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Ground motion uncertainty as a rug to sweep things under

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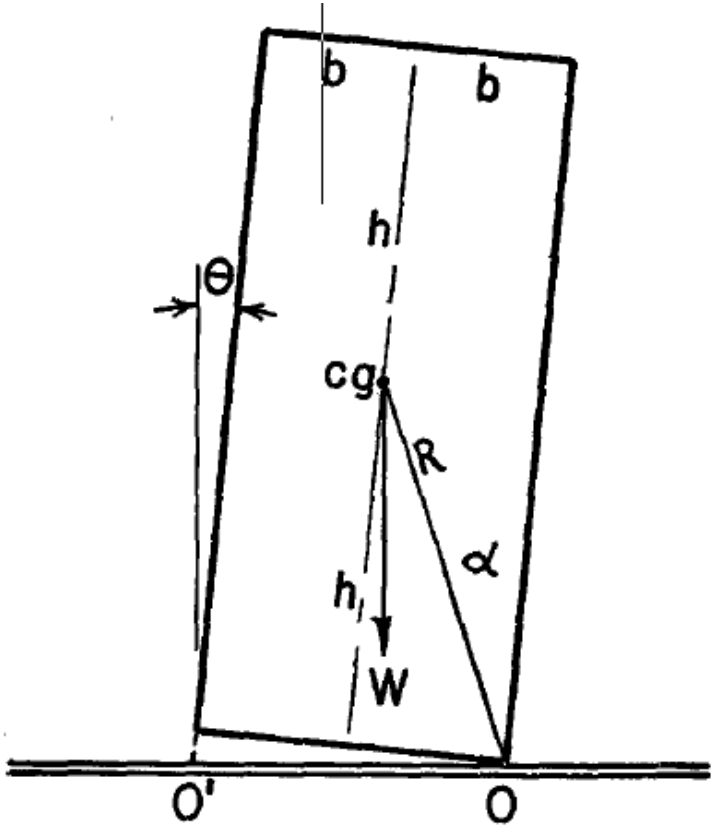
Outline

Inspired by our work on rocking structures we will suggest that numerical models might need to be validated statistically.

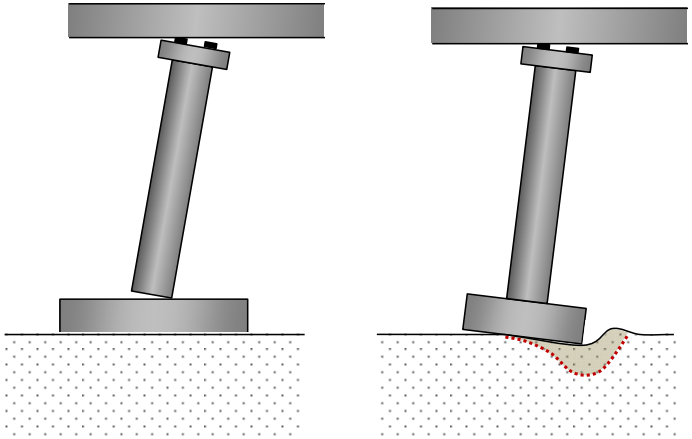
Rocking oscillator

“Inverted pendulum” (Housner, 1963)



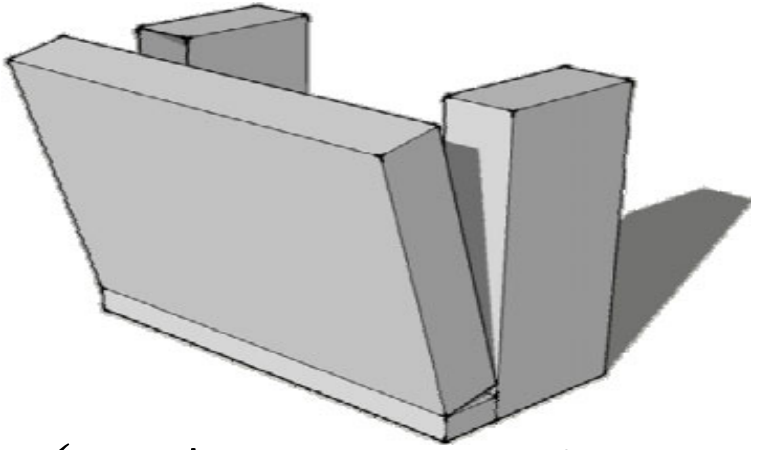
Motivation to study rocking

✓ Bridge Desgin



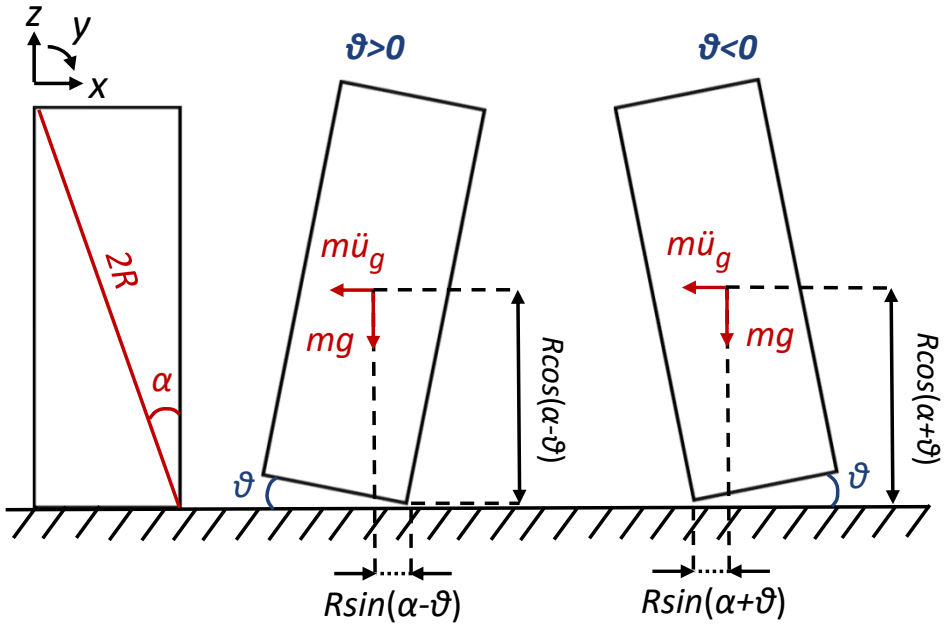
✓ Museum artifacts

✓ Out of plane behavior of masonry



✓ Nuclear waste containers

Equation of motion of the rocking oscillator



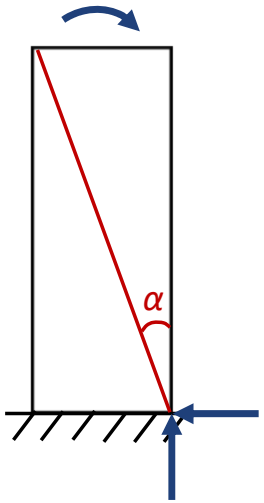
Assumptions:

1) *Rigid body on rigid surface* ✔
2) *No sliding* ✔
3) *Planar motion* ✔

Apart from the assumptions, it is only Newton's laws. There is no constitutive model.

$$\ddot{\theta}(t) = -p^2 \left\{ sin[\alpha sgn\theta(t) - \theta(t)] - \frac{\ddot{u}_g(t)}{g} cos[\alpha sgn\theta(t) - \theta(t)] \right\}, \qquad where\ p^2 = \frac{mgR}{I_o} = \frac{3g}{4R}$$

Treatment of Impact



Housner Assumptions(1963)

1. Instantaneous Impact ✔
2. Impact forces concentrated at the new pivot point (?)

$$r = \frac{\dot{\theta}_{after}}{\dot{\theta}_{before}} = 1 - \frac{3}{2} sin^2 \alpha$$

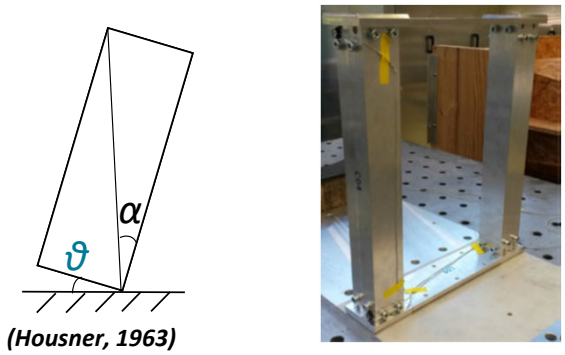
«Coefficient of restitution»

Energy dissipation

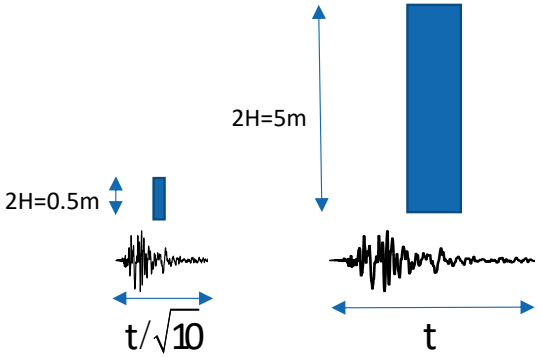
- Only during impact
- Depends on the geometry – not on the material

