Application of Horizon HZ 100-100 Rotation Rate Sensors in Structural Damage Detection

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Presentation outline

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Introduction

Introduction

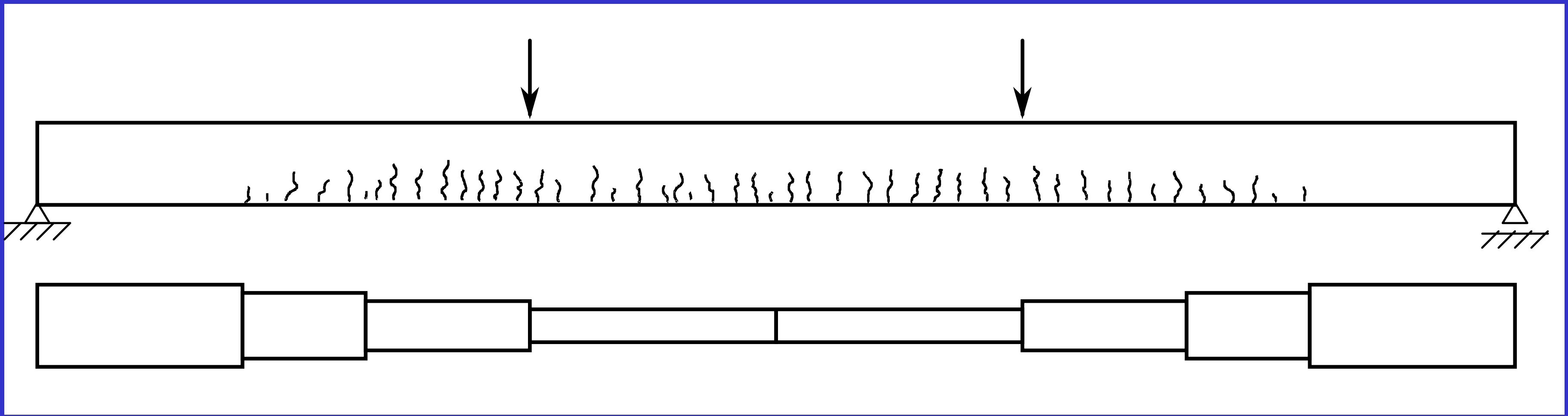
The use of translational vs. rotational sensors

- In seismology and seismic engineering
- In vibration based structural health monitoring usually translational degrees of freedom have been used to measure translational accelerations or displacements. However, recent advances in rotational sensors and their wider availability, inspired us to check their applicability and effectiveness in the field of damage detection,

Introduction

Reinforced concrete beam in bending

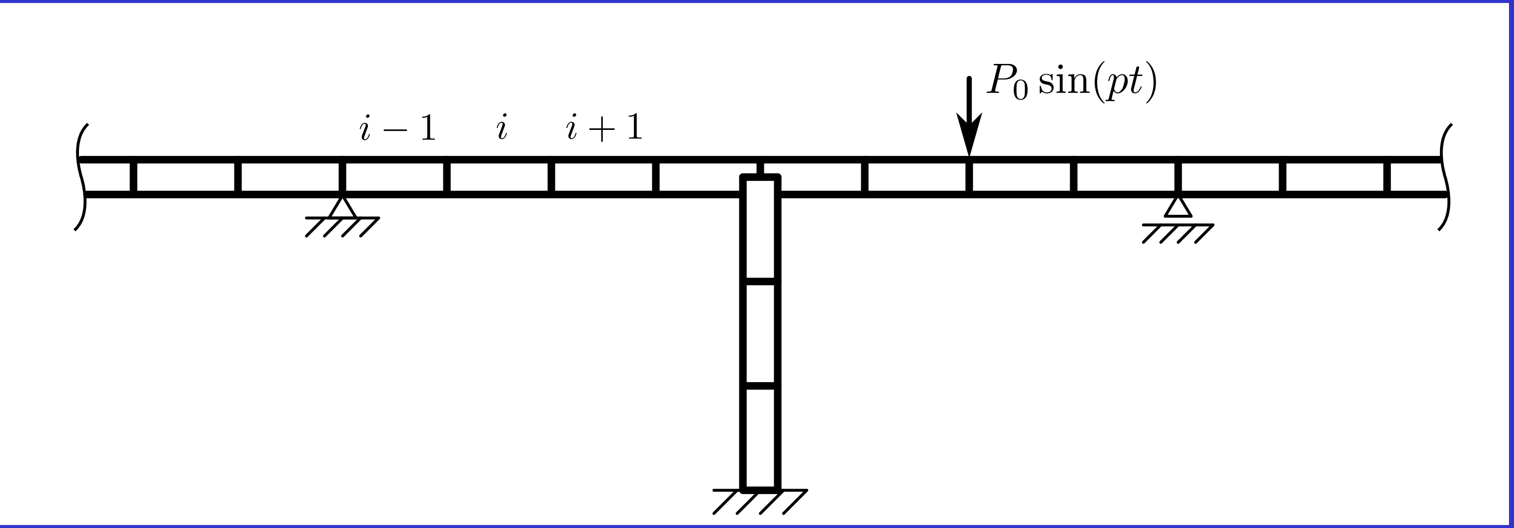
- Reinforced concrete structures exhibit decrease in stiffness mainly due to cracking and since dynamic response and dynamic characteristics of structures depend on structural stiffness, we can monitor response and try to infer about the state of the structure.
- However how to measure such bending ?
  How to monitor non-localised damage? How to "reconstruct" changes in the stiness distributions over wide length?



- Perhaps one can use **rotation rate sensors** in measuring bending of these structures?

Method description

Consider a frame structure under harmonic force, divided into finite elements



Equation of motion of a structure in a damaged state

$$\boldsymbol{M}^d\ddot{\boldsymbol{q}} + \boldsymbol{C}^d\dot{\boldsymbol{q}} + \boldsymbol{K}^d\boldsymbol{q} = \boldsymbol{P}_0 e^{ipt}, \tag{1}$$

Reconstruction of stiffness distribution using harmonic vibrations

If the harmonic vibrations are outside resonance zones then we can neglect damping and Eq. (1) simplifies to

$$\boldsymbol{M}^d\ddot{\boldsymbol{q}} + \boldsymbol{K}^d\boldsymbol{q} = \boldsymbol{P}_0 e^{ipt}, \tag{2}$$

Since the solution (response) is also harmonic $\boldsymbol{q} = \boldsymbol{u}e^{ipt}$ where $\boldsymbol{u}$ is a vector of displacement amplitudes then we get the quasi-static equation

$$(\boldsymbol{K}^d - p^2\boldsymbol{M})\boldsymbol{u} = \boldsymbol{P}_0, \tag{3}$$

