POLITECNICO DI MILANO

Towards the development of a MEMS-based health monitoring system for lightweight structures

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Introduction and motivation

MEMS accelerometers for structural health monitoring (SHM): why?

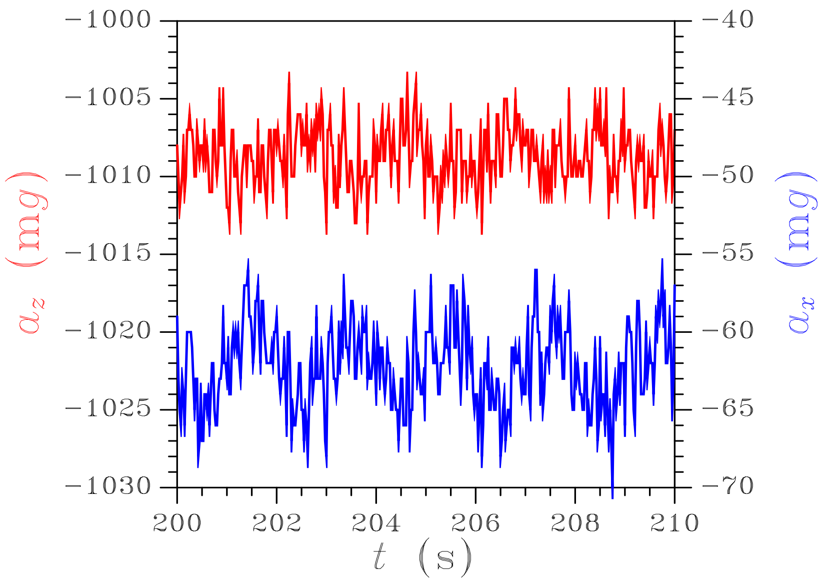
PROS

- lightweight (0.2 g) → no impact on dynamics
- low power consumption
- cheap (0.50$ each!) → deploy in large numbers

→use redundancy to increase the quality of information

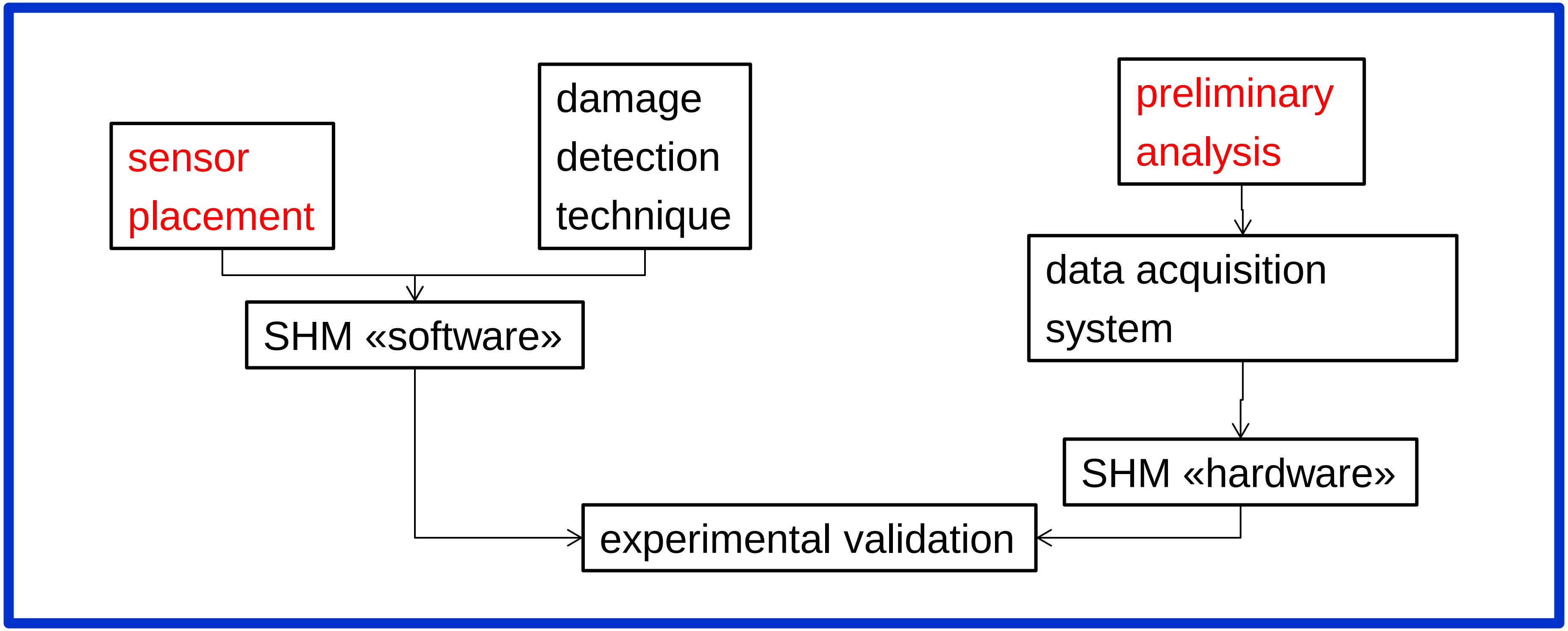
CONS

- noisy signals, low precision



Outline of the reasearch project

Aim: a **SHM system** using MEMS



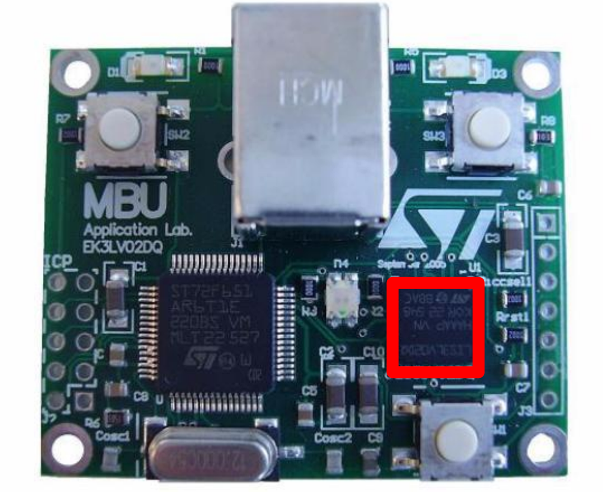
Focus of the presentation

- assessment of MEMS applicability
- sensor placement strategy

Sensor

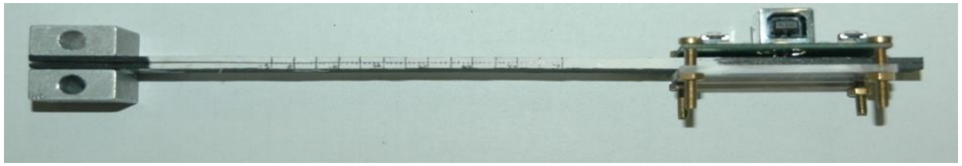
Features of 3-axis, digital output **MEMS** (micro electro-mechanical sensor) accelerometer **LIS3LV02DQ** (STMicroeletronics):

