15th Munich Earth Skience School
ObsPy goes Downtown: Seismology in Cities

6C Structural Monitoring

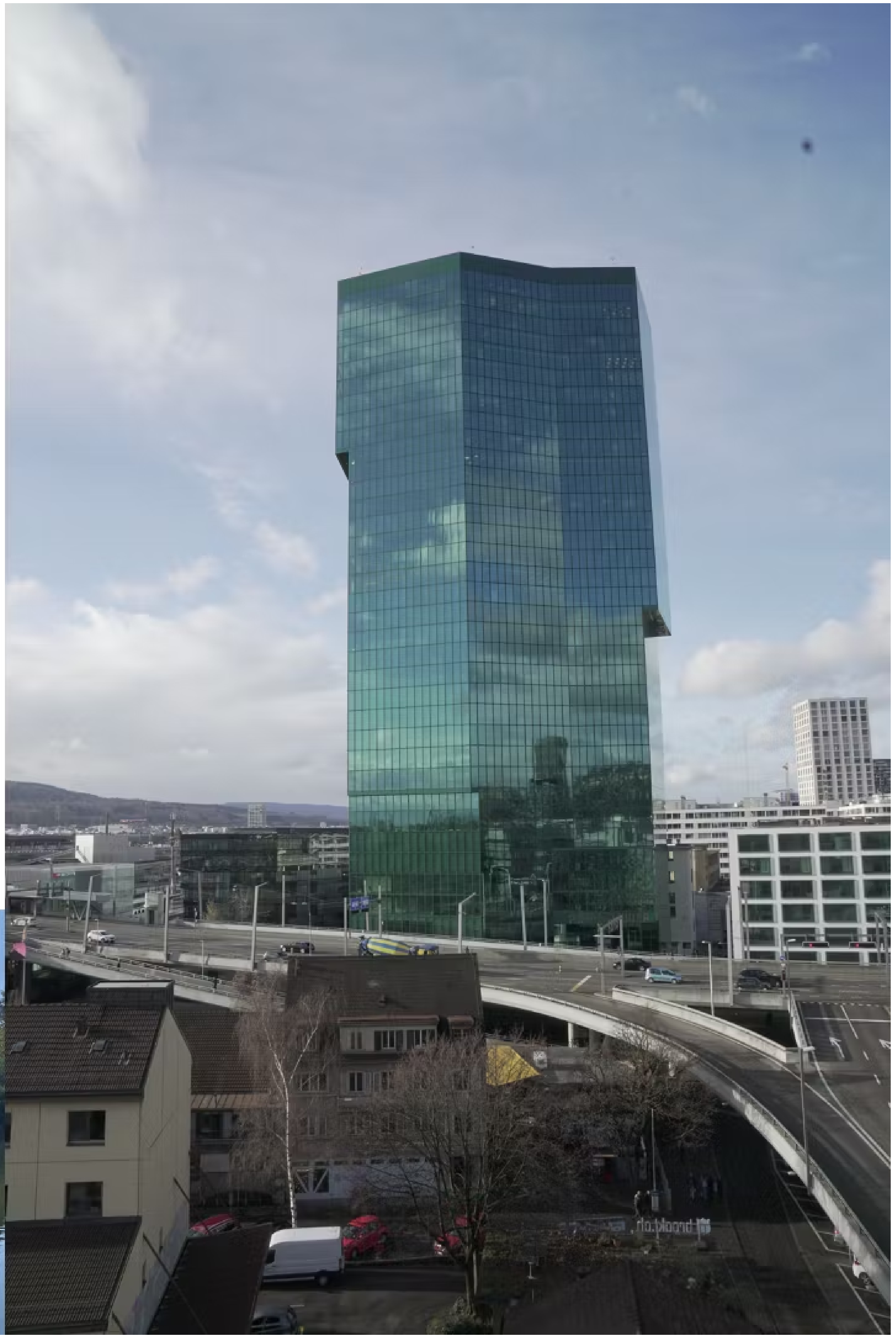
Yara Rossi

27 February 2025

Structural Characterisation

System Properties of Structures

- Frequency
- Mode shape
- Damping



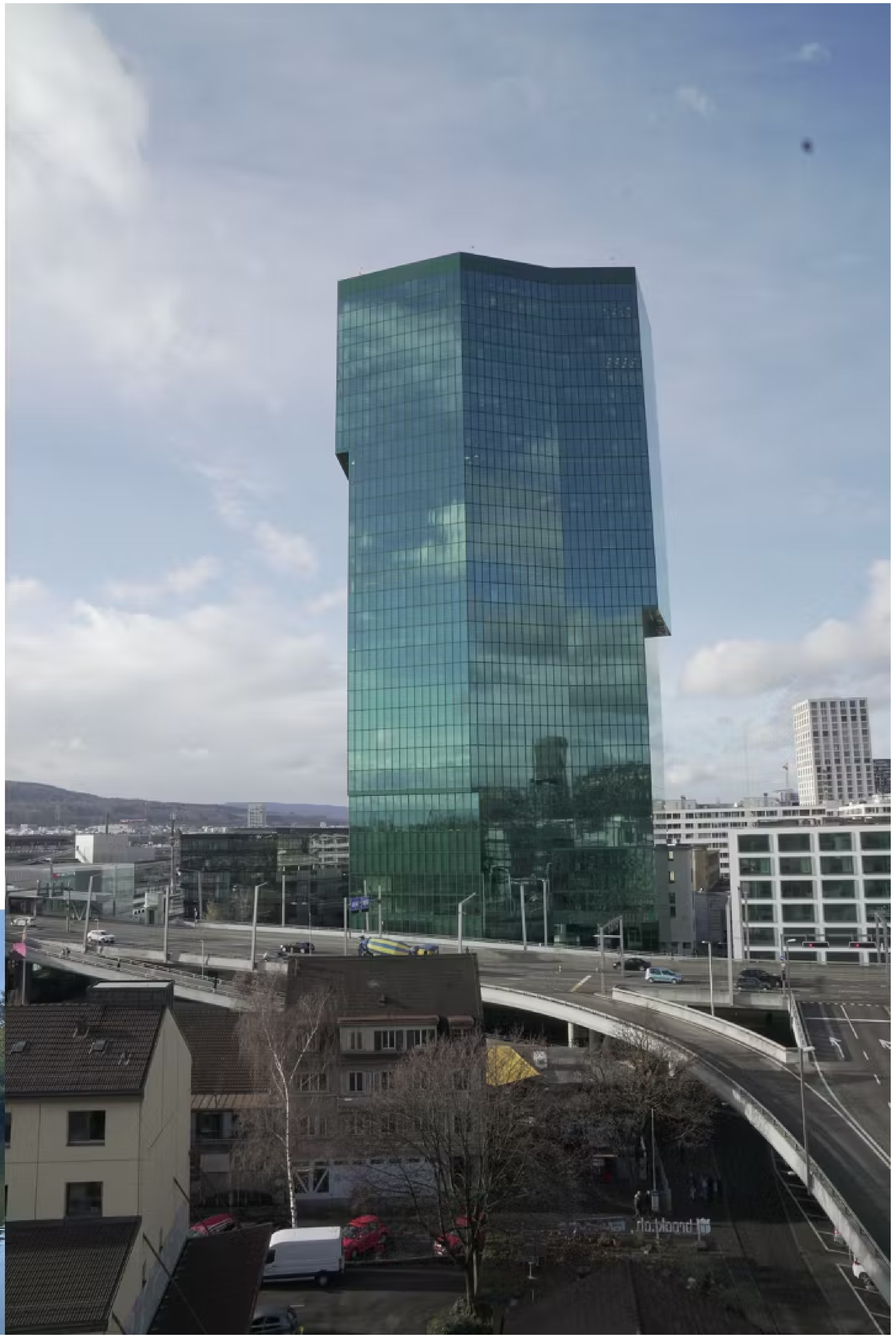
Structural Characterisation

System Properties of Structures

- Frequency
- Mode shape
- Damping

Structural Health Monitoring

- Detect, localise, identify and predict damages
- System properties of healthy structure
- Monitor these properties



Structural Characterisation

System Properties of Structures

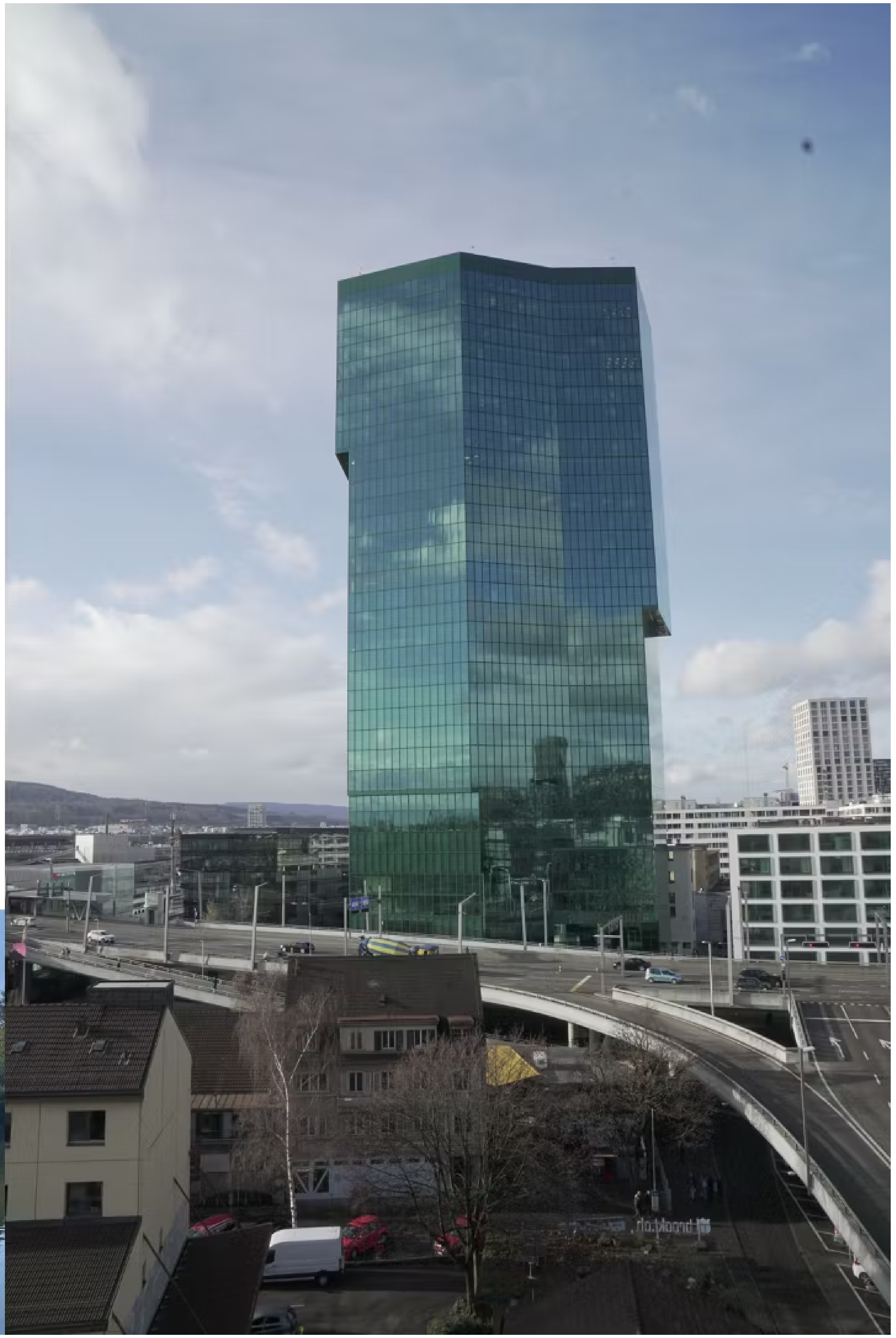
- Frequency
- Mode shape
- Damping

Structural Health Monitoring

- Detect, localise, identify and predict damages
- System properties of healthy structure
- Monitor these properties

Variability of System Properties

- Temperature, humidity, subsurface
- Wind, earthquakes
- Structural changes



Examples of why structures fail.

Ponte Morandi 2018

- collapse during strong rainstorm
- decay over time
- corrosion, cracking of concrete, settling of ground

——› Material properties

https://en.wikipedia.org/wiki/Ponte_Morandi

Examples of why structures fail.

Tacoma Narrows Bridge, 1940

- collapse during wind 64 km/h
- only 4 months old
- enhanced vibration motion

——› resonance frequency

Examples of why structures fail.

Earthquake, Tohoku 2011, Mw 9.1

- high acceleration
- enhanced vibration motion
- unstable ground (i.e., liquefaction)

——› resonance frequency + material

Examples of why structures fail.

Landslide, Brienz, CH 2023

- unstable ground (2 m/a)
- cracks from shifting ground
- impact

——› Material properties

Vibration of a building

Example: the strings of a guitar

Each string has different sound. Why?

Vibration of a building

Example: the strings of a guitar

Each string has different sound. Why?

- frequency
- thickness
- material
- length

Vibration of a building

Example: the strings of a guitar

Each string has different sound. Why?

