15th Munich Earth Skience School

ObsPy goes Downtown: Seismology in Cities

Damage detection

Felix Bernauer

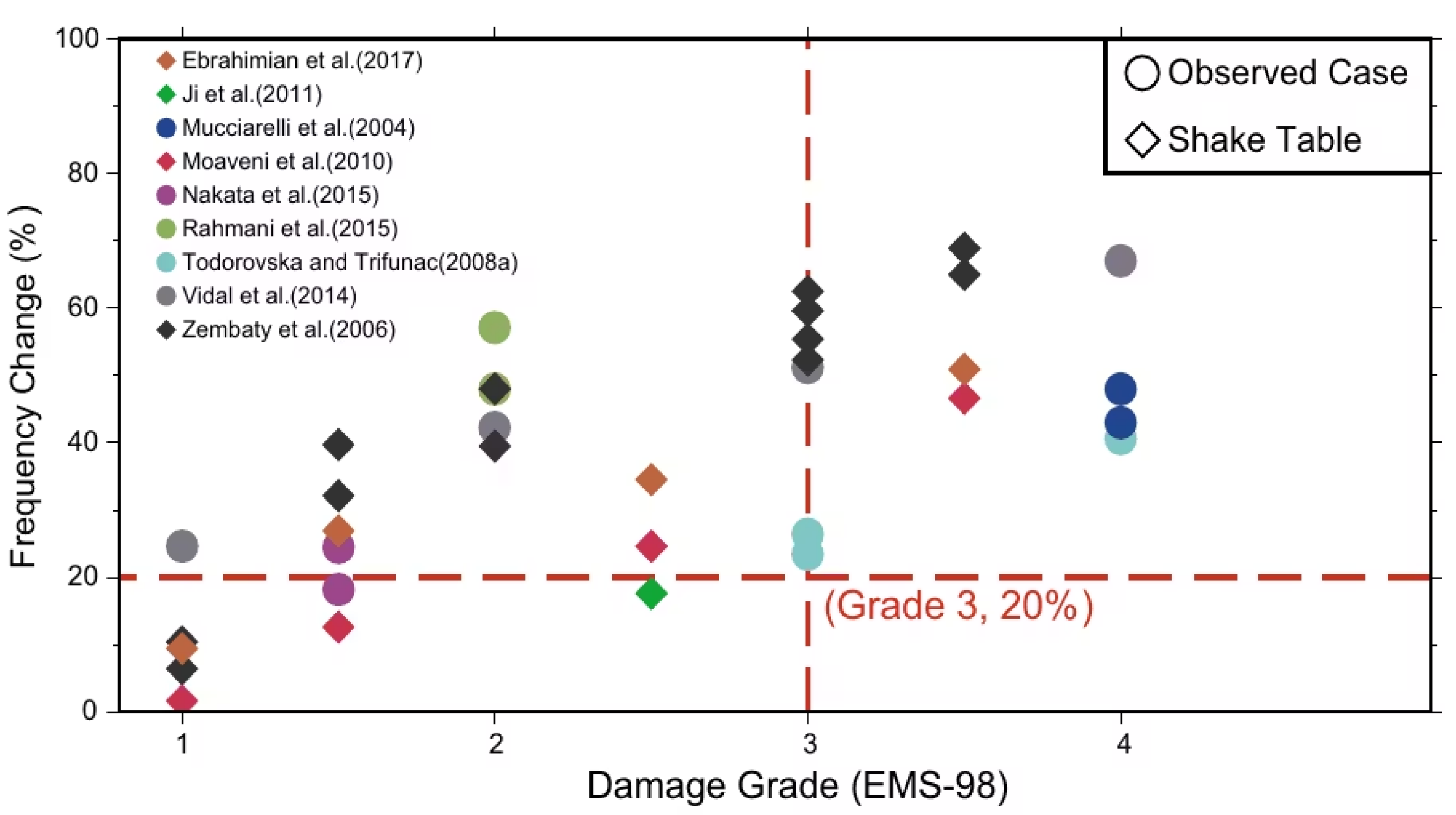
27 February 2025

Credit: City of Dresden

in collaboration with
Yara Rossi (LMU Munich)
Anjali Dhabu (University of Hamburg)
Angelin Binny (LMU Munich)
Georgios Balaskas (RWTH Aachen)

System identification

How does the modal frequency relate to structural damage?

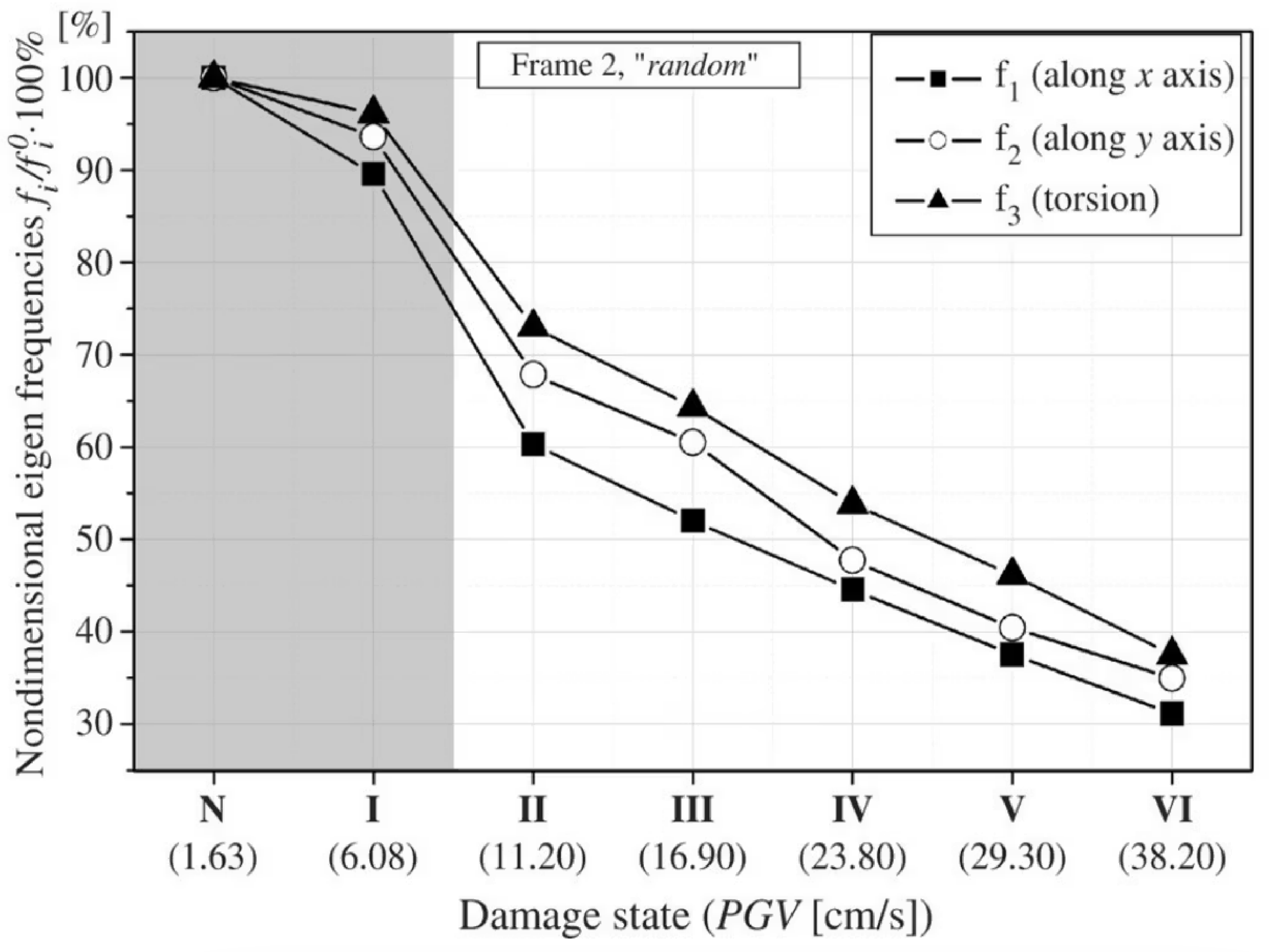


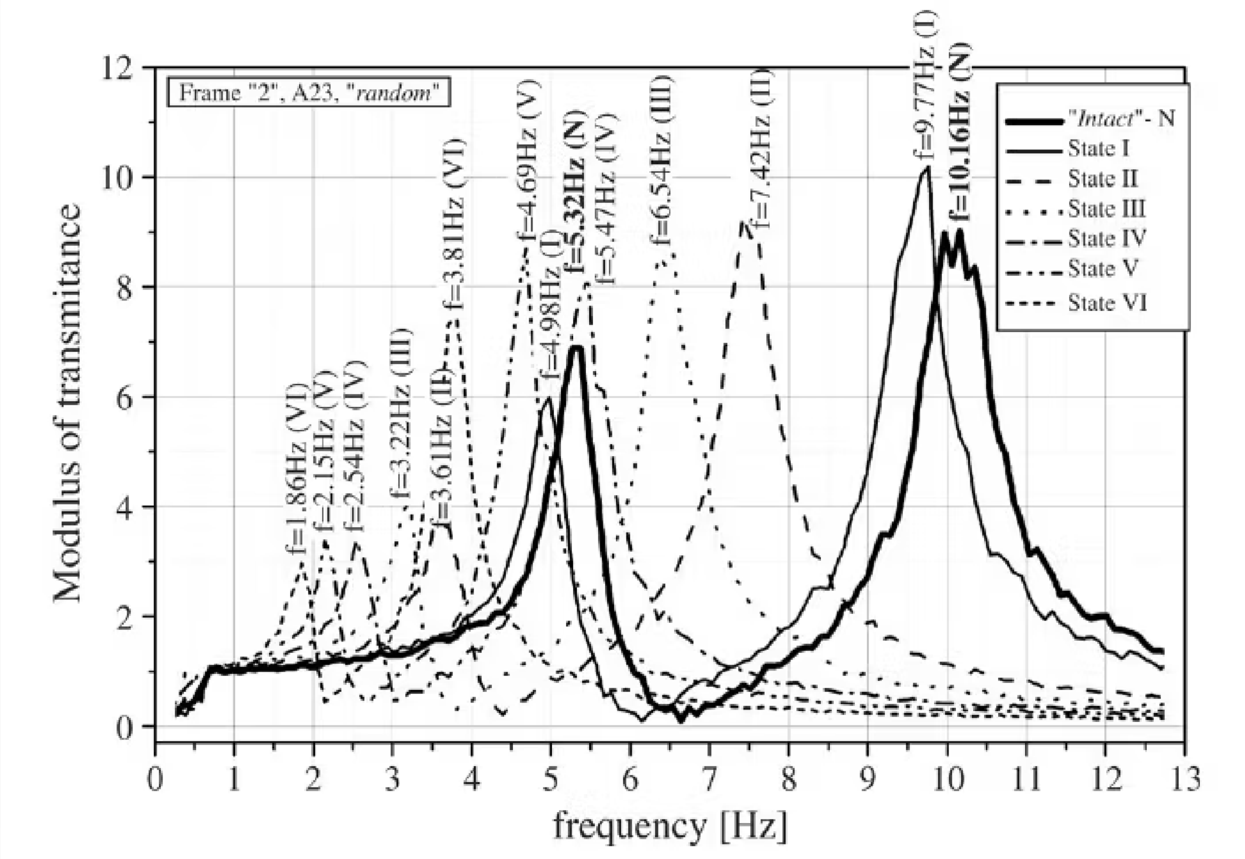
Chao et al. 2024

Some examples

Shake table test with a single story reinforced concrete structure

Zembaty et al. 2006





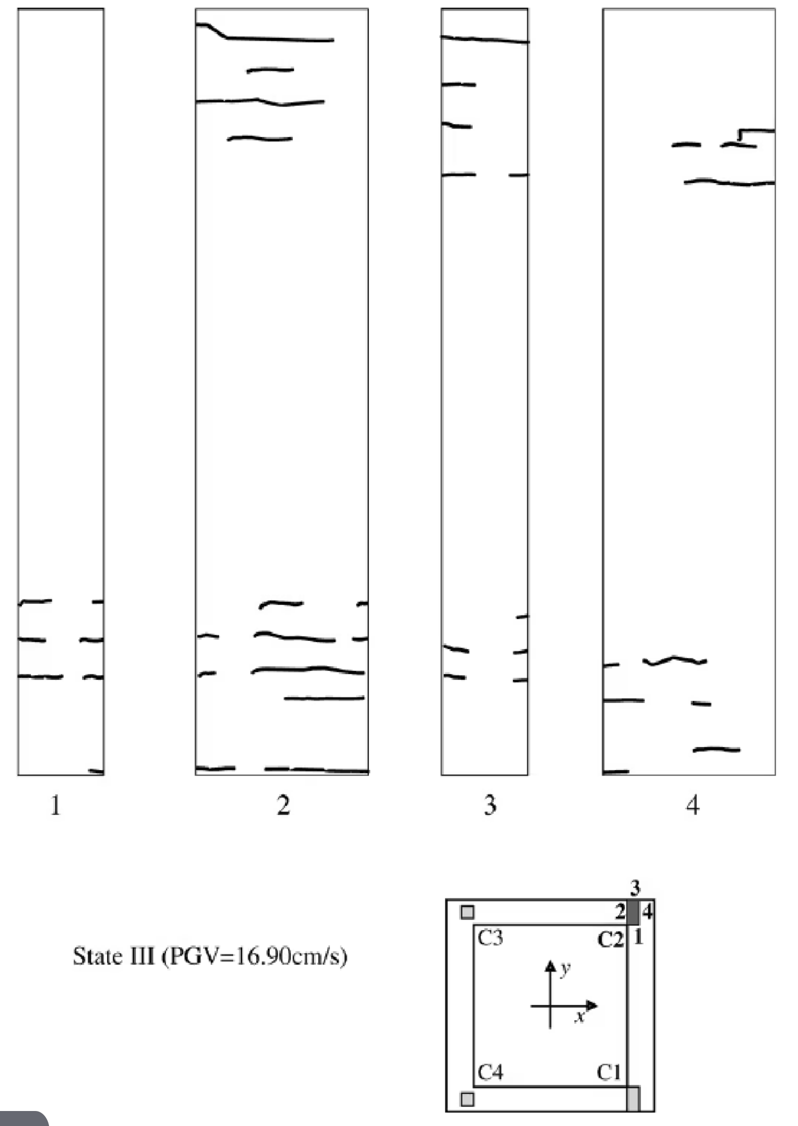
Try Pitch

Some examples

Shake table test with a single story reinforced concrete structure

Zembaty et al. 2006

Fig. 18. Detail of damaged frame after seismic tests.



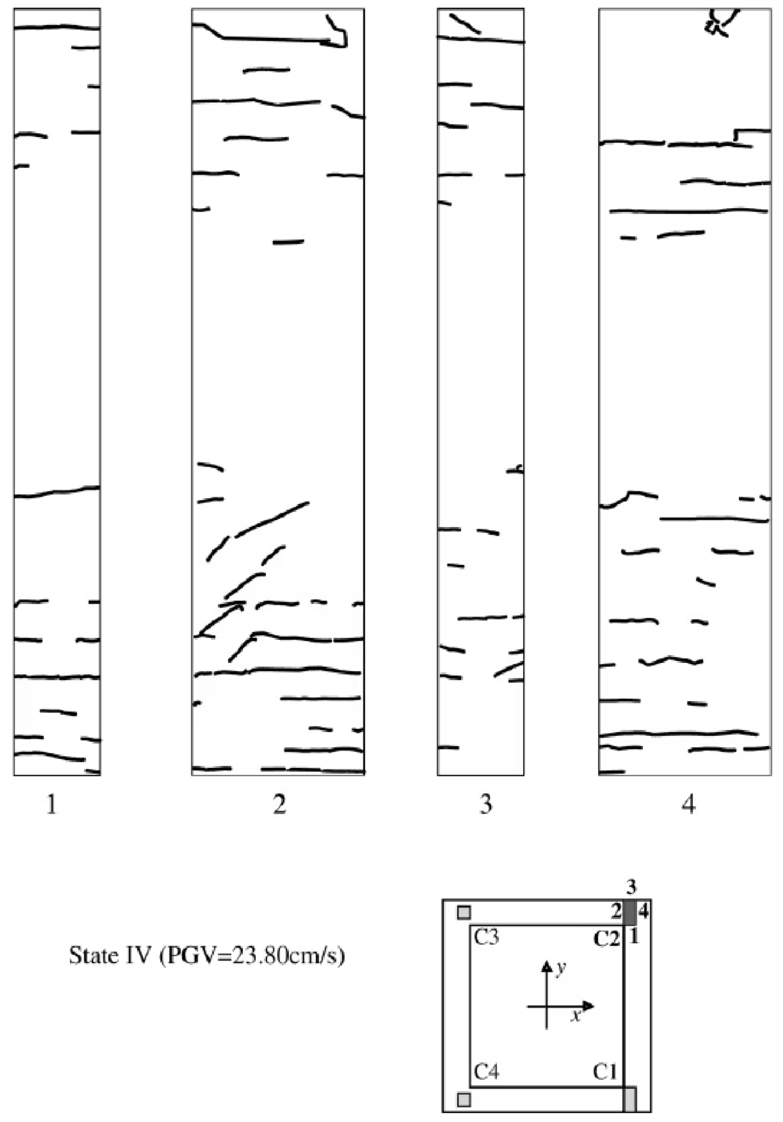
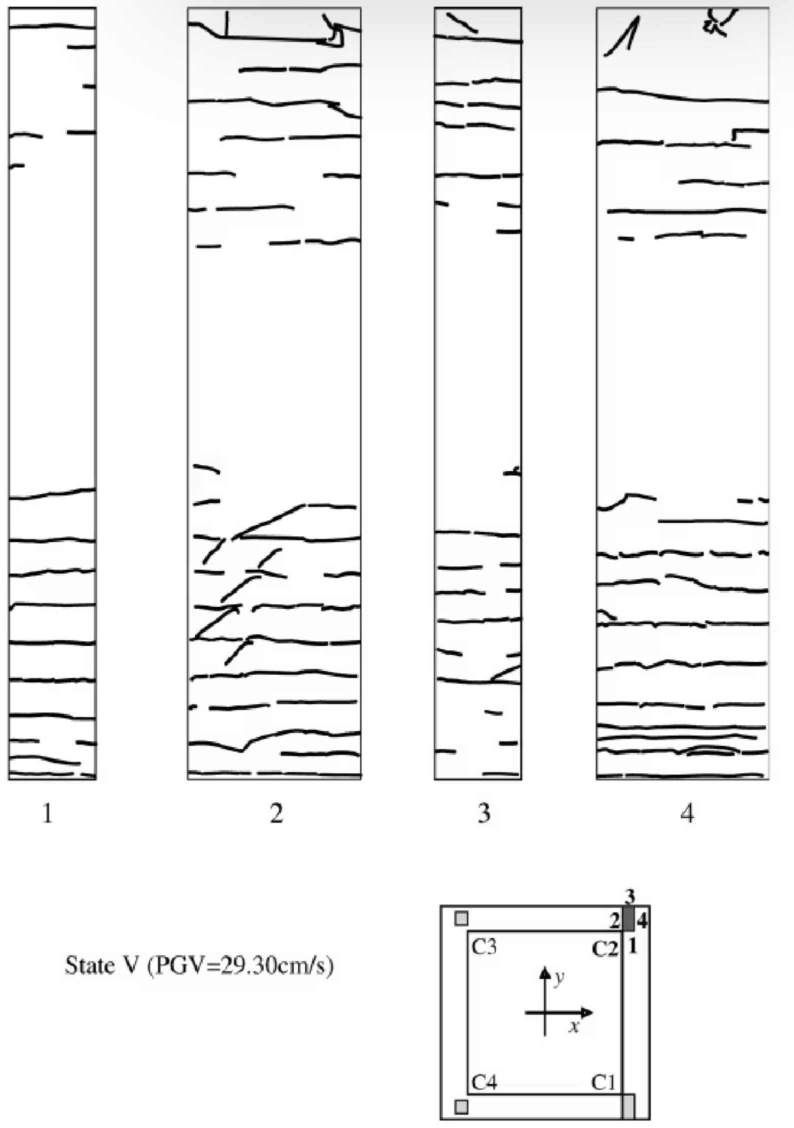


Fig. 14. Damage of column no. 2 of frame no. 2 after excitation at level of 9 dB (State III).

