International Conference on Earthquake Engineering

CISMID: 40 Years of Science, Innovation and Infrastructure Assessment for Resilient Cities

Inverse identification of structural paremters and hysteretic models through swarm intelligence algorithms

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1. Introduction

To SHM and damage identification

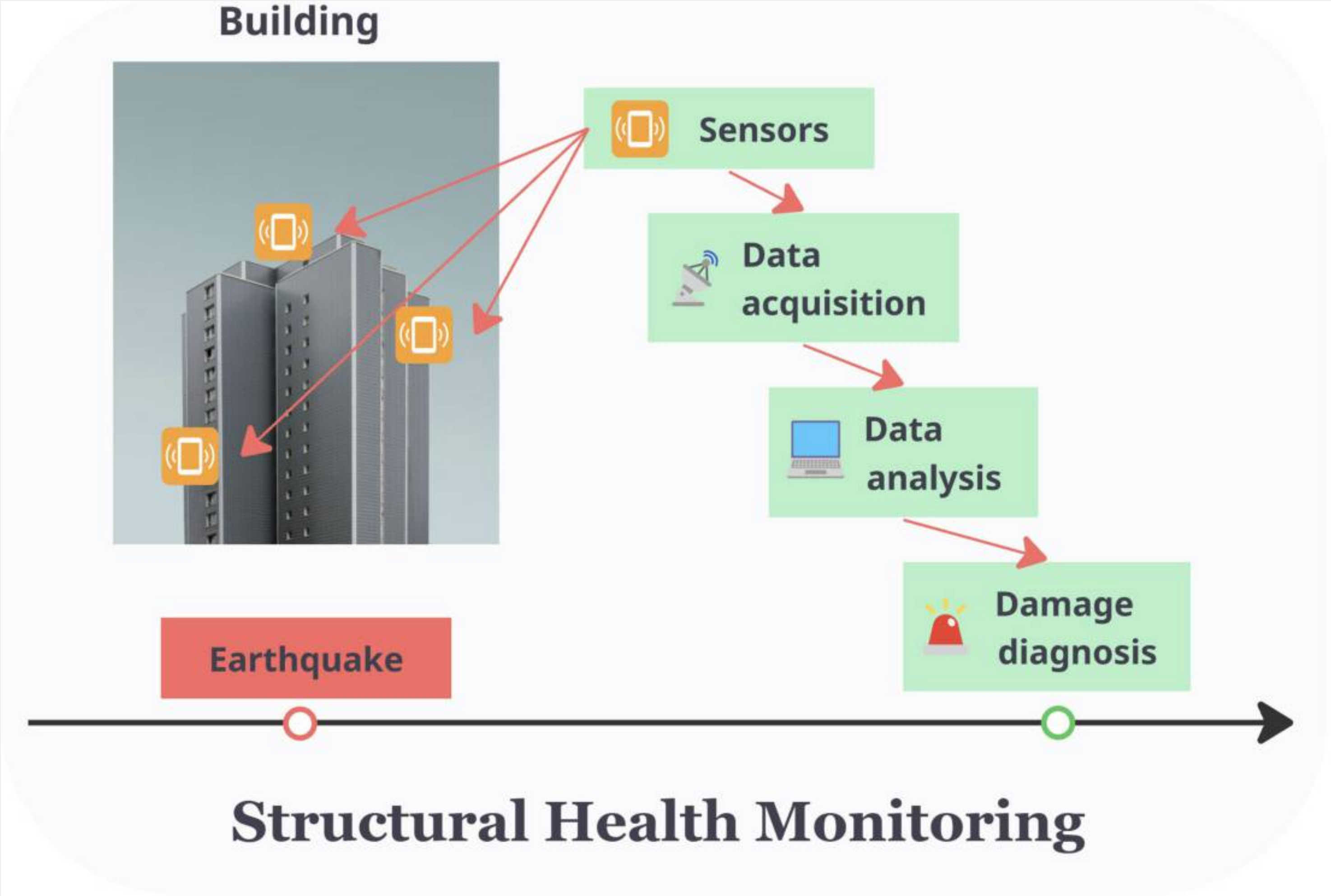
How to assess the damage of a building?

Non damaged

Damaged

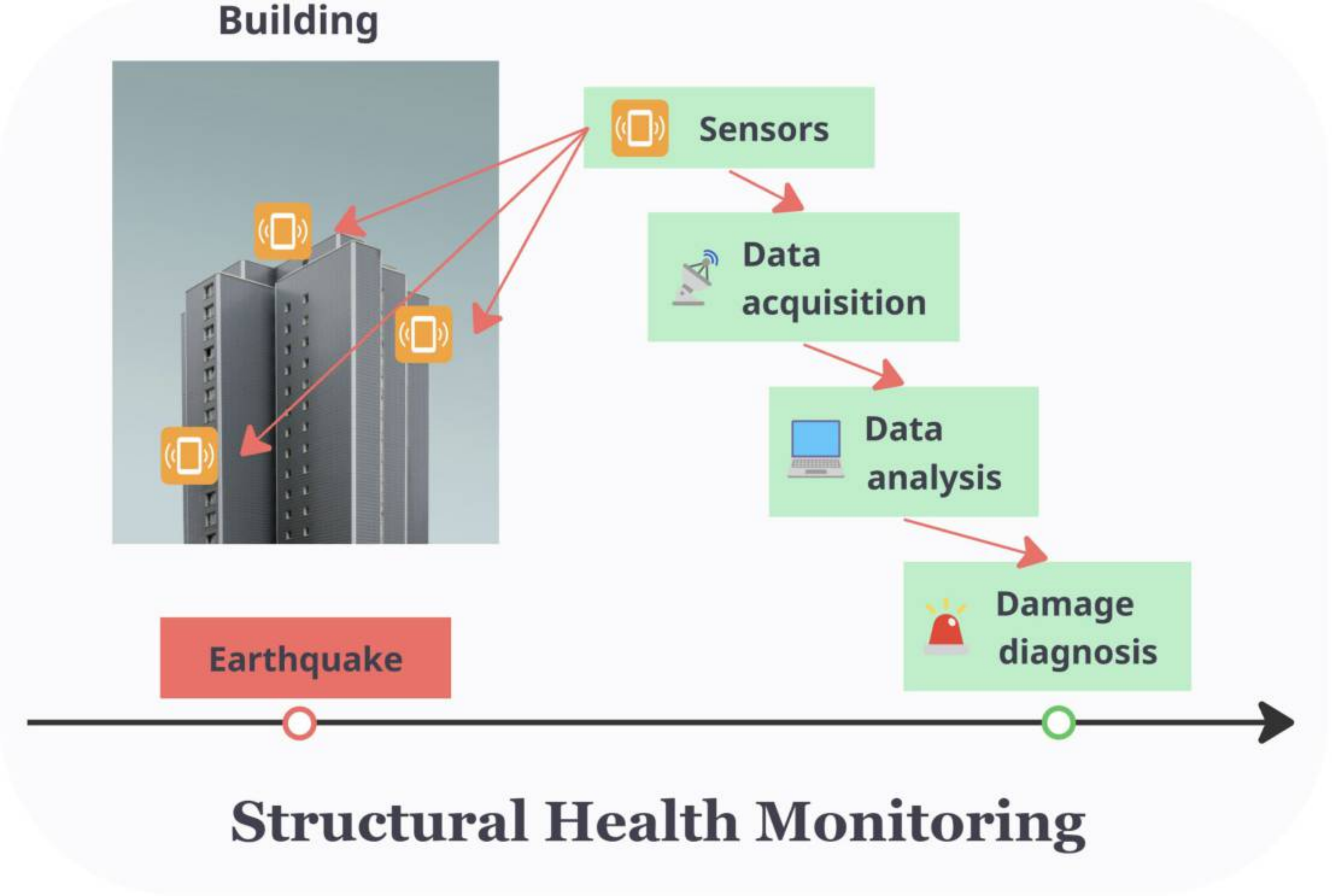
According to previous research:

Accurate **measurement** of **interstory drift ratio**, could allow us to **detect damage**.



Structural Health monitoring

- Continuous monitoring of the building
- **Recognize the parameters of the building.**
- Detect damage as early as possible.
- Assess the remaining capacity of the building.



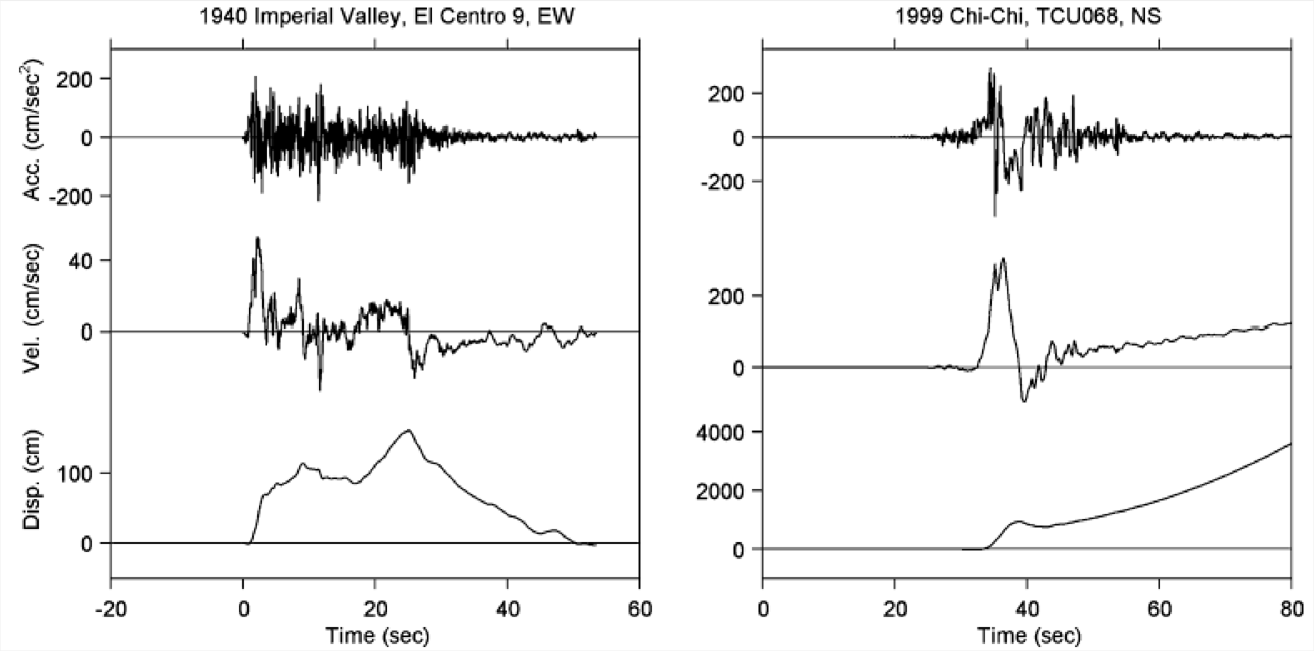
Accelerometers: Ups and downs

- Accelerometers – Widely used sensors on buildings.
- Return reliable data.
- Easy to implement, no need of intricated setups.

- Cannot provide direct information about damage.
- Several methods are developed to obtain displacements from accelerations

How to obtain displacements from recorded accelerations?

Double integration method



$$\hat{x} = \iint_t \ddot{x}$$

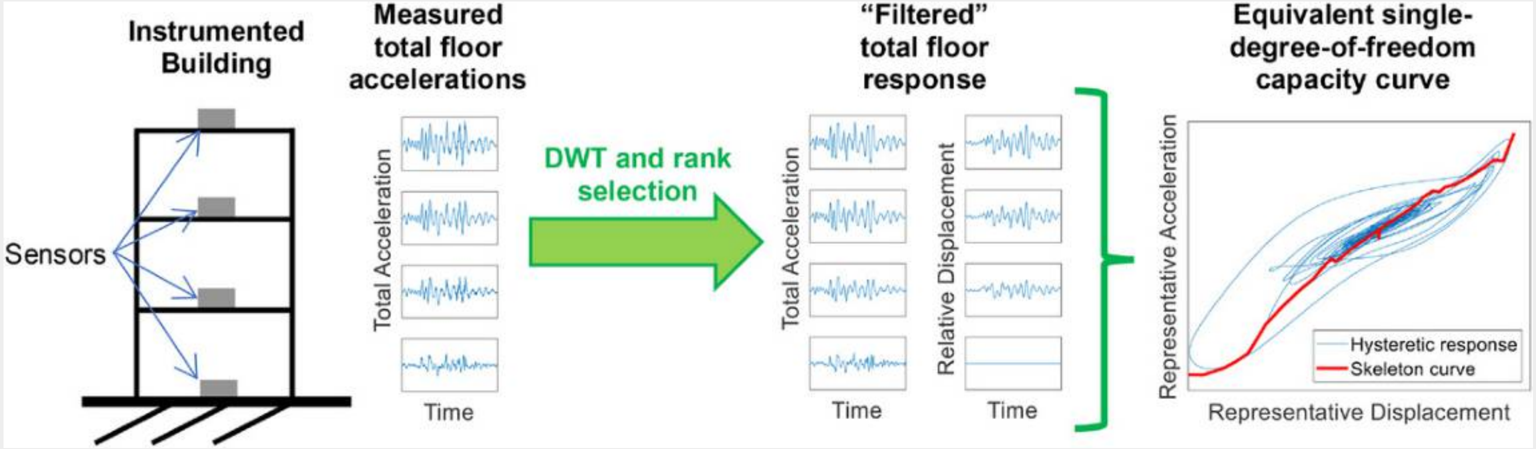
Where $\hat{x}$ is the calculated displacement from double integration and $\ddot{x}$ is the recorded acceleration from the sensors

Figure Source: Boore, D. M. & Bommer, J. J. (2005). Processing of strong-motion accelerograms: needs, options and consequences. Soil Dynamic and Earthquake Engineering 25 (2005) 93-115

How to obtain displacements from recorded accelerations?

Discrete Wavelet Transform (DWT) method

(Yeow et al. Framework for DWT application to SHM)



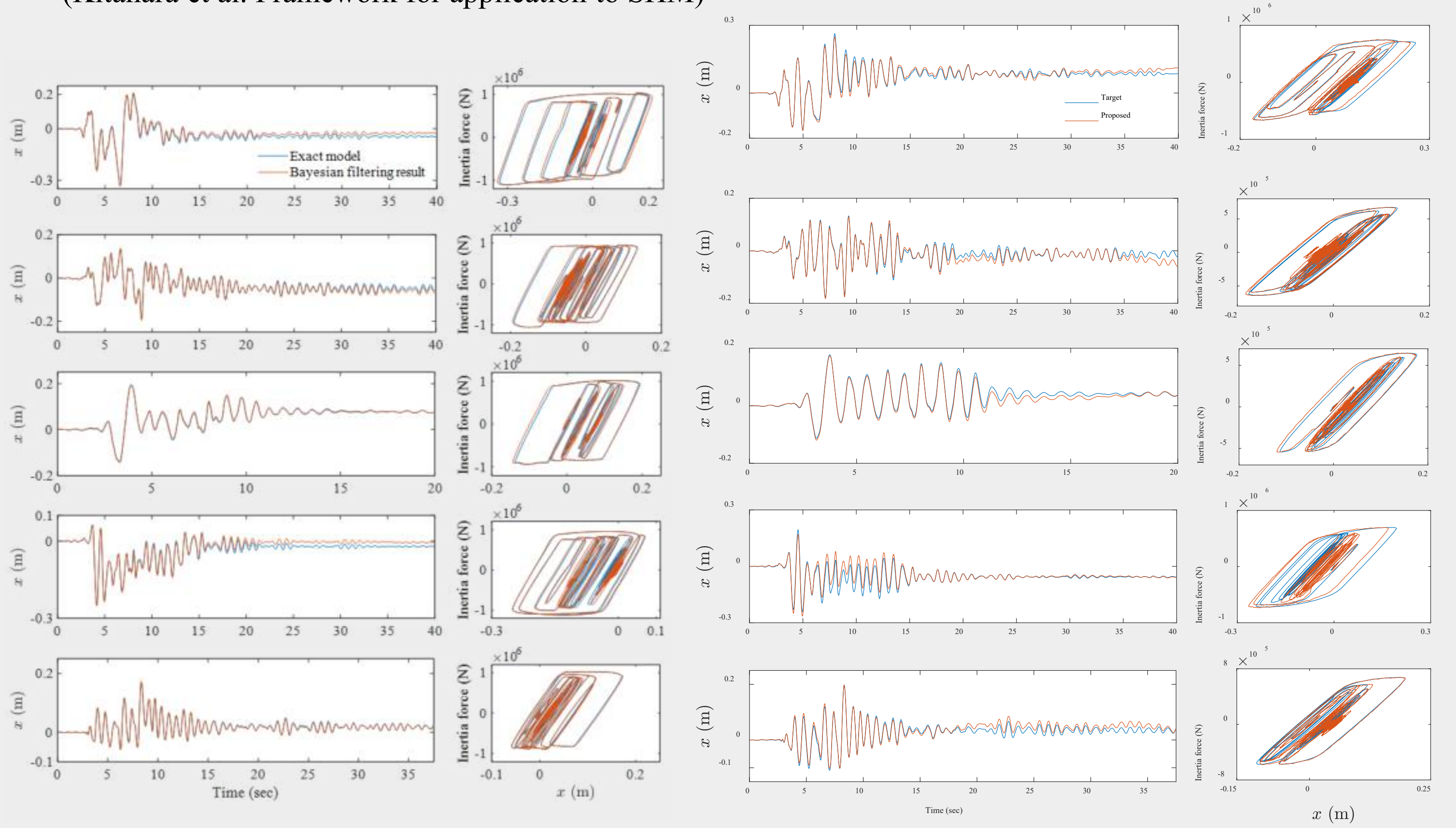
- Wavelet method acts as a " noise filter" that considers frequency bands over time.
- A rank selection method is conducted to avoid the noise effects.
- Long-period frequencies are usually not selected. Then, estimated **residual displacements** are **close to zero**.