Validation of Housner's model

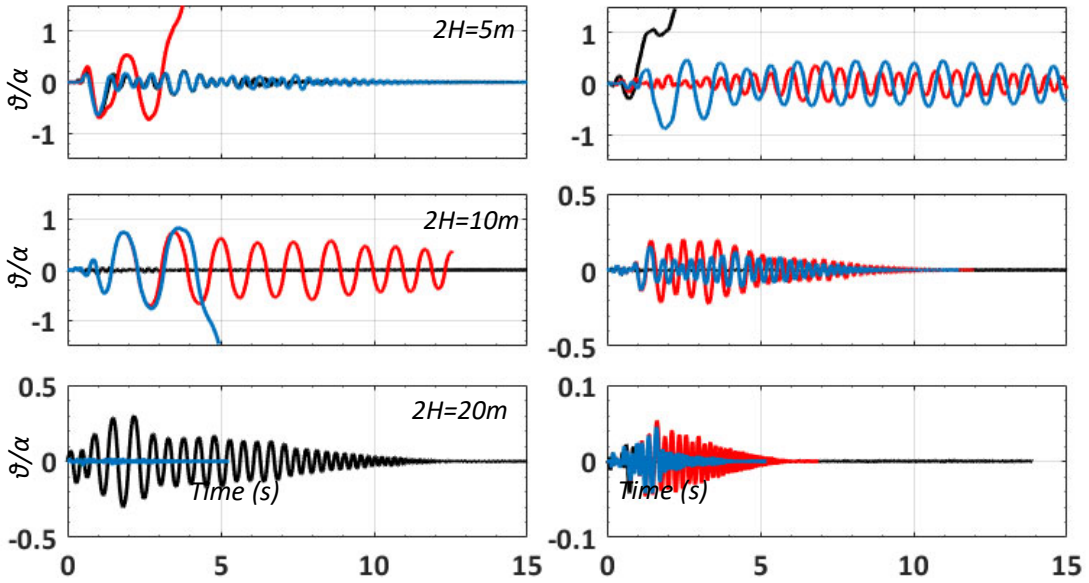
Specimen on ETH shake table



(Housner, 1963)



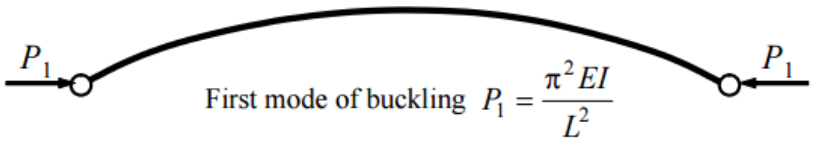
El Centro 1940 *Lefkada 2003*



The results look bad! Small perturbations in *r* give very different responses. The motion looks non predictable. People have called it *chaotic*.

Chaotic or not chaotic? It depends on the question.

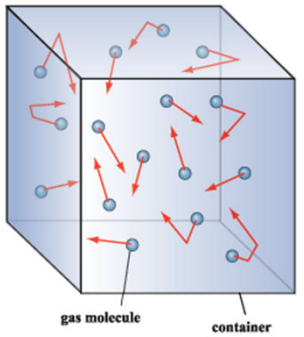
Buckling of a cylindrical bar



What is the buckling load?
Absolutely predictable: $P=\pi^2 EI/L^2$

What is the direction of buckling;
Absolutely chaotic and non predictable.

Kinetic theory of gases



What is the force on the wall of the cube?

Absolutely predictable : $F = \frac{Nm\overline{v_x^2}}{L}$

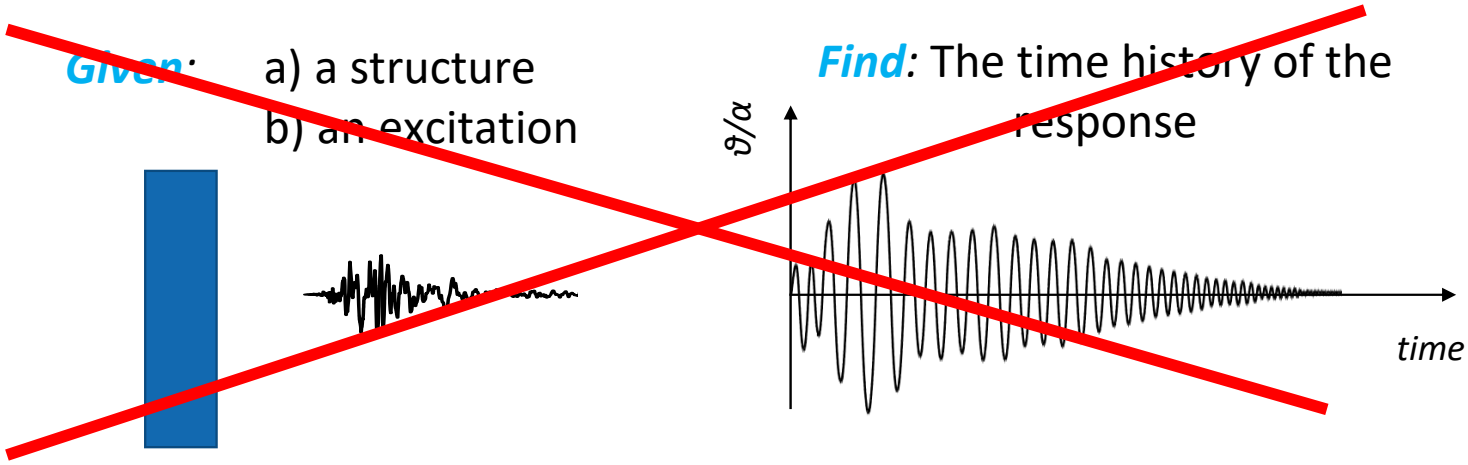
What is the trajectory of the molecules?
Absolutely chaotic and non predictable.

The “right” question in earthquake engineering

This is NOT the earthquake engineering question.
It is too strict of a test, a “strong validation”.

Given: a) a structure
b) an excitation

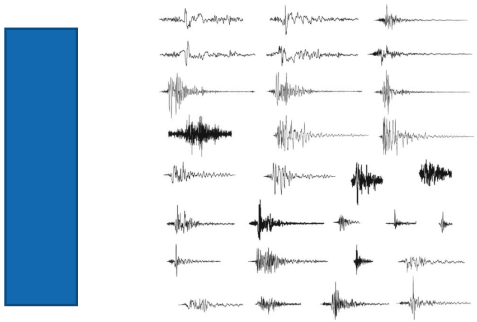
Find: The time history of the response

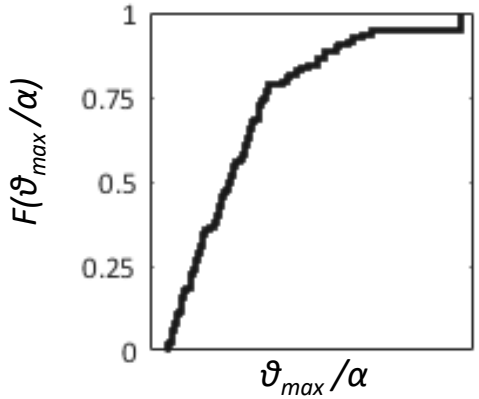


Given : a) a structure
b) an **ENSEMBLE** of ground motions

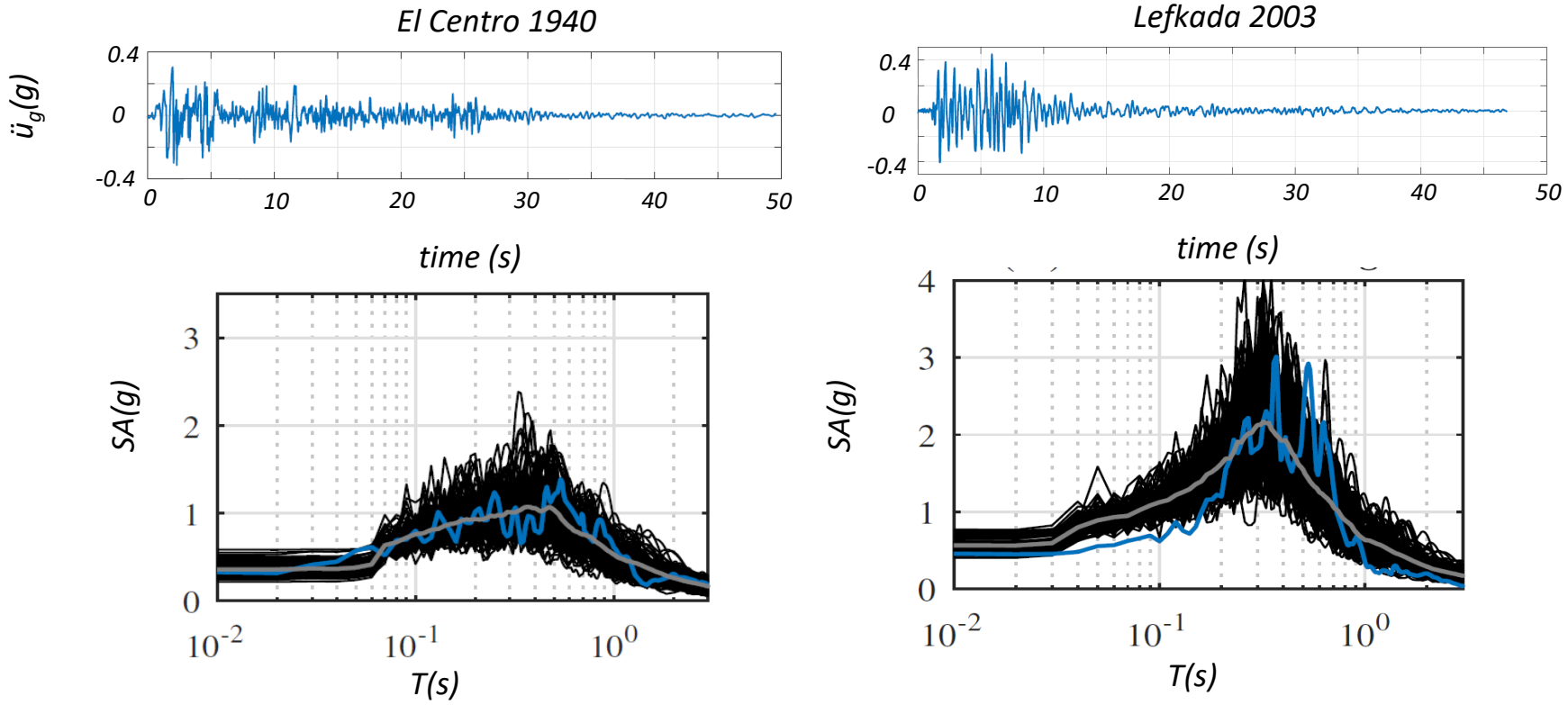
Find: The **STATISTICS** of the maxima of the reponses

This IS the earthquake engineering question.
This is the appropriate test, a “weak validation”.