Fig. 15. Damage of column no. 2 of frame no. 2 after excitation at level of 12 dB (State IV).



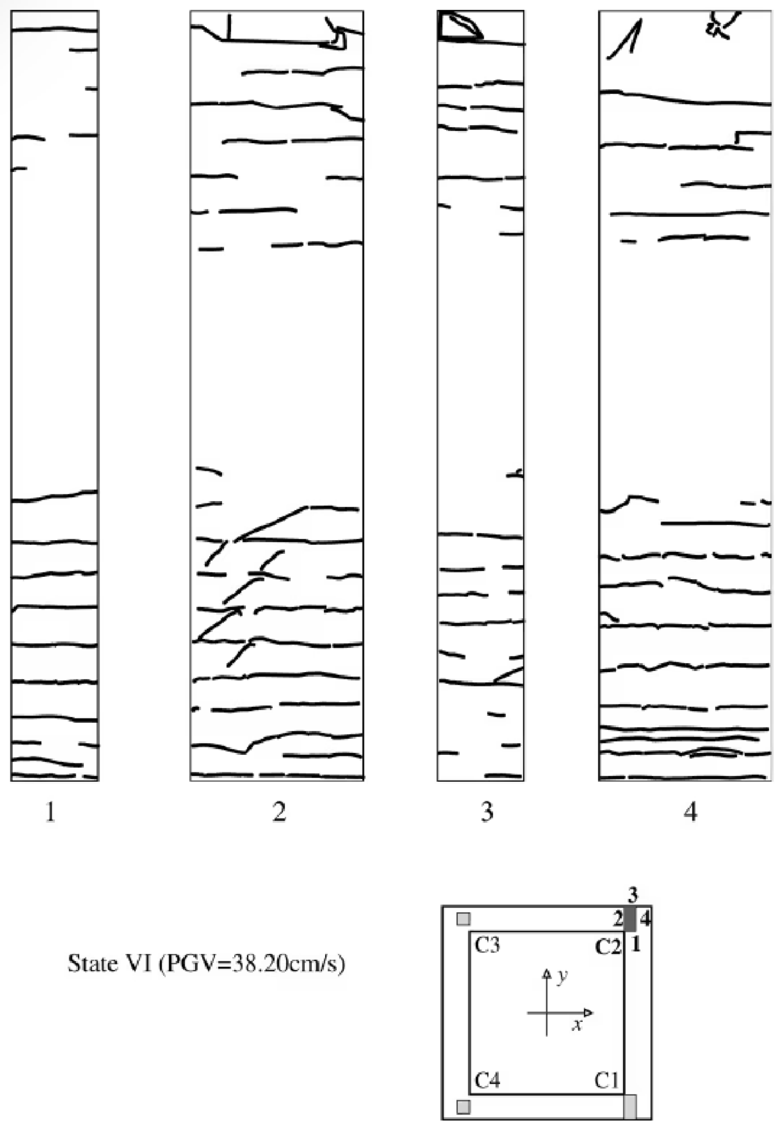


Fig. 16. Damage of column no. 2 of frame no. 2 after excitation at level of 14 dB (State V).

Fig. 17. Damage of column no. 2 of frame no. 2 after excitation at level of 16 dB (State VI).

Some examples

Full-scale seven-story reinforced concrete building on the UCSD-NEES shake table

from Moaveni et al. 2010

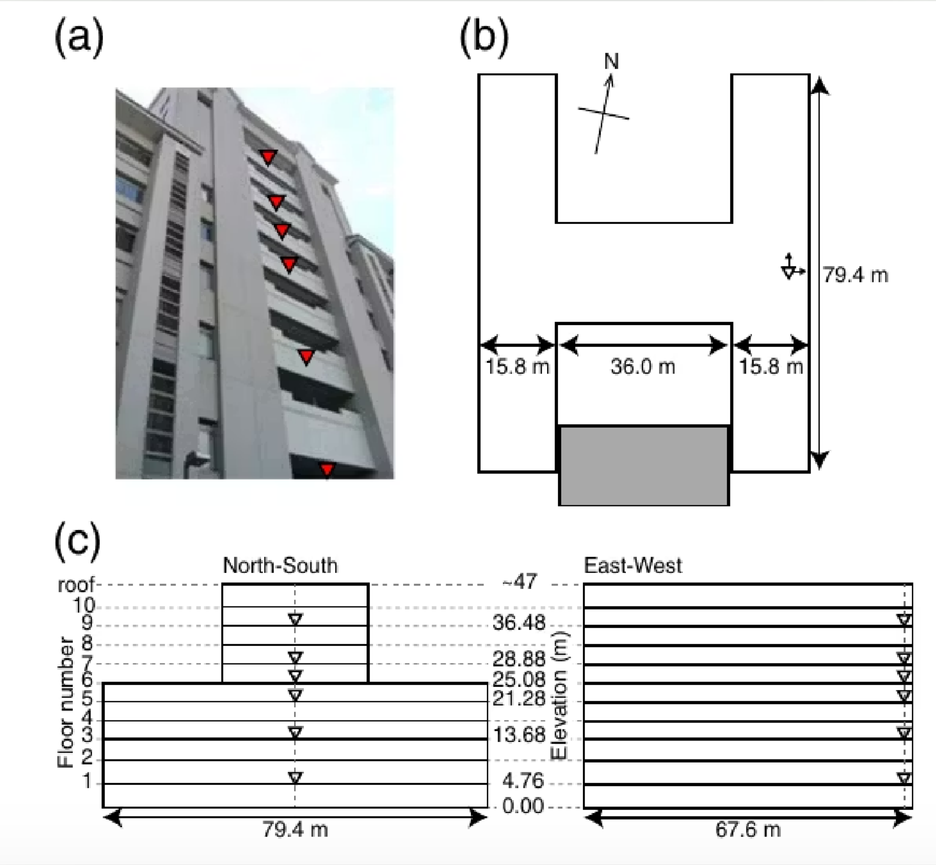
Fig. 8 Extent of flexure-shear cracking at the first story (plastic-hinge region) of the web wall during EQ4 (at instants of time near maximum base rotation)

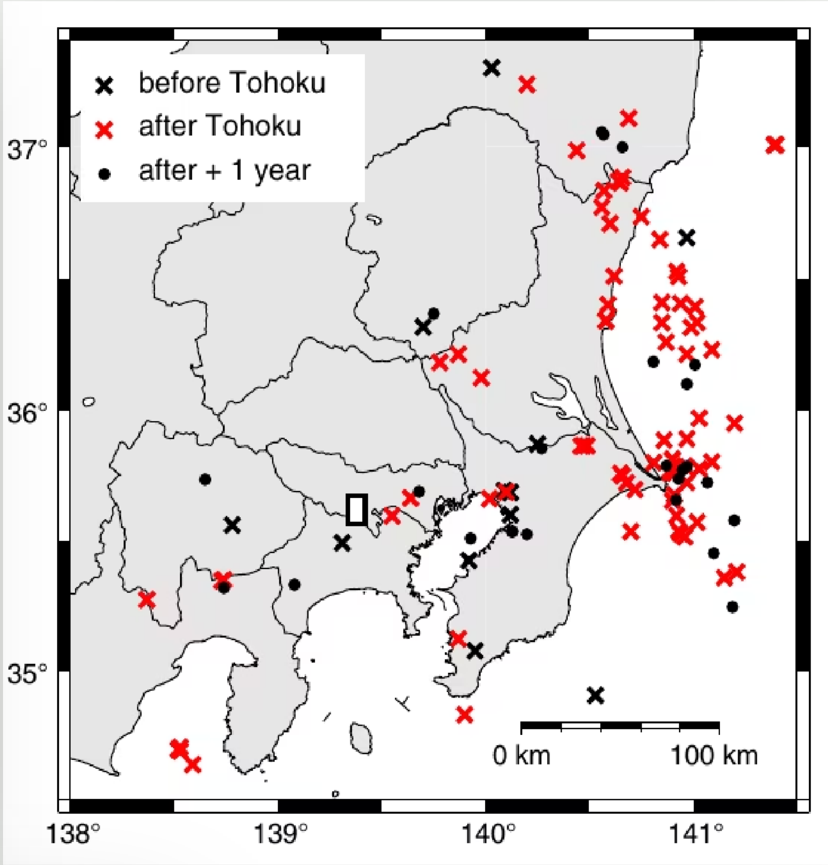
State	Ambient Vibration			0.03g RMS White Noise			0.05g RMS White Noise		
	1st-L mode	2nd-L mode	3rd-L mode	1st-L mode	2nd-L mode	3rd-L mode	1st-L mode	2nd-L mode	3rd-L mode
S0	1.91	10.51	24.51	1.71	11.05	24.31	NA	NA	NA
S1	1.88	10.21	24.31	1.54	10.98	24.28	1.40	11.38	24.29
S2	1.67	10.16	22.60	1.24	11.11	21.59	1.14	10.24	22.46
S3.1	1.44	9.23	21.82	1.14	9.77	19.68	1.06	10.23	18.98
S4	1.02	5.67	15.09	0.88	4.81	13.29	0.81	4.62	13.29

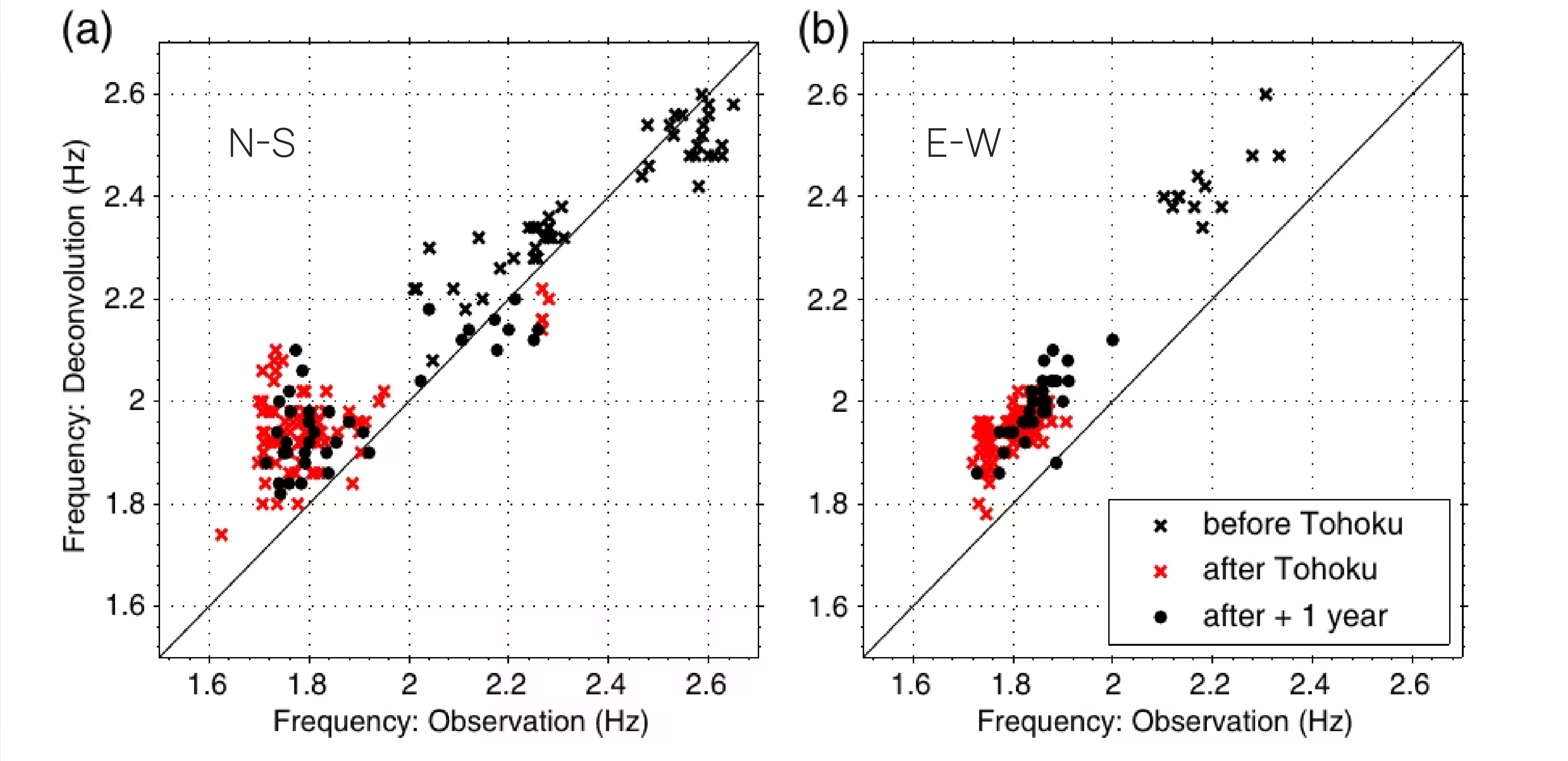
Some examples

damage detected in a building after the Tohoku-Oki earthquake

- deconvolution interferometry
- directly observed





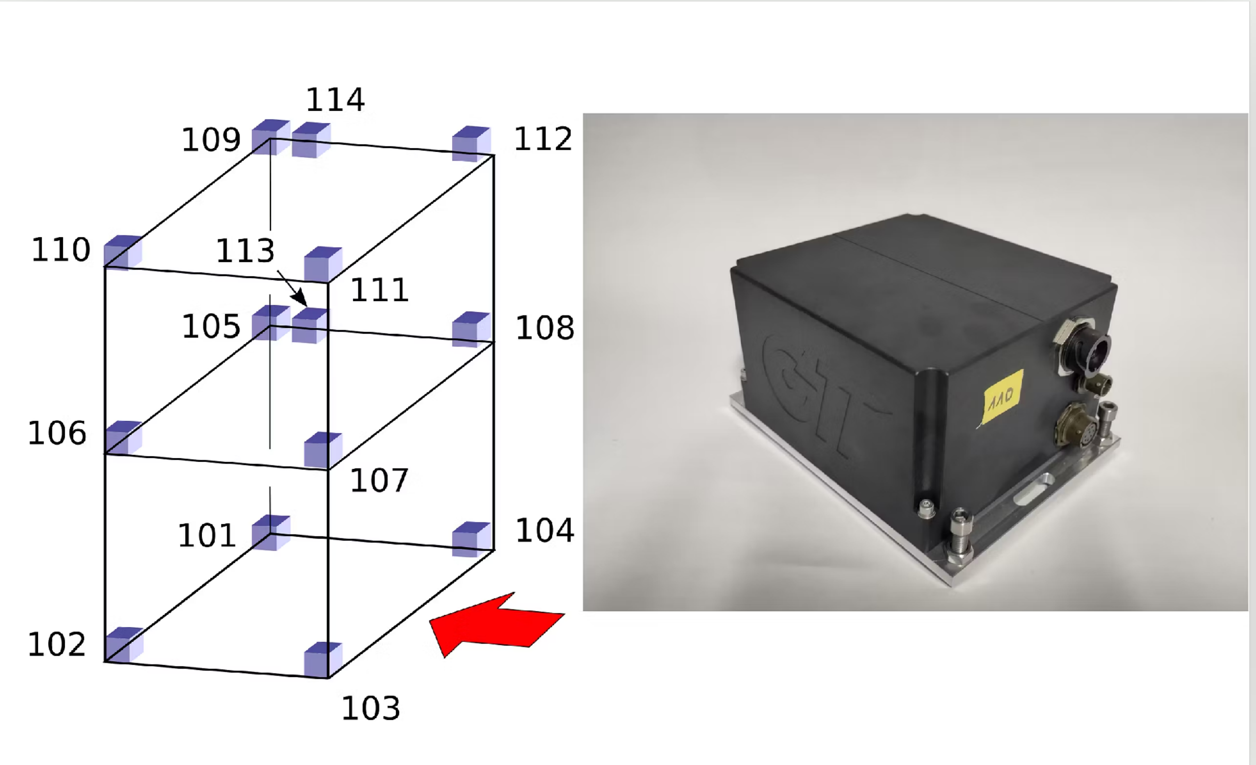


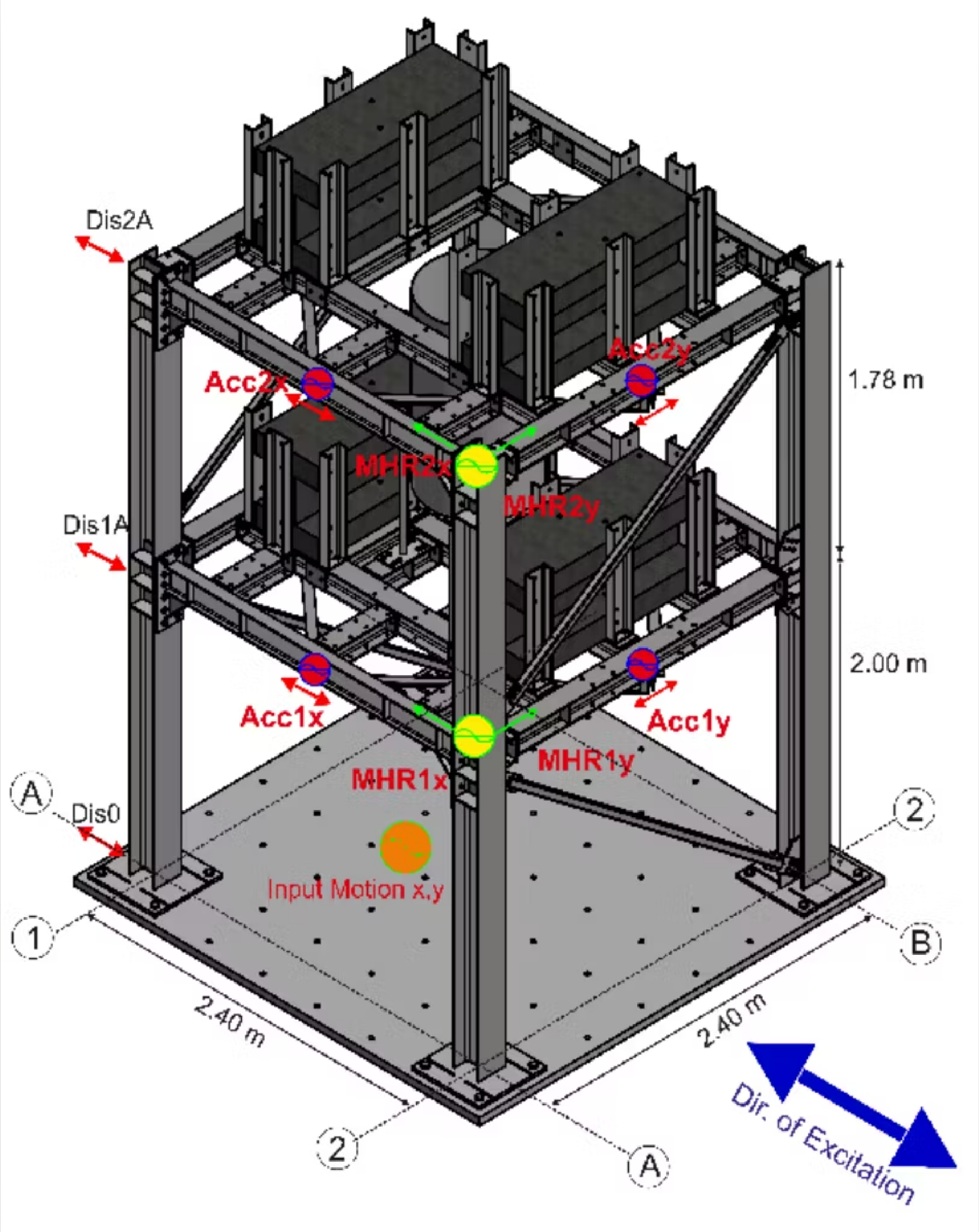
Nakata et al. 2015

Try Pitch

Let's look at some shake table test data

In collaboration with Georgios Balaskas (RWTH Aachen)