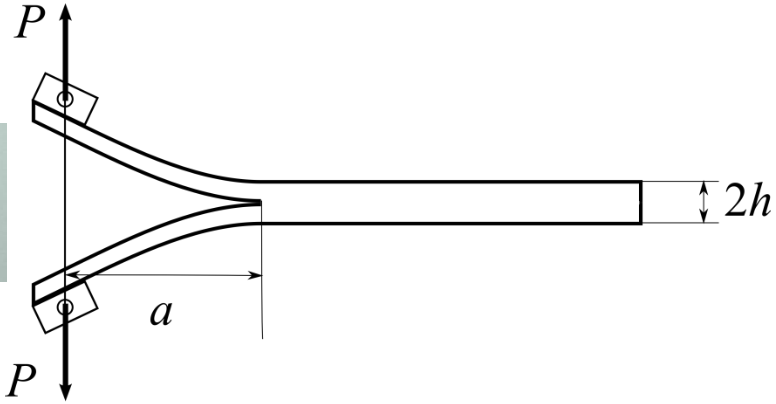
- full scale $\pm 2g$
- bandwidth 640 Hz
- sensitivity 1,000 LSb(Least_Significant_bit)/g
- resolution 1 mg
- weight 0.2 grams
- side: ~5 mm

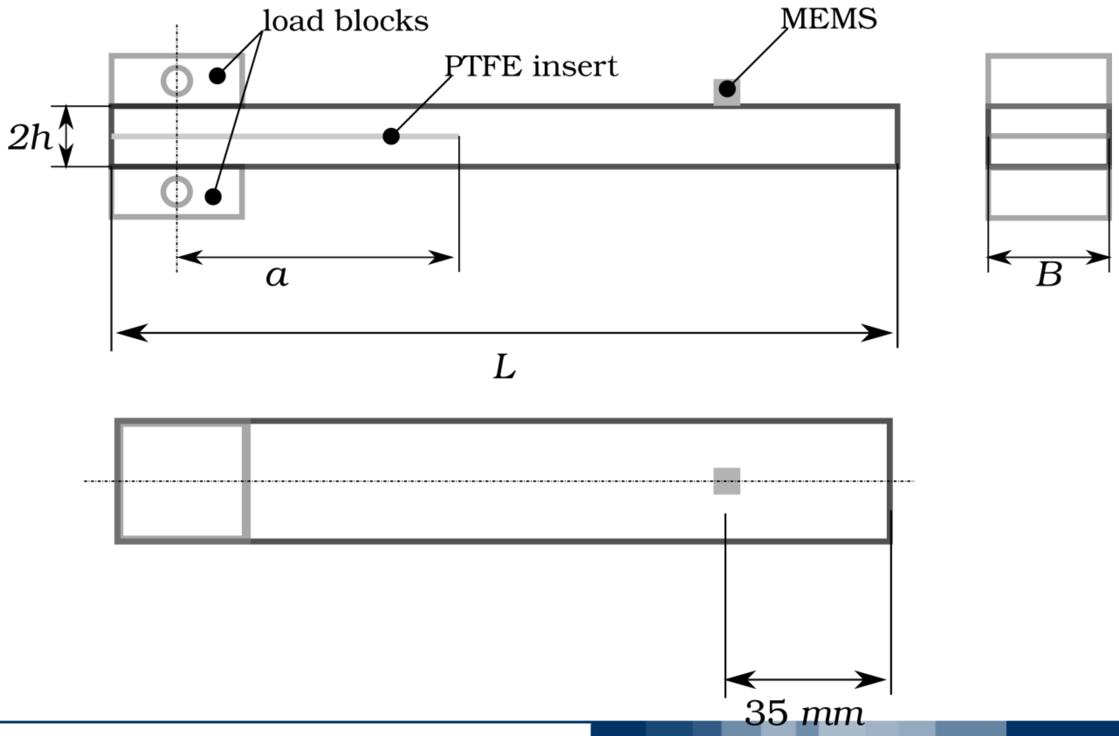


Preliminary analisys: test specimens

Standard DCB …

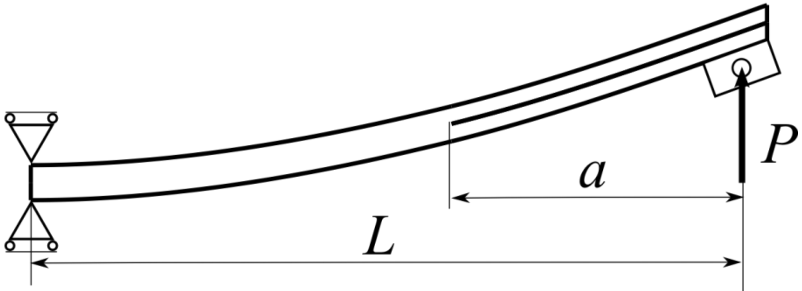