Figure Source: Yeow, T. Z. & Kusunoki, K. (2022). Unbiased rank selection for automatic hysteretic response extraction of RC frame buildings using acceleration recordings for post-earthquake safety evaluations. Earthquake Engineering Structural Dynamics 2022; 51: 515–536.

How to obtain displacements from recorded accelerations?

Adaptative Bayesian filter (UKF+Bayesian updating) approach

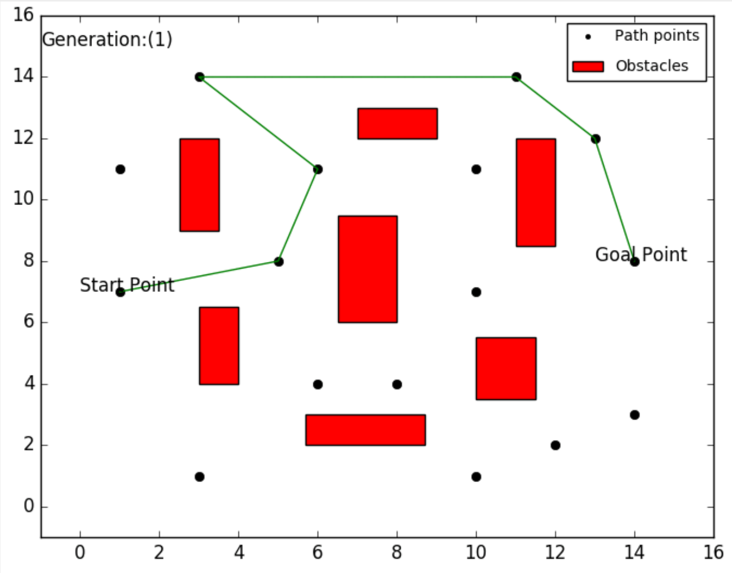
(Kitahara et al. Framework for application to SHM)

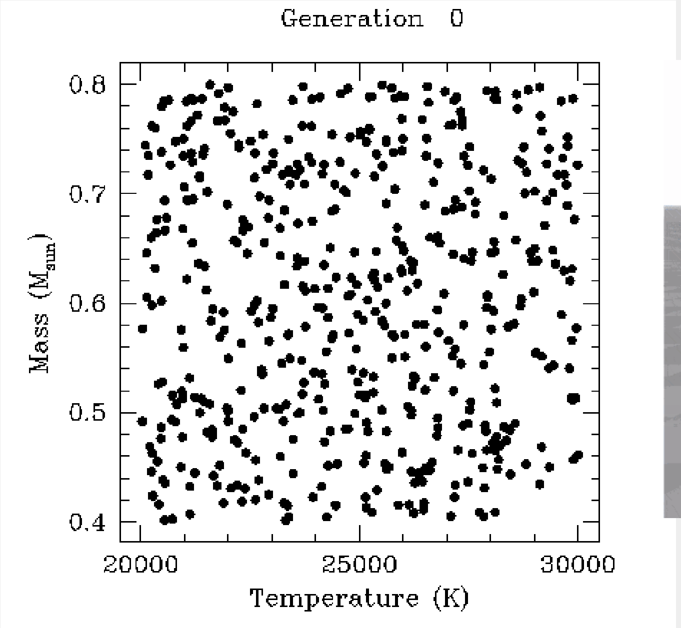


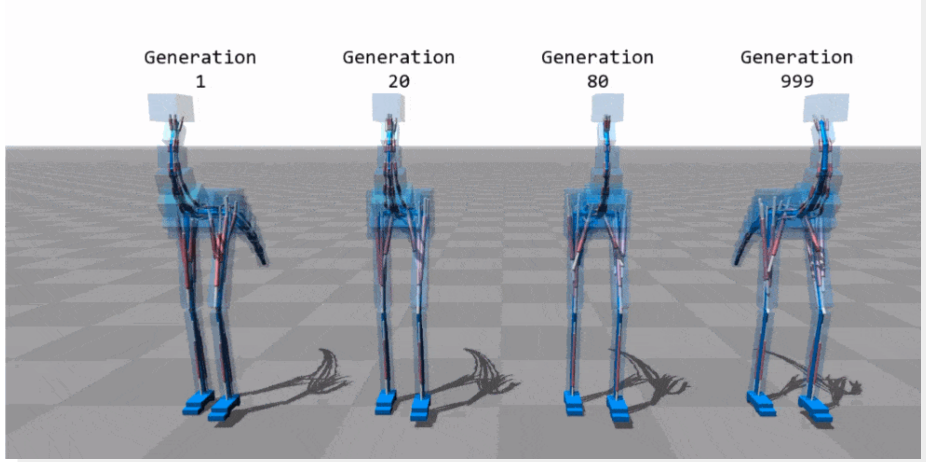
- Some parameters are highly sensitive to initial estimations.
- Capturing the residual displacement is not guaranteed in all cases.
- Application to artificial responses only, should be tested under real recorded data.

Figure Source: Kitahara, M., Kakiuchi, Y., Yang, Y. & Nagayama, T. (2024). Adaptive Bayesian filter with data-driven sparse state space model for seismic response estimation. Mechanical Systems and Signal Processing 208, 111048

Genetic algorithm: “procedure inspired by the process of natural selection… Commonly used to generate high-quality solutions to optimization and search problems.”

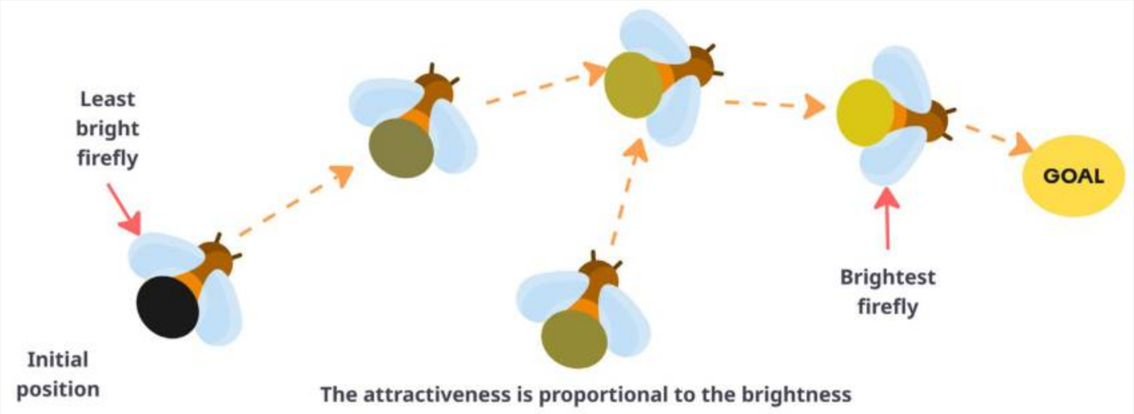


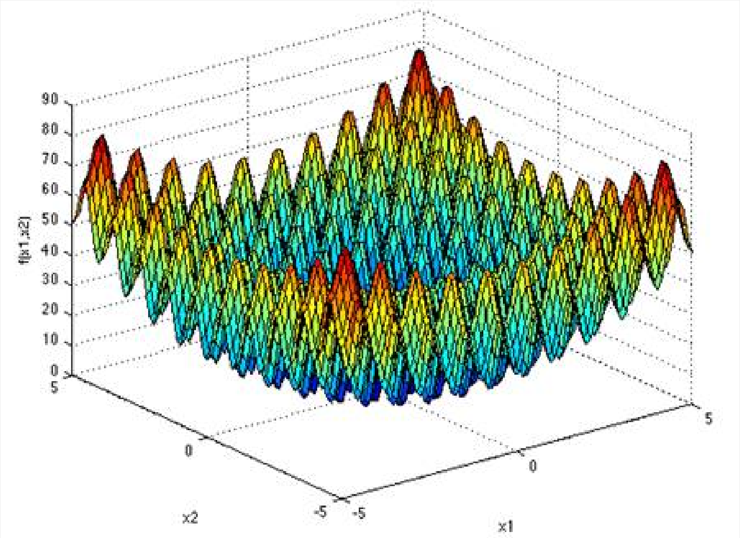




Source: Mitchell, Melanie (1996). An Introduction to Genetic Algorithms. Cambridge, MA: MIT Press.

Firefly Algorithm (FA)





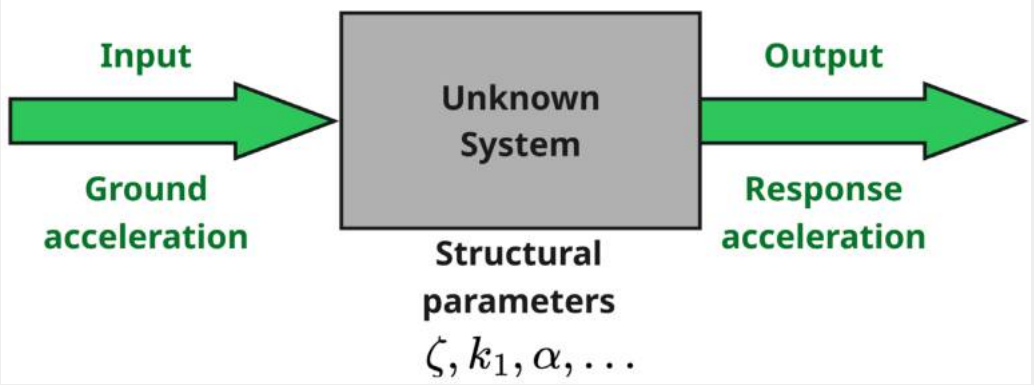
Rastrigin function

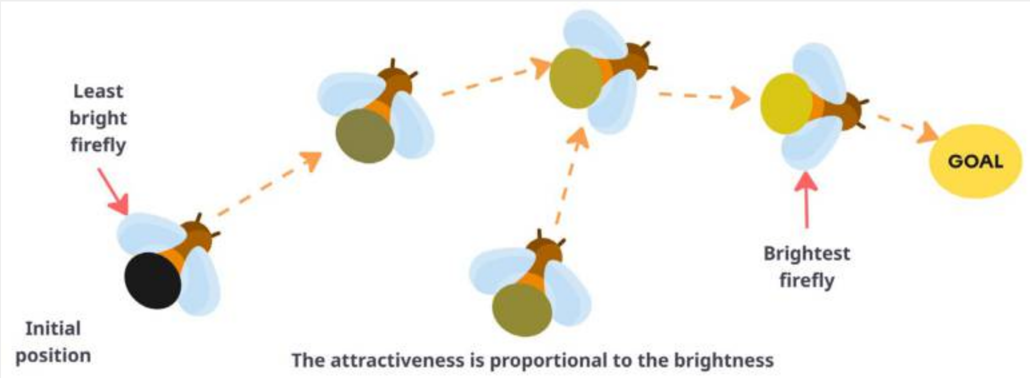
- Population based algorithm (as PSO).
- The algorithm adjusts its exploration (coarse tuning) vs exploitation (fine tuning) behavior throughout the simulation.
- The movement towards a better solution is based on the fitness function value and distance, suitable for nonlinear problems.
- No explicit global best is considered to make decisions (unlike PSO algorithm).

2. Modified Firefly Algorithm

Overview of the methodology

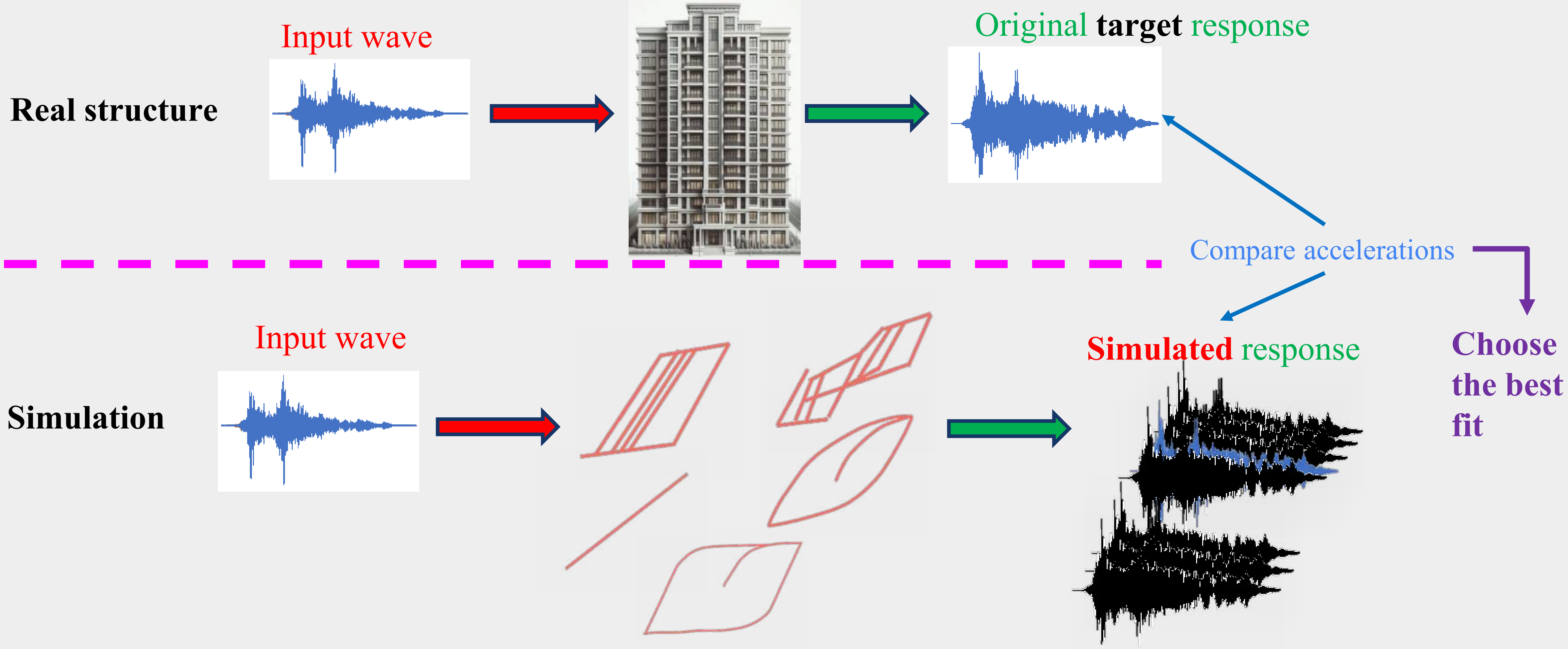
The Modified Firefly Algorithm is a **genetic algorithm** used for **solving optimization or search problems**.