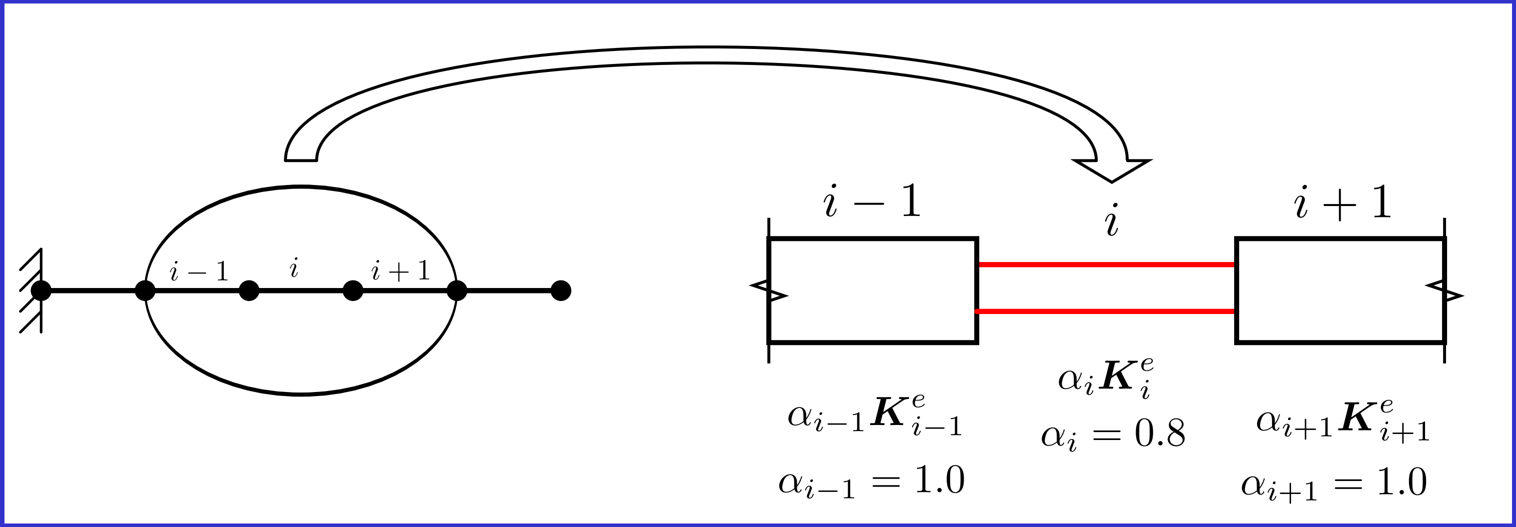
from which we can obtain calculated vector of displacement amplitudes based on $\boldsymbol{K}$, $\boldsymbol{M}$, p, $\boldsymbol{P}_0$.

Stiffness and mass reduction factors

Dimensionless multipliers $\alpha_i \in (0, 1)$ and $\beta_i \in (0, 1)$ which indicates how a given finite element is damaged.

total damage

intact element



$$\boldsymbol{K}^d = \sum_{i=1}^{n} \boldsymbol{K}_i^{de} = \sum_{i=1}^{n} \alpha_i \boldsymbol{K}_i^{ue}, \quad \boldsymbol{M}^d = \sum_{i=1}^{n} \boldsymbol{M}_i^{de} = \sum_{i=1}^{n} \beta_i \boldsymbol{M}_i^{ue} \tag{4}$$

$$\left(\sum_{i=1}^{n} \alpha_i \boldsymbol{K}_i^{ue} - p^2 \sum_{i=1}^{n} \beta_i \boldsymbol{M}_i^{ue} \right) \boldsymbol{u} = \boldsymbol{P}_0 \quad \text{or} \quad \left(\sum_{i=1}^{n} \alpha_i \boldsymbol{K}_i^{ue} - p^2 \boldsymbol{M} \right) \boldsymbol{u} = \boldsymbol{P}_0. \tag{5}$$

Inverse problem as an optimisation problem

The following objective function expresses the sum of relative squares of harmonic response for calculated ($\boldsymbol{u}^c$) and measured ($\boldsymbol{u}^m$) amplitudes.

$$J(\boldsymbol{\alpha}) = \sum_{j=1}^{m} \left(\frac{\boldsymbol{u}^c(\boldsymbol{\alpha}) - \boldsymbol{u}^m}{\boldsymbol{u}^m} \right)^2, \tag{6}$$

where m is the number measured harmonic response amplitudes.

Solution of the optimisation problem

- enumerative method: very expensive. For large scale optimisation problems we need a robust global optimisation algorithm.
- hybrid method:

Global search: Genetic algorithms

$$\Downarrow$$

Local search: Levenberg-Marquardt method

$$\Downarrow$$

$$\boldsymbol{\alpha} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix} \tag{7}$$

Quality of the solution

Weighted Average Error (WAE)

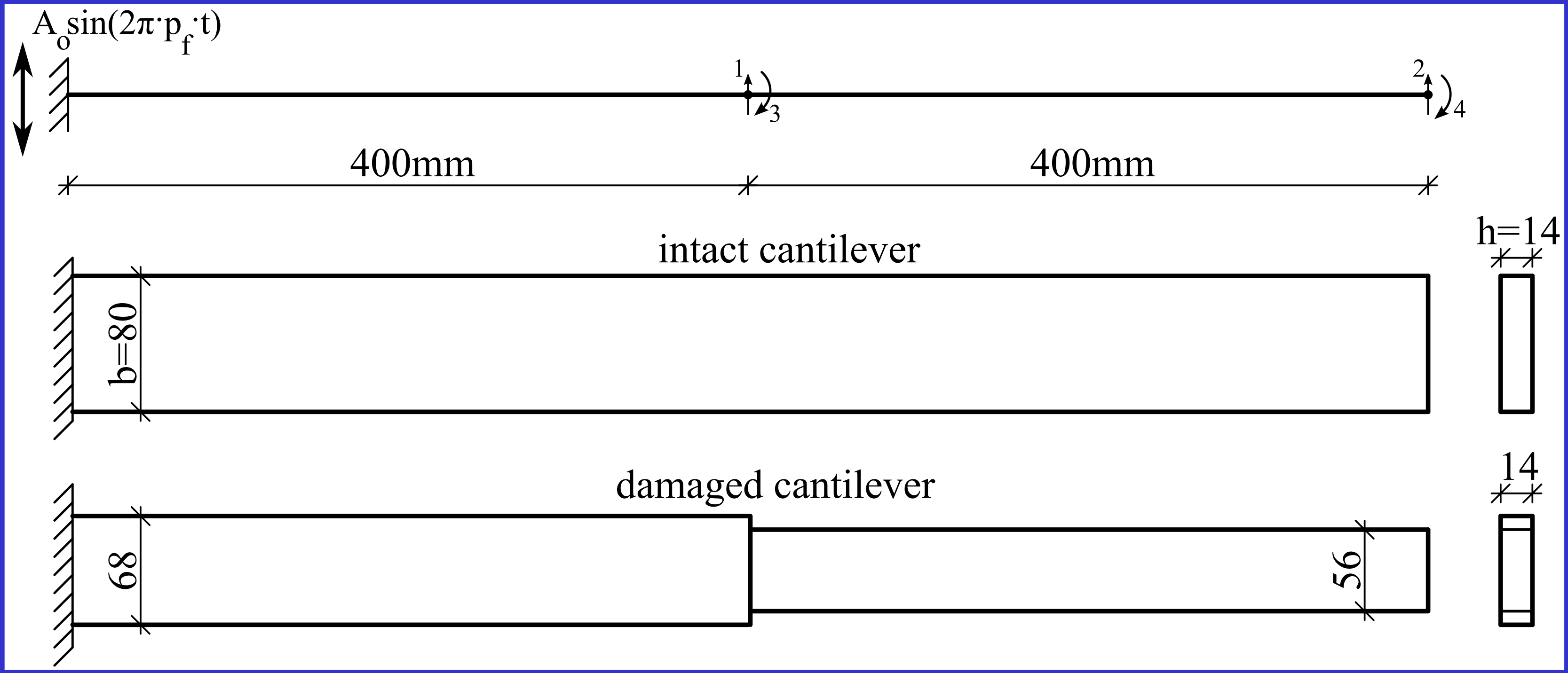
$$WAE = \sqrt{\sum_{i=1}^{n} \left(\frac{\alpha_i^c - \alpha_i^d}{\alpha_i^d} \right)^2} \tag{9}$$