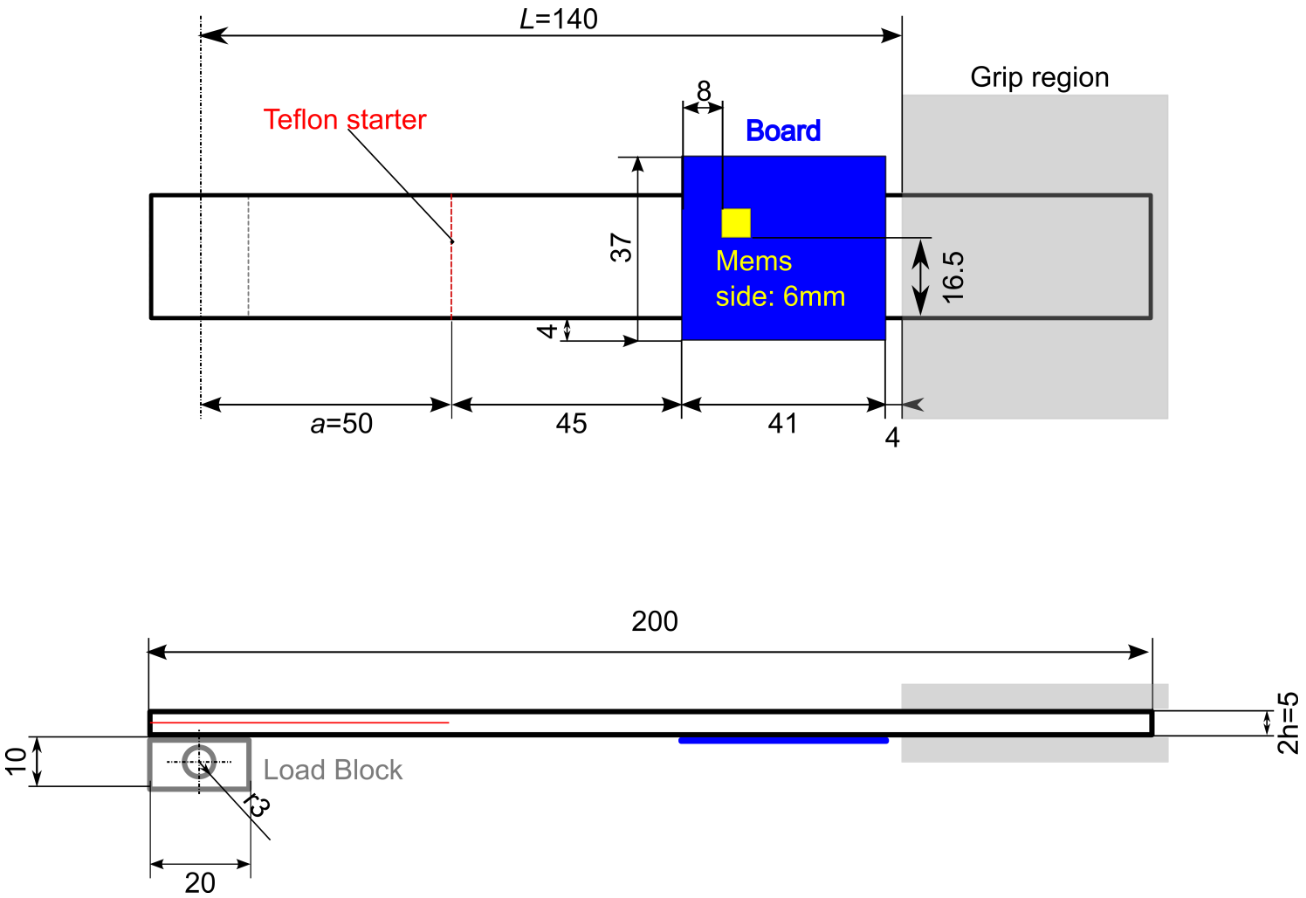




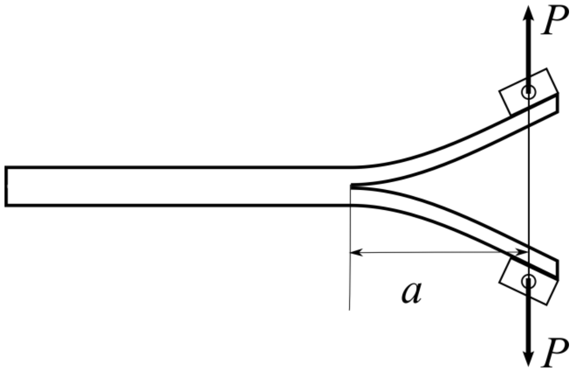
Preliminary analisys: test specimens

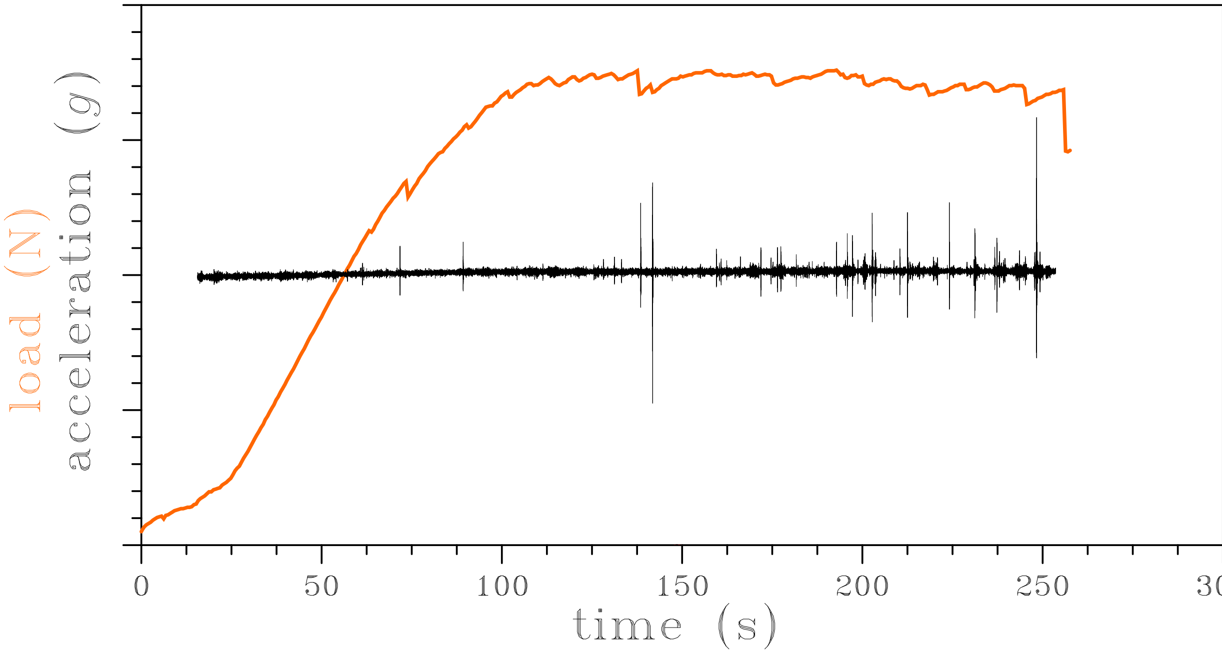
…and ELS test specimens





Test #1: DCB test under continuously increasing displacement



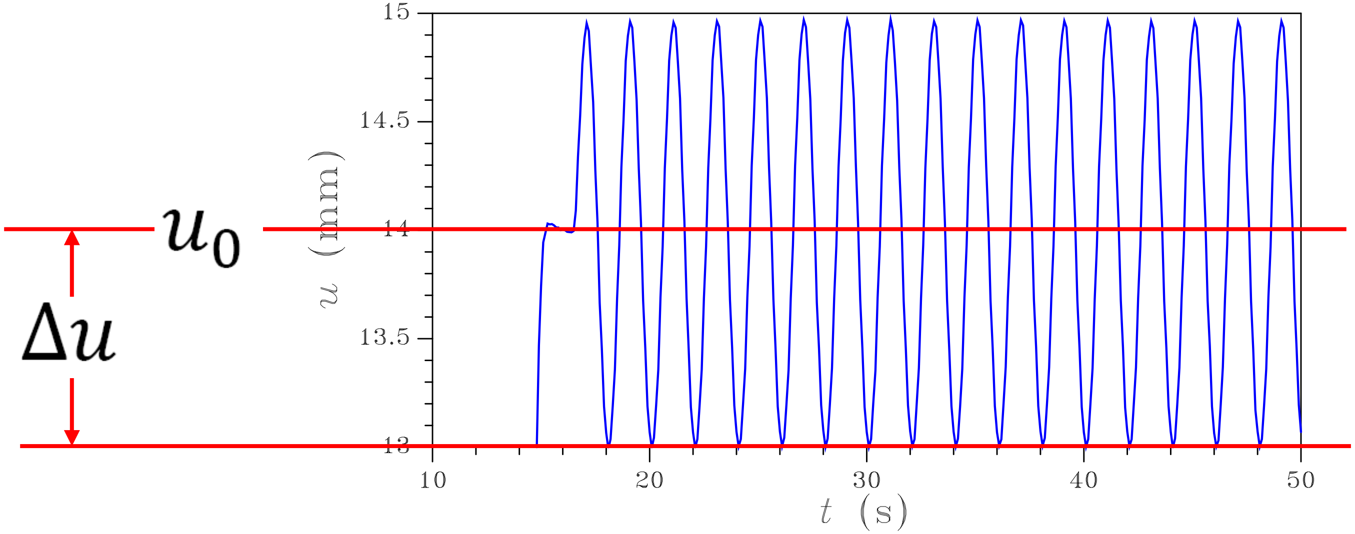


