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SEISMIC PERFORMANCE ASSESSMENT OF OIL & GAS PIPING SYSTEMS THROUGH NONLINEAR ANALYSIS

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Abstract. *Piping systems, a vital part of energy industries, e.g. petrochemical, oil & gas and chemical plants, have been found particularly vulnerable under earthquake loading, as reported in recent publications. During past earthquakes, piping systems and their components suffered significant damages causing severe consequences. Thus, seismic assessment/evaluation of these structures has become an imperative for their proper design to safeguard them against seismic events. Nevertheless, there exists an inadequacy of proper seismic analysis and design rules for petrochemical piping systems, and designers have to follow seismic standards conceived for other structures such as buildings and nuclear plants. Moreover, the modern performance-based design approach is still not widely adopted for piping systems, where the allowable design method is the customary practice. Along these lines, this paper presents a performance-based seismic analysis of petrochemical plants through two case studies. Initially, main issues on seismic analysis and design of industrial piping systems and components are addressed followed by a discussion on the selection of proper seismic inputs. The current allowable stress and strain based seismic verification methods are presented afterward. Then, nonlinear finite element analyses of two typical petrochemical piping systems under modern design earthquake levels are presented. Finally, performance of these piping systems is commented by comparing the maximum stress and strain levels -found from the analyses- with the allowable design values that exhibited a favourable behaviour of the analysed systems under earthquake limit state levels.*

1. INTRODUCTION

Piping systems play a critical role in meeting the increasing global energy demand. Currently, there exists about 3.5 million kilometers of transmission pipelines, while about 231900 km of oil and gas pipelines are under construction or planned (www.dnv.com); a great portion of which is located in high seismic-prone areas. A piping system consists several components and support structures, e.g. flange joints, tee joints, elbows, valves, pressure vessels and storage tanks, where failures in a single component may hinder the whole transmission process and cause catastrophic consequences. Hence, such systems deserve particular attention to safeguard them against any accidental event such as earthquakes. Nevertheless, piping systems and their components have been found particularly vulnerable under seismic events and suffered severe damages during past earthquakes causing serious accidents both to human lives and to the environment [1, 2, 3, 4].

Current seismic design approach to petrochemical piping systems are mainly based on the allowable design method; the most modern Performance-Based design approach is not strongly implemented yet. One of the main reasons of this is the scarcity of information about the definitions of limit states for pipes and the structural modelling, which have not yet been treated in a satisfactorily manner. Moreover, most seismic codes and standards don't contain enough rules and details for the proper design of industrial piping systems in seismic-prone areas. For example, [5], the Structural Eurocodes that introduce novel seismic design concepts for industrial structures, lacks adequacy for seismic design of pipelines [6]. Also, seismic problem is only partially treated in EN 13480-3 (2002) [7], the main European contribution for piping system design. EN 13480-3, like American codes ASME B31.1 (2001) [8] and ASME B31.3 (2006) [9], prescribes an allowable stress verification method under a design/operating basis (OBE) and a safe shutdown (SSE) earthquake, the latter being addressed only in EN 13480-3. However, no indications on the selection of earthquakes and analysis methods are provided in these standards, instead they refer to general seismic standards conceived for buildings, e.g. [10, 11], or for nuclear plants, e.g. [12]. Some standards have recently been developed in the US that specifically addresses natural gas plants, e.g. [13]; but, in general, there exists a clear scarcity of adequate seismic design rules for petrochemical/Oil & Gas piping systems.

To this end, this paper presents a performance-based seismic analysis of petrochemical piping systems through two realistic case studies. In a greater detail, several aspects of seismic analysis and design of piping systems, such as proper modelling of support structures, straight pipes, elbows etc., dynamic interaction analysis, selection of seismic inputs and analysis methods, have been discussed. Current allowable stress and strain based verification methods for piping systems are presented, which are followed by non-linear analyses of two case studies that investigate two realistic petrochemical piping systems under several limit states. Finally, performance of the piping systems is commented by comparing stress and strain values found from these analyses with allowable stress and strain limits suggested by relevant codes and standards.