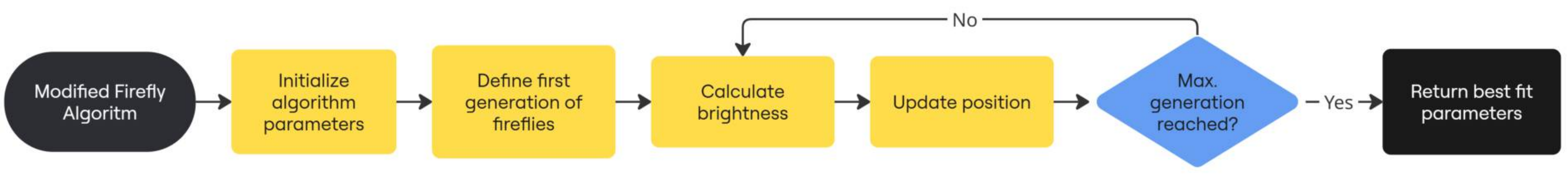
ζ: Damping coefficient
k_1: Initial stiffness
α: Stiffness ratio

Scheme of proposed framework

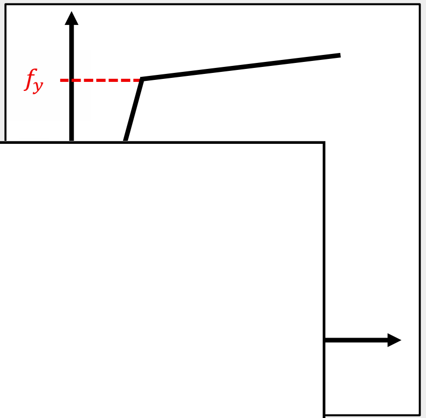


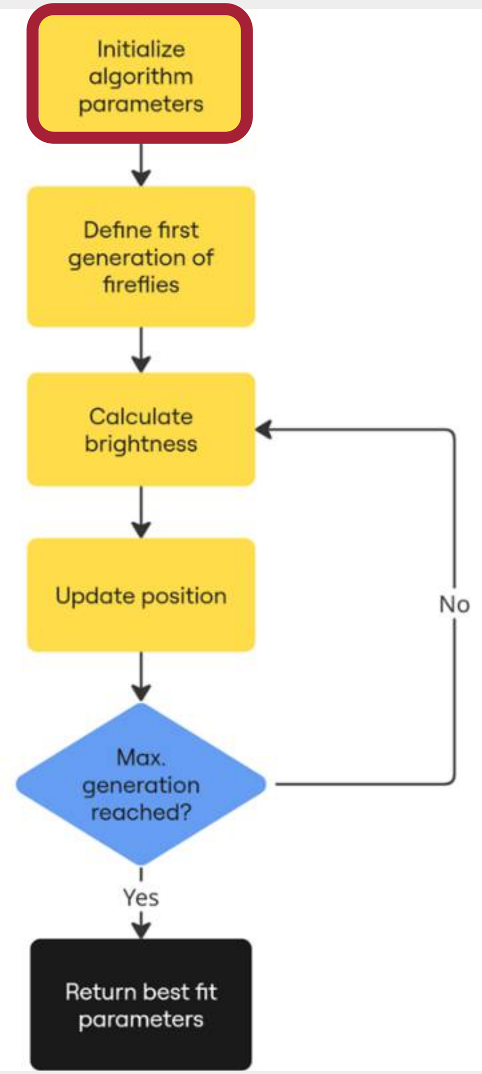
Models with different structural parameters.

Modified Firefly Algorithm (MFA) flowchart:

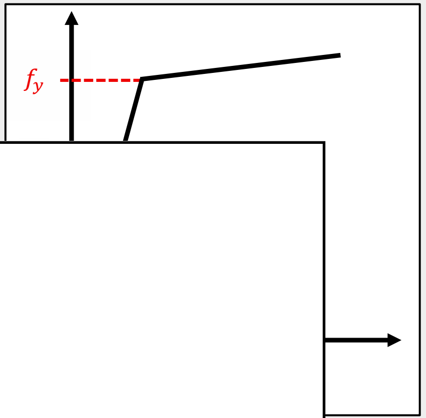


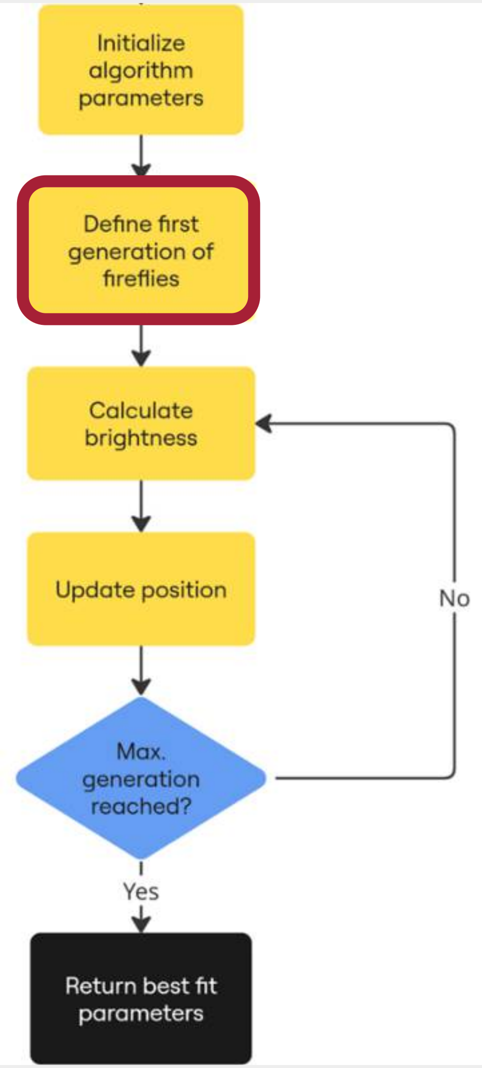
Algorithm parameters: $D = 2$, $G_{max} = 100$, $N_{fire} = 60$



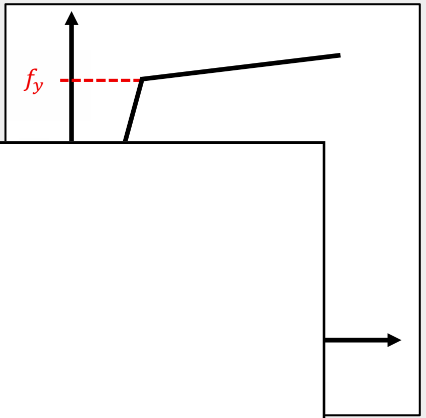


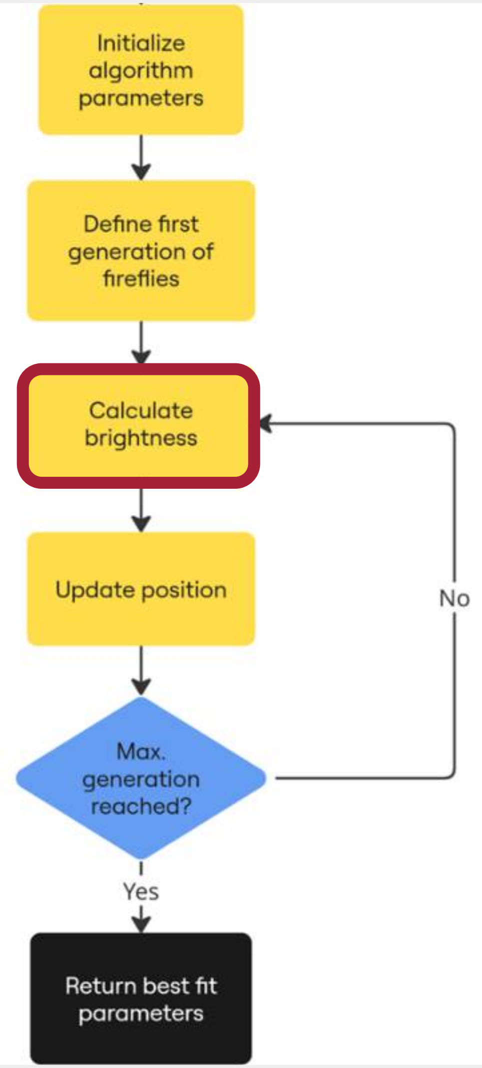
Algorithm parameters: $D = 2$, $G_{max} = 100$, $N_{fire} = 60$



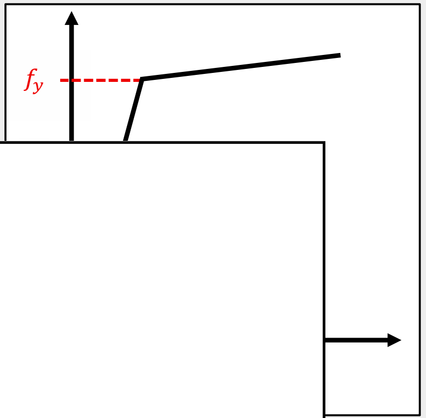


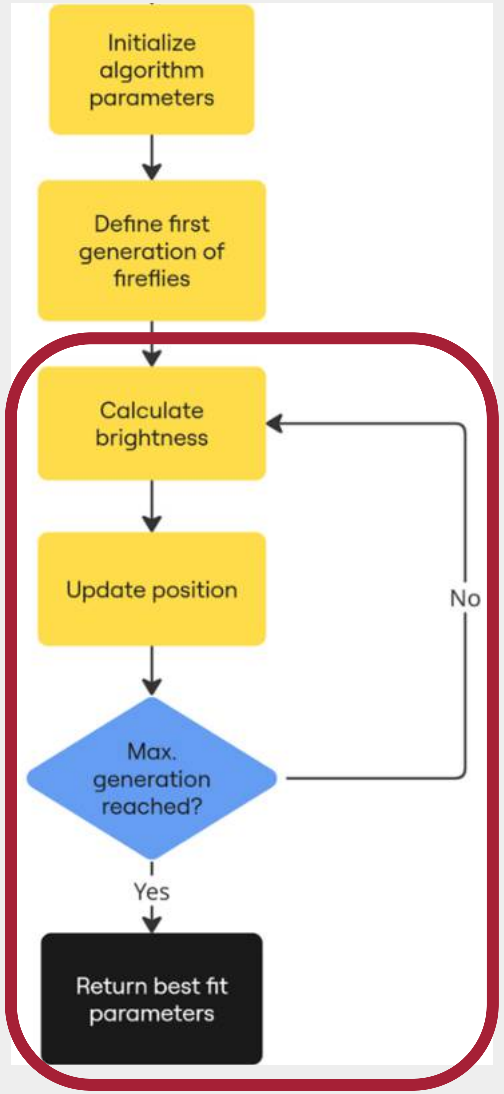
Algorithm parameters: $D = 2, G_{max} = 100, N_{fire} = 60$





Algorithm parameters: $D = 2$, $G_{max} = 100$, $N_{fire} = 60$

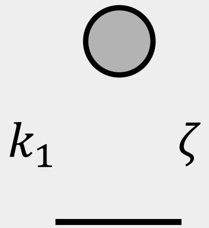




Range selection for the solution space – **Elastic model**

Damping coefficient

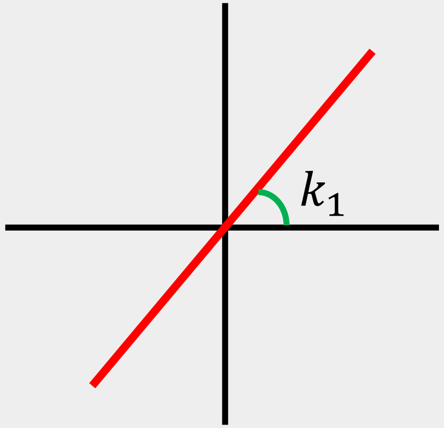
$$\zeta_{range} = [0.01\,, 0.1]$$



Unitary mass $m = 1$.

Initial stiffness

$$k_{1_{range}} = [50\%\,, 150\%]k_{FFT}$$



k_{FFT}: Stiffness corresponding to the predominant frequency obtained from a FFT's frequency analysis (f_{FFT}).

$$k_{FFT} = (2\pi f_{FFT})^2$$

Range selection for the solution space – **Bilinear model**

Post-yielding stiffness over elastic stiffness parameter $\boldsymbol{\alpha_{BL}}$

$$\alpha_{BL_{range}} = [0.0, 0.1]$$

Yielding strength

$$\ddot{x} + \tilde{f}_D + \tilde{f}_S = -\ddot{x}_g$$

$$\left(\tilde{f}_D + \tilde{f}_S\right)_{max} = -\left(\ddot{x} + \ddot{x}_g\right)_{max}$$

$$\left(\tilde{f}_D + \tilde{f}_S\right)_{max} = f_y + (\mu - 1)x_y\alpha k_1$$

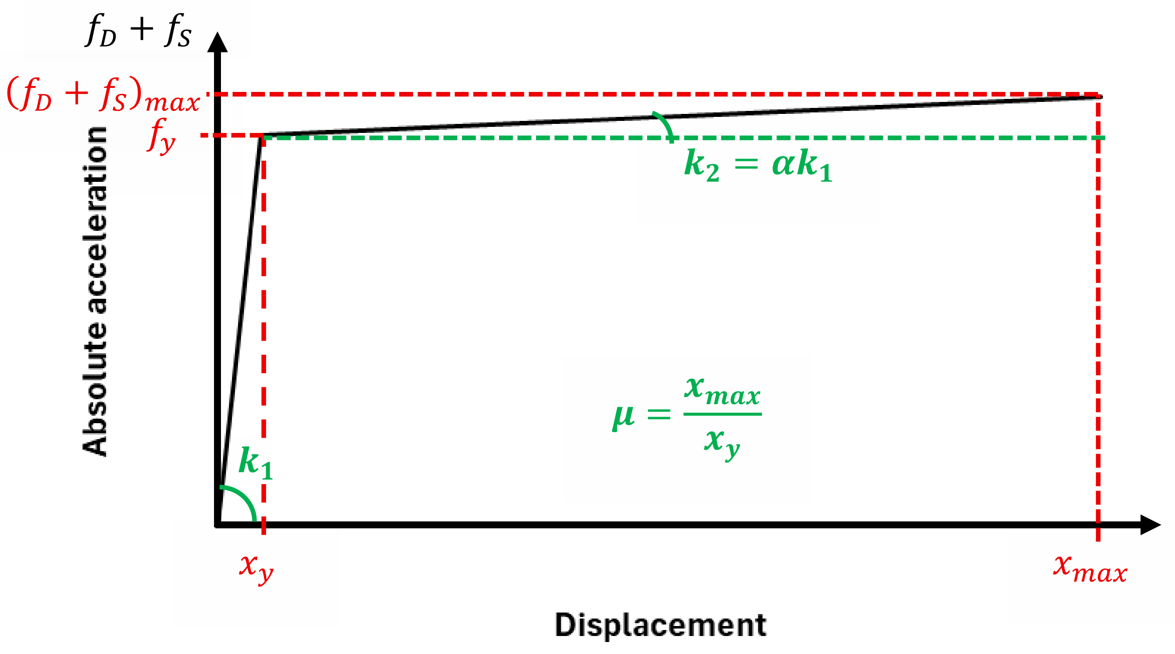
$$f_y = \frac{\left(\ddot{x} + \ddot{x}_g\right)_{max}}{1 + (\mu - 1)\alpha}$$

Considering a maximum μ of 10 and α of 0.1:

$$f_{y_{range}} = [50\%, 100\%]\left(\ddot{x} + \ddot{x}_g\right)_{max}$$

$\tilde{f}_D$: Damping force with unitary mass

$\tilde{f}_S$: Hysteretic force with unitary mass



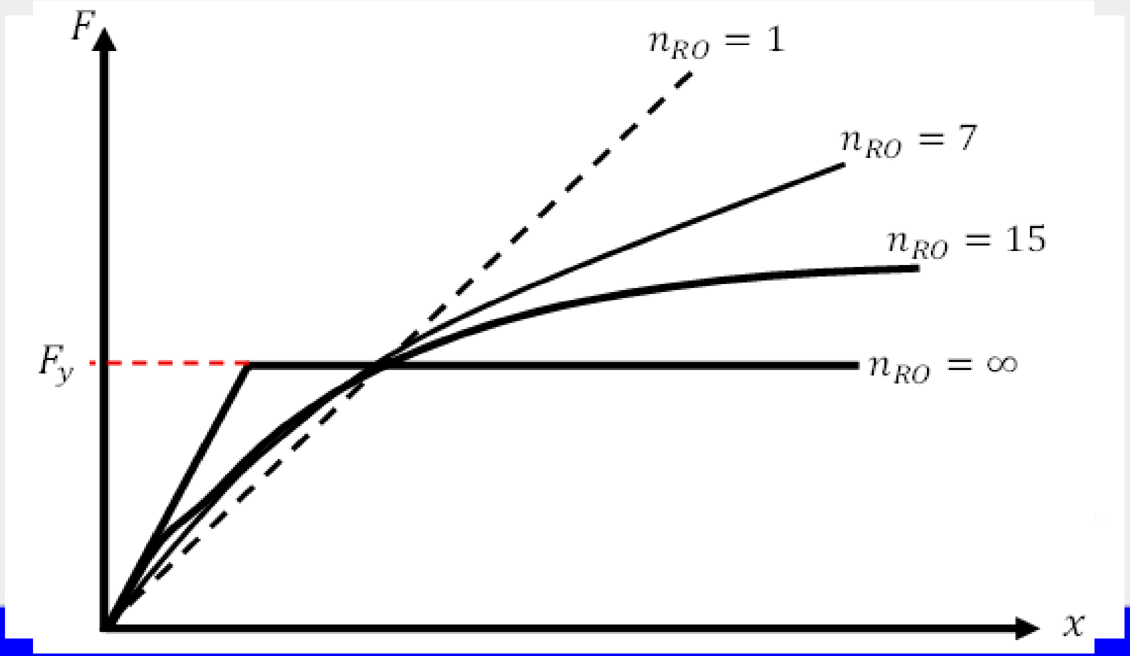
Range selection for the solution space – **Ramberg-Osgood model**