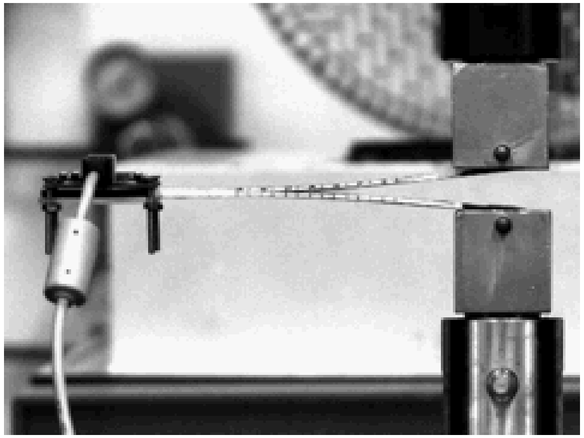
Fair correlation between load drops and acceleration peaks

test #2: tests under cyclic loading

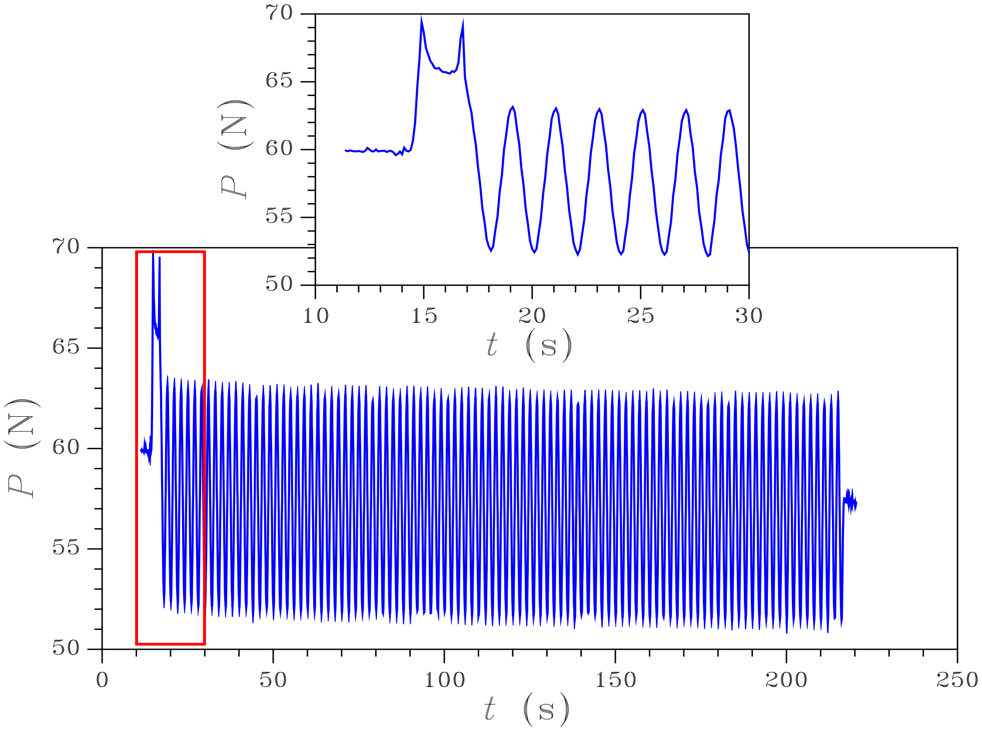
Input: Sinusoidal displacement u

(at increasing u_0, $\Delta u = 2.5$ mm, frequency = 0.5 Hz, 200 cycles)