2. SEISMIC DESIGN ISSUES OF PIPING SYSTEMS

The seismic design of a piping system entails a number of issues. They are essentially related to overall structure modelling, to a correct definition of the seismic action, to a proper analysis method to be applied, and finally, to an appropriate design method to be used. In the following, relevant aspects are analysed under the light of the current standards recalled above and, in particular, of the European (EN13480-3) and the American (ASME 31.3) standards.

2.1 Definition of numerical models of piping systems

A synthetic scheme of what European and American Standards prescribe for a correct numerical modelling of a piping system and the definition of the seismic conditions is reported in [6]. In that occasion it was clearly shown that the suggested numerical model to use in seismic analysis is always elastic both for EN13480 and ASME B31.3. This choice comes certainly from the old way to evaluate the safety level of a structure: the allowable stress method still diffused in designing of piping systems. Usually, only the piping system is modelled, using the supporting structure only to evaluate the seismic action at pipes level (e.g., in-structure spectra). The supporting structure (e.g. pipe-tack) is treated as elastic too. The assumption of elastic behaviour would not be a strong limitation if a correct value of the behaviour factor were adopted.

A key point in modelling a piping system is the possibility to neglect the interaction (static and dynamic) between the pipes and the supporting structure. EN13480 does not provide any indication about it, whereas ASME B31.3, by means of ASCE-07, prescribes a crude rule based on the ratio, W, between the weights of pipes and supporting structure. In particular, if W< 25% the interaction can be excluded and the piping system can be considered as a non-building structure, loaded by a seismic action coming from the supporting structure at pipes level.

This rule has been recently analysed by several authors. For example, in [14] the rule has been analysed using time-history analysis. From the results and discussion, the author concluded that in some cases this decoupling rule could produce gross errors in the evaluation of the dynamic behaviour of piping systems. In particular, it seems that in dynamic assessment of such systems, in addition to the primary-secondary system weight ratio criteria, attention should be paid to other aspects as "end conditions of pipes", "relative stiffness of supporting structure to piping system" and "relative stiffness of pipes to pipe-supports", even though only partial conclusions where reached by the authors, that suggested more investigations on this matter.

Another relevant aspect about modelling of piping systems is the adoption of a proper model for pipes and fittings (elbows, tee-joints, nozzles, etc.). At this regards, usually beam elements with hollow section are used for straight pipes. The fittings are also modelled using beam elements, but modifying the stiffness for the effect of geometry. For this purpose, both European and American Codes define a flexibility factor (k >1) using which the moment of inertia of the pipe is reduced. In addition, to take into account the stress concentration effect, the Stress Intensification Factor (SIF) is used to increase the stress calculated using the beam theory. The values of k and SIF calculated according to EN13480 and ASME B31.3 are very similar. Alternatively, it is possible to use shell elements to model fittings [15]. This approach is appropriate to account for ovalization of the section and stiffening pressure effect also in non-linear field [16]. For these reasons, this model has been used for the Case Study and a comparison with beam model has been carried out. We can anticipate that the numerical simulations have shown a similar behaviour of both the models and the reliability of modified beam element, at least for standard fittings, like pipe elbows.

A last but not less important aspect regards the boundary conditions of the pipes. In fact, because a piping system is realized by hundreds of miles of pipes, the analysis involves necessarily a limited part of the structure. Consequently, proper boundary conditions have to be accurately adopted to simulate the remaining part of the structure. Also, for this delicate aspect no indications are provided by European and American Standards. As already shown in literature, uncertain boundary conditions may significantly influence the dynamics of the piping system; however, their proper modelling vary from case to case [14, 17].

2.2 Seismic actions and analysis methods

Both European and American Standards assume the following two types of analysis for pipes:

- Movements due to inertia effects.
- Differential movements of the supports (within the supporting structure or between adjacent pipe-racks).

The first type of analysis is essentially related to the effects of the absolute acceleration on the pipe mass. The second one is due to the relative movements between two supports, within the supporting structure or belonging to adjacent structures. Often the relevant effects are due to the displacement effect rather than acceleration effects.