- frequency
- thickness
- material
- length

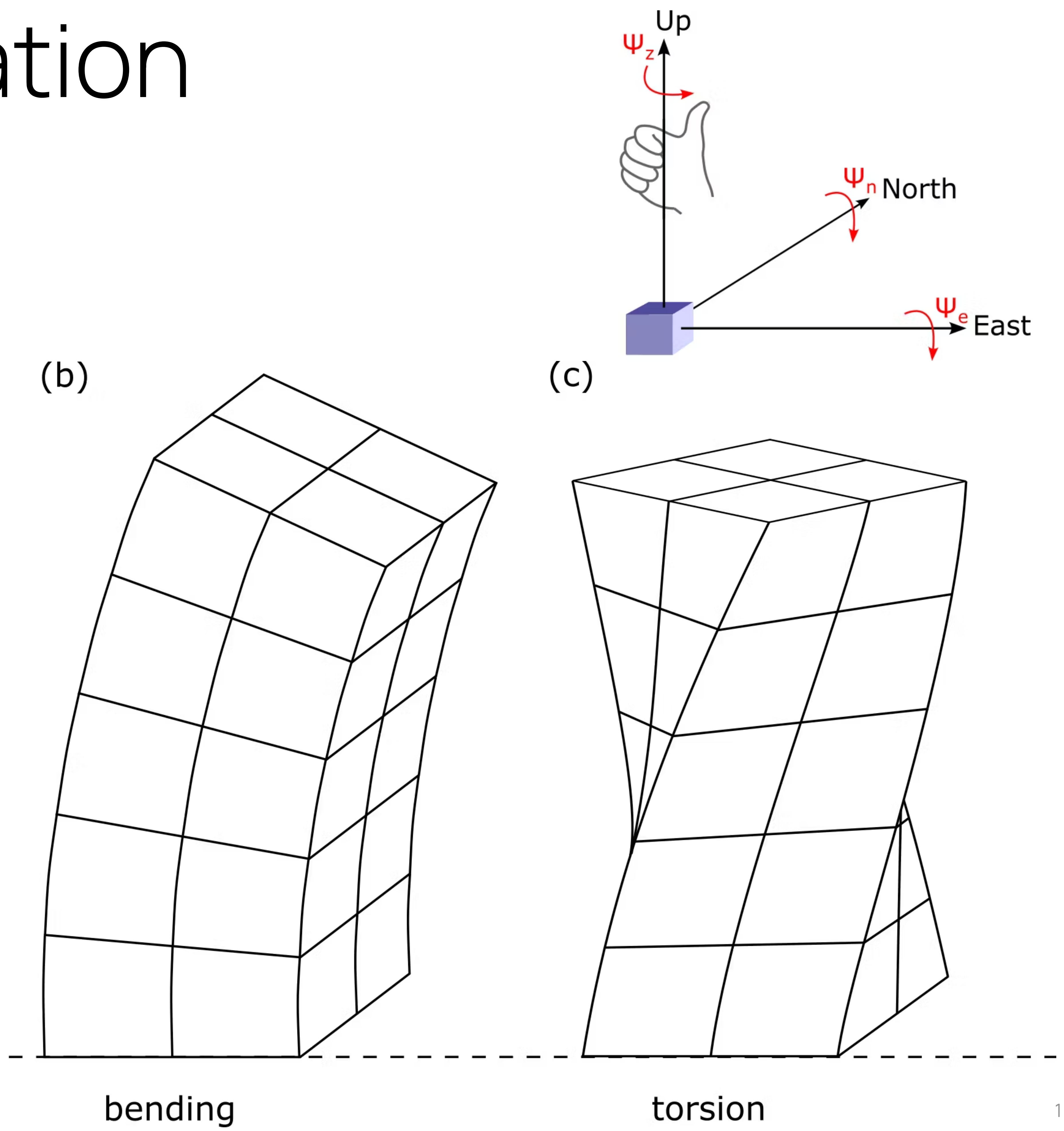
- vibration frequency
- floor plan
- concrete, wood
- height

Try Pitch

Mode shape of vibration

Each Mode:
1. specific frequency
2. specific shape (12 components)

Defined by:
- material properties
- structural design

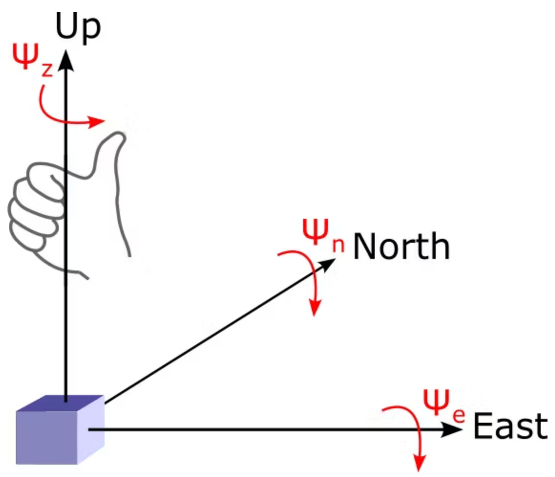


Try Pitch

Mode shape of vibration

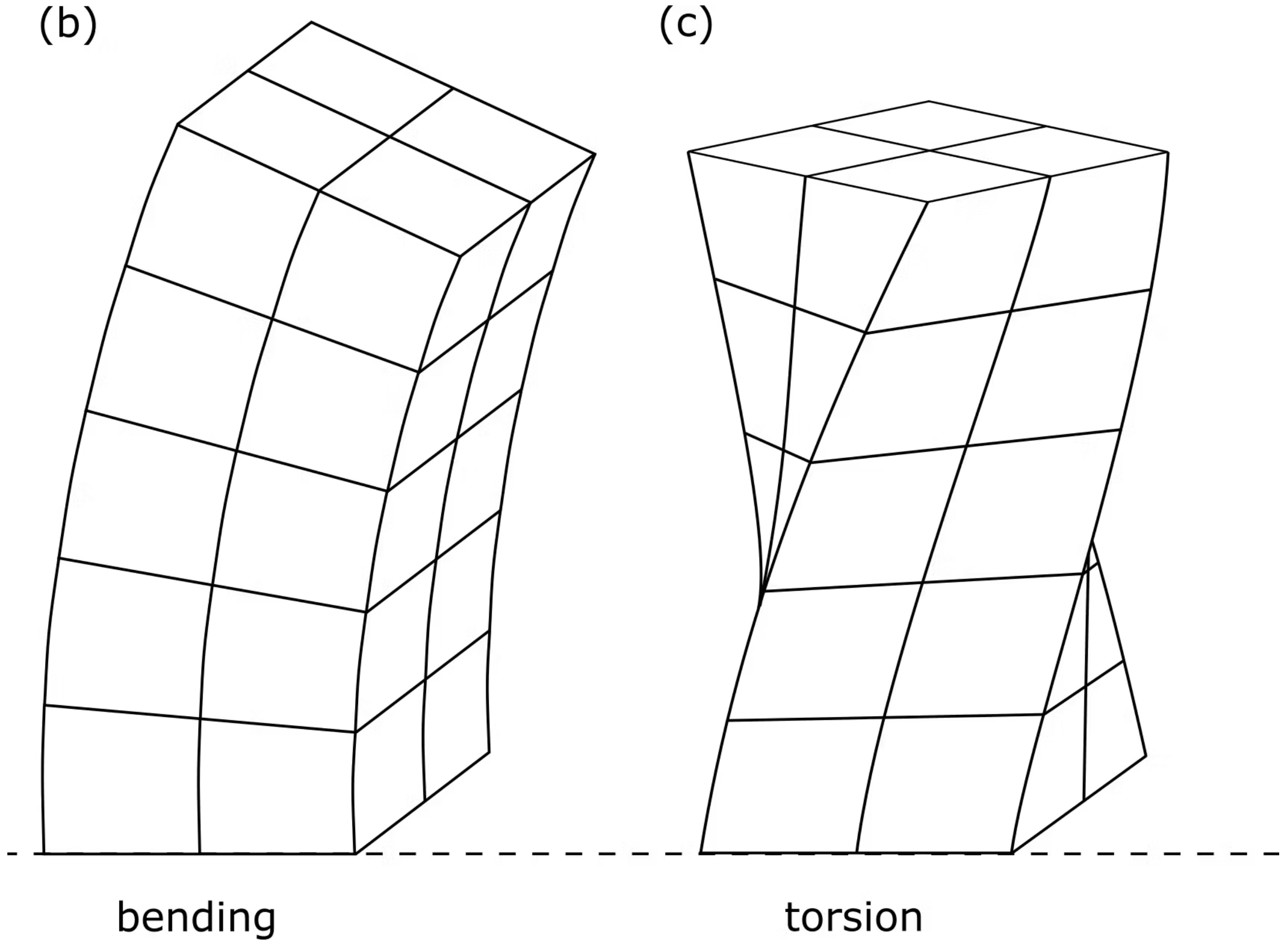
First three modes:

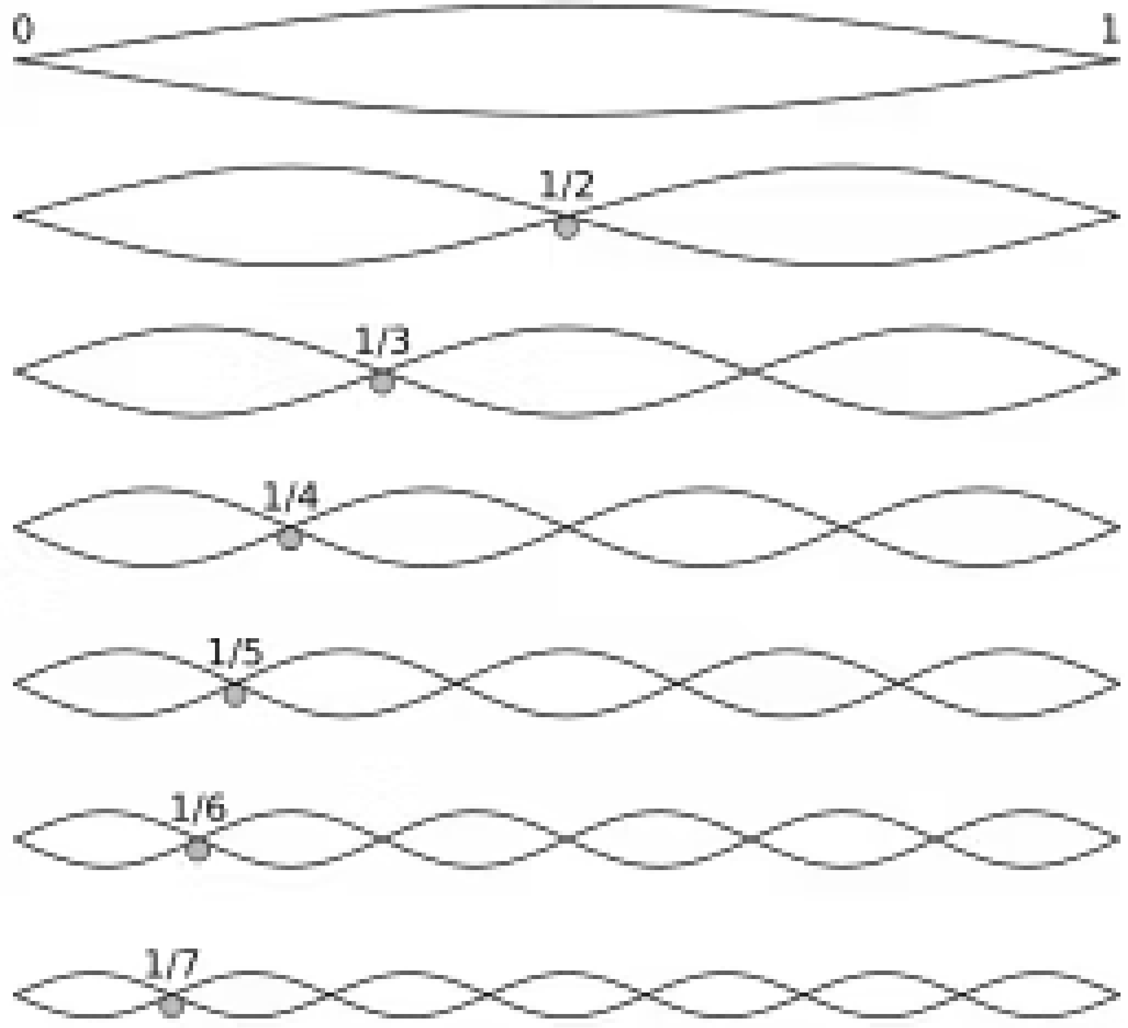
1. mode is bending in East
2. mode is bending in North
3. mode is torsion around Up



Overtones:

- adding zero crossing
- infinite amount



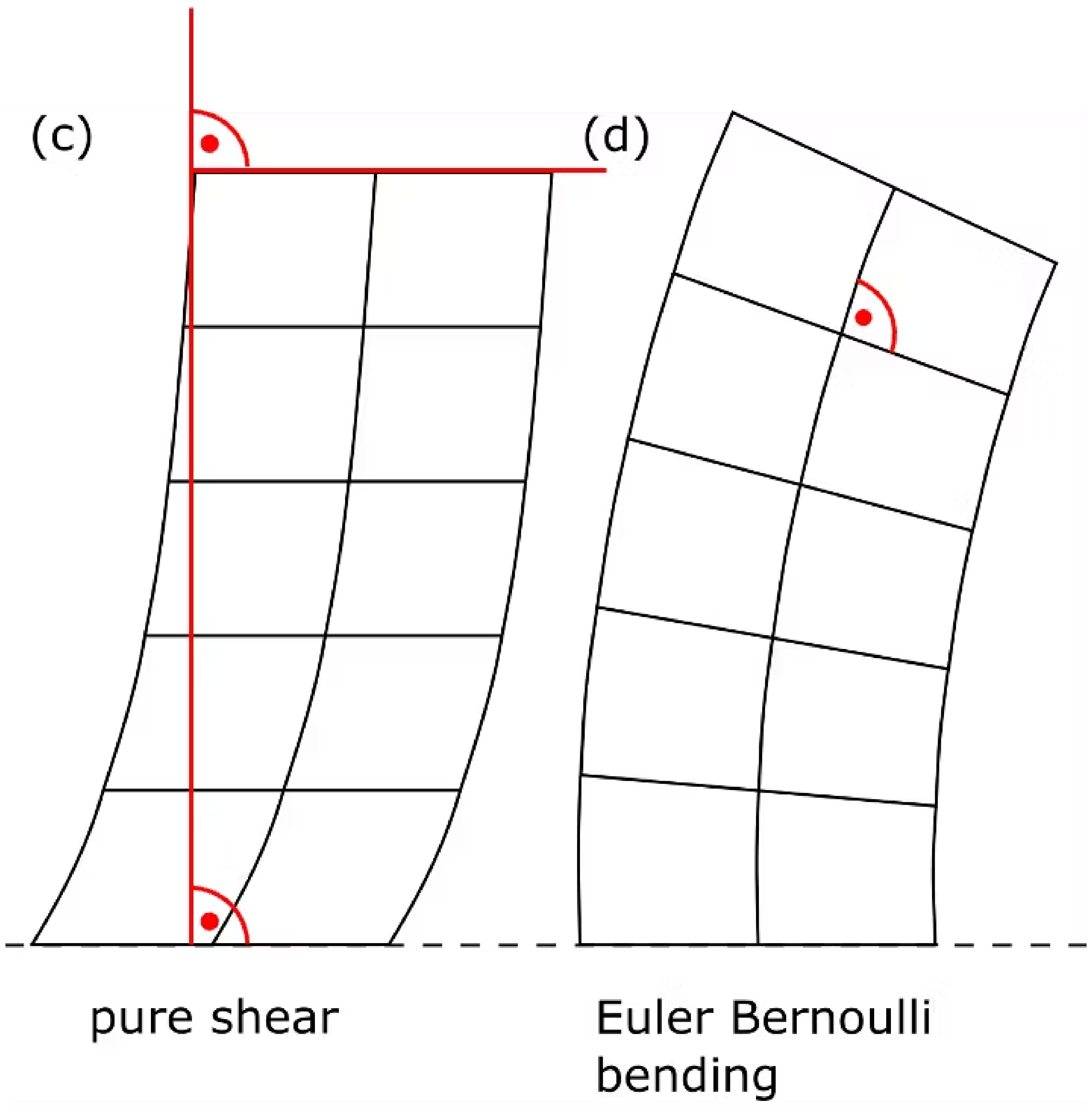


Try Pitch

Shear and Bending

Depends on:

- Material properties
- Shear walls
- Columns
- Structural design
- Height-to-width ratio



Try Pitch

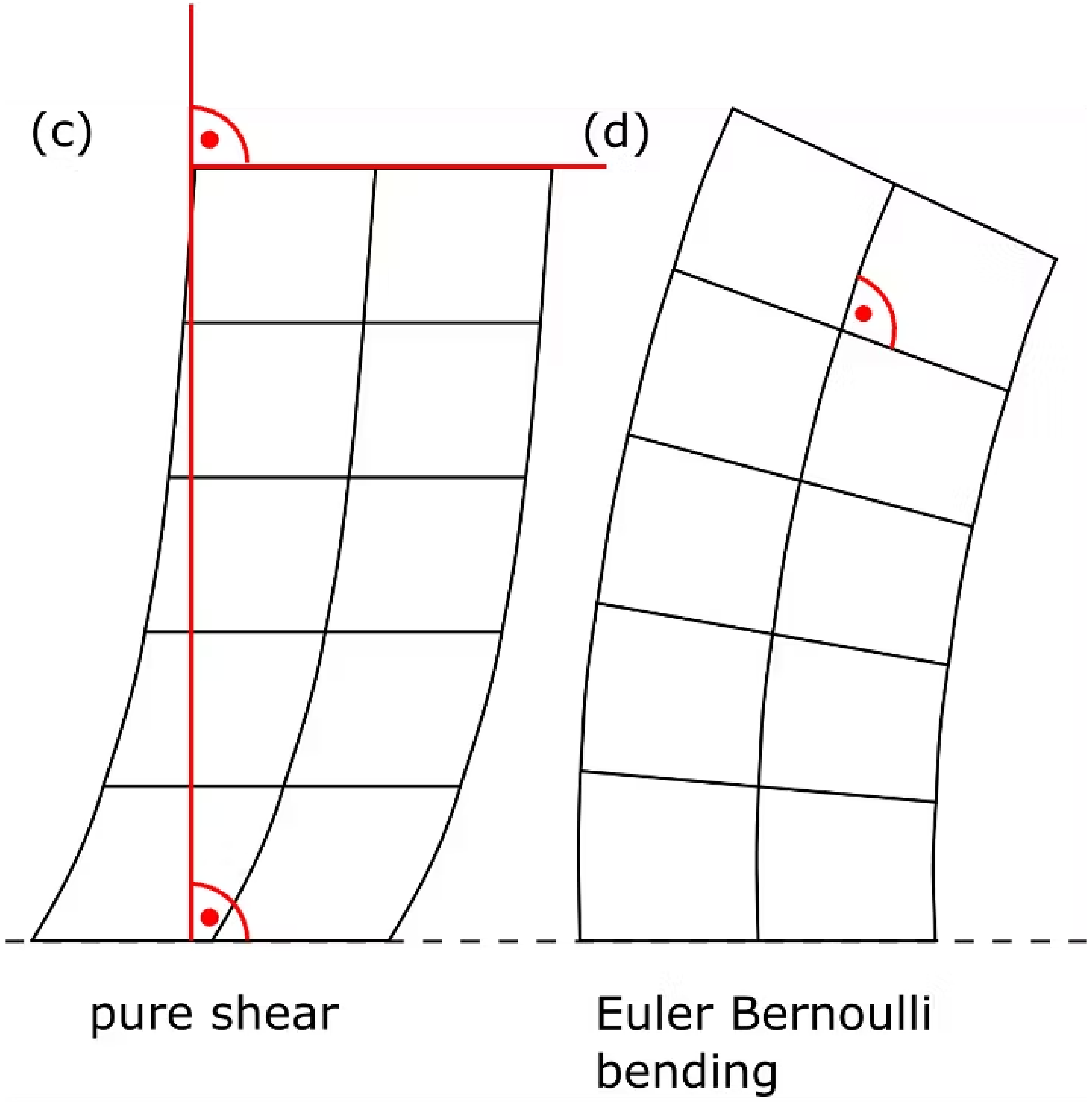
Shear and Bending

Depends on:

- Material properties
- Shear walls
- Columns
- Structural design
- Height-to-width ratio

Bending: more rotation
Shear: more deflection

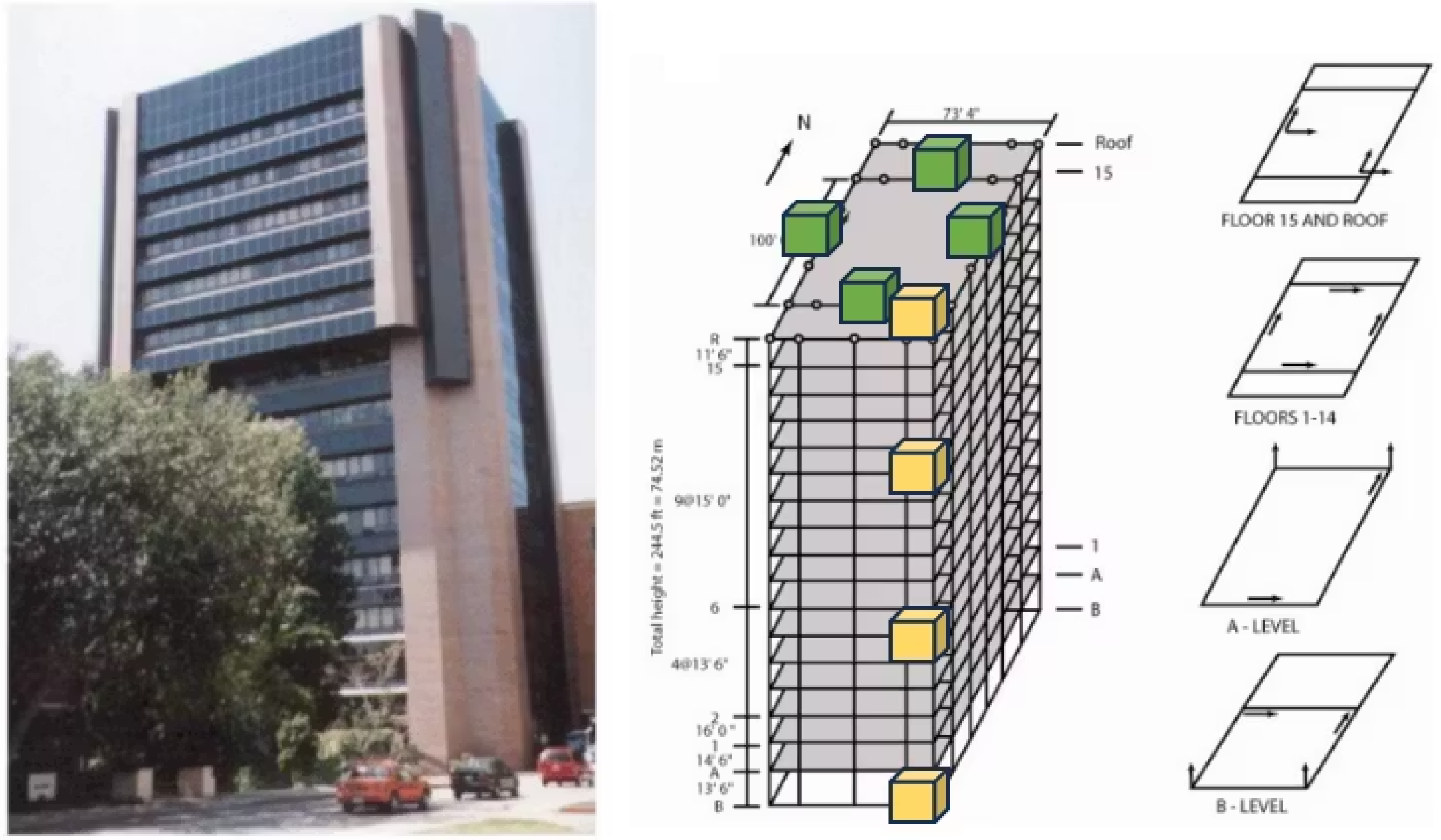
- 6C data can distinguish between shear and bending



Monitoring Structures

Type of instrument set ups

- Horizontal array of translation sensors
- Vertical array of translation sensors



(a) (b)

Figure 2. (a) Overview of the Factor building, (b) its overall dimensions and sensor locations/directions (http://factor.gps.caltech.edu).