Maximum Error (ME)

$$ME = \max \left\| \frac{\alpha_i^c - \alpha_i^d}{\alpha_i^d} \right\| \tag{10}$$

Experimental set-up

beam with two cross-sectional reductions

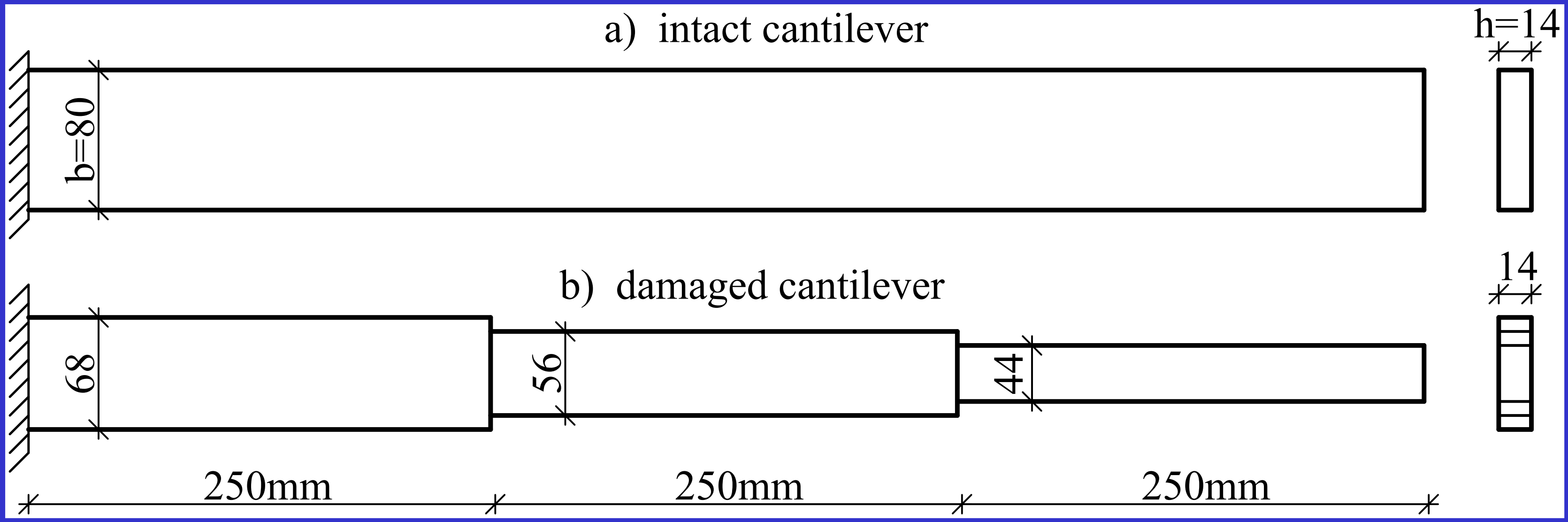


The geometry of the beams in intact and damaged state.

Advantages:

- enumerative method can be used,
- we can observe the surface of the objective function with regard to two stiffness reduction factors (α_1, α_2).

Beams with three cross-sectional reductions

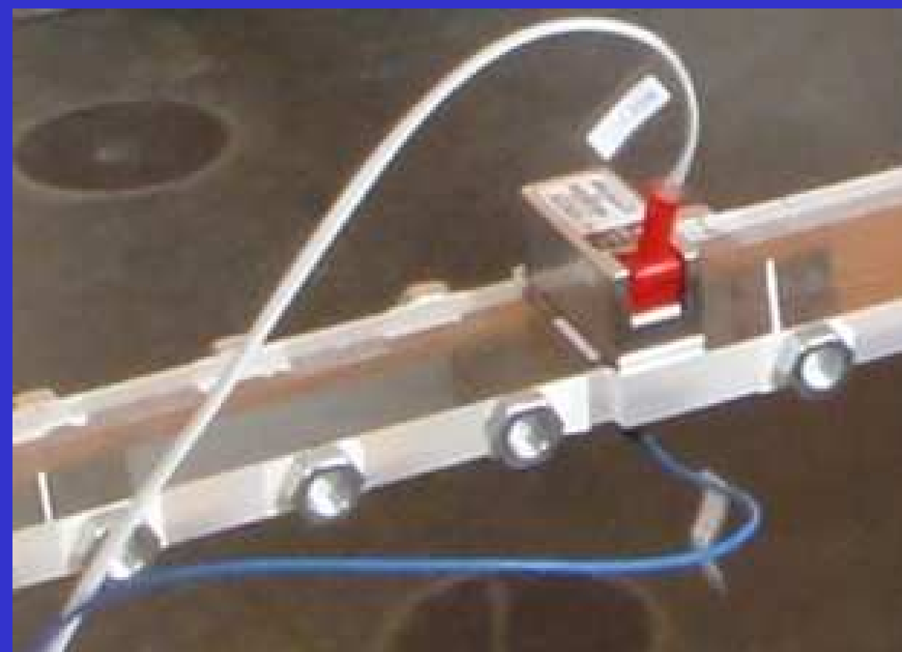


The geometry of the beams in intact and damaged state.

- hybrid optimisation method: genetic algorithms and Levenberg-Marquardt method.