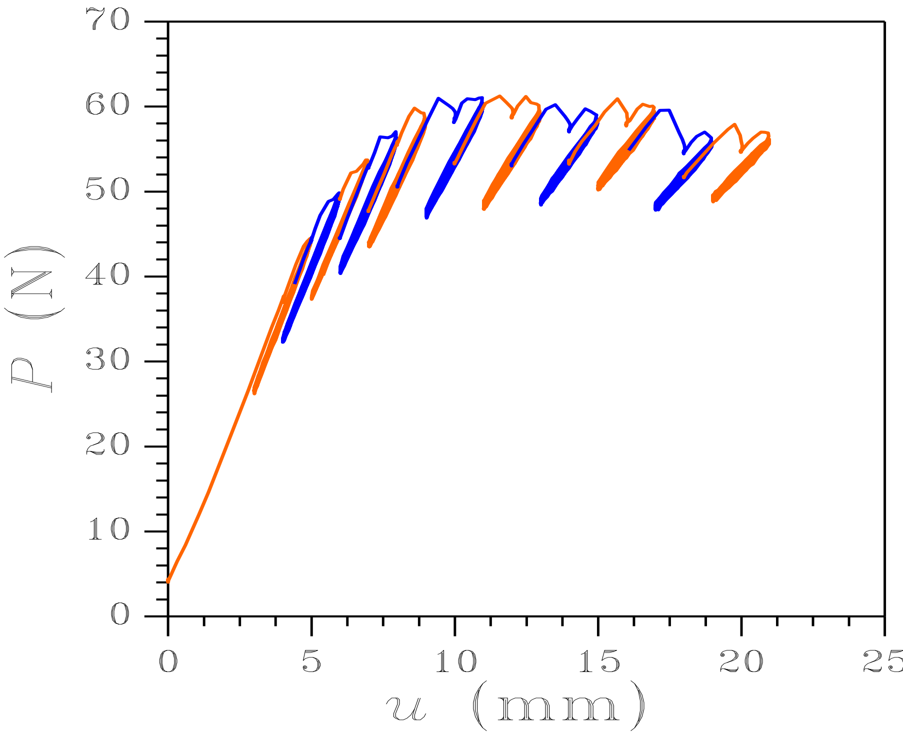




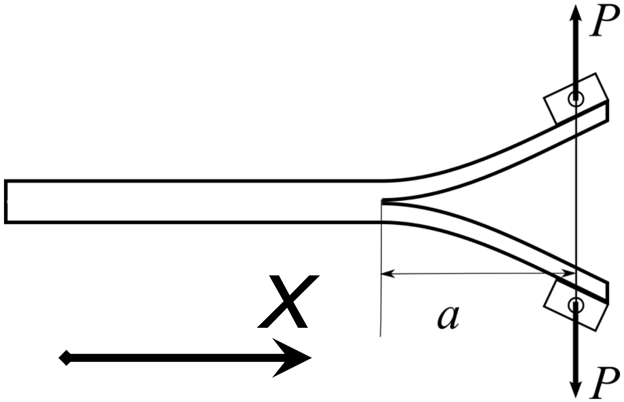
test #2: load output

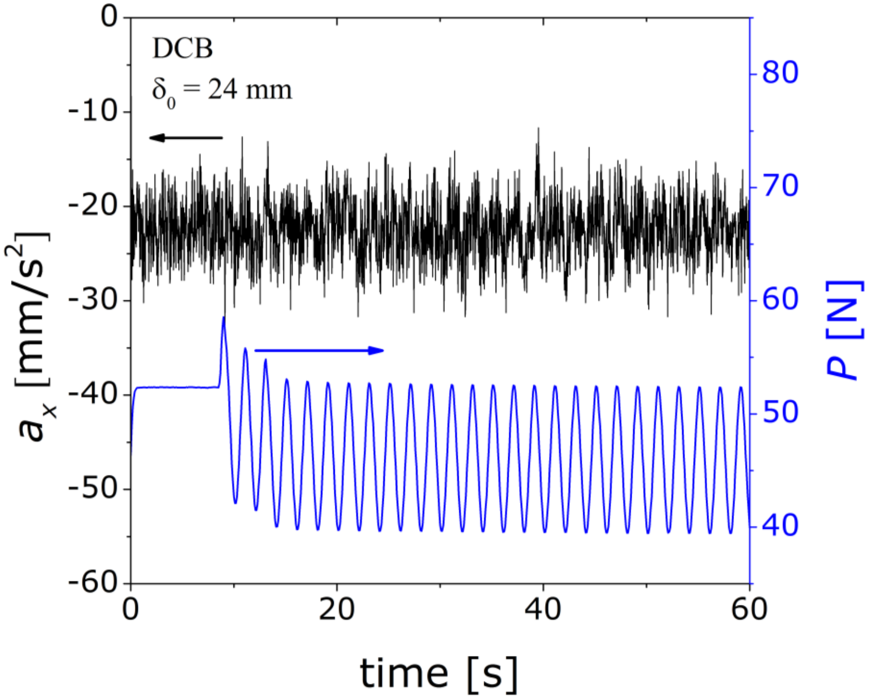


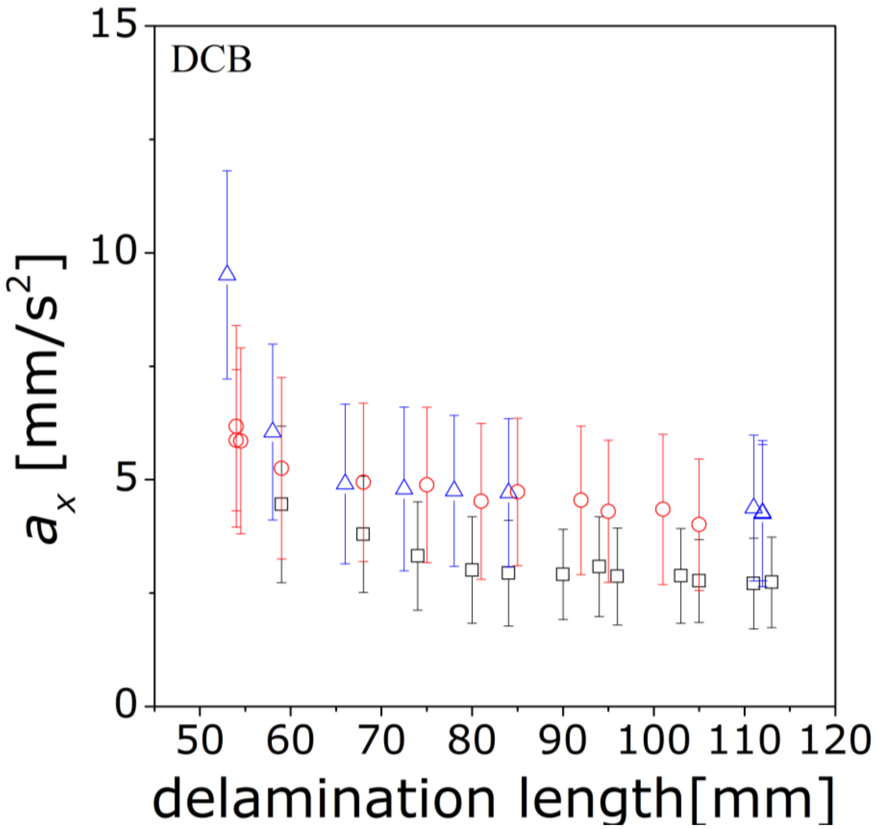
Load *P* suffers drops because of delamination growth at the beginning of load steps