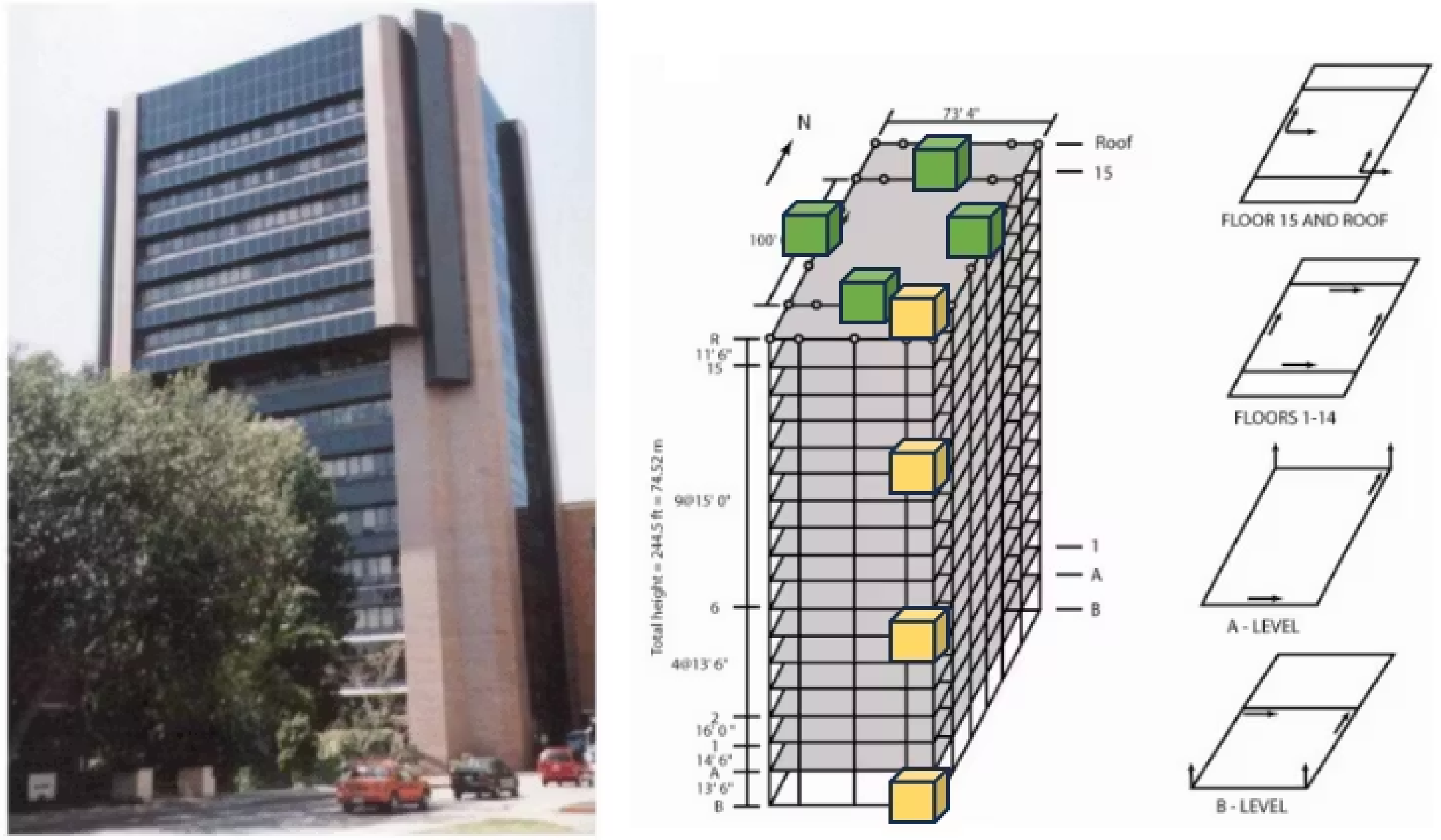
Nayeri, R., et al. (2008)

Description	Primary modal freqs.	Mode shapes: translation vs. torsion	Mode shapes: bending vs. shearing	Installation
Horizontal array	✓	✓	partly	difficult
Vertical array	✓	✗	✓	very difficult

Rossi, Y., et al. (2023)

Monitoring Structures

Type of instrument set ups
- Horizontal array of translation sensors
- Vertical array of translation sensors
- Single 6C-station



(a) (b)

Figure 2. (a) Overview of the Factor building, (b) its overall dimensions and sensor locations/directions (http://factor.gps.caltech.edu).

Nayeri, R., et al. (2008)

6C-station: rotational seismometer, accelerometer

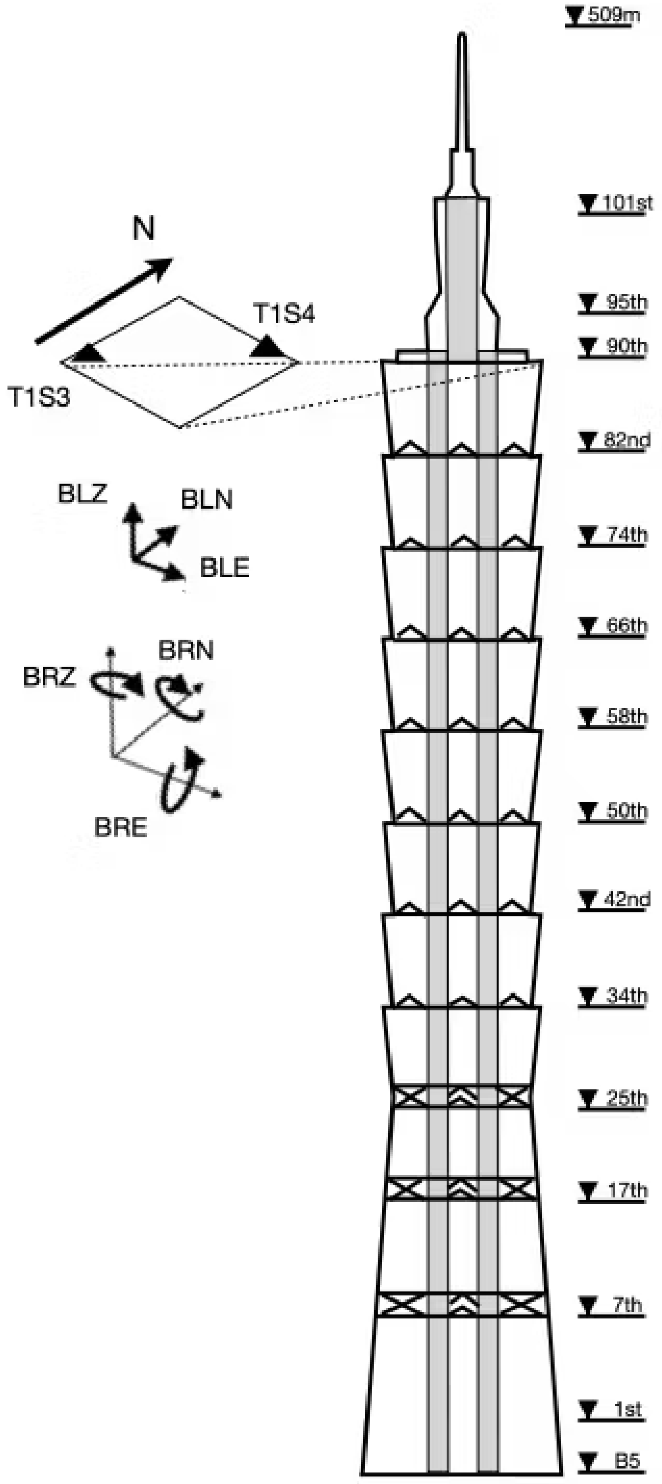
Description	Primary modal freqs.	Mode shapes: translation vs. torsion	Mode shapes: bending vs. shearing	Installation
6C-station	✓	✓	✓	simple
Horizontal array	✓	✓	partly	difficult
Vertical array	✓	✗	✓	very difficult

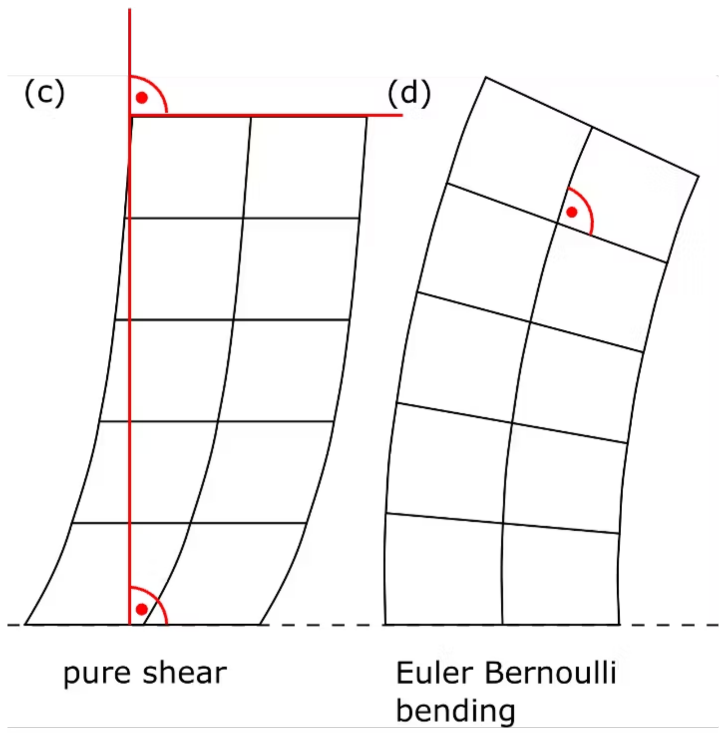
Rossi, Y., et al. (2023)

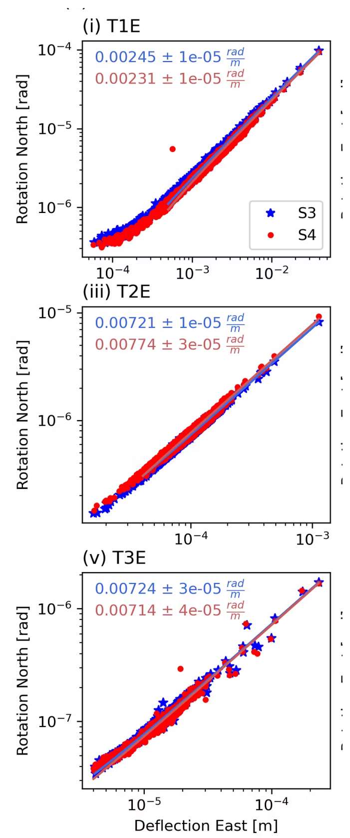
Shear vs Bending

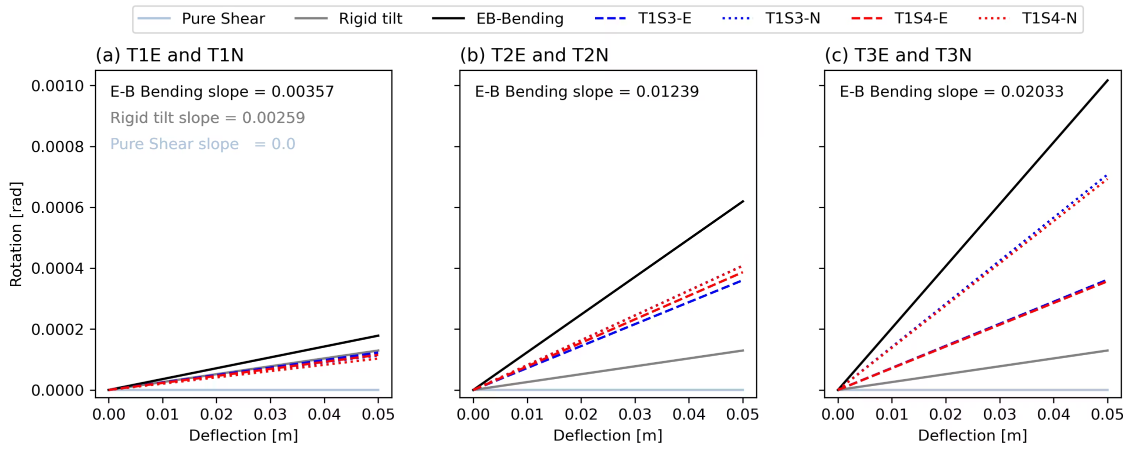
TAIPEI 101, Taiwan:

- analysis of two 6C stations
- Jan - Dez 2014
- ratio between angle and deflection
- ratio as proxy for shear









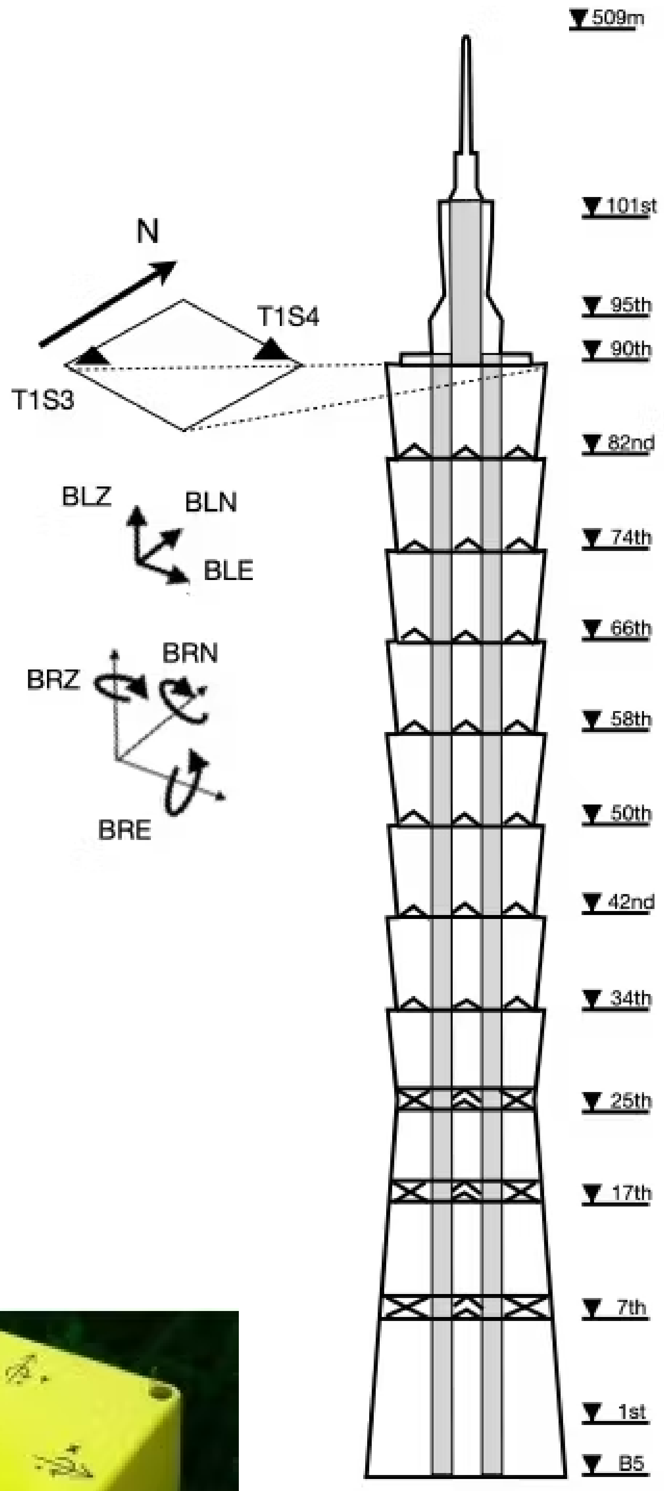
Rossi Y., Gueguen P., Bernauer F., Chen K.H., Lin C.J., Ku S.C., Chen Y.. (in preparation)