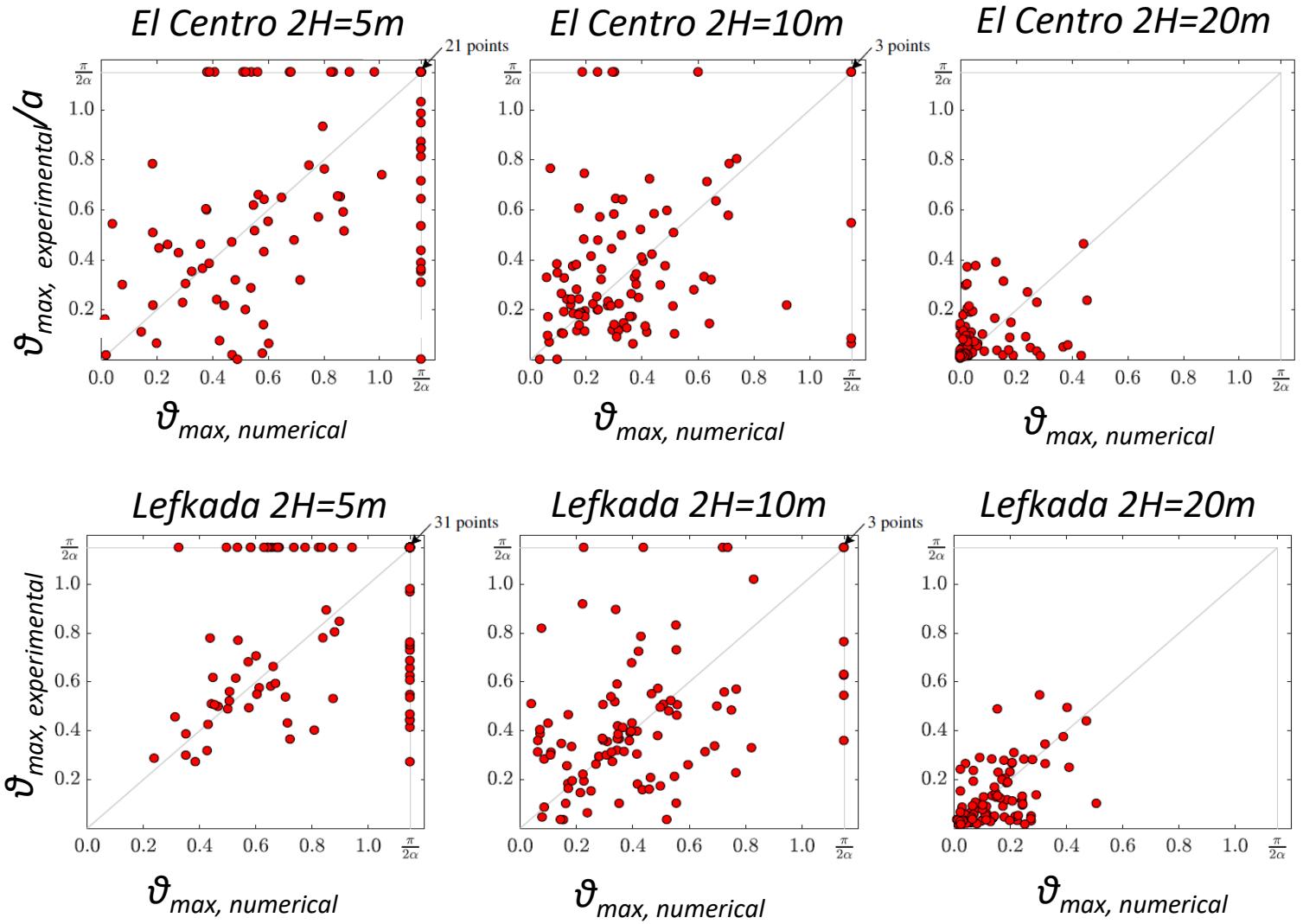


Statistical model validation



1. Used Rezaeian and Der Kiureghian*'s model (2010) to create 2 sets of 100 simulated ground motions.*
2. *Scaled the 200 ground motions in time to match specimens of 5, 10 and 20m height.*
3. *Ran 600 shaking table tests.*

Statistical model validation

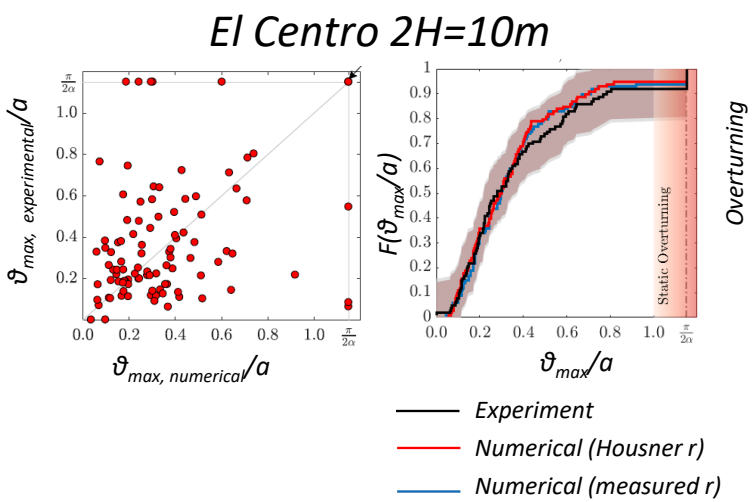


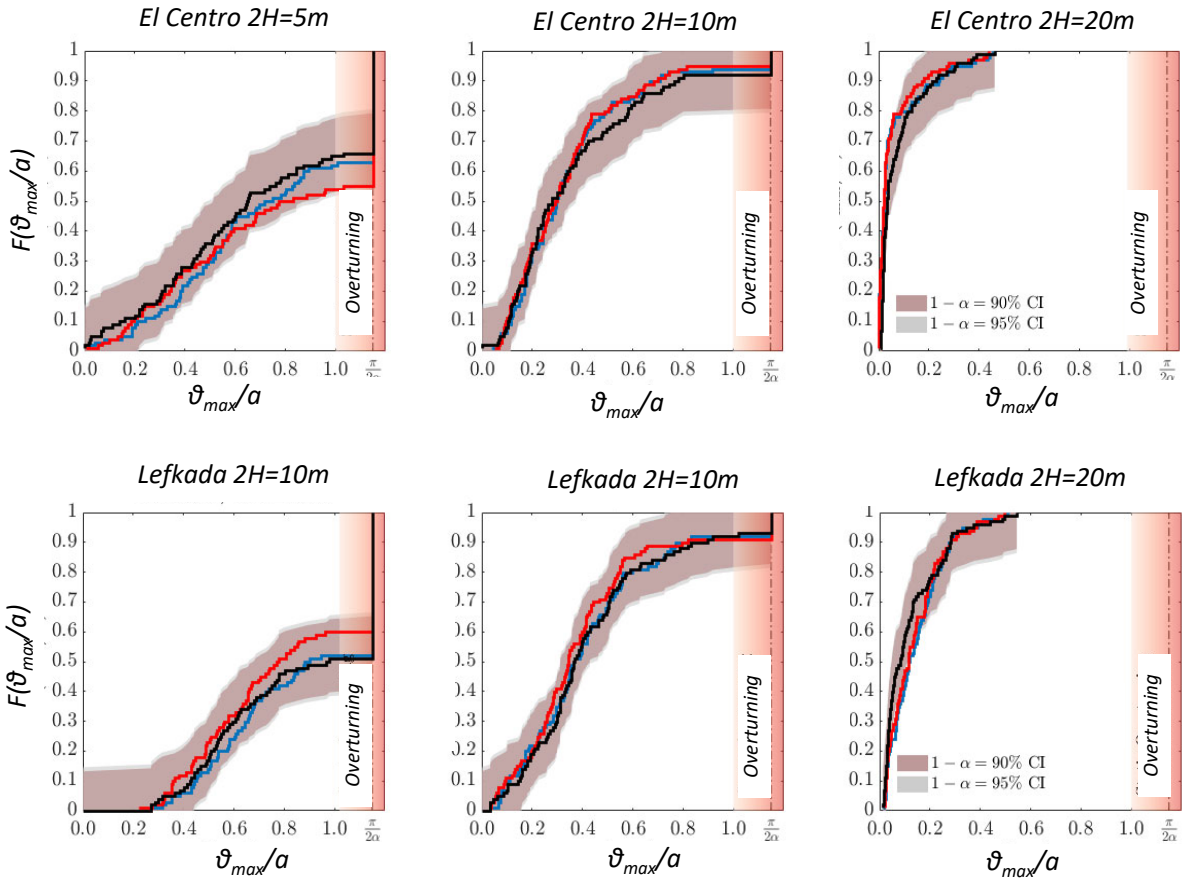
Again, the results look bad.

