CONVEGNO
"Strategie per la riduzione
della vulnerabilità sismica
degli elementi non strutturali"

Bologna – 19 ottobre 2018

Risposta sismica, progetto e verifica di elementi non strutturali

G. M. Calvi
Scuola Universitaria Superiore Pavia
Fondazione Eucentre, Pavia

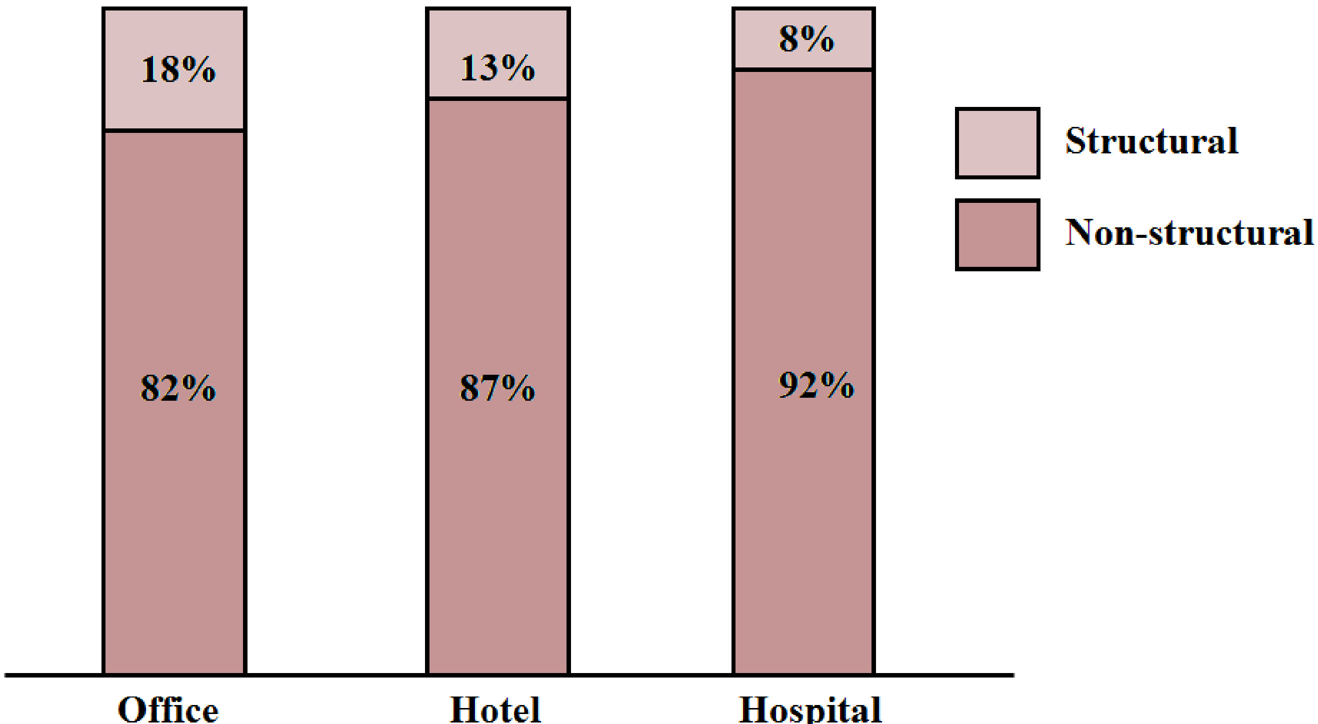
[Performance-Based Seismic Design of Non-Structural Building Components]

Acknowledgements

- Daniele Perrone, PhD, Post-doctoral Researcher
- Roberto Merino, PhD Candidate
- André Filiatrault, PhD, P. Eng., Professor

Why should we consider Nonstructural Building Components in Seismic Design?

1. Non-structural components represent the major portion of the total investment in typical buildings.



Source: Miranda and Taghavi (2003)

Why should we consider Nonstructural Building Components in Seismic Design?

2. Non-structural damage can limit severely the functionality of critical facilities, such as hospitals.

Emergency Room of Veteran Administration Hospital following the 1994 Northridge Earthquake in California

2. Non-structural damage can limit severely the functionality of critical facilities, such as hospitals.

2. Non-structural damage can limit severely the functionality of critical facilities, such as hospitals.

2. Non-structural damage can limit severely the functionality of critical facilities, such as hospitals.

Why should we consider Nonstructural Building Components in Seismic Design?

3. Failure of nonstructural components can become a safety hazard or can hamper the safe movement of occupants evacuating or of rescuers entering buildings.

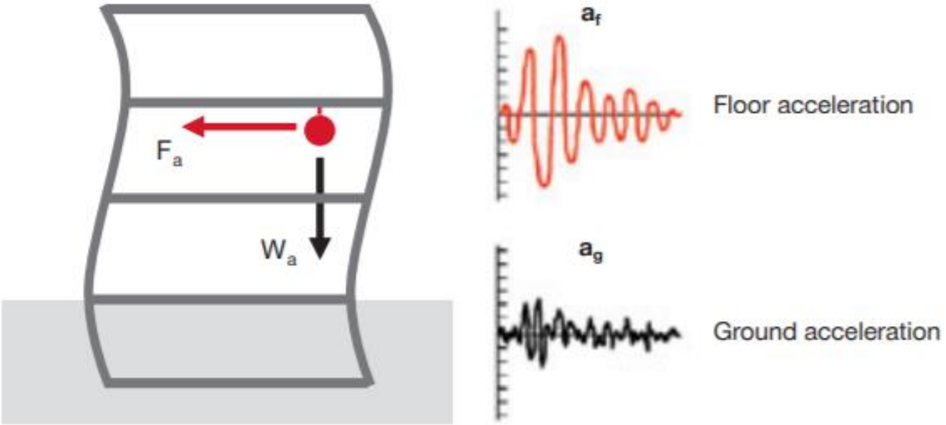
Christchurch Earthquake - February 2011

Source: EERI

Current Force-Based Seismic Design Procedure for Non-structural Components

- Estimate of elastic floor spectral accelerations at center of mass of components used to determine required lateral elastic strength.

- Elastic strength divided by a force reduction (behaviour) factor q_a representative of inherent overstrength and ductility capacity of components and attachments.



Eurocode 8:

$$F_a = \frac{S_a \gamma_a}{q_a} W_a$$

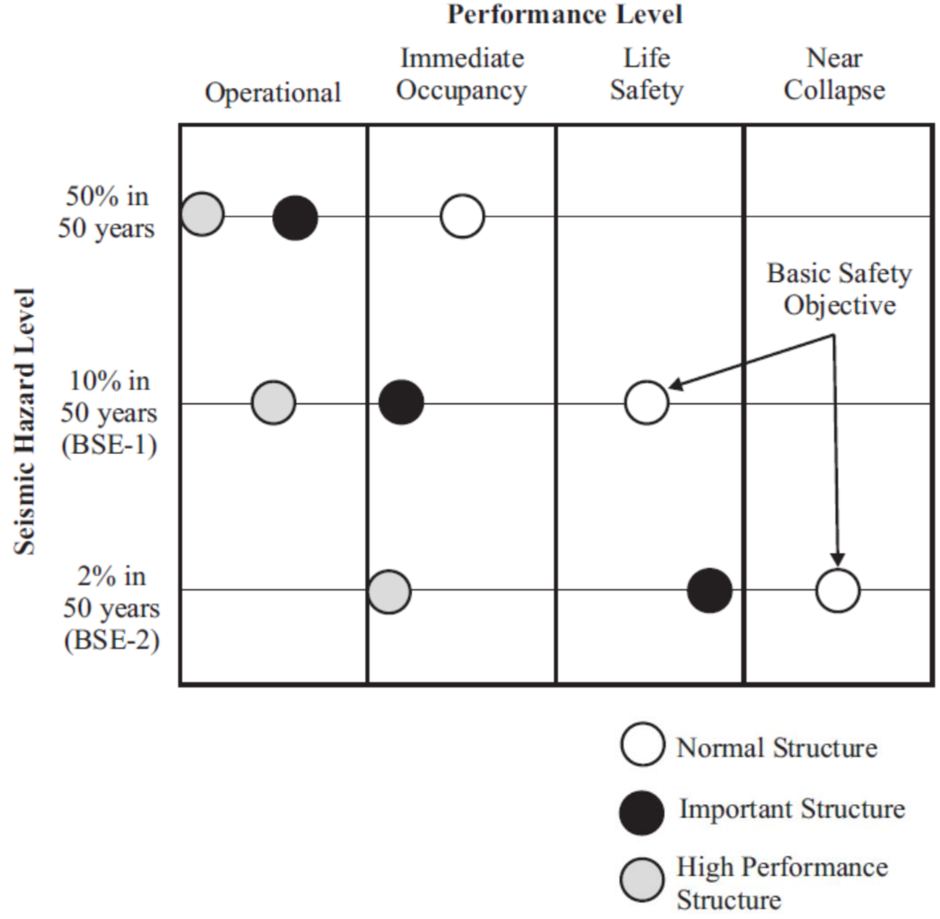
$$S_a = a_g S\left(\frac{3(1+z/H)}{1+(1-T_a/T_n)^2} - 0.5\right) \geq a_g S$$

Current Force-Based Seismic Design Procedure for Non-structural Components

- Major shortcomings:
  1. Estimation of the fundamental period of a non-structural component is difficult.
  2. Use of fundamental periods of a non-structural component and of the supporting structure is fallacious.
  3. Linear amplification of peak floor acceleration with height assumes first mode response of the supporting structure.
  4. Damping characteristics of non-structural components ignored.
  5. Force reduction (behaviour) factors q_a assigned to non-structural components are highly judgmental.
  6. Deformations of non-structural components not directly addressed.
  7. Single performance objective (life-safety) considered.

Performance-Based Seismic Design

- Coupling of performance levels to different seismic intensity levels.
- Application to non-structural components unexplored.
- Current seismic provisions for non-structural components: force-based seismic design procedure.



Adapted from Vision 2000 document (SEAOC 1995)

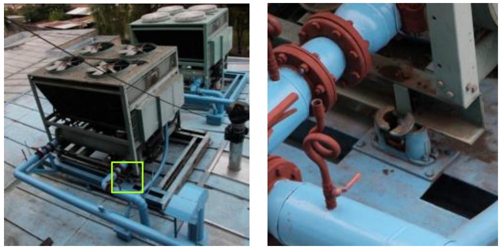
Performance-Based Seismic Design Procedure for Non-structural Components

- Damage driven by excessive displacements relative to the supporting structure for many non-structural component typologies.

- Wouldn’t a displacement-based seismic design procedure for non-structural components makes more sense?