test #2: DCB acceleration output



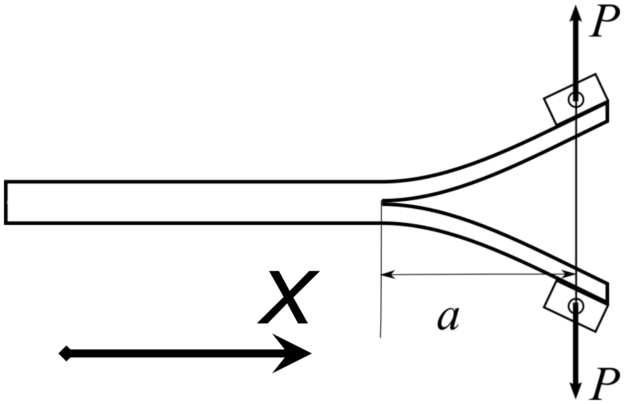


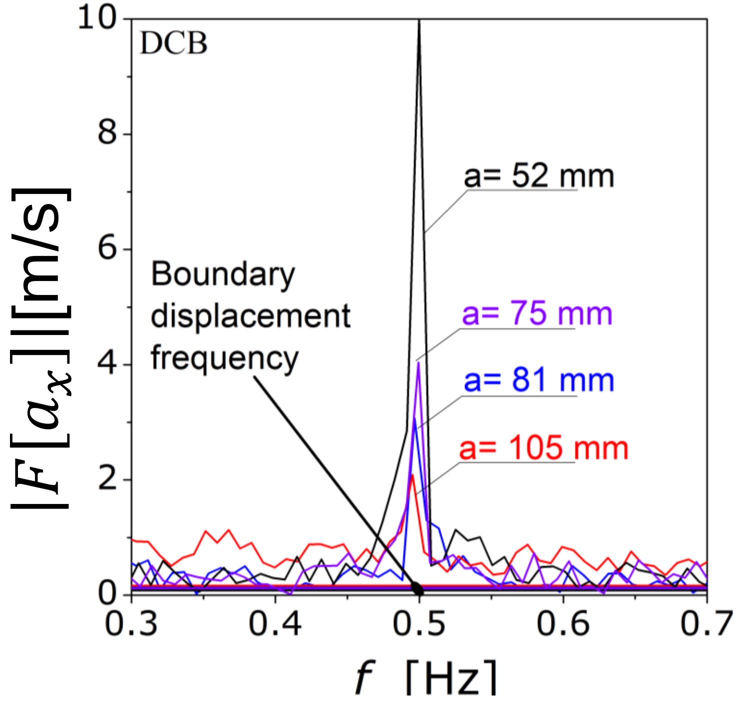


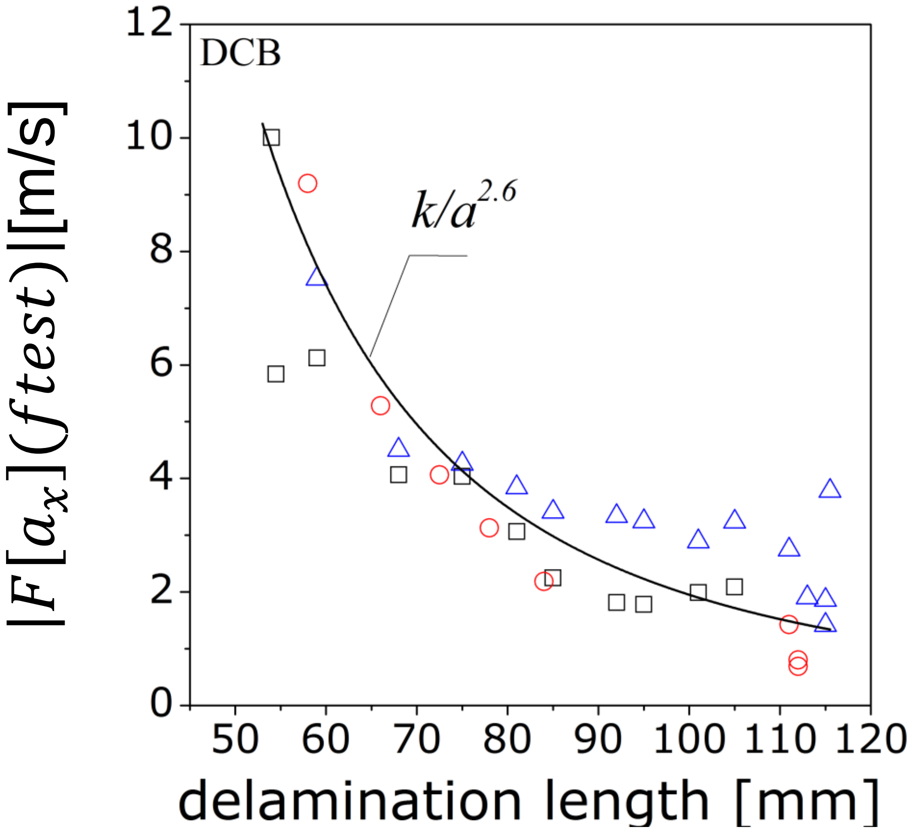
the acceleration, a_x, is too noisy to reliably determine the crack length