A one to one comparison shows that the Housner model cannot accurately predict the response

BUT there are some good news: The model looks non biased.

Statistical model validation

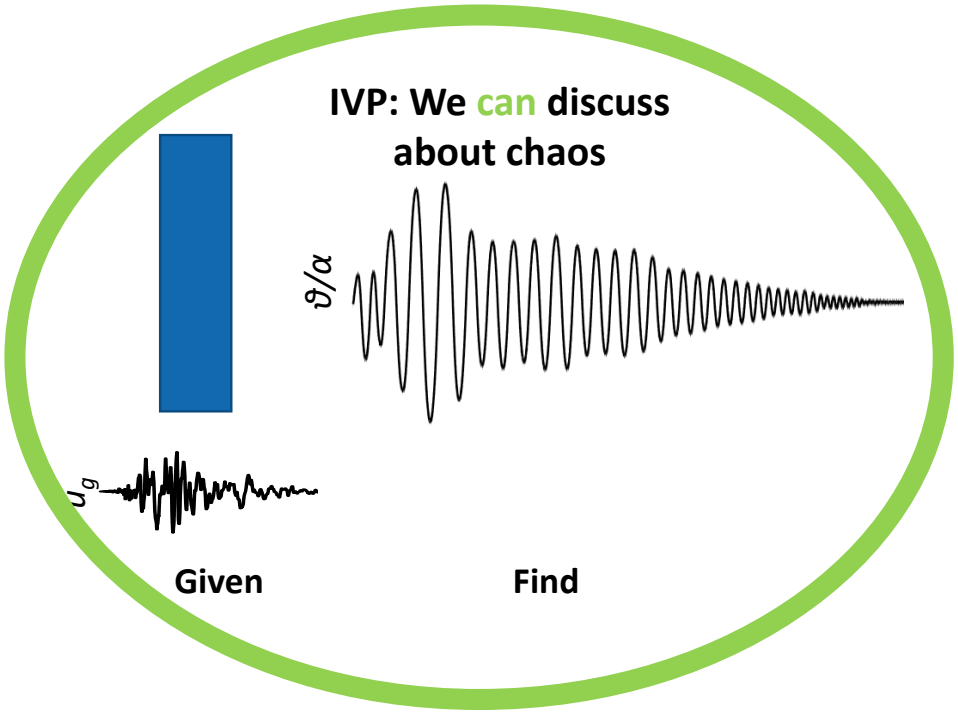


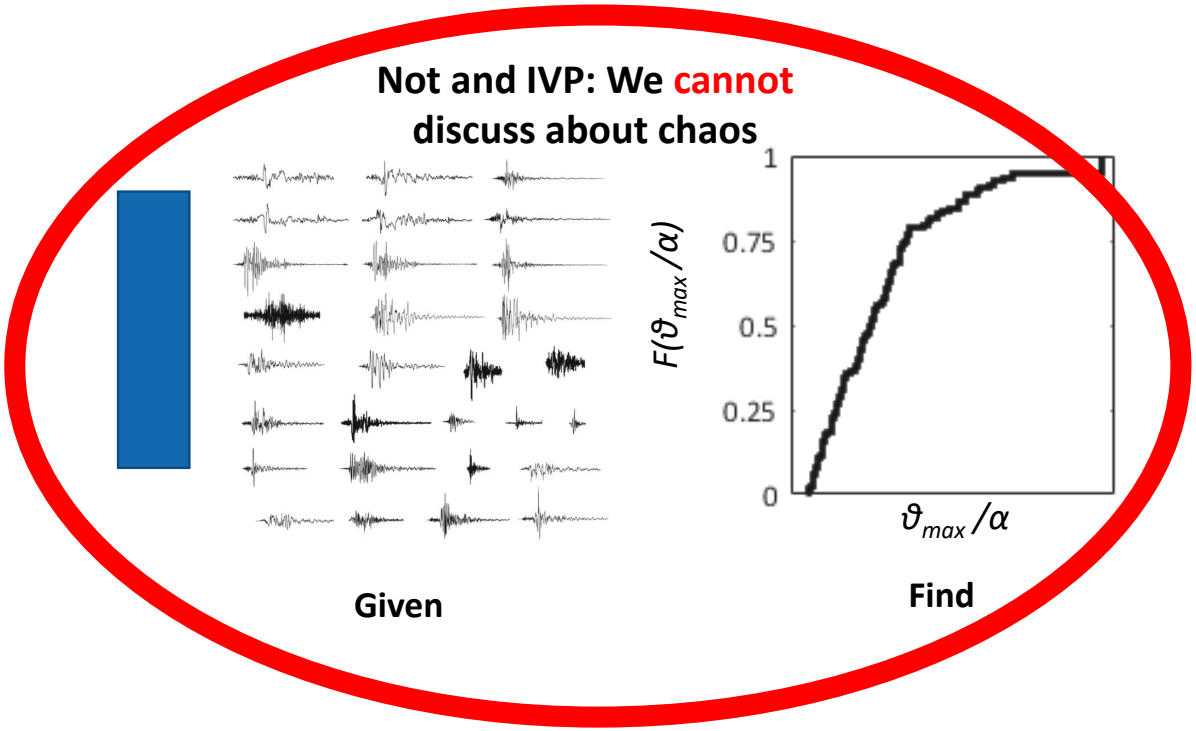


Bachmann et al. 2017

What is chaos?

Mathematically speaking : Chaos is only defined for Initial Value Problems (IVPs).





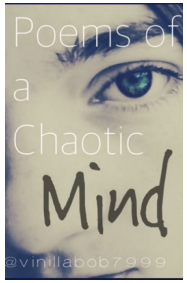
Is rocking motion chaotic?

But the term has been coined 2700 years ago. Why give it away to mathematicians?

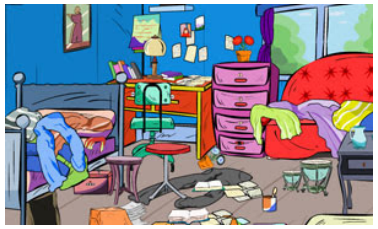
Mathematically speaking : Chaos is only defined for Initial Value Problems (IVPs). The term was first used in the 1960s.

Historically speaking (wikipedia) : Chaos (Greek χάος, *khaos*) refers to the *formless or void state preceding the creation of the universe* or cosmos in the Greek creation myths, or to *the initial "gap" created by the original separation of heaven and earth*. In Hesiod's *Theogony* (c. 700 BC), Chaos was the first of the primordial deities, followed by Gaia (Earth), Tartarus (the nether abyss) and Eros (Love). From Chaos came Erebus (Darkness) and Nyx (Night).

Modern use (Oxford dictionary):
1) Complete disorder and confusion. *Snow caused chaos in the region*
2) Physics: The property of a complex system whose behaviour is so unpredictable as to appear random, owing to great sensitivity to small changes in conditions.

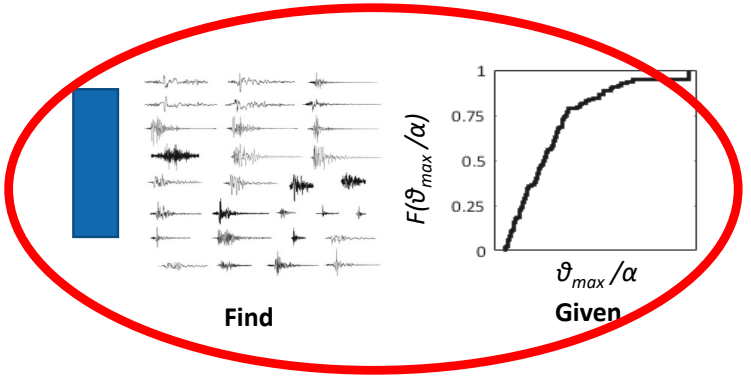


Chaotic mind


Chaotic room

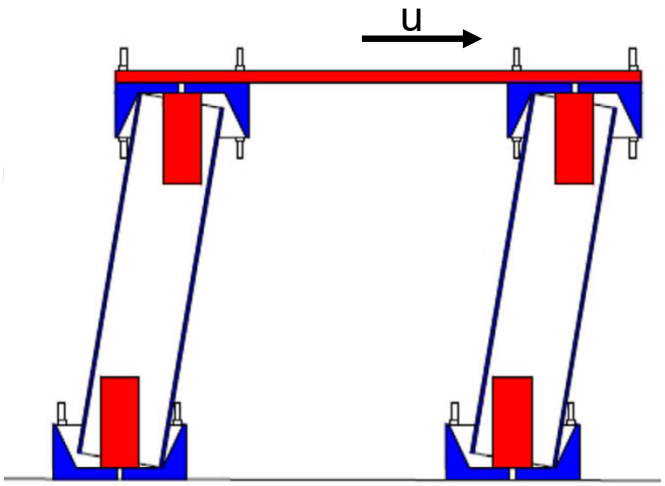
There is no IVP here!