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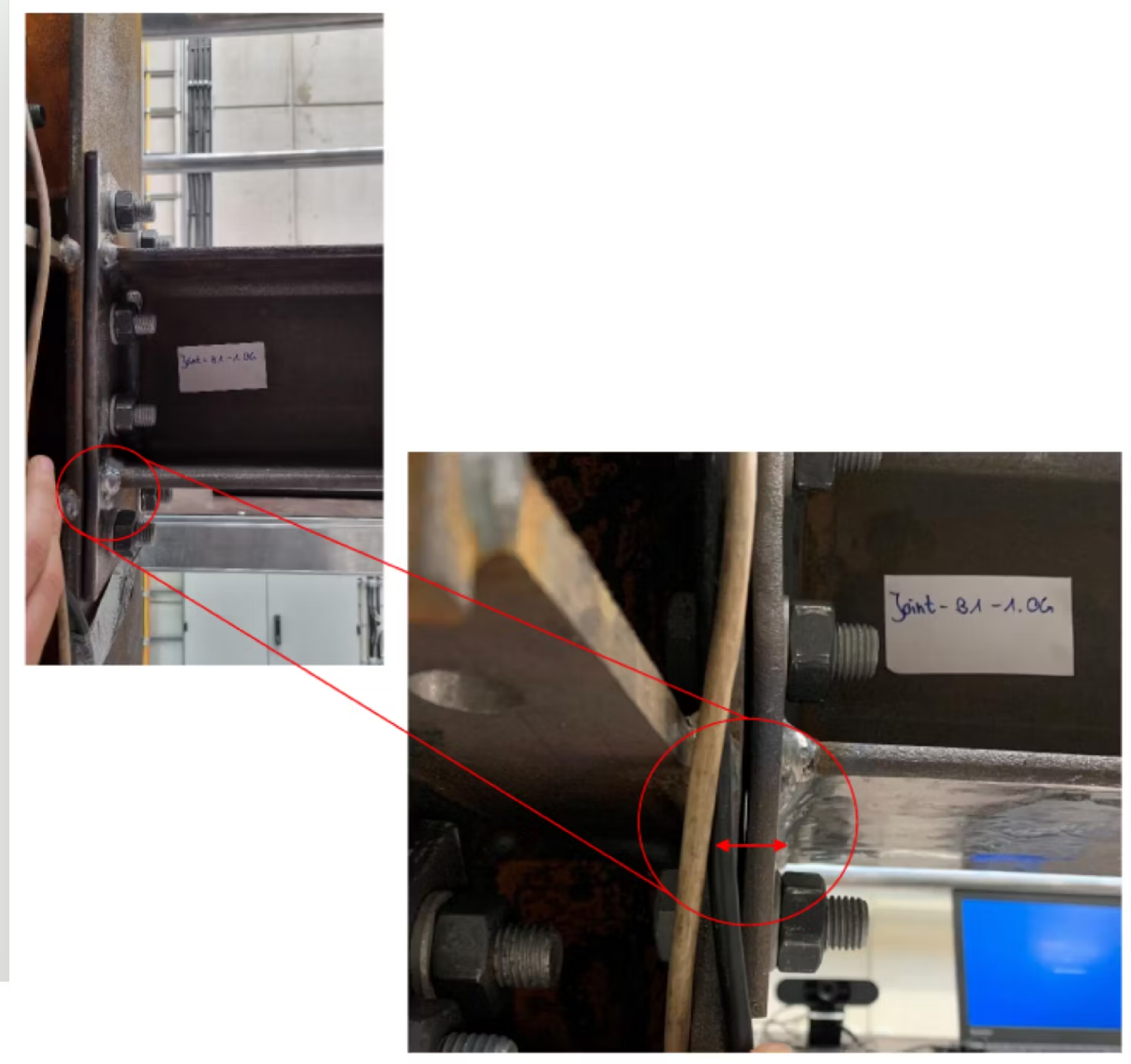
Produced damage

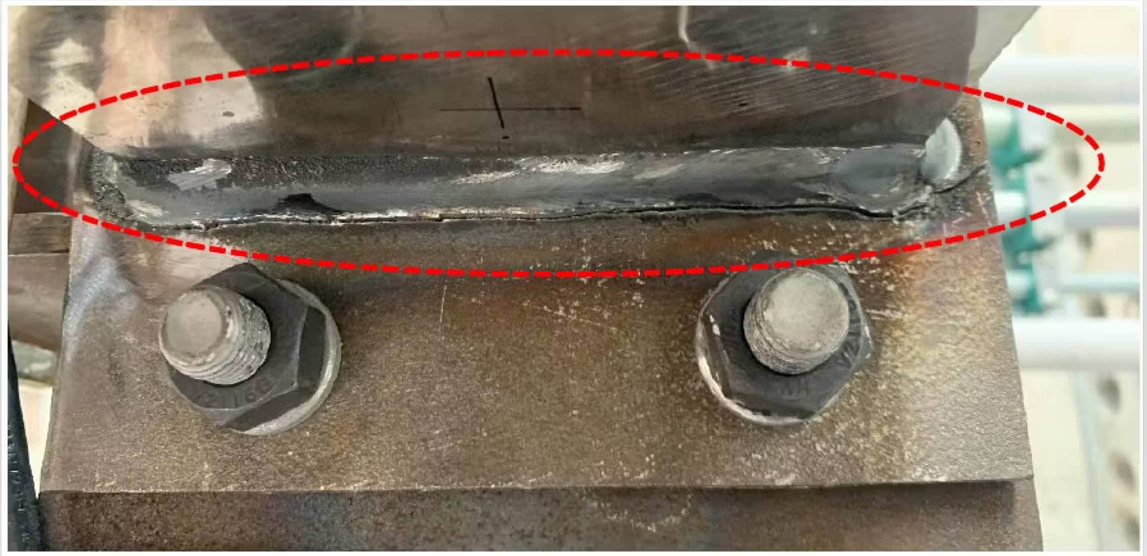
Cluster 2

damage: local ductile deformation < 2mm



Cluster 3

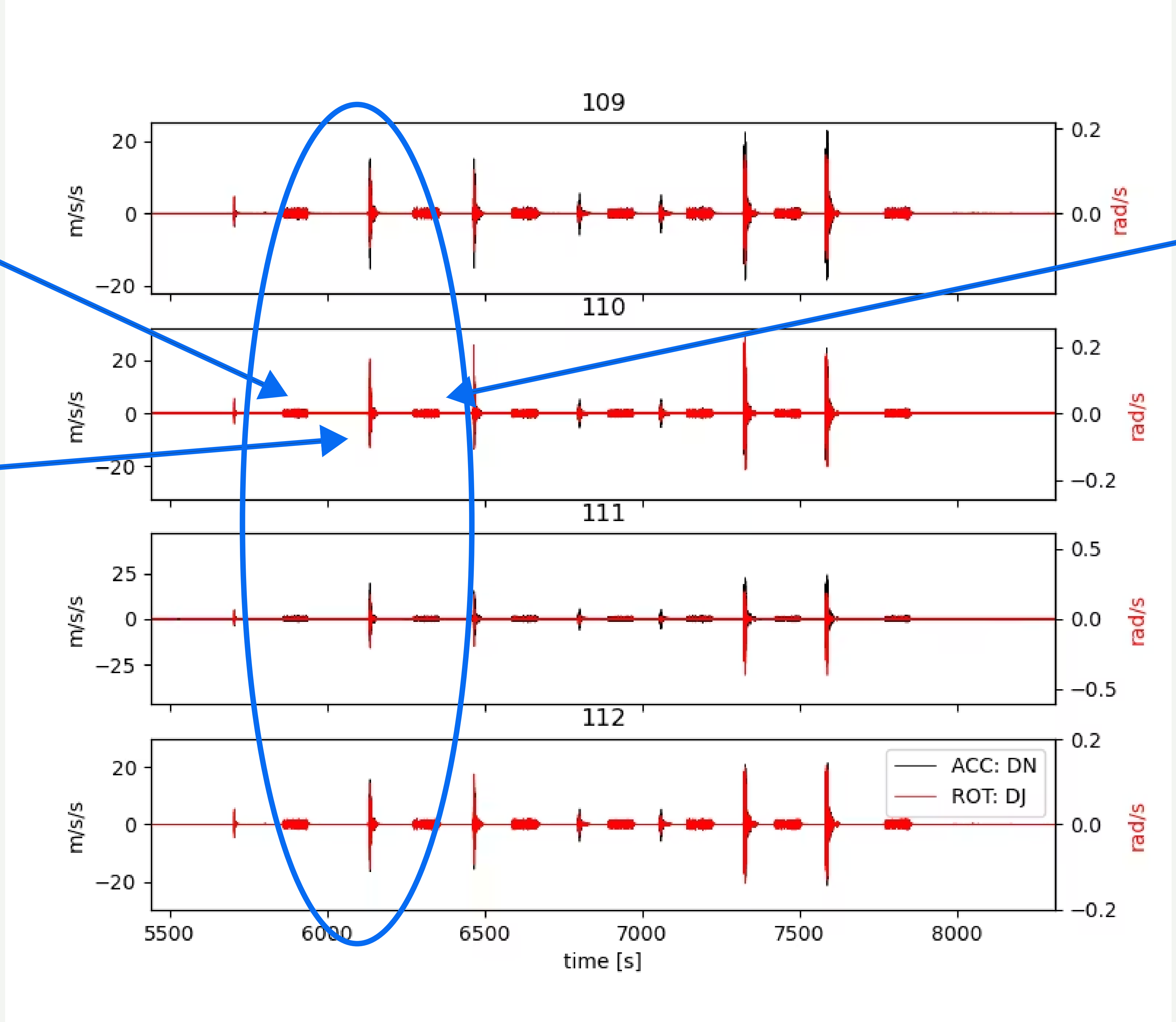
damage: plastic deformation > 2mm, cracks



The test sequences

white noise excitation
system characterization
before the event

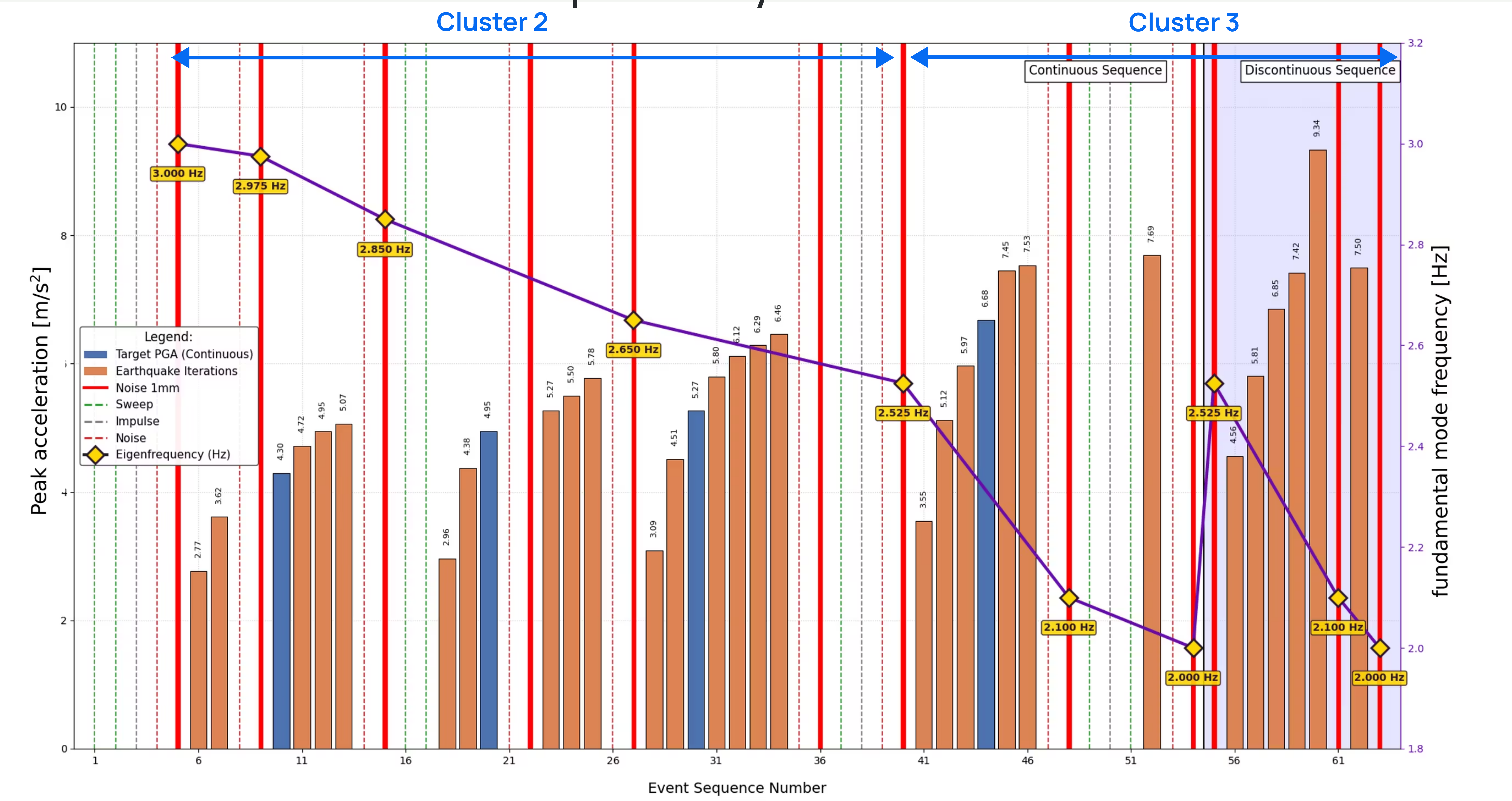
earthquake sequence
causing damage



white noise excitation
system characterization
after the event

Identification of frequency shift

Master thesis from Angelin Binny



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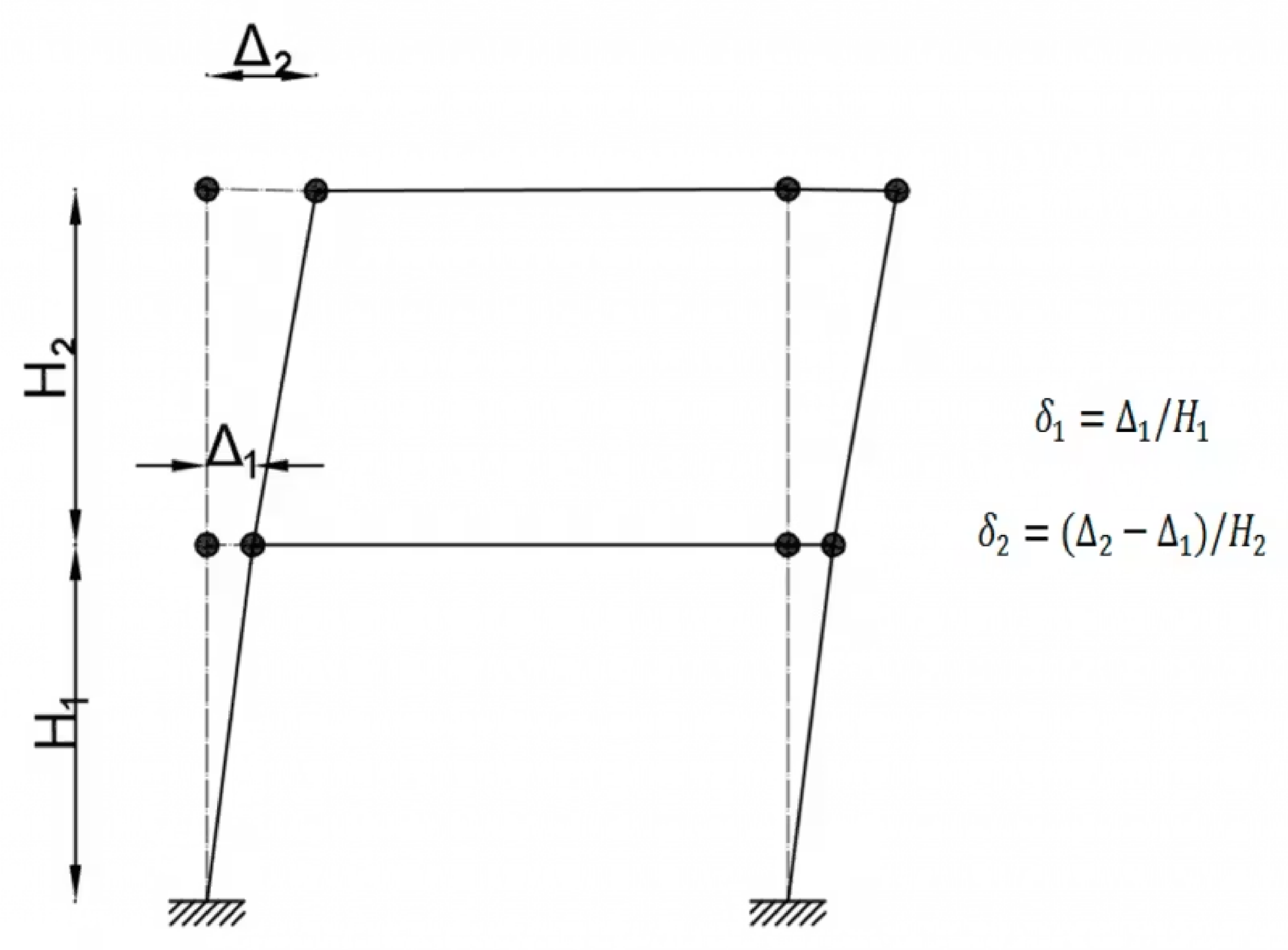
Practical

Identify damage with shift in modal frequency

Inter-story drift

The relative translational displacement between two consecutive stories



from skyciv.com

Inter-story drift

assessing building safety

Provisions for building peak interstory drift (PID) ratio and residual interstory drift (RID) ratio in selected codes and standards.