test 2#: simple sensing system for DCB specimens

but taking the Fourier transform $F[a_x]$ of the signal

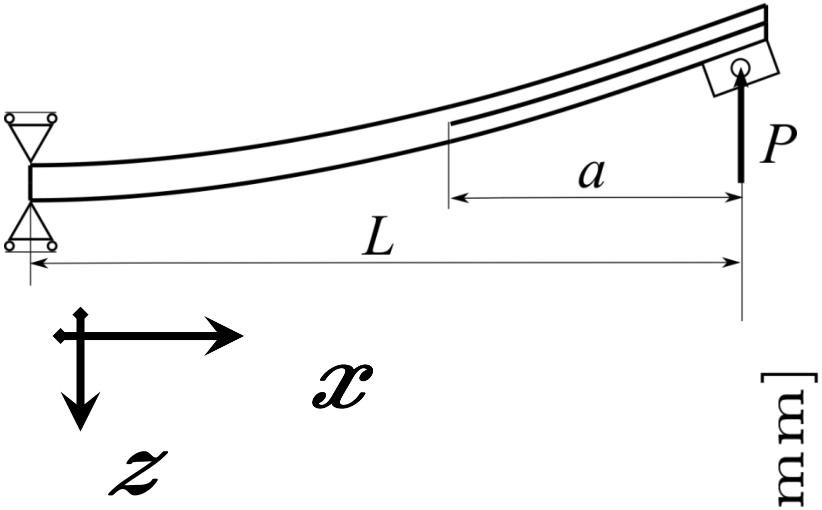




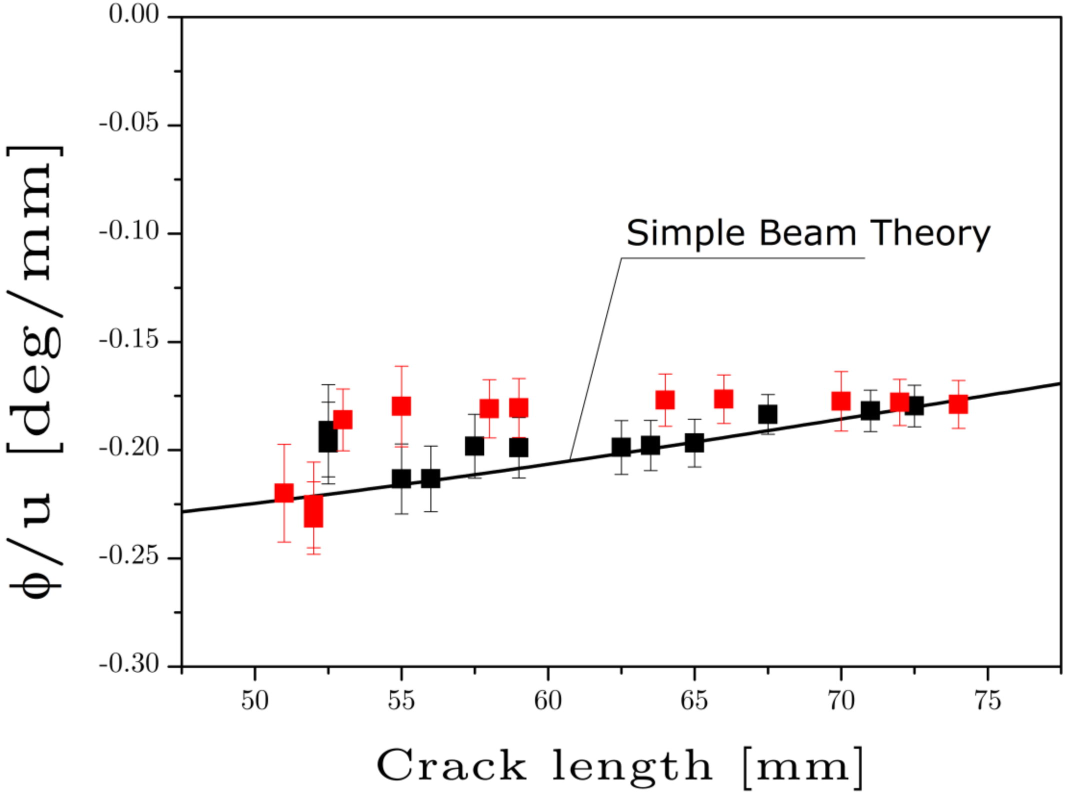


test 2#: simple sensing system for ELS specimens

ELS: mean rotation

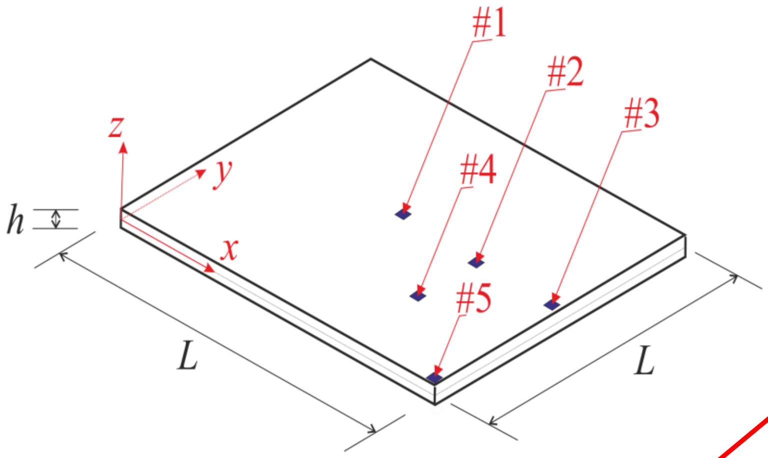


$$\phi = \frac{du}{dx} \simeq \text{atan}\frac{a_x}{a_z}$$



Optimal sensor placement

- **Topology approach**: define a density distribution $\boldsymbol{x}$ representing sensor position and optimize it in order to make damage detection easier
- **Finite elements (FE)** for structural analysis (plates)
- **Method of moving asymptotes (MMA)** for optimization



undamaged plate solution

damaged plate solution

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

penalization term to approach pure 0-1 distributions

number of possible sensor locations (FE)

max allowed number of sensors

Objective functions for an arbitrary number of damaged regions

number of damaged areas

In case of a **multiple damaged regions** (and/or unknown position),

to maximize the sensitivity to the magnitude of the effects of damage [FORM-1]:

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

or, to maximize the sensitivity to

damage [FORM-2]:

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

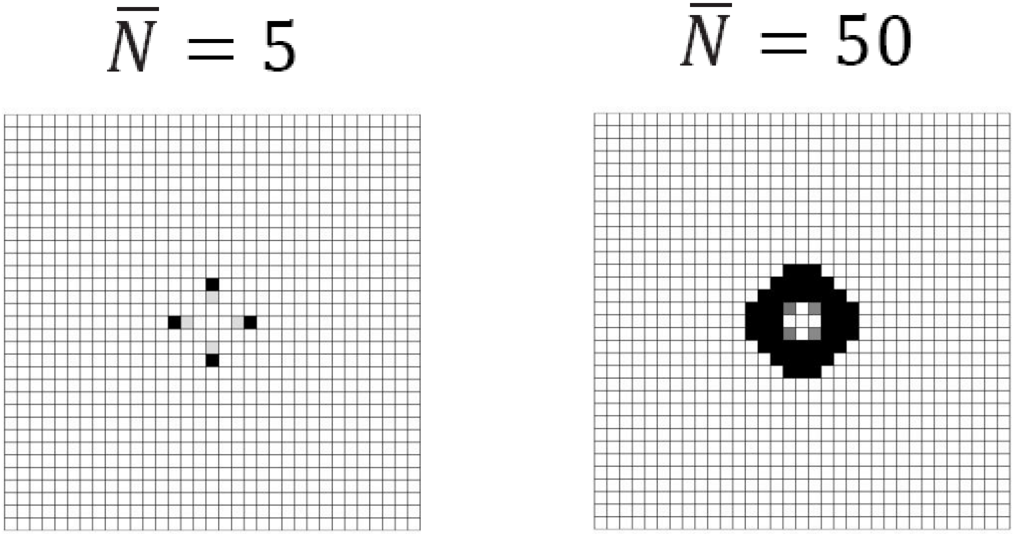
displacement variable:

$$u_{ki} = \sqrt{{\phi_{x,ki}}^2 + {\phi_{y,ki}}^2}$$

Simply supported plate, distributed load

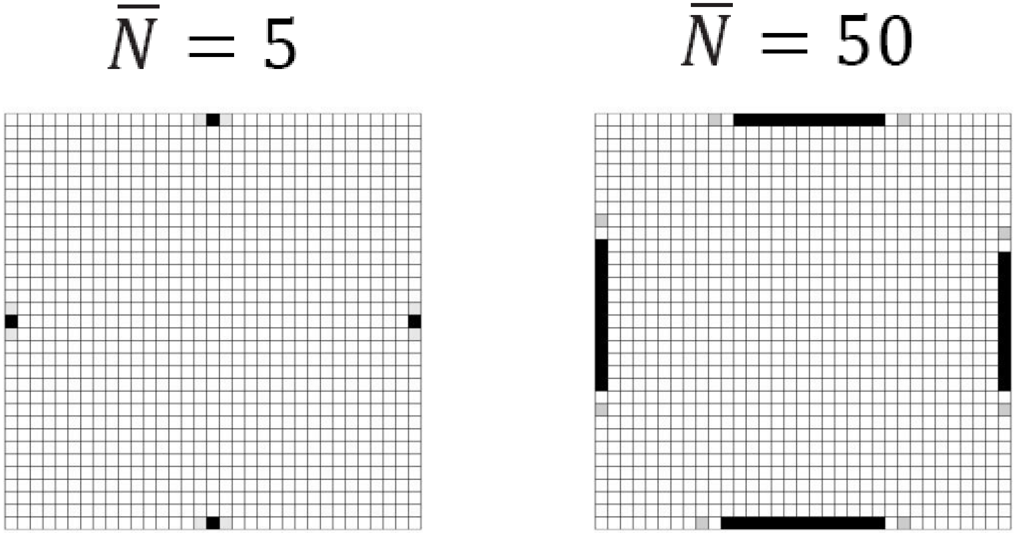
damage can be anywhere, known size (1 FE)

[FORM-1]



$\bar{N} = 5$ $\bar{N} = 50$

[FORM-2]

