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**SHAKE TABLE TESTING FOR A MULTI-COMPONENT PROTOTYPE INDUSTRIAL PLANT:  
INPUT AND SYSTEM MODELLING ISSUES**

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**ABSTRACT**

*Recent destructive earthquakes in China (Sichuan, 2008 and Yushu, 2010), Japan (Tohoku, 2011) and Italy (Emilia, 2012) highlighted the social and the political consequences of seismic risk due especially to industrial facilities. More precisely, critical interactions between the supporting structure and process components reveal to be extremely vulnerable in a seismic scenario and capable to lead serious damage of process equipment and potential release of hazardous substances. This latter circumstance, underestimated by current codes, in addition to loss of production, pose a serious danger to humans and the surrounding environment. Based on these premises, the 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. In greater detail, the goal of the project is the investigation of both the seismic behavior and the dynamic interactions of a representative industrial substructure equipped with complex process technology by means of shaking table tests. A full-scale mock-up composed by two single-bay moment resisting frames with three floors equipped with tanks, flanges, pipes, cabinet etc. was built and tested using a unidirectional shaking table activated with several earthquake levels. More precisely, the salient features investigated by shaking table testing are: i) the interaction between a primary moment resisting frame steel structure and secondary process*

*components that influence the performance of the whole system; ii) input and system modelling capable to faithfully reproduce the seismic response of SPIF tested structure.*

*The comprehensive testing campaign demonstrated a clear dynamic interaction between the primary steel structure and secondary process units that emphasizes the need of further investigations and studies.*

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

**NOMENCLATURE**

|     |                                                  |
|-----|--------------------------------------------------|
| BFJ | Bolted Flange Joint                              |
| FEM | Finite Element Method                            |
| OBE | Operating Basis Earthquake Condition limit state |
| LoC | Lost of Containment                              |
| PGA | Peak Ground Acceleration                         |
| PBD | Performance-Based Design                         |
| PSD | Power Spectrum Density                           |
| QRA | Quantitative seismic Risk Analysis               |
| SSE | Safe Shutdown Earthquake limit state             |
| T-H | Time History                                     |

## 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 NaTech events. These include releases from fixed chemical installations and spills from oil and gas pipelines. One of the main issues of NaTech 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. NaTech events derives from the interaction between industrial and natural hazards. In particular, earthquakes have been recognized as one of the most disruptive natural hazards, as demonstrated by many past earthquakes, which raised public concern because of the general unpreparedness of the countries in predicting effects and consequences in the aftermath of a disaster [1].

The objective of this work is the simulated investigation of the seismic behavior of industrial plants equipped with complex process technology by means of shaking table tests. The necessity exists, since past earthquakes have shown that critical interactions can occur in these plants between the supporting structure and plant components, but also between the individual plant components. The structural or process-related interactions can lead to serious secondary damages which, in addition to loss of production, also pose a danger to humans and the environment if hazardous substances are released due to leakages. The main objective of the test is to investigate the interactions between the primary structure and components as well as between the components among themselves, with the use of a shaking table test. In this paper the prediction numerical analysis of the test and its comparison with the experimental results have shown.

### 1. MODELLING ISSUES

The seismic behavior of support structures in major-hazard industrial plants (e.g refineries) is of paramount importance as undoubtedly demonstrated by many contributions present in the literature, where the main issues concerning the analysis and component design of industrial plant substructure equipped with process components (pipes, tanks, etc.) have been deeply analyzed. Notwithstanding, several aspects are still unresolved, resulting in codes and standards often dated and inadequate, especially in terms of consequences on humans and environment.

For example, [2] drawn the conclusion that both European [3] and American [4] standards provide the same indications for the assessment of the seismic response of refinery piping systems, where support structure (rack) and components (pipes) are present. In particular, an allowable stress design approach is still preferred, even though in view of a more modern performance-based design (PBD) approach have been proposed in the literature [5]. The main obstacle to a wide spreading of

PBD is represented by the need of accurate non-linear models, which are computationally costly and requires specific skills. A few studies can be found in the literature, where an explicit performance-based approach has been used for the seismic analysis of this special structures. For example, in [5] the application of the performance-based approach is illustrated through full non-linear seismic analyses of two realistic petrochemical piping systems. The authors concluded that a general over conservatism in designing piping systems is typically adopted, even though it is clearly neither economic nor rationale.