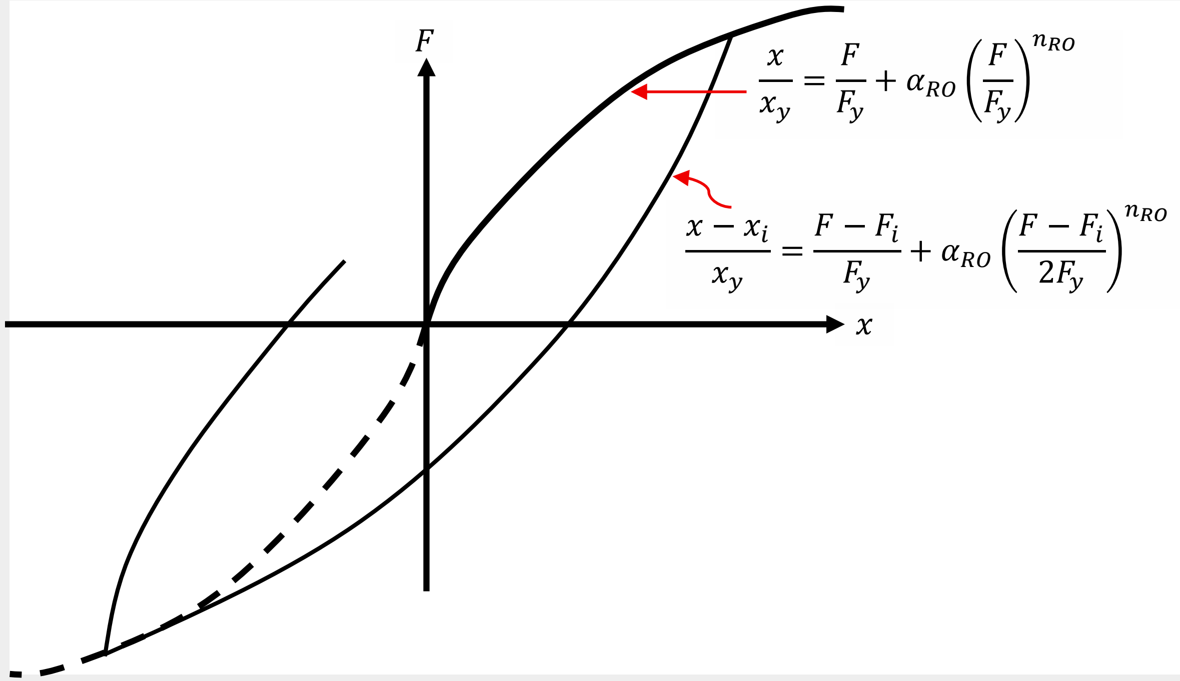
Horizontal offset parameter α_{RO}

$$\alpha_{RO_{range}} = [0.5, 10.0]$$

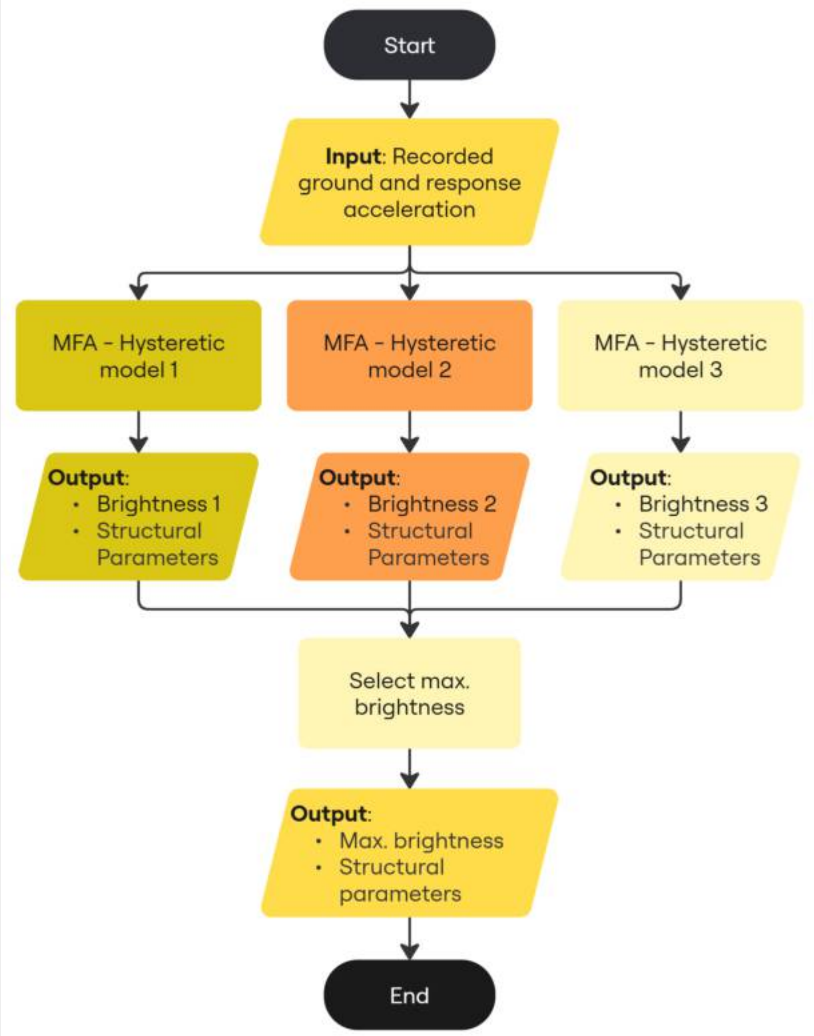
Exponential parameter n_{RO}

$$n_{RO_{range}} = \{3, 5, 7, 9, 11, 13, 15\}$$





Flowchart for the application of MFA using a set of hysteretic models

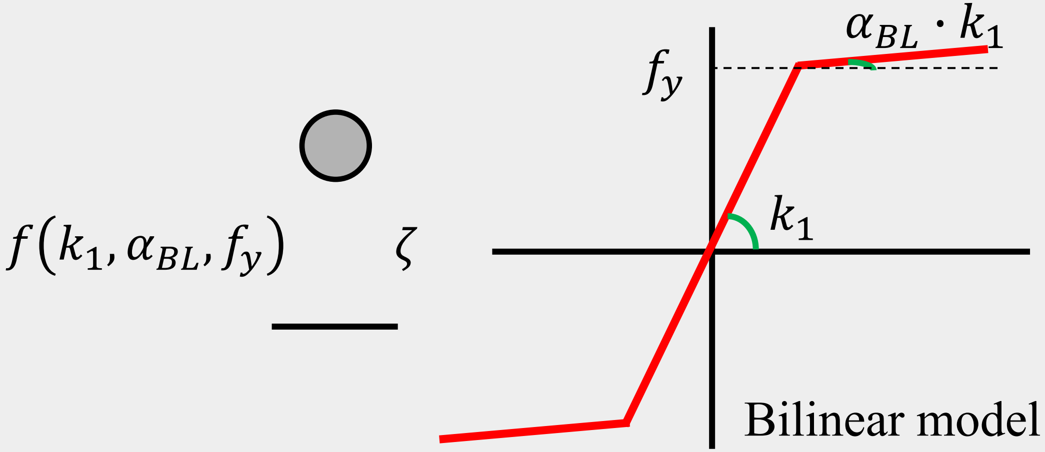


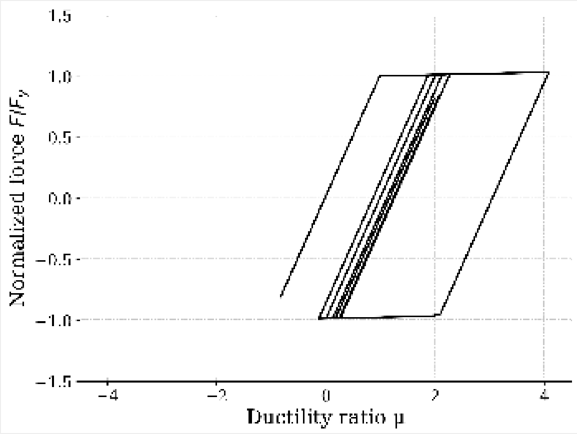
3. Validation of the proposed framework

Application on synthetic SDOF models

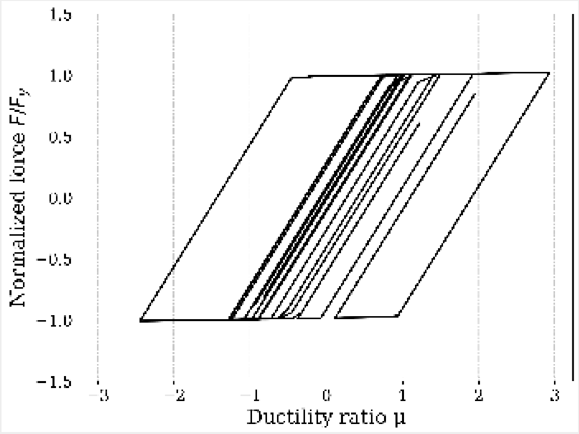
A set of 50 recorded ground motions were selected from USGS-CESMD

Parameter	Target value
ζ	0.05
k_1	k_{wave}
α_{BL}	0.01
f_y	$\dfrac{S_a(T_n, 5\%)}{3.5}$

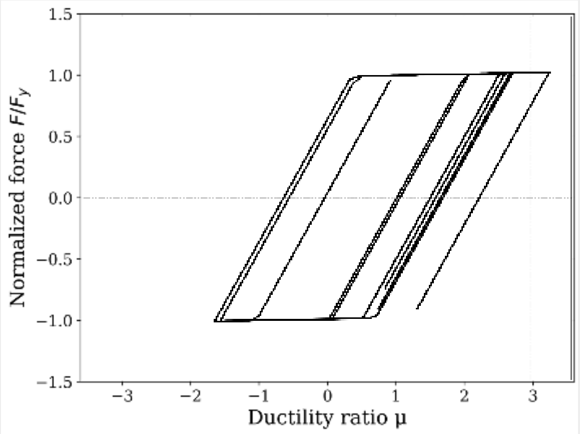




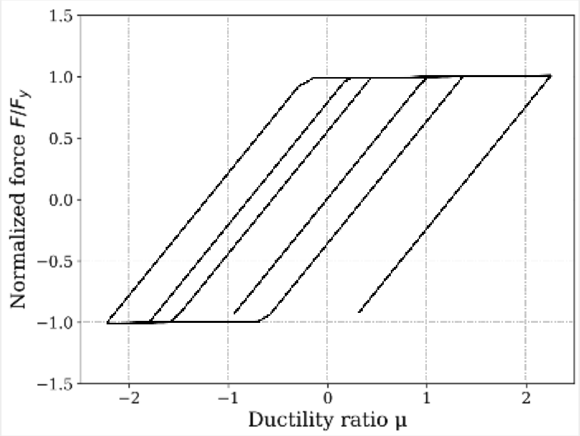
a) 04SepE1



b) 11FebN



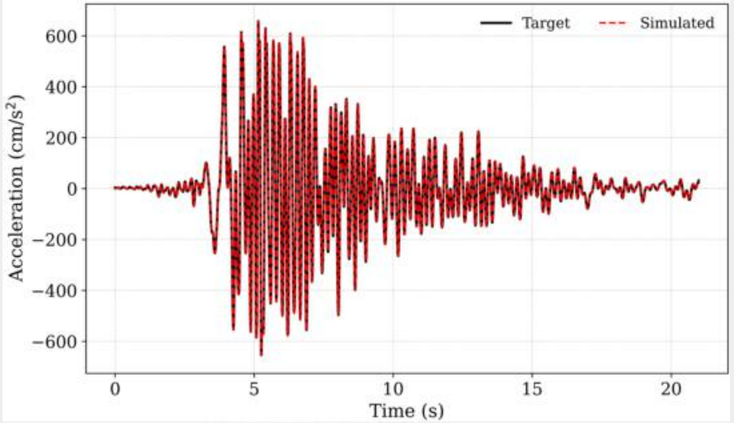
c) 23FebE2

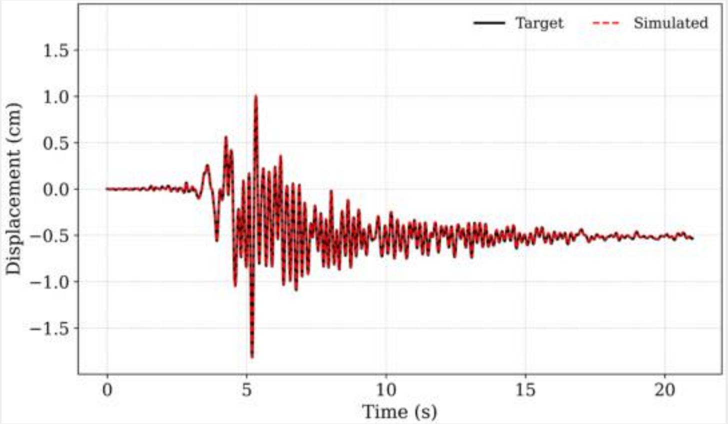


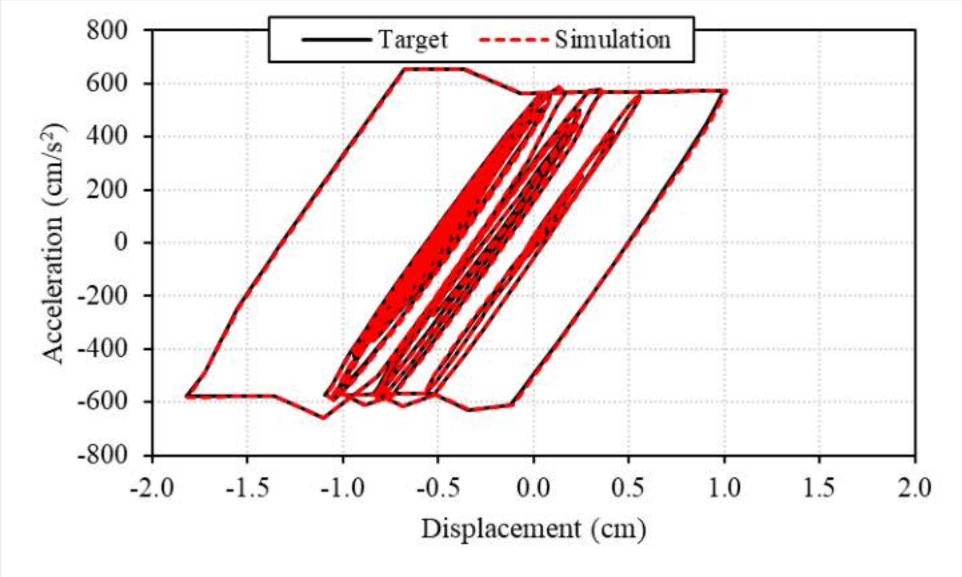
d) 89OctE1

Obtained **simulated** vs **target** acceleration and displacement response.

For 04SepN3 case.

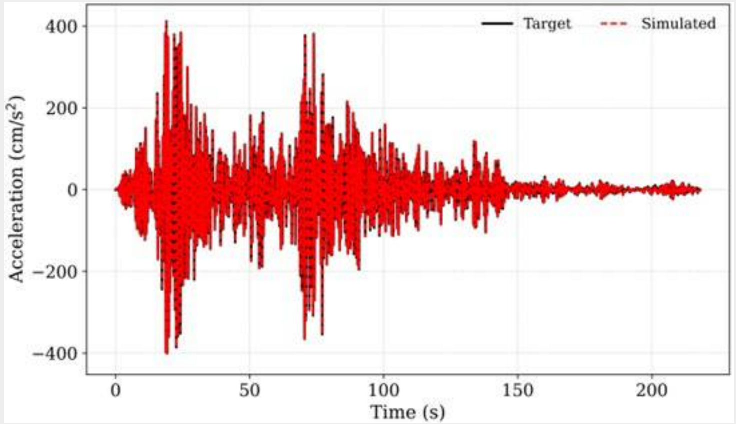


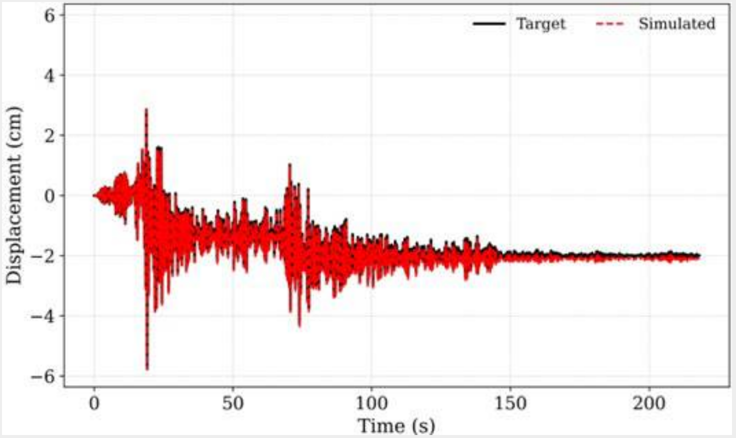


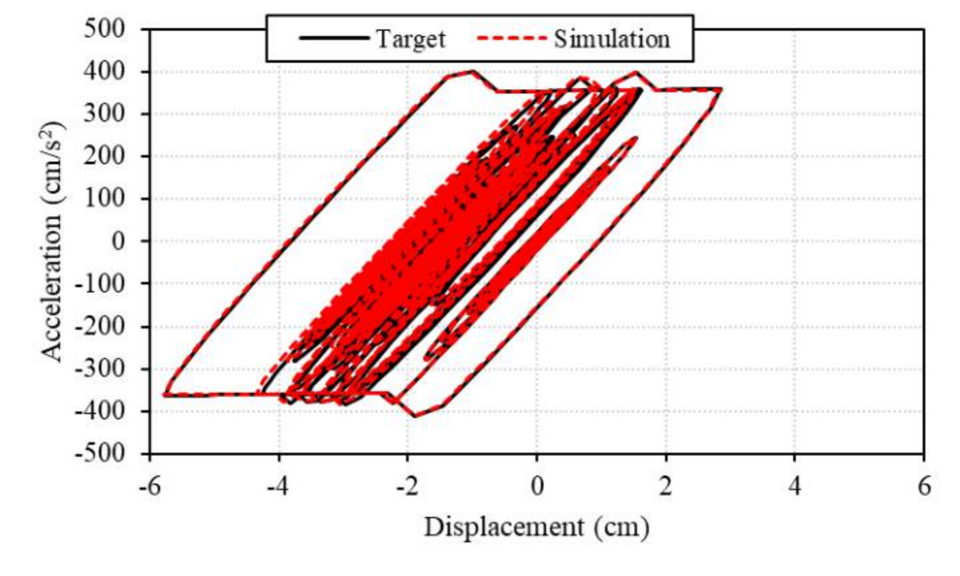


Obtained **simulated** vs **target** acceleration and displacement response.

