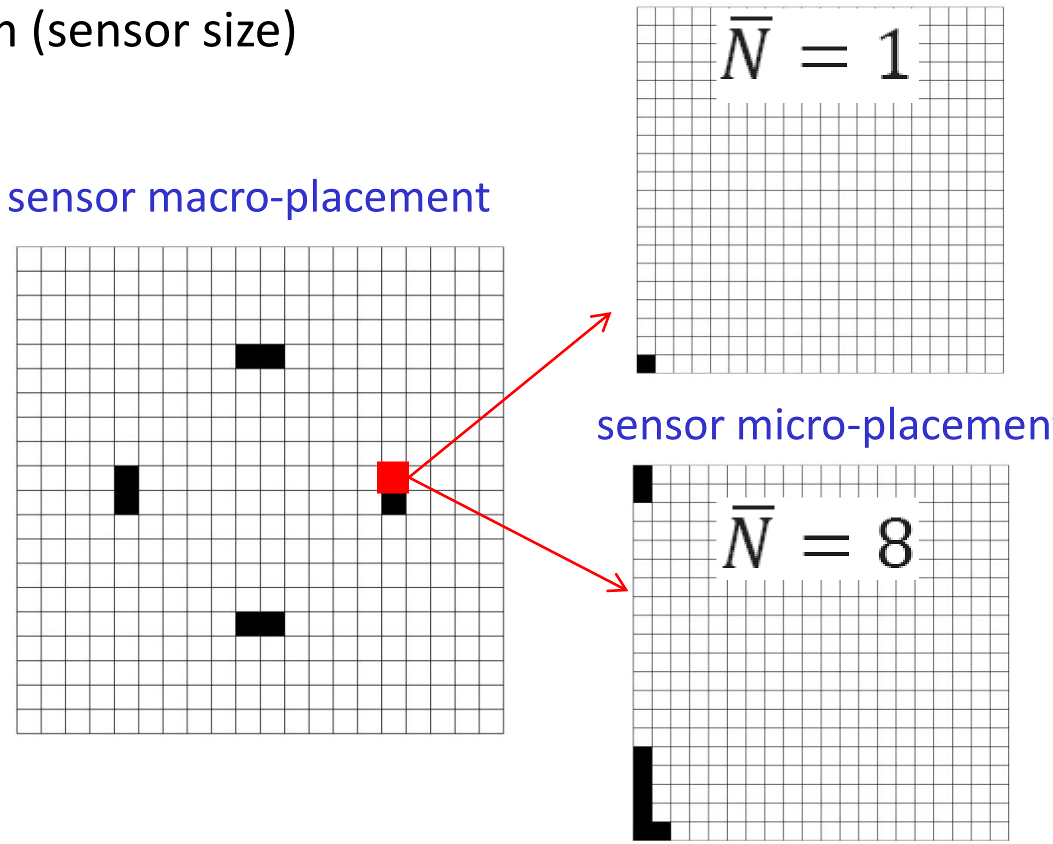
Multi-scale analysis:

L=1 m (side length, or structural size)
s=5 cm (element, or damaged area size)
l=2.5 mm (sensor size)

objective function



sensor macro-placement



Conclusions

- We proposed a MEMS-based SHM system, sensitive to damage (delamination) extent in composite
- We proposed a multi-scale topology optimization-like procedure to deploy MEMS, so as to maximize sensitivity to damage

Ongoing activities and future work

- robustness of the SHM system
- networking of (possibly self-powered) MEMS sensors
- real-time damage detection and identification for flexible (composite) plates
- Application: engineered bike and ski helmets, to understand links between impacts and brain injuries

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