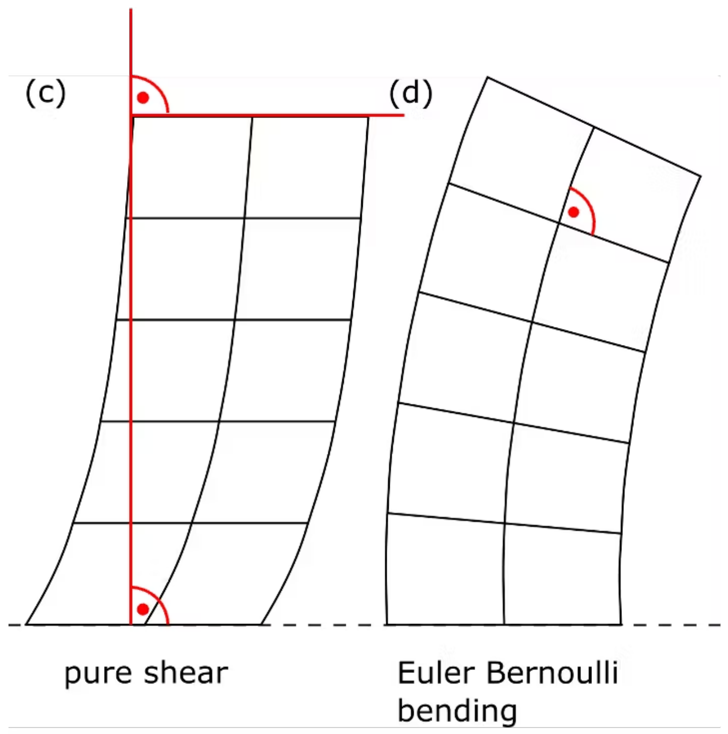
Shear vs Bending

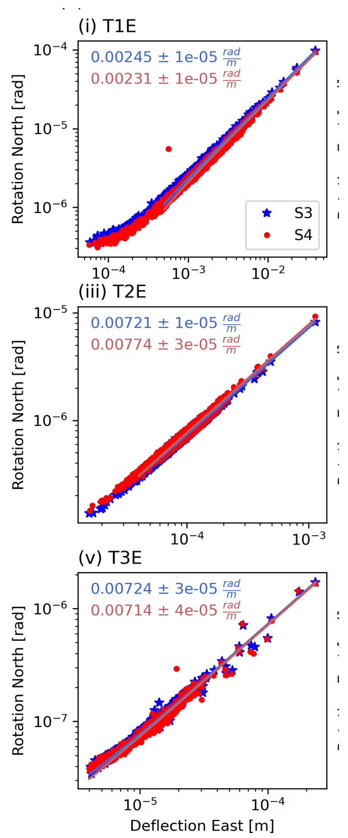
Taipei 101:

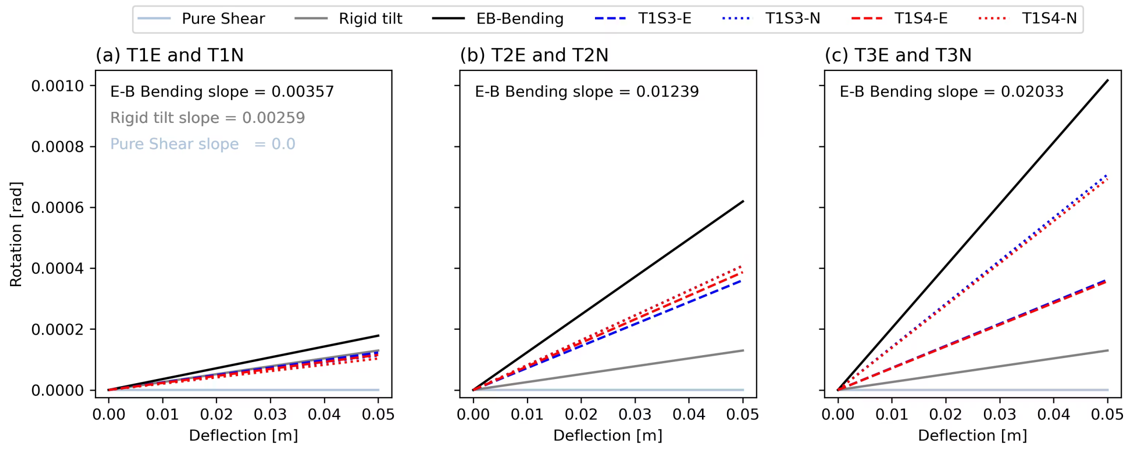
- analysis of two 6C stations
- Jan -Dez 2014
- ratio between angle and deflection
- ratio as proxy for shear

... but needs high amplitude precision!







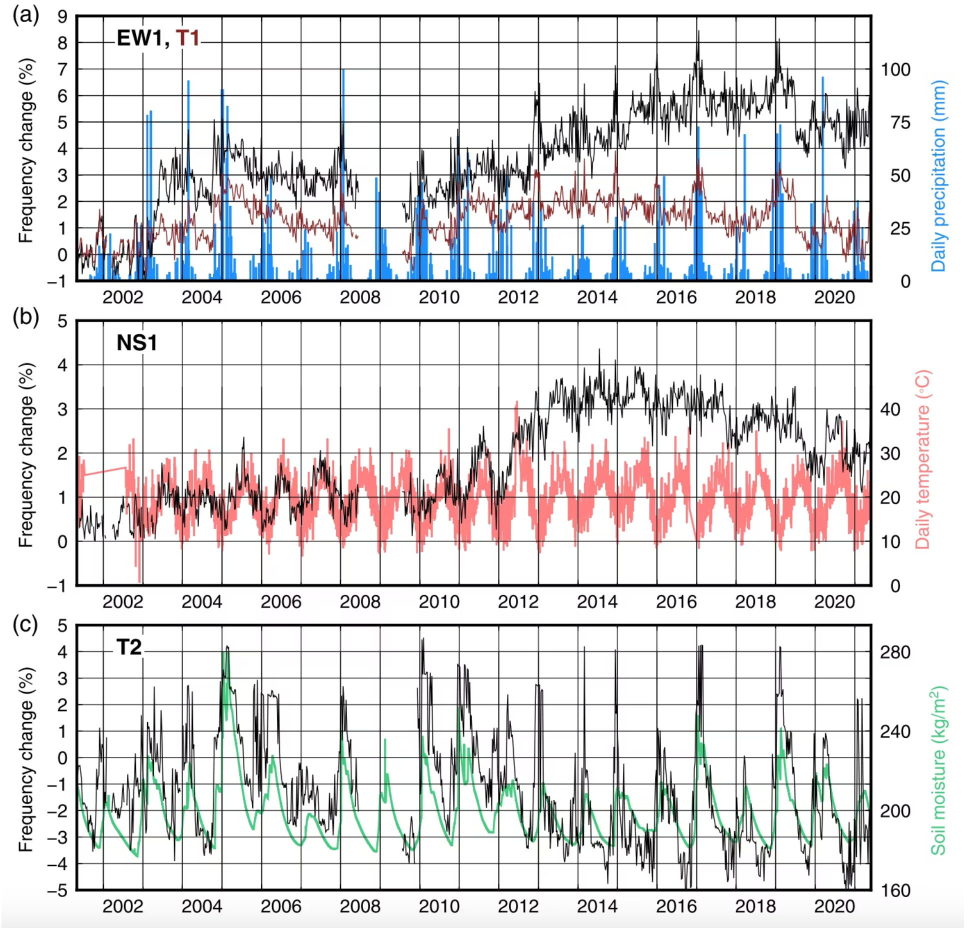


Rossi Y., Gueguen P., Bernauer F., Chen K.H., Lin C.J., Ku S.C., Chen Y.. (in preparation)

Frequency Variation

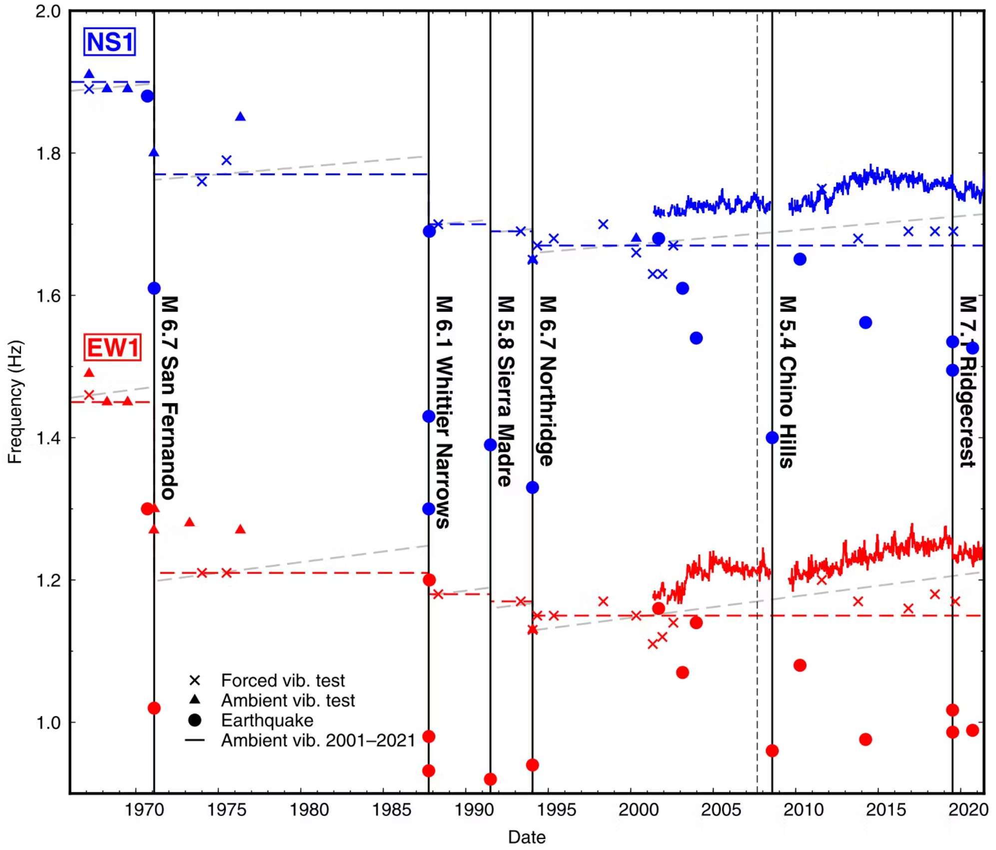
Why does it vary?

- Environmental influences:
  - temperature
  - humidity
  - wind → amplitude change
- Earthquakes
- Structural changes
- Damage



Williams, E., et al. (2022)