Suspended Utilities and Equipment:

Suspended Ceilings



Anchored Equipment

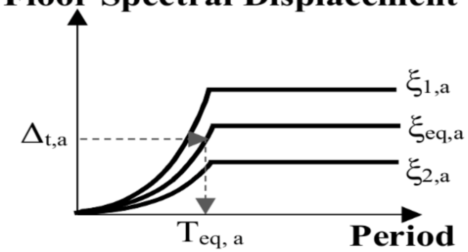
Storage Racks and Shelving

Direct Displacement-Based Seismic Design Procedure for Non-structural Components

Start

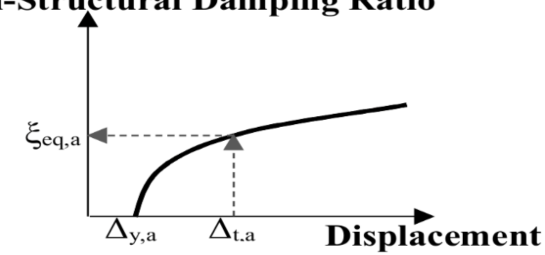
Step 1:
- Define target non-structural displacement, $\Delta_{t,a}$.
- Define seismic hazard.

Floor Spectral Displacement



Step 2:
- Select appropriate value of equivalent non-structural viscous damping, $\xi_{eq,a}$, for selected non-structural system at target displacement.

Non-Structural Damping Ratio



Step 3:
- Determine equivalent non-structural period, $T_{eq,a}$, from floor relative displacement response spectrum at damping $\xi_{eq,a}$.

Step 4:
- Compute equivalent non-structural lateral stiffness:

$$k_{eq,a} = \frac{4\pi^2 W_a}{g T_{eq,a}^2}$$

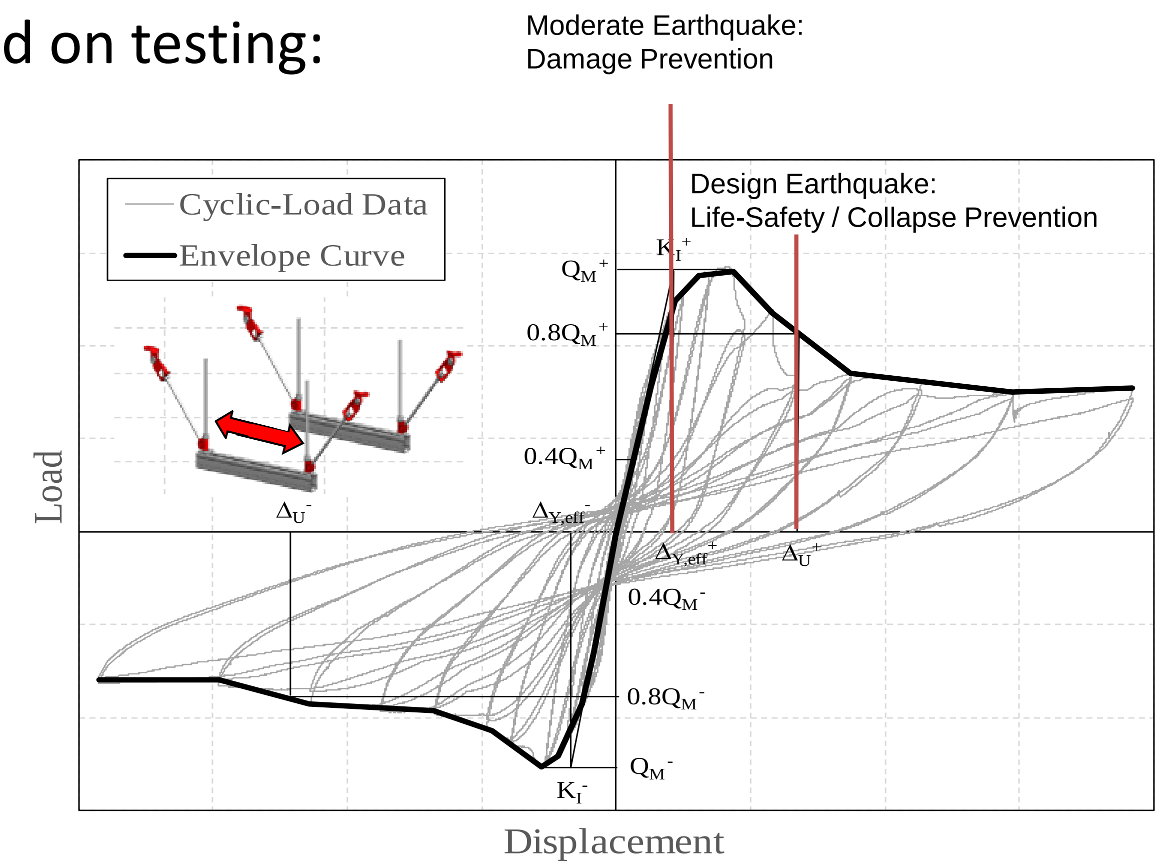
Step 5:
- Compute design seismic force:

$$F_a = k_{eq,a}\, \Delta_{t,a}$$

End

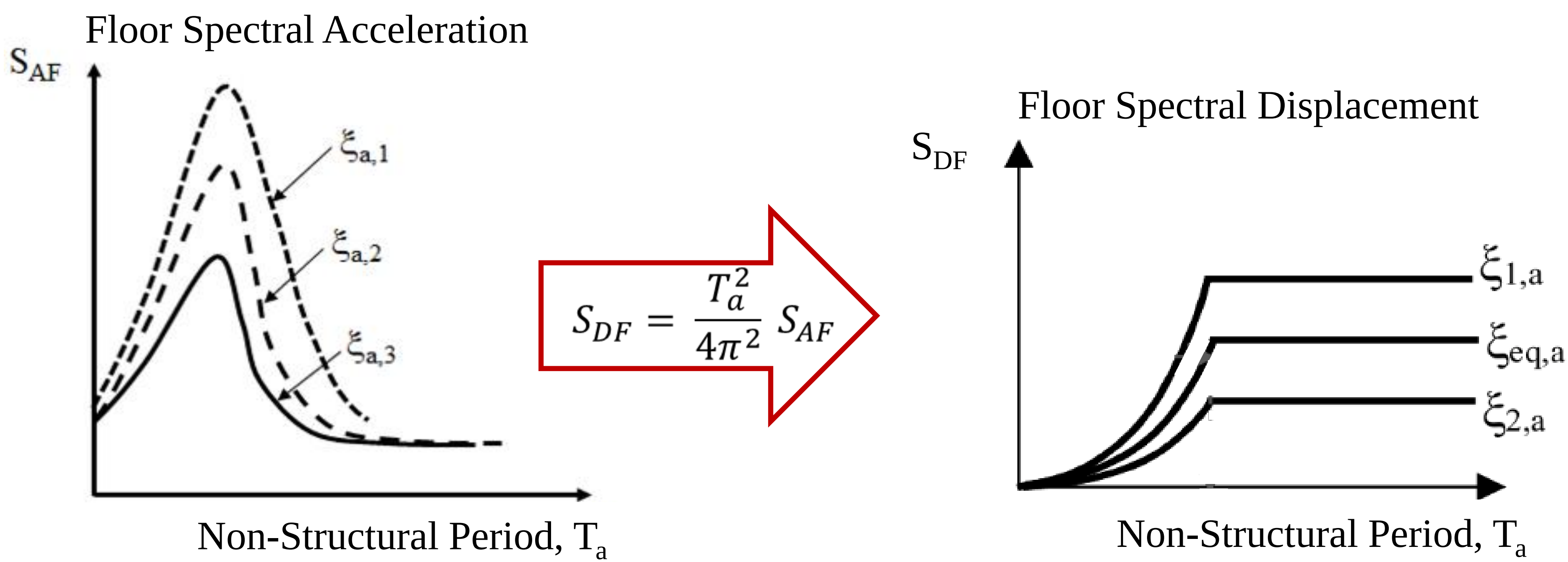
Direct Displacement-Based Seismic Design Procedure for Non-structural Components

- Step 1: Definition of Target Non-Structural Displacement.
  - Based on testing:



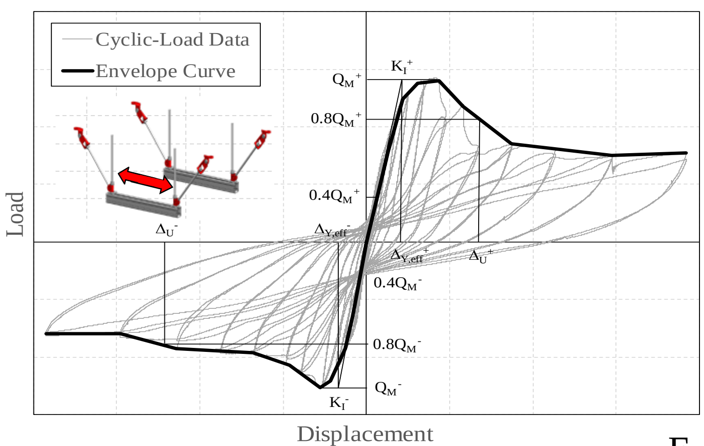
Direct Displacement-Based Seismic Design Procedure for Non-structural Components

- Step 1: Definition of Seismic Hazard.
  - Based on transformation of floor acceleration spectra into floor relative displacement spectra:

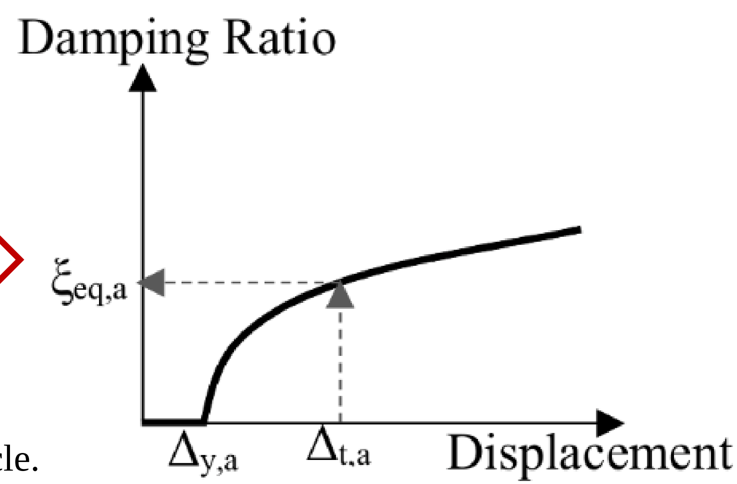


Direct Displacement-Based Seismic Design Procedure for Non-structural Components

- Step 2: Determination of Equivalent Viscous Damping.
  - Based on testing and Jacobsen's damping model:



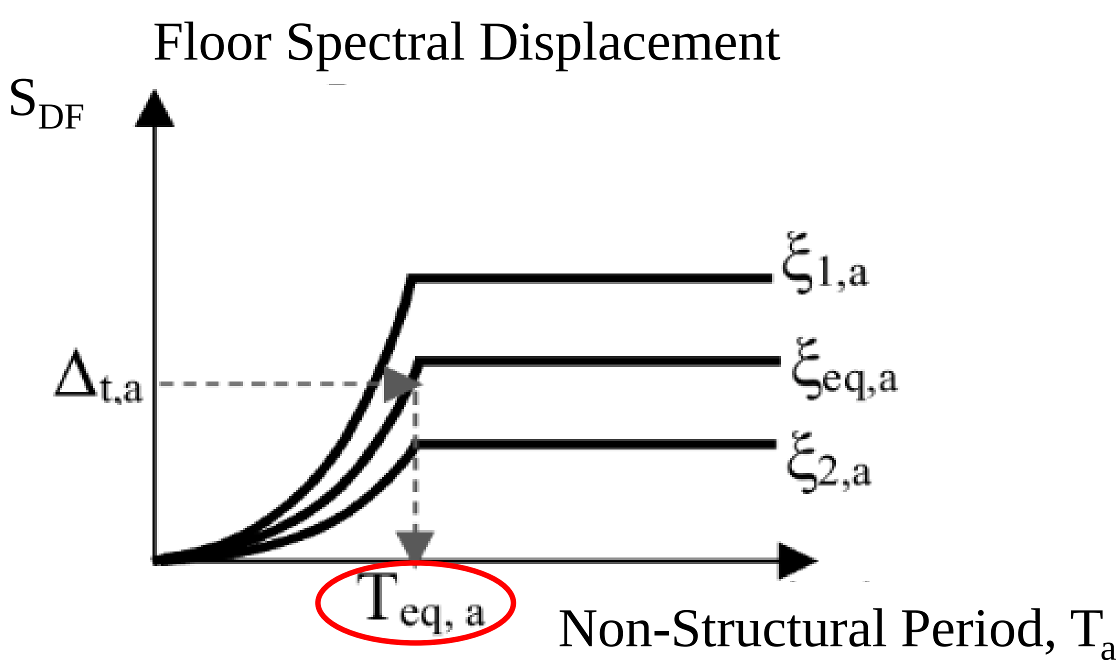
$$\xi_{eq,a} = \frac{E_{D,\Delta t,a}}{2\pi k_{eq,a}\Delta_{t,a}^2}$$



$E_{D,\Delta t,a}$ = Energy dissipated per cycle.
$K_{eq,a}$ = Equivalent (secant) lateral stiffness

Direct Displacement-Based Seismic Design Procedure for Non-structural Components

- Step 3: Determination of Equivalent Non-Structural Period.
  - Enter floor relative displacement spectra with target non-structural Displacement :



Direct Displacement-Based Seismic Design Procedure for Non-structural Components

- Step 4: Determination of Equivalent Non-Structural Lateral Stiffness.
  - Based on equivalent single degree-of-freedom system:

$$k_{eq,a} = \frac{4\pi^2 W_a}{g T_{eq,a}^2}$$

- Step 5: Compute design seismic force.

$$F_a = k_{eq,a} \, \Delta_{t,a}$$

Direct Displacement-Based Seismic Design Procedure for Non-structural Components

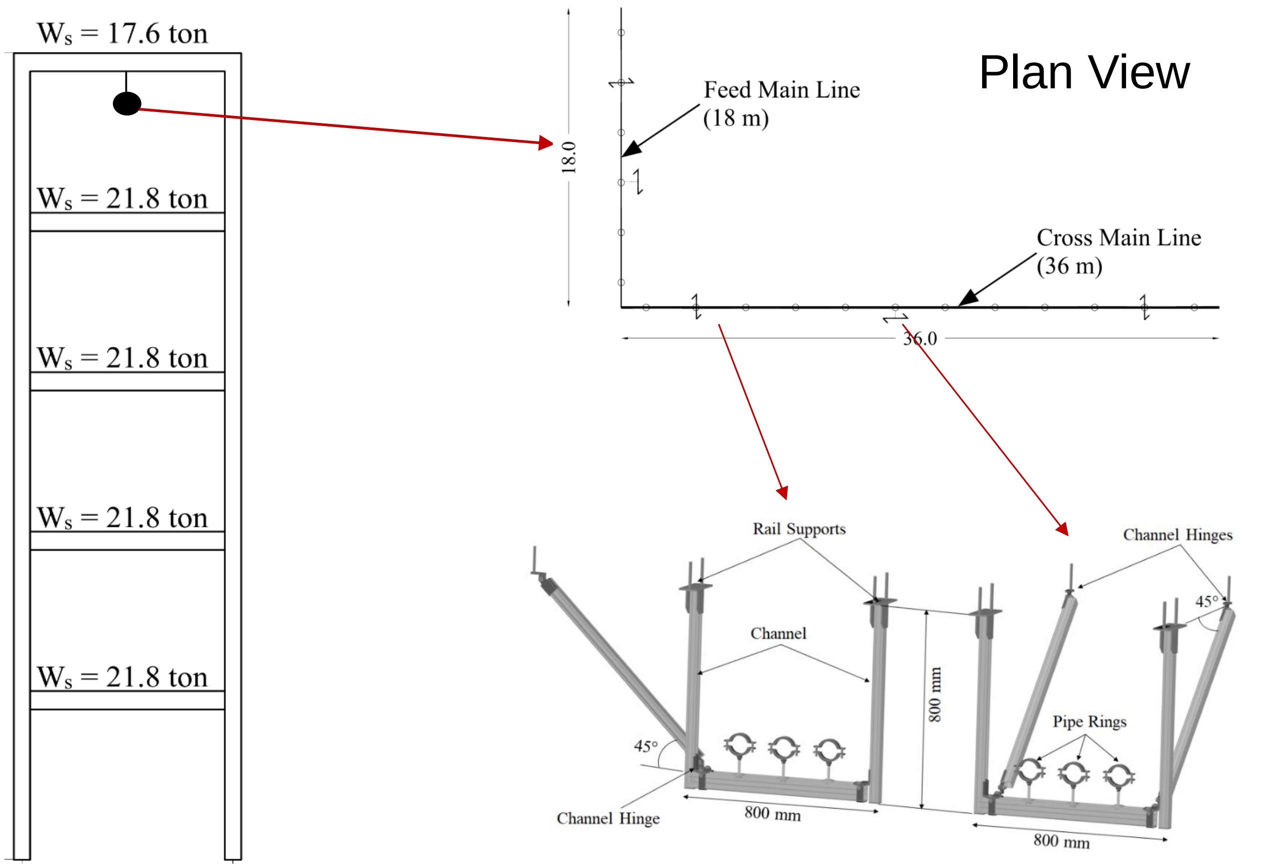
- Major Advantages:
  1. No estimation of the elastic period of the non-structural component and of the supporting structure is required.
  2. The highly empirical force reduction (behavior) factors do not enter in the design process.
  3. Displacements/deformations of the non-structural components relative to the supporting structure, known to cause damage to several non-structural typologies, drive the design process.
  4. Multiple performance objectives can be considered.

Direct Displacement-Based Seismic Design Procedure for Non-structural Components

- Single Current Disadvantage:
  - Requires knowledge of the variation of the global equivalent non-structural viscous damping with non-structural displacement amplitude ($\xi_{eq,a}$ - $\Delta_{t,a}$ relationship).
    - Knowledge of the cyclic behaviour of the multitude of non-structural typologies commonly used in buildings is not well established at this time.
    - Non-structural system level testing is required in parallel with the development of analytical/numerical models for various non-structural typologies.
    - These research activities, however, not different from those conducted over the last century for structural systems.

Design Example

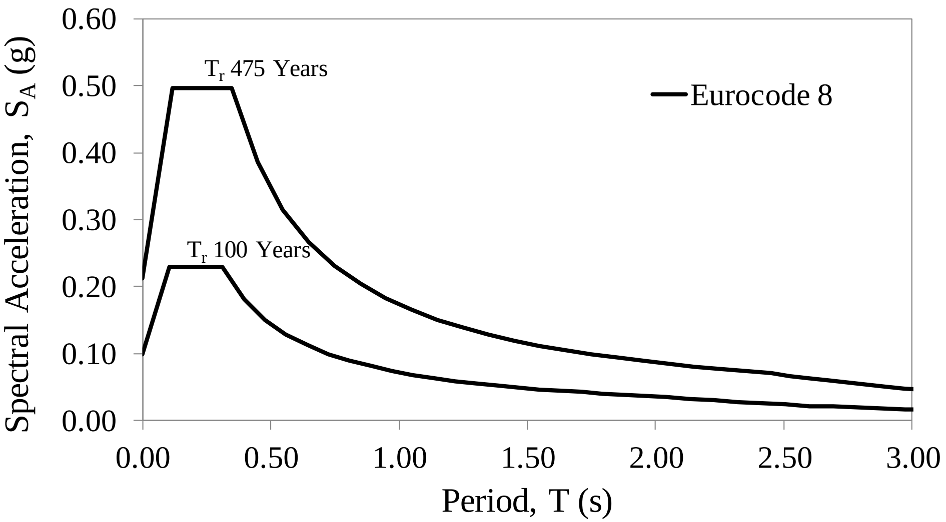
- Mechanical Piping System Suspended from the Top Floor of a Five-Storey Reinforced Concrete Frame.