Concerning the inertia effects the seismic action for pipe-racks is usually represented by design response spectra or accelerograms (natural records or synthetic accelerograms). For the analysis of pipes only, “In-structure” spectra or “filtered response spectra” are instead used. The design spectra are the main representation of a seismic action and usually are defined by the seismic codes in terms of hazard conditions of the site, the level of dissipation capability of the supporting structure and pipes (response or behaviour factor), the right level of damping to be employed, and the level of structure reliability to impose, identified by the importance factor. For the support structure, hazard conditions apart, the damping usually adopted is equal to 5%, as suggested by Eurocode 8 and 3 for steel structures, whereas the behaviour factor, q, depends on the type of structure used for the pipe-rack. While for building-type structure this aspect has been well identified and quantified, for structures like pipe racks that may often be considered as non-building structures [10], the problem may be quite different.

The current American and European seismic codes provide a q factor for steel racks equal to 3 ½ and 4 respectively. This choice probably derives from the hypothesis of no-coupling between the rack (primary system) and the pipes (secondary system). In fact, usually the level of dynamic coupling between pipes and rack can be neglected. But in other some cases its influence cannot be excluded a priori [14]. The spectral responses of the modal oscillators are then combined to obtain the resultant response of the system. Moreover, the resultant forces and displacements from bi-directional analysis are typically obtained by the square root sum of square of the response in each direction, or by applying the well-known 100-30 rule.

The in-structure spectra allow a seismic action to be defined for single pipes at several floors of the pipe-rack, in which the pipe is placed. Both European and American Codes provide their explicit expressions. They are defined as the spectrum acceleration multiplied by an amplification factor AF defined by codes. The behavior factor provided by the Codes, especially by the American one, seems to be overestimated. For example, ASCE-07 prescribes the use of a behavior factor 6 or 12 according to the deformability of the material used. In some cases this hypothesis may not be totally true [18].

A time history seismic input is rarely used for the design or retrofit of piping systems. Often it is used to generate facility specific response spectra analyses, or as a research tool, to study in detail the full non-linear behavior of a component or system as a function of time. Nowadays, the scientific community has widely accepted the use of natural records to reproduce a real input, for several reasons. For many engineering applications, the purpose of selection and scaling of real earthquake is to fit the Code design spectrum considering the seismological and geological parameters of the specific site. To help engineers in selecting a proper set of records, some tools have already been proposed in the literature.

Seismic anchor motion (or “SAM”) is the differential motion between pipe support attachment points (for example, supports attached to an upper floor would sway with the building, with a larger amplitude than supports attached at a lower elevation), or the differential motion between equipment nozzles and pipe supports. Seismic anchor movements are input as displacements (translations and rotations) at the support attachments or at equipment nozzles. The resulting stresses and loads in the piping system can be properly combined to obtain stress and loads in the pipes.

No specific indications are provided by EN13480:3, whereas, ASCE-07 provides a simplified criterion based on the elastic analysis of the pipe-rack. Here, it is suggested to evaluate first the relative displacements between two connection points within the structure and at the same level for each vibration modes and then to combine them using a proper combination rule as the SRSS rule.

2.3 Verıfıcatıon methods

One of the fundamental steps for the qualification of a pipe system is the fulfillment of some limits of the pipe stress or strain, for a given working condition. For a seismic action, usually two working conditions, namely an Operating Basis Earthquake (OBE) and a Safe Shutdown Earthquake (SSE) as will be discussed later, are used.

Both European and American standards, e.g., EN 13480-3, ASME B31.1, ASME B31.3, provide guidelines for allowable stress based verifications of pipes subject to earthquakes. For instance, ASME B31.1 and EN 13480-3 provide a similar formula expressed as,

$$\sigma = p_c\, d_o / (4e_n) + 0.75i\, M_A/Z + 0.75i\, M_B/Z \leq kf_h \tag{1}$$

where 0.75i is the stress intensity factor whose value is 1 for straight pipes; M_A is the moment from sustained mechanical loads; M_B defines the moment from occasional loads; Z is the modulus of inertia; p_c defines the internal pressure; d_o represents the pipe outer diameter; e_n is equal to the pipe wall thickness and f_h represents the allowable stress as defined in these Codes. For an Operating Basis Earthquake ground motion (OBE), the value of k is given as 1.2 and 1.33 in EN 13480-3 and ASME 31.3, respectively; conversely, the Safe Shutdown Earthquake ground motion (SSE) entails values of k equal to 1.8 for EN 13480-3; no value is foreseen for ASME 31.3. Corresponding moments are indicated as $M_{a,OBE}$ and $M_{a,SSE}$, respectively.