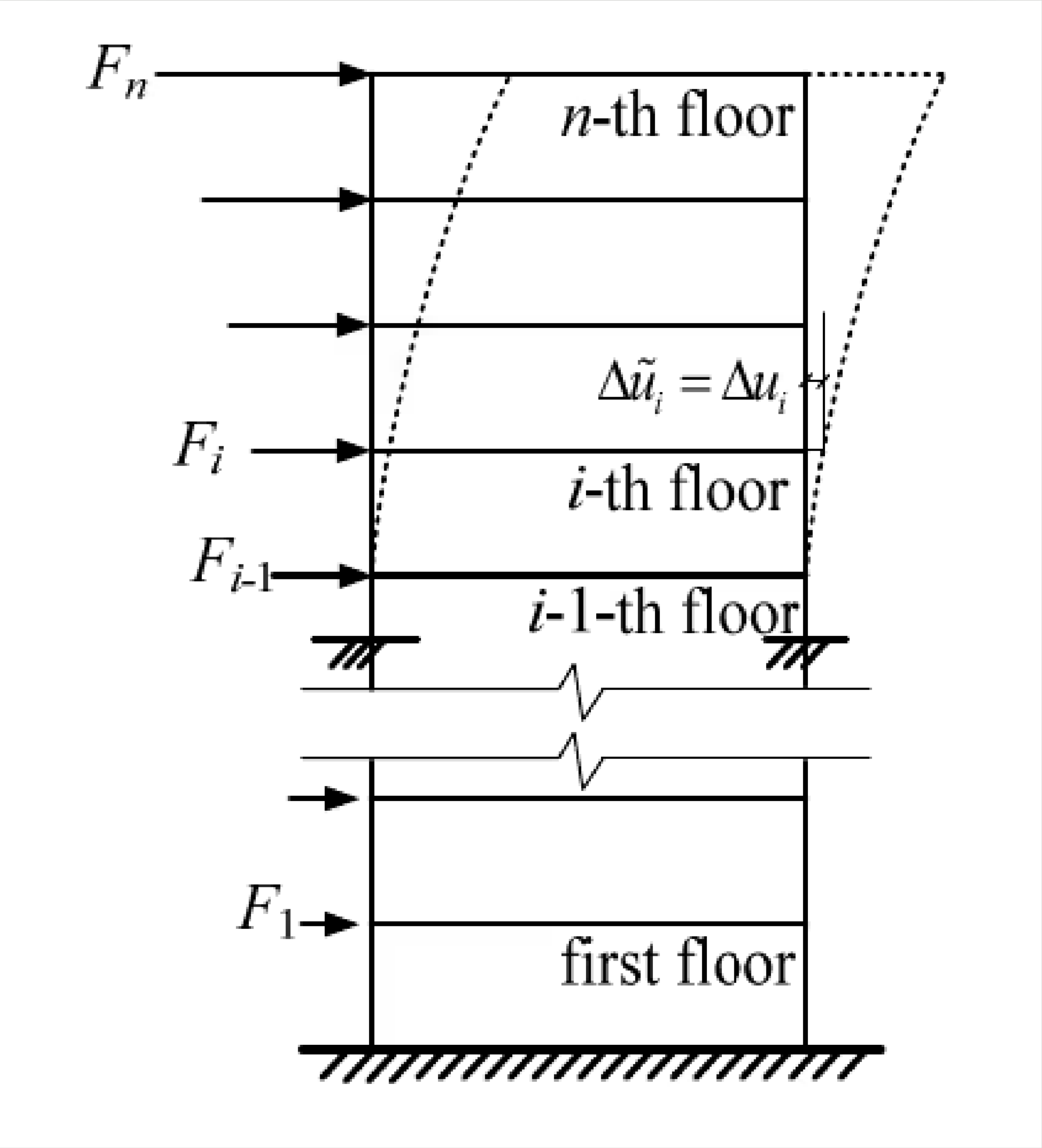
Specification	Standard	Drift Specifications			
Specification of performance limit states (drifts for steel moment frame example)	ASCE 43-05	*Limit State A* Large permanent distortion short of collapse *Significant Damage* PID 3.5%	*Limit State B* Moderate permanent distortion *Generally repairable damage* PID 2.5%	*Limit State C* Limited permanent distortion *Minimal damage* PID 1.0%	*Limit State D* Essentially elastic behavior *No damage* PID 0.5%
Specification of maximum allowable drift limits	ASCE 7-16	*Risk Category I or II* PID 2.5%		*Risk Category III* PID 2.0%	*Risk Category IV* PID 1.5%
	Eurocode EN 1998-1 (2004)	Buildings with non-structural elements that do not interfere with structural deformation PID 1.0%/v		Buildings having ductile non-structural elements PID 0.75%/v	Buildings having brittle non-structural elements PID 0.5%/v
	New Zealand Standard NZS – 1170.5 (2004)	Upper bound limit applicable to the ultimate limit state of all buildings, imposed to limit the probability of instability PID 2.5%			
	Tall Building Initiative (TBI) 2.01 (2017)	Drift limit to provide protection against nonstructural element damage and ensure permanent lateral displacement of the structure is negligible PID 0.5% Story transient drift from analyses not to exceed PID 3.0%			
	Chilean Standard NCh433.Of96 (1996)	Drift limit to control stiffness, torsional plan rotation and damage of nonstructural componentsPID 0.2% (when evaluated at the center of mass) + 0.1% (if evaluated at a point different from the center of mass)			

from Petrone et al. 2018

Inter-story drift

building design

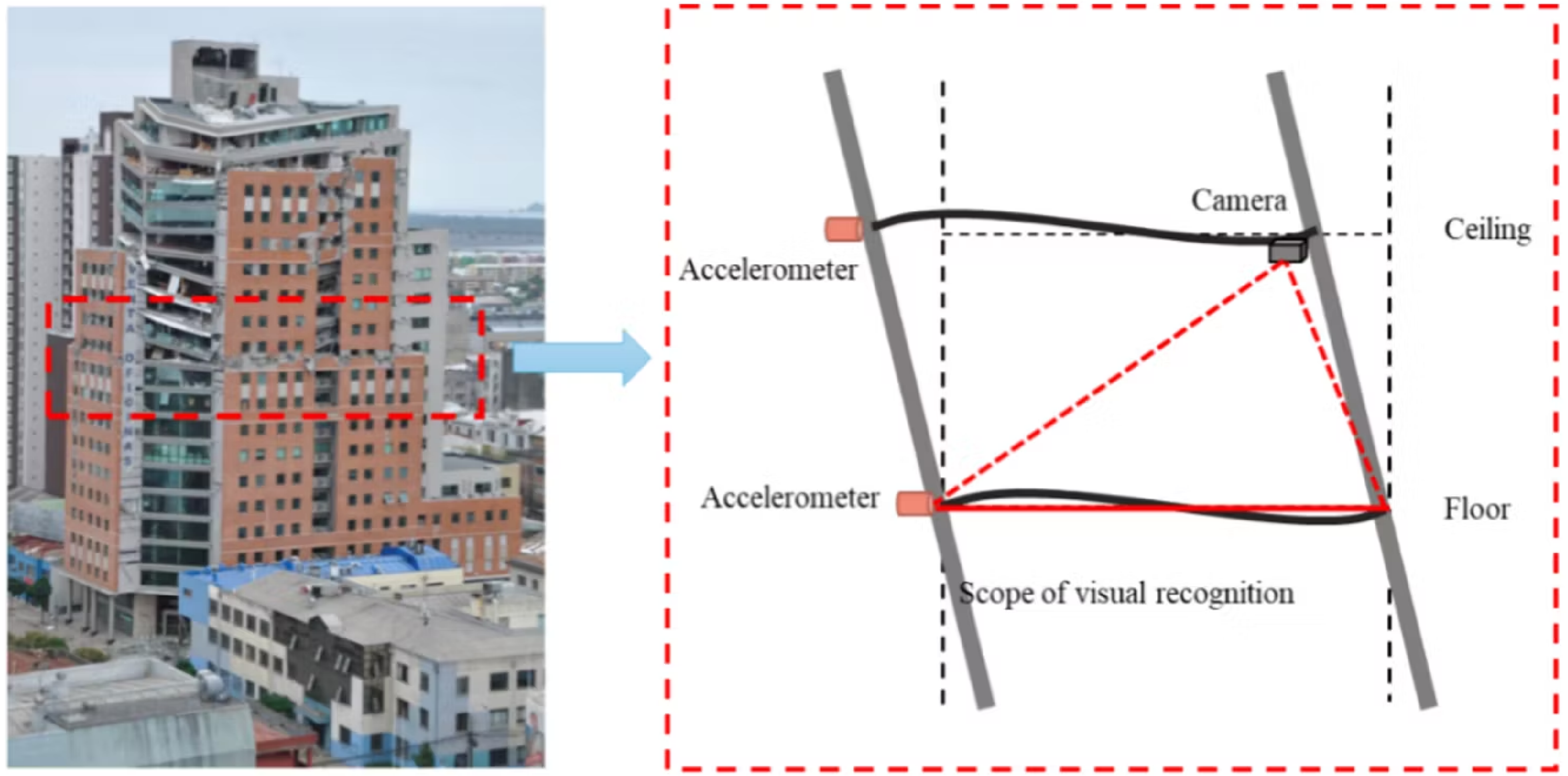
- in a general shear-bending model IDR increases with the number of the floor



Inter-story drift

21-story building O'Higgins tower after the 2010 Chiliean Earthqhake

- significant damage above the 13th floor
- severe damage of all floors above the 19th floor



(a) Post-earthquake story-level damages (b) Single story with monitoring devices

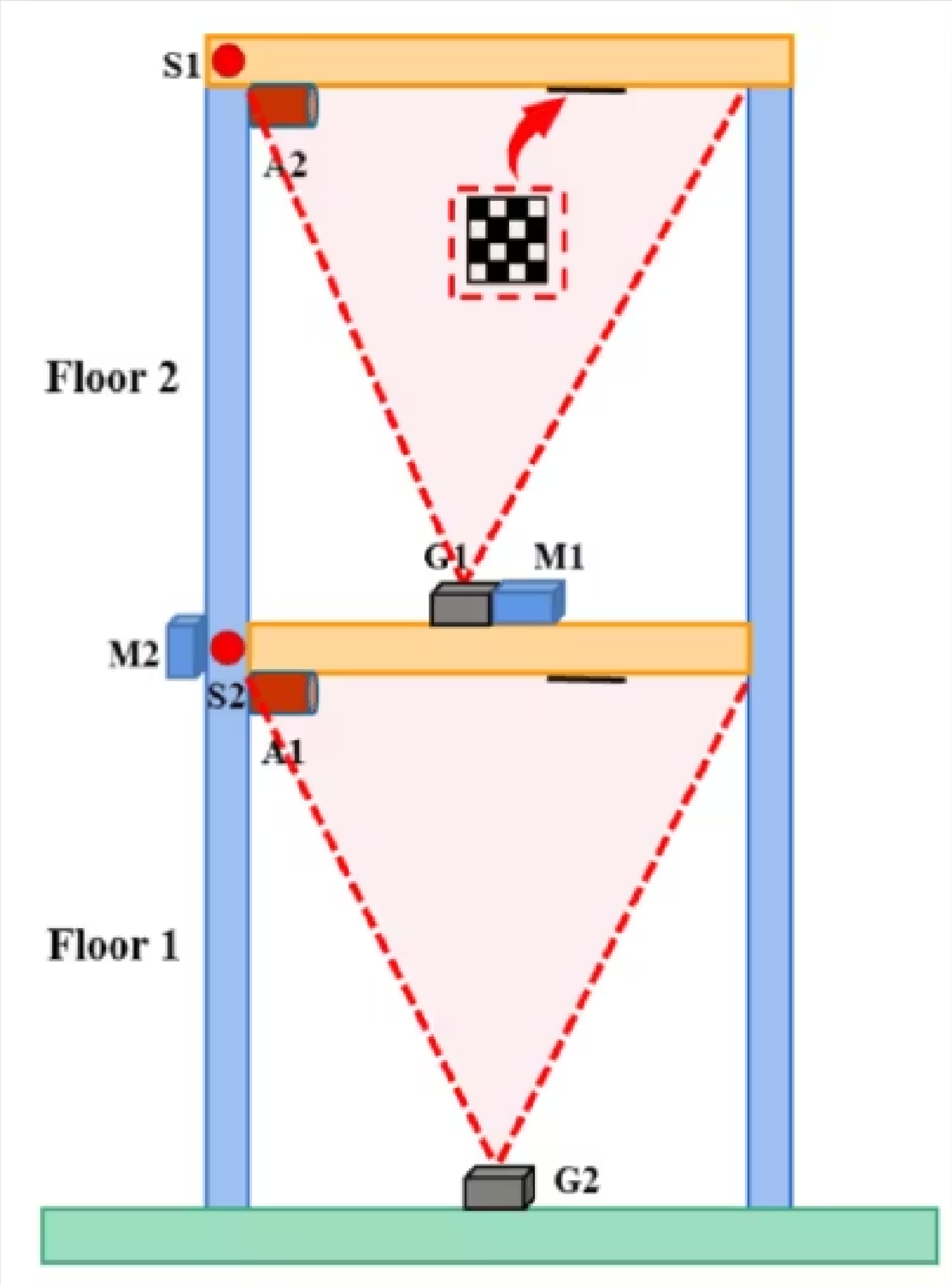
from Shan et al. 2025

Inter-story drift

How to observe it?

Computer vision (Shan et al. 2025)

- internal cameras on each floor
- identify and track physical objects

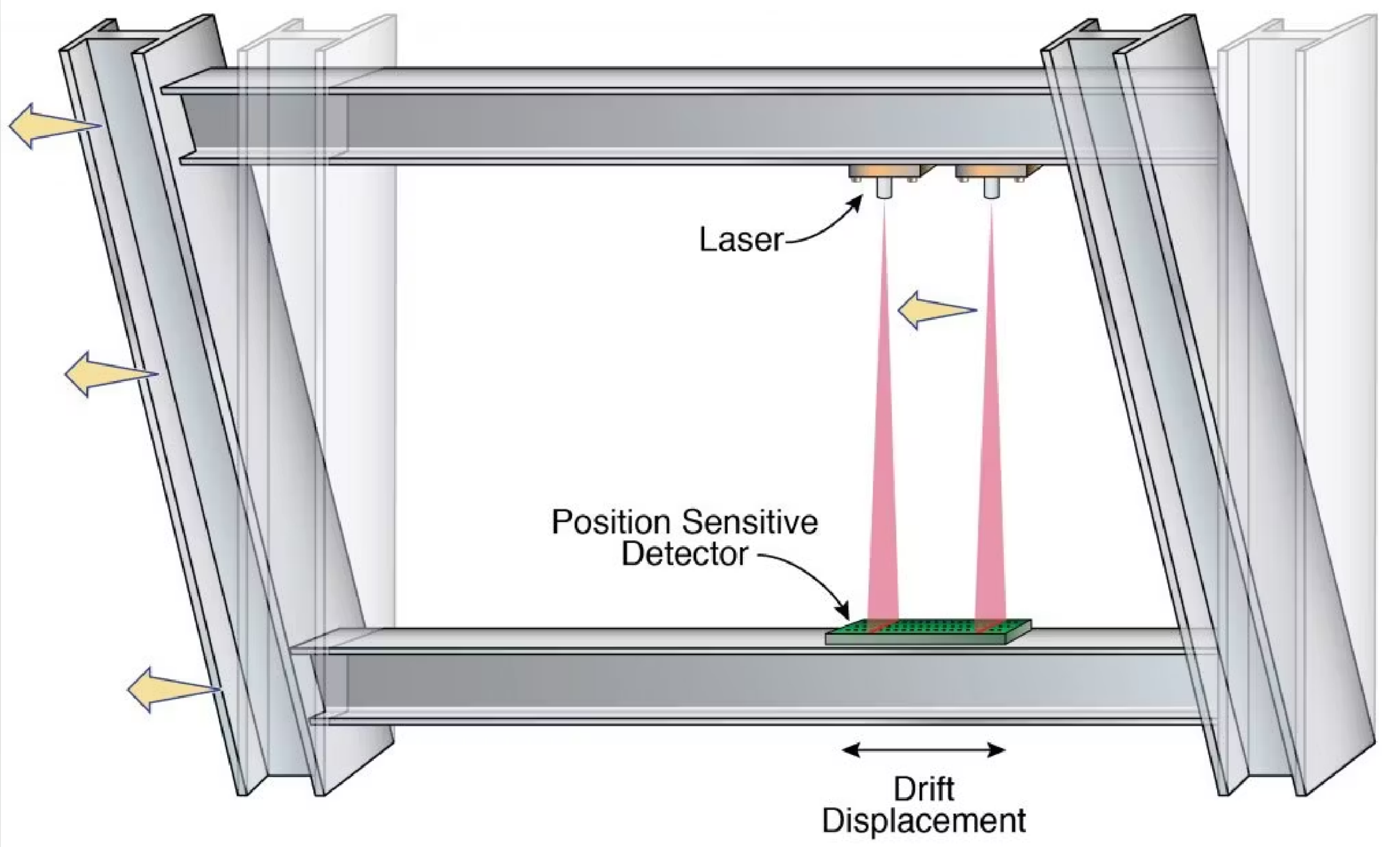


Try Pitch

Inter-story drift

How to observe it?

Position sensitive devices

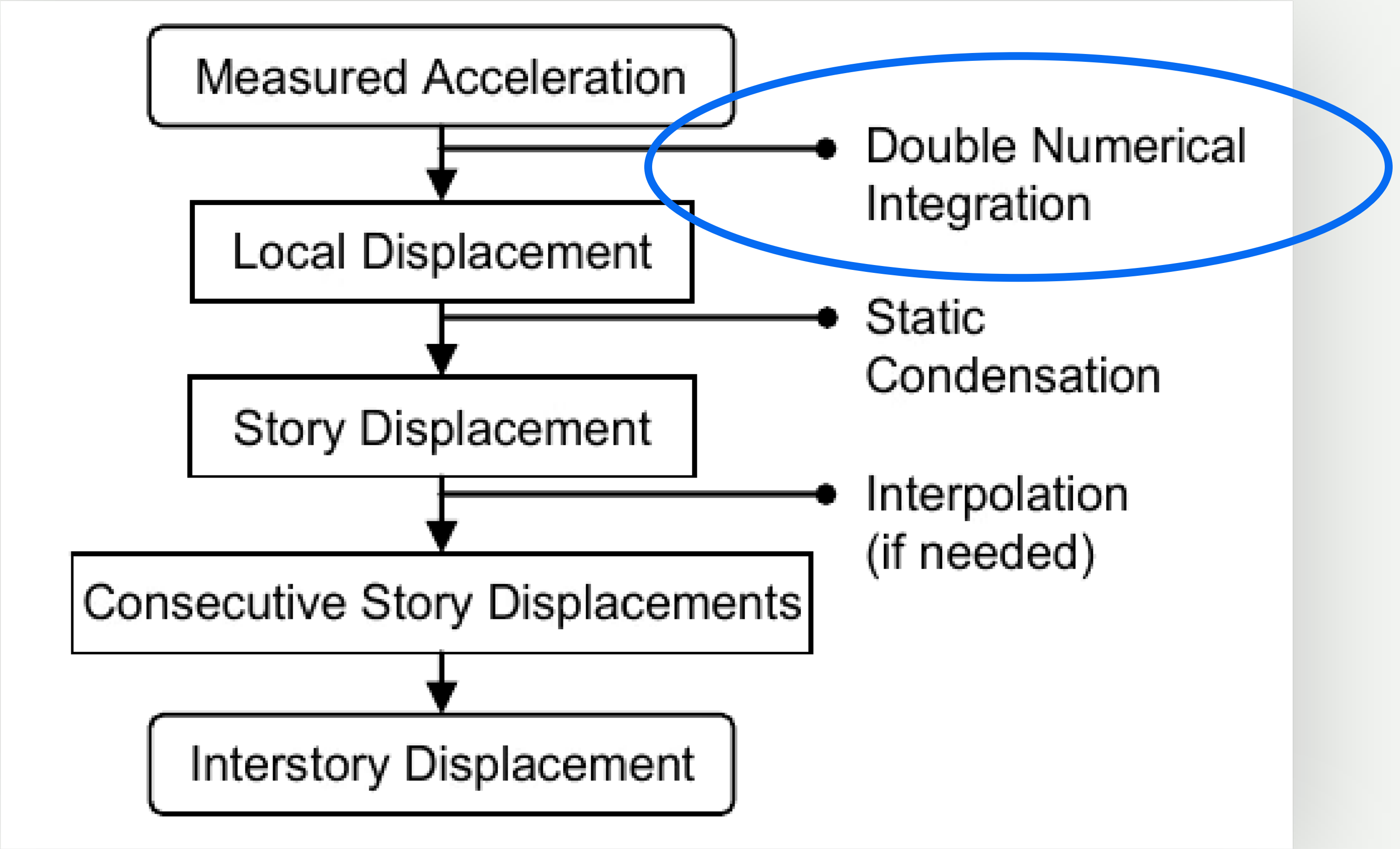


from Petrone et al. 2018

Inter-story drift

How to observe it?