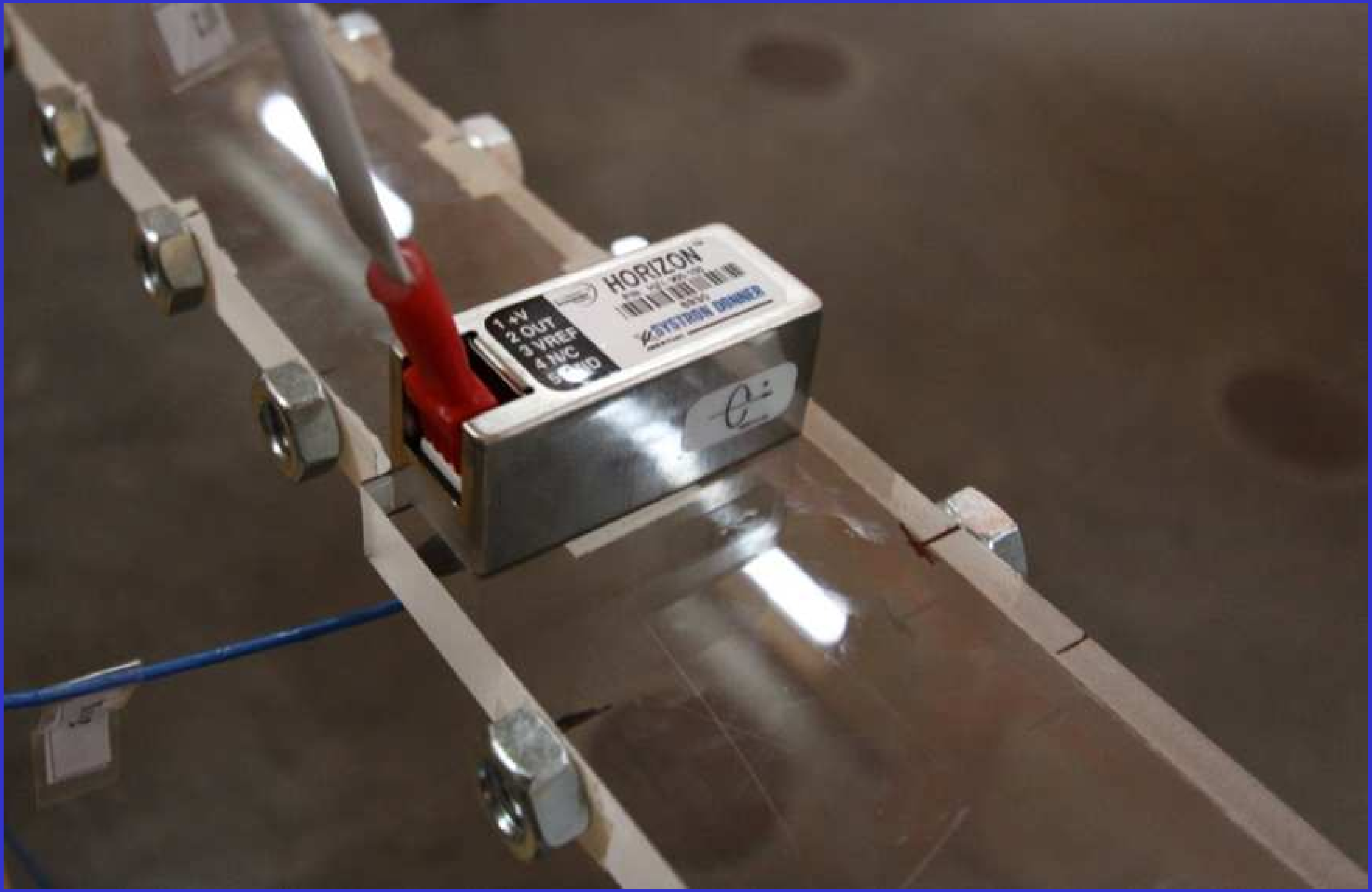
Experimental set-up

Experimental set-up



mass losses
are
compensated

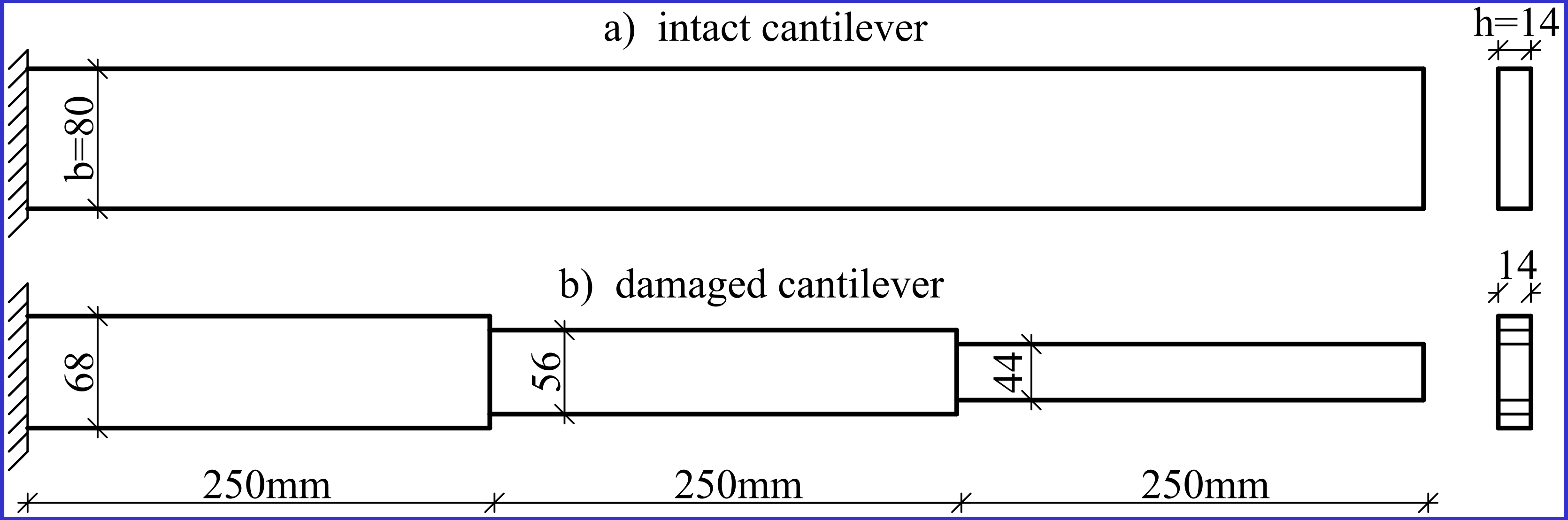
Experimental set-up



- "gyros" Horizon HZ 100-100 of Systron Donner (range: ±100deg/s, sensitivity: 0.06 deg/s) and (below) "translational" accelerometers PCB 333B52,
- nuts compensate for the reduction of mass due to cutting out a fragment of the beam cross-section