A strain based verification method is also provided in the newly developed strain-based design equation [19] that entails an ultimate design load for a pipe based on the maximum strain, i.e.,

$$\varepsilon_c^{crit} = 0.5t/D - 0.0025 + 3000\,((P_i - P_e)D / (2tE_s))^2 \tag{2}$$

where ε_c^{crit} defines the ultimate compressive strain capacity of a pipe wall; P_i is equal to the internal pressure; P_e defines the external pressure; t is equals to the pipe wall thickness; D is the pipe outer diameter; E_s is the modulus of elasticity of pipe material.

Moreover, several standards provide tensile strain limits in pipes [20] as reported in Table 1.

Table 1. Tensile strain limits in pipelines

Code	Tensile strain limit
CSA-Z662 (2007)	2.5%
DNV-OS-F101 (2000) [31]	2.0%
ASCE (2005) [32]	2.0%

3. APPLICATIONS RELEVANT TO TYPICAL PETROCHEMICAL PIPING SYSTEMS

3.1 Selection of seismic loading

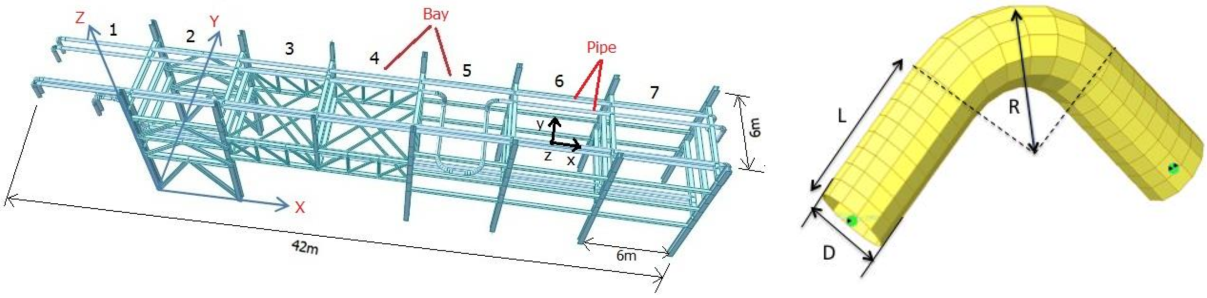
The definition of the levels of earthquake motions to be considered for analysis requires extra attention and assumptions. In fact, several standards dealing with seismic analysis of onshore petrochemical and process plants, e.g., EN 13480-3, ASME B31.1, ASME B31.3 and NFPA 59A, among others, in view of enhanced performance and damage limitation, use the same seismic hazard definitions adopted by nuclear standards [12]. Nonetheless, intended safety objectives are different: in fact, (i) conventional facilities are designed for human lives protection and damage limitation, see for instance Eurocode 8, Part 1 [11], and therefore, crossing to elastoplastic domain is allowed; conversely, (ii) nuclear seismic rules enforce integrity and functionality of structures systems and components important to safety; as a result, incursions in the elastic plastic domain is not allowed. Thus in moderate seismicity regions, one can establish a correspondence between the 10% probability of exceedance in 50 years, i.e. 475 years return period used in Eurocode 8 Part 1 and the OBE ground motion defined in nuclear standards. For clarity, the OBE can be defined as the ground motion for which those features of the –nuclear power- plant necessary for continued operation without undue risk to the health and safety of the public will remain fully functional. Increased return periods can be achieved through additional peak ground acceleration (pga) multipliers; for instance, the importance factor γ_I can reach a value of 1.4 for power plants of vital importance [11].