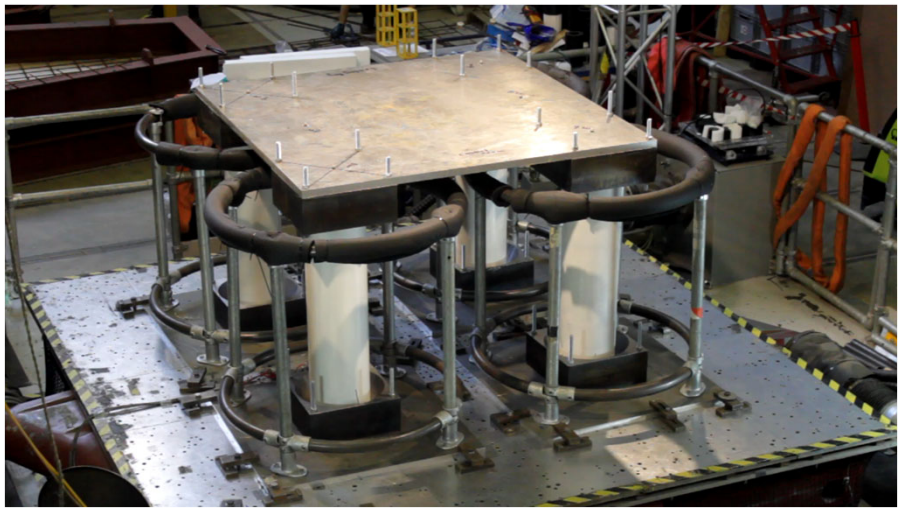

Chaotic city

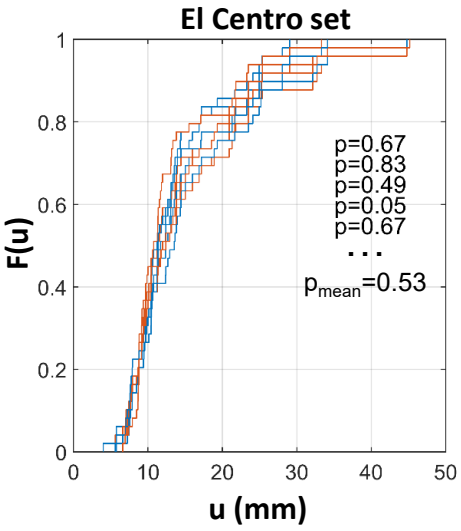


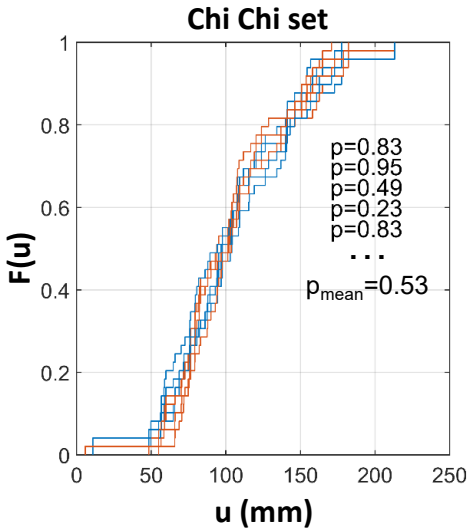
Extension to 3 Dimensions: Repeatability and predictability