Transverse and Longitudinal Sway Braced Trapezes

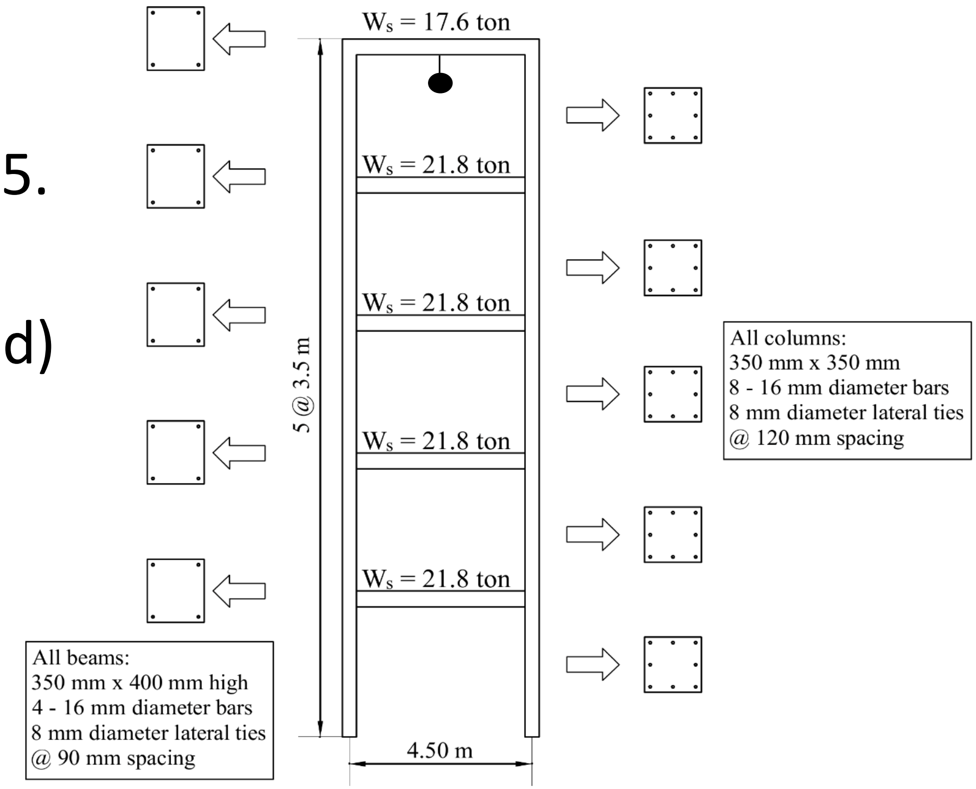
Design Example

- Seismic Hazard
  - High seismicity site in Italy.
    - Design (475 years return period) peak ground acceleration of 0.21 g.
    - Serviceability (100 years return period) peak ground acceleration of 0.10 g.
    - Eurocode 8 Design Response Spectral Shapes.



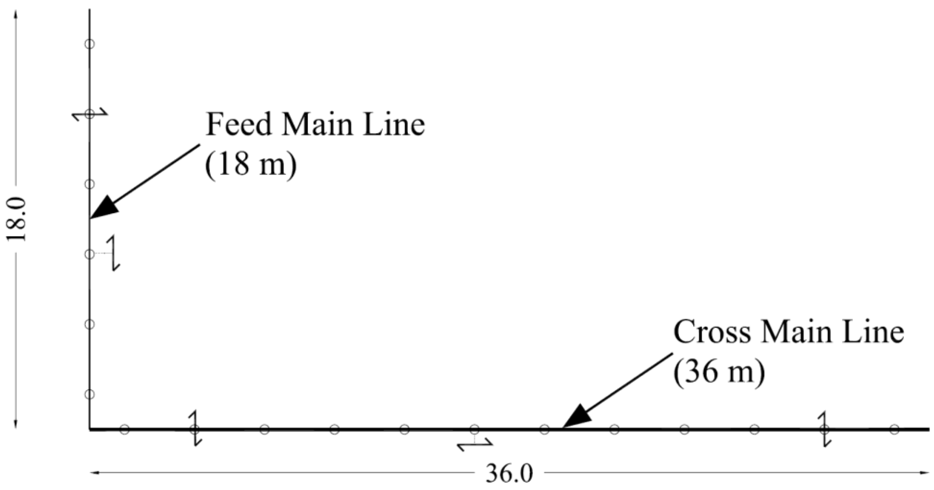
Design Example

- Design of Supporting Frame:
  - Eurocode 8 Seismic Design Provisions.
  - Force reduction factor q = 3.75.
    - Ductility class B.
  - Design (475-year return period) peak ground acceleration of 0.21 g.
  - Concrete strength = 30 MPa.
  - Yield strength of steel reinforcement = 450 MPa.



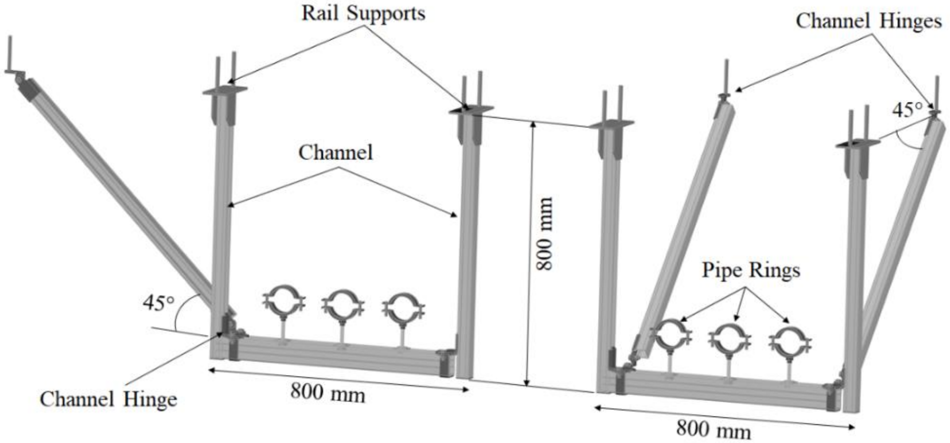
Design Example

- Layout of Suspended Mechanical Piping System:
  - Feed main line (18 m long) perpendicular to a cross main line (36 m long).
  - Three separate pipes:
    1. Cold-water distribution line.
    2. Hot-water distribution line.
    3. Hot-water recirculation line.
  - Black standard steel pipes:
    - Diameter = 127 mm (5 inch).
    - Wall thickness = 6.5 mm.
    - w_a = 0.31 kN/m for each pipe.
  - All pipe elbows and longitudinal splices rigidly welded.



Design Example

- Seismic Restraint Configurations and Properties:
  - Transverse and longitudinal sway braced trapezes.
  - All channels 41 mm deep.
  - 45° diagonal bracing channels.
  - Drop height = 800 mm.
  - Rail support connections to top floor slab.
  - Hinge connections between channels.
  - Pipe rings connected to horizontal channels vertical 12-mm diameter threaded rod (50 mm long).

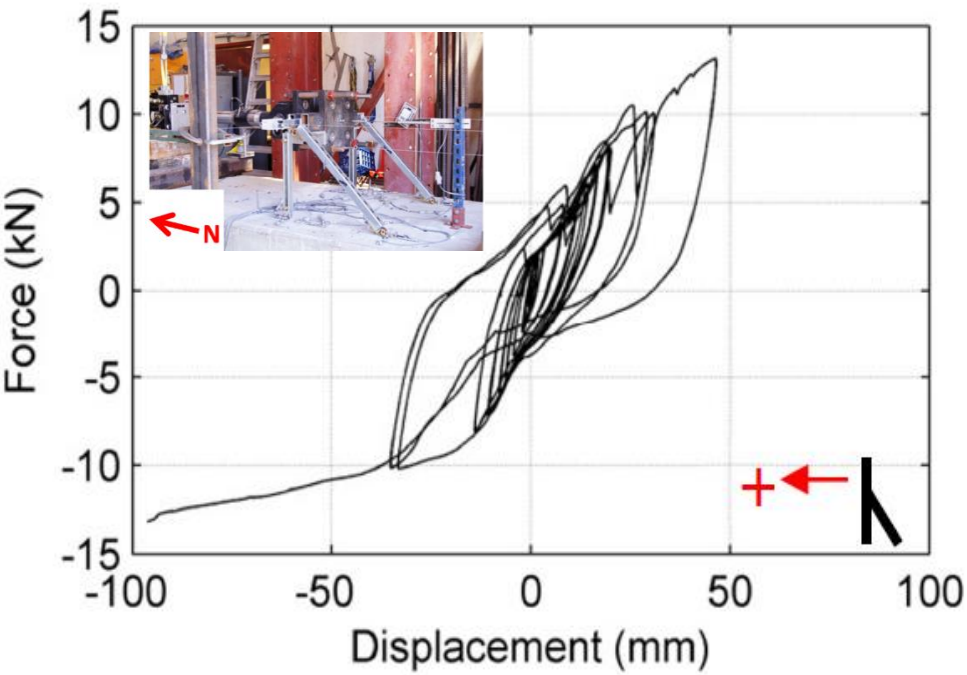


Transverse and Longitudinal Sway Braced Trapezes

Design Example

- Step 1: Definition of Target Non-Structural Displacements.
  - Based on testing by Wood *et al.* (2014).
  - Mean peak strengths and extracted.
  - Two performance objectives considered:

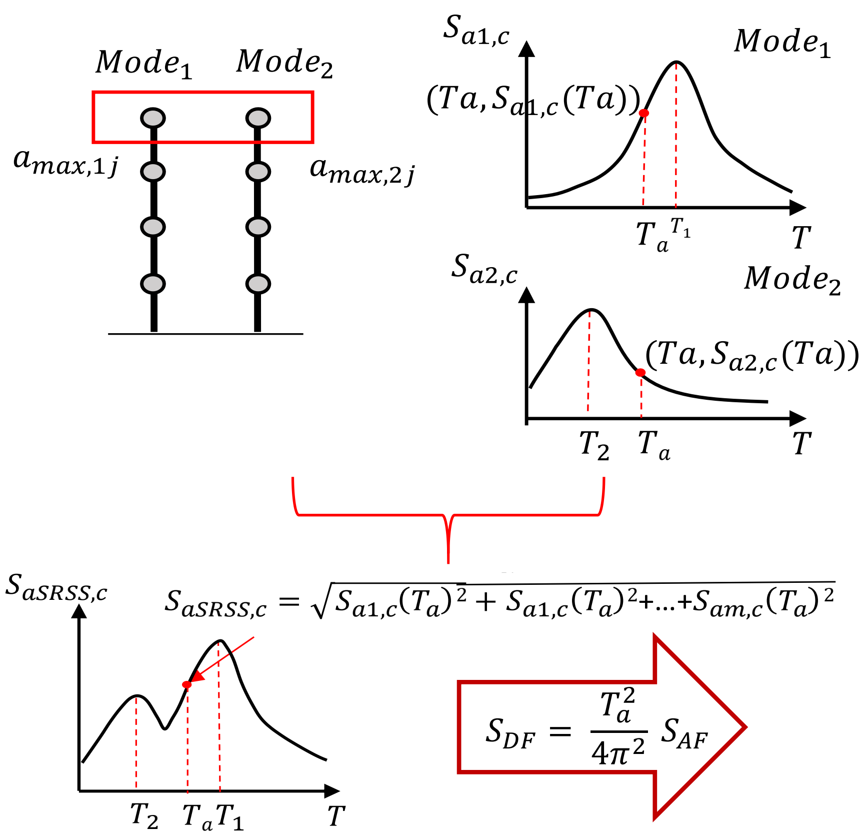
Performance Objective	Ground Motions Return Period, T_r (year)	Sway Braced Trapeze Target Ductility Ratio, $\mu_{t,a}$	
		Transverse Direction	Longitudinal Direction
Damage Prevention	100	1.0	1.0
Life-Safety / Collapse Prevention	475	1.5	2.5