The link of the return periods corresponding to the SSE (pga) is more involved; in fact in NFPA 59A (2013) the SSE pga at the site can be defined as the "risk-adjusted maximum considered earthquake (MCER) ground motion" per the definition in [10]. For most locations except near active faults, ASCE 7 adjustment establishes a uniform probability of failure criteria for a 1% probability of exceedance within a 50 year period corresponding to 4975 year return period. However, ASCE 7 requires the base design level earthquake to be 2/3 of MCER; thus, setting γ_I = 1.5 for structures containing extra hazardous materials results in a design level equal to MCER. Also in France the return period for new "special risk" plants corresponds to 5000 years [21]; whilst the corresponding value defined in nuclear seismic standards is based on 0.5% to 0.05% probability of exceedance in 50 years, e.g. 10000 to 100000 years return period. We recall that the SSE is the ground motion in which certain structures, systems and components important for - nuclear- safety must be designed to remain operational.

For each of the two case studies presented and analysed in the following, the seismic input is represented by the elastic spectrum provided by the current seismic European and Italian codes, based on which a set of natural records have been selected and used to perform linear non-linear analysis.

3.2 Case Study #1

The first Case Study (CS) is relevant to a typical petrochemical piping system as illustrated in Fig. 1(a); details of the CS can be found in [6]. The support steel structure was composed of seven transverse moment resisting frames placed every 6 m, made of commercial steel profiles. The piping system presented a typical layout with pipes having different diameters. In order to simplify the analysis, only the structural contribution of 8" pipes was considered; the remaining pipes acted only as weight. Several flanged elbows were present within the piperack and at both ends of the piping system. Columns and beams of the support structure were modelled by using inelastic fibre-discretized beam elements, whereas straight truss elements were used both for vertical and horizontal bracings. The straight braches of pipes were modelled by linear beam elements whilst shell elements were used to better capture the behaviour of elbows as depicted in Fig. 1(b). In order to better simulate the boundary conditions/flexibility of elbows, that is the connection between the straight portions of pipe and elbows, a portion of the connected straight pipes of length (L) was modelled using shell elements as well. In this specific case, we assumed L=1100 mm, R=8'' and R/D=1.5.



(a) (b)

Figure 1. (a) The piping system considered in the Case Study; (b) shell element assemblage used for each pipe elbow.

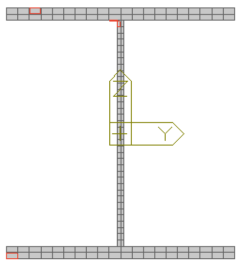


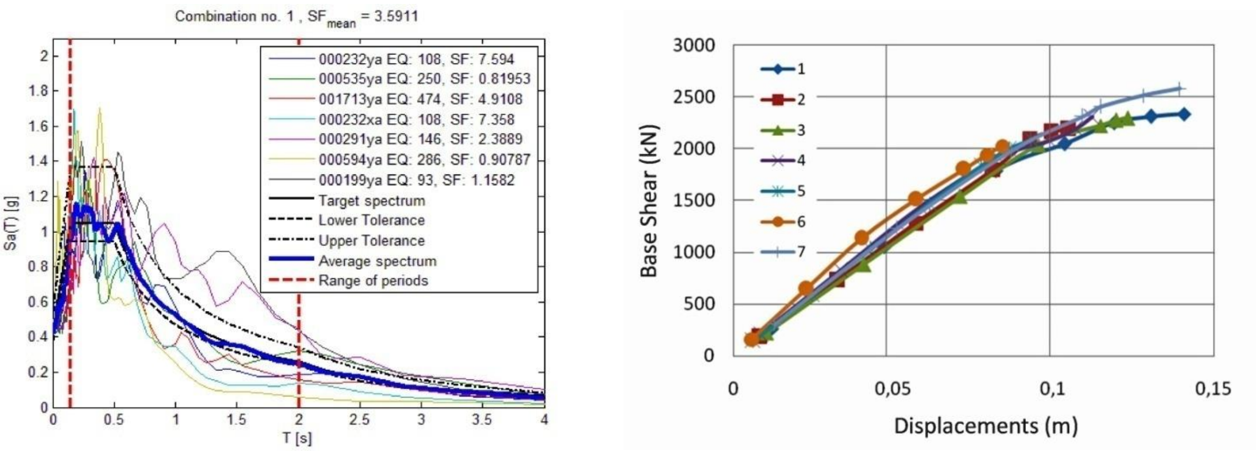
Figure 2. Fiber discretization of an element section of the support frame

