SEISMIC PERFORMANC OF MULTIPLE-COMPONENT SYSTEMS IN SPECIAL RISK INDUSTRIAL FACILITIES

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Abstract

Past earthquakes demonstrated the high vulnerability of industrial facilities equipped with complex process technologies leading to serious damage of the process equipment and multiple and simultaneous release of hazardous substances in industrial facilities. Nevertheless, the design of industrial plants is inadequately described in recent codes and guidelines, as they do not consider the dynamic interaction between the structure and the installations and thus the effect of seismic response of the installations on the response of the structure and vice versa. The current code-based approach for the seismic design of industrial facilities is considered not enough for ensure proper safety conditions against exceptional event entailing loss of content and related consequences. Accordingly, SPIF project (Seismic Performance of Multi-Component Systems in Special Risk Industrial Facilities) was proposed within the framework of the European H2020 - SERA funding scheme (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe). The objective of the SPIF project is the investigation of the seismic behavior of a representative industrial structure equipped with complex process technology by means of shaking table tests. The test structure is a three-story moment resisting steel frame with vertical and horizontal vessels and cabinets, arranged on the three levels and connected by pipes. The dynamic behavior of the test structure and installations is investigated with and without base isolation. Furthermore, both firmly anchored and isolated components are taken into account to compare their dynamic behavior and interactions with each other. Artificial and synthetic ground motions are applied to study the seismic response at different PGA levels. After each test, dynamic identification measurements are carried out to characterize the system condition. The contribution presents the numerical simulations to calibrate the tests on the prototype, the experimental setup of the investigated structure and installations, selected measurement data and finally describes preliminary experimental results.

Keywords: industrial facilities; piping; installations; seismic loading; earthquakes; shaking-table

1. Introduction

The impact of a natural disaster on a facility storing or processing dangerous substances can result in the release of those hazardous substances with possible severe off-site consequences through toxic-release, fire or explosion scenarios. Accidents triggered by a natural hazard, involving release of dangerous substances are commonly referred to as Na-Tech events. These include releases from fixed chemical installations and spills from oil and gas pipelines. One of the main issues of Na-Tech accidents is the simultaneous occurrence of a natural disaster and a technological accident; both require simultaneous efforts in dealing with a situation in which lifelines designed for a disaster mitigation are likely unavailable, as they may have been damaged by the natural disaster. Na-Tech events derives from the interaction between industrial and natural hazards. In

particular, earthquakes have been recognized as one of the most disruptive natural hazard, as demonstrated by many past earthquake, which raised public concern because of the general unpreparedness of the countries in predicting effects and consequences in the aftermath of a disaster [1, 2].
The objective of this work is to investigate the seismic behavior of industrial plants equipped with complex process technology by means of shaking table tests. In fact, past earthquakes have shown that critical interactions can occur in these plants between the primary (frame) and secondary structures (equipment), but also between single units. The structural or process-related interactions can lead to serious secondary damages which, in addition to business interruption, can provoke human losses and environmental damages in case of hazardous material release. In this paper both numerical analysis and preliminary test results will be presented and discussed.

2. Description of the case study

The primary steel structure of the prototype is a three-storey moment resisting frame with flexible diaphragm, with dimension 3.7 x 3.7 m in the horizontal plane and interstory height of 3.1 m for a total of 9.3 m. Fig.1 shows an image of the structure on the shaking tables at EUCENTRE laboratory. The frame is simply supported on a reinforced concrete base plate and crossbeams are hinged to the frame beams.
In total four tanks are installed: two vertical tanks on the first level and two horizontal tanks on the second level (Fig. 3a). Furthermore, one electrical cabinet is placed on the first level. The piping layout is composed by DN 100 pipes, except the one suspended at the third level, which is composed by DN 80 elements. The pipe branches with the most critical bolted flange joints are filled with water and pressurized at 20 bars. Storage tanks re instead filled with aggregates to avoid to release of water on the shaking table. In addition, small single degree of freedom (SDOF) oscillators are installed on each of the three levels to investigate the structure component interaction for different periods in the linear and non-linear range. The steel columns are welded on steel base plates, which are anchored to the reinforced concrete slab using special anchors. This configuration allowed to investigate both isolated and non-isolated configuration. In fact, in the latter case the isolators can be deactivated and the horizontal movement of the table transferred directly to the test frame.

Fig.1 – The frame structure on the table.


Fig. 2 – Marker of the vision system for the displacement measurement

3. Design of the experimental test

The primary structure has been designed in order to remain elastic during all the tests, while the secondary elements (pipes and storage tanks) are designed to reach, for increasing level of seismic intensity, both the design basis earthquake (OBE) and the safe shutdown earthquake (SSE) conditions, as typical design prescriptions for industrial components [3].

3.1 Test system

The first set of simulation tests are executed on the isolated structure first, while the second set are executed on the non-isolated configuration. In each configuration, after tuning the shaking table, input signals will be launched and then scaled with coefficient γ_I, reported in Tab.~(1), related to the probability of exceeding the seismic action, P_L, in T_L, years other than the reference probability of exceedance P_{LR}, over the same T_L, years $\gamma_I = (P_L/P_{LR})^{-1/k}$, as reported in Tab.(2) according to Italian codes [4].

Table 1: probability of exceedance according to Italian code (NTC18)

Probability of Exceedance NTC18: 3.2.1		
OP	81%	Fully Operational
DL	63%	Damage Limit
SD	10%	Significant Damage
NC	2,5%	Near Collpase

Table 2: Coefficient γ_I for scaling input signal

	NC	SD	DL	OP	units
γ_I	1,000	0,625	0,541	0,498	[-]
a_{gR}	0,690	0,431	0,233	0,215	[g]

In the isolated configuration, both spectrum compatible acclerograms and natural records will be used. The firts have been selected assuming a nominal life 50 years, a soil type C –T1, a damping 5%, a peak ground acceleration: a_{gR}=0.69g and an importance class II.
These accelerograms are eventually assigned to both the configuration setup, i.e. structure with and without base isolation, with the 4 aforementioned different scale factors related to separated limit states. Finally, on the non-isolated configuration setup, in order to induce damage or collapse in previous analyzed components, as for example leakage in selected flanges or collapse of vessel's footing, seismic records from ground motion model, see [**Fehler! Textmarke nicht definiert.**], are selected, thanks to the high variability of the ensemble site-characteristic generated, and assigned to the test structure.

3.2 Instrumentation

During the test campaign, different signals are measured to characterize the dynamic behavior of the system. In particular, 38 uniaxial accelerometers are placed, both in X and Y direction and on each floor, in order to analyzed the frequency response of the prototype. In particular, 12 accelerometers have been applied to the 4 tanks to study the behavior of the vessels. Moreover, 16 LVDTs and 8 strain gauges have been used to study the response of the steel frame structure and pipe flanges (Fig.3b). A vison system with markers has been used to measure the displacements of some points of the primary and secondary structures (Fig 2). Finally, a new system of FBG fiber optic sensors have been installed in critical flanges in order to detect possible loss of containment events (Fig. 3c).

(a) (b) (c)

Fig.3 - System of sensors applied to the test structure, with particular reference to LVDT sensors (a,b) and FBG fiber optics (c) applied to critical flanges.

4. Numerical analysis

A numerical investigation has been carried out in order to simulate the behavior of the primary structure and secondary elements during the test. A FEM model has been built with Midas Gen and a modal analysis and a non-linear time history analysis have been performed.

4.1 Description of the FEM model

The primary structure is composed of steel columns and beams (Fig. 4). These elements have been modeled as beam FE elements with fiber sections.

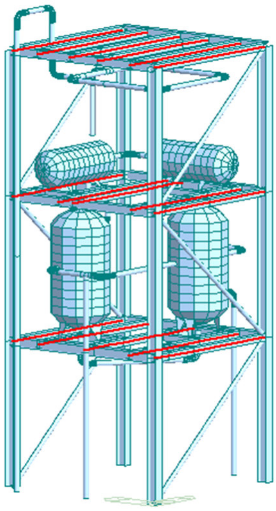


Fig. 4 - Finite element model

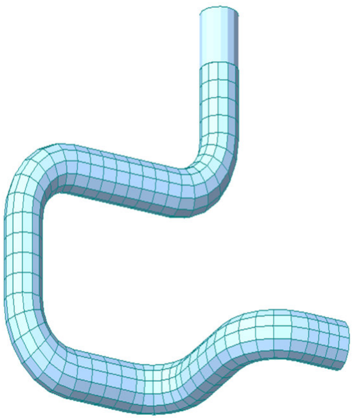


Fig. 5 Pipe model

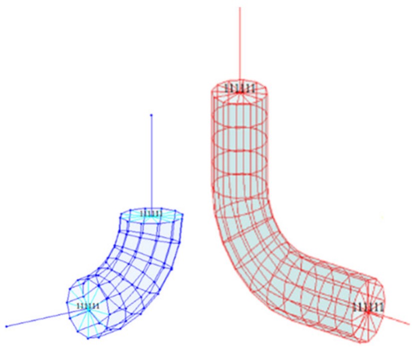


Fig. 6 Elbows modeling

Columns are fixed at the base and rigidly connected to the primary beams. The simply supported secondary beams (red element in Fig. 4) are used to sustain tanks as well as the other live loads. No floor diaphragm constraint is adopted.

Tanks are modelled with shell elements. The liquid inside the tanks is simulated using lumped masses rigidly connected to the nodes of shell elements. Piping system is mainly composed of straight segments, elbows and tees joints (Fig. 5). The first one are modelled by linear elastic beam elements with hollow section of diameter 114.3 mm and thickness of 3 mm. Elbows are modelled using shell elements with a thickness of 3 mm. Elbows are linked to the piping system with rigid links, as shown in Fig. 6. This approach is appropriate to account for roundness of the section. In order to better simulate the boundary conditions a portion of the connected straight pipes of length 1.5 D is modelled using shell elements as well, where D is the diameter of the pipe [3].

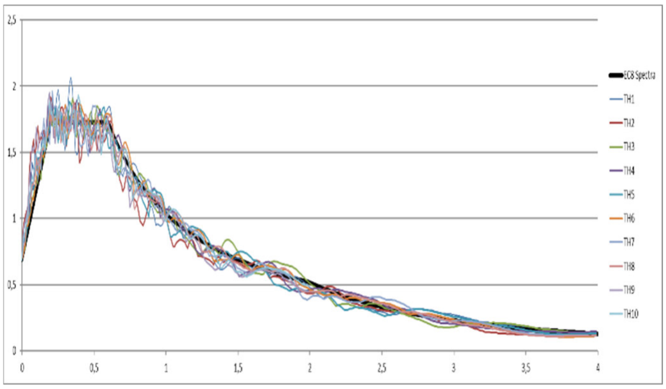


Fig. 6 - Median spectrum of the artificial accelerograms

4.2 Seismic actions and analysis methods

A set of 10 artificial accelerograms is selected in order to design the main structure in the elastic range and to observe the effects on the secondary element as tanks, piping system ecc. This records are depicted in Fig. 6 where it also shown the relative median spectrum.

A modal analysis has been computed on the FE model, using Lanczos method. This method uses Tridiagonal Matrix to perform eigenvalue analysis and it is recommended when performing the analysis for lower modes. The number of natural frequencies to be computed is twelve. In addition, a nonlinear time history analysis is carried out to study the behavior of the system under a given accelerogram. The method used for the time history analysis (TH) is the direct integration. The time increment of a time history analysis with direct integration significantly affects the accuracy of the analysis results. In this analysis, the time increment is set to 0.004 second, according to the rule of thumb of 1/100 of the first eigenmode period. To take in account the non-linearity behavior of the system each beam element's cross-section is divided into small fibers and each fiber cell within the cross-section retains a nonlinear Stress-Strain relationship.

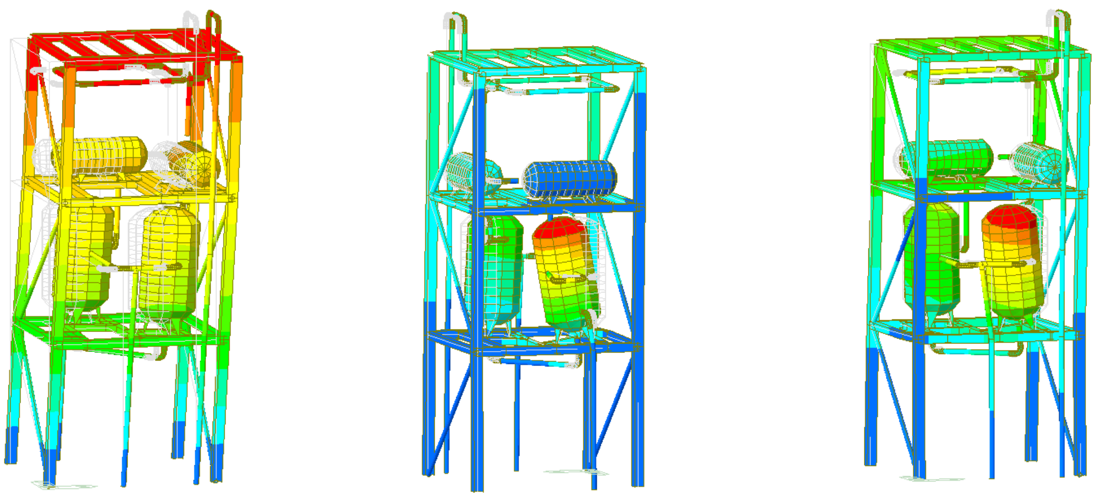
5. Numerical Analysis Results

5.1 Modal Analysis results

The modal analysis results have shown a fundamental frequency of 2.9 Hz with more than 90% of the total mass in X direction (direction of the seismic test). In Table 3 the frequencies of first twelve eigenvalues are reported along with the participating mass. The eigenmodes higher than the first can be considered as local vibrations, which activate only a low percentage of mass. For example, the second eigenmode represents the vibration of one of the tanks at the first floor. These local vibrations can represents important informations about the behavior of secondary elements and fittings, as flange joints between pipes and tanks. Fig. 7 shows the first four vibration modes.

Table 3: Eigenvalues and participating mass

EIGENVALUES			PARTICIPATING MASS			
Mode Num.	Frequency (Hz)	Period (sec)	TRAN-X MASS (%)	SUM (%)	TRAN-Y MASS (%)	SUM (%)
1	2.905	0.344	90.3	90.3	0.1	0.1
2	4.043	0.247	1.0	91.3	1.1	1.2
3	4.500	0.222	0.7	92.0	27.2	28.4
4	5.353	0.187	2.8	94.8	42.8	71.1
5	5.747	0.174	0.0	94.8	0.9	72.0
6	6.004	0.167	0.0	94.8	0.5	72.5
7	8.119	0.123	0.1	95.0	20.1	92.6
8	9.873	0.101	0.3	95.3	0.1	92.7
9	10.599	0.094	0.1	95.4	0.9	93.6
10	12.036	0.083	0.5	95.9	0.1	93.7
11	12.635	0.079	0.1	96.0	0.1	93.7
12	13.085	0.076	2.4	98.4	0.1	93.9

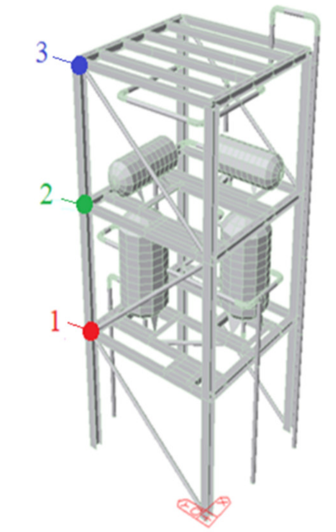


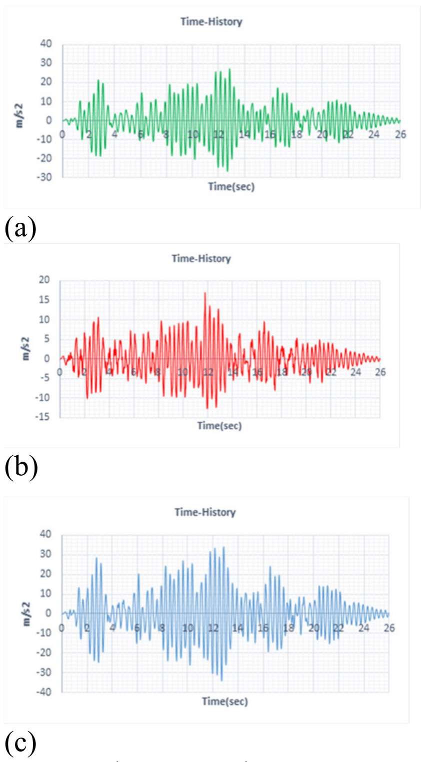
(a) (b) (c)

Fig. 7 – Vibration modes of the structure: (a) 1st, (b) 2nd, c) 3rd

5.1 Non-linear time history analysis results

The time-History results, in terms of acceleration at each floor, are shown in Fig. 8. They demonstrate that the primary steel structure remains in the elastic field in accordance with the design conditions, while the non-structural elements shows some important stress level. In the straight pipes that connect the vertical tanks at first floor and the ground, the tee-joint and the elbow are expected to yield as shown in Fig. 9. Finally, the pipes that connect the tanks at first floor with the second floor tanks peak of stress are observed due to relative motion between vertical tanks and the steel structure as observed in the 3rd and 4th vibration mode.





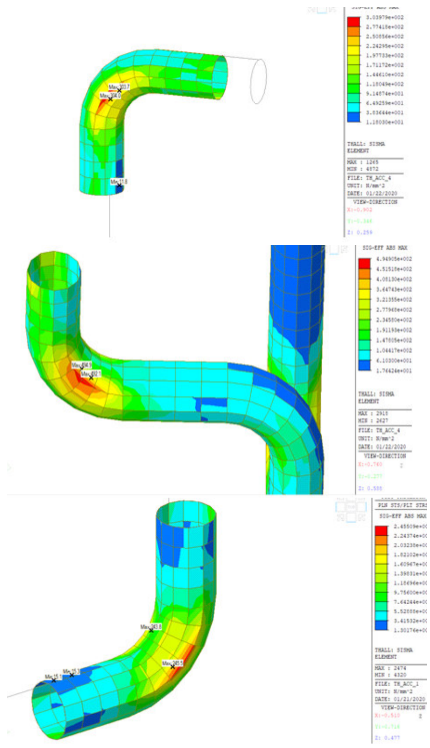


Fig. 8 – Acceleration at 1st (a), 2nd (b) and 3rd (c) floor

Fig. 9 – Stress level on elbows

6. Dynamic identification through experimental test

The experimental test are currently under execution and therefore only preliminary results can be reported in this paper. In particular, the dynamic identification of the structure has been performed by using a random test, whose results in terms of FFT and transfer function of the acceleration at first floor are illustrated in Fig. 9 and 10. In particular it is possible to clearly identify the fundamental frequency at about 2.9 Hz as predicted in table.

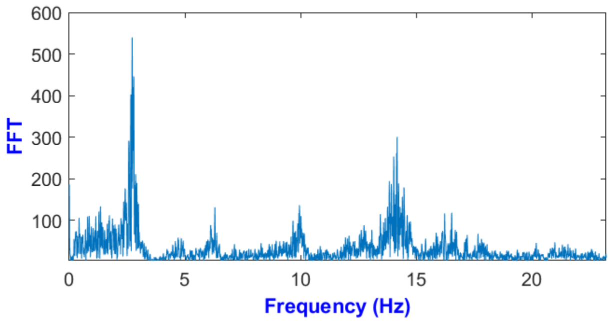


Fig. 9 Fast Fourier Transform of the acceleration at first floor

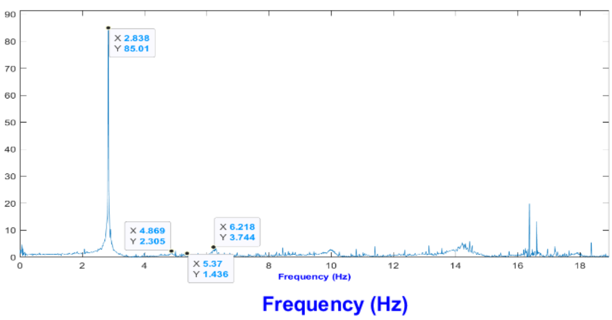


Fig. 10 Transfer function of the acceleration at first floor

Other relevant frequencies are also identified as shown in Fig. 10. In fact, it is easy to recognize the 3rd (3.8 Hz) the 4th (5.37 Hz) and the 6th (6.2 Hz) vibration mode that are not highly excited. This confirm that secondary structure are usually difficult to stress, unless to have relevant differential displacements, typically generated by structures of part of the same structure with different deformability. In any case, a certain deformability is expected by the secondary elements, especially in the vertical tanks that could induce a certain level of stress in the flange joints. This will be analyzed during the seismic tests.

7. Conclusion

The present paper addresses the problem of secondary element in the common facilities structure. The aim of this work is to predict the behavior of a multi-component system for major-hazard industrial facilities that will be tested on a shaking table in order to evaluate the seismic response. A FEM model of the structure has been developed a modal and a nonlinear time-History analysis have been performed. The modal analysis results shown as the relative displacement between primary structure and secondary elements as the tanks could cause increased stress in the piping system. Furthermore, possible relative displacement between the secondary elements (tank and pipes) could cause a leakage condition in some flange joints of the piping system. Preliminary tests confirmed the good prediction of the vibration modes of the structure and confirm the potential activation of local modes capable in principle to induce possible leakage conditions.

7. Acknowledgements

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8. Copyrights

9. References

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