Photo: Felix Bernauer



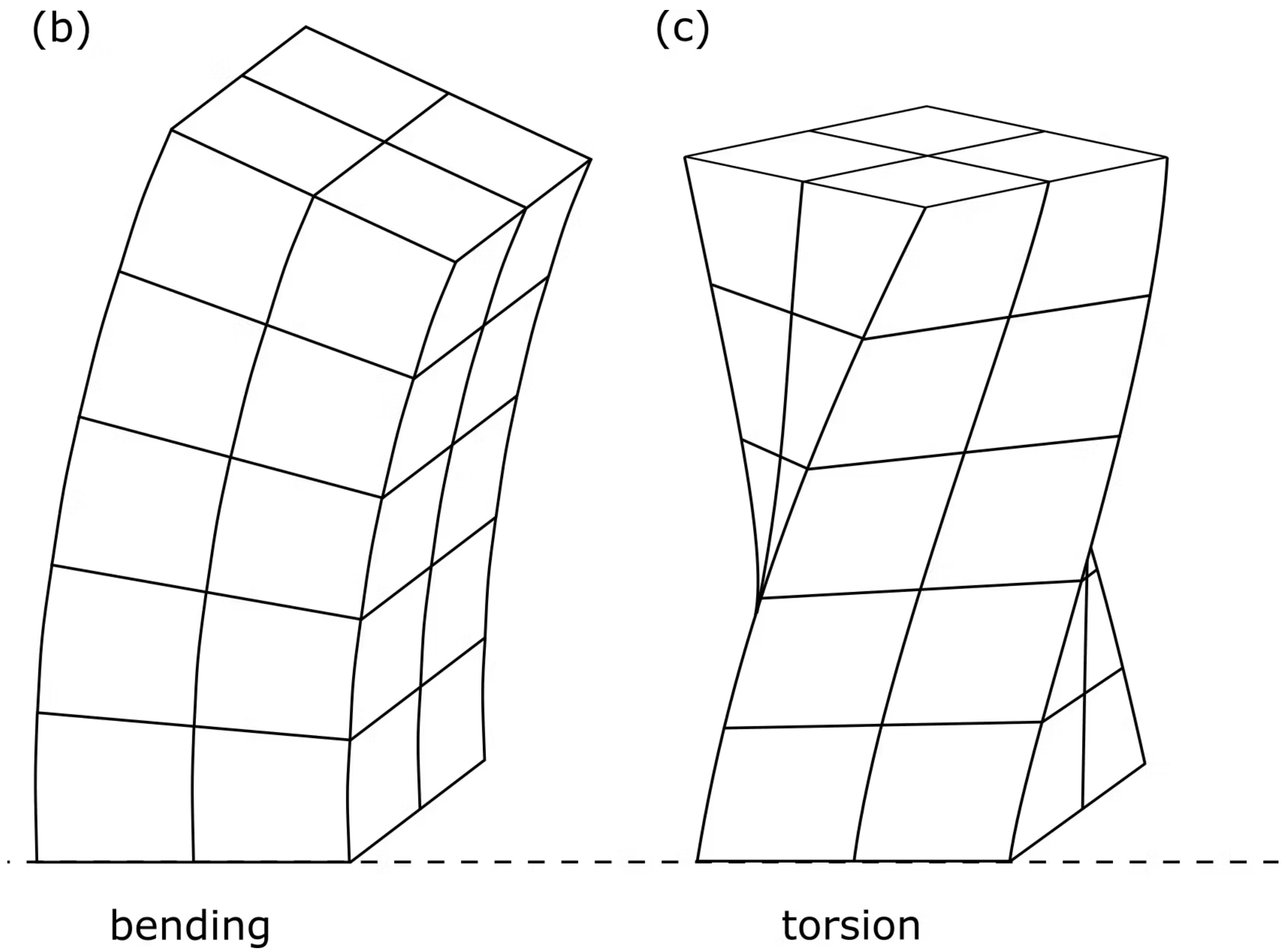
Williams, E., et al. (2022)

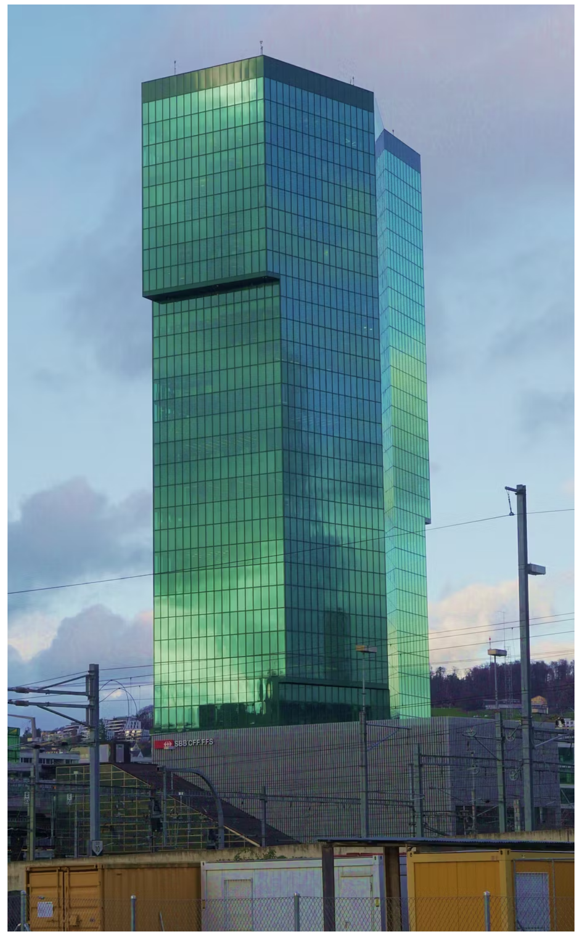
Hands on Part:

Objective:

- apply simple modal analysis to real 6C data
- extract different modes

1. Frequency
2. 6C Mode shape
   - 3C translation
   - 3C rotation



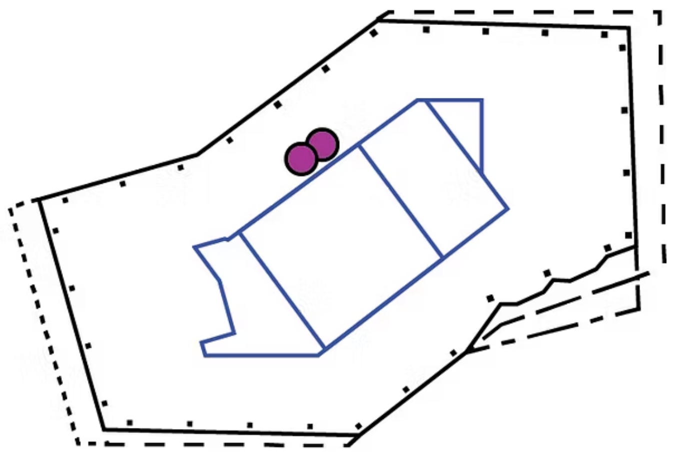


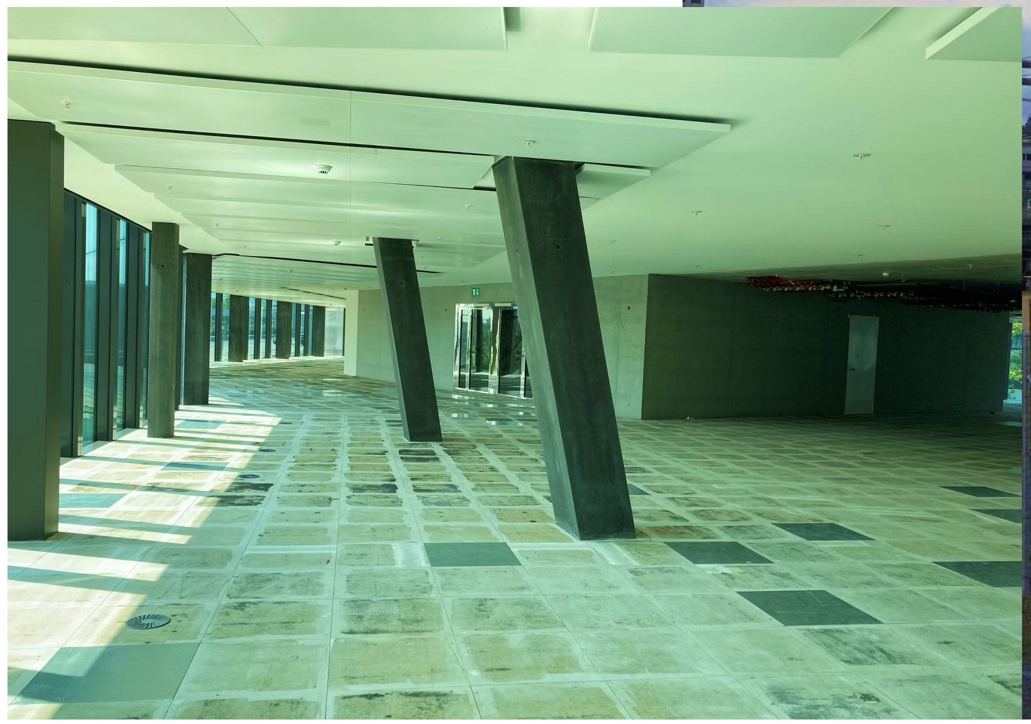
Try Pitch

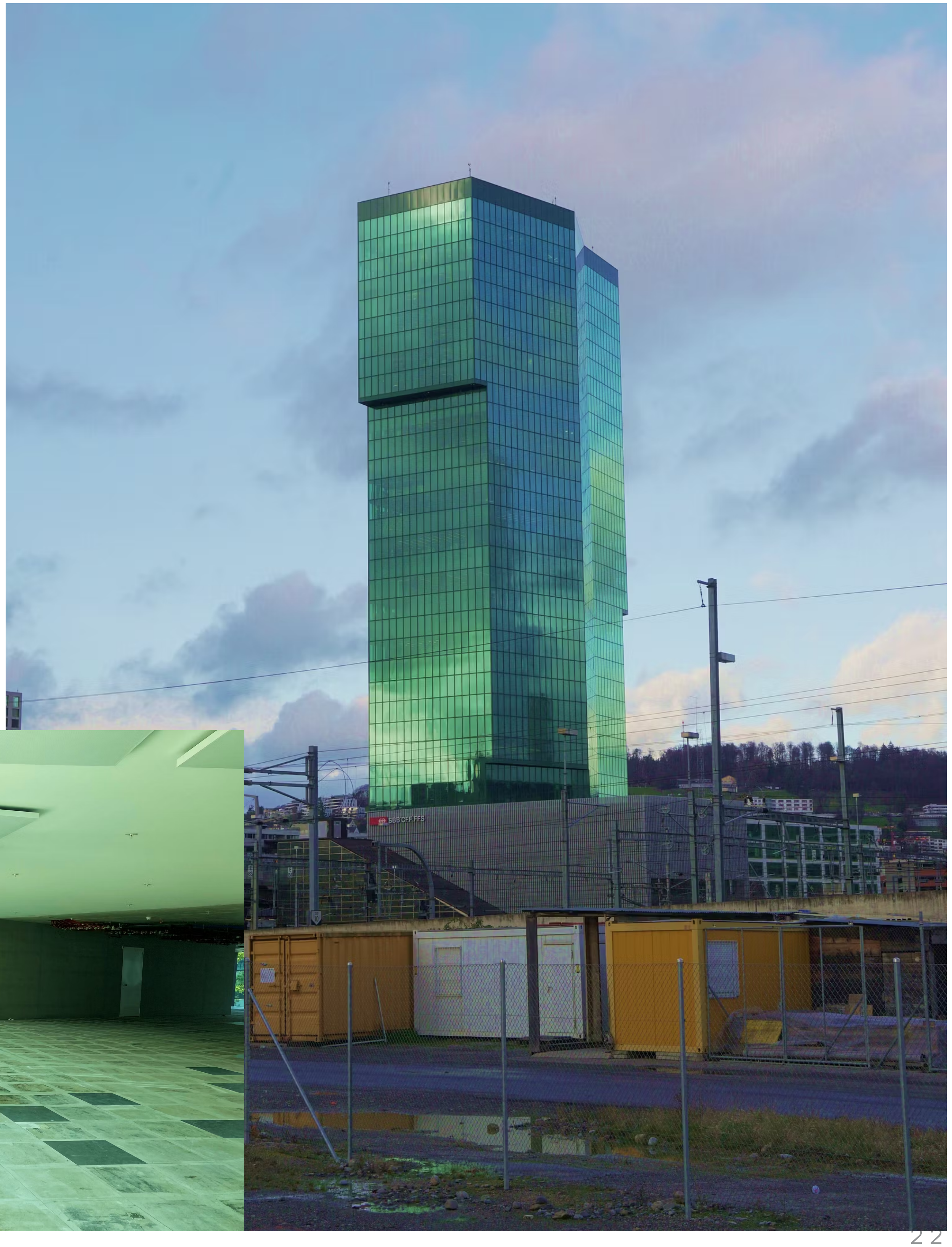
Data used in Jupyter notebook

Prime Tower

- 124 m, 36 floors (3rd highest in CH)
- Surrounded by trains, highways
- Excited by **ambient noise**
- Large reinforced concrete core
- Flat ceiling supported by pillars at edge
- Floors change shape along the height





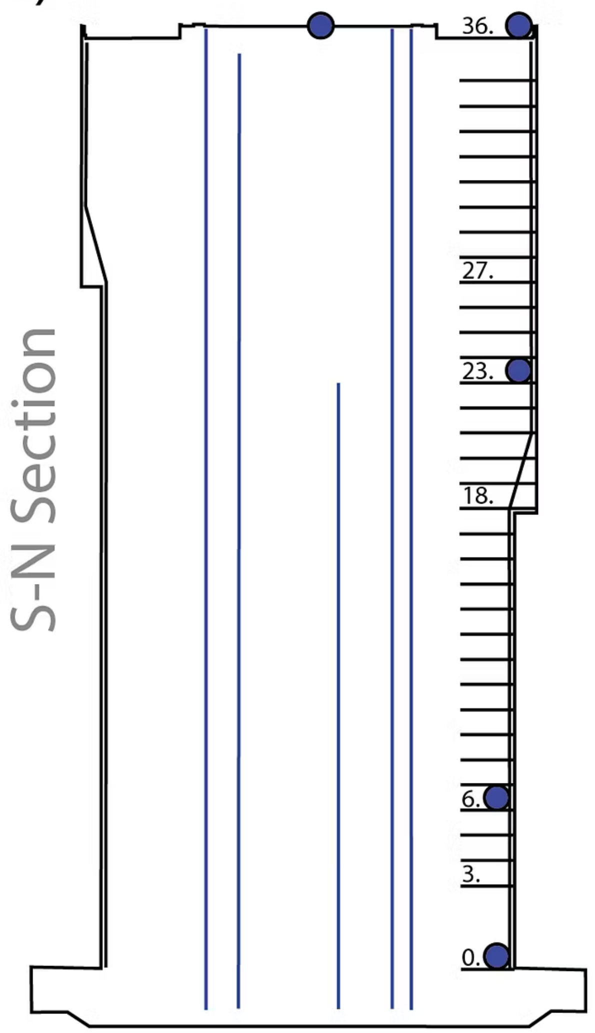


Instrument set-up

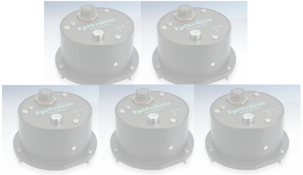
3 components acceleration
3 components rotation rate