The most commonly used method: **double integration of accelerometer recordings**

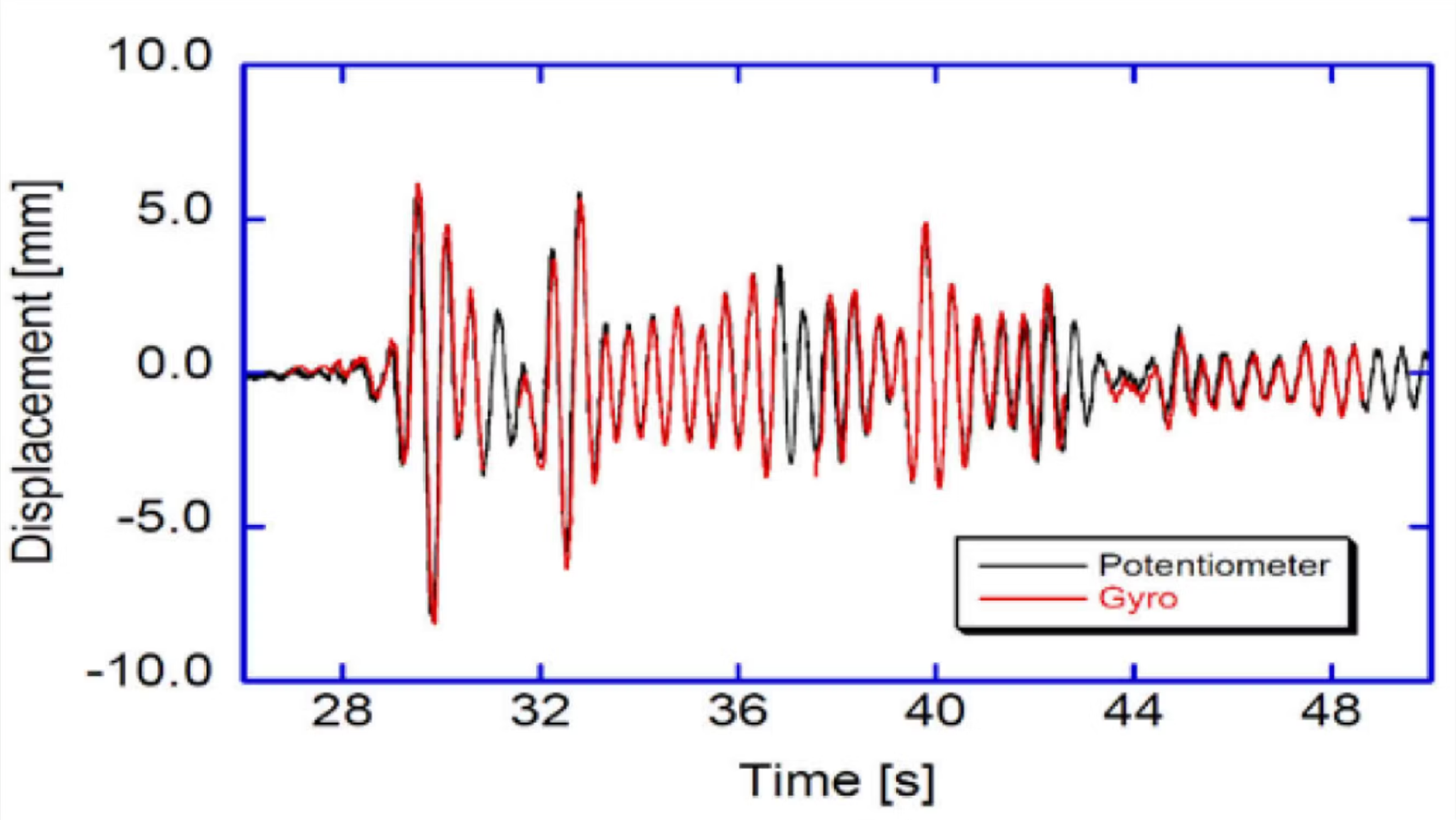


from Skolnik and Wallace, 2010

Inter-story drift

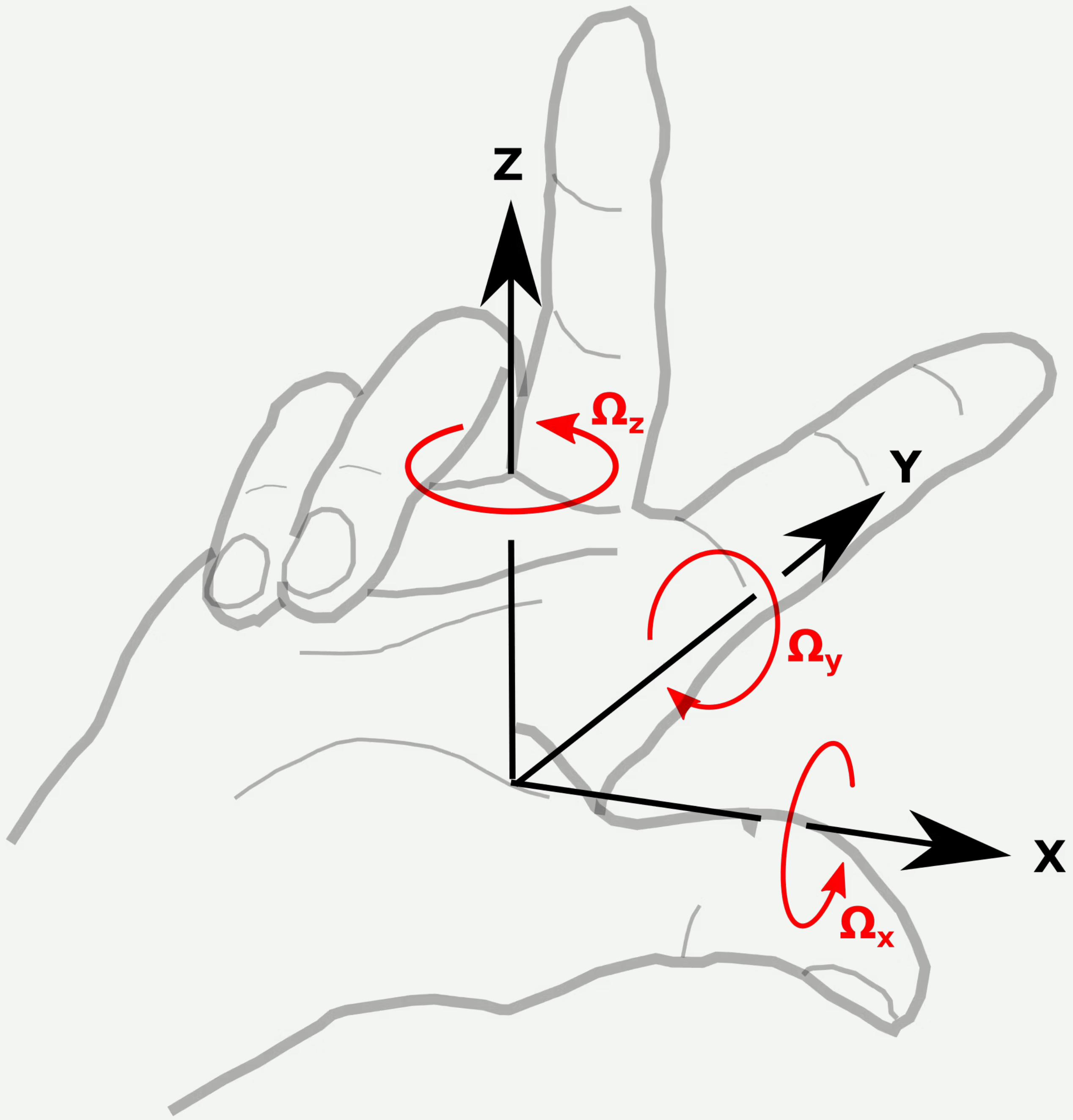
How to observe it?

Using single integration of horizontal rotation rate recordings



from Schreiber et al. 2009

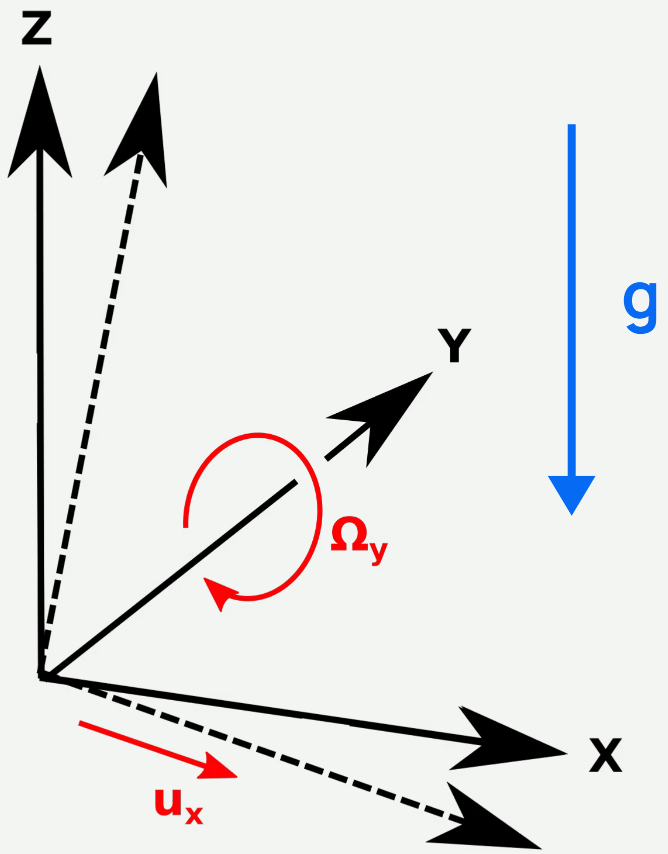
How can 6C observations help?

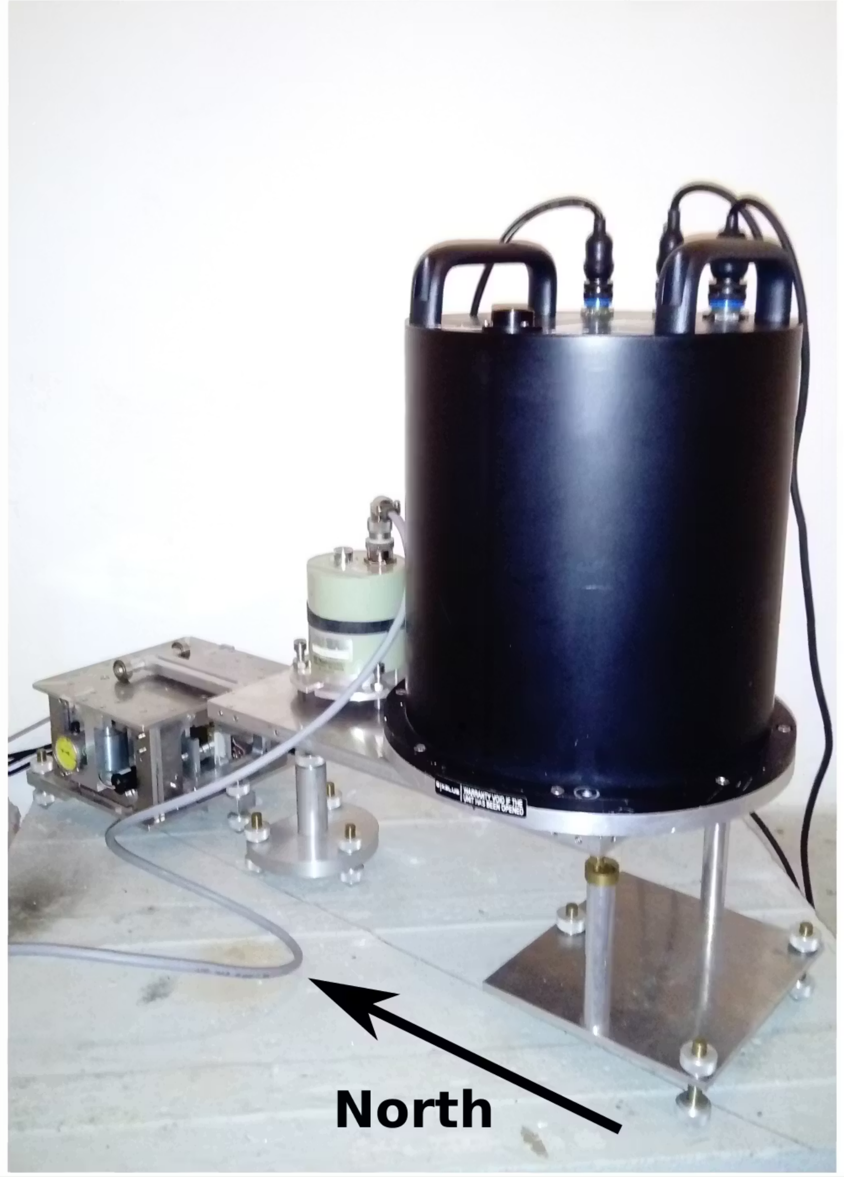


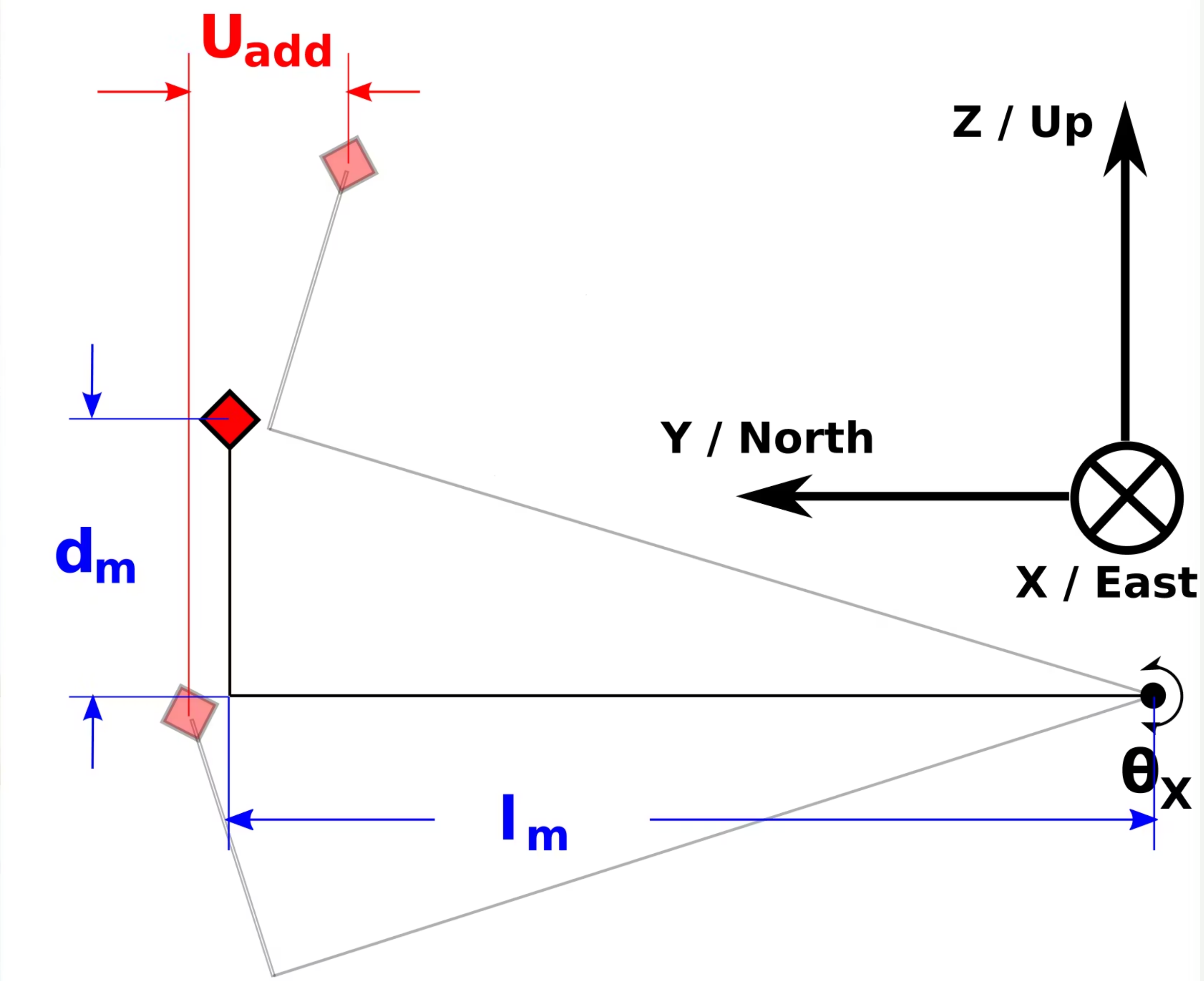
Tilt - horizontal coupling

Seismometers are sensitive to both: horizontal acceleration and tilt

Measuring the horizontal rotation allows for dynamic tilt correction of horizontal seismometer recordings