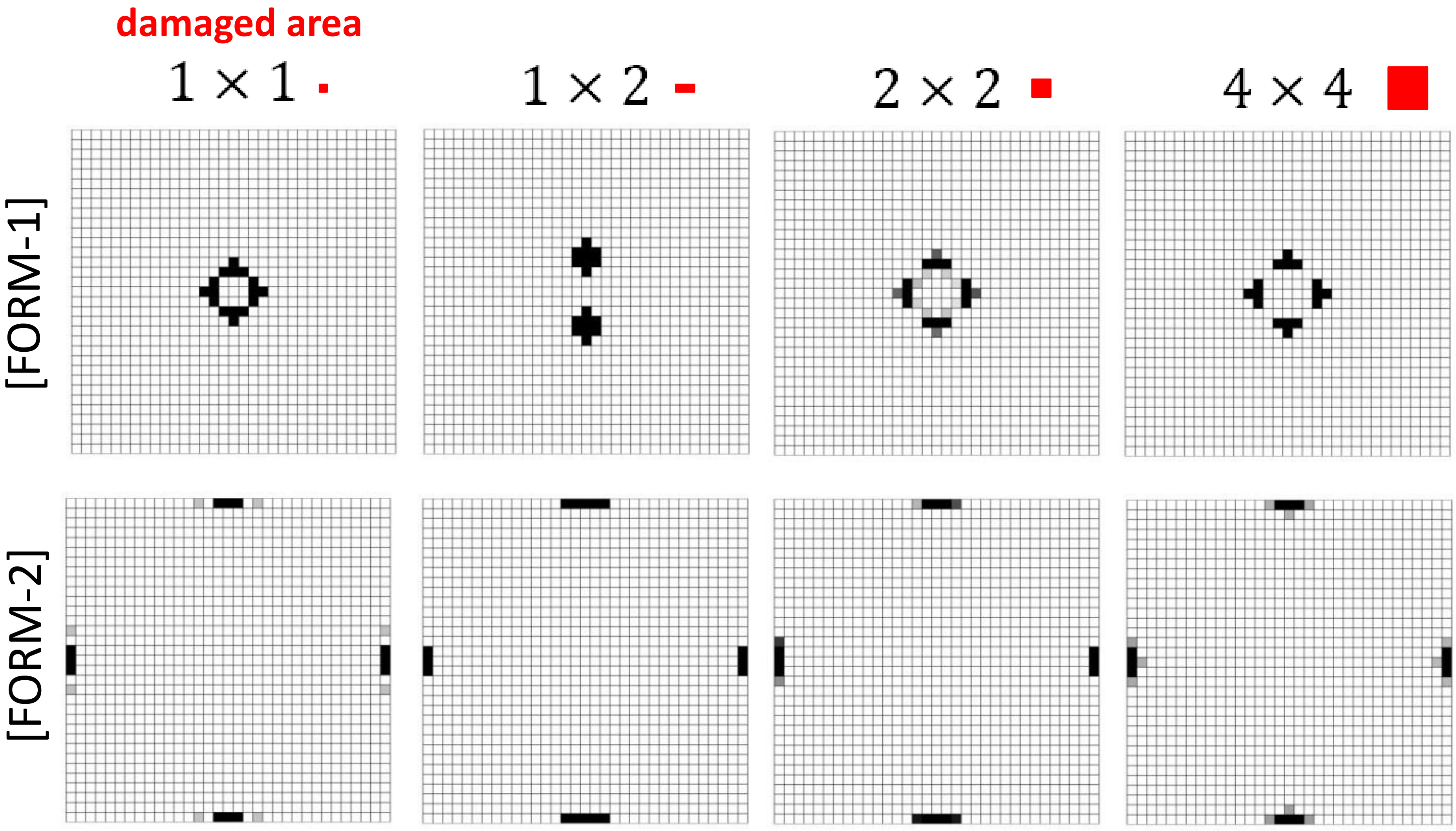


$\bar{N} = 5$ $\bar{N} = 50$

(Mariani et al., JIMSS 2013;24:1105)

effect of damage area

simply supported plate, distributed load



Multi scale approach

clamped plate, concentrated load, [FORM-2],

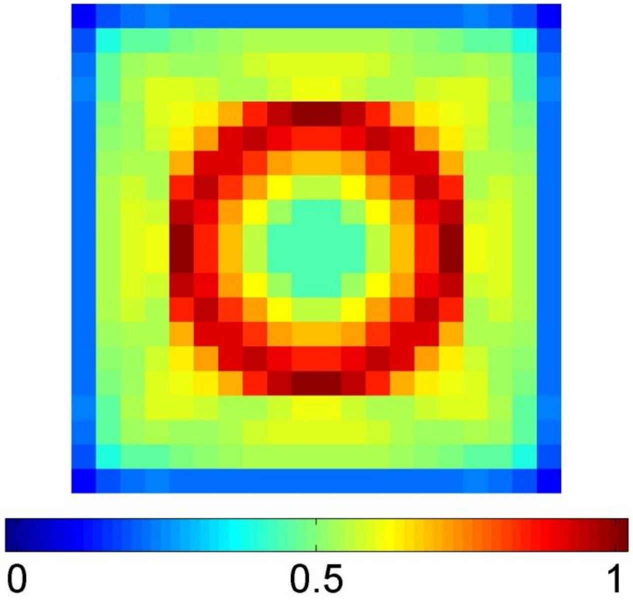
Multi-scale analysis:

L=1 m (side length, or structural size)

s=5 cm (element, or damaged area size)

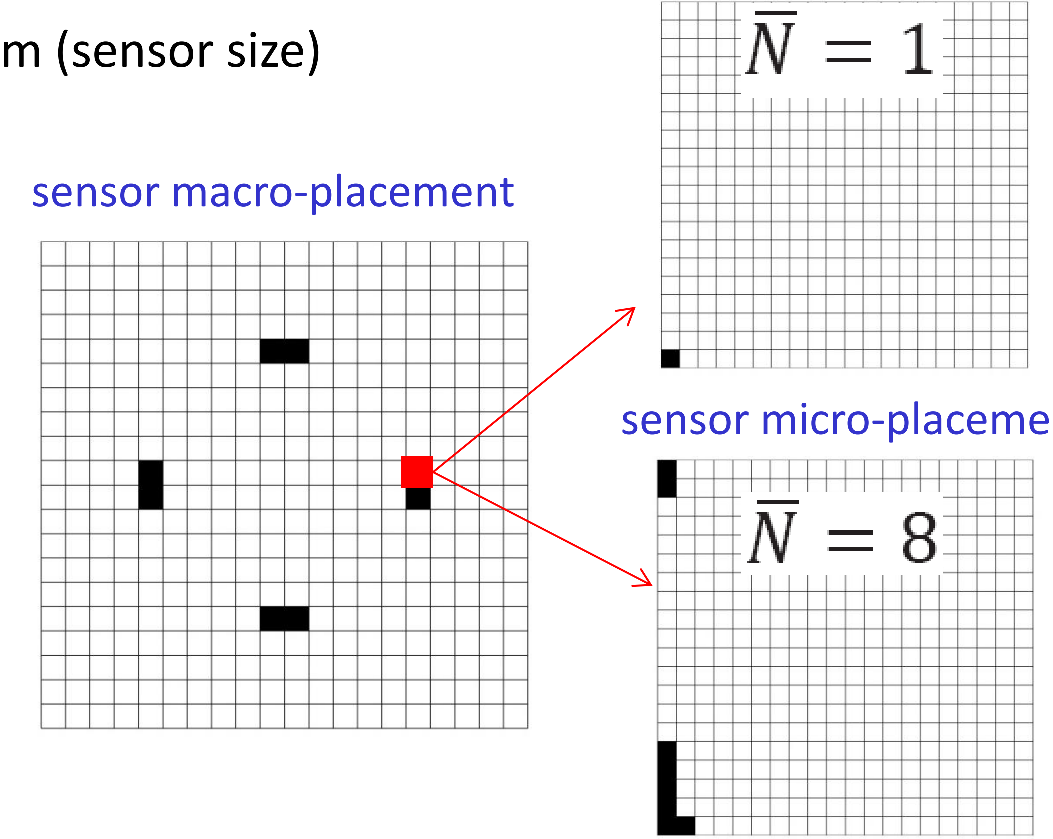
l=2.5 mm (sensor size)

objective function



sensor macro-placement

sensor micro-placement



In conclusion…

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

Ongoing activities and future work

- real-time damage detection and identification for flexible (composite) plates
- minimization of $\overline{N}$
- Application: engineered bike and ski helmets (to understand links between impacts and brain injuries)

Acknowledgments

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