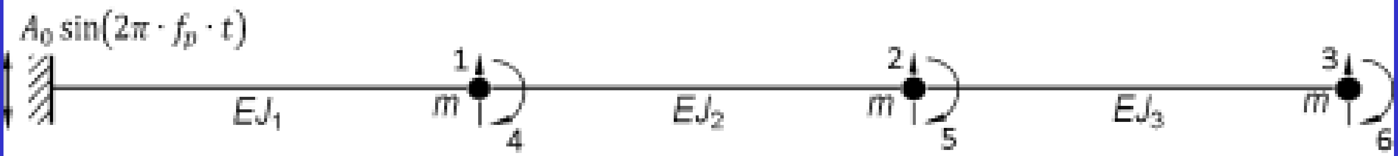
Results

beam with three cross-sectional reductions



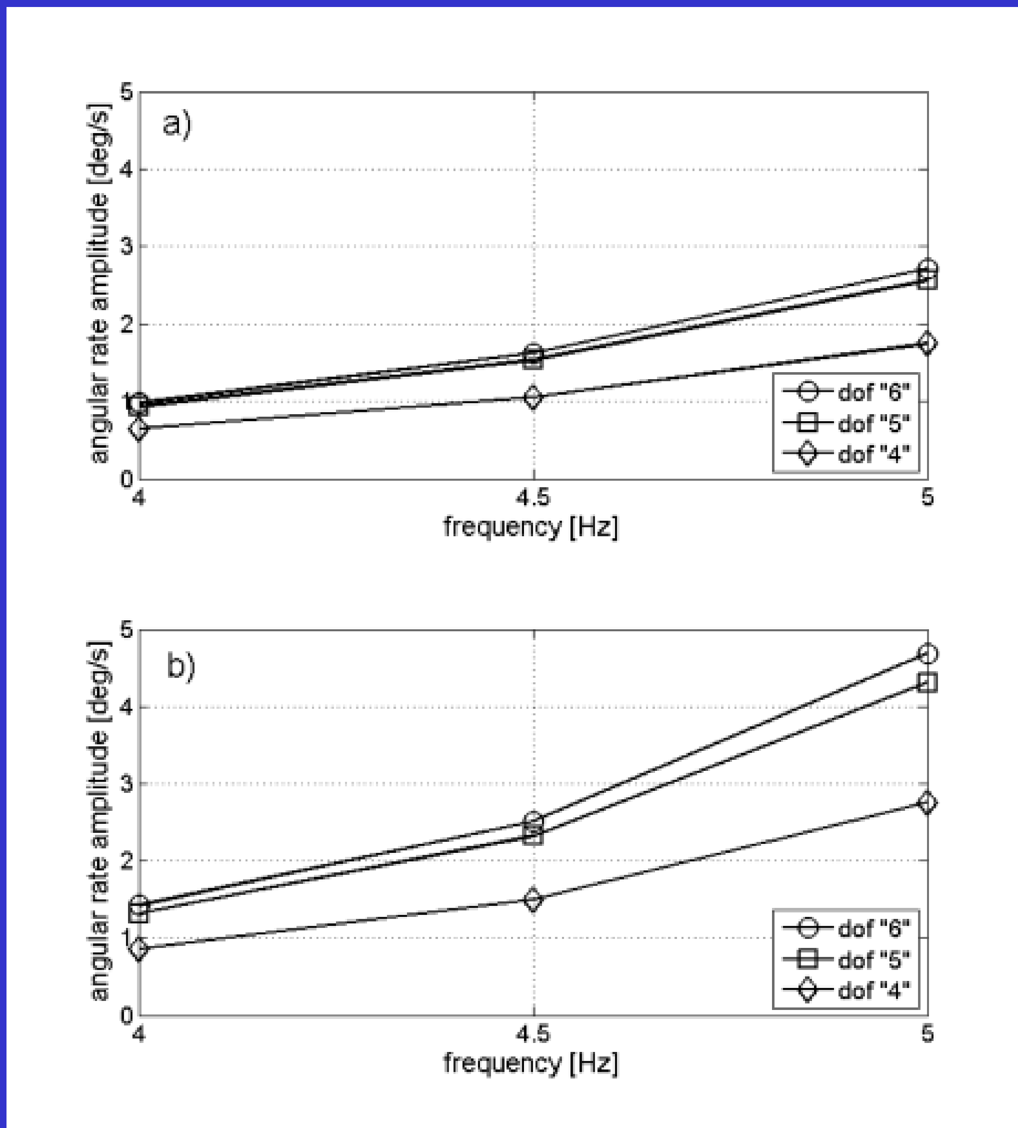
beam with three cross-sectional reductions

- measured amplitudes of vibration for the vibrations @ frequency 4.5Hz



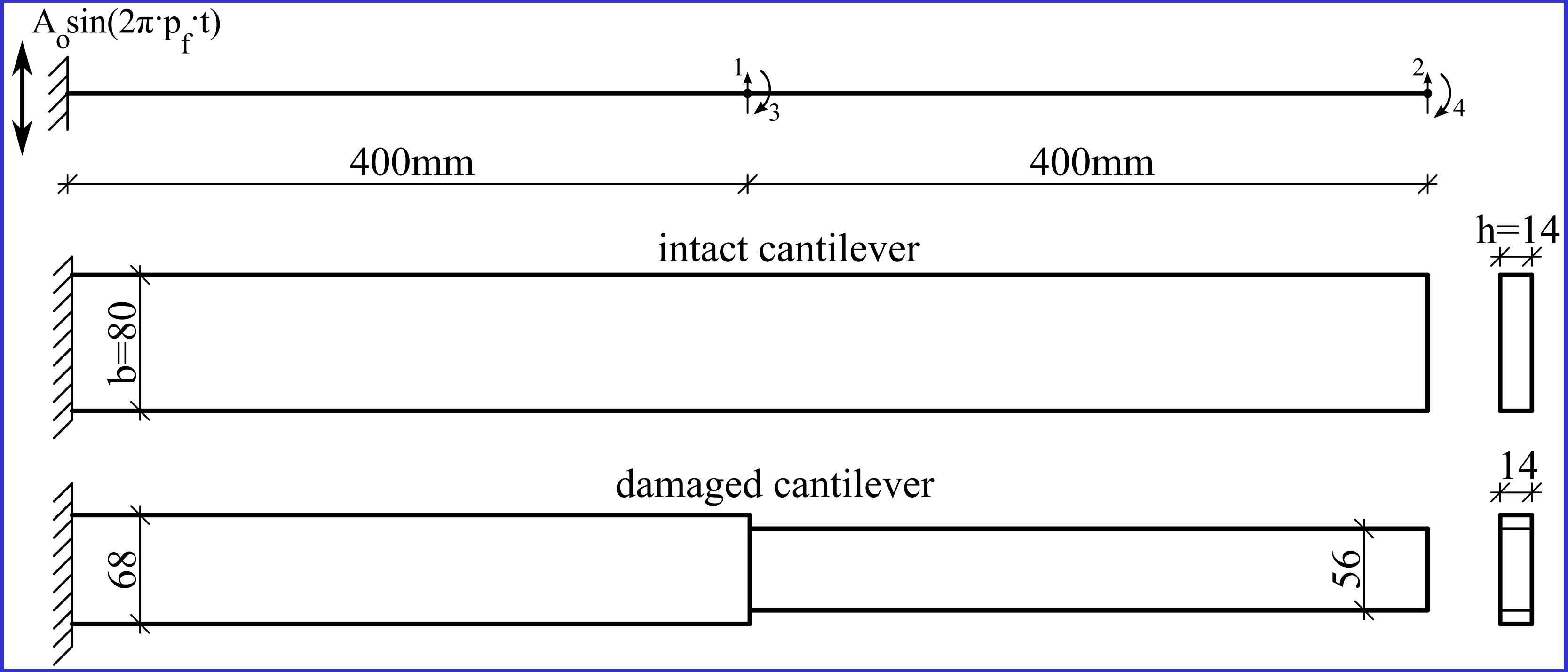
description	degree of freedom (Fig. 3)	"intact" beam	"damaged" beam	unit
amplitude of (kinematic) excitation accelerations		0.383	0.383	m/s^2
amplitude of (kinematic) excitation displacements		0.480	0.480	mm
amplitude of tip transversal accelerations	3	0.945	1.189	m/s^2
amplitude of tip transversal displacements	3	1.182	1.487	mm
amplitude of rotational velocity (rotation rate) of the tip of the beam	6	1.612	2.512	deg/s
amplitude of rotation of the tip of the beam	6	0.057	0.089	deg
amplitude of transversal accelerations	2	0.646	0.749	m/s^2
amplitude of rotational velocity (rotation rate)	5	1.526	2.320	deg/s
amplitude of transversal accelerations	1	0.462	0.492	m/s^2
amplitude of rotational velocity (rotation rate)	4	1.047	1.501	deg/s