Given the fact that this Case Study (CS) is not part of a hazardous facility and is located in a site characterized by a PGA=0.24g, the OBE ground motion was firstly considered, associated with a 5% damped response spectrum foreseen in EN 1998-1, with 475 years return period. The far field spectrum associated with Soil B for the CS is illustrated in Fig. 2(a). Because of unintended consequences of the plant associated with possible failure, a value of γ_I=1.2 foreseen for the plant was assumed [11]. The elastic spectrum was employed to select a set of compatible accelerograms; in greater detail, they have been extracted from the European strong motion database (ESD, http://www.isesd.hi.is/ESD_Local/frameset.htm) according to a Magnitude range 6-7, a distance from the epicentre less than 30 km, and a pga in the range 0.25-0.35 g. The natural accelerograms selected using the REXEL software [22] were characterized by the mean spectrum -bold blue line- shown in Fig. 2(a). The accelerograms were scaled to ensure full compatibility with the target elastic spectrum of Eurocode 8 Part 1, being endowed with a mean spectrum within the lower (-10%) and upper bound (+30%) spectra (line-dot graphs) with respect to the target spectrum.

The selected accelerograms have been used to perform a series of non-linear analyses on the CS evaluating the response both at pipes and support structure. The dynamic characterization of the system provided vibration periods of the support structure equal to T_x=0.35 sec and

T_y=0.46 sec in longitudinal and transversal directions, respectively, which correspond to an excited mass of 53% and 68%. The period of the first modes with and without pipes was similar, whereas the excited mass was higher in the second case, showing some coupling effect of the transverse frames along the Y-axis owing to pipes.

The obtained level of non-linear behaviour of the analysed system was limited and mainly concentrated in the support structure. This is clearly shown in Fig. 2(b) where the results of an incremental dynamic analysis [23] applied to the piping system are shown in terms of dynamic pushover curves, plotted for each accelerogram. Each dot corresponds to the maximum base-shear calculated for a given value of pga and the corresponding displacement measured at the pipe level. The limited plastic deformations level exhibited by the steel structure suggest an actual value of behaviour factor q – equivalent to the response modification factor R_p of ASCE 7- of about 1.8.



(a) (b)

Figure 2. (a) Elastic spectra of the set of seven chosen accelerograms; (b) Dynamic pushover curve of the piping system.

This value underlines that the use of q factors for support structures from [11] must be done with care. In fact, the value of q=4 suggested in that Standard is unsafe for this particular CS, because the layer of present pipes cannot ensure a rigid floor behaviour in the Y direction, see Fig. 1(a), typical of buildings. On the other hand also [13] allows a maximum R_p value of 6 for Seismic Categories II and III. Only for Seismic Category I, the use of R_p is not allowed.

Results of the analysis in terms of moments along local axes y, M_y and z, M_z (see Fig. 1(a)) of the pipe are reported in Table 2. The resultant moments M_R of the single moments M_y and M_z calculated according to the [7] are reported too. ASME B31.3 does not provide a definition of M_R whereas the definition contained in the ASME B31.1, the standard for power piping, is the same. For this reason the same definition has been adopted for the American standard for process piping. The maximum moment was found near the left edge of the rack (bay 2); similar values were also obtained within bay 6 and 7. The average values of the maximum moment was found to be 16.79 kNm; the maximum axial force corresponding to the maximum tensile stress, i.e., 86.41 MPa, was about 180.50 kN.

Table 2. Maximum bending moment and tensile stress in the pipes of the Case Study (OBE)

Moment	Bay						
	1	2	3	4	5	6	7
M_y (kNm)	1.56	6.91	5.98	4.94	5.04	3.47	2.50
M_z(kNm)	13.72	15.30	14.15	7.01	8.75	15.84	15.84
M_R (kNm)	13.81	**16.79**	15.36	8.58	10.10	16.22	16.04
Tensile stress (MPa)	76.71	**86.41**	81.76	59.67	64.62	84.54	83.96

These values were far from the leakage and yield loads of pipe itself and bolted flange joints typically used in piping systems, as already evidenced in [24, 25]. It is, therefore, evident that piping systems like the analysed one possess a good capacity to operate safely under a typical OBE ground motion. The level of stress is well under the elastic limit of the material, i.e. 241 MPa, and allowable stresses at OBE, i.e. 165.60 MPa and 183.50 MPa according to EN13480-3 and ASME B31.3, respectively (see [6]). Moreover, the maximum strain, i.e. about 0.04%, in the pipes was much lower than the allowable limits suggested by standards; see Table 1 in this respect.