For 07AugN case.

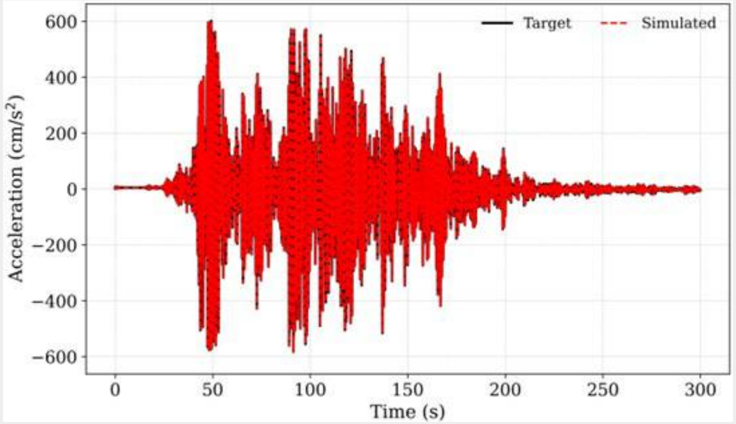


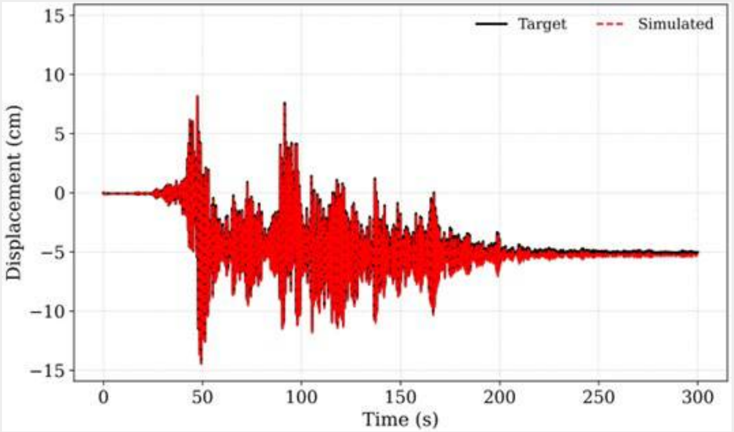


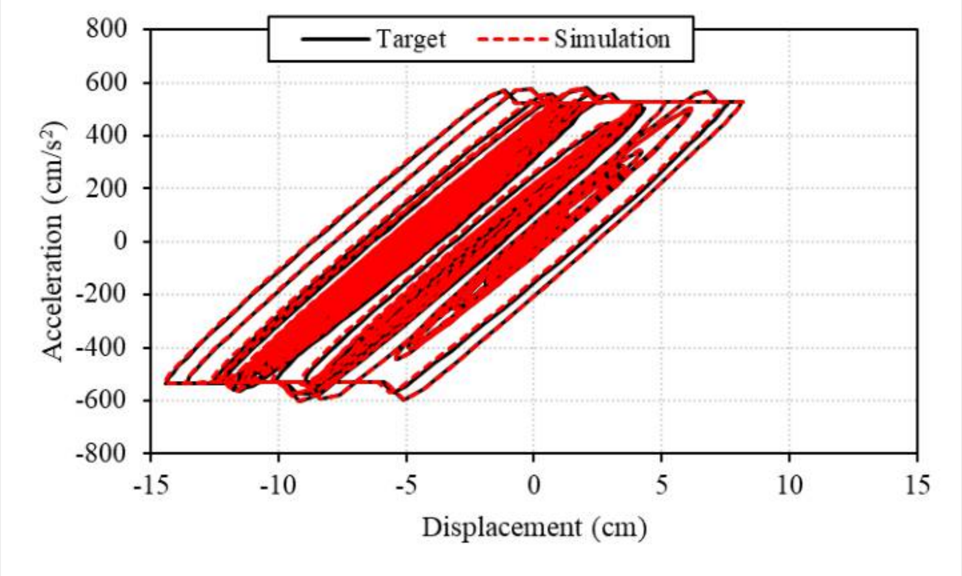


Obtained **simulated** vs **target** acceleration and displacement response.

For 11MarE case.

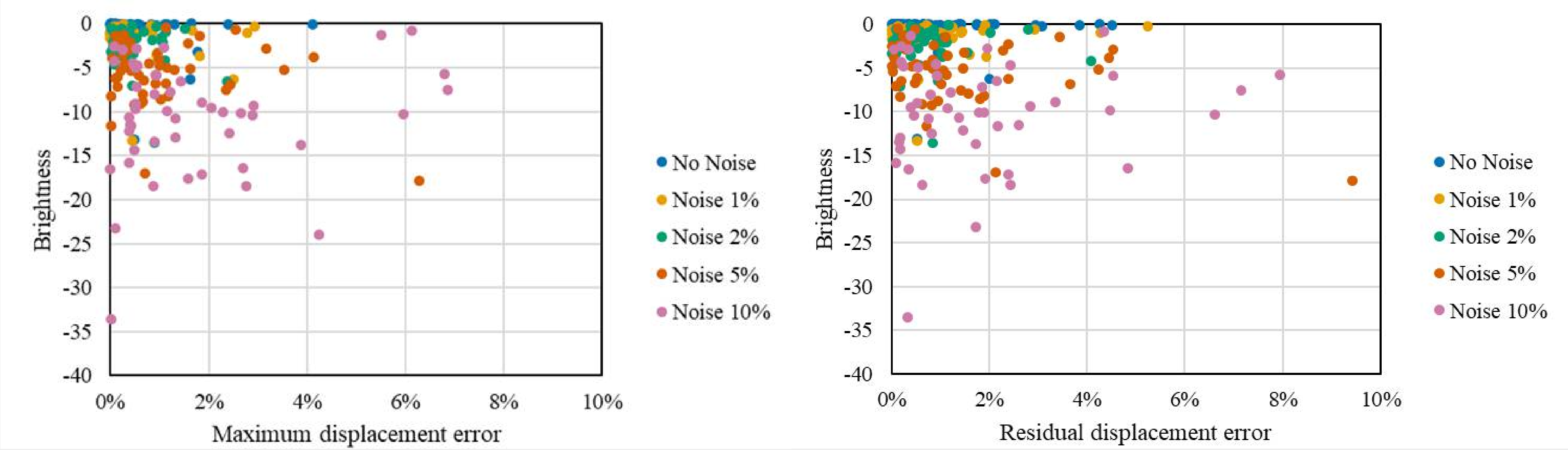






MFA applied with previously defined parameters.

Brightness vs displacement error for all cases



3. Application of the MFA framework

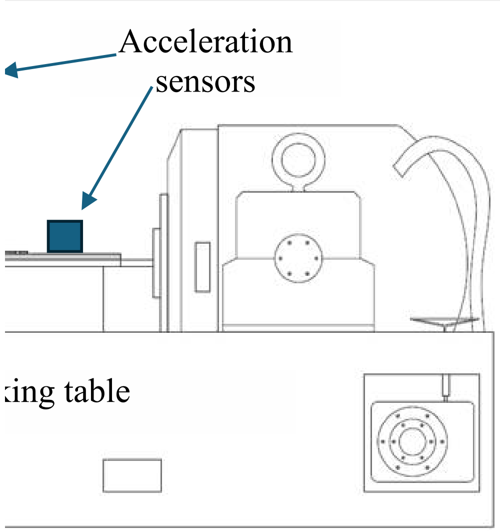
To real shaking table test experiments

1-story steel frame structure with 4 columns and beams.

Accelerations and displacements were recorded.

One directional ground motions were applied.

Model number	Input wave	Testing direction	Code name
1	Lima 66	90°	L66-90
2	Lima 66	45°	L66-45
3	**Lima 66**	**0°**	**L66**
4	**Lima 74**	**0°**	**L74**
5	Lima 74	30°	L74-30



Test Source: Peru-Japan center for Earthquake Engineering Research and Disaster Mitigation. (2022). Propuesta de metodología para la evaluación de la capacidad residual de edificaciones basado en el monitoreo de la salud estructural. Caso aplicativo en viviendas de albañilería [Technical Report]. Programa 0068 - Reducción de la vulnerabilidad y atención de emergencias por desastres.

MFA simulation L66-3

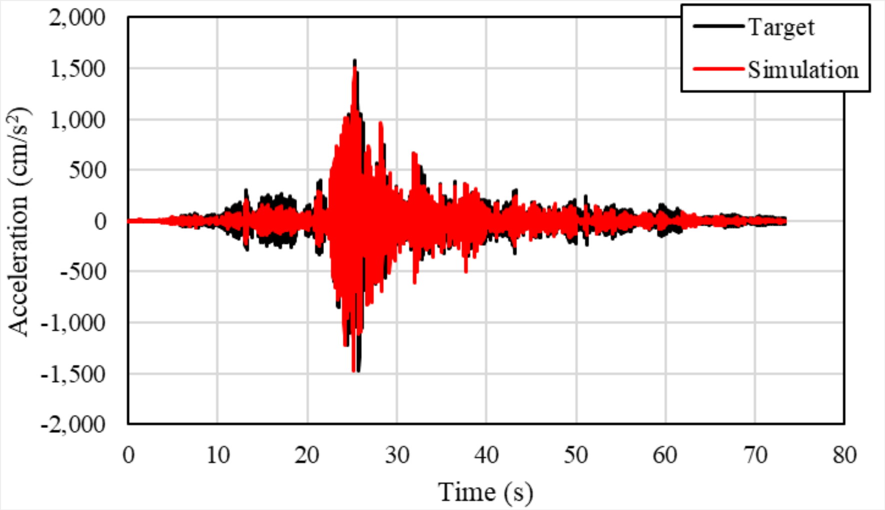
Simulation results:

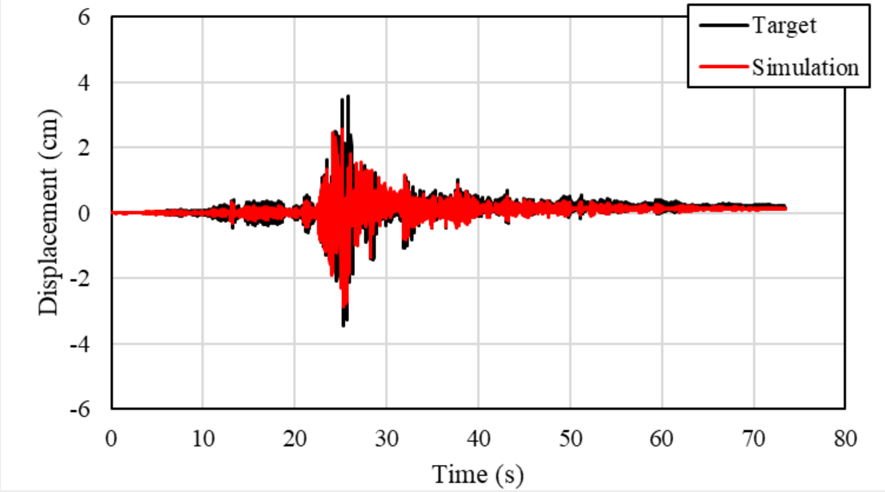
Maximum brightness per model

Hysteretic model	Brightness
Elastic	-123.8
Bilinear	-69.1
Ramberg-Osgood	$\mathbf{-66.4}$

Relative errors for displacements

Displacement (cm)	Target	Simulated	Relative error
Maximum	3.6	2.9	19.5%
Residual	0.16	0.12	1.0%





MFA simulation L66-5

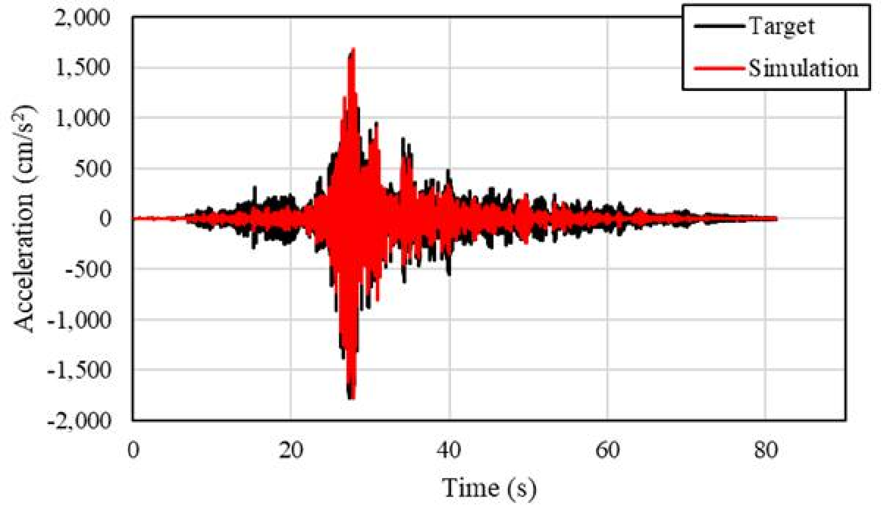
Simulation results:

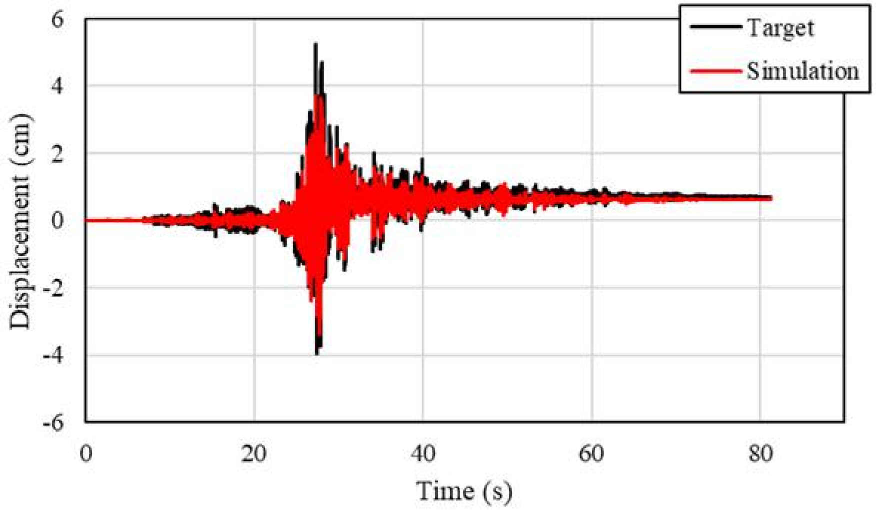
Maximum brightness per model

Hysteretic model	Brightness
Elastic	-228.0
Bilinear	$\mathbf{-68.3}$
Ramberg-Osgood	-87.9

Relative errors for displacements

Displacement (cm)	Target	Simulated	Relative error
Maximum	5.3	3.7	29.4%
Residual	0.71	0.61	1.9%