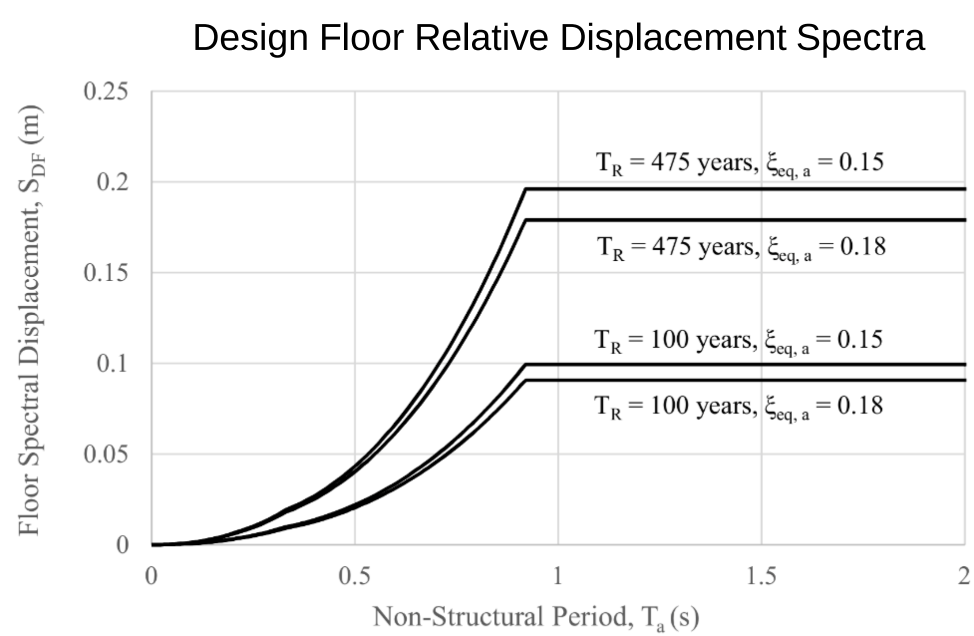


Direction	Mean Properties		
	Peak Strength $F_{max,a}$ (kN)	Yield Displacement $\Delta_{y,a}$ (mm)	Ductility Ratio μ_a
Transverse	8.6	13.8	1.5
Longitudinal	11.9	18.2	2.5

Design Example

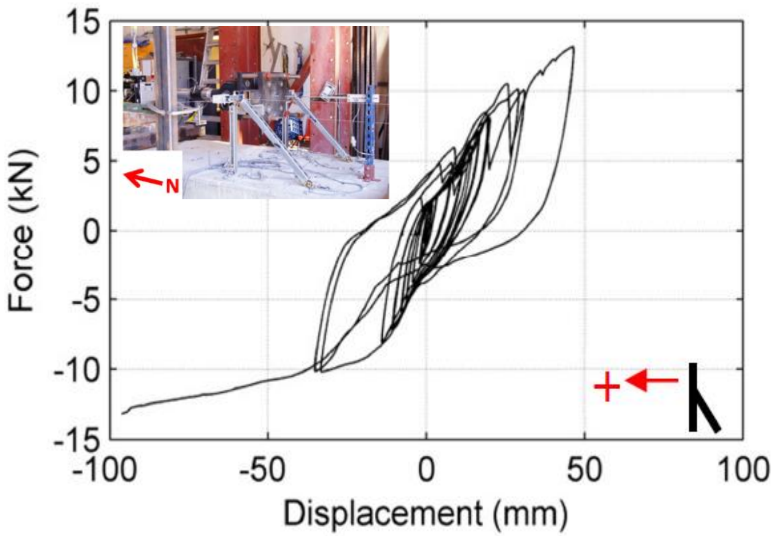
- Step 1: Definition of Seismic Hazard.
  - Transformation of an existing floor acceleration spectra model (Sullivan *et al.* 2013; Calvi and Sullivan; 2014) into floor relative displacement spectra:



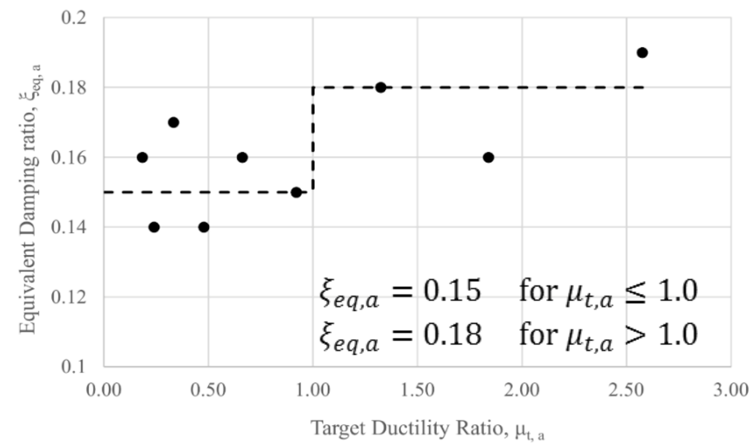


Design Example

- Step 2: Determination of Equivalent Viscous Damping.
  - Based on testing by Wood *et al.* (2014) and Jacobsen's damping model:



$$\xi_{eq,a} = \frac{E_{D,\Delta_{t,a}}}{2\pi k_{eq,a} \Delta_{t,a}^2}$$



Design Example

- Steps 3 to 5 Determination of Design Forces.
  - Design equation for individual sway brace:

$$F_a \leq \frac{F_{Rk}}{\gamma_m}$$

    - F_{Rk} = Characteristic strength from test results.
    - γ_m = Resistance factor = 0.8 in this example.
  - From DDBD Steps 4 and 5:

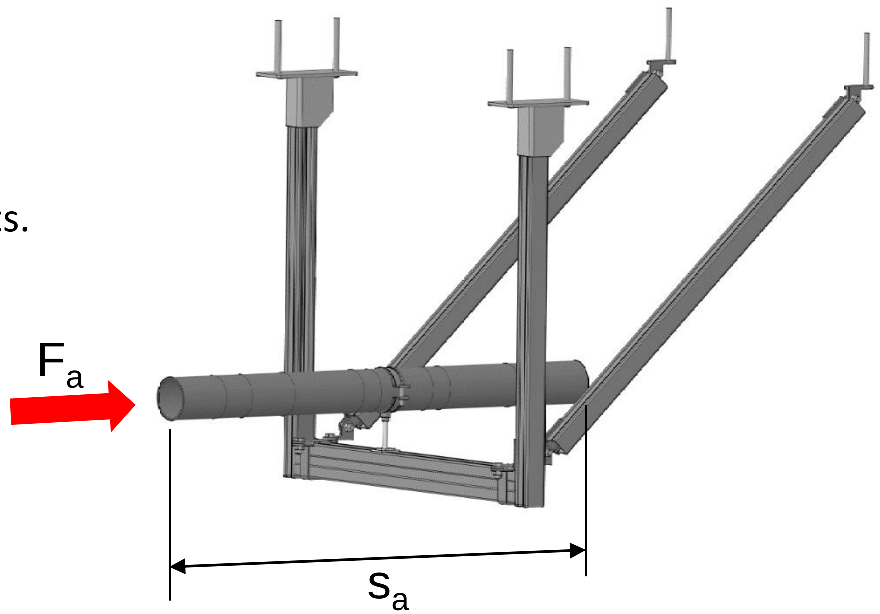
$$F_a = k_{eq,a}\,\Delta_{t,a} \qquad k_{eq,a} = \frac{4\pi^2 W_a}{gT_{eq,a}^2}$$

  - Tributary seismic weight:

$$W_a = 1.15 N_p w_a s_a$$

    - N_p = Number of pipes = 3 in this example.
    - *1.15* = Amplification factor to take into account weight of fittings and connections.
  - Combining, required spacing of sway braces:

$$s_a \leq \frac{gT_{eq,a}^2}{4\pi^2\Delta_{t,a}}\,\frac{F_{Rk}}{1.15\gamma_m N_p w_a}$$



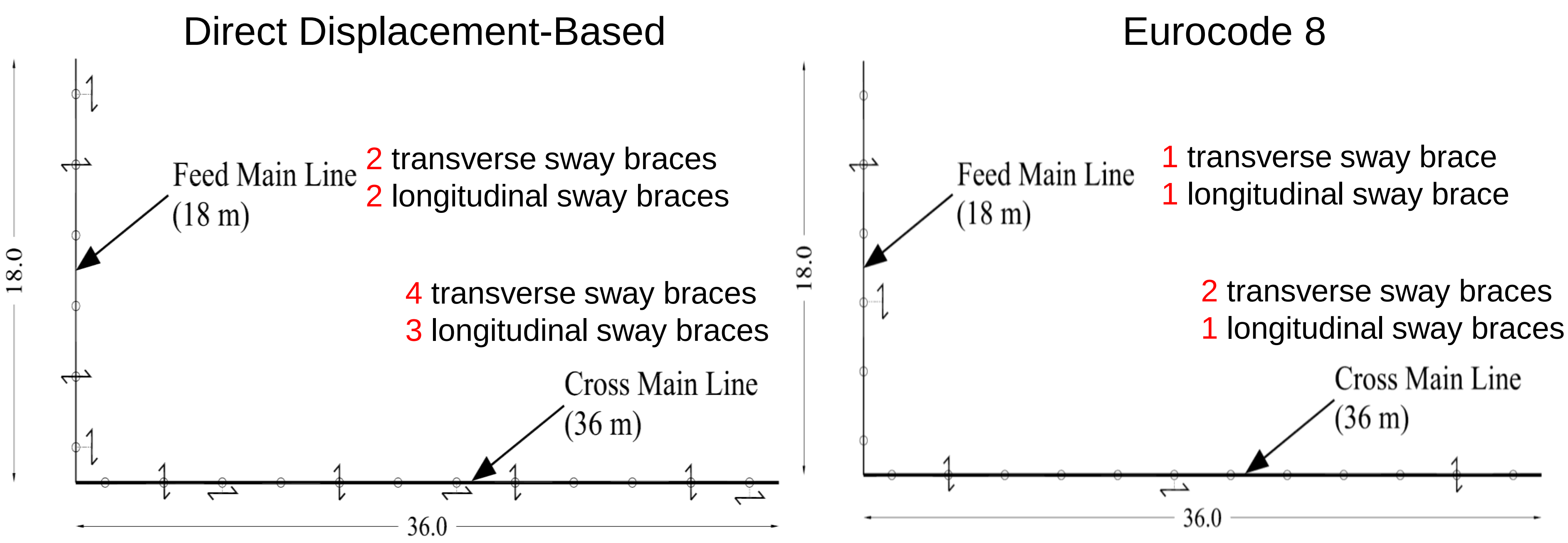
Design Example

- Final required spacing and number of sway braces:

	Design Parameter	Final Design Values			
		Damage Prevention Hazard Level T_r = 100 years		Safety Prevention Hazard Level T_r = 475 years	
		Transverse	Longitudinal	Transverse	Longitudinal
Step 1 →	Sway Braced Trapeze Target Ductility Ratio, $\mu_{t,a}$	1.0	1.0	1.5	2.5
Step 2 →	Sway Braced Trapeze Equivalent Viscous Damping Ratio, $\xi_{eq,a}$	0.15		0.18	
Step 3 →	Sway Braced Trapeze Equivalent Period, $T_{eq,a}$	0.40 s	0.46 s	0.36 s	0.53 s
	Number of Pipes, N_p	3			
	Unit Weight of One Water Filled Pipe, w_a	0.31 kN/m			
	Resistance factor, γ_m	1.25			
	Characteristic Strength, F_{Rk}	8.6 kN	11.9 kN	8.6 kN	11.9 kN
Steps 4 & 5 →	Required Spacing of Sway Braces, s_a	18.5 m	25.7 m	10.0 m	13.7 m
	Required Number of Sway Braced Trapezes in Feed Main Line (L = 18 m)	1	1	2*	2*
	Required Number of Sway Braced Trapezes in Cross Main Line (L = 36 m)	2	2	4*	3*

Design Example

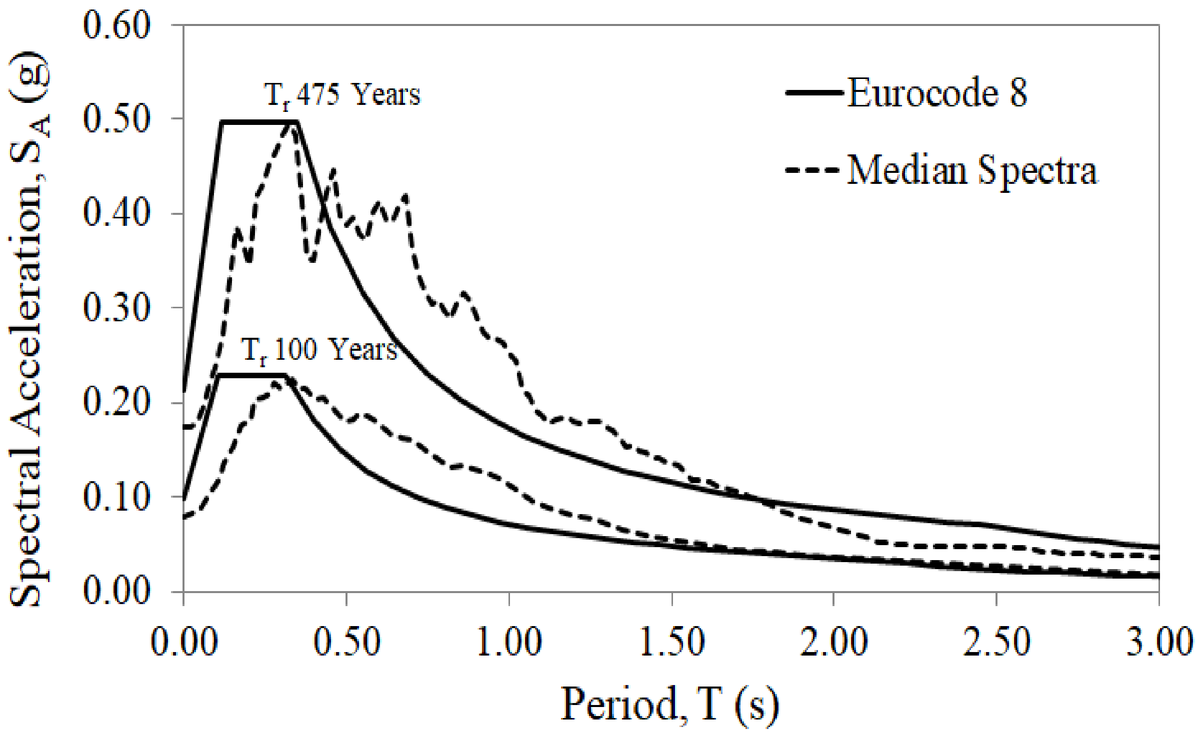
- Final Direct Displacement-Based Design and Comparison with Force-Based Eurocode 8 Design.



Note: Prescriptive spacing requirements not considered

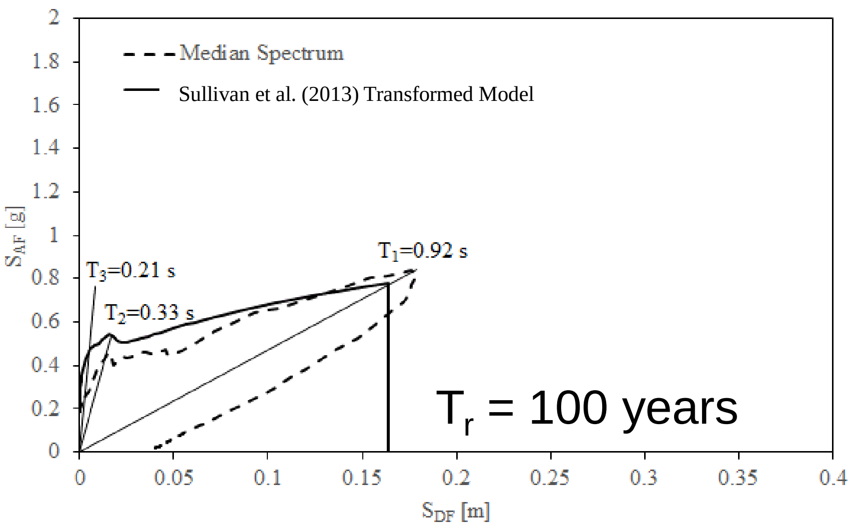
Design Appraisal

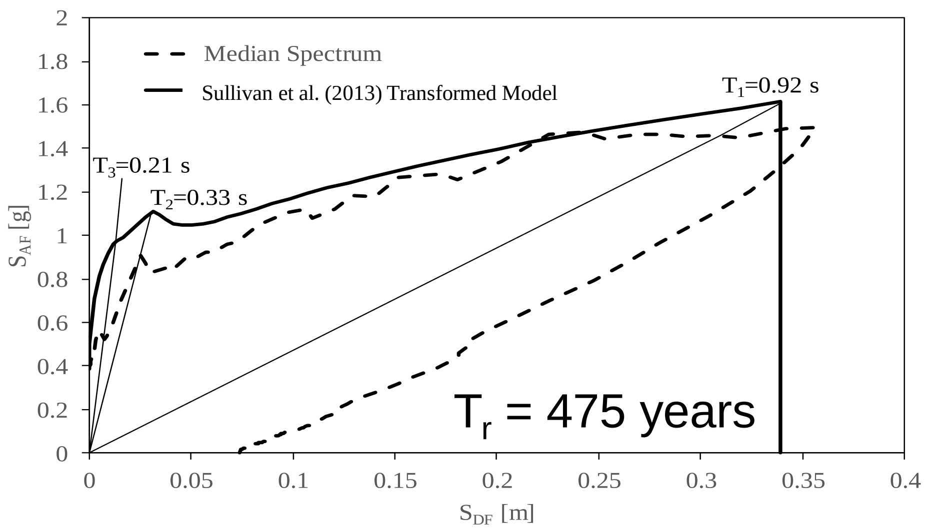
- Ensemble of 20 three-dimensional ground motions generated for each of the two design return periods (T_r = 100 and 475 years) considered at the site of the supporting frame.



Design Appraisal

- Non-linear time-history dynamic analyses of the supporting frame under both horizontal components of 20 horizontal ground motions (40 records) generated for each of the return periods considered (T_r = 100 and 475 years).
- Generations of top floor horizontal acceleration time-histories and floor acceleration/displacement spectra.





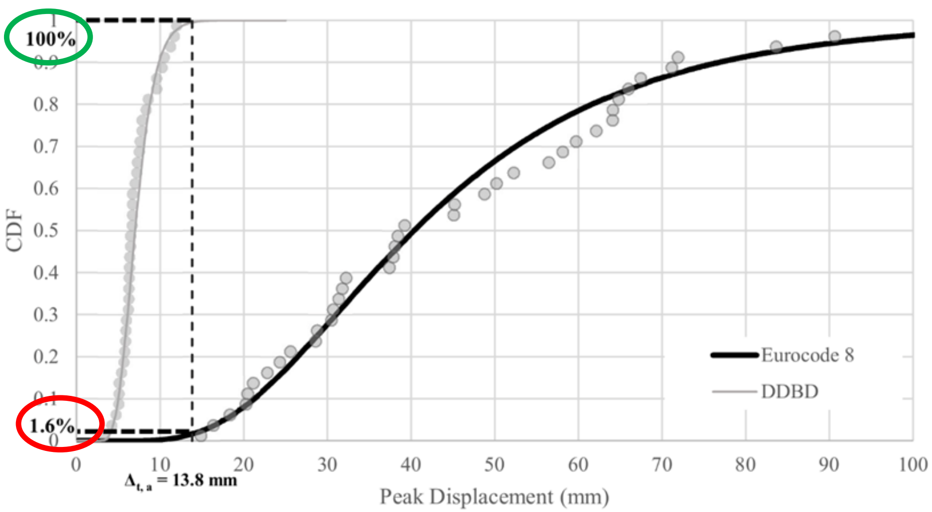
Design Appraisal

- Non-linear time-history dynamic analyses of the suspended mechanical piping system retrained by the direct displacement-based and Eurocode designs under three-dimensional top floor accelerations time-histories.
  - Horizontal components generated from the analysis of the supporting frame.
  - Vertical ground accelerations.
    - Supporting frame assumed rigid.
- Computation of Cumulative probability Distribution Functions (CDFs) of maximum relative transverse and longitudinal displacements between the sway braced trapezes and the supporting structure.
- Percentiles of target displacements computed.