beam with three cross-sectional reductions

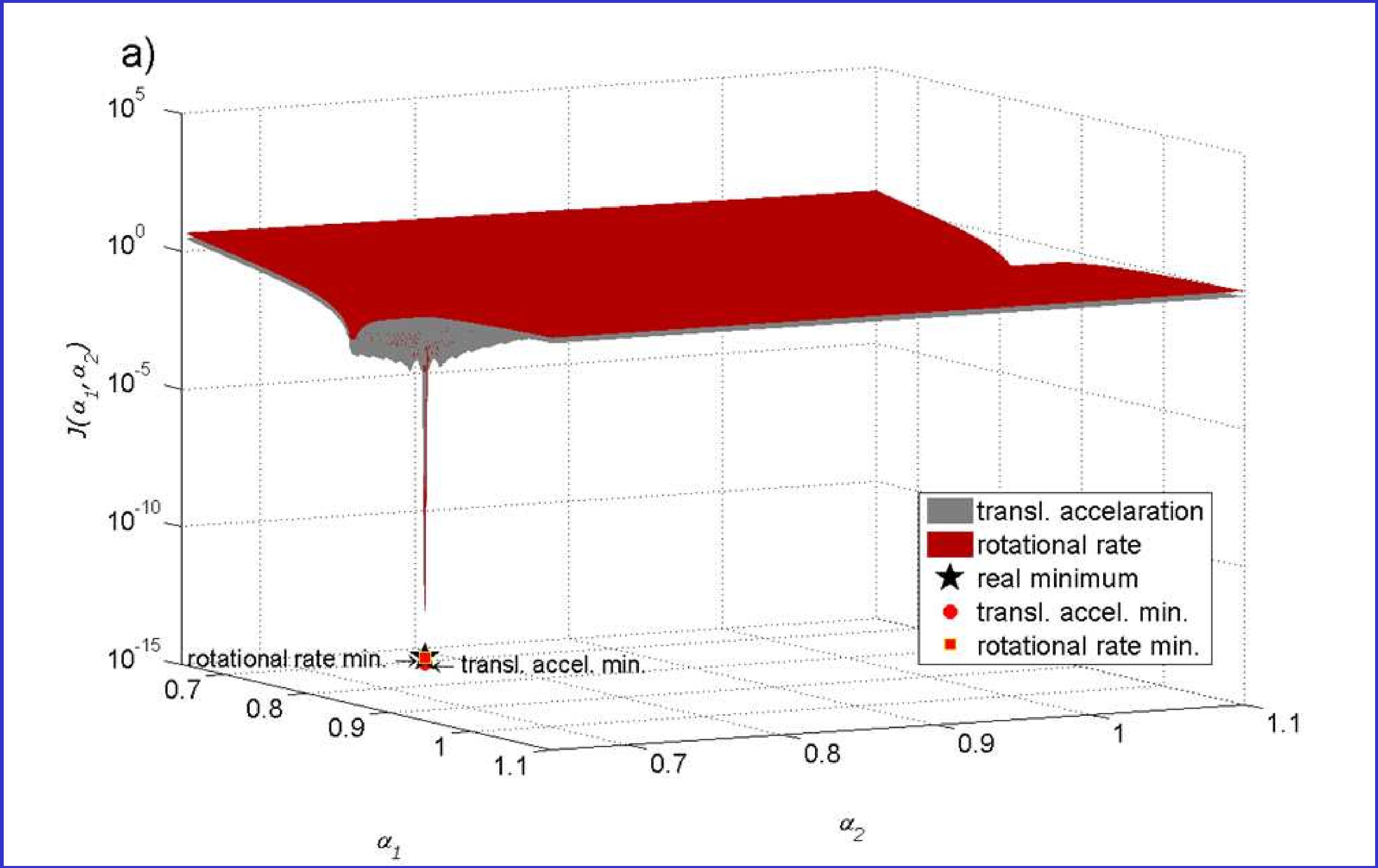


⇐ Intact and "damaged" beam amplitudes ⇐ @ 4, 4.5 and 5Hz

"reconstruction" for beam with 2 cross-section reductions

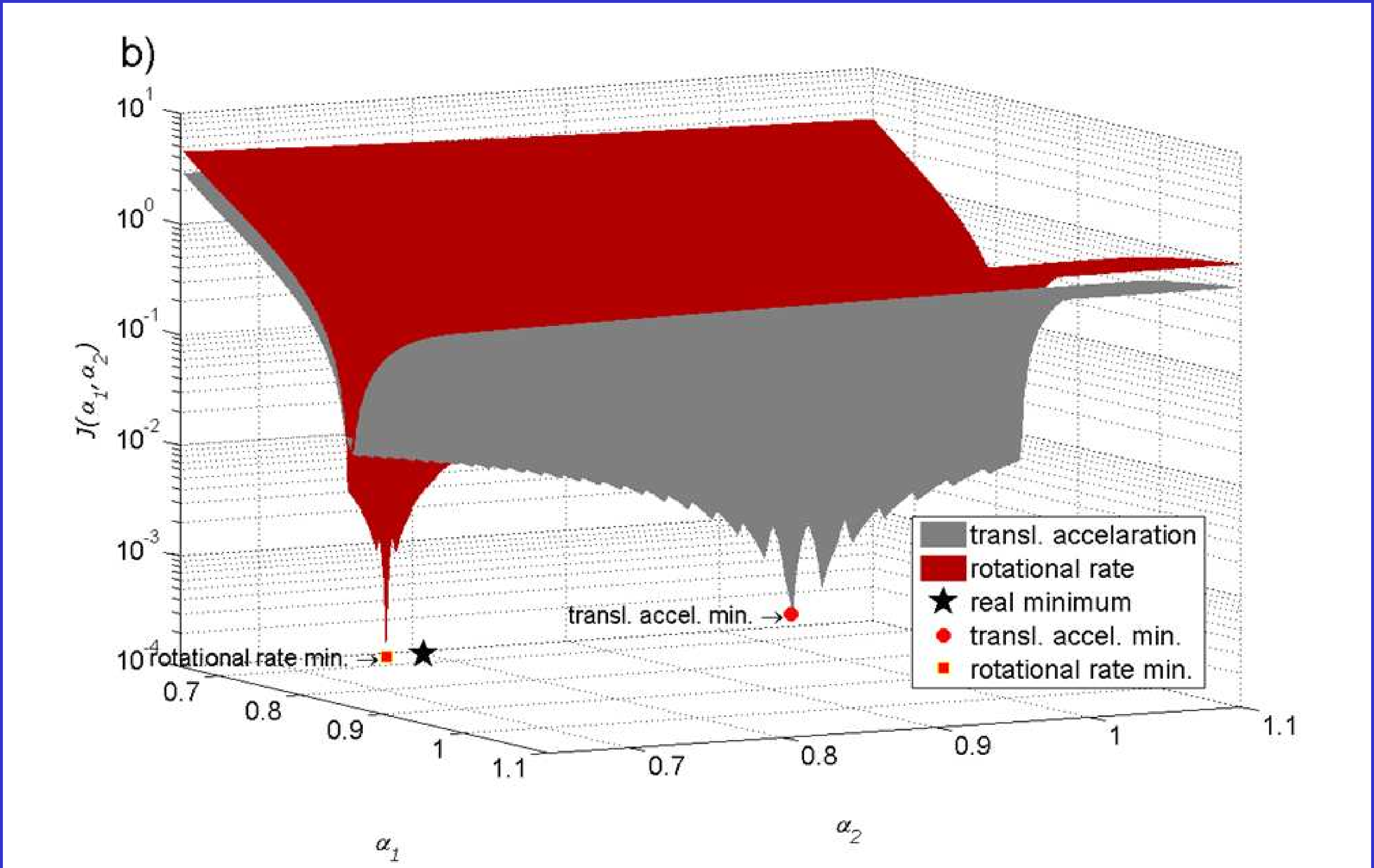


Surface of the objective function - simulation



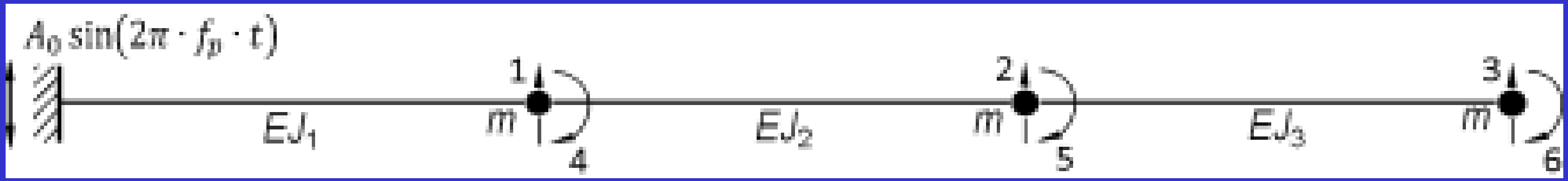