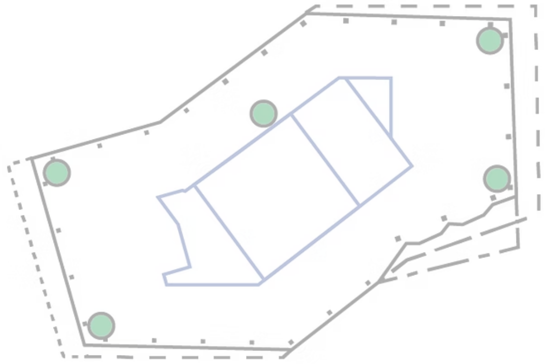
c) 6C-station

d)

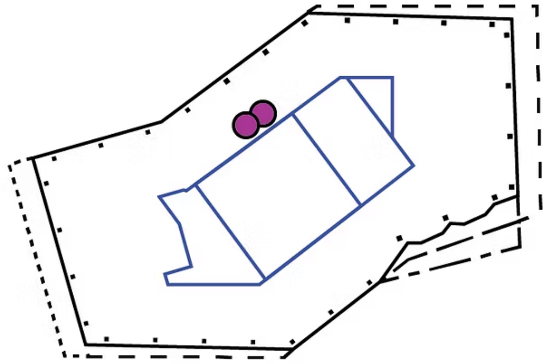


e) H-array





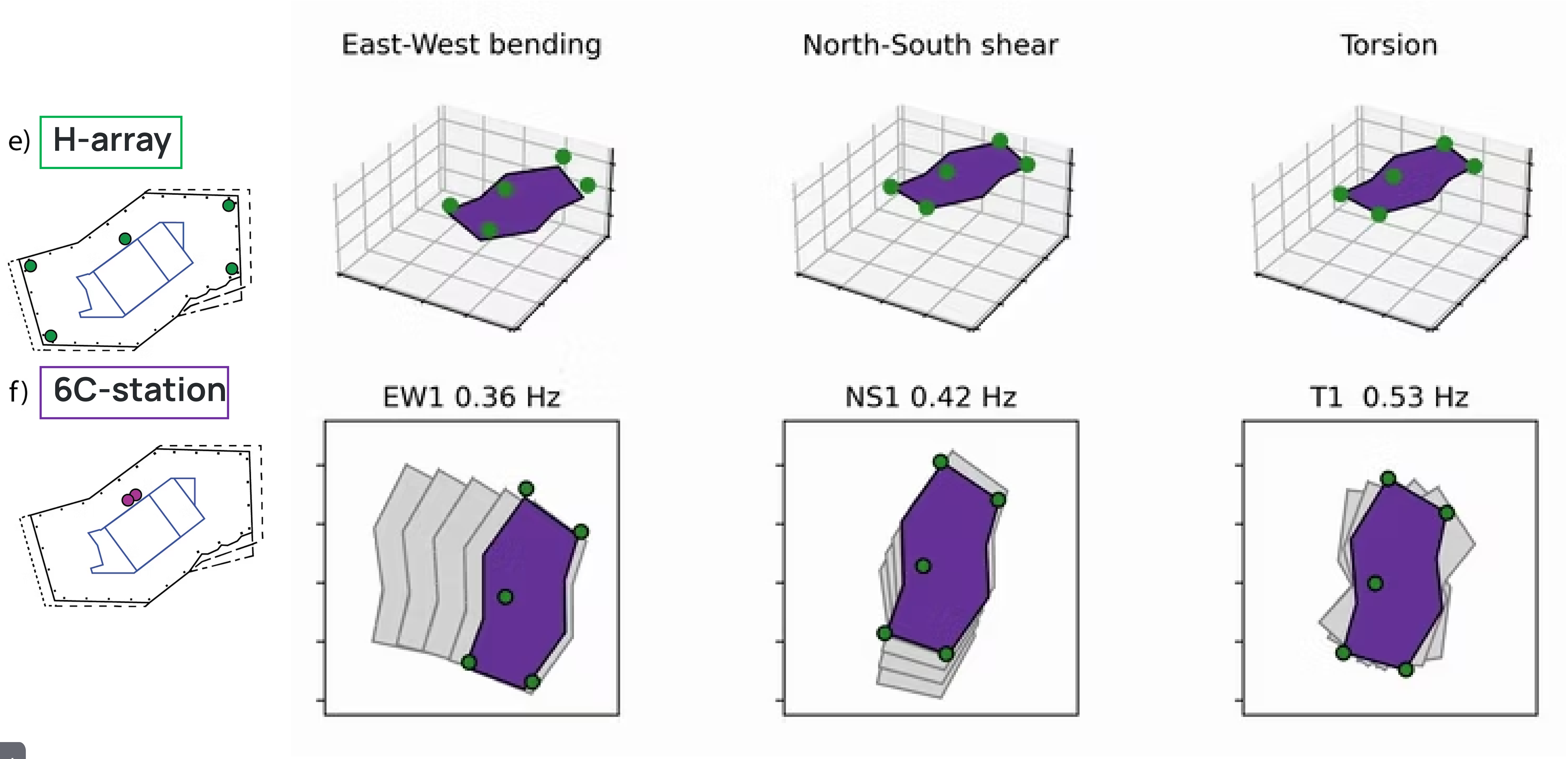
f) 6C-station



Accelerometer (200 sps)
EpiSensor

Rotation Sensor (200 sps)
blueSeis-3A FOG

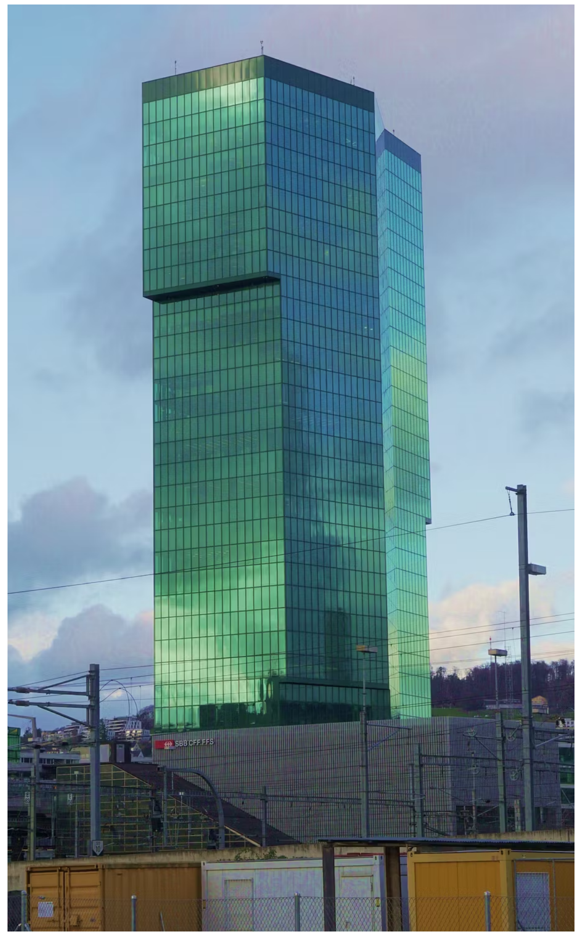
Modal Analysis Prime Tower

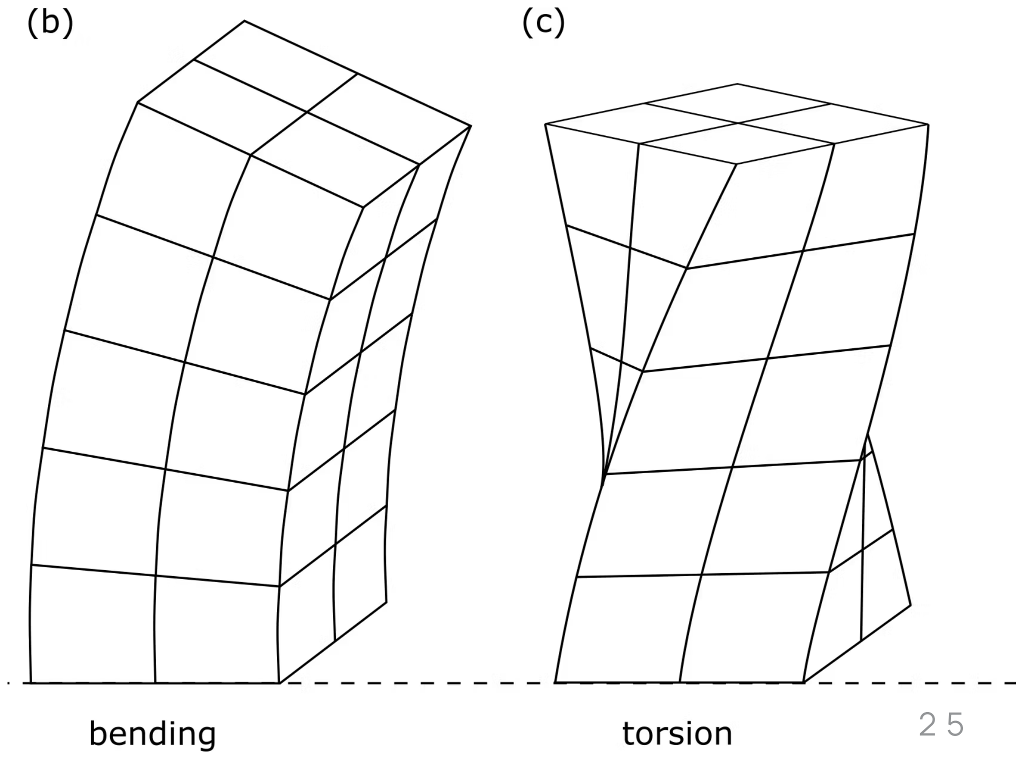


Hands on Part:

Objective: apply simple modal analysis to real 6C data

1. Estimate first 6 frequencies
   a. Using each channel individually
   b. Pick frequency from power spectral amplitude plot