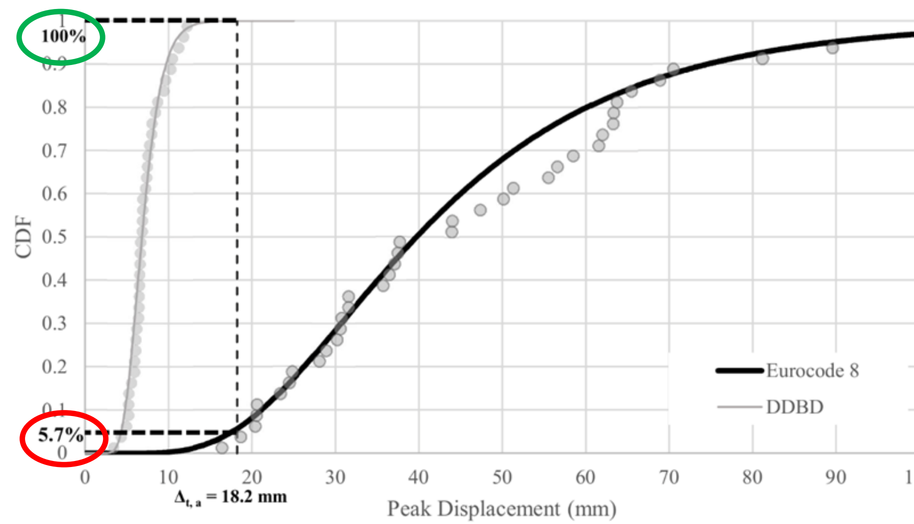
Design Appraisal

- Analysis Results.
  - 100 years return period:

Transverse Direction



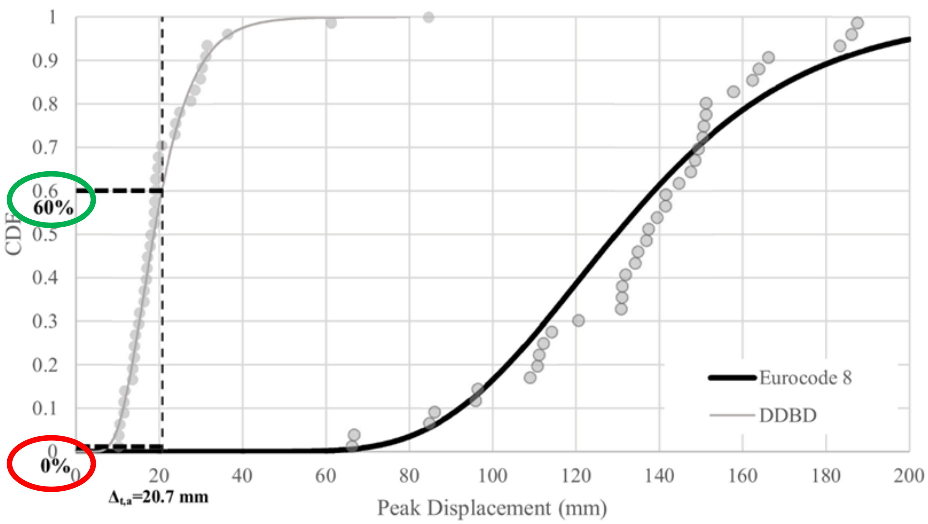
Longitudinal Direction



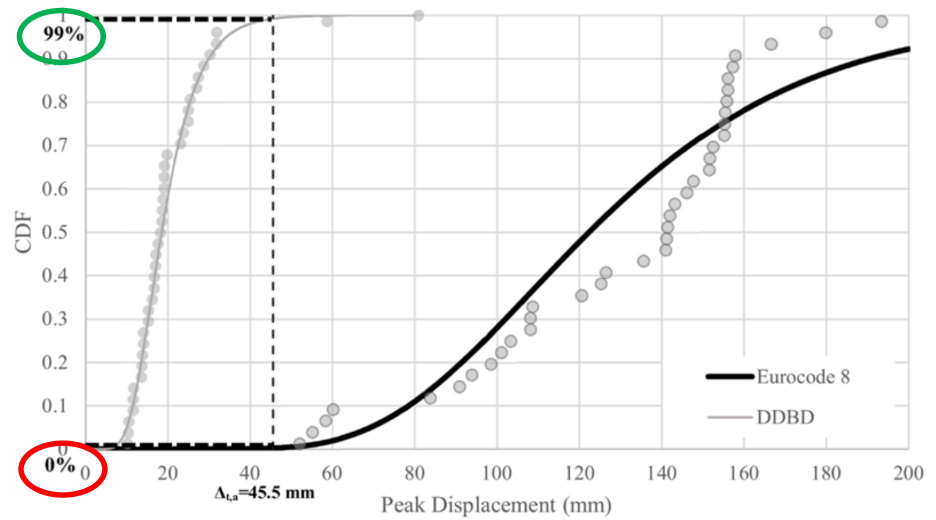
Design Appraisal

- Analysis Results.
  - 475 years return period:

Transverse Direction



Longitudinal Direction



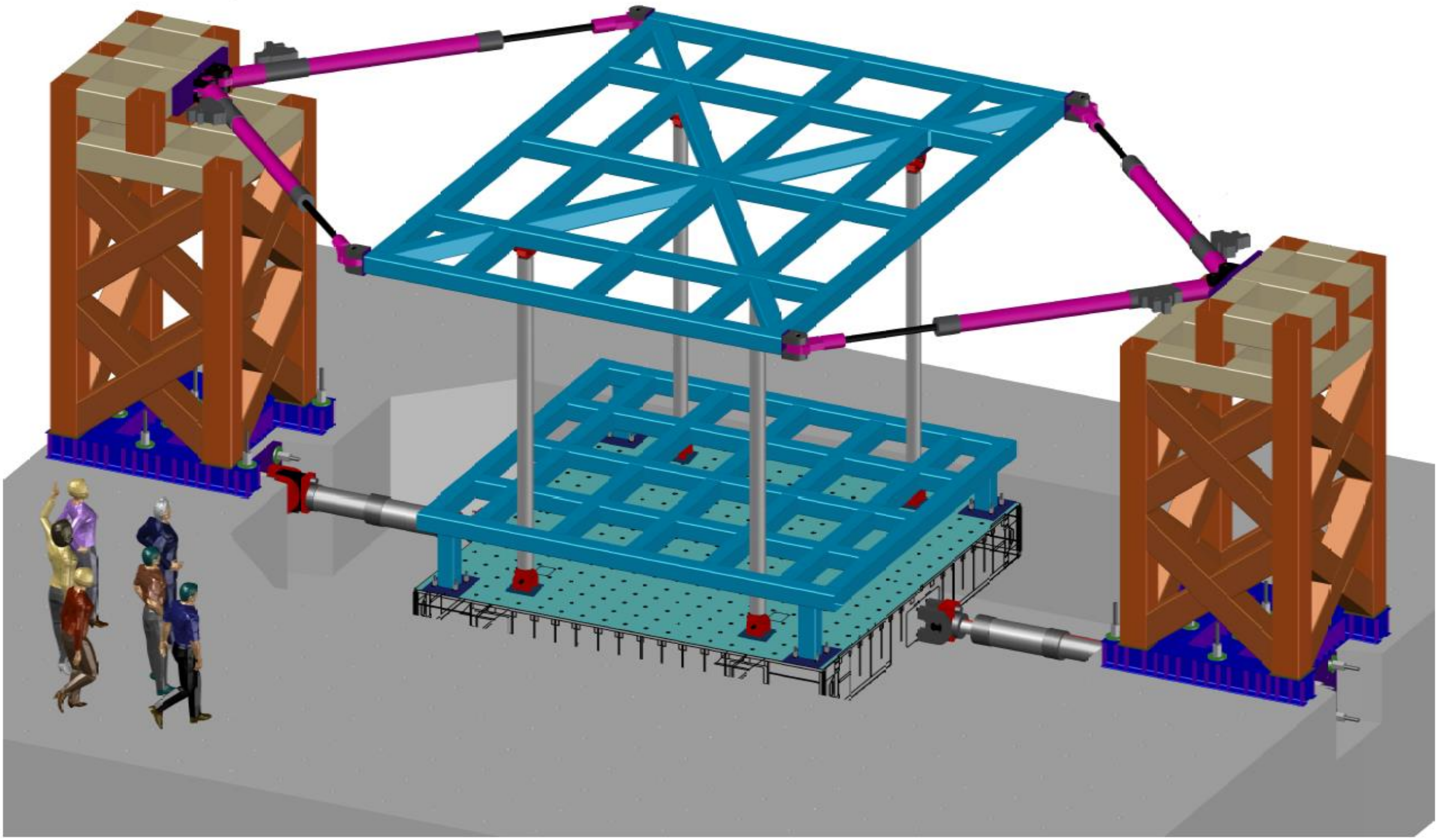
References

- Calvi, P.M., and Sullivan, T.J. 2014. “Estimating floor spectra in multiple degree of freedom systems,” Earthquakes and Structures, An International Journal, Techno Press, 6(7), 17-38.
- Filiatrault, A., Perrone, D., Merino, R. and Calvi, G.M. 2018. “Performance-Based Seismic Design of Non-Structural Building Elements,” Journal of Earthquake Engineering, DOI: 10.1080/13632469.2018.1512910.
- Miranda, E., and Taghavi, S. 2003. “Estimation of seismic demands on acceleration-sensitive non-structural components in critical Facilities,” Proc. of the Seminar on Seismic Design, Performance, and Retrofit of Non-structural Components in Critical Facilities, ATC 29−2, Newport Beach, California, 347−360.
- Sullivan, T.J., Calvi, P.M., and Nascimbene, R. 2013. “Towards improved floor spectra estimates for seismic design,” Earthquakes and Structures, An International Journal, Techno Press, 4(1), 109-132.
- Wood, R.L., Hutchinson, T.C., Hoehler, M.S., and Kreidl, B. 2014. “Experimental characterization of trapeze assemblies supporting suspended non-structural systems,” Proc. of the Tenth U.S. National Conference on Earthquake Engineering, Paper No. 905, Anchorage, Alaska, 10 p.

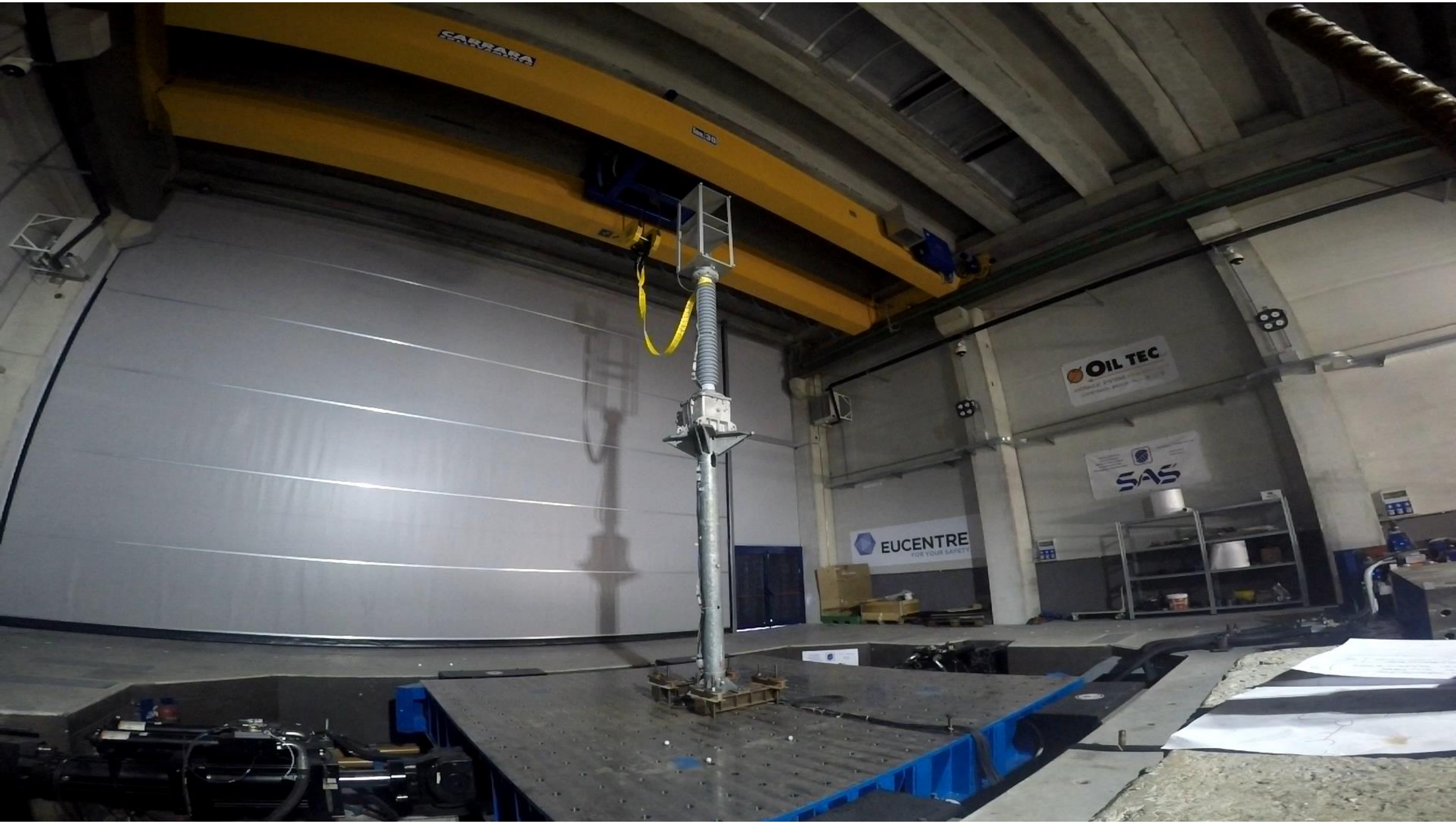
Conclusions

- Proposed direct displacement-based seismic design of non-structural components is appropriate for acceleration-sensitive non-structural components suspended or anchored at a single location (floor) in the supporting structure and for which damage is the result of excessive displacements.
- The new procedure requires, however, detailed information of the cyclic response of non-structural components that is not available for the multitude of non-structural typologies.
- Experimental work is needed to develop the information required for the wide scale applications of the direct displacement-based seismic design of non-structural components.

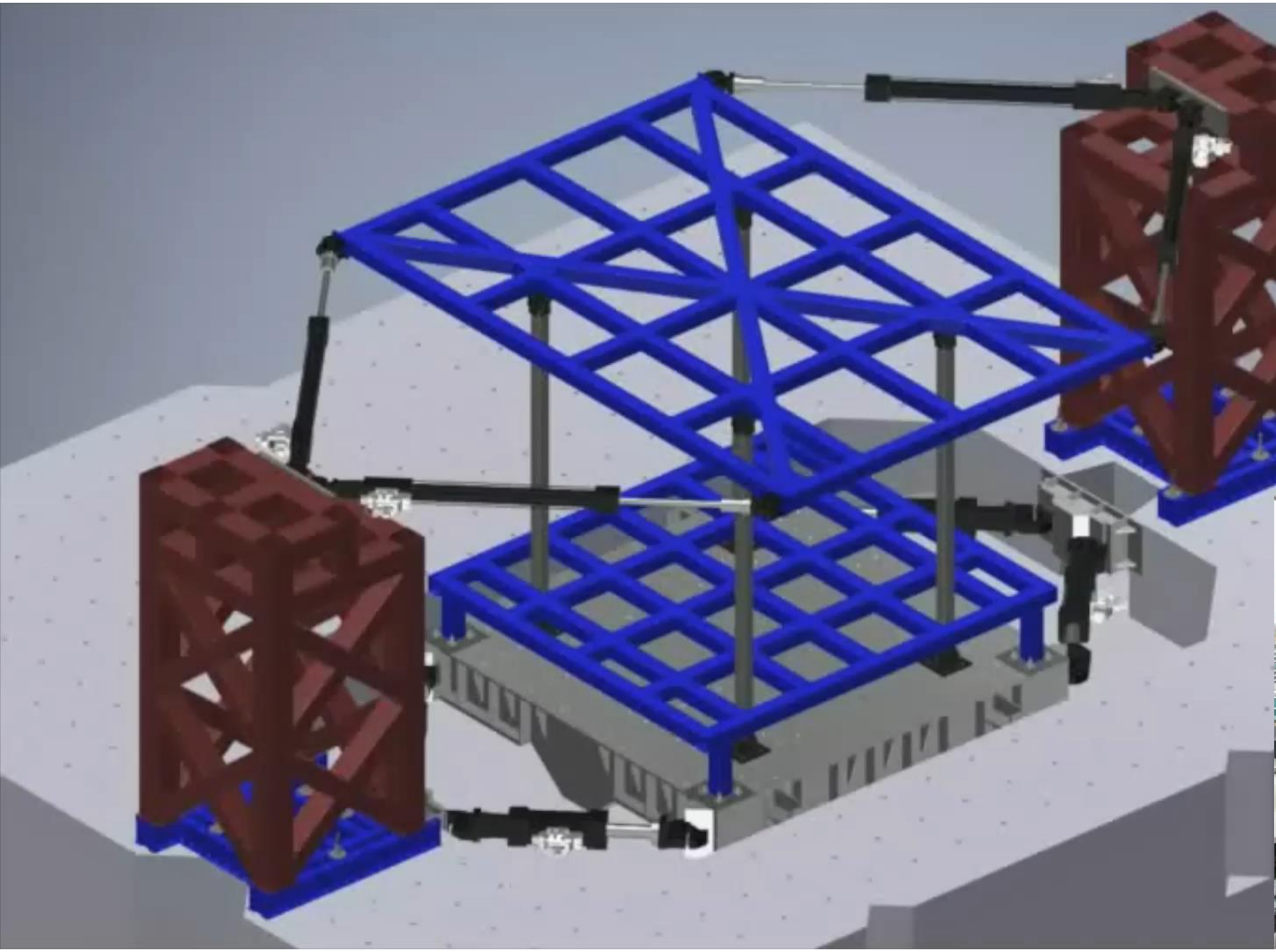
New 6D Lab



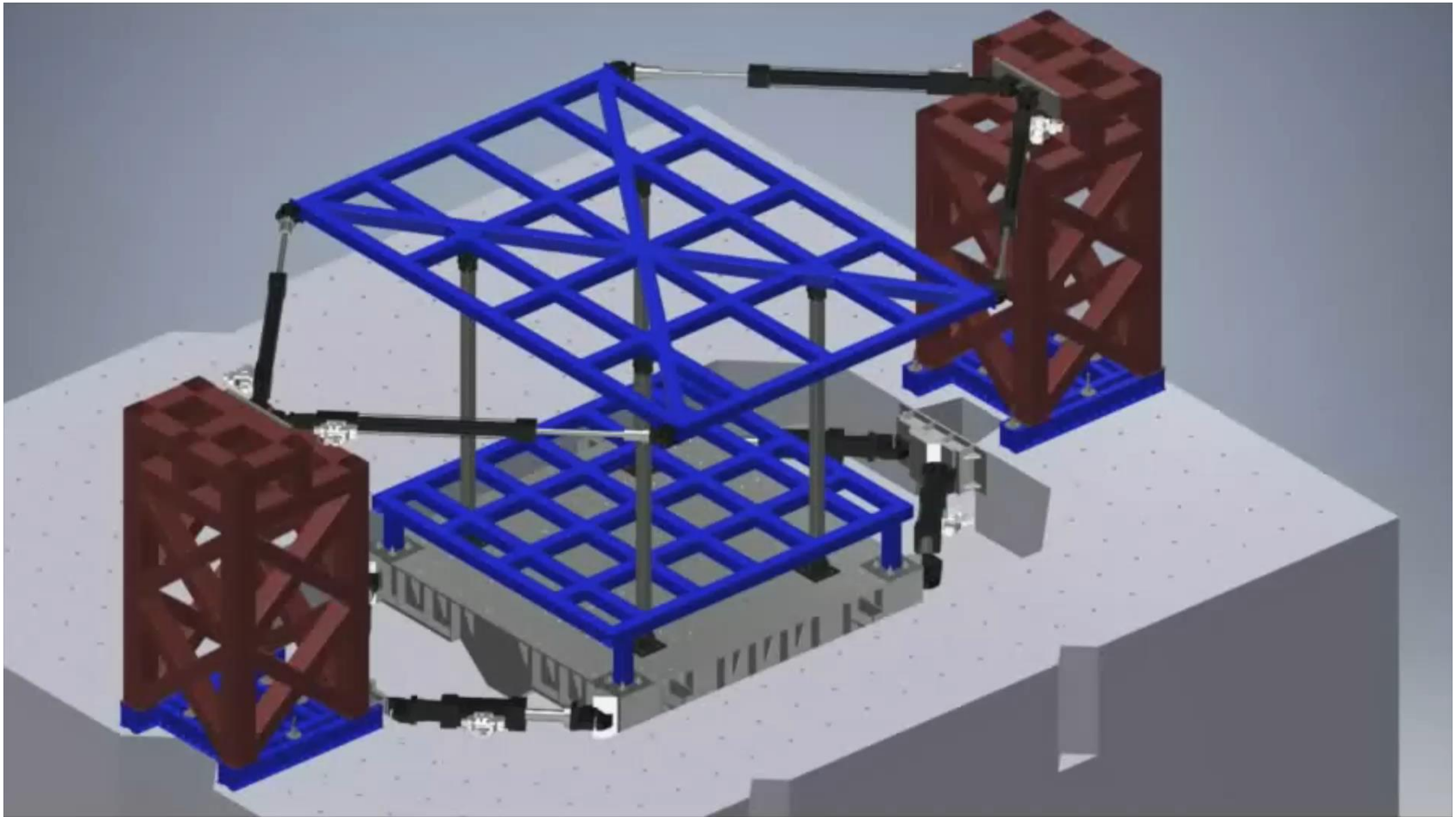
6 DOF shaking table



Towards 9 DOF



Actuators Stroke:	2 m
Free height between the open floors:	3.4 m
Upper table:	7.1 x 4.95 m
Reaction steel structures:	13 t, f = 60 Hz



Thank you!

What the client wanted.

The architect's solution.

The structural engineer's solution.

The non-structural engineer's Solution.