



Seminario tecnico: “Il Rischio NATECH negli stabilimenti industriali: le principali sfide poste dalle attività di analisi, valutazione e controllo”

Il rischio NATECH negli impianti a rischio di incidente rilevante: lo studio del comportamento dinamico e la modellazione numerica dei componenti industriali



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Ordine degli Ingegneri della Provincia di Roma, P.zza della Repubblica 59 – Roma 25/01/2024



OUTLINE

- INTRODUCTION AND MOTIVATION
- DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGNS AND PRINCIPAL RESULTS ON A BFJ
- DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGNS AND PRINCIPAL RESULTS – SPIF#1
- DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGNS AND PRINCIPAL RESULTS – SPIF#2
- MODELLING ISSUES OF INDUSTRIAL NON-STRUCTURAL ELEMENTS
- RISK ASSESSMENT OF A NON-STRUCTURAL ELEMENT
- CONCLUSIONS AND FUTURE DEVELOPMENTS

INTRODUCTION AND MOTIVATION

Process plants are complex systems which includes a numerous components such as **tanks, piping system, vessels** etc.

Due to the nature of these **raw materials** that are treated in petrochemical plants, they are the second most vulnerable type of industrial installation after nuclear plants when subjected to **Na-Tech events** (especially earthquakes).



Pacific Coast of Tohoku Earthquake (Mw9.0) Japan, 2011

Seismic behavior of support structures in major hazard industrial plants is therefore of **paramount importance**.

Approximately **8% of total accidents** in industrial facilities are caused by **earthquakes**



Kocaeli, Turkey, 1999

It is noteworthy that whilst several aspects in terms of **design and analysis are still unresolved, code-compliant methods** demonstrated to result in **very poor predictions** and to be often dated and inadequate.

The seismic behaviour of industrial facilities was intensively studied with numerical models, but there is a **lack of experimental test in literature**.



STATE OF ART OF SEISMIC RISK ASSESSMENT OF INDUSTRIAL PLANTS AND THEIR NON-STRUCTURAL COMPONENTS (NSC)

MAIN CRITICAL ISSUES IN THE SEISMIC RISK ASSESSMENT OF NSC:

1. **Lack of information** in the literature and in the codes about the **seismic response** of the secondary element and related **reliable limit states**. In particular, the seismic behaviour of **NSCs** is a topic to be deeply investigated, since their particular dynamic interaction with the primary structure. Furthermore, the presence of **hazard materials** within them, **whose release can trigger dramatic accidents** is paramount of **importance**.

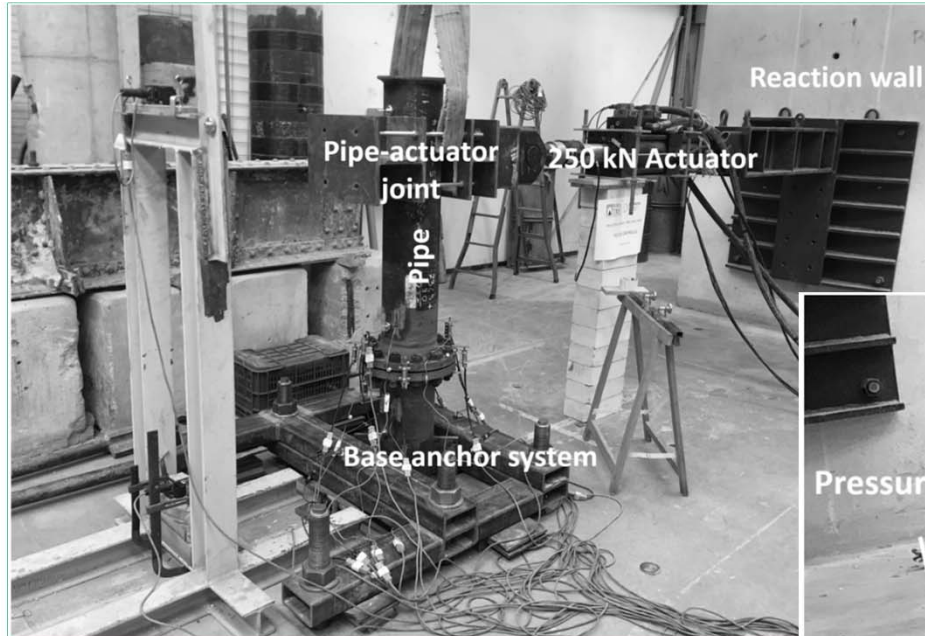
RESEARCH PROJECT CONTRIBUTION:

1. **Wide experimental campaigns** have been conducted during this research, in order to fix point 1. The **first two** campaigns have been developed within the SPIF project, developed inside the **European H2020 SPIF** research framework. The aims were to **test** by means a **shaking table test** two different configuration of **primary industrial steel structures** equipped with **NSC**. The **last one** was conducted in **Roma Tre Laboratory** in order to investigate the **mechanical behaviour** of a **Bolted flange joint (BFJ)** of a pipe under **cyclic loads**.

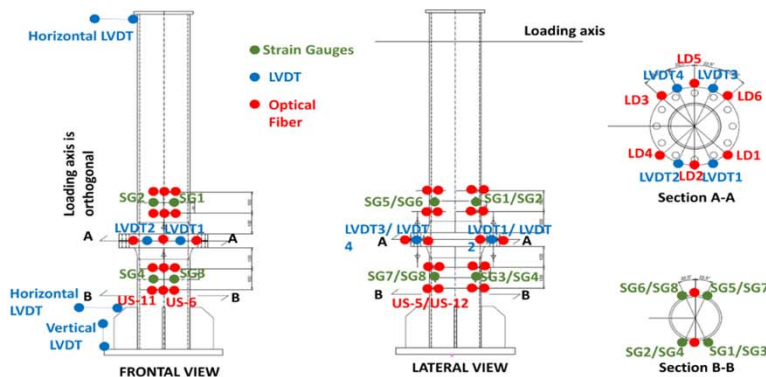


EXPERIMENTAL TEST CAMPAIGN

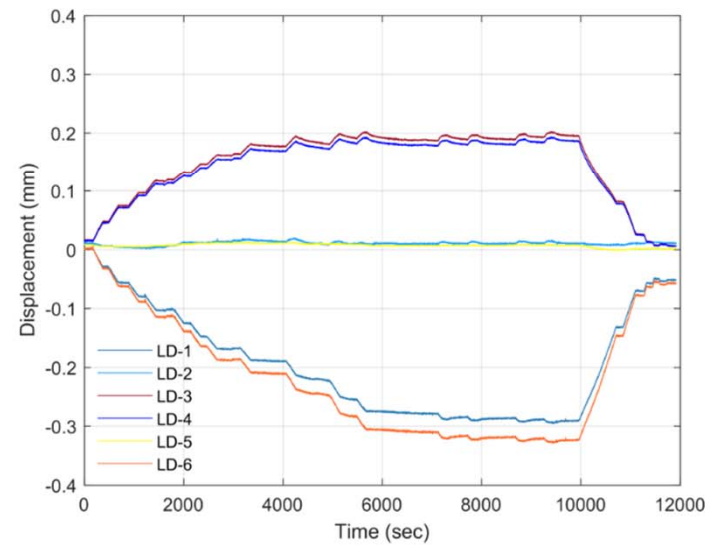
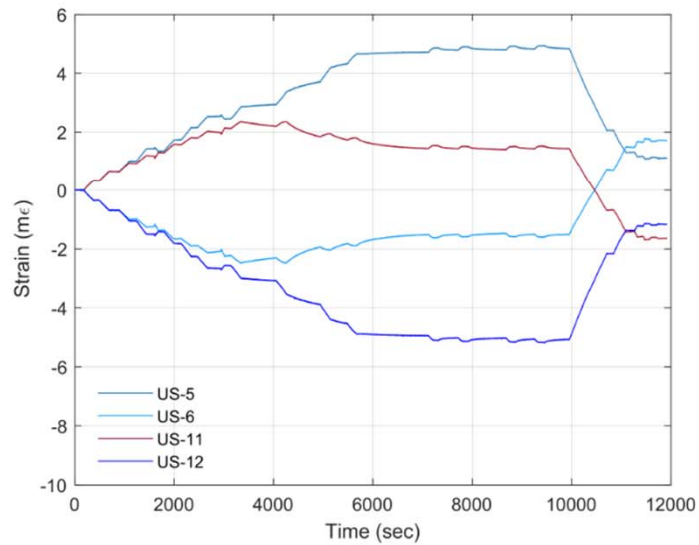
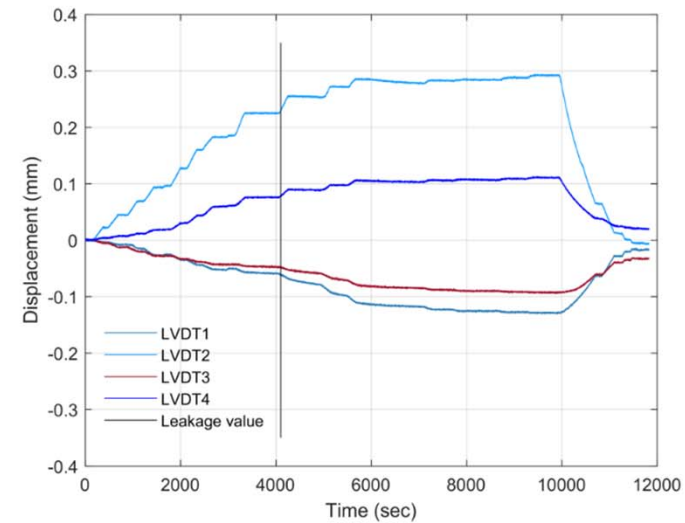
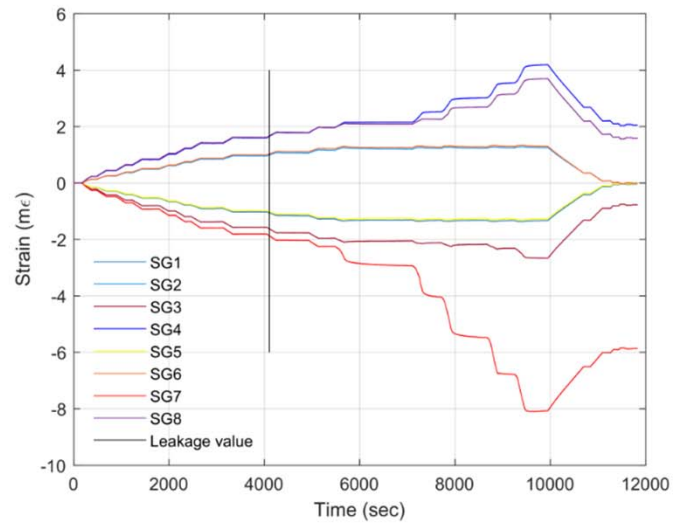
Bolted Flange Joint test at Roma 3 Laboratory



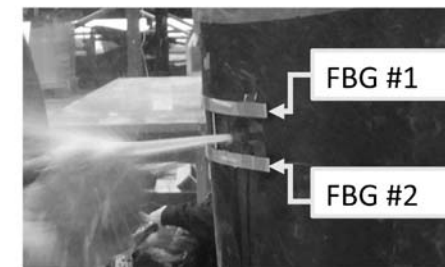
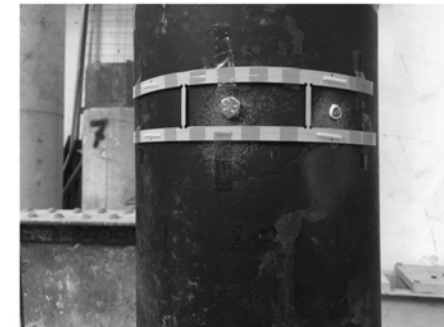
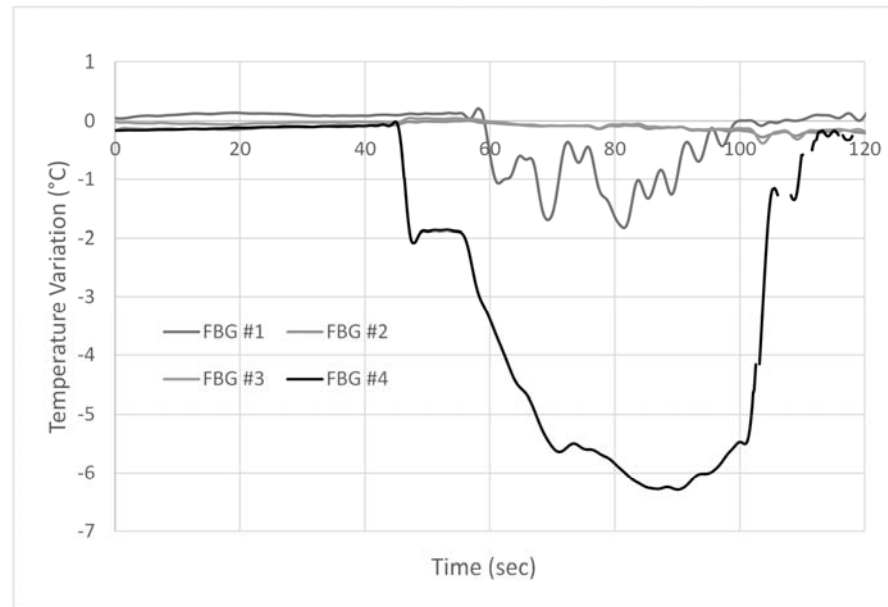
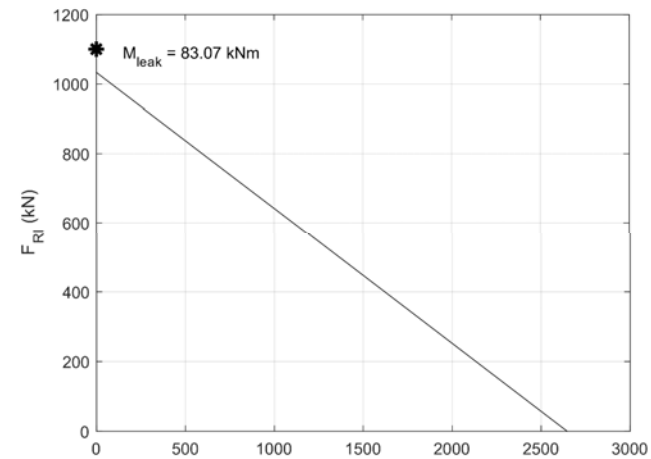
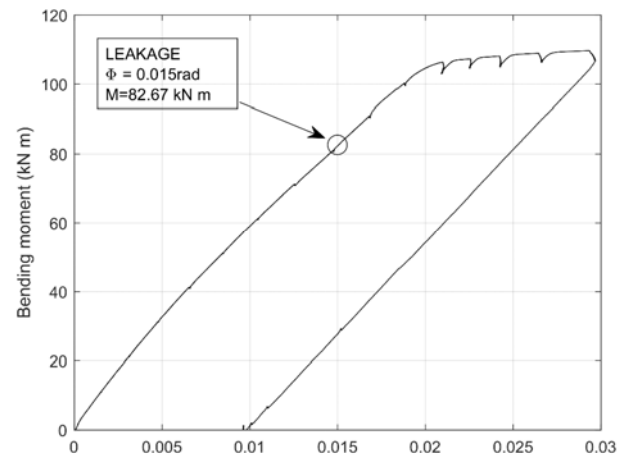
A BFJ equipped with traditional and FBG sensors has been tested by means of an hydraulic actuator with 250kN and velocity of 0.02mm/s



EXPERIMENTAL TEST CAMPAIGN – BFJ test at Roma 3 Laboratory



EXPERIMENTAL TEST CAMPAIGN – Leakage detection





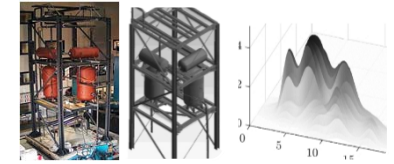
SUMMARY EXPERIMENTAL TEST CAMPAIGN BFJ TESTED AT ROMA3 LABORATORY

- The importance of studying the behavior of a Bolted Flange Joint
- The importance to establish a leakage domain in order to predict the leakage detection
- The possibility to monitor the BFJs with FBG sensors in ATEX environment

REFERENCES

Paolacci, F., Quinci, G., Nardin, C., Vezzari, V., Marino, A., & Ciucci, M. (2021). Bolted flange joints equipped with FBG sensors in industrial piping systems subjected to seismic loads. *Journal of Loss Prevention in the Process Industries*, 72, 104576.

DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGNS AND PRINCIPAL RESULTS



SPIF #1- #2 EXPERIMENTAL TEST CAMPAIGNS OBJECTIVES:

- Study of the **seismic behavior** of multi-component systems in special risk industrial facilities
- **Dynamic behaviour** of pipes and their connections due to seismic induced relative displacements
- Derivation of **simplified calculation approaches** to consider structure-component interactions
- Definition of **performance objective** and reference **limit states** for **industrial primary structure** and **equipment** based on experimental results
- Study of **structure-component interaction**



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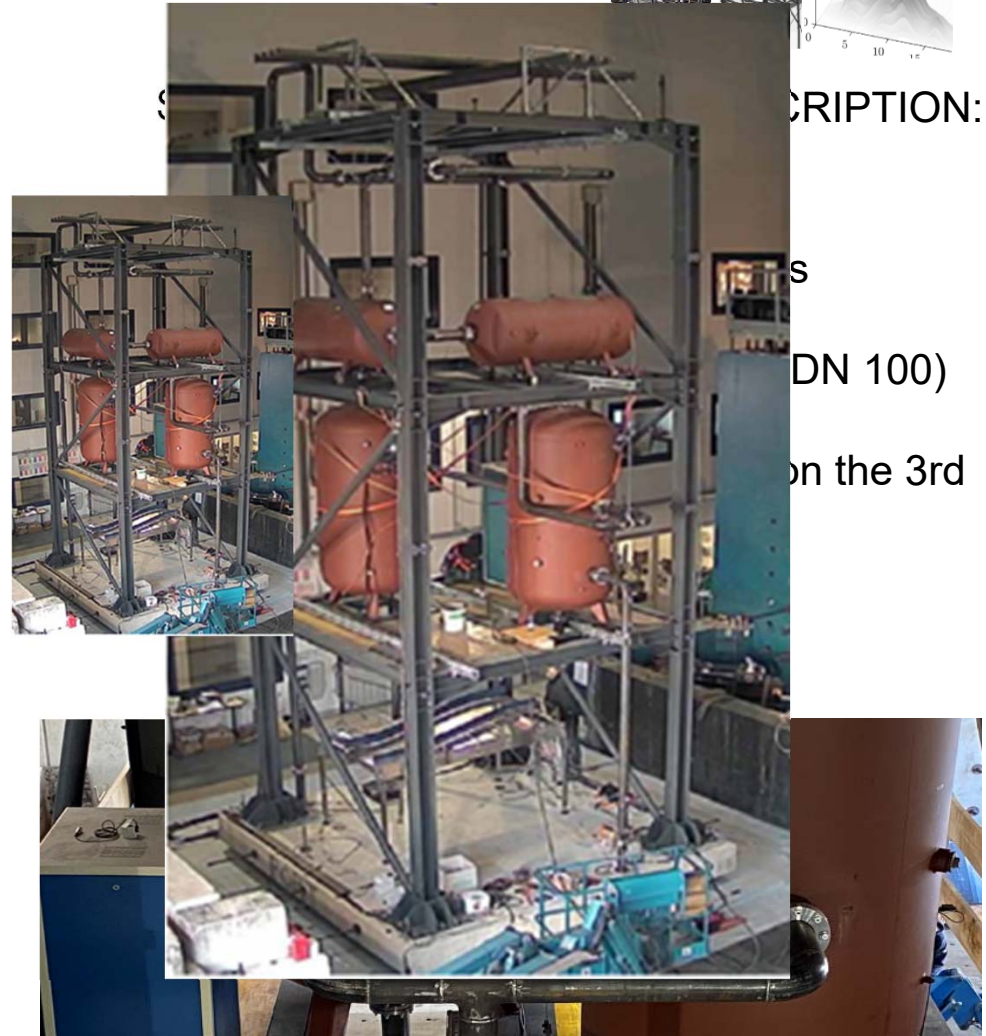


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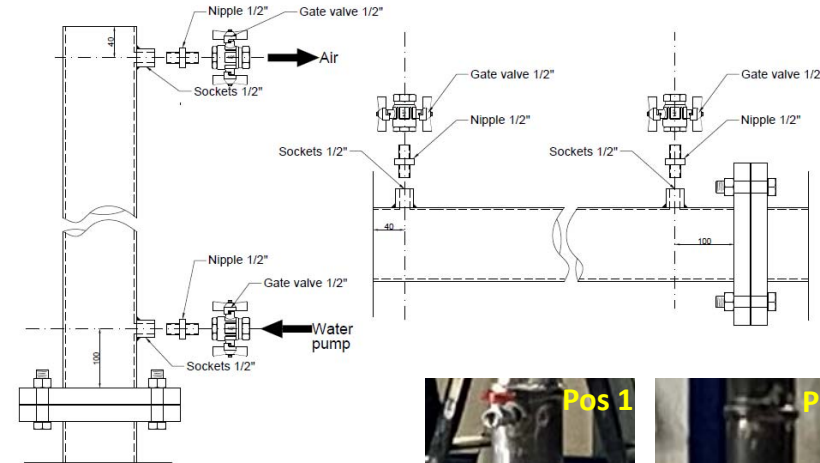
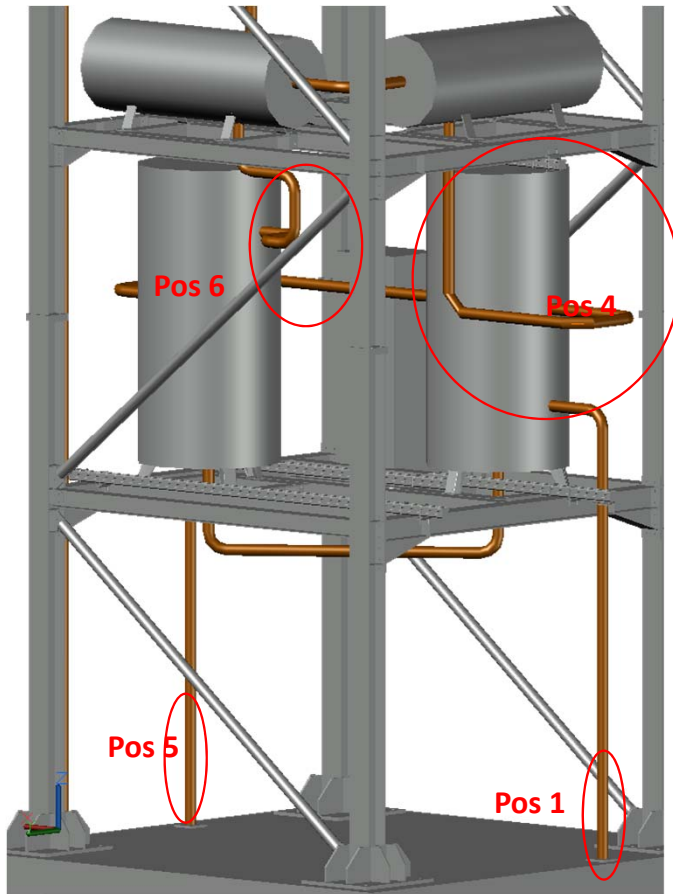


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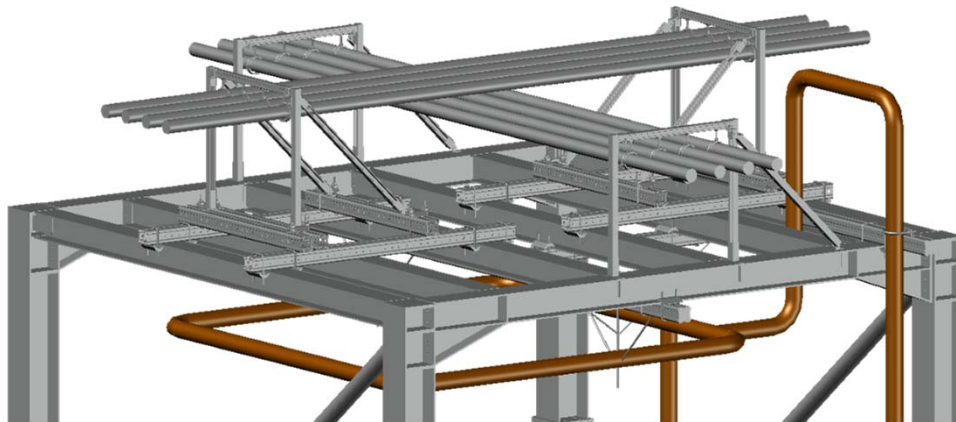
- DN 100)
on the 3rd



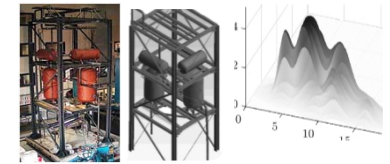
Pumps and valves for pressurization



Suspended pipes, 3rd level

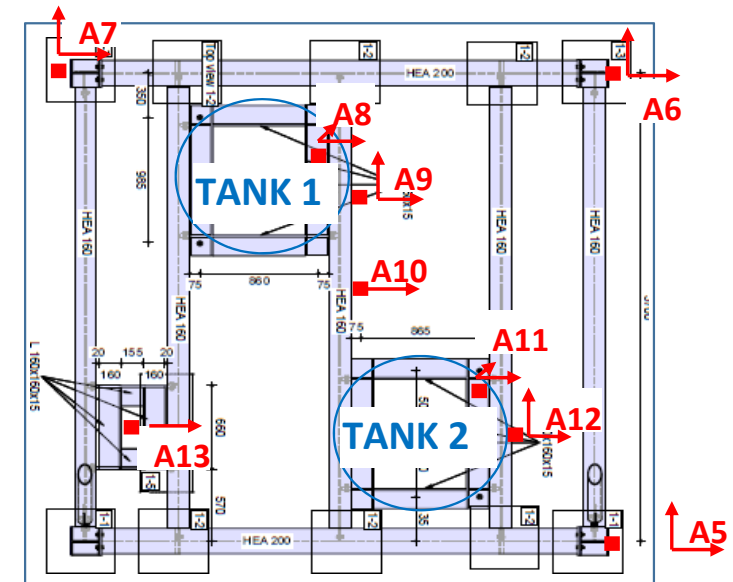
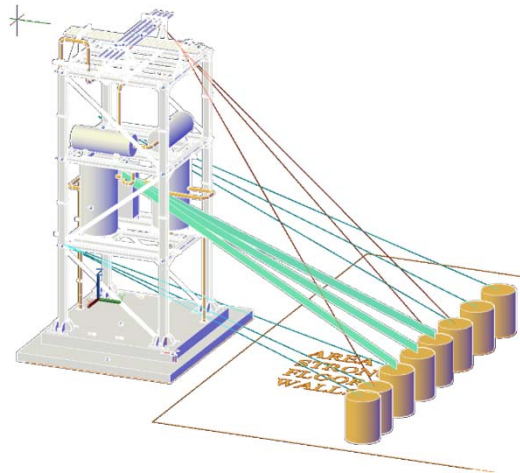
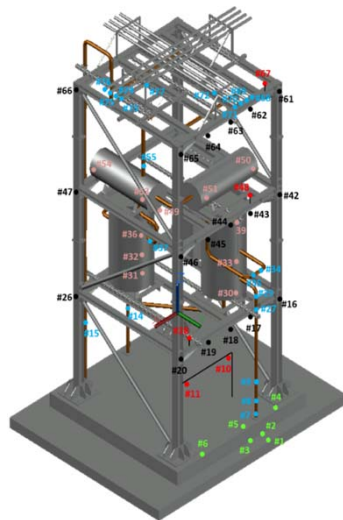


DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGN – SPIF #1

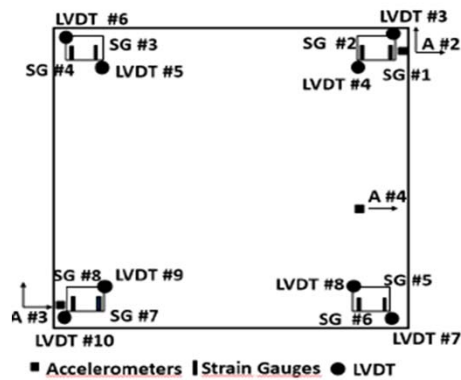
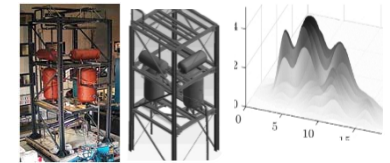


INSTRUMENTATION

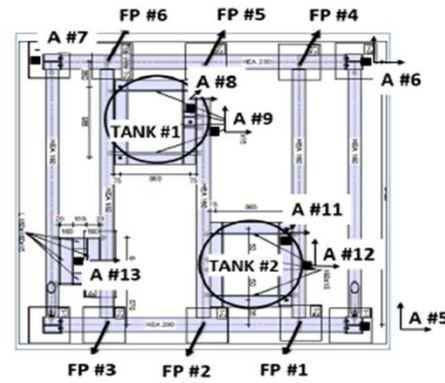
- Acceleration sensors
- Strain gauges
- Displacement transducers
- Fiber sensors
- Optical measurement system



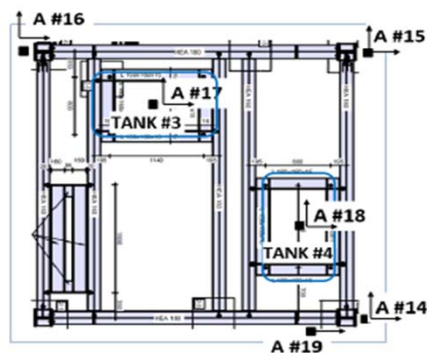
DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGN – SPIF #1



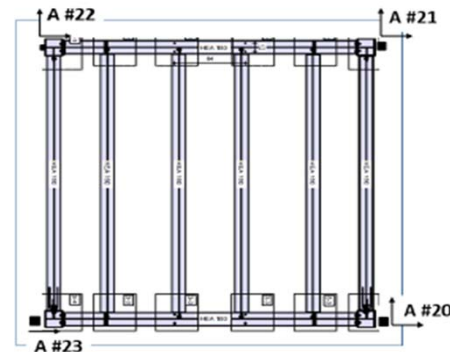
(a) Ground floor



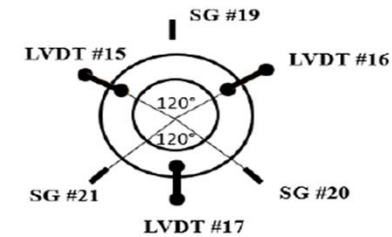
(b) First floor



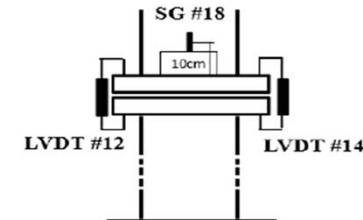
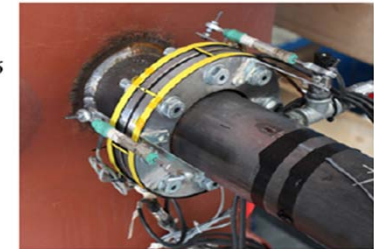
(c) Second floor



(d) Third floor



(a) BFJ Pos #4 - Top and side view

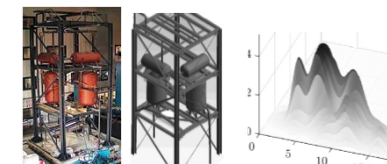


(b) BFJ Pos #1 - Top and side view

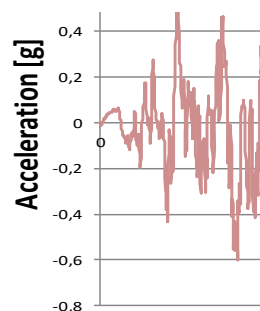
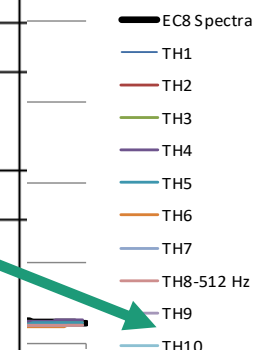


Level	Accelerometer	LVDT	Strain gauges
Floor 0	6	15	12
Floor 1	16	-	-
Floor 2	11	-	-
Floor 3	7	-	-
Roof top	14	4	-
Pipes (Pos. 1, 4, 5, 6)	-	12	12

TEST PROGRAMME AND PRINCIPAL RESULTS – SPIF #1

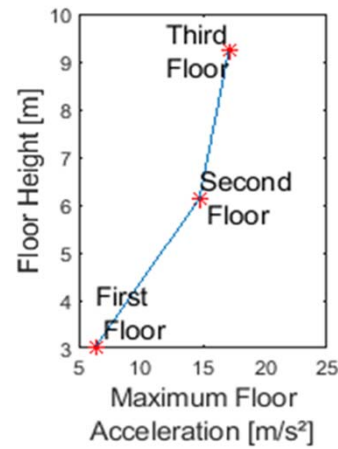
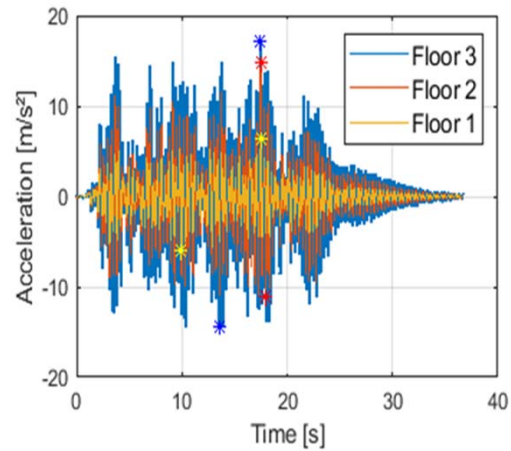
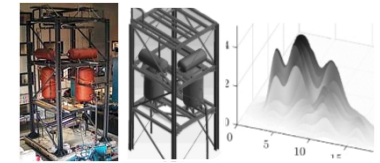


RUN	PGA Level	OBSERVATION
TH8_25%	0.159g	- Overall elastic behaviour
TH8_37%	0.235g	- Overall elastic behaviour
TH8_50%	0.318g	- Overall elastic behaviour - Some drops in pressure of pipes recovered before the next test
TH8_37%	0.235g	- 3 rd floor: Collapse of pipe rack in the transversal direction
TH8_70%	0.445g	- Large displacements (+/- 30 mm) of vertical Tank 2 at 1 st floor - Relevant rotation of the cross beam under the vertical Tank 2 and warping of the web - Strengthening of the cross beam underneath Tank 2
TH8_100%	0.635g	- Other cross beams experienced cracking
TH8_111%		

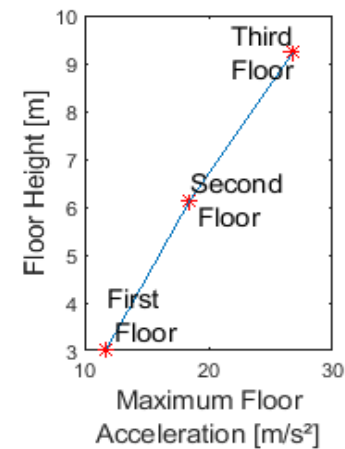
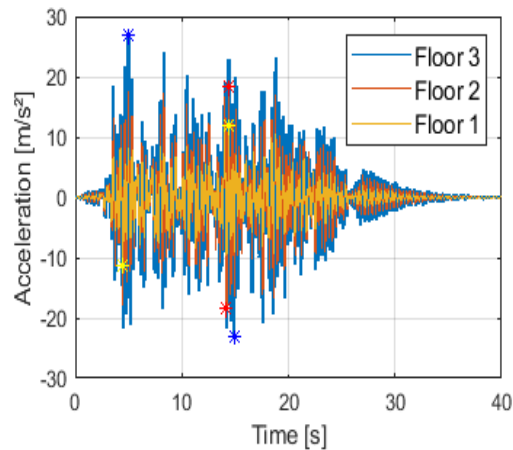
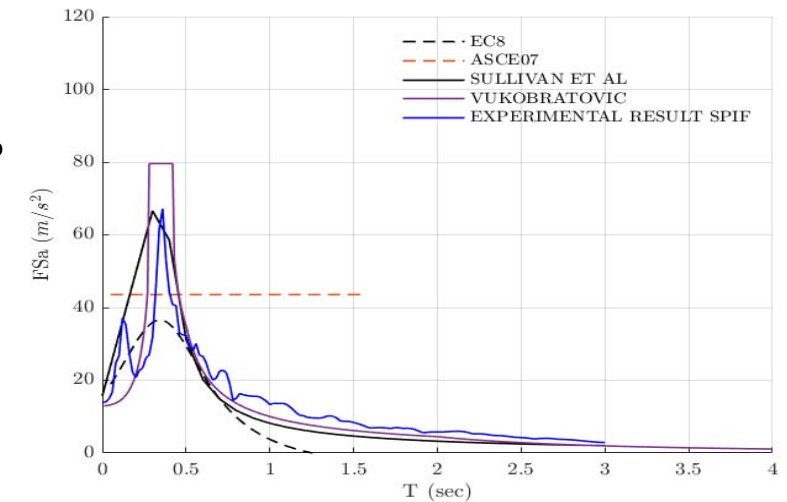


Period T[s]

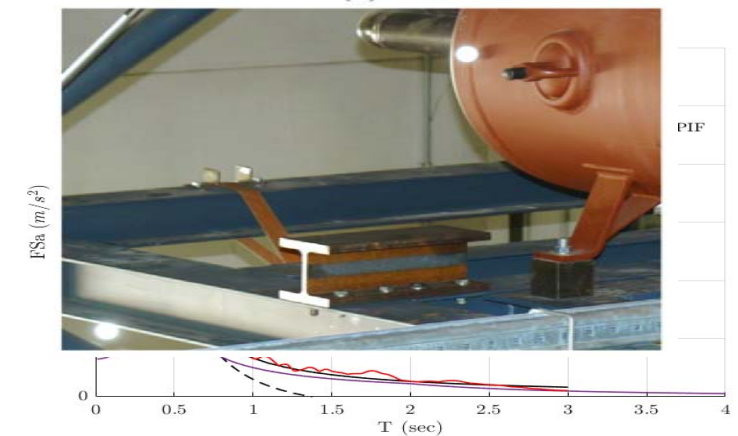
TEST PROGRAMME AND PRINCIPAL RESULTS – SPIF #1



TH 70%

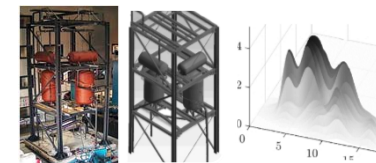
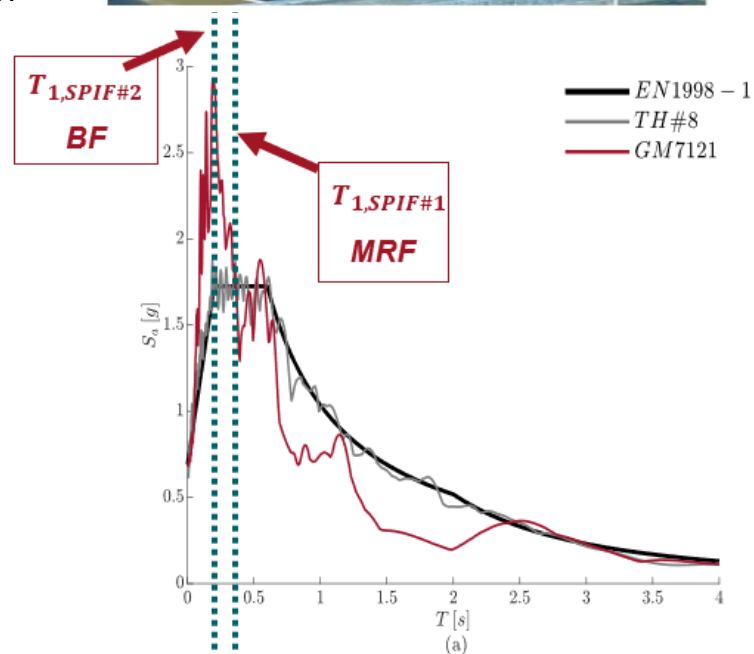
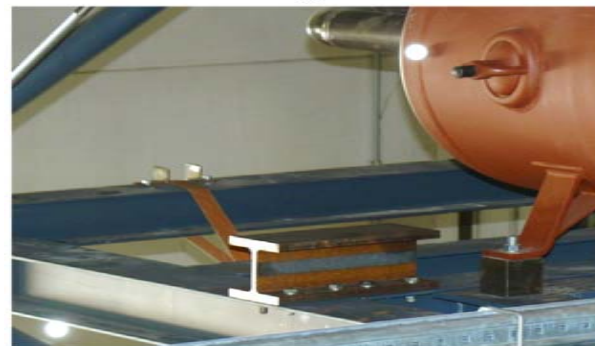


TH 100%

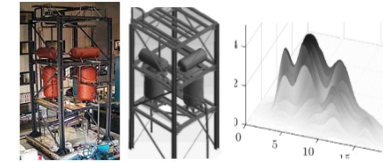


DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGN – SPIF #2

- Three-storey braced steel frame
- Bracing system, it is endowed with circular sections of 24mm diameter and with a non-dimensional slenderness $\lambda = 1.44$, in the direction of the seismic input
- No pipe rack were present at third floor
- Damages of the first test were fixed
- New seismic input



TEST PROGRAMME AND PRINCIPAL RESULTS – SPIF #2



Label	Excitation	Limit State	Scaling Factor [%]	PGA Level [g]	Observations
RND#1	Random	DBE-OP	-	0.08	- Overall elastic linear behaviour
RND#2	Random	DBE-OP	-	0.08	- Overall elastic linear behaviour
GM7121#31%	Seismic	DBE-OP	31	0.22	- Overall elastic linear behaviour
GM7121#38%	Seismic	DBE-DL	38	0.26	- Overall elastic linear behaviour
GM7121#62%	Seismic	DBE-DL	62	0.43	- Relevant rotation of the cross beam under the vertical Tanks #1-#2 - Buckling of SE bracing system at 1 st floor
RND#3	Random	DBE-OP	-	0.08	- Overall elastic linear behaviour
RND#4	Random	DBE-OP	-	0.14	- Overall elastic linear behaviour
GM7121#81%	Seismic	SSE-SD	81	0.56	- Buckling of bracing system at 1 st floor - Severe stresses on bottom wall of Tank #1-#2
RND#5	Random	DBE-OP	-	0.14	- Overall elastic linear behaviour
GM7121#81%-2	Seismic	SSE-SD	81	0.56	- Severe stresses on bottom wall of Tank #1 - Buckling of bracing system at 1 st floor
RND#6	Random	DBE-OP	-	0.14	- Overall elastic linear behaviour
GM7121#93%	Seismic	SSE-SD	93	0.64	- Relevant rotation of the cross beam under the vertical Tanks #1-#2 - Buckling of bracing system at 1 st floor - SG #7 plasticization at bottom wall of Tank #2
RND#7	Random	DBE-OP	-	0.14	- Overall elastic linear behaviour
GM7121#100%	Seismic	SSE-NC	100	0.69	- Significant displacement of LVDT at Pipe POS #6 - Buckling of bracing system at 1 st floor - Relevant rotation of the cross beam under the vertical Tank #2 and warping of the web of fin plate FP #1-#2
RND#8	Random	DBE-OP	-	0.14	- Overall elastic linear behaviour
GM7121#115%	Seismic	SSE-NC	115	0.79	- Cracking on previously detail FP #1 and #2 significantly increased - Yielding of LVDT at Pipe POS #6 - Severe stresses on elbow Pipe POS #6 - Buckling of bracing system at 1 st floor
RND#9	Random	DBE-OP	-	0.14	- Overall elastic linear behaviour



TEST PROGRAMME AND PRINCIPAL RESULTS – SPIF #2

Leakage predictions for BFJ

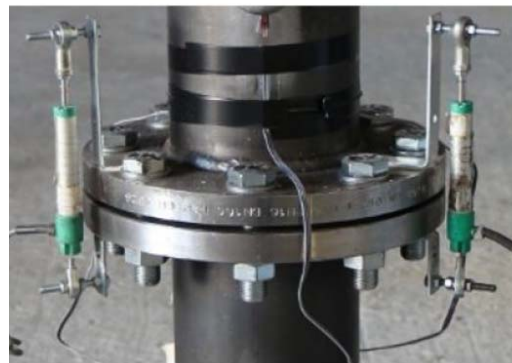
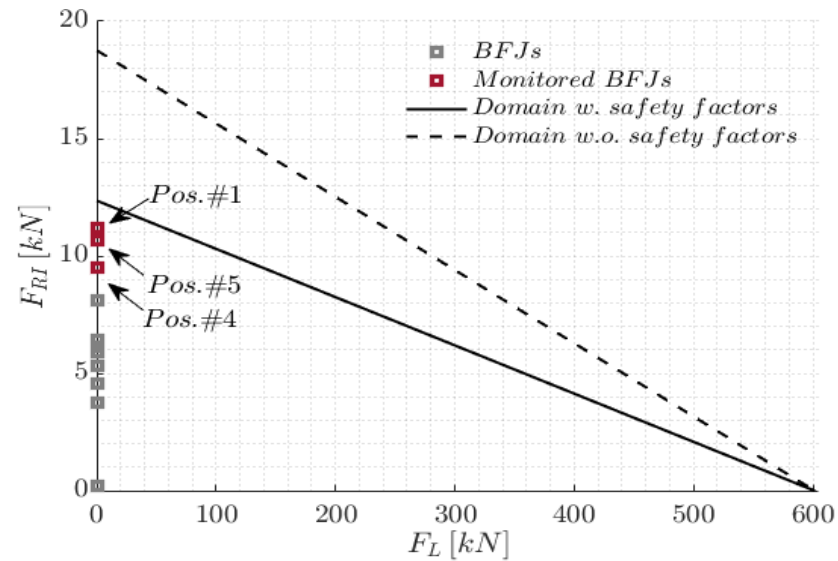


Fig.2 - 2 Leakage predictions for BFJs and interaction domains with and w.o. safety factors for DBE condition.

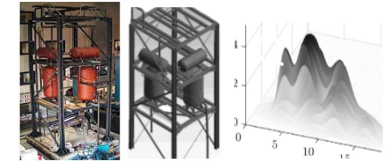
TEST PROGRAMME AND PRINCIPAL RESULTS – SPIF #2

TABLE 1 Limit states and performance objectives for industrial plants.

Limit States	P_{VR}	T_R	PGA	Primary structure			NSC				
				Performance requirement	Performance requirement		Tank	Piping			
DBE	10 %	1200	0.56	All components devoted to to normal operations remain functional. Damage to structure is limited. Structures do not experience permanent drift.	EDP	Performance threshold	Post-earthquake damage state in which the NSCs remain fully functional.	EDP	Performance threshold	EDP	Performance threshold
Design Basis				Storey drift	0.5%		Max tensile local strain	$\epsilon < \epsilon_y$	Tensile strain	$\epsilon_t < \epsilon_y$	
									Compressive strain	$\epsilon_c < \epsilon_y$	
SSE	5%	2475	0.69	Minor yielding or buckling of braces. Transient drift that causes minor nonstructural damage. Negligible permanent drift.	Storey drift	1.5%	Post-earthquake damage state in which NSCs can be damaged, but they allow for a safe closure	Max tensile local strain	$\epsilon_y < \epsilon < 0.5\%$	Tensile strain	$\epsilon_y < \epsilon_t < 0.5\%$
Safe Shutdown									Compressive strain	$\epsilon_y < \epsilon_c < \epsilon_{C_u}$	
										$\epsilon_{C_u} = 0.5 \cdot (t/D) - 0.0025 + 3000 \cdot (\sigma_h/E)^2$	

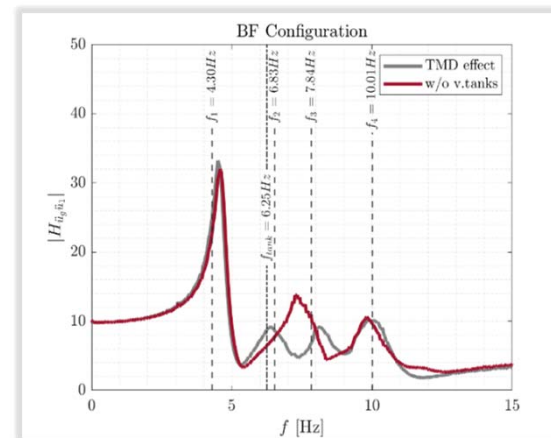
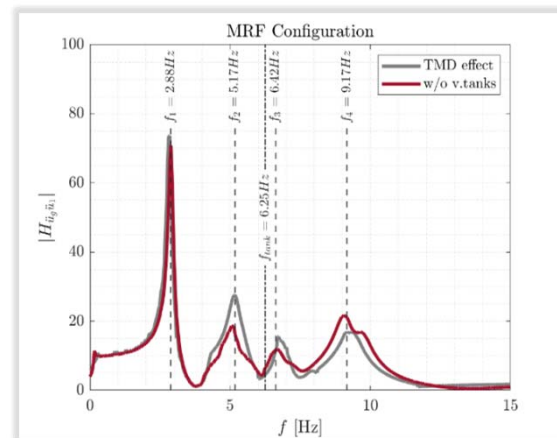
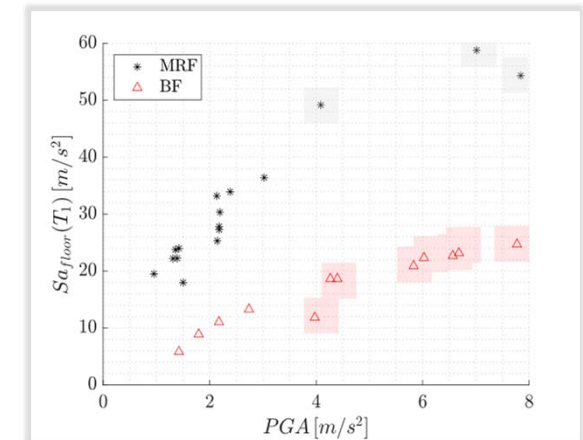
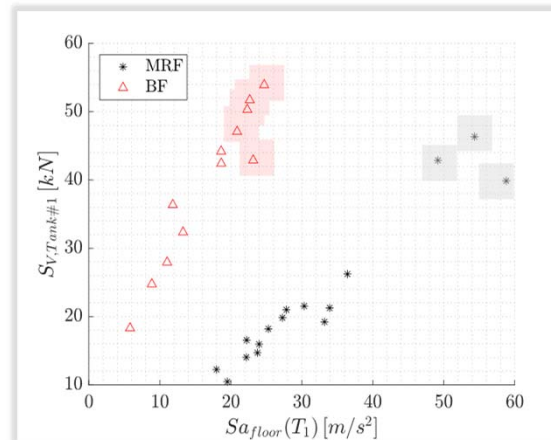
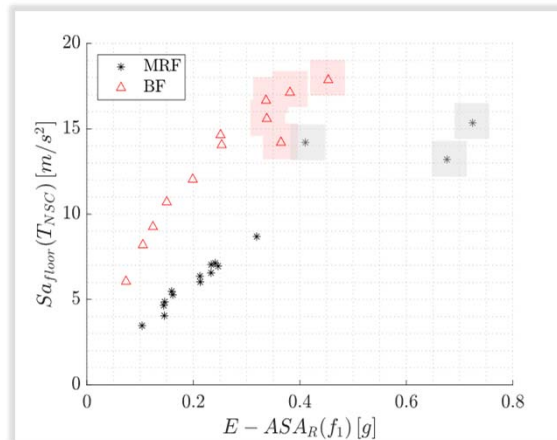
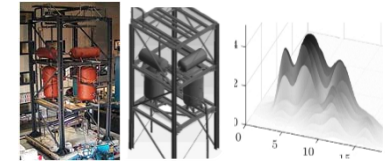
TABLE 8 Experimental EDP values and observed damage.

Limit State	PGA	Primary structure		Tank		NSCs		Piping	
		Observed damage	EDP	Observed damage	EDP	Observed damage	EDP	Observed damage	EDP
DBE	0.56	Minor buckling of the bracing system at the 1 st floor	Storey drift 0.35%	Sever stresses on the bottom wall of Tank #1	Max tensile local strain 0.11%	-	-	Tensile strain 0.08%	0.08%
SSE	0.69	Buckling of the bracing system at the 1 st floor. Warping in fin plate connections FP #1-#2	Storey drift 0.4%	Yielding on the bottom wall of Tank #1	Max tensile local strain 0.18%	Yielding of elbow in Pos. #6	Tensile strain 0.14%	Compressive strain	0.12%
								Compressive strain	0.12%



Vathi M, Karamanos S, Kapogiannis I, Spiliopoulos K. Performance Criteria for Liquid Storage Tanks and Piping Systems Subjected to Seismic Loading. Journal of Pressure Vessel Technology 2017; 139. doi: 10.1115/1.4036916

COMPARISON SPIF #1 - SPIF #2



	Modal Values	
	MRF	BF
Modal frequency [Hz]	6.42	6.83
$m_{coupled}$ [ton]	≈ 0.95	≈ 8.55
$m_{w/o v. Tanks}$ [ton]	≈ 0.59	≈ 2.34
μ_{mod}	0.51	0.82

Table 1 – Modal masses values and ratios.



SUMMARY EXPERIMENTAL TEST CAMPAIGN

SPIF #1– SPIF #2

- Study of the seismic behaviour of two different industrial substructures equipped with technical components by means of a shaking table test
- Dynamic interaction between primary structure and installations shall be considered and the influence of the primary structure has to be taken in account
- Flexible pipe system showed a high robustness
- Rather high amplification of floor accelerations
- The definition of reliable limit states and performance requirements for NSC is a critical open issue to be fixed

REFERENCES

- Butenweg, C., Bursi, O. S., Paolacci, F., Marinković, M., Lanese, I., Nardin, C., & Quinci, G. (2021). Seismic performance of an industrial multi-storey frame structure with process equipment subjected to shake table testing. *Engineering Structures*, 243, 112681.
- Nardin, C., Bursi, O. S., Paolacci, F., Pavese, A., & Quinci, G. (2022). Experimental performance of a multi-storey braced frame structure with non-structural industrial components subjected to synthetic ground motions. *Earthquake Engineering & Structural Dynamics*, 51(9), 2113-2136.
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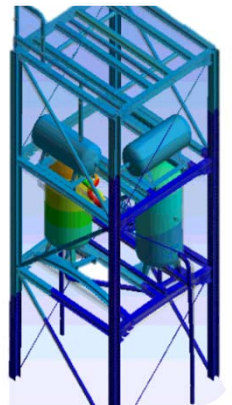


STATE OF ART OF SEISMIC RISK ASSESSMENT OF INDUSTRIAL PLANTS AND THEIR NON-STRUCTURAL COMPONENTS (NSC)

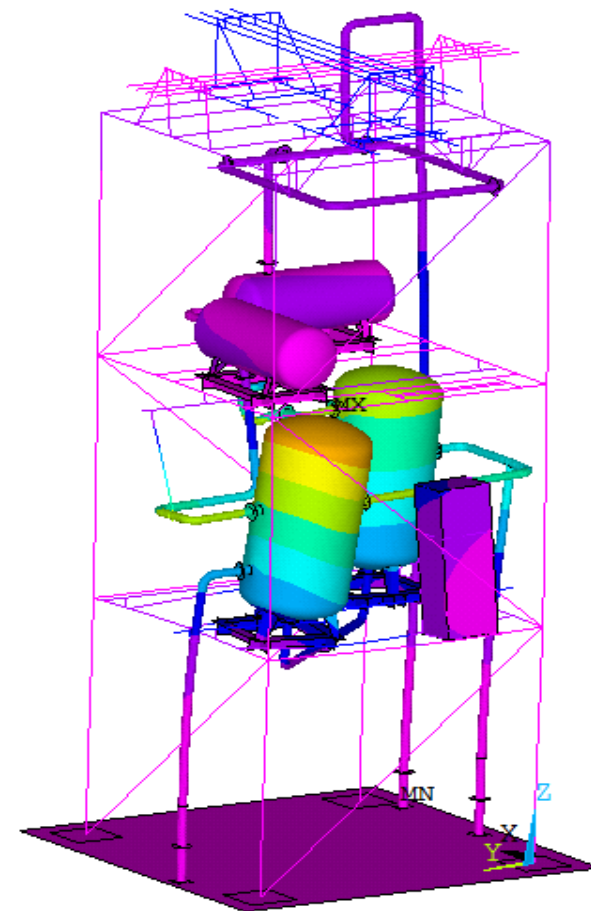
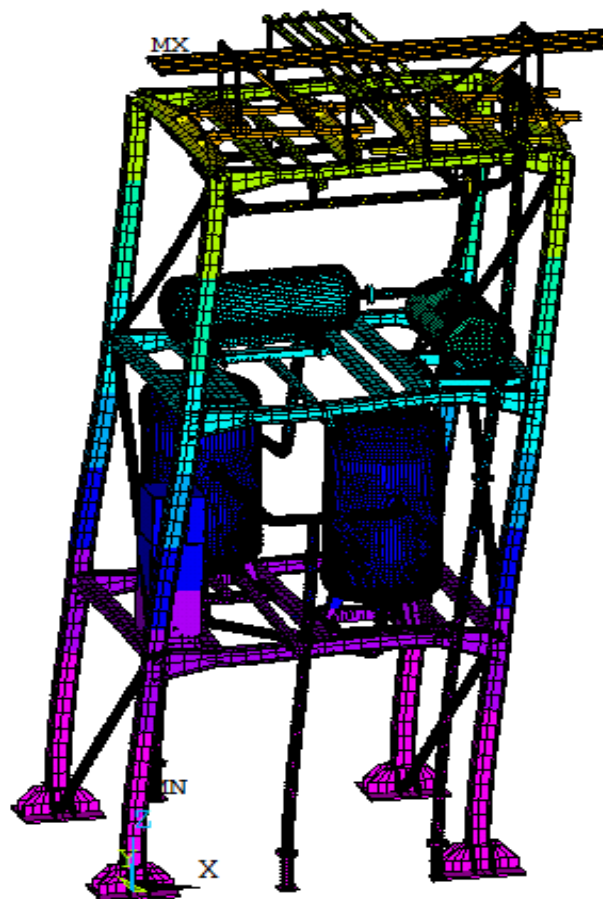
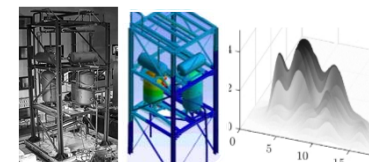
2. **The definition** of reliable and effective **models** of this particular kind of structures. It is necessary, in fact, to develop efficient finite element models that are, on the one hand, (i) **reliable** and, on the other hand, (ii) **accurate** to the point of being able to capture the complex **dynamic interactions** between the main structure and components. In particular, attention must be paid to the computational burden: for a practical seismic risk assessment, a **good trade-off** between **computational weight** and **calculation time** must be found.

RESEARCH PROJECT CONTRIBUTION:

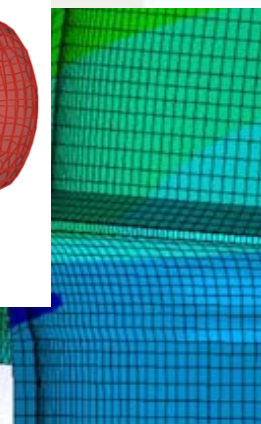
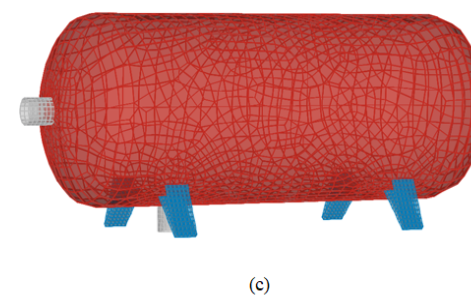
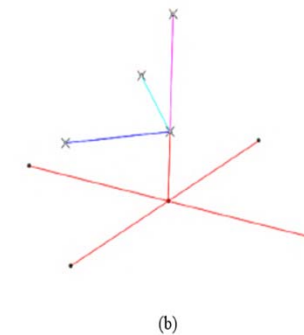
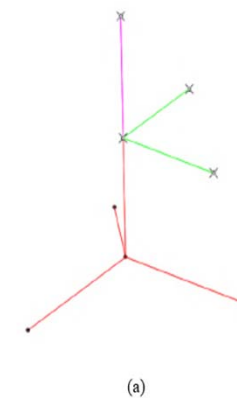
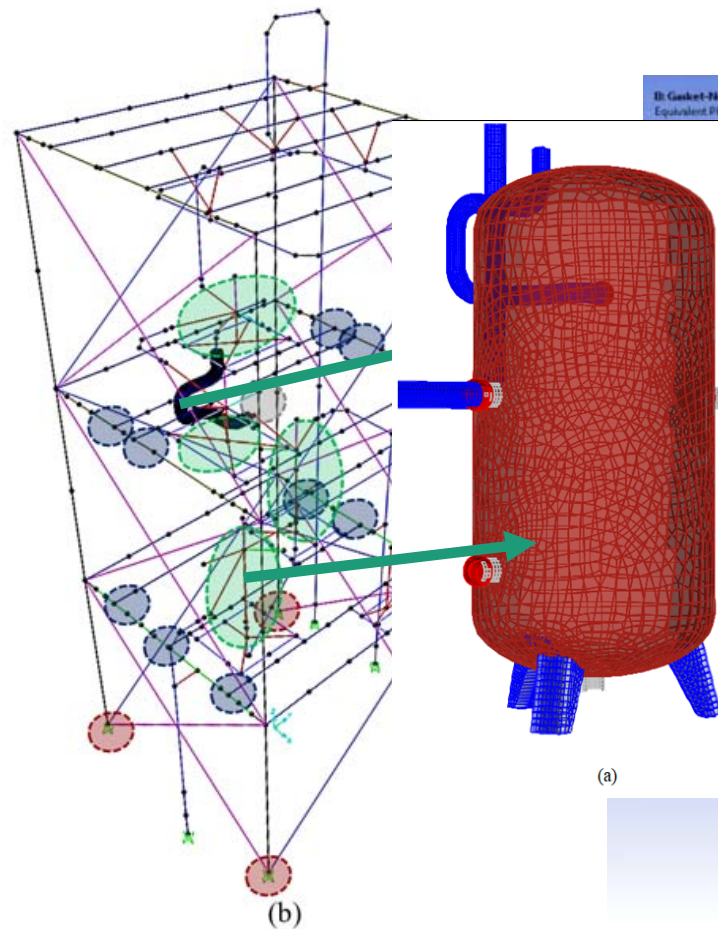
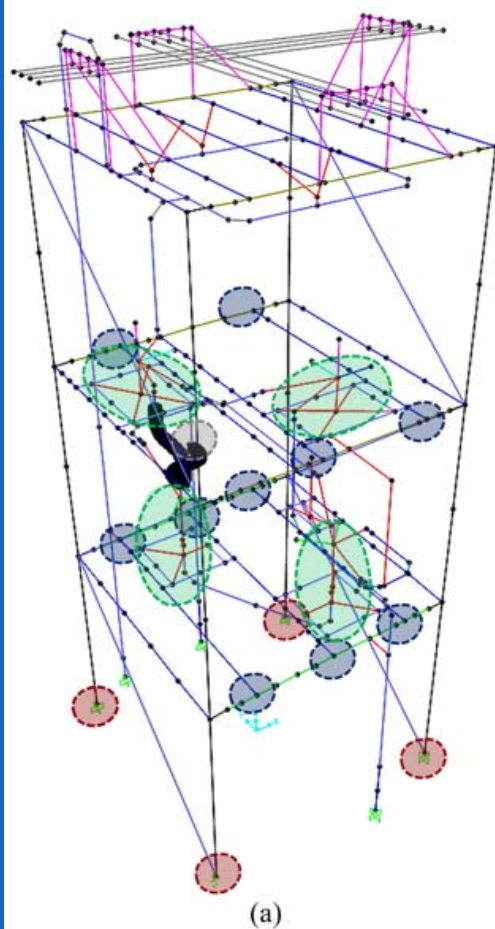
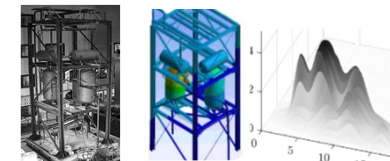
2. **This study** have examined the **design and performances of a 3D FE** model validated against data acquired during shake table tests of the real mock-ups, in order to better analyze issue (2). The rationale behind implementing the models relies on finding an optimum between (i) **accuracy and fidelity** to the experimental data and (ii) the **computational and time burden** required by a single run of the FE model.



REFINED FINITE ELEMENT MODEL



MODELLING DESCRIPTION



MODELLING CALIBRATION AND VALIDATION

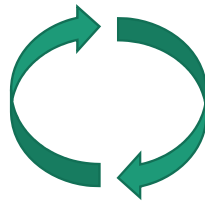
Prior PDF, Parameters

θ_1	Young Modulus	[GPa]	Gaussian, $\mu = 220 - \sigma = 50$
θ_2	Part. mass of v.tanks	[ton/m]	Uniform, $a = 0 - b = 1.22$
θ_3	H. of pressure profile	[m]	Uniform, $a = 0 - b = 1.87$
θ_4	Base Joint stiffness	[MNm/rad]	Gaussian, $\mu = 22.5 - \sigma = 5$

Posterior PDF, Parameters

Gaussian, $\mu = 219 - \sigma = 30$
 Gaussian, $\mu = 0.85 - \sigma = 0.55$
 Gaussian, $\mu = 0.35 - \sigma = 0.1$
 Gaussian, $\mu = 28.5 - \sigma = 4.5$

ITERATION

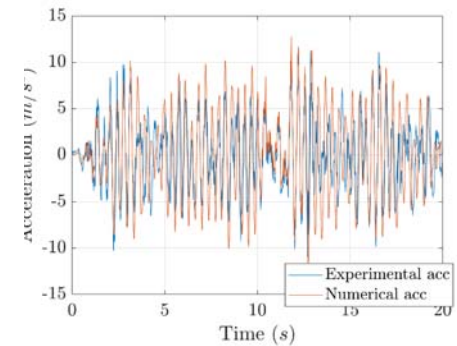
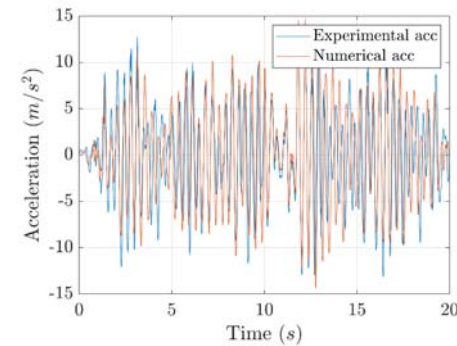


	Numerical [Hz]	Experimental [Hz]	$\Delta\%$ [-]
f_1	2.81	2.88	2
f_2	4.84	4.24	-14
f_3	6.73	6.38	-5
f_4	9.18	8.95	-3

(a) MRF updated frequencies.

	Numerical [Hz]	Experimental [Hz]	$\Delta\%$ [-]
f_1	4.54	4.50	-1
f_2	6.36	6.83	7
f_3	7.94	7.84	-1
f_4	9.91	10.04	1

(b) BF updated frequencies.



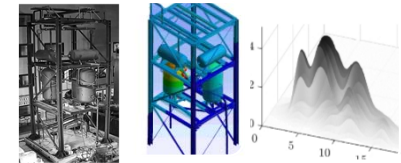
$$NEE(x_n, x_e) = \frac{\sum_{i=1}^n x_{n,i}^2 - \sum_{i=1}^n x_{n,e}^2}{\sum_{i=1}^n x_{n,e}^2}$$

MRF	
NEE	
Tank#2 acc	0.0748
Tank#2 acc	0.0653

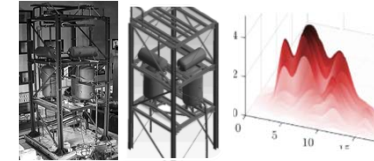
(a) MRF configuration

BF	
NEE	
Tank#1 acc	0.0505
Tank#2 acc	0.0702

(b) BF configuration



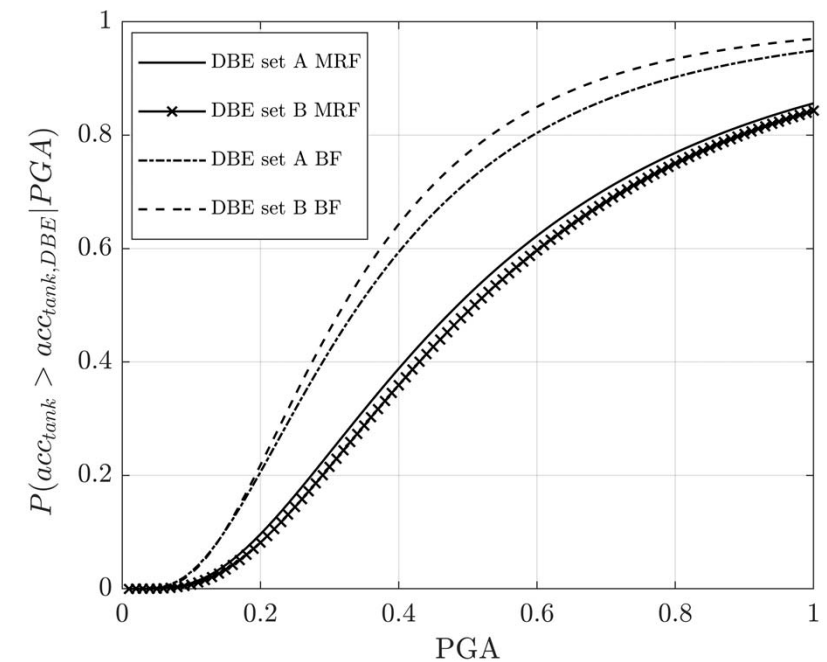
FRAGILITY ANALYSIS



Limit state	Failure mode	Max tensile local strain (ε_T)	Max tank acc ($S_a[T]$)
DBE	Base plate fracture	$\varepsilon_y < \varepsilon_T \leq 0.5\%$	10 m/sec^2
SSE	Base plate fracture	$0.5\% < \varepsilon_T \leq \varepsilon_{TU}$	16 m/sec^2

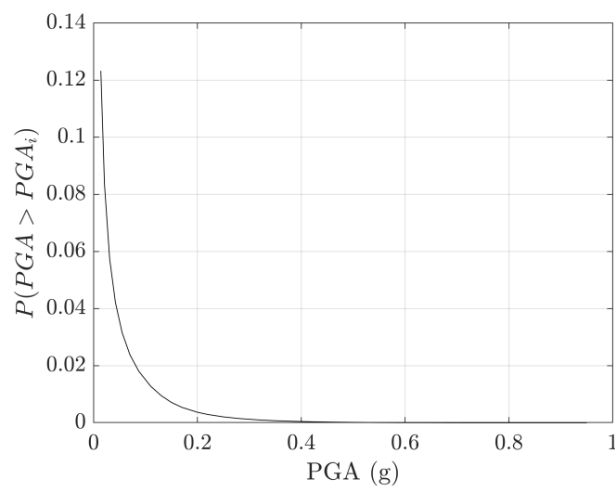
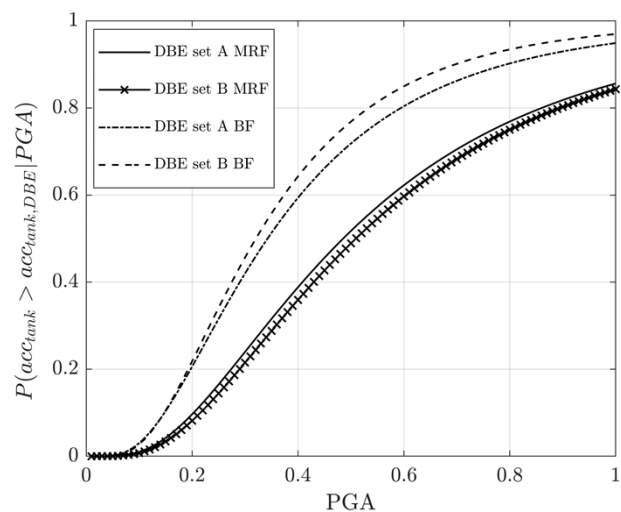
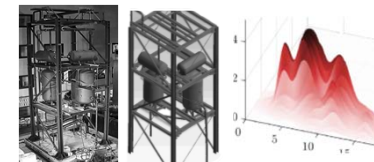
$$P(D|IM = y) = \Phi\left(\frac{\log(y/\theta)}{\beta}\right)$$

FRAGILITY CURVE



RISK ANALYSIS

$$\lambda(D) = \int P(D|IM=y) |d\lambda(y)|$$



DBE		
	Set A	Set B
MRF	0.00027	0.00024
BF	0.00054	0.00053

SSE		
	Set A	Set B
MRF	0.00012	0.00014
BF	0.00013	0.00015



SUMMARY EXPERIMENTAL TEST CAMPAIGN

SPIF #1– SPIF #2

- The importance of taking secondary elements into account when modelling industrial plants
- The importance of obtaining reliable, yet efficient numerical models that allows a certain number of simulations to carry out risk assessment
- The possibility of obtaining hybrid models calibrated to more refined local models

REFERENCES

Quinci, G., Nardin, C., Paolacci, F., & Bursi, O. S. (2023). Modelling of non-structural components of an industrial multi-storey frame for seismic risk assessment. *Bulletin of Earthquake Engineering*, 21(13), 6065-6089.



CONCLUSIONS AND FURTHER DEVELOPMENT

- **Analysis** of the existing **seismic risk** assessment **methodologies** for industrial plants, individuating the relative **open issues**.
- **Development** of a wide **experimental test campaign** on **industrial facilities** and their secondary elements, in order to better understand the **structural behavior** of this kind of complex structures and evaluate reference **limit states** and relative **threshold**.
- **Study** of a **simplified FEM** calibrated and validated on the base of experimental results to carry out **efficiently structural analysis**.
- **Development** of a **Machine Learning** based **framework** for **the risk assessment** of industrial structures and equipment

FUTURE RESEARCH

- **Integrate** within the **ML based framework** the ability to update the **ANN** surrogate model with **data** coming from the **Structural Health Monitoring**, in order that **up-to-date risk assessment** are always **available**, considering the effective **health condition** of the **structure**.



GRAZIE PER L'ATTENZIONE



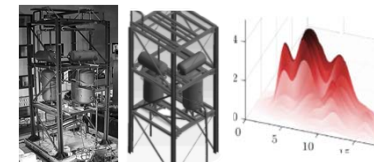
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AN INTERESTING ALTERNATIVE – MACHINE LEARNING TECHNIQUES



ANN-2 classification model to generate damage events

ANN-1 Regression model for the generation of the components of the Vector-Valued IM

$$\frac{\text{n. damage events}}{\text{n. Total events}}$$

Mean annual frequency of occurrence of damage