MFA simulation L74-1

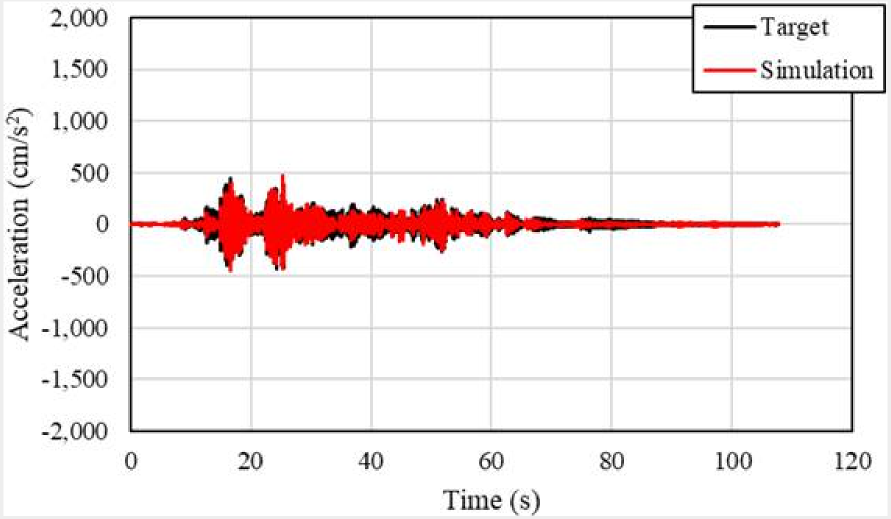
Simulation results:

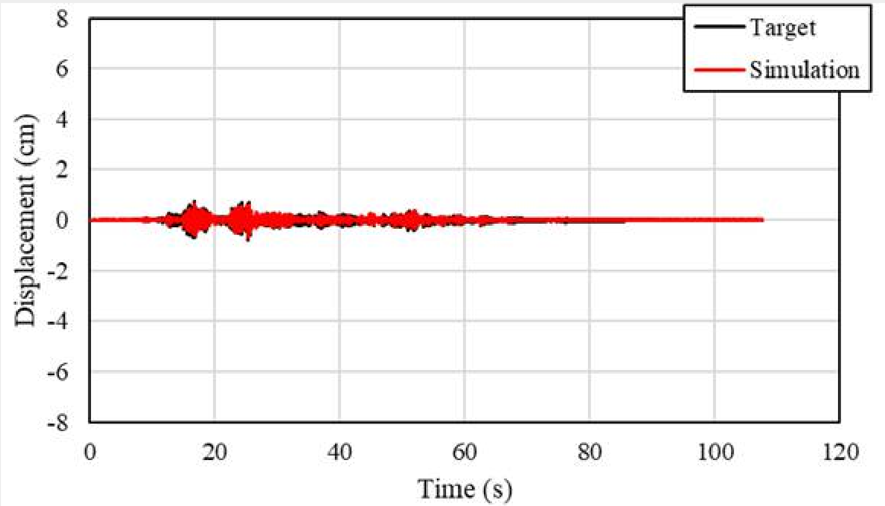
Maximum brightness per model

Hysteretic model	Brightness
Elastic	**−22.3**
Bilinear	−25.9
Ramberg-Osgood	−56.6

Relative errors for displacements

Displacement (cm)	Target	Simulated	Relative error
Maximum	0.78	0.69	11.6%
Residual	0.02	0.01	1.6%





MFA simulation L74-2

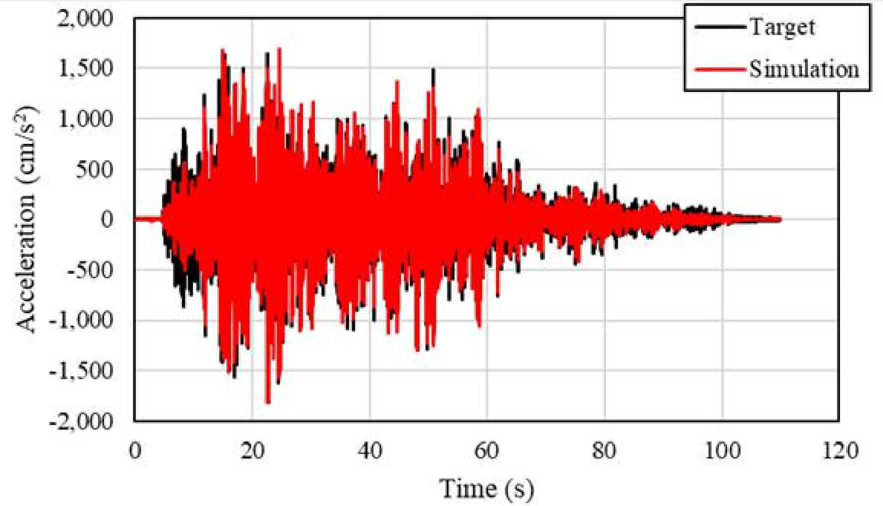
Simulation results:

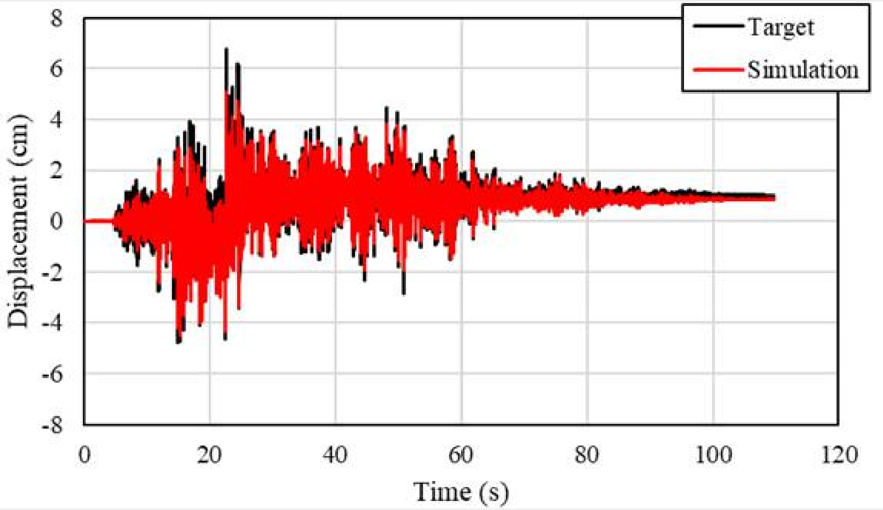
Maximum brightness per model

Hysteretic model	Brightness
Elastic	−362.5
Bilinear	−83.7
Ramberg-Osgood	**−75.5**

Relative errors for displacements

Displacement (cm)	Target	Simulated	Relative error
Maximum	6.75	5.09	17.6%
Residual	1.00	0.85	2.5%



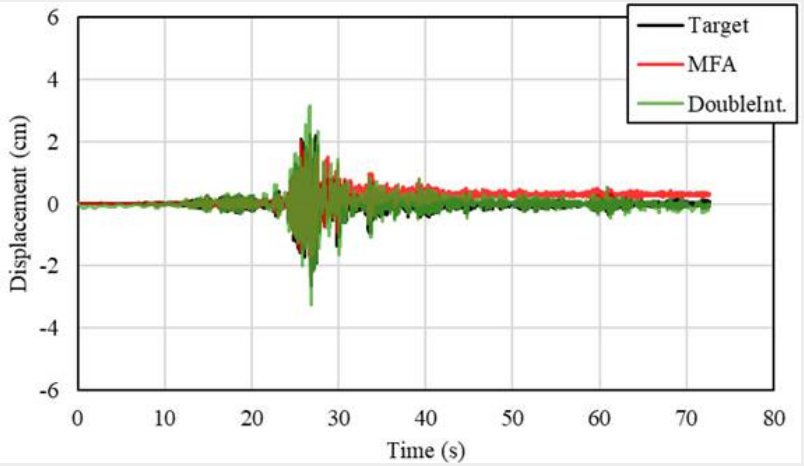


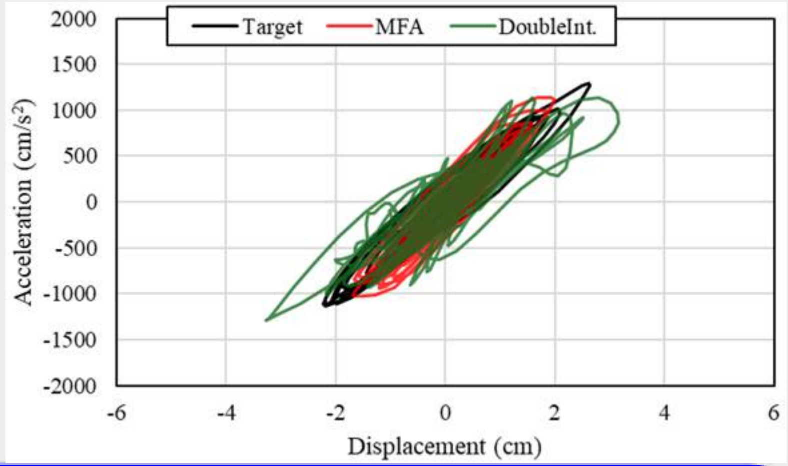
Comparison of obtained maximum displacement with MFA vs Double integration method*

*Double integration method including a linear detrend of the obtained velocity and displacement.

Case	Relative error – Displacements			
	MFA		Double integration	
	Maximum	Residual	Maximum	Residual
L66-2	**24.0%**	9.5%	23.9%	**3.4%**
L66-3	**19.5%**	**1.5%**	29.7%	4.4%
L66-4	**27.1%**	**2.0%**	35.6%	7.0%
L66-5	29.4%	**1.9%**	**22.0%**	13.5%
L74-1	**11.6%**	**1.6%**	37.0%	2.4%
L74-2	17.6%	**2.5%**	**11.5%**	14.8%
L74-3	21.1%	**1.4%**	**6.6%**	15.8%

L66-2



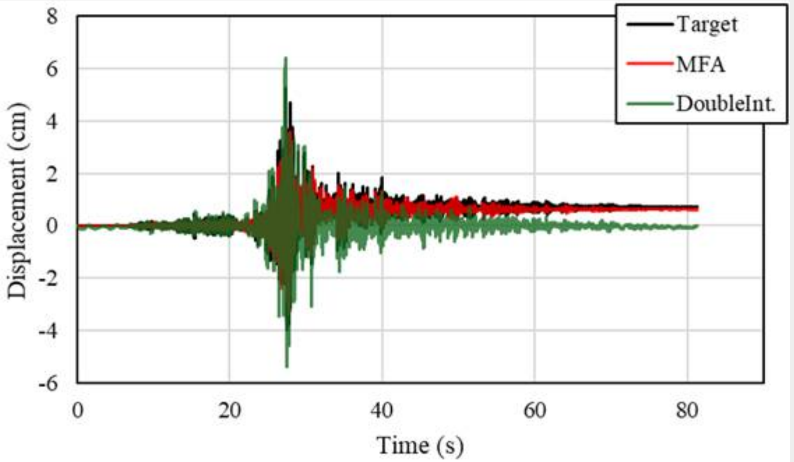


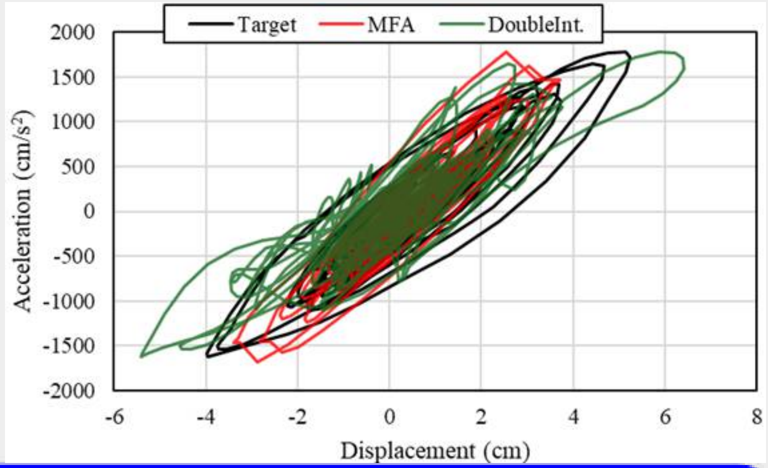
Comparison of obtained maximum displacement with MFA vs Double integration method*

*Double integration method including a linear detrend of the obtained velocity and displacement.

Case	Relative error – Displacements			
	MFA		Double integration	
	Maximum	Residual	Maximum	Residual
L66-2	**24.0%**	9.5%	23.9%	**3.4%**
L66-3	**19.5%**	**1.5%**	29.7%	4.4%
L66-4	**27.1%**	**2.0%**	35.6%	7.0%
L66-5	29.4%	**1.9%**	**22.0%**	13.5%
L74-1	**11.6%**	**1.6%**	37.0%	2.4%
L74-2	17.6%	**2.5%**	**11.5%**	14.8%
L74-3	21.1%	**1.4%**	**6.6%**	15.8%

L66-5



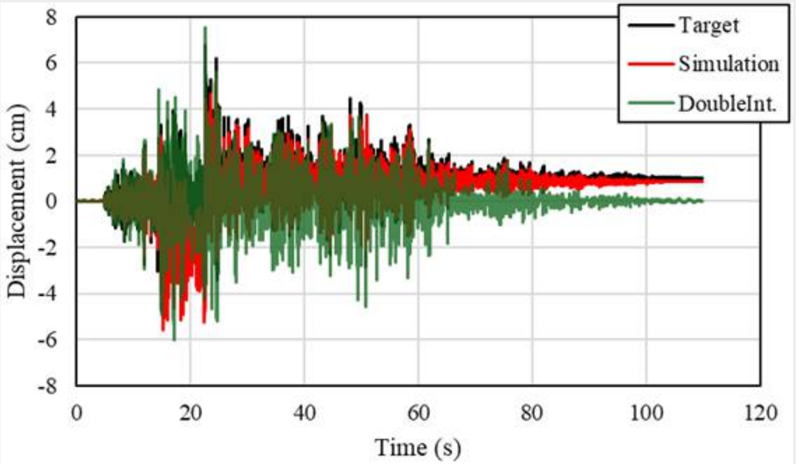


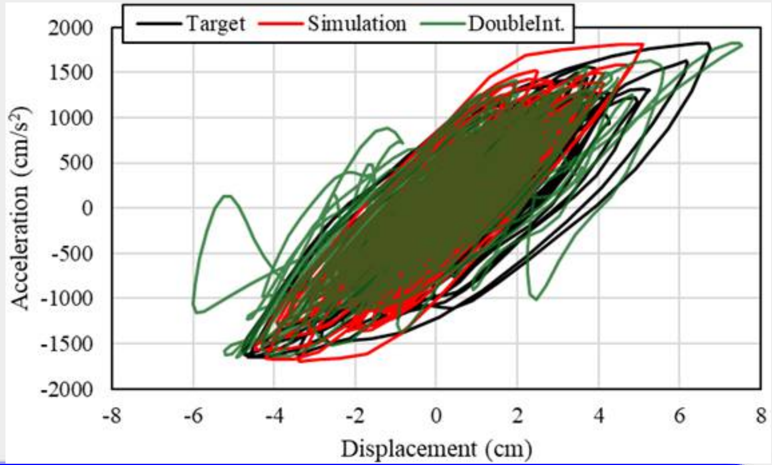
Comparison of obtained maximum displacement with MFA vs Double integration method*

*Double integration method including a linear detrend of the obtained velocity and displacement.

Case	Relative error – Displacements			
	MFA		Double integration	
	Maximum	Residual	Maximum	Residual
L66-2	**24.0%**	9.5%	23.9%	**3.4%**
L66-3	**19.5%**	**1.5%**	29.7%	4.4%
L66-4	**27.1%**	**2.0%**	35.6%	7.0%
L66-5	29.4%	**1.9%**	**22.0%**	13.5%
L74-1	**11.6%**	**1.6%**	37.0%	2.4%
L74-2	17.6%	**2.5%**	**11.5%**	14.8%
L74-3	21.1%	**1.4%**	**6.6%**	15.8%

L74-2



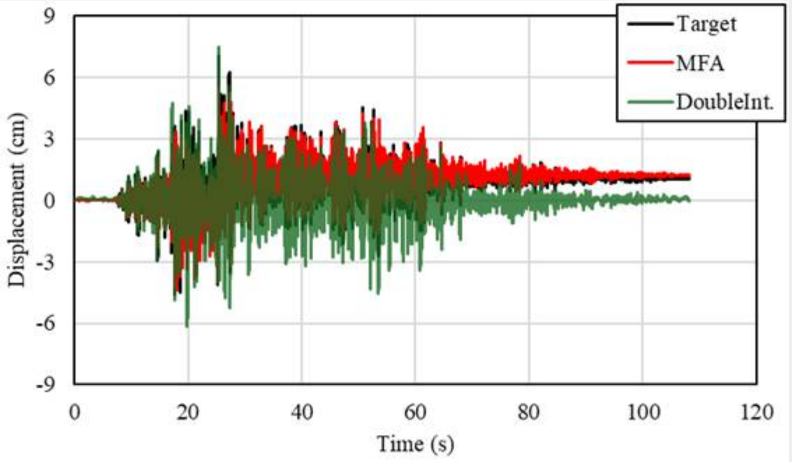


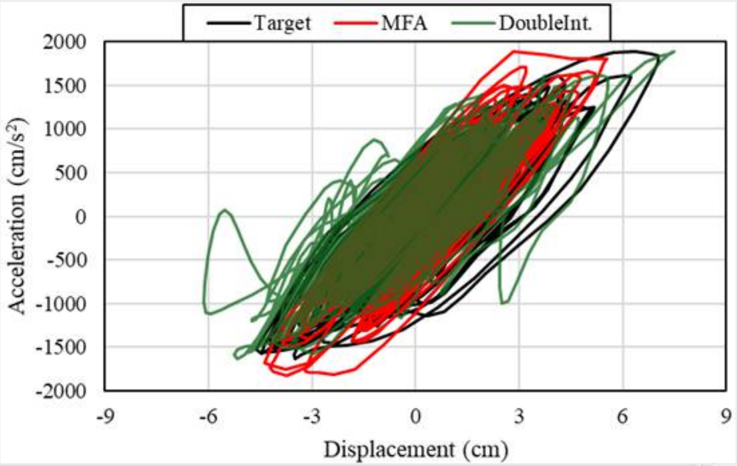
Comparison of obtained maximum displacement with MFA vs Double integration method*

*Double integration method including a linear detrend of the obtained velocity and displacement.