Only two angular rate amplitudes (in red) and two translational accelerations (in grey) are used, the excitation frequency of 4.5Hz

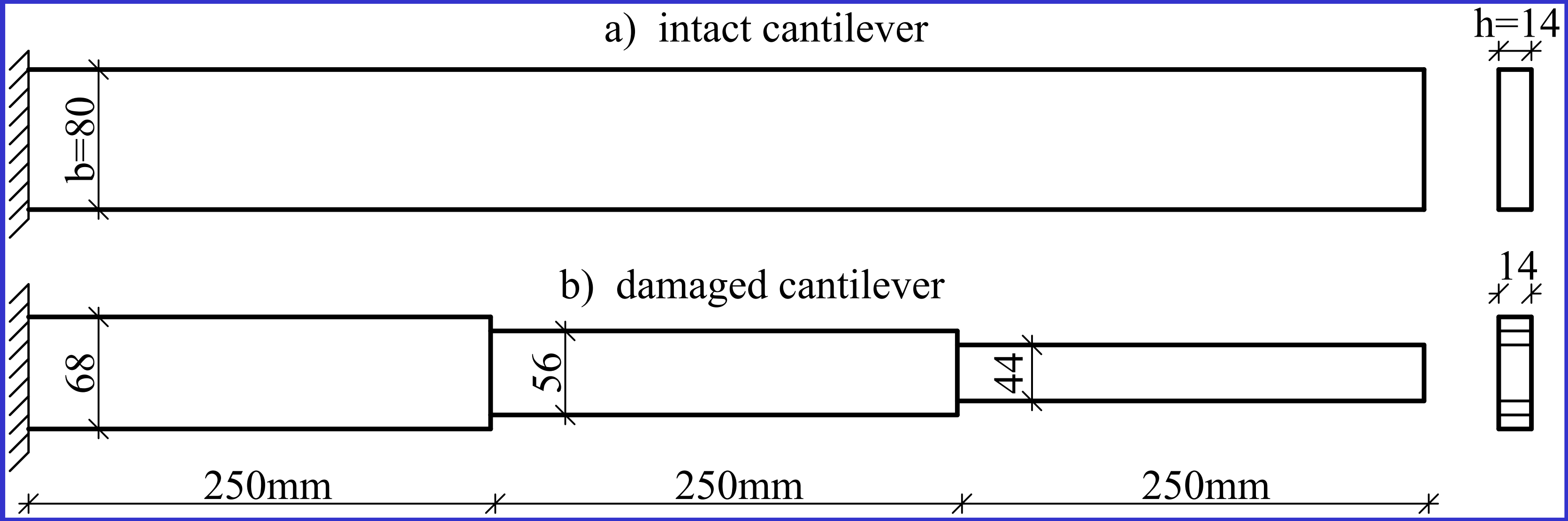
Surface of the objective function - experiment



Only two angular rate amplitudes (in red) and two translational accelerations (in grey) are used, the excitation frequency of 4.5Hz