Moreover, the definition of performance parameters and limit states has a certain degree of difficulty, given the scarcity of experimental data. An interesting attempt to rationalize this aspect can be found in [6]; however, the lack of experimental results on the local behaviour of industrial components still represents a critical aspect, on which limited contributions are present in the literature [7]. For example, in [8], the authors investigated the behaviour of non-standard bolted flange joints endowed with plastic deformation capacity, demonstrating that the release of elastic behavior in case of strong earthquakes can be beneficial, also in presence of potential release of hazardous material. [9] used the hybrid test techniques to investigate a full-scale petrochemical pipe under strong motions, demonstrating, also in this case, that refinery pipes, which are designed according to the current codes, presents a clear overstrength.

Strictly related to the previous aspect, the identification of proper nonlinear analysis methods for the correct evaluation of limit states exceeding conditions represents another particular delicate issue. Dynamic integration of a structure, where explicit nonlinear behavior of primary and secondary structure is considered, is clearly the most reliable analysis method. Nonetheless, simplified approach as for example the use of static analysis or the use of floor spectra are preferred. However, these latter are not problem-free. For example, [10] demonstrated that the common nonlinear static analysis cannot be used to assess the response of pipe-rack and that the behavior factor suggested by the current standards is improper. This derives essentially by the presence of non-building characteristics of this kind of structures [4]. The absence of a rigid floor and the dynamic interaction between primary (support) and secondary (components) structure are among the main causes of this difference [11].

In this respect, the type of analysis method becomes crucial. For example, [12] focused on the development of floor acceleration spectra for an industrial special concentrically braced frame supporting a liquid storage tank. The authors demonstrated that in most of the cases, code-compliant analytical approaches overpredict the results with respect to analyses that explicitly consider the interaction between the supporting structure and the liquid storage tank. Differences up to 30-35% were detected when EN1998 [3] are used for the quantification of the seismic input (floor spectra). This demonstrates the importance of accurately predicting the spectral shape. Moreover, the quantification of the behaviour

factor of supported components can also be crucial if a reliable prediction of floor actions is needed. For example, [4] prescribe for piping systems a behavior factor  $q$  that falls in the range 6-12, which is clearly overestimated as demonstrated by [13]. In fact, the authors evaluated, through direct nonlinear analyses, values of  $q$  not greater than 3-4. The plasticization of the primary structure and the presence of higher modes is also of utmost importance for floor response spectra derivation as highlighted by [14]. In fact, they demonstrated that there is a significant influence on the floor acceleration values as well as the dimensioning of the anchorages between primary structures and components. Similar observations were derived by [15]. In fact, the authors observed that nonlinearity in the primary structure can reduce seismic fragility, decreasing the effect of tuning between the piping and support. Moreover, [16] demonstrated that the response of a pipe can be greatly reduced by explicitly including the nonlinear behavior of the local supports of a pipe.

A special attention should also be paid on the consequences that a failure of supported components (e.g. pipe flanges and elbows, tanks etc.), can induce on humans and environment. [17] analyzed the problem in view of a quantitative seismic risk analysis (QRA) of major-hazard process plants. They evidenced that one of the critical points that caused a limited diffusion of QRA techniques is the limited knowledge of the seismic behavior of critical units, among which the support structures play a key rule. In fact, release of hazardous materials from secondary elements (pipes, tanks, etc.), even not directly considered by the current standards could generate uncontrollable disasters, dramatically amplifiable by the domino effect [18]. The main problem in evaluating loss of containment (LOC) is the relation between seismic damage and LOC that is still under discussion [19], and often only empirical approaches are adopted in guidelines and codes [20]. Therefore, it is clear the need of additional data coming from experimental campaigns where real seismic conditions on support structure endowed with secondary elements can be reproduced.