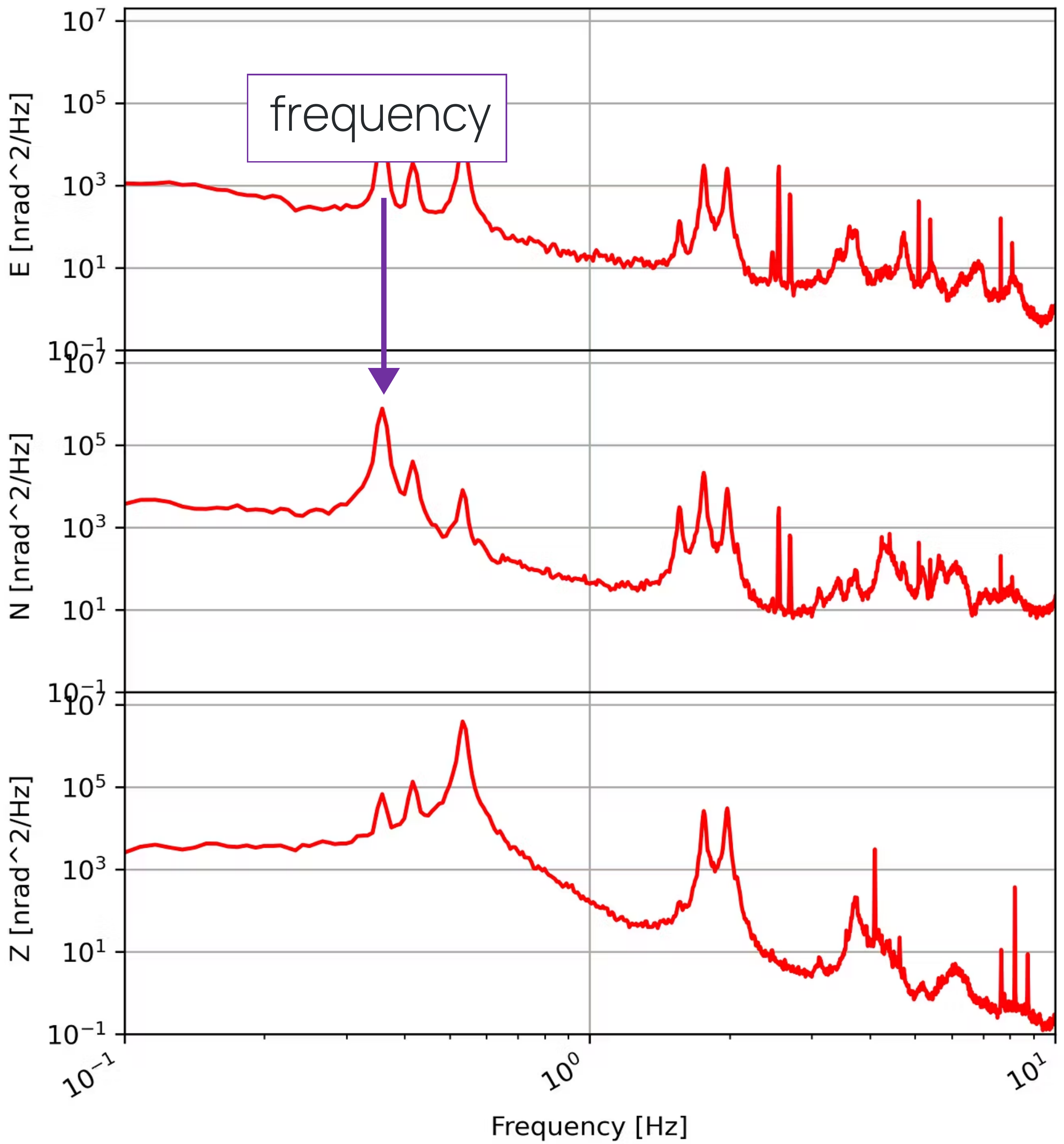


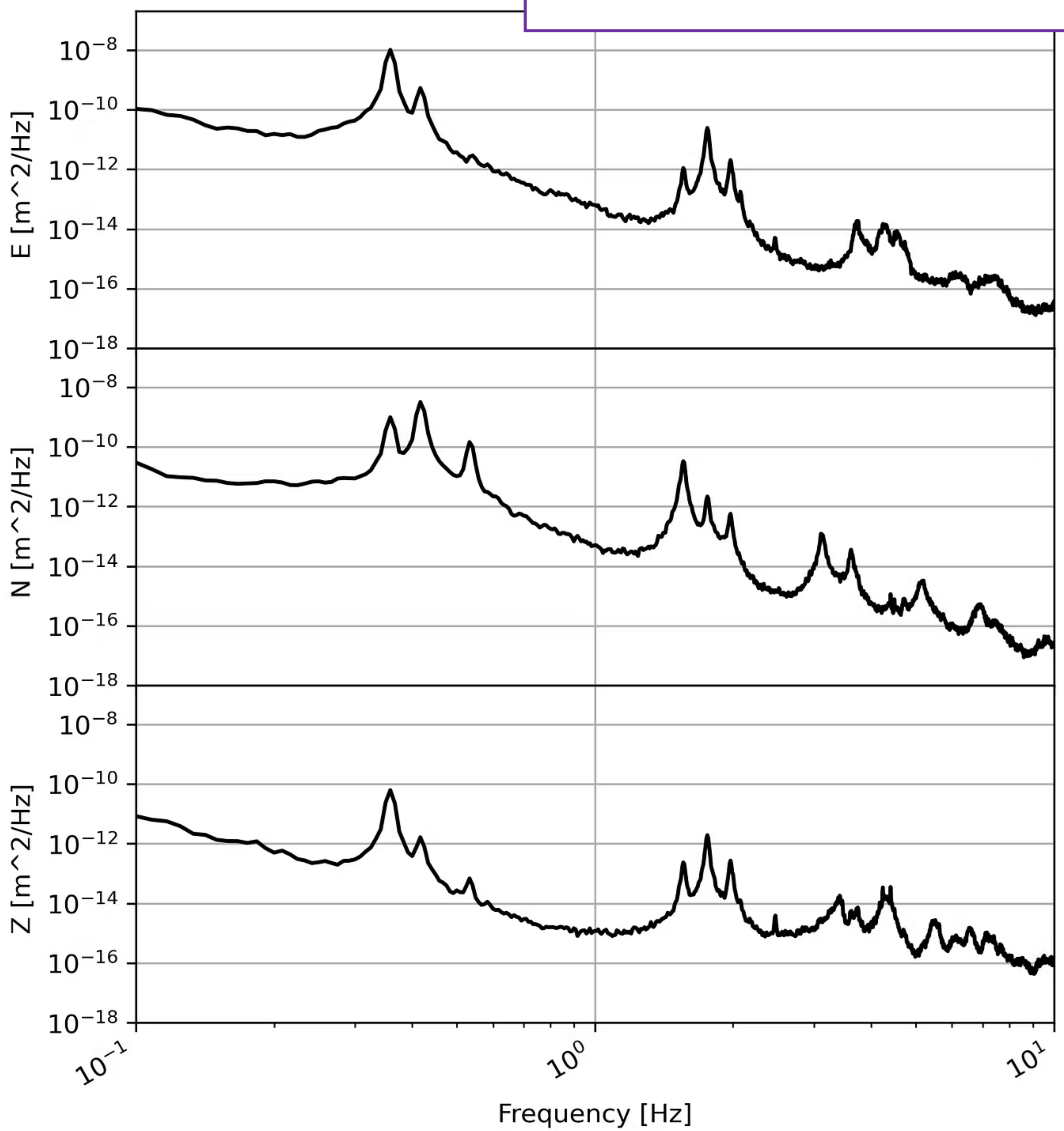


Try Pitch

Power Spectral density Plot

Do we expect to see the same frequency on each channel for a single mode?





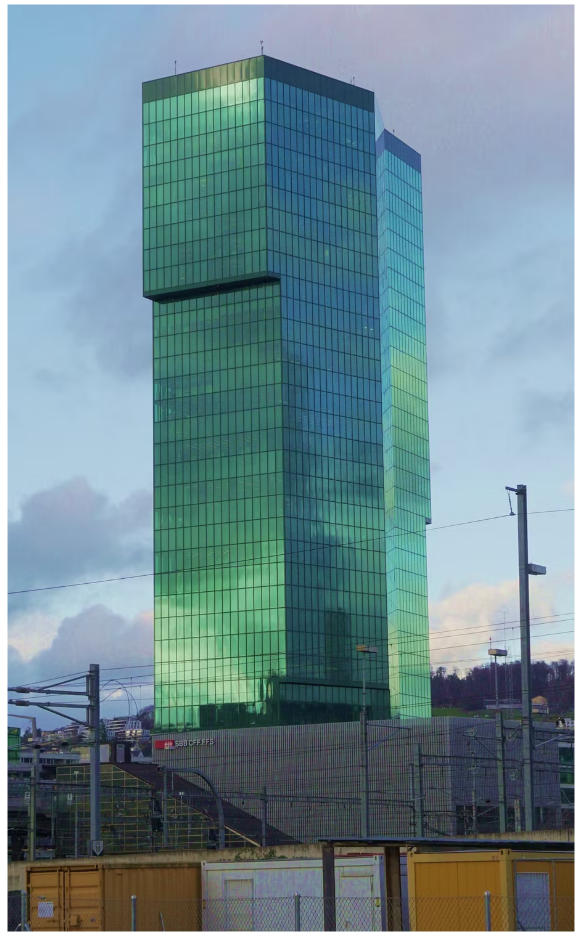
Try Pitch

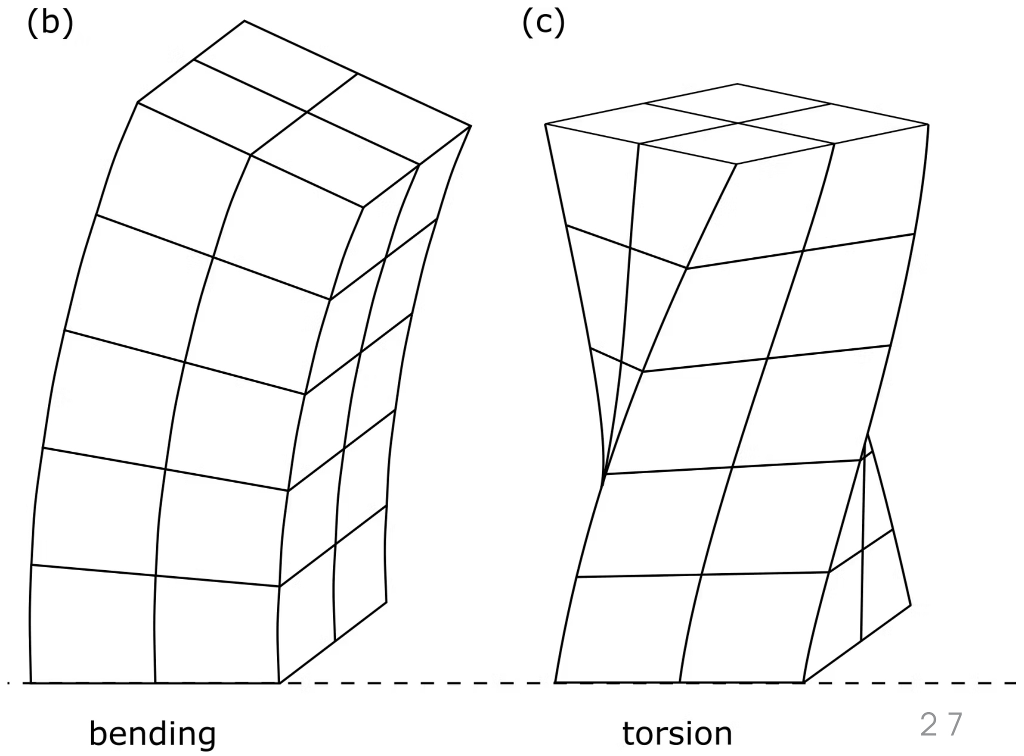
Hands on Part:

Objective: apply simple modal analysis to real 6C data

1. Estimate the frequencies of first 6 modes
   a. Using each channel individually
   b. Pick frequency from power spectral amplitude plot

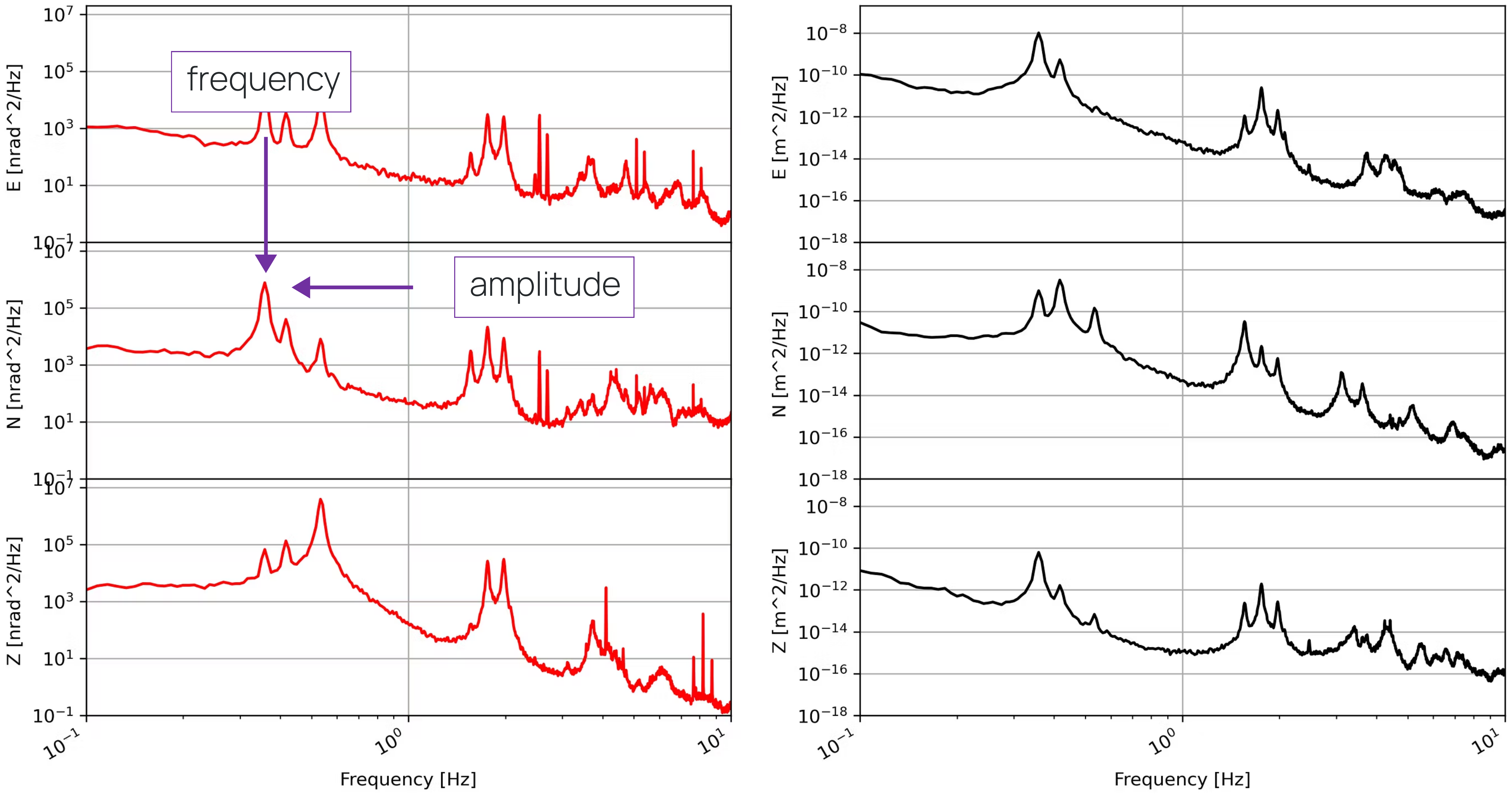
2. Estimate the modeshape for each mode
   a. Using main direction of motion as frequency indicator
   b. Pick amplitude from power spectral density plot
   c. Plot vibration mode





Try Pitch

Power Spectral density Plot



Try Pitch

Let’s get started!!