"reconstruction" for beam with 3 cross-section reductions



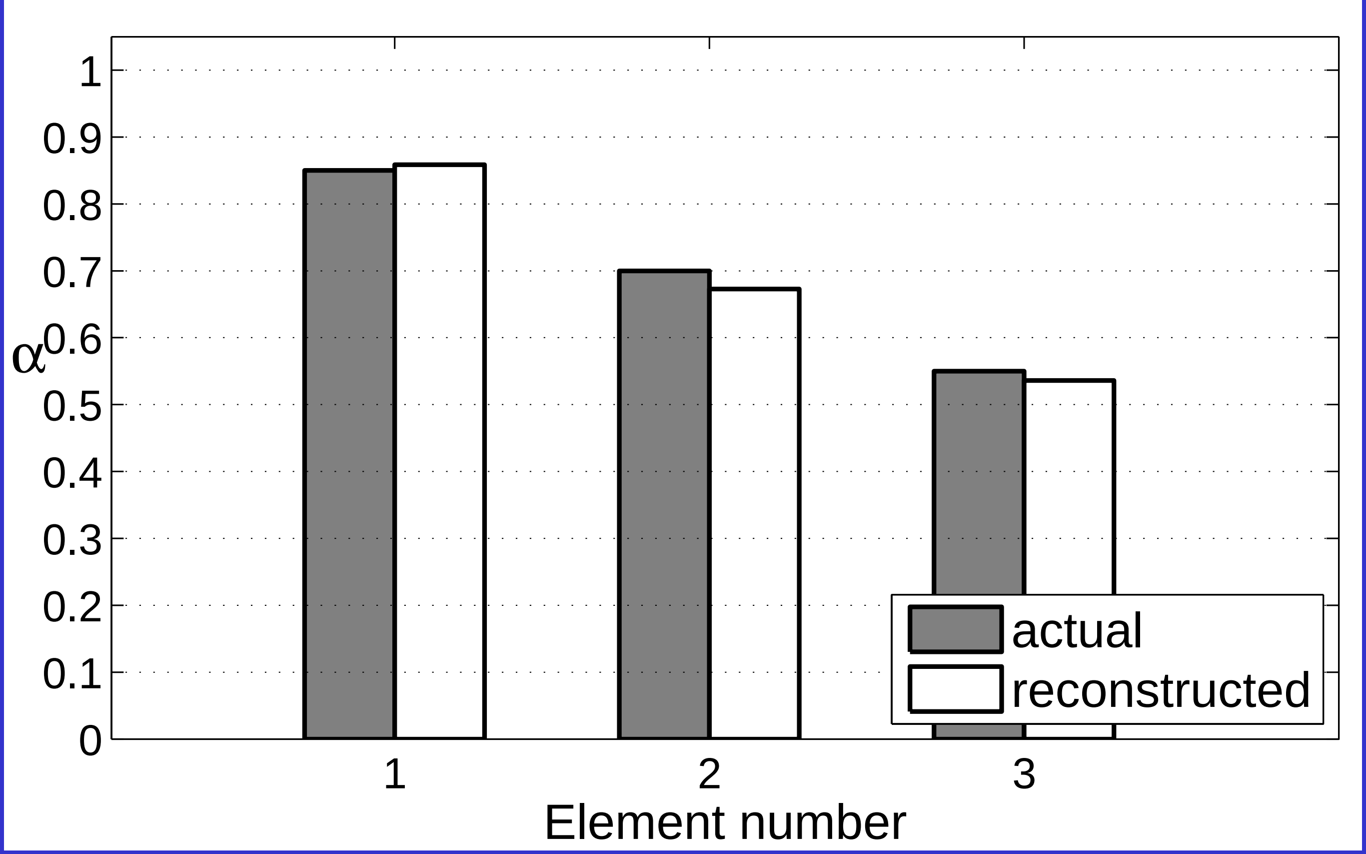


The geometry of the beams in intact and damaged state.

- hybrid optimisation method: genetic algorithms and Levenberg-Marquardt method.

Identified stiffness reduction factors

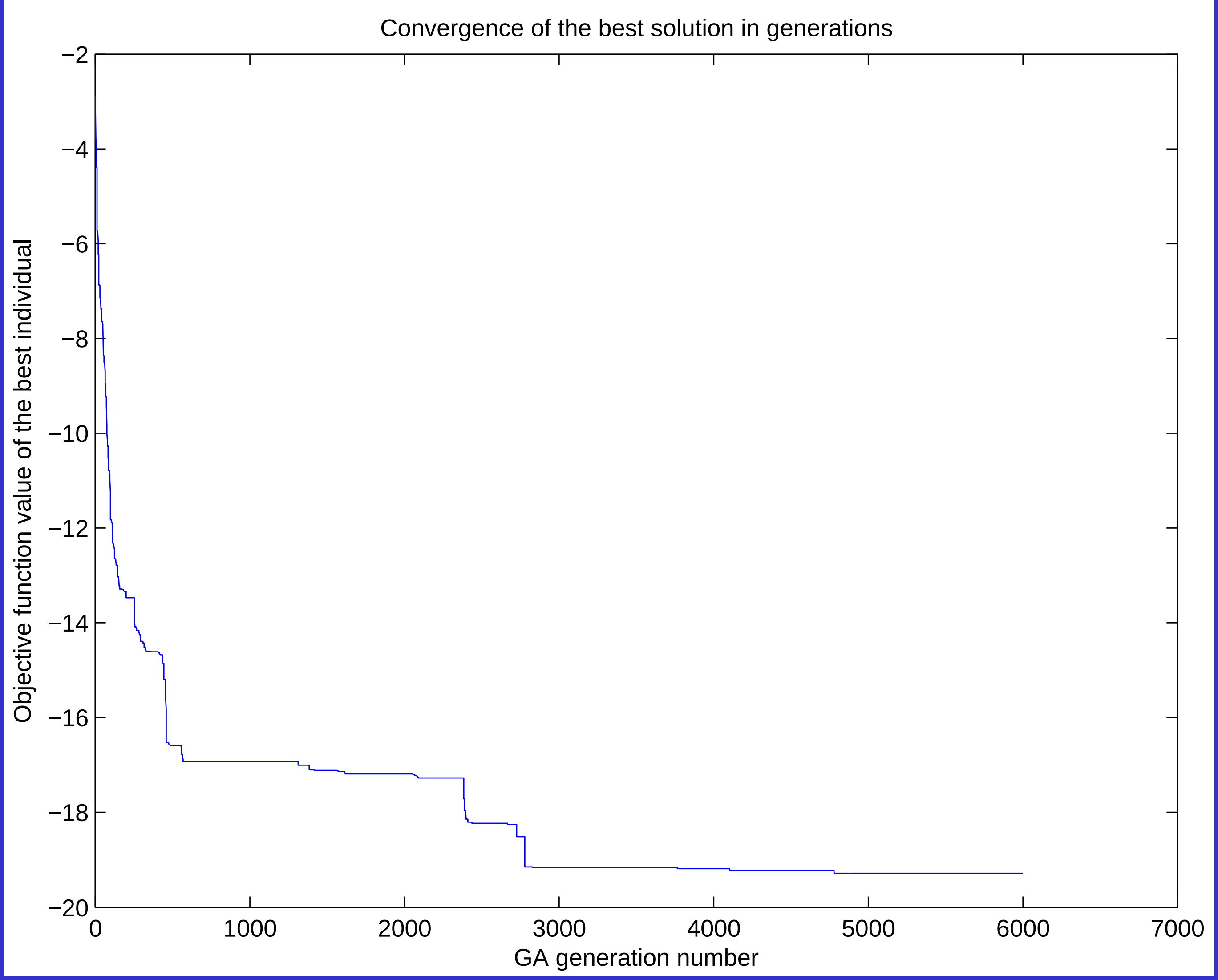
Beam with three stiffness reductions under harmonic kinematic excitation at frequency 4.5Hz, displacement amplitude 1mm.



The errors of reconstruction: WAE=2.48% and ME=3.87%.

Objective function convergence

The progress of the objective function values of the best solution in subsequent genetic algorithm generations



Conclusions

Conclusions

- effectivness of the rotation rate sensors in structural damage detection was analyzed
- experiments on small, laboratory scale, cantilever beams proved that

  the reconstruction of stiness distribution is much more accurate when using 'gyro' sensors than when using conventional accelerometers,
- thus, the intuitive expectation of better following variations of structural

  flexural stiffness by rotation rate sensors than by the translation ones was experimentally confirmed.
- a promissing future for the application of rotation rate sensors in Structural Health Monitoring may be expected

PUBLICATIONS

ZEMBATY Z., KOKOT S. and BOBRA P., Application of rotation rate sensors in an experiment of stiffness 'reconstruction', *Smart Materials and Structures*, vol.**22,** No. 7, June 2013

KOKOT S., ZEMBATY Z. and BOBRA P., An analysis of the effectiveness of application of rotation rate sensors in non destructive damage evaluation, *Key Engineering Materials*, 2013, vol.**569-570**, pp.783-790