In order to evaluate the seismic behaviour of the structure also in beyond-design conditions the response at SSE level has been evaluated. As stated before, SSE can be identified with the Near Collapse condition that corresponds to a return period T_L=2475 years [11] and thus to a importance factor γ_L=2.2 that is a peak ground acceleration a_g= 0.55g. All records of Fig.2 have been scaled accordingly, and used for another set of non-linear analyses. The average values of bending moment and stress in the pipes at several bays are reported in Table 3.

Table 3. Maximum bending moment and tensile stress in the pipes of the Case Study (SSE)

Moment	Bay						
	1	2	3	4	5	6	7
M_y (kNm)	1,78	5,28	6,94	5,67	5,62	3,36	2,39
M_z(kNm)	23,09	26,11	22,18	10,07	10,01	16,94	16,9
M_R (kNm)	23,16	**26,64**	23,24	11,56	11,48	17,27	17,07
Tensile stress (MPa)	132,44	**147,57**	132,80	82,00	81,66	106,84	105,96

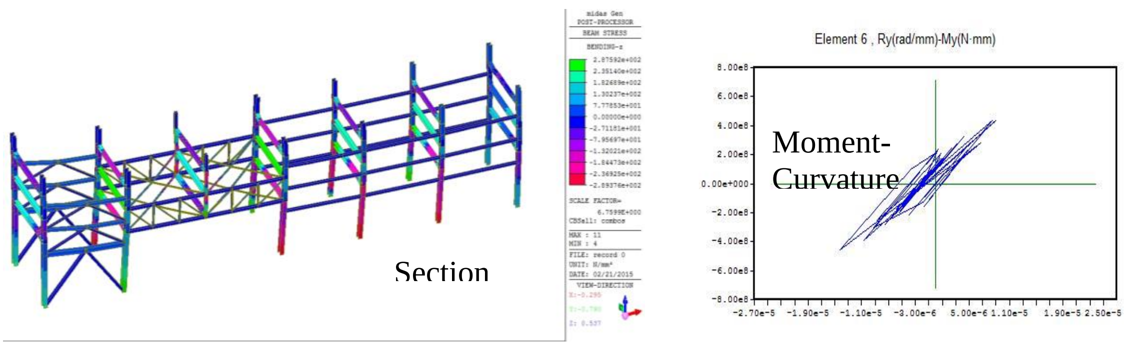


Figure 3. SSE: (a) Stress in the support structure, b) Moment-Curvature - Section A (Acc. 1)

The maximum moment was found to be 26.64 kNm that correspond to a maximum stress equal to 147.57 MPa. The maximum stress in the support structure is located in the columns, whose value is about 280 MPa, slightly greater than the yielding strength, symptom of a slight plasticity in the elements (Fig. 3).

In conclusion, even in presence of a stronger seismic action, the stress level in the pipe at SSE is still confined in the elastic range, as already shown applying the pushover analysis (Fig. 2b). This demonstrates once again the strong conservatisms generally adopted in designing this kind of structures and fully justify the typical usage of linear models for their seismic analysis.

3.3 Case Study #2

The piping system considered within Case Study #2 is a typical petrochemical piping system placed on a steel support structure as illustrated in Fig. 3(a) and 3(c). General dimensions and other geometrical properties of the piping system –presented in Fig. 3(b)- were taken from [15]. The piping system contained 8” and 6” scheduled 40 straight pipes, several elbows, a Tee joint and an EN 1092-1 Standard PN 40 weld-neck bolted flange joint. The pipes were made of API 5L Gr. X52 steel (nominal yield and ultimate strengths: 418 MPa and 554 MPa, respectively) and were filled with water at an internal pressure of 3.2 MPa, corresponding to 80% of the maximum allowable pressure of the piping network.