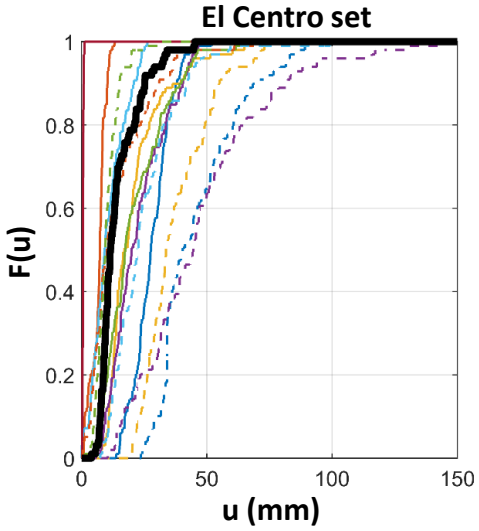
Vassiliou et al. 2021

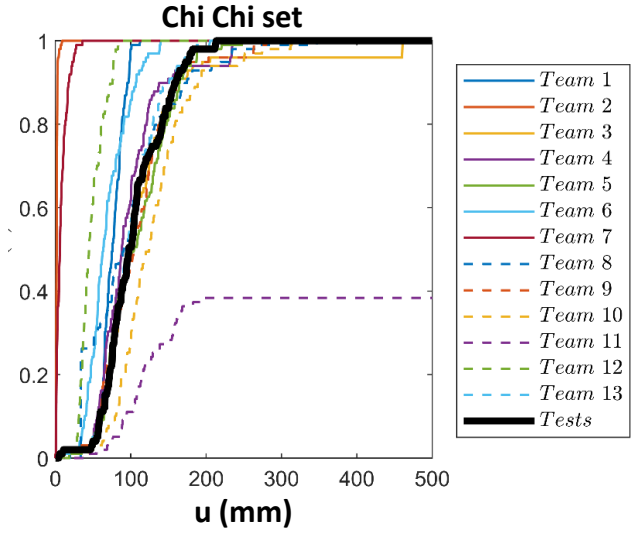




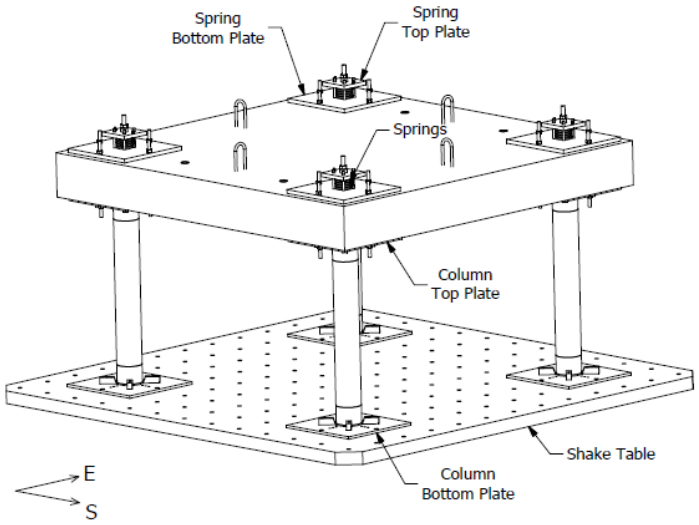


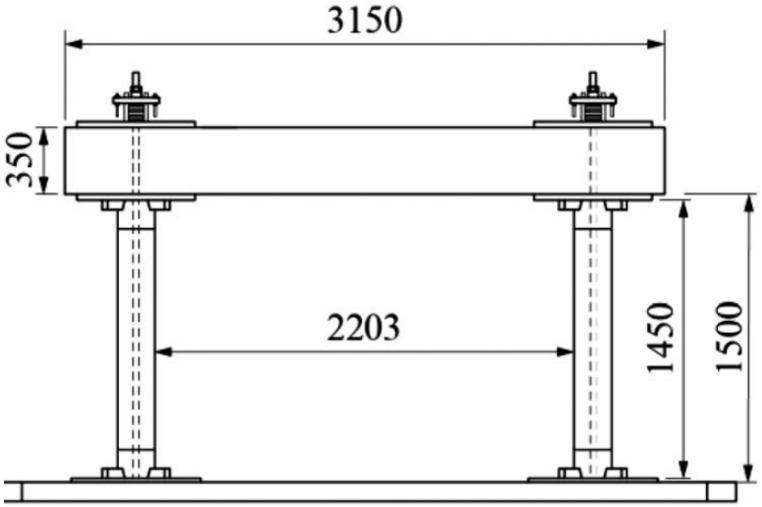


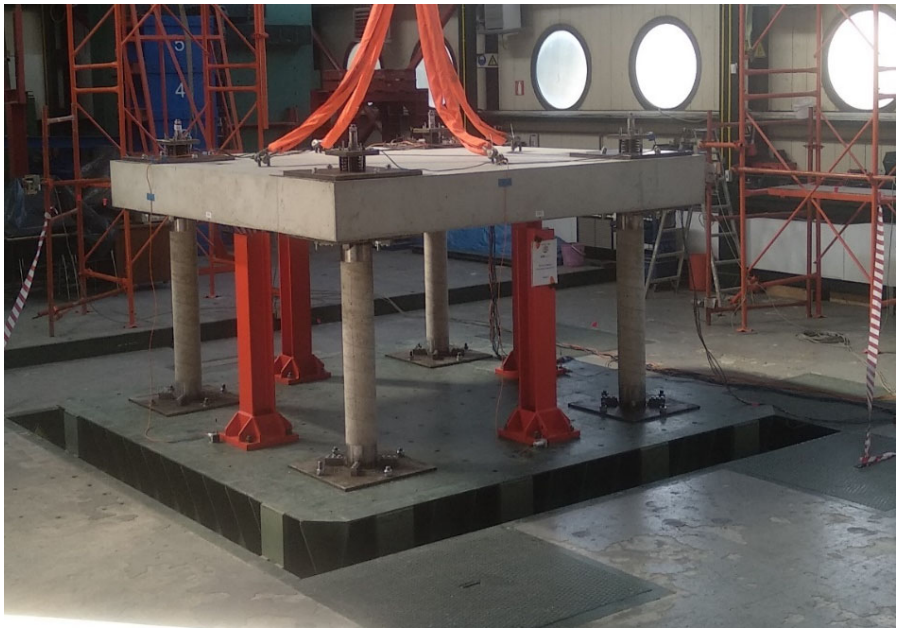




Shake table tests of a precast RC system

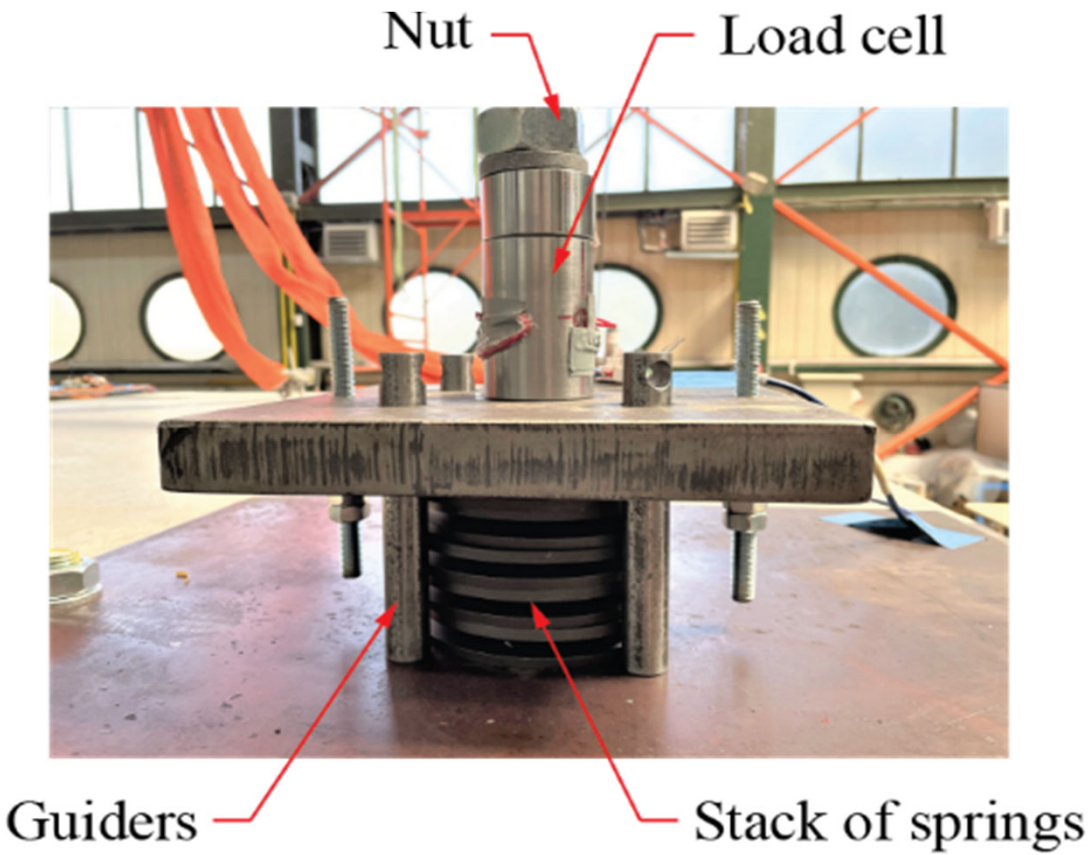




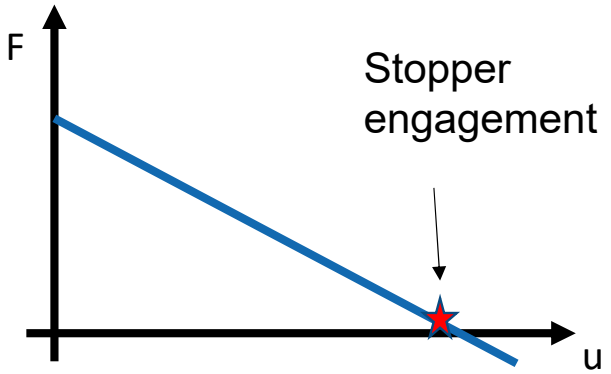


(Reggiani Manzo et al. 2022)

Custom made spring device



(Reggiani Manzo et al. 2022)



Excitations

Near Field Pulse like
26 motions

Near Field Non
Pulse like
26 motions

Far Field (FF)
43 motions

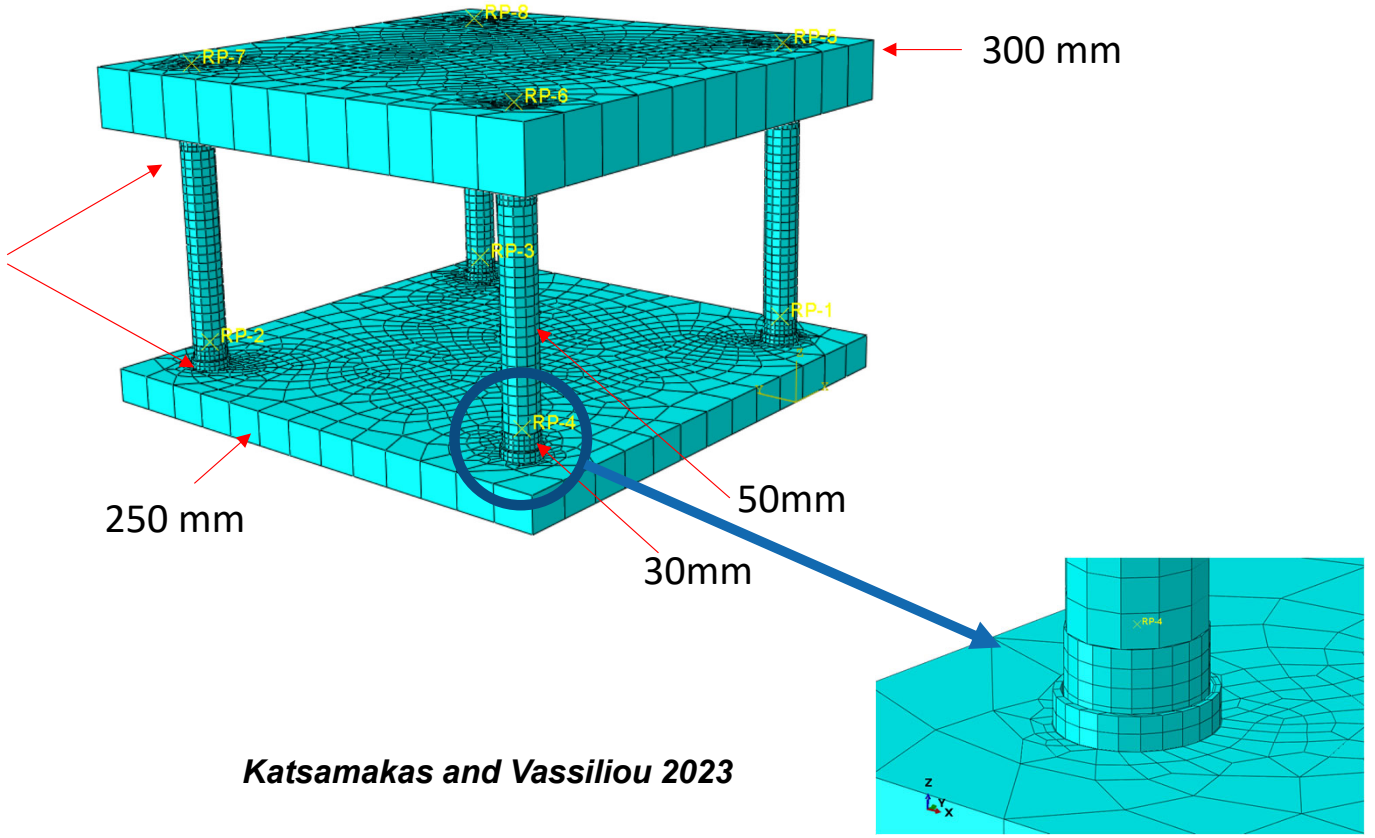
= **95** excitations

Each group was scaled to PGV=16.75cm/s and PGV=33.5cm/s (model scale) = total of **190** scheduled tests

Can we model it numerically?

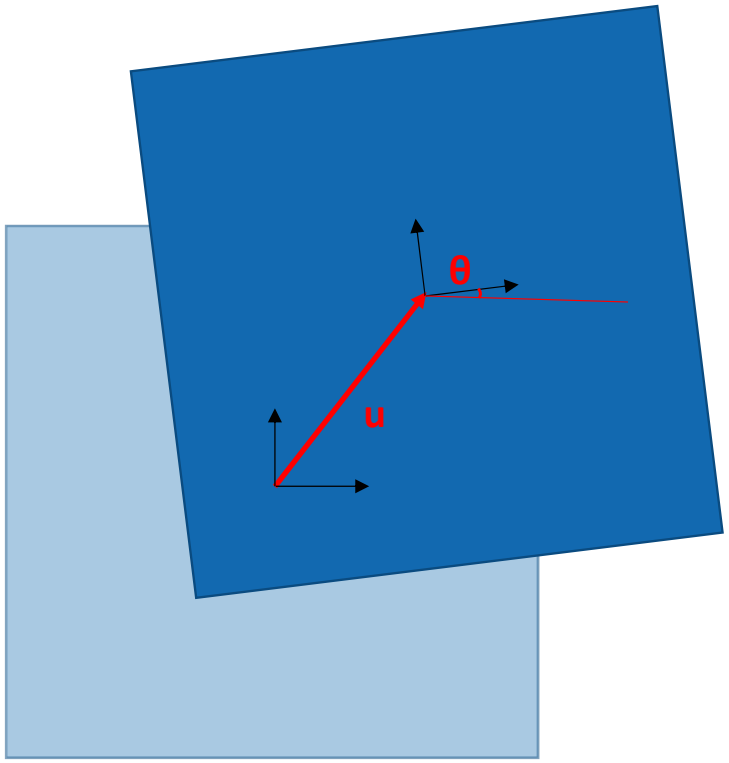
ABAQUS FE Model

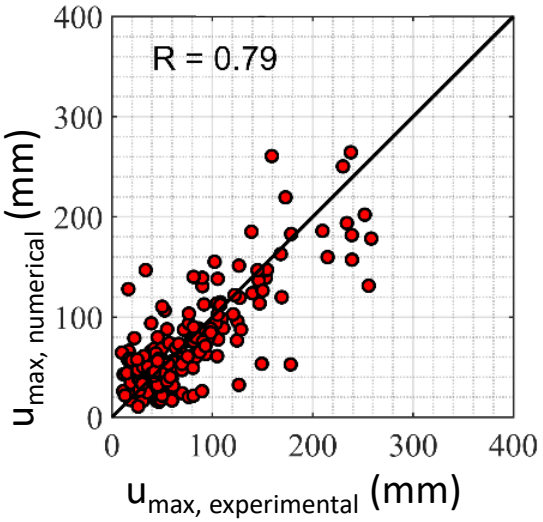
- 8-node elastic hexaedral elements
- Tendon-spring system spring element
- HHT, dt=1e-3 sec, α=-0.2