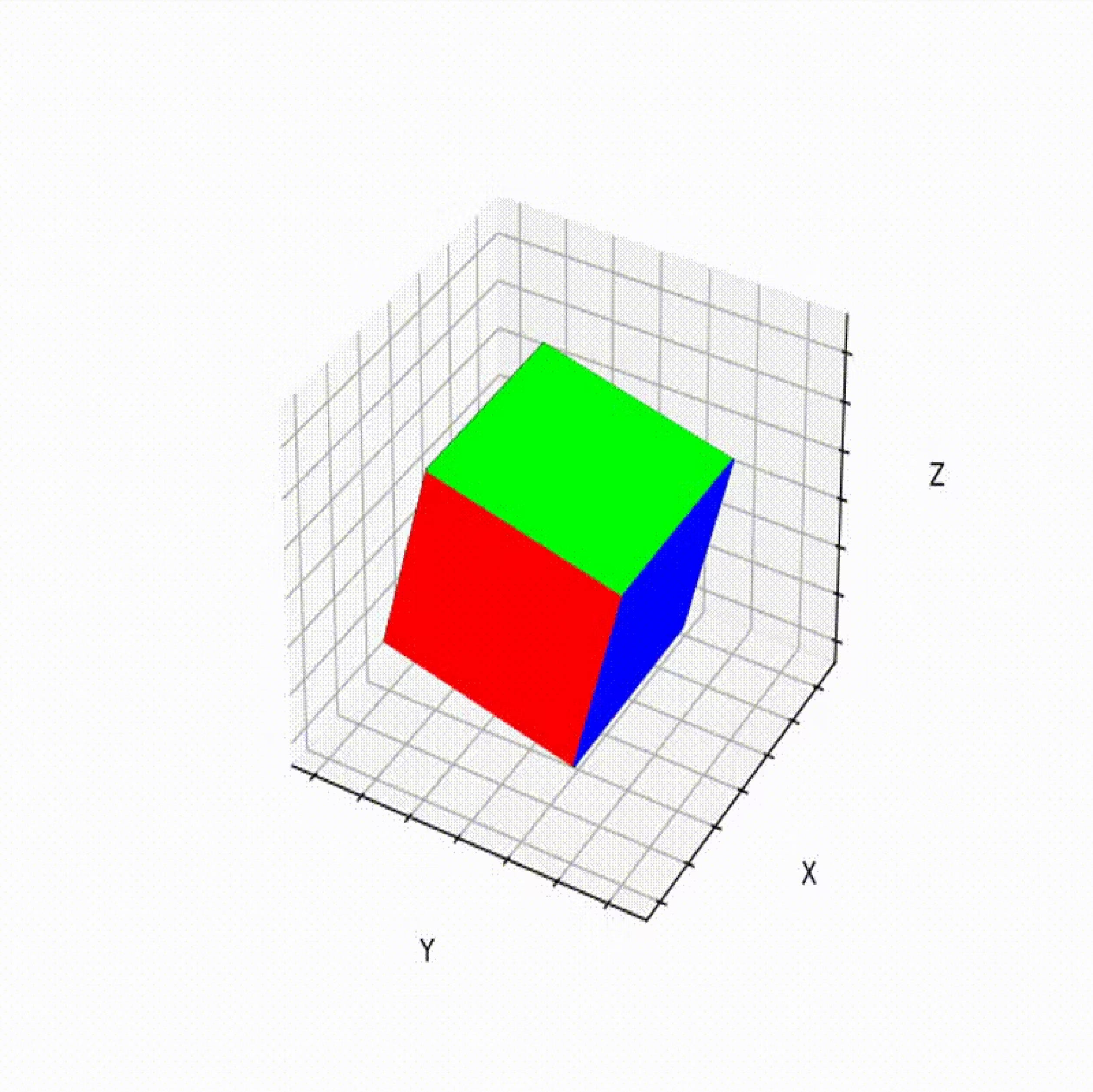




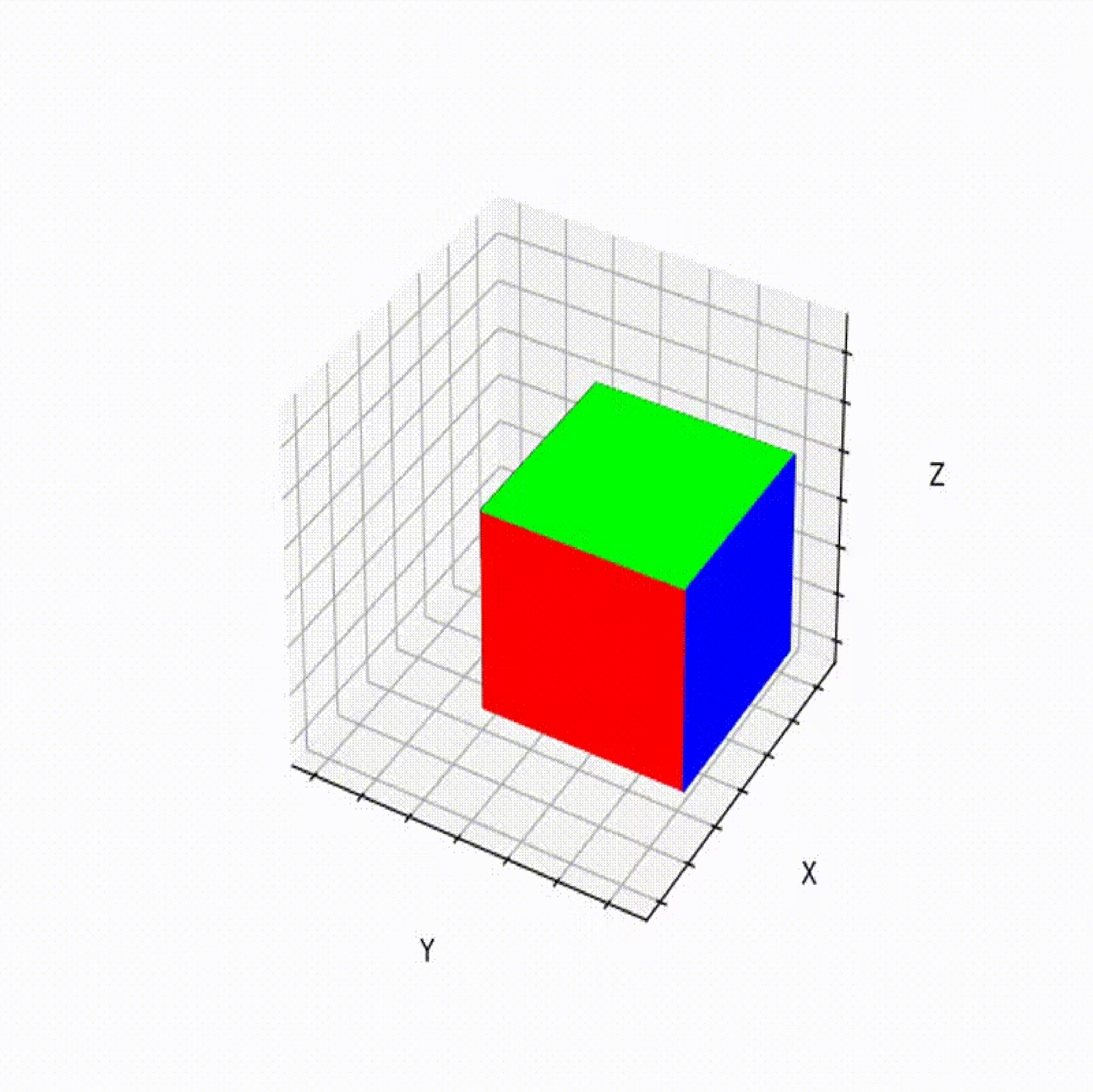
Tilt-horizontal coupling

Tilt = rotation around a horizontal axis

input motion



seismometer output

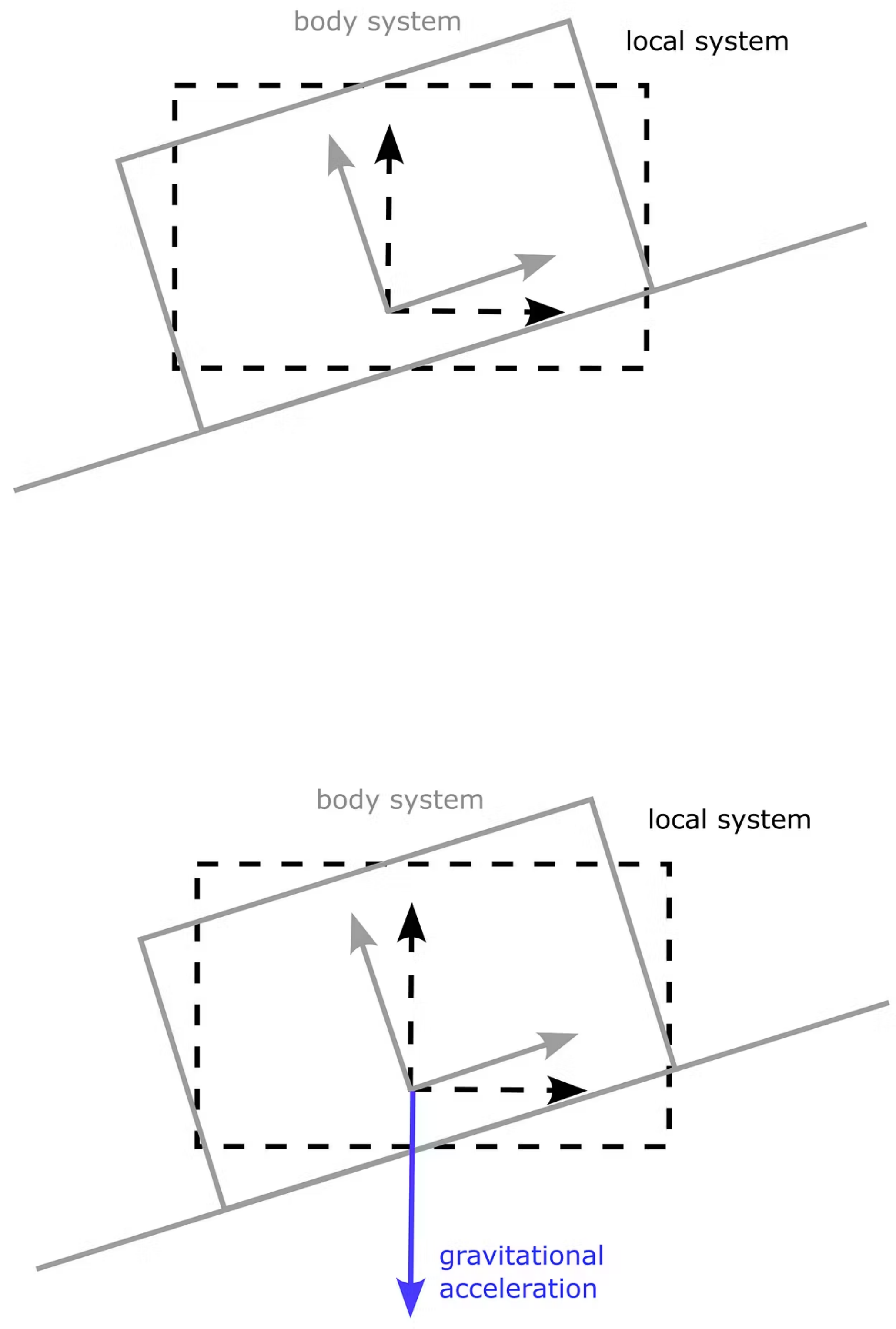


Attitude correction

standard procedures in inertial navigation

different problems in seismology:

- no transitions between north/south hemisphere
- very week motions
- worse SNR



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Attitude correction

Lin et al. 2010

Transform the rotation rate recordings from the body system to the local system

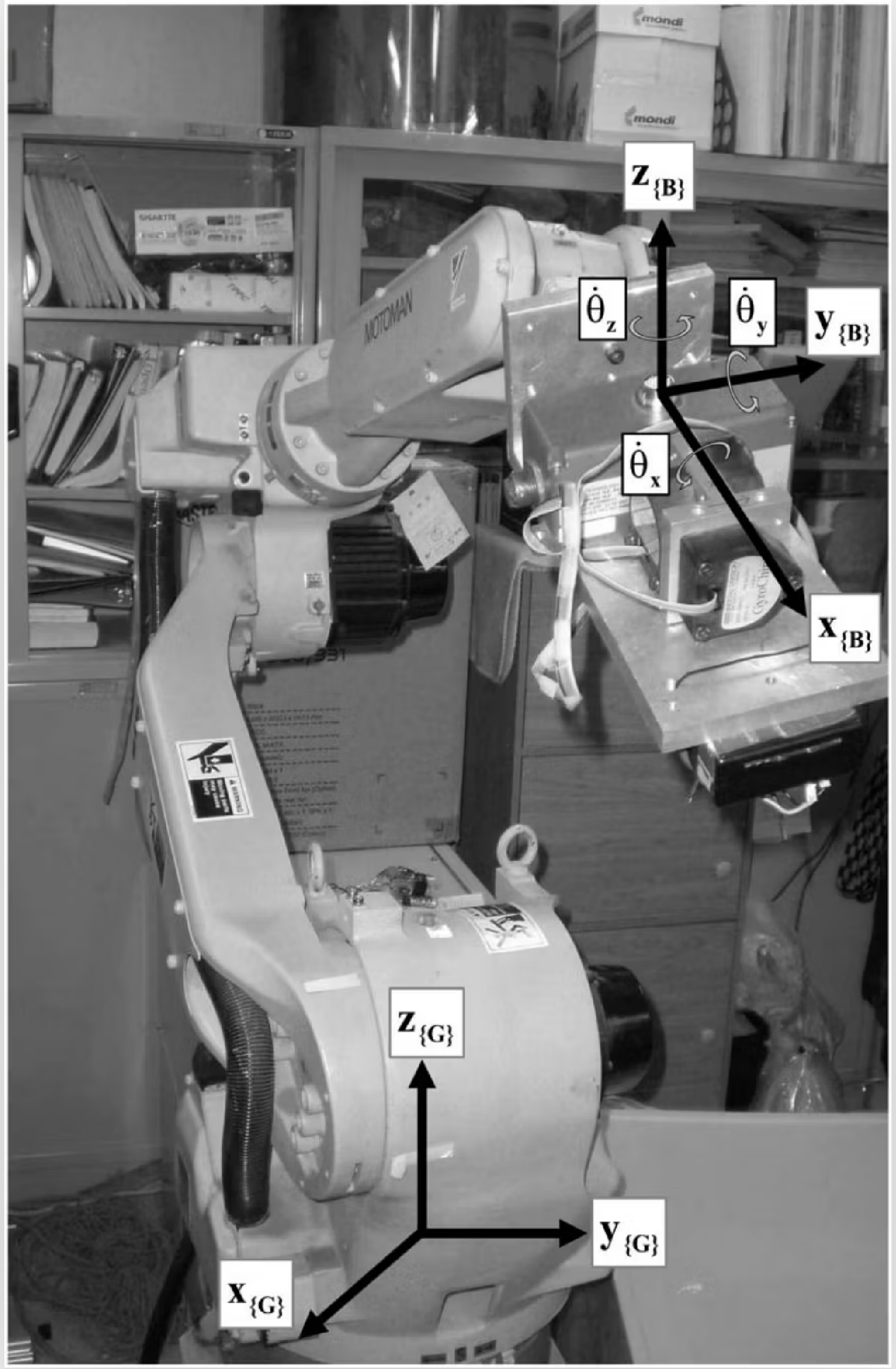
$$\begin{bmatrix} \dot{\Psi}_x(t) \\ \dot{\Psi}_y(t) \\ \dot{\Psi}_z(t) \end{bmatrix} = \begin{bmatrix} 1 & S_x \tan\Psi_y & C_x \tan\Psi_y \\ 0 & C_x & -S_x \\ 0 & S_x \sec\Psi_y & C_x \sec\Psi_y \end{bmatrix} \dot{\boldsymbol{\theta}}_i. \qquad (10)$$

correct acceleration recordings for tilt and centrifugal acceleration

$$\begin{aligned} \ddot{u}_x &= f_x - \dot{\theta}_y \dot{u}_z + \dot{\theta}_z \dot{u}_y + g S_y \\ \ddot{u}_y &= f_y - \dot{\theta}_z \dot{u}_x + \dot{\theta}_x \dot{u}_z - g C_y S_x \\ \ddot{u}_z &= f_z - \dot{\theta}_x \dot{u}_y + \dot{\theta}_y \dot{u}_x + g(1 - C_y C_x). \qquad (15) \end{aligned}$$

transform acceleration recordings from body frame to local frame

$$\begin{aligned} \mathbf{P_G} &= \mathbf{TP_B} = (\mathbf{T}_z \mathbf{T}_y \mathbf{T}_x)\mathbf{P_B} \\ &= \begin{bmatrix} C_z & -S_z & 0 \\ S_z & C_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_y & 0 & S_y \\ 0 & 1 & 0 \\ -S_y & 0 & C_y \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_x & -S_x \\ 0 & S_x & C_x \end{bmatrix} \mathbf{P_B} \\ &= \begin{bmatrix} C_z C_y & C_z S_y S_x - S_z C_x & C_z S_y C_x + S_z S_x \\ S_z C_y & S_z S_y S_x + C_z C_x & S_z S_y C_x - C_z S_x \\ -S_y & C_y S_x & C_y C_x \end{bmatrix} \mathbf{P_B}, \qquad (4) \end{aligned}$$



Practical

Practical on inter-story drift calculation

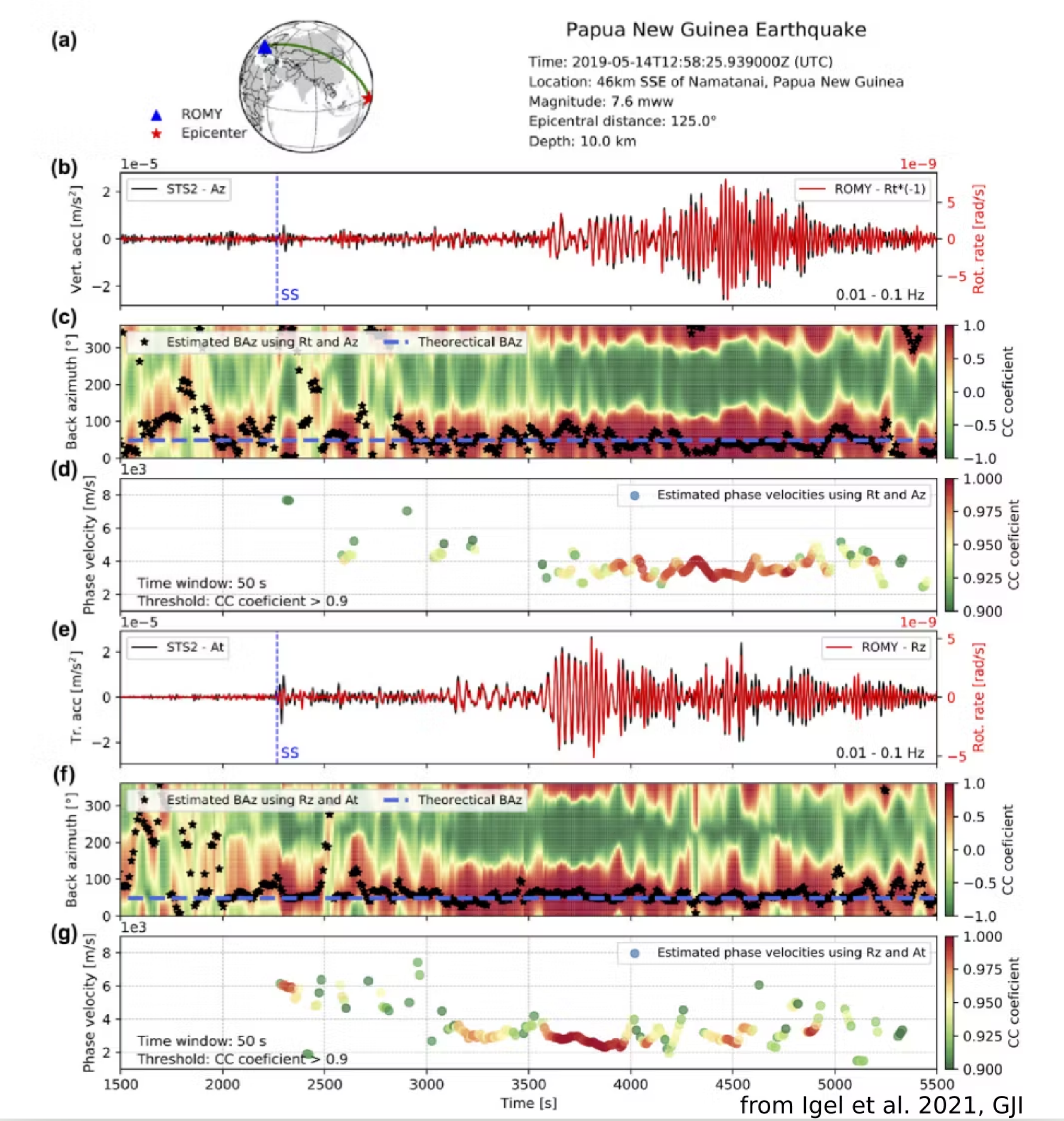
- double integration of accelerometer recordings
- using horizontal rotation
- using 6C recordings to correct for attitude and tilt