The support structure was a steel frame structure, 12m high, mainly composed by steel HE and IPE profiles and some vertical and horizontal cross or K-steel bracings. Only a single pipeline ran on the frame supported by sub-frames placed at 3rd floor of the main frame. Two edges of the frame were connected to cylindrical storage tanks whereas the third one was connected to the frame by an anchor. Some design parameters considered for the structure are presented in Table 3.

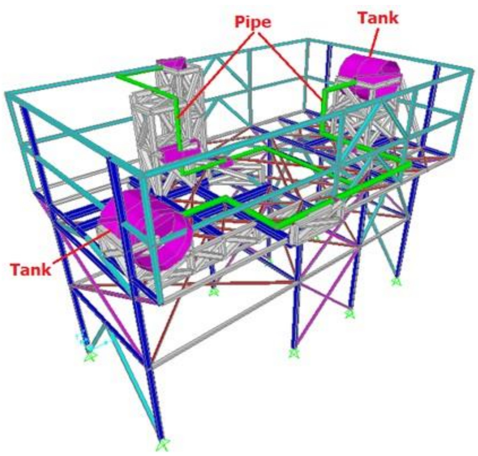


Figure 3(a). A 3D FE model of the support structure of the piping system.

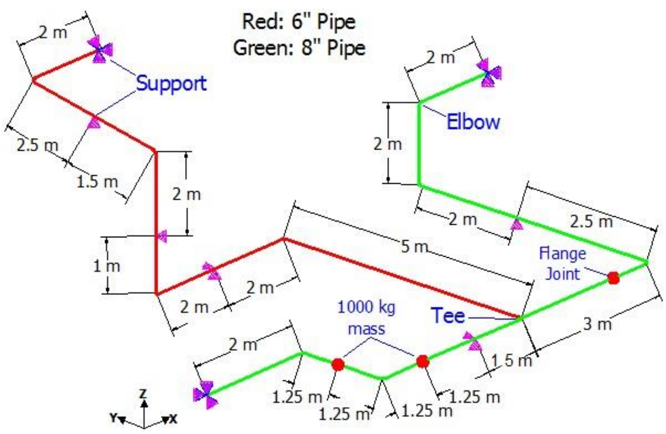


Figure 3(b). Specifications and dimensions of the piping system.

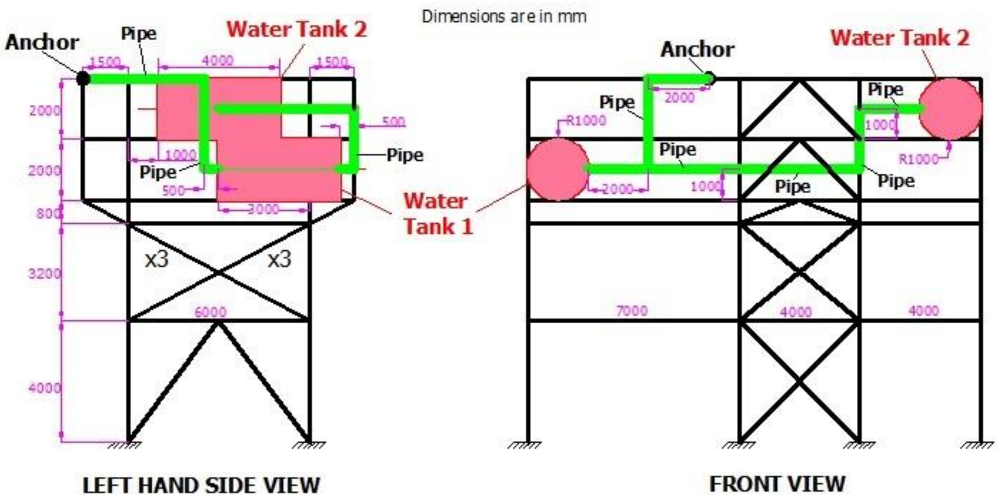


Figure 3(c). Dimensions and lateral views of the support structure.

In order to perform non-linear seismic analysis, a 3D Finite Element (FE) model of the piping system was developed in [26] software. The pipes including elbows