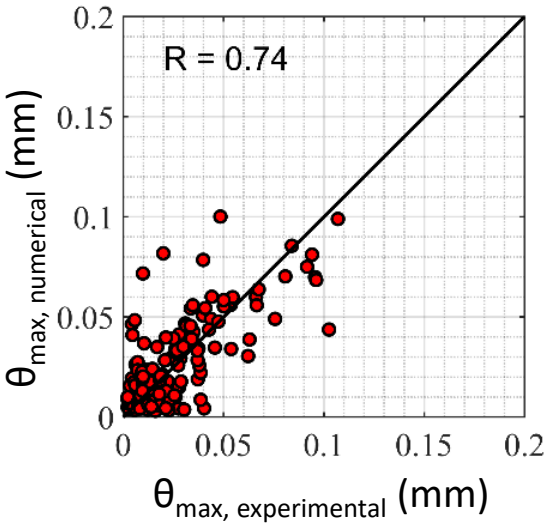


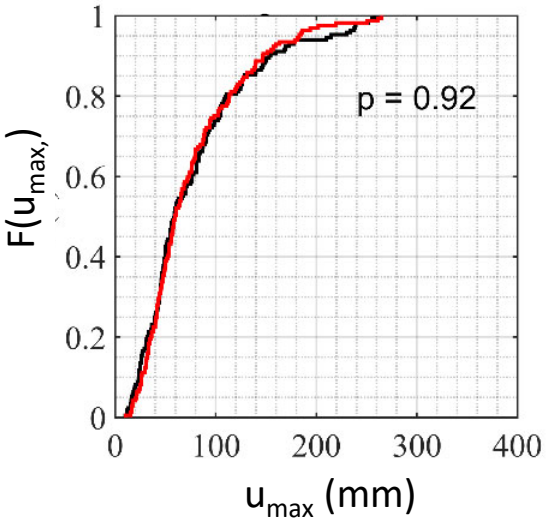
Katsamakas and Vassiliou 2023

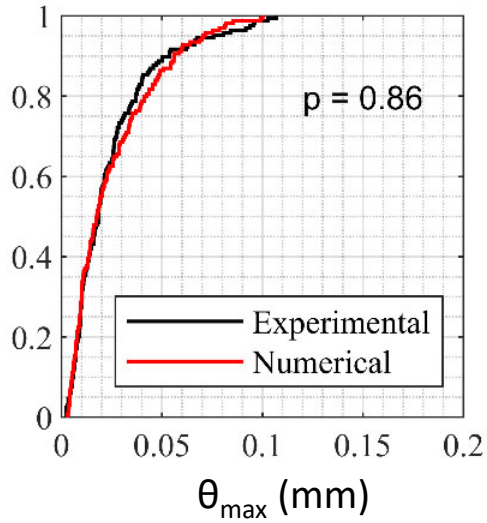
Results: Displacement and Rotation



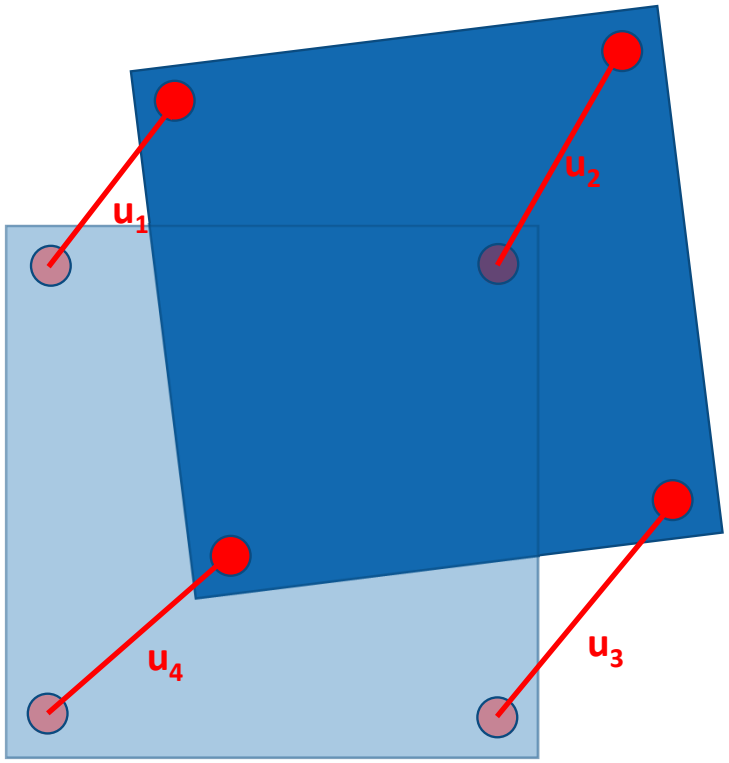




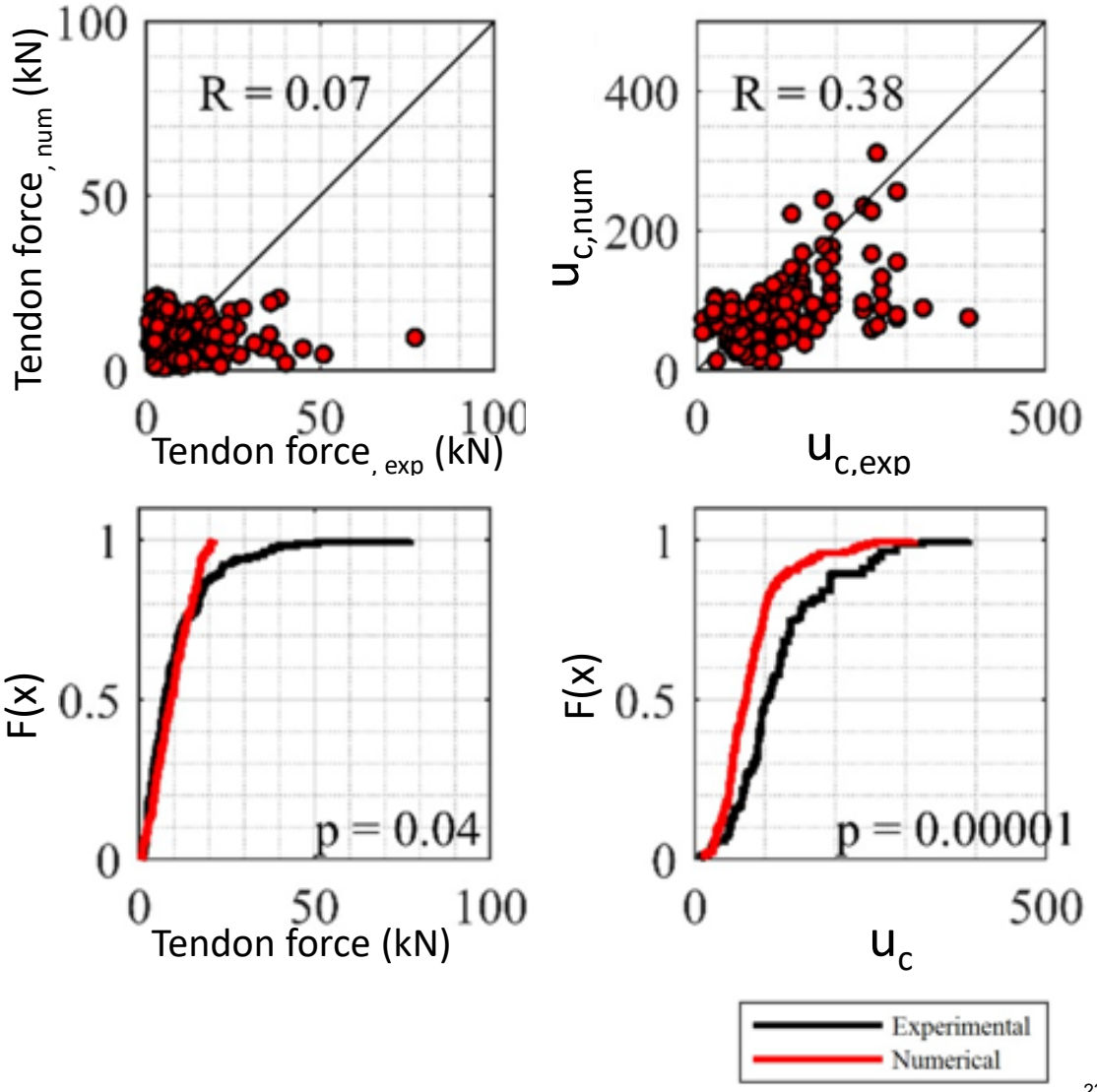




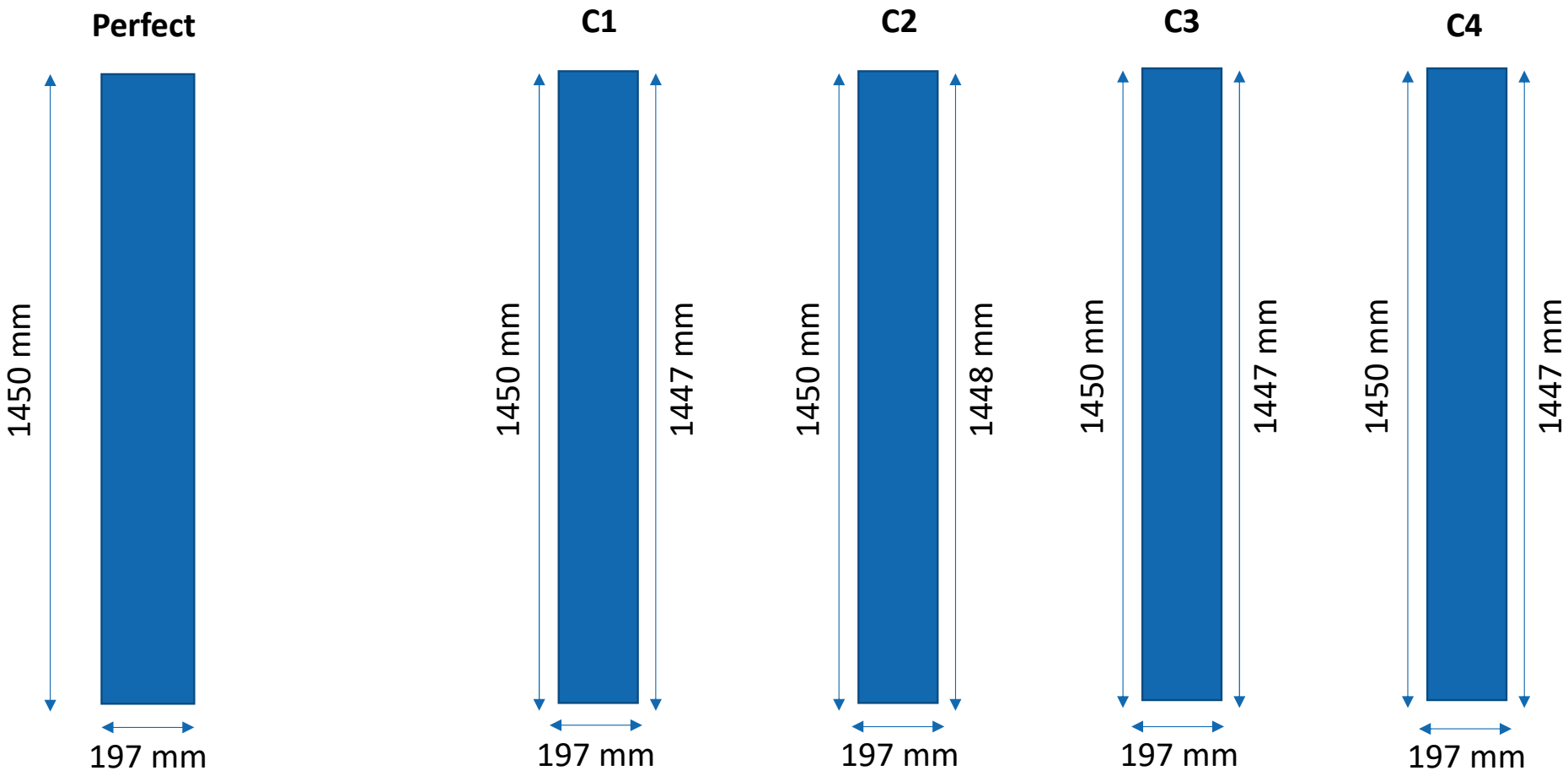
Results: Tendon Forces and Column Drifts



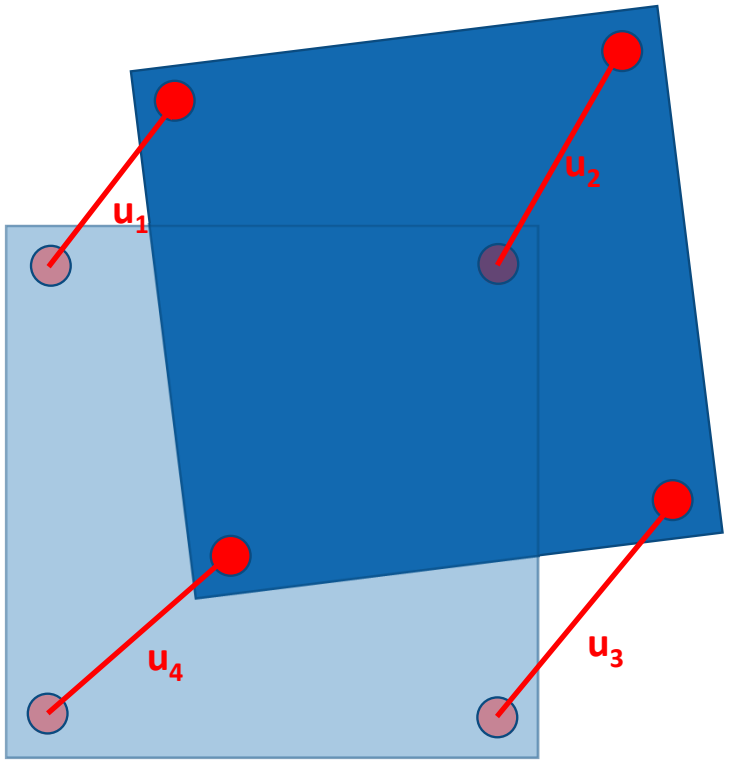
$u_c = \max(u_1, u_2, u_3, u_4)$



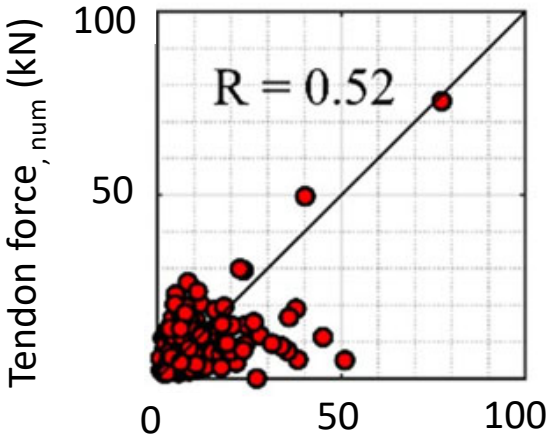
Imperfections

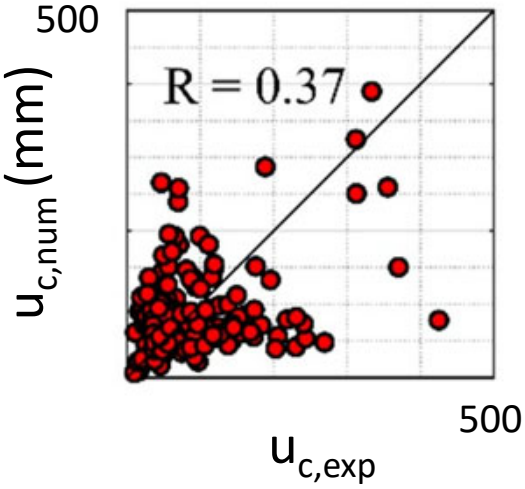


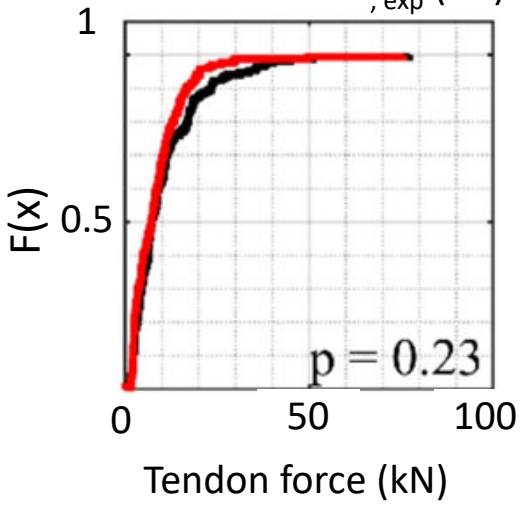
Results: Column Drifts (imperfections included)

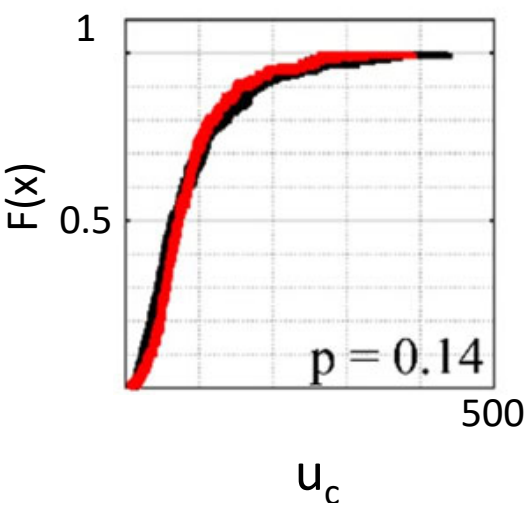


$u_c = \max(u_1, u_2, u_3, u_4)$









Conclusions

- If possible, model validation should be performed statistically.
- Sometimes, this is the only possible way.
- Rocking is predictable – in the statistical sense.

References

Bachmann, J. A., Strand, M., Vassiliou, M. F., Broccardo, M., & Stojadinović, B. (2018). Is rocking motion predictable?. *Earthquake Engineering & Structural Dynamics*, *47*(2), 535-552.

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Reggiani Manzo, N., Vassiliou, M. F., Mouzakis, H., & Badogiannis, E. (2022). Shaking table tests of a resilient bridge system with precast reinforced concrete columns equipped with springs. *Earthquake Engineering & Structural Dynamics*, *51*(1), 213-239.

Vassiliou, M. F. and Katsamakas A., (2023) Finite element modelling of the shake table response of a bridge model comprising rocking columns, COMPDYN 2023, Athens, Greece