6C amplitude ratios

remember from Sabrinas talk:

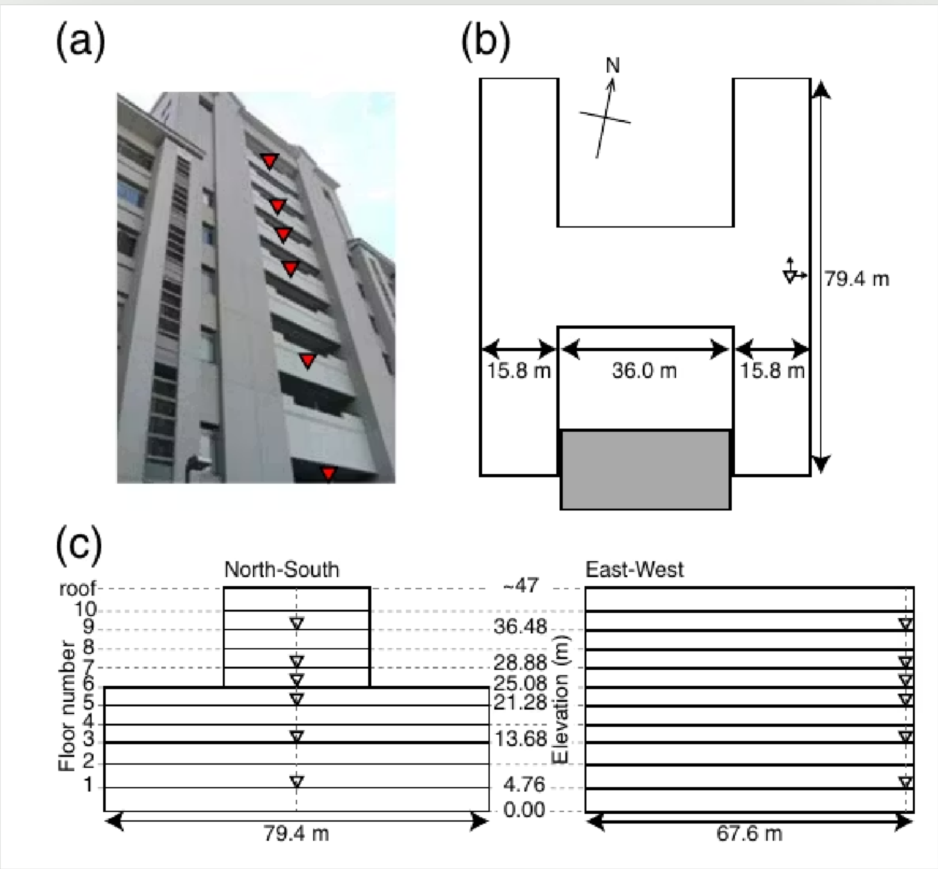
Local Love / Rayleigh wave phase velocity can be determined from amplitude ratios.

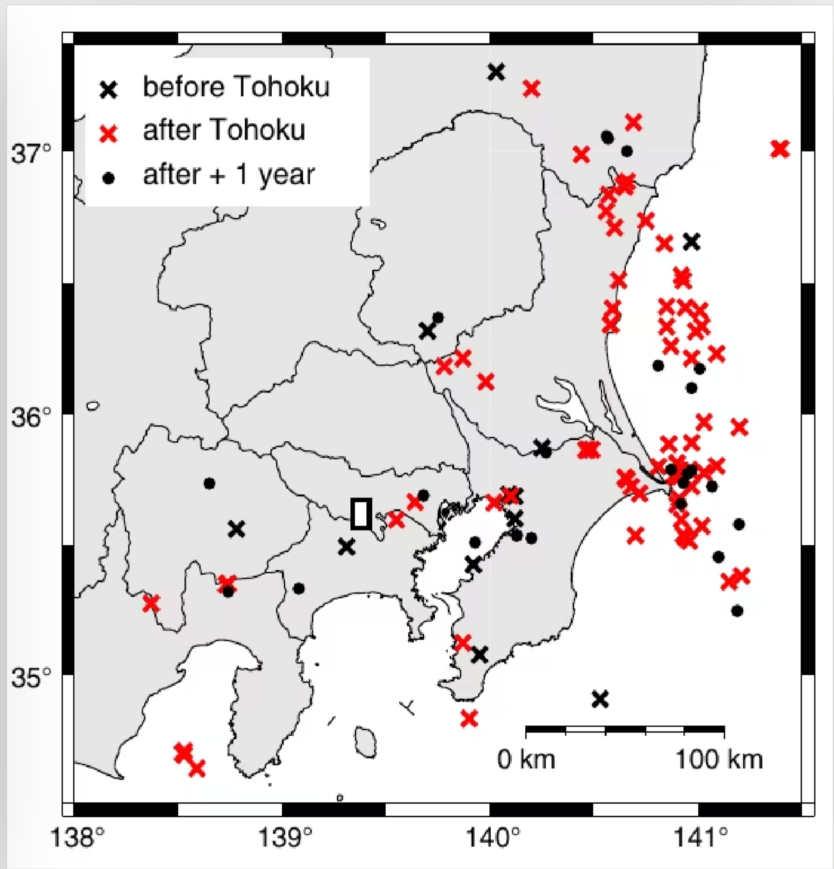
Can we transfer this concept to structural health monitoring?

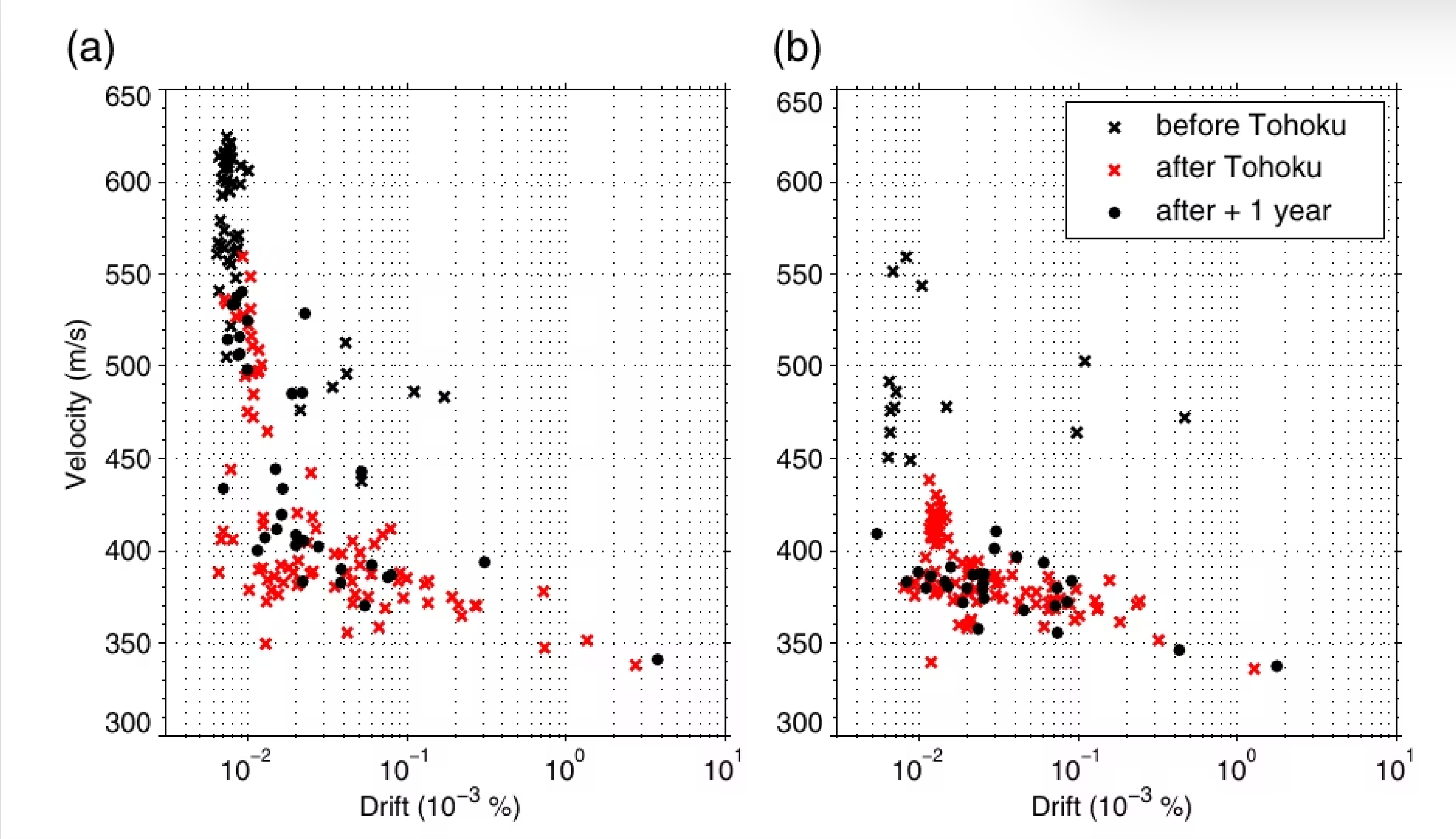


from Igel et al. 2021, GJI

Phase velocity and structural damage







Nakata et al. 2015

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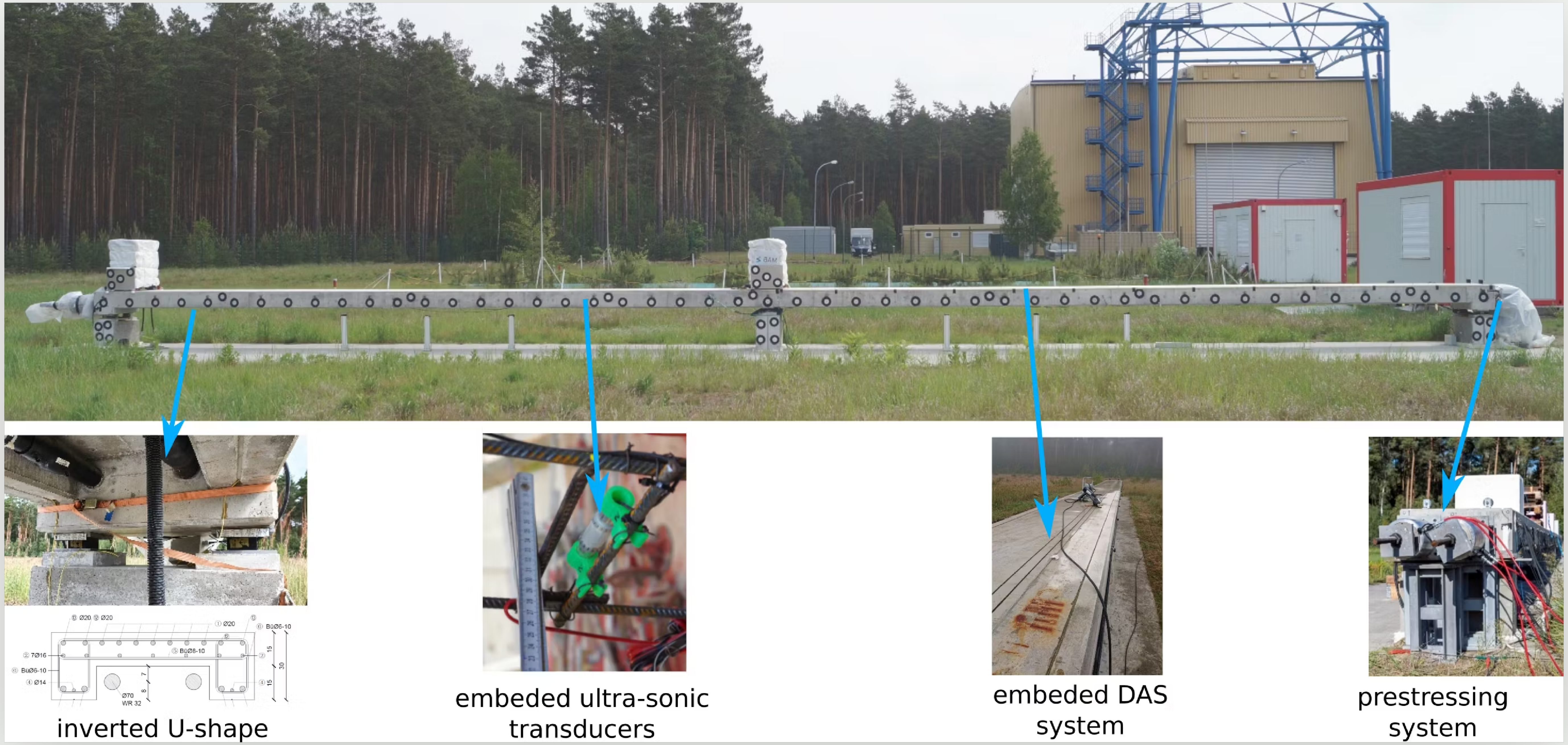
The experiment

The BLEIB test structure



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The experiment

the pre-stressing system

the instrumentation

putting static load on top

the source

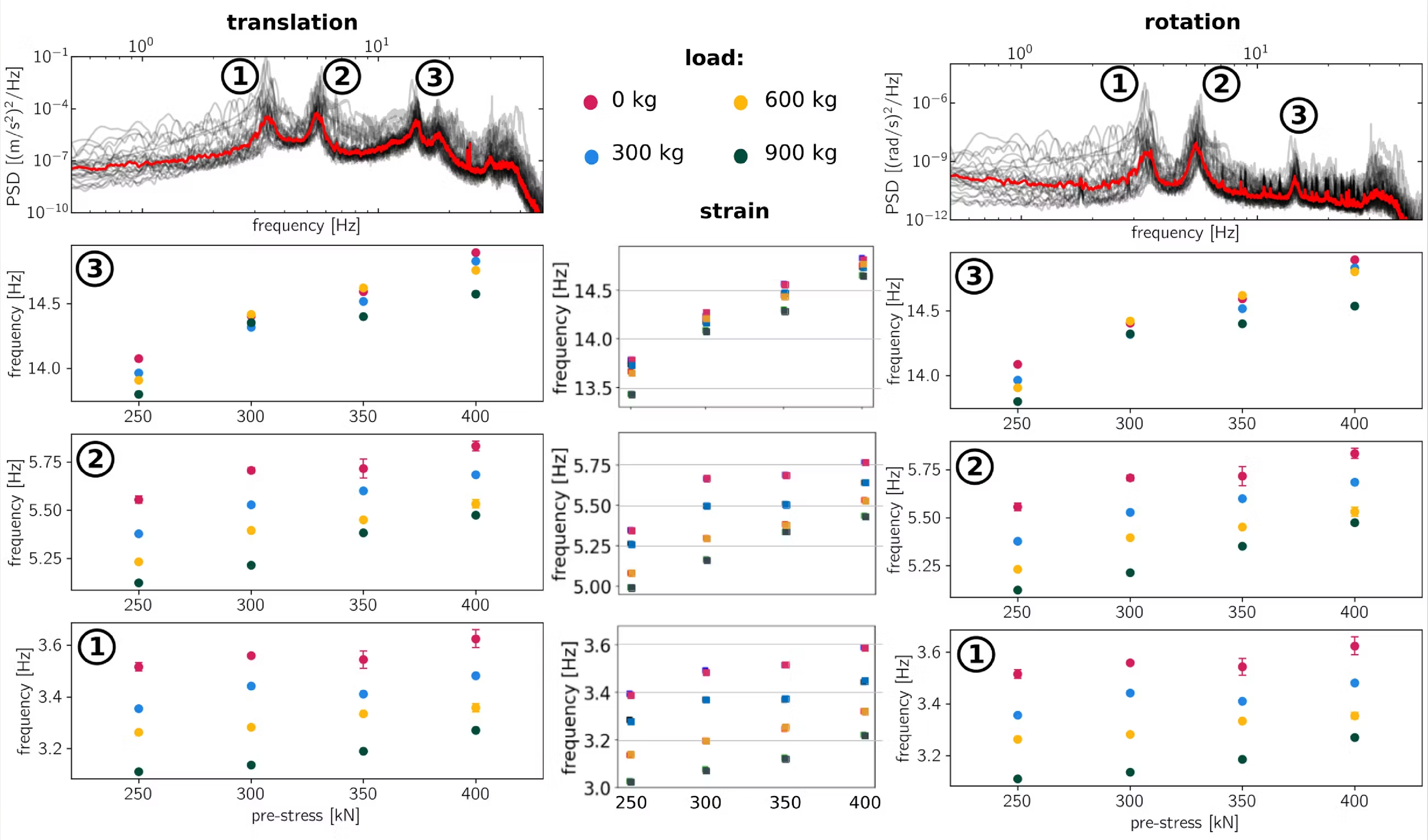
The experiment

the pre-stress - load - source sequence

pre-stress	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★
400kN	0kg	300kg	600kg	900kg																0kg	300kg	600kg	900kg
350kN					0kg	300kg	600kg	900kg											0kg				
300kN									0kg	300kg	600kg	900kg						0kg					
250kN													0kg	300kg	600kg	900kg	0kg						

★ = 3 hammer hits

Results - frequency picking



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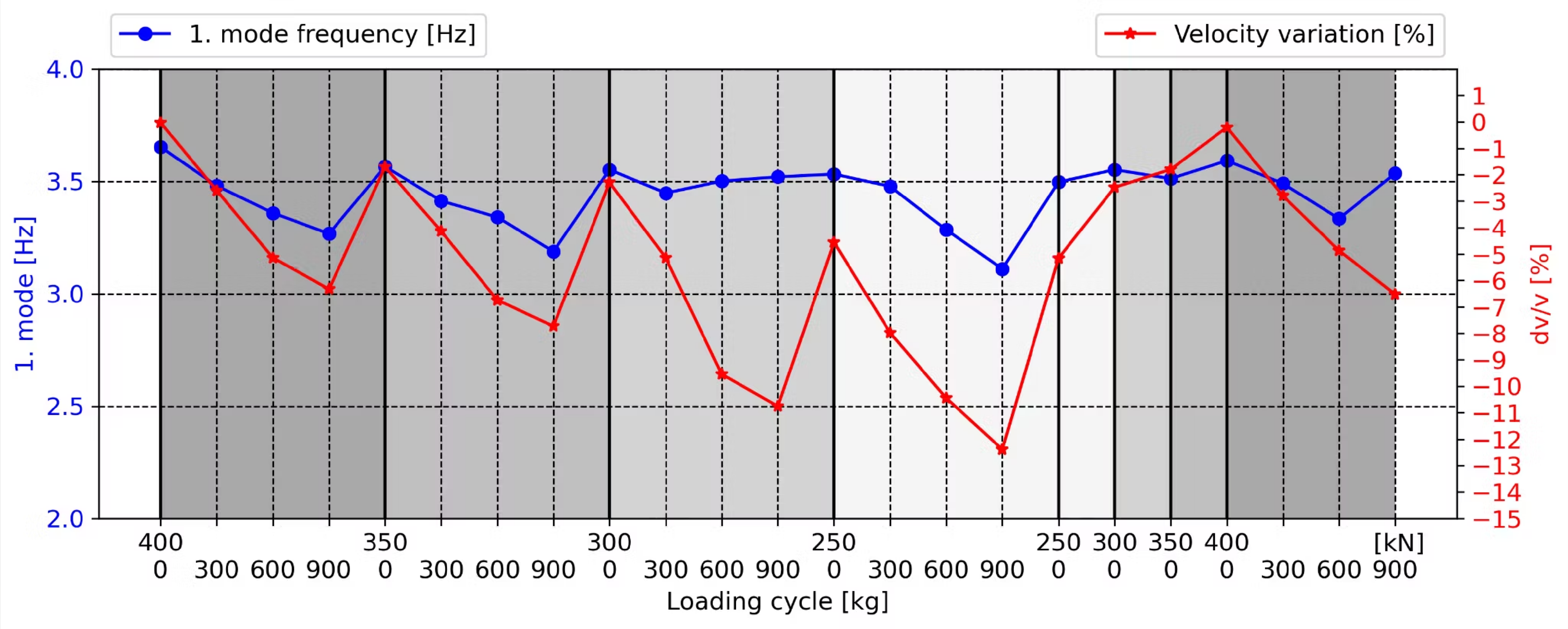
Results - interferometry



Try Pitch

Practical

How to detect damage with 6C amplitude ratios?