Case	Relative error – Displacements			
	MFA		Double integration	
	Maximum	Residual	Maximum	Residual
L66-2	**24.0%**	9.5%	23.9%	**3.4%**
L66-3	**19.5%**	**1.5%**	29.7%	4.4%
L66-4	**27.1%**	**2.0%**	35.6%	7.0%
L66-5	29.4%	**1.9%**	**22.0%**	13.5%
L74-1	**11.6%**	**1.6%**	37.0%	2.4%
L74-2	17.6%	**2.5%**	**11.5%**	14.8%
L74-3	21.1%	**1.4%**	**6.6%**	15.8%

L74-3





Analyzing the **Elastic model's maximum brightness** per case, it is found that its **similarity** with **nonlinear** models is related to the **degree of nonlinearity** of the response.

L66-2

Record	Maximum brightness		
	Elastic	Bilinear	Ramberg-Osgood
L66-2	-62.2	-54.8	$\mathbf{-51.8}$
L66-3	-123.8	-69.1	$\mathbf{-66.4}$
L66-4	-130.2	$\mathbf{-75.5}$	-75.8
L66-5	-228.0	$\mathbf{-68.3}$	-87.9

L74-1

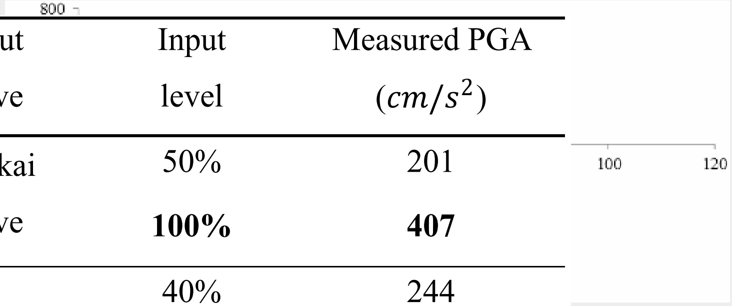
Record	Maximum brightness		
	Elastic	Bilinear	Ramberg-Osgood
L74-1	$\mathbf{-22.3}$	-25.9	-56.6
L74-2	-123.8	-69.1	$\mathbf{-66.4}$
L74-3	-130.2	-75.8	$\mathbf{-75.5}$

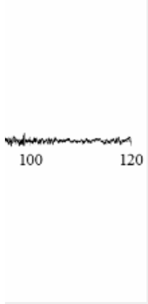
3-story steel frame structure – E-Defense 2013 experiment (“Experimental study on seismic safety measures for earthquake-damaged steel-framed buildings”)

Accelerations and displacements were used for the simulation and validation, respectively.

One directional ground motions were applied with different amplification factors.

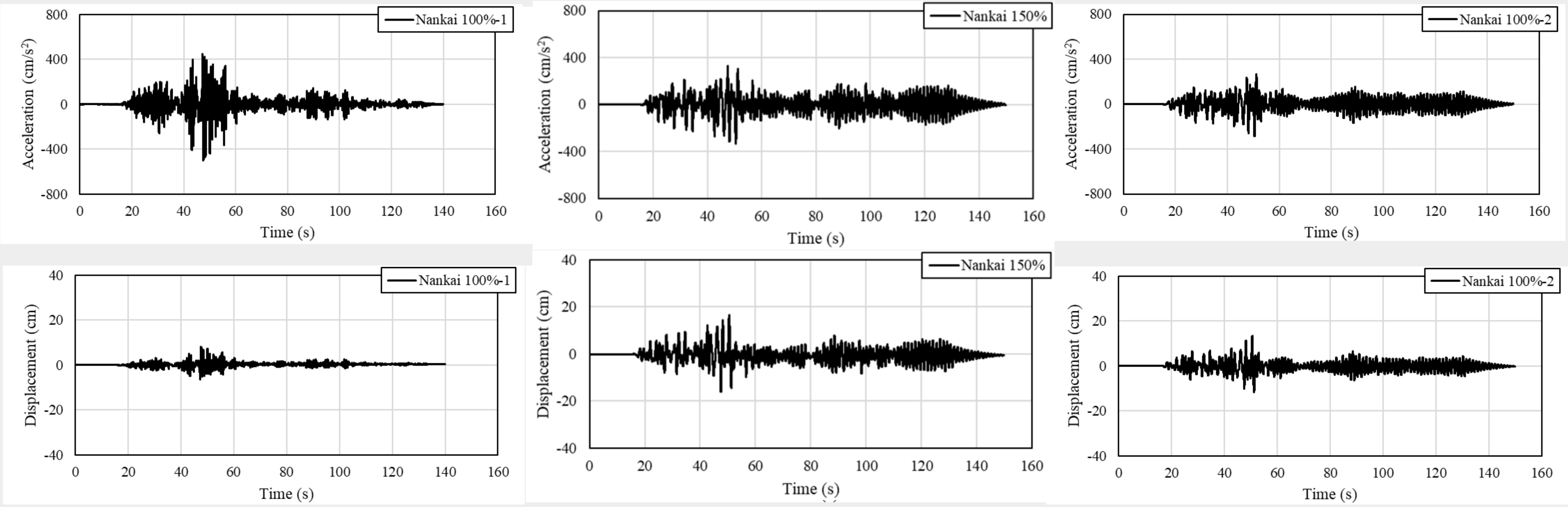
Input number	Experiment name	Input wave	Input level	Measured PGA (cm/s^2)
No. 1	Nankai 50% - 1	Nankai wave	50%	201
No. 2	**Nankai 100% - 1**		**100%**	**407**
No. 3	Takatori 40%	Takatori wave	40%	244
No. 4	Takatori 60%		60%	373
No. 5	Takatori 80%		80%	534
No. 6	**Takatori 100%**		**100%**	**706**
No. 7	Nankai 50% - 2	Nankai wave	50%	203
No. 8	**Nankai 100% - 2**		**100%**	**410**
No. 9	**Nankai 150%**		**150%**	**650**





Test Source: 防災科学技術研究所 - National Research Institute for Earth Science and Disaster Resilience. (2013). ASEBI: Archives of E-Defense Shaking table Experimentation Database and Information.

Equivalent SDOF responses (Filtered)



MFA simulation Nankai 100%-1

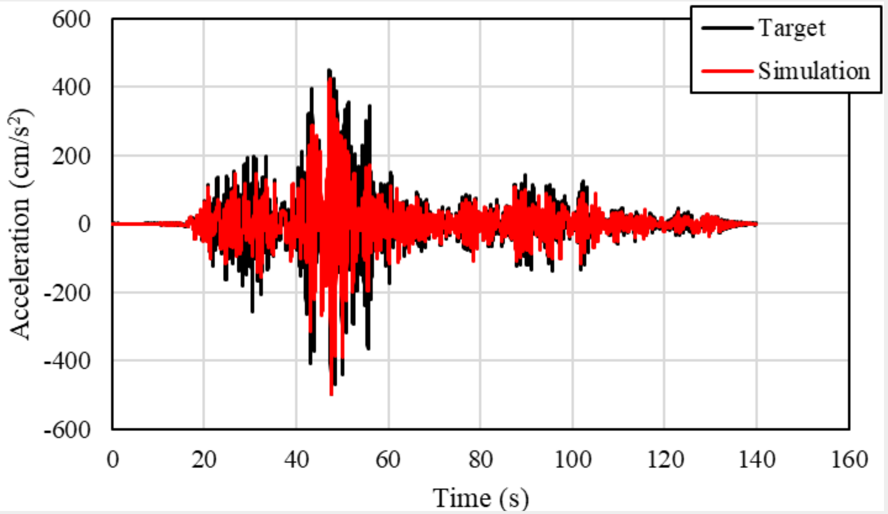
Simulation results:

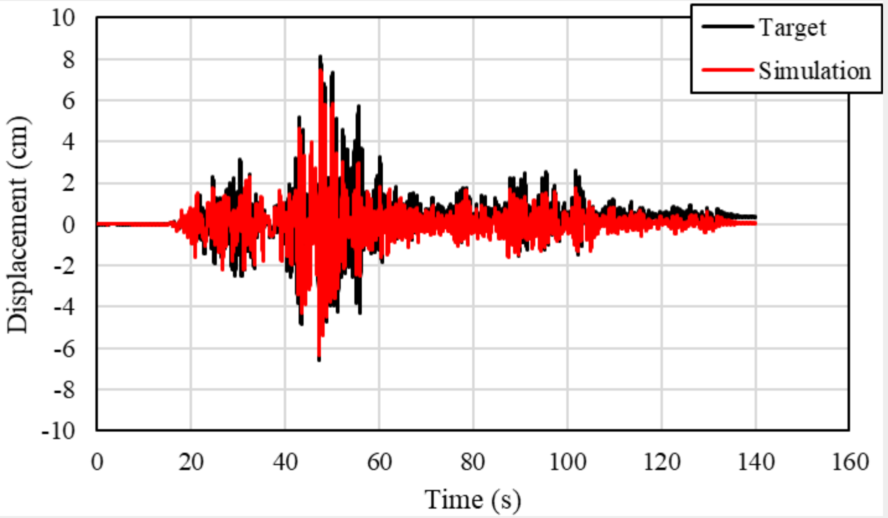
Maximum brightness per model

Hysteretic model	Brightness
Elastic	-37.7
Bilinear	$\mathbf{-28.0}$
Ramberg-Osgood	-28.2

Relative errors for displacements

Displacement (cm)	Target	Simulated	Relative error
Maximum	8.1	7.45	8.2%
Residual	0.4	0.1	3.9%





MFA simulation Takatori 100%

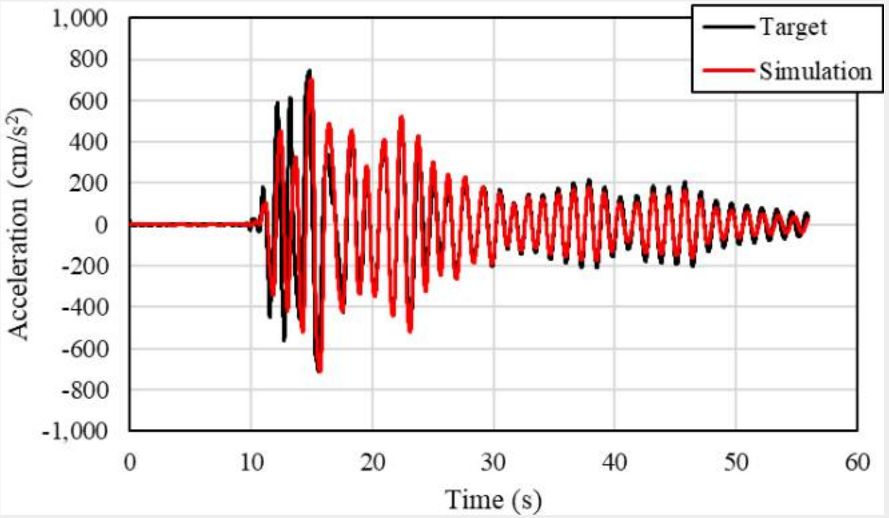
Simulation results:

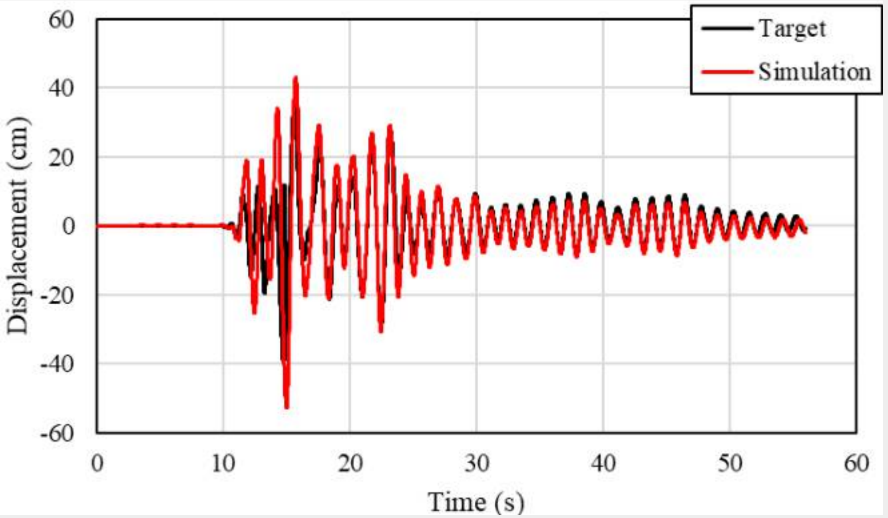
Maximum brightness per model

Hysteretic model	Brightness
Elastic	−93.9
Bilinear	−79.0
Ramberg-Osgood	**−56.0**

Relative errors for displacements

Displacement (cm)	Target	Simulated	Relative error
Maximum	38.9	52.7	35.7%
Residual	0.4	2.0	2.8%



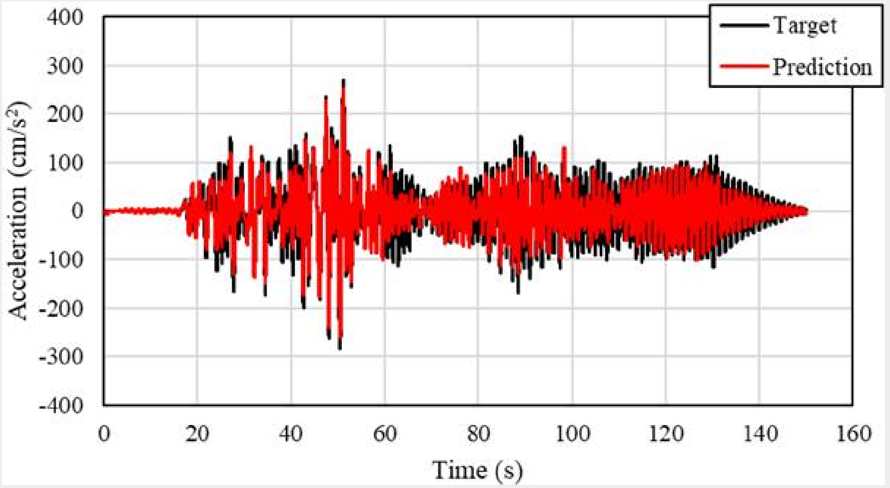


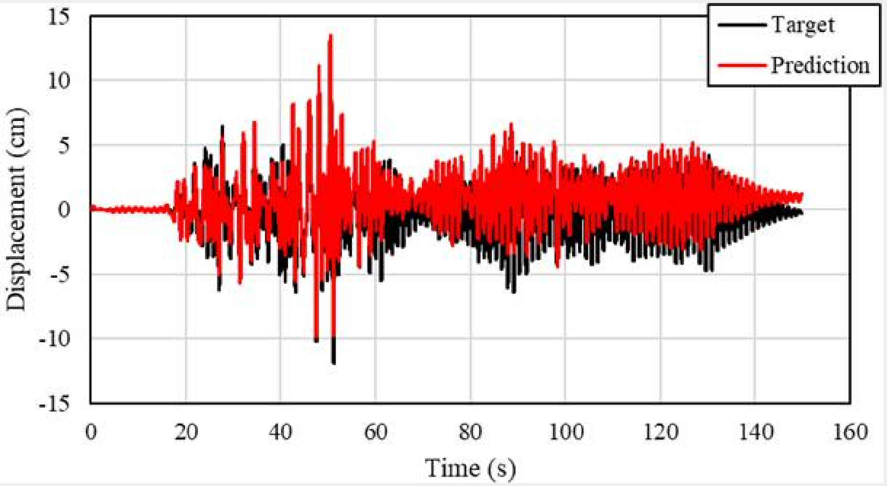
Prediction for Nankai 100%-2

Obtained parameters from the previous case:

Parameter	Value
ζ	0.02
k_1	23.89
α_{RO}	9.88
n_{RO}	3
f_y	437.47

Displacement (cm)	Target	Simulated	Relative error
Maximum	13.2	13.5	2.3%
Residual	0.3	1.2	7.2%



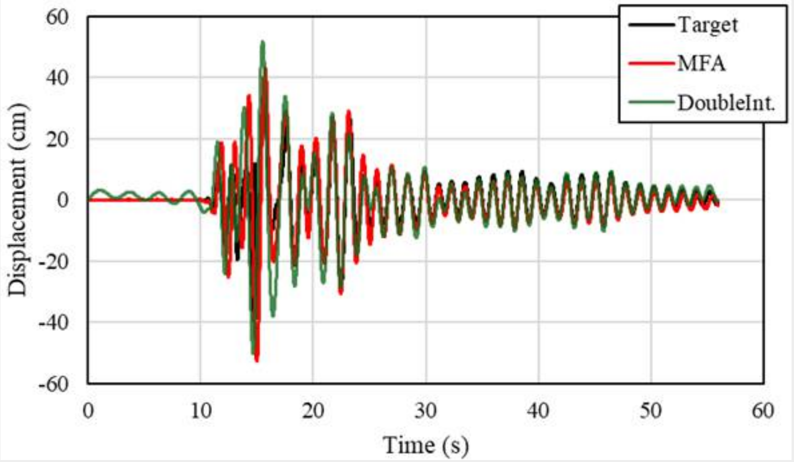


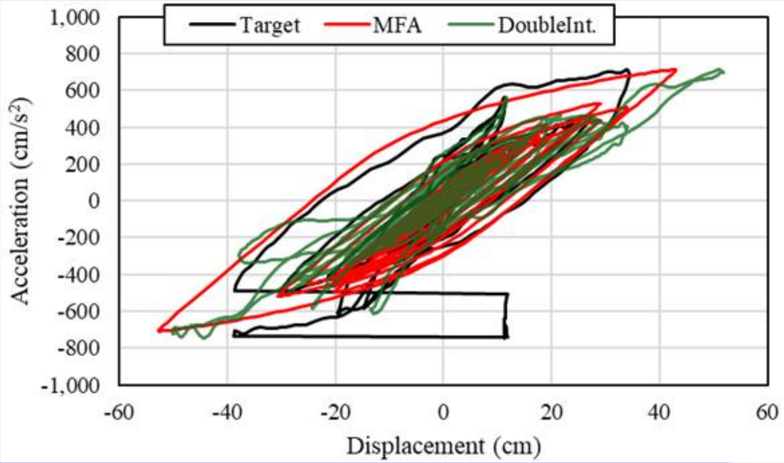
Comparison of obtained maximum displacement with MFA vs Double integration method*

*Double integration method including a linear detrend of the obtained velocity and displacement.

Takatori 100%

Case	Relative error – Displacements			
	MFA		Double integration	
	Maximum	Residual	Maximum	Residual
Nankai 100%-1	**8.2%**	**3.9%**	38.0%	4.5%
Takatori 100%	35.7%	2.8%	**33.4%**	**2.6%**





4. Conclusions

1. Developed an **accurate displacement response estimation methodology** based on the application of the **MFA** with proposed **simulation parameters**, hysteretic **parameter seeking ranges** and **guidelines** for its application.

2. Validated the **MFA simulation parameters** for its application to a structural parameter identification framework with **different ground motions on synthetic SDOF models**.

3. Defined a **multi-hysteresis framework** for obtaining the **best-fit hysteretic model** within a set of proposed options.

4. Obtained a relation between the **brightness value** from the **Elastic model** and the **nonlinearity of the response**.

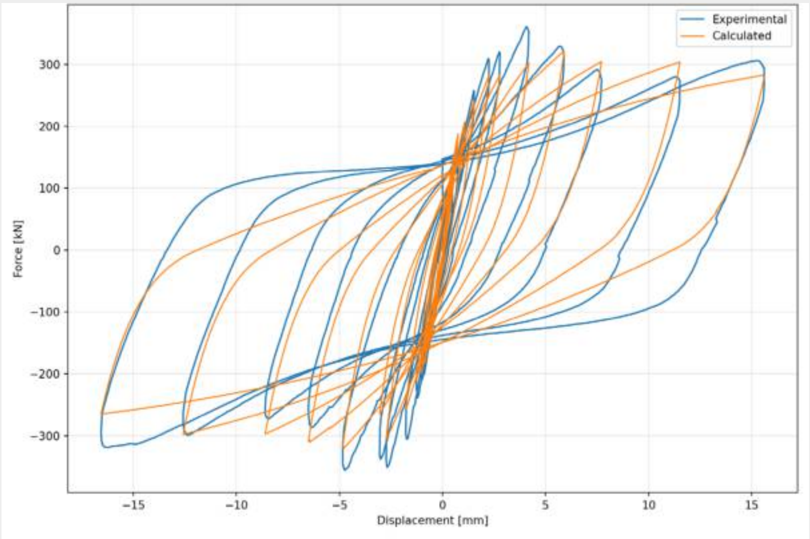
5. Validated the proposed framework with **real data**, for a **1-story** test and a **3-story steel frame shaking table test**.

6. Tested the capability of the **obtained structural parameters** for **displacement response prediction** of an **upcoming event**.

5. Recent applications

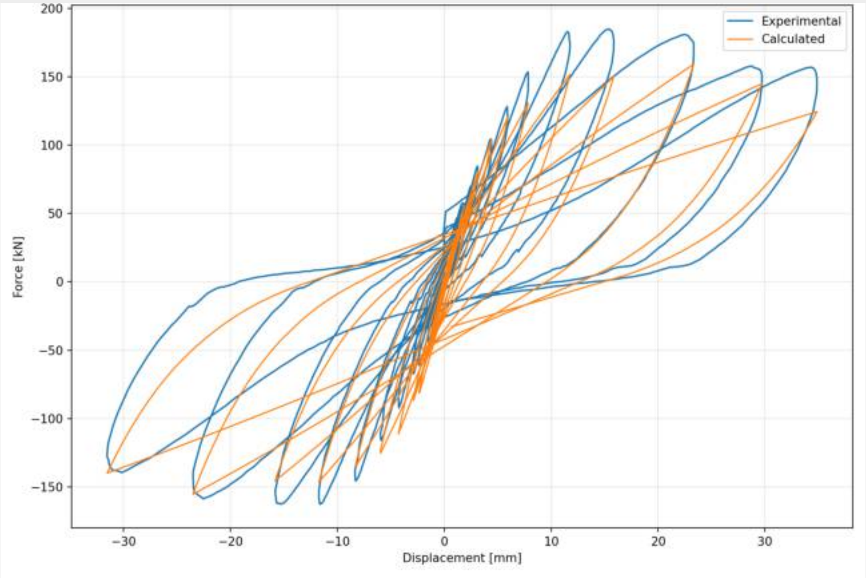
Automatic hysteretic parameter identification of walls

Data obtained from pseudo-dynamic cyclic loading tests of masonry walls.



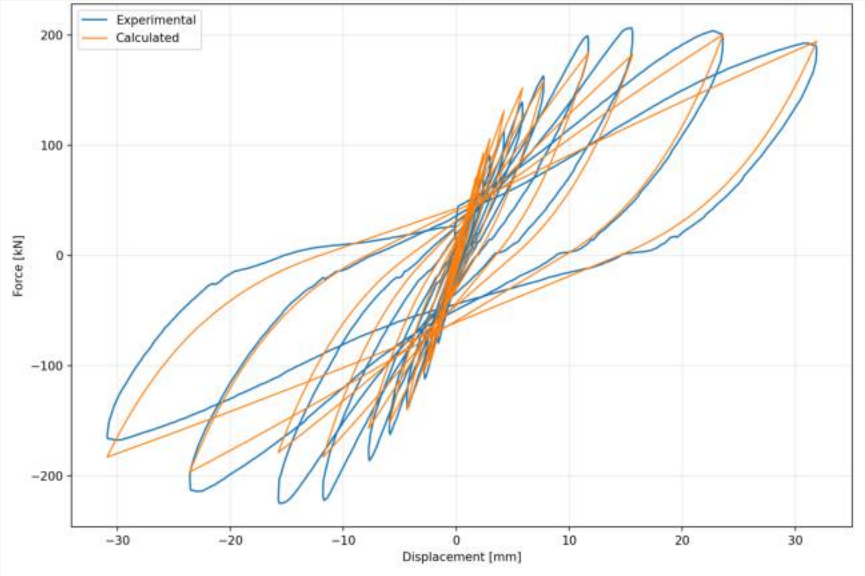
Automatic hysteretic parameter identification of walls

Data obtained from pseudo-dynamic cyclic loading tests of masonry walls.

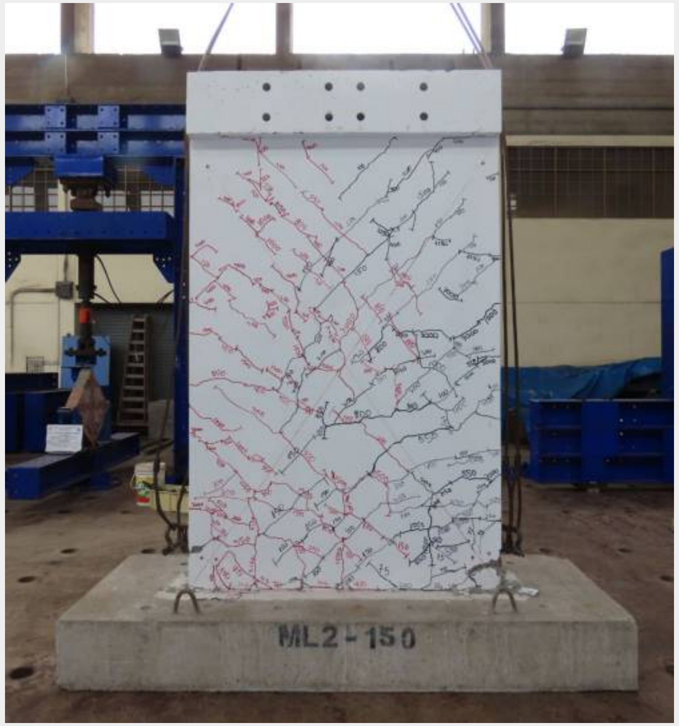


Automatic hysteretic parameter identification of walls

Data obtained from pseudo-dynamic cyclic loading tests of masonry walls.

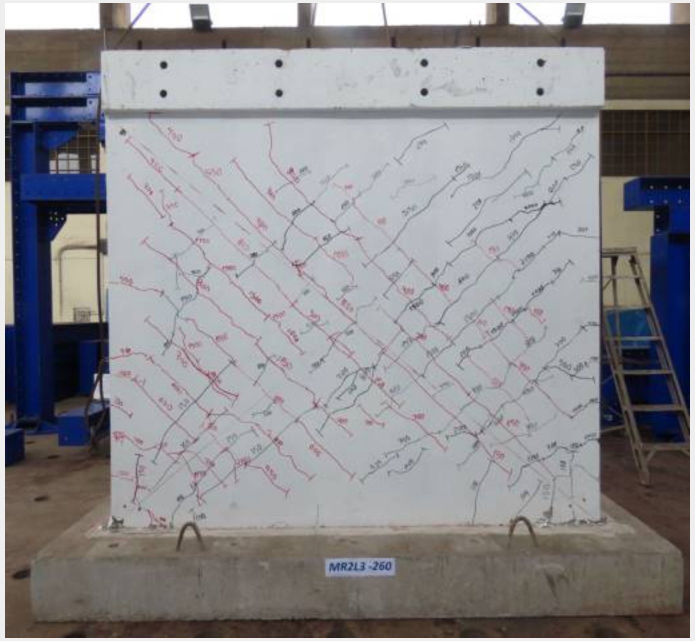


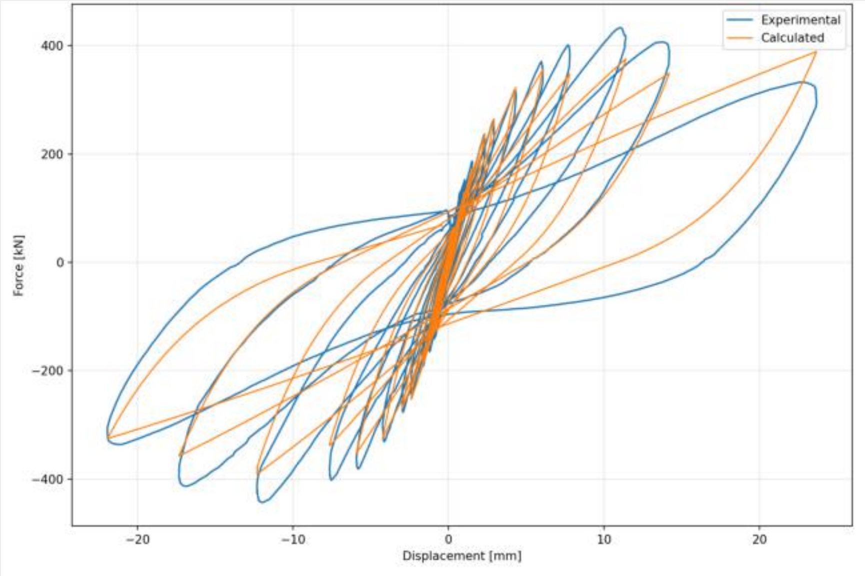
MR2L2-150



Automatic hysteretic parameter identification of walls

Data obtained from pseudo-dynamic cyclic loading tests of masonry walls.



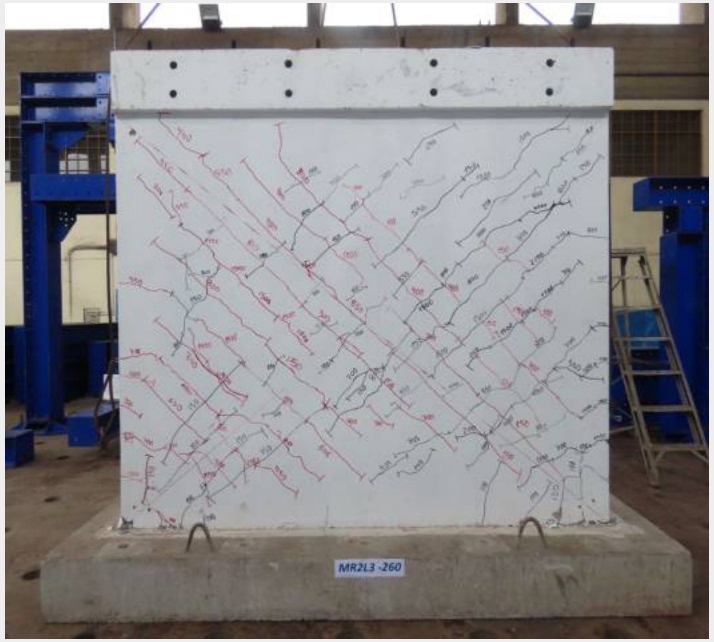


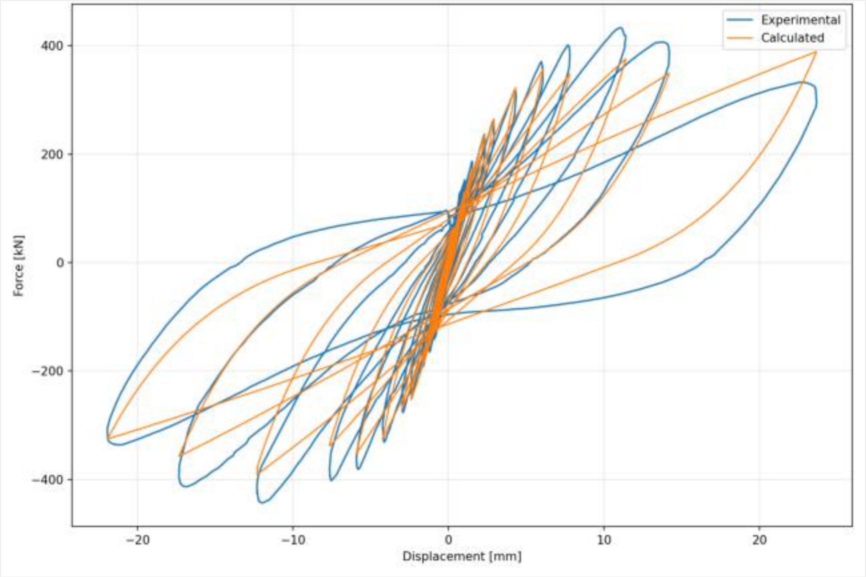
Automatic hysteretic parameter identification of walls

- About 5 min per wall (trying 9 different hysteretic models).

Next steps:

- Add non-symmetric models
- Digitalize all CISMID Wall's database





Acknowledgements

CISMID

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ASEBI
E-Defense実験データアーカイブ

¡Gracias!

ありがとうございます

Thank you!