Finally, a still open issue, concerning units like industrial structures supporting critical equipment in seismic prone areas, is represented by a clear definition of limit states and related seismic action. While, seismic hazard conditions-limit states dichotomy (including consequences) is clearly identified for civil structures, almost nothing can be found in the literature for hazardous industrial equipment. A shy attempt of imitating the consolidated approaches coming from the nuclear industry, can be found in [9], where typical refinery piping system was analyzed, referring to Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE). The first corresponds to the typical Safety Life Condition and is representative of a damage limit state, whereas the second is related to near collapse conditions. However, these results should be extended to other type of structures, with the identification of the return period of the seismic action corresponding to a real OBE and SSE condition.

## 2. DESCRIPTION OF THE CASE STUDY AND TEST PROGRAMME

### 2.1 Mock up

The primary steel structure of the prototype industrial plant is a three-storey moment resisting frame with flexible diaphragm made of crossbeams. In Figure 1 the mounted test structure equipped with the secondary elements are shown.

The ground plan dimensions are 3.7 m x 3.7 m and the storey's height is 3.1 m, which leads to a total height of 9.3 m. The frame is simply supported on the reinforced concrete base plate and crossbeams are hinged connected 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 both filled with granular material with density equal to petroleum. Furthermore, one electrical cabinet is placed on the first level. The piping layout is designed with DN 100 elements with 3.6 mm of thickness. In addition, smaller single degree of freedom (SDOF) oscillators systems are installed on each of the three levels to investigate the structure component interaction for different periods in the linear and non-linear range. Besides, test structure will be equipped with a complex system of sensors which includes FBG fiber optics sensors, for LoC and leakage detection, strain-gauges SG, LVDT and accelerometer in strategical positions, to study the dynamic behavior of the structure and its interaction with secondary elements.



**FIGURE 1: MOCK-UP PHOTOGRAPHS AT THE EUCENTRE LABORATORY.**

### 2.2 Selection of seismic input

In order to define proper limit states for the multi-storey frame with process equipment, we recall the main goals of the SPIF project i.e. the quantification of the interaction between the primary MRF structure and process components. With respect to the objective and according to the PBEE approach [21], the primary structure was designed to cope with the Near Collapse (NC) limit state; as a result, a severe earthquake prone-scenario was assumed leading to a design PGA of 0.69 g.

Conversely, the secondary process components were designed according to nowadays common practice; nonetheless, these components satisfy both the OBE and SSE requirements. Therefore, in agreement with the cited standards, for the primary structure we correlated different limit states to PGA levels as collected in Table 1; whilst Table 2 gathers limit states to PGA levels for process plant components.

| Limit States       |      | $P_{VR}$ |   | $T_R$ | $S.F.$ | $PGA$ |
|--------------------|------|----------|---|-------|--------|-------|
| Fully Operational  | - OP | 81       | % | 75    | 0.31   | 0.22  |
| Damage Limitation  | - DL | 63       | % | 125   | 0.37   | 0.26  |
| Significant Damage | - SD | 10       | % | 1188  | 0.79   | 0.54  |
| Near Collapse      | - NC | 5        | % | 2438  | 1.7    | 0.69  |

**TABLE 1:** SIGNIFICANT LIMIT STATE FOR PRIMARY STRUCTURES.

| Limit States    |       | $P_{VR}$ |   | $T_R$ | $S.F.$ | $PGA$ |
|-----------------|-------|----------|---|-------|--------|-------|
| Operating Basis | - OBE | 10       | % | 1200  | 0.80   | 0.54  |
| Safe Shutdown   | - SSE | 5        | % | 2475  | 1.01   | 0.69  |

**TABLE 2:** SIGNIFICANT LIMIT STATE FOR PROCESS PLANTS

The applied seismic action was based on a linear elastic response spectrum Type 1, with soil condition C, a  $PGA=0.6\text{ g}$  and a damping ratio of 5 % in agreement with Eurocode 8-Part 1 [3]. This spectrum, depicted in Figure 2, exhibits an initial spectral acceleration of 0.63 g and a plateau range between the periods 0.2 s and 0.6 s with a spectral acceleration of 1.725 g.

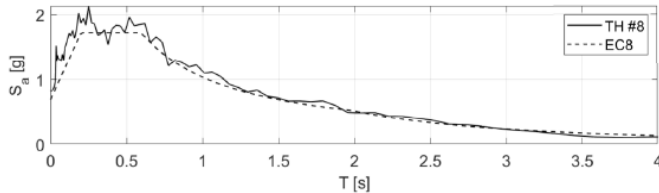


**FIGURE 2:** EUROCODE 8-PART 1 TARGET SPECTRUM AND ARTIFICIALLY GENERATED SPECTRUM FOR TIME HISTORIES TH #8.

In compliance with the aforementioned spectrum, a set of 10 stochastically independent accelerograms, TH #1-TH #10, was generated. The simulations conducted on a finite element (FE) model of the mock-up, with all generated accelerograms, allowed for the identification of the accelerogram TH #8, due to the relative amount of damage induced. In this respect, Figure 3 shows the acceleration time history TH #8 for a reference  $PGA$  of 0.63 g and its corresponding velocity and displacement time histories. The signal was applied through the shaking table with a sampling rate of 256 Hz, a total duration of 25 s and a baseline correction.

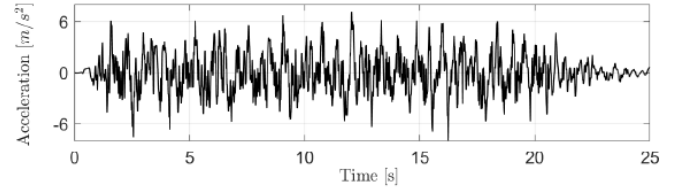


**FIGURE 3:** ARTIFICIALLY-GENERATED TIME HISTORIES

### 3. NUMERICAL ANALYSIS

A numerical analysis has been implemented in order to predict the behaviour of primary structure and secondary elements during the test. A FE model has been built in Midas Gen environment [22] and both modal analysis and non-linear time history analysis have been run. The most important results and their comparison with the experimental results has been shown in the next paragraphs.

#### 3.1 Finite element model description

The primary structure is composed of steel columns and beams: these elements have been modelled as beam elements, as shown in Figure 4.

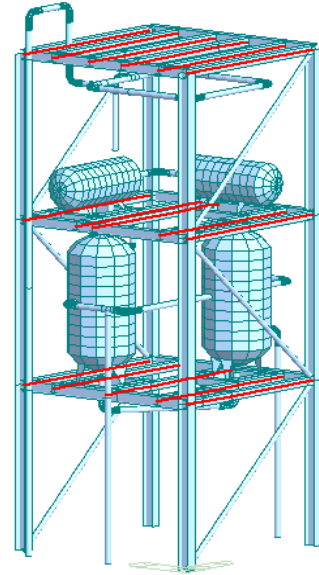


**FIGURE 4:** FINITE ELEMENT MODEL OF SPIF'S MOCK-UP

Columns are hinged at the base and the connections with the primary beams allow all the stresses to be transferred. The simply supported secondary beams (highlighted in red in Figure 3) sustain tanks as well as the other live loads. No floor diaphragm constraints are inserted.

Tanks wall are modelled with plate elements and tree mass points, that are connected to plate elements by elastic links with a high axial stiffness and null shearing stiffness (in order to

simulate the behavior of the liquid), are located in each tank, as shown in Figure 5.

Piping system is mainly made of straight segments, elbows and tees joints. The straight segments of pipes are modelled by linear beam elements, while elbows are modelled using shell elements and they are linked to the piping system with rigid links. This approach is appropriate to account for roundness of the section to better simulate the boundary condition and to consider an appropriate stiffness, 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 [23].

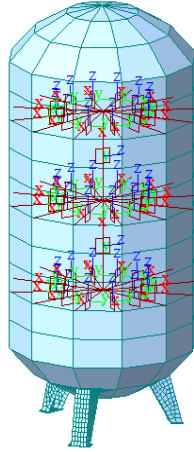


**FIGURE 5: FINITE ELEMENT MODEL OF THE TANK**

Pipes have a hollow section with a diameter of 114.3 mm and a thickness of 3.6 mm, as well as elbows and tees joints.

The pipes boundary conditions have been chosen taking into account the most common industrial pipes connection used in the industrial plant. At the ground level the pipes are all fixed to the base just as the rest of the structure. Meanwhile, the connection between the pipes and the supporting structure is achieved with hinges that allow all the relative rotations and one relative movement in the longitudinal direction of the pipe, in order to catch the real behavior of the boundaries, as shown in Figure 6.

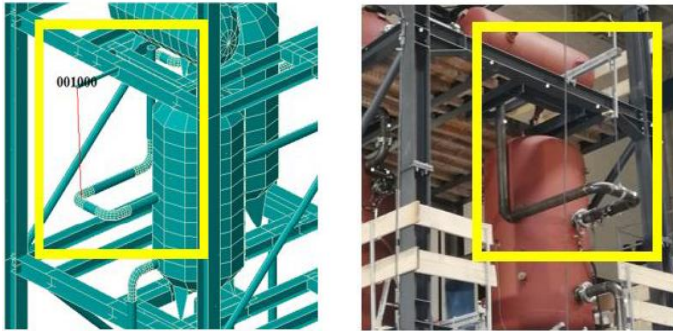


**FIGURE 6: BOUNDARY CONDITIONS OF PIPING SYSTEM**

### 3.2 Numerical results

Modal analysis results have shown the first eigenmode as the most important one for the structure, since it alone activates more than 90% of the total mass in X direction (where seismic action will be applied during the test). In Table 3 the frequencies of first six eigenvalues are summarized, and the participating mass relative to each mode is indicated.

The eigenmodes higher than the first are local vibration on each floor level and activate only a low percentage of mass. For example, the second eigenmode is a vibration mainly concentrated on the first level tanks. These local vibrations can be relevant for the behavior of second elements interactions, as flange joint between pipes and tanks. In Figure 7 the first four vibration modes are shown.

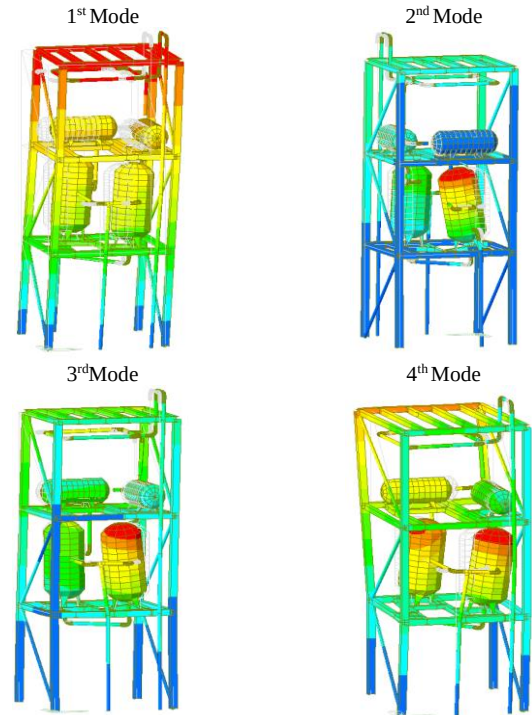


**FIGURE 7: VIBRATION MODESHAPE**

| EIGENVALUES |                |              | PARTICIPATING MASS |         |          |         |
|-------------|----------------|--------------|--------------------|---------|----------|---------|
| Mode Num.   | Frequency (Hz) | Period (sec) | TRAN-X             |         | TRAN-Y   |         |
|             |                |              | MASS (%)           | SUM (%) | MASS (%) | SUM (%) |
| 1           | 2.905          | 0.344        | 91.91              | 91.91   | 0.37     | 0.37    |
| 2           | 4.043          | 0.247        | 0.15               | 92.06   | 1.28     | 1.66    |
| 3           | 4.500          | 0.222        | 0.10               | 92.16   | 30.01    | 31.67   |
| 4           | 5.353          | 0.187        | 2.58               | 94.74   | 37.46    | 69.13   |
| 5           | 5.747          | 0.174        | 0.01               | 94.75   | 0.87     | 70.00   |
| 6           | 6.004          | 0.167        | 0.07               | 94.83   | 0.97     | 70.97   |

**TABLE 3: EIGENVALUES AND PARTICIPATING MASS**

The time history results have shown that the primary steel structure remains in the elastic field in accord with the structure design, while the non-structural elements have shown some issues. In the straight pipes, that connect the vertical tanks at first floor and the ground, the yield stress has been exceeded in the tee-joint and in the elbow as shown in Figure 8. In 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 3<sup>rd</sup> and 4<sup>th</sup> vibration mode. A sensitivity mesh-check of the identified critical stressed-concentrated elements has been then deployed in order to avoid too coarse or too refined mesh definition.

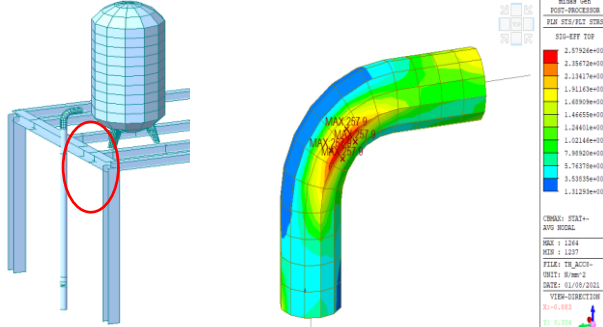


**FIGURE 8: STRESS VALUE IN THE ELBOW PIPE**

### 3.3 Comparison with experimental results

The numerical results have been compared with the experimental results from the shaking table test campaign, in order to evaluate the efficiency and the accuracy of the FE model to predict the behaviour of both primary and secondary elements.

Signals recorded by the accelerometers located at each floor have been analyzed in order to evaluate the Power Spectrum Density (PSD), in accord with the method described in [24], with the aim to obtain the system identification of the frequencies. The adoption of the PSD of recorded accelerometers' signals provide robust indicators and rapid checks on the structural behavior of the mock-up along the experimental campaign. As can be noted from Figure 9, representing PSD function of the primary structure, a really good approximation between the experimental results and the numerical dynamic identification shown in Table 3 is achieved.

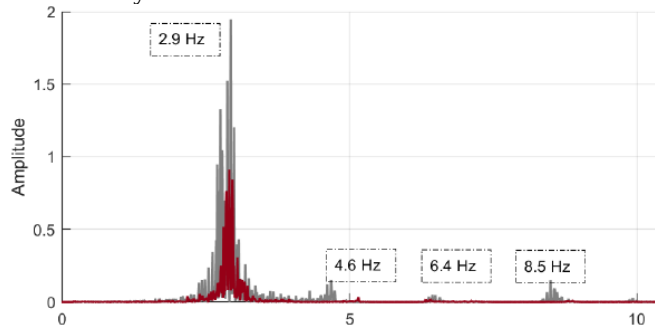


**FIGURE 9: EXPERIMENTAL PSD FUNCTION**

The comparison of the results has shown a good capability of the FE model to predict the global behaviour of the primary structure. A good match can be observed between the experimental and numerical TH function results in terms of acceleration and displacement at each floor of the structure, as can be noted from Figure 10 that shown the TH acceleration results at third floor. The results comparison shows that the dynamic behavior of the secondary elements can be predict with a good approximation too by the FE model. As can be appreciated in Figure 11, that shown the TH function results in terms of displacement of the vertical tank located at first floor, the model has a good capability to predict the peak and the trend of the displacement. Although, the instrumentation recorded residual displacements due to local damages on fin plates joints that characterize the detail connections onto which are mounted tanks at floor levels.

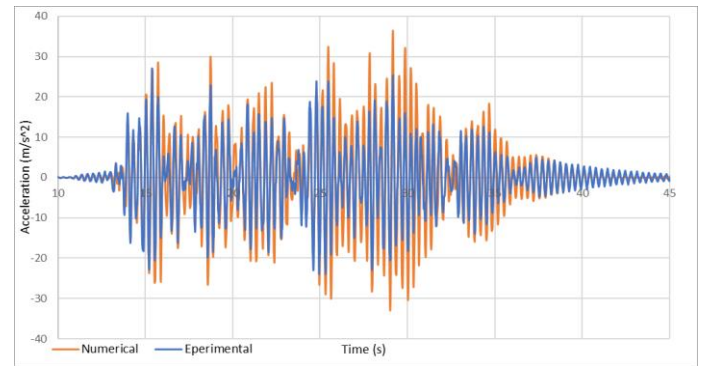


**FIGURE 10: ACCELERATION RESULTS AT THE THIRD FLOOR**

However, the comparison has shown a weakness of the model to predict the stress value in the BFJs. As can be appreciated in Figure 12, there is an important lack between the numerical and experimental results.

The reason lies in the fact that an appropriate stiffness is needed in order to catch the real behavior of the BFJs that have been simply modelled with a straight beam element. In this respect, a refined local FE model of the BFJ has been developed, to catch the effective stiffness of the joint and improve the global FE model. As can be noted in Figure 13, the improved FE model is able to predict the stress field in the BFJs more carefully.

## 4. CONCLUSIONS

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 to evaluate the seismic response. A FEM model of the structure has been developed on Midas Gen and a modal and a Time-History analysis have been performed.

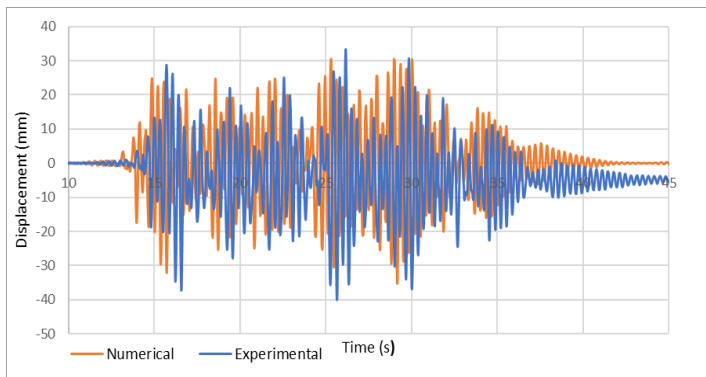


**FIGURE 11: DISPLACEMENT RESULTS OF VERTICAL TANKS**

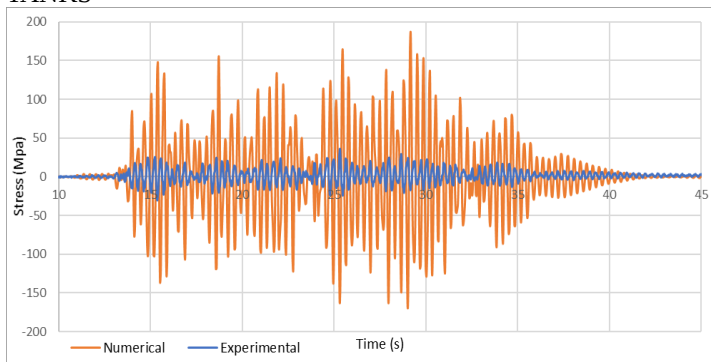


**FIGURE 12: STRESS RESULTS OF THE BFJ – SIMPLIFIED FE MODEL**

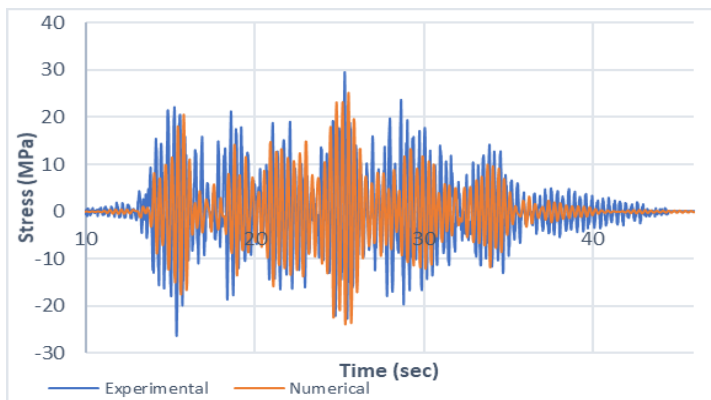


**FIGURE 13: STRESS RESULTS OF THE BFJ – REFINED FE MODEL**

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. The FEM model have shown how it is possible evaluate the global dynamic behavior of the primary structure and secondary element, but more refined modellings are needed to catch the local behaviour of the equipment.

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