6C instrumentation for SHM

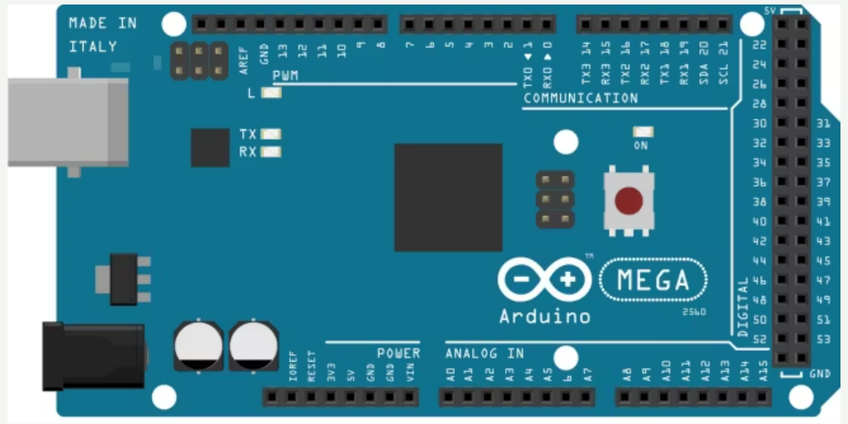
it all started with a donation from iXblue: 20 non-compliant IMU50 sensor units

6C instrumentation for SHM

IMU50 sensor unit

+

microcontroller



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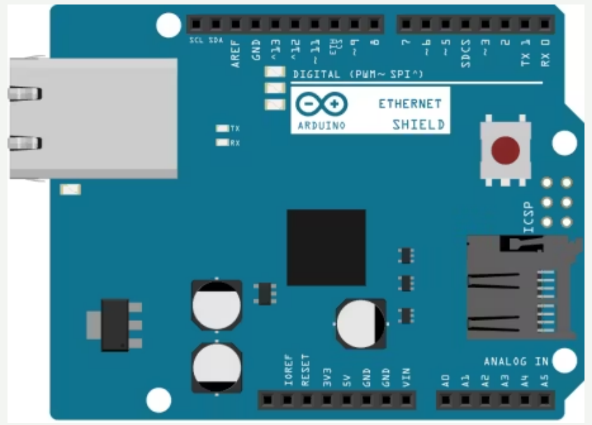
network interface



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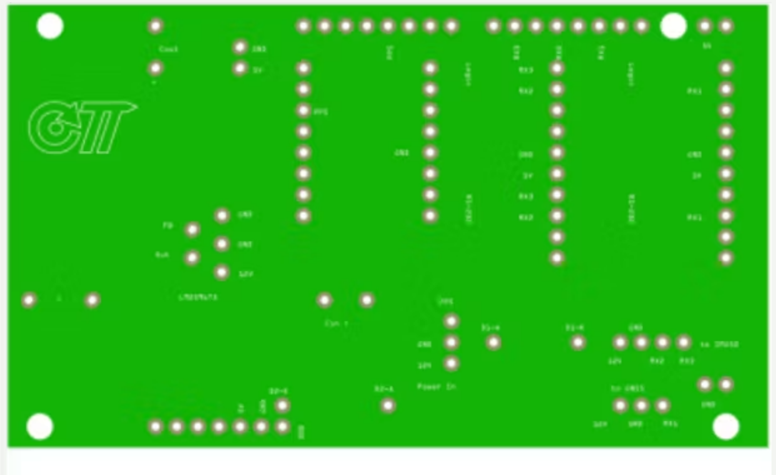
interface board



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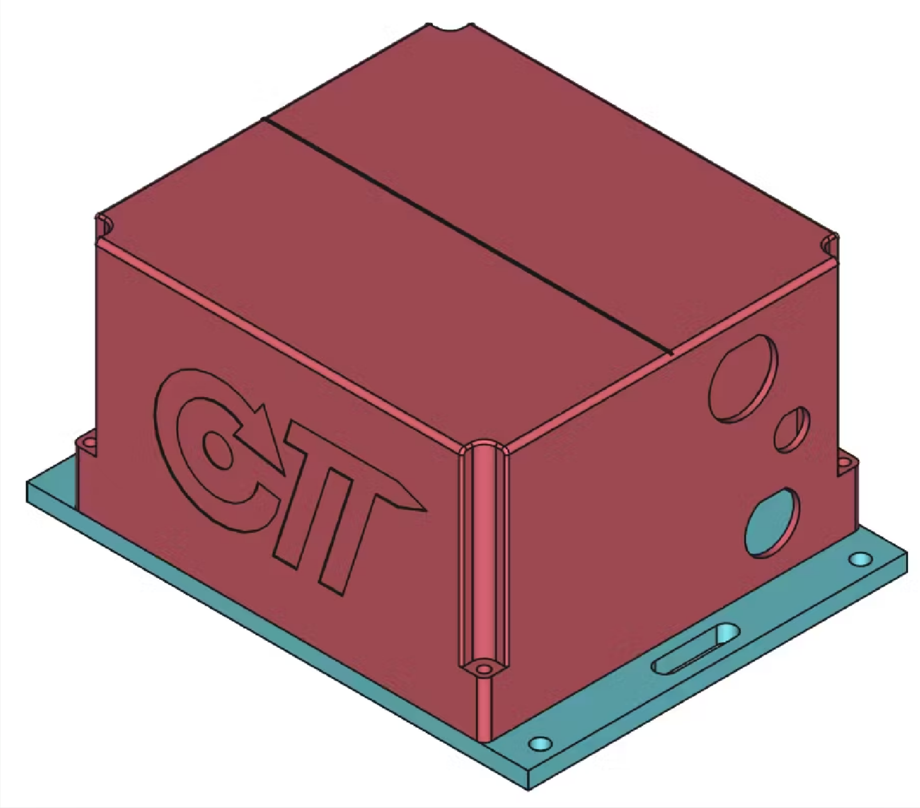
base plate and housing



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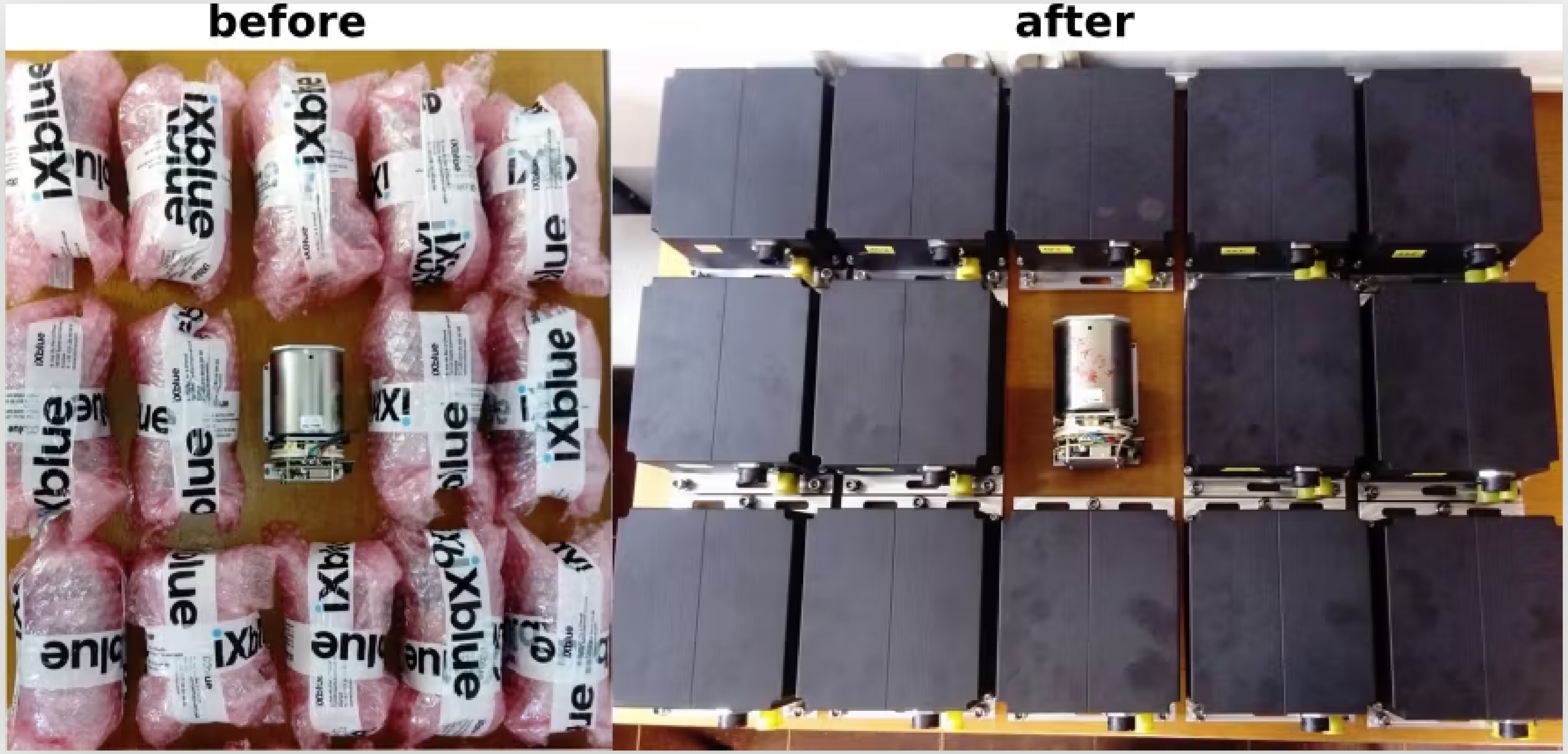
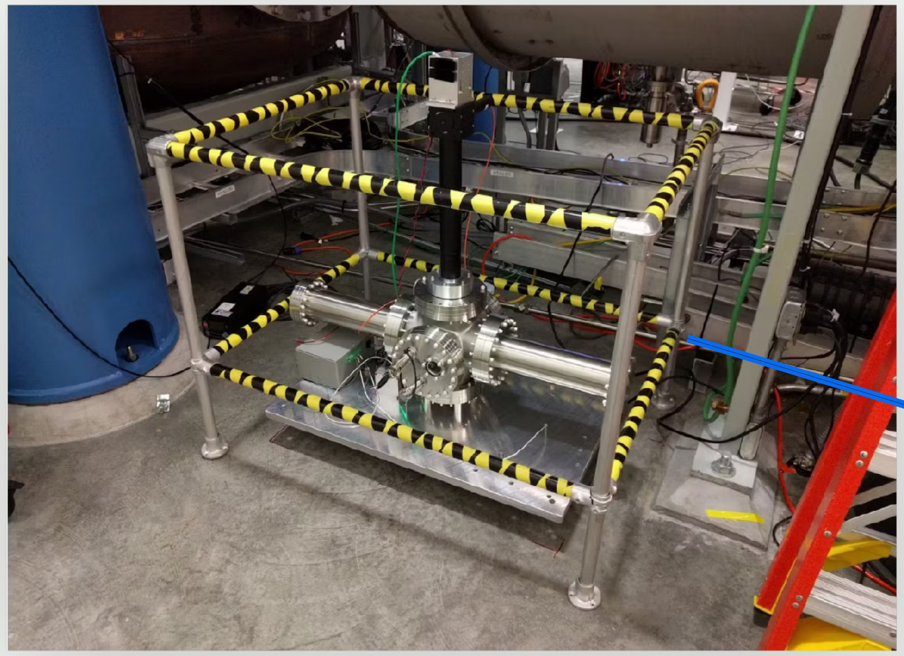
6C instrumentation for SHM

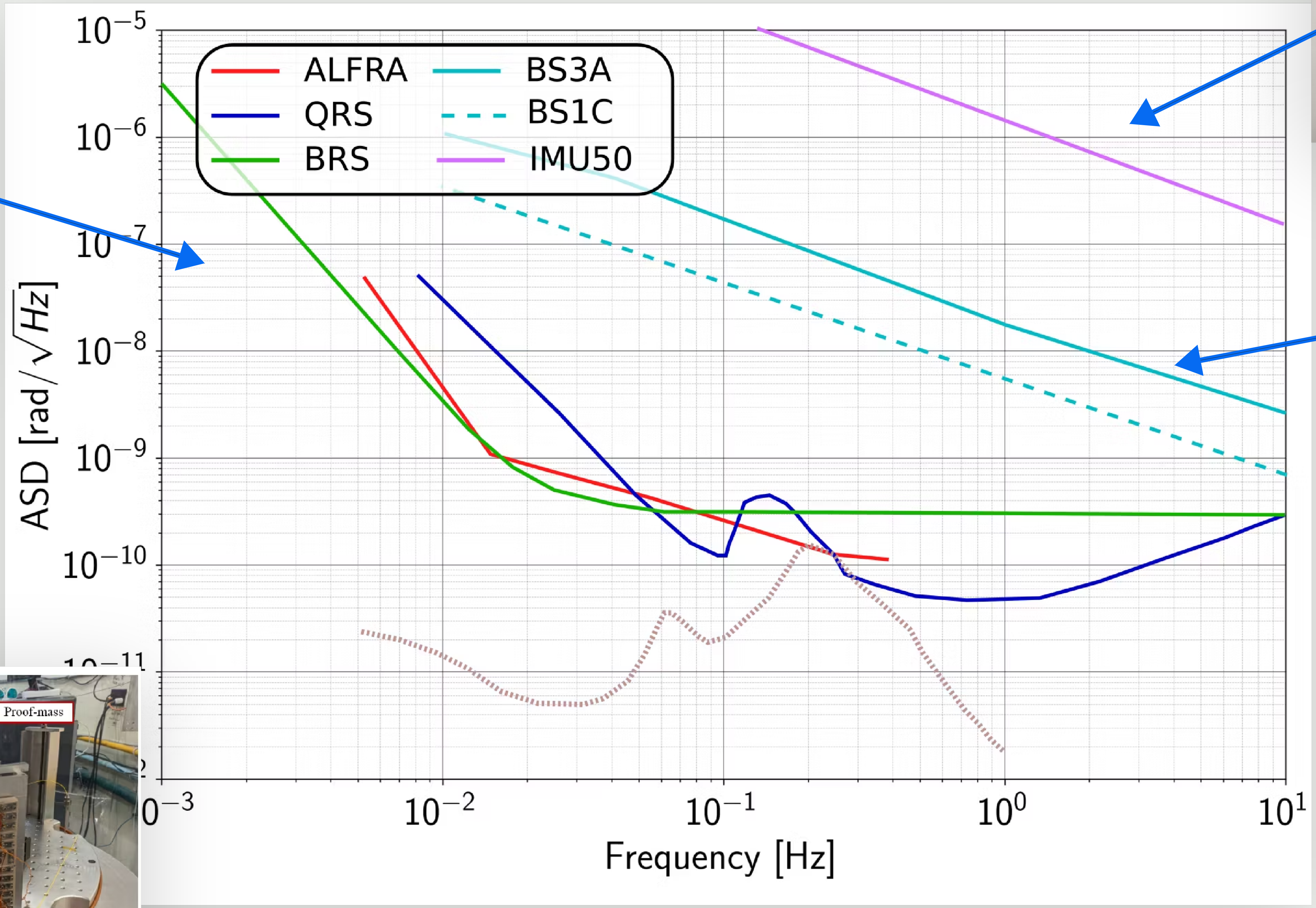
14 6C strong motion sensors for SHM

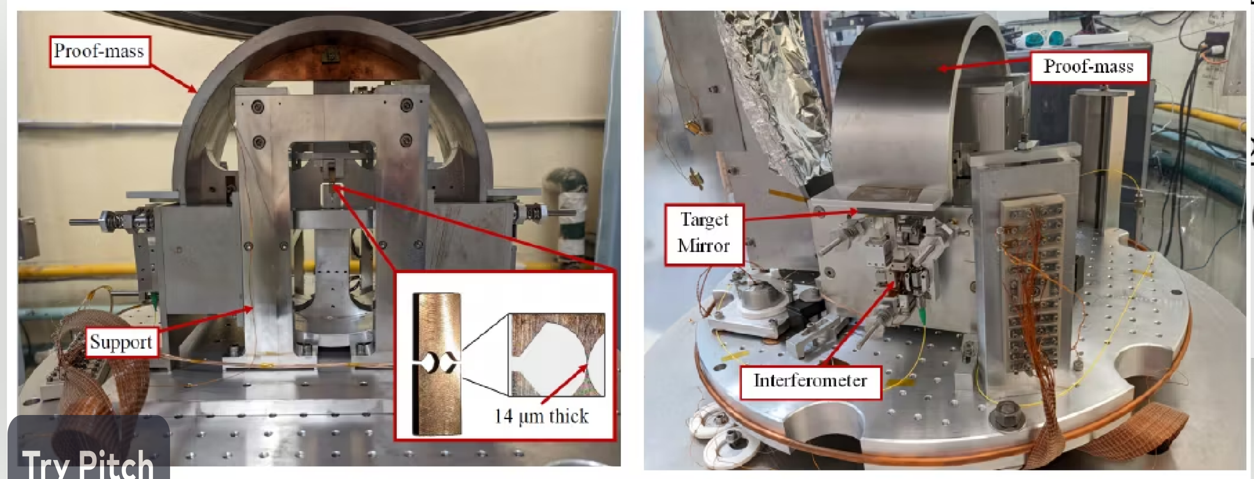
- 400Hz sampling rate
- GNSS / PPS synchronized
- miniseed output via TCP / IP
- operable in a network or stand-alone



6C instrumentation for SHM







latest beam balance version (Ross et al. 2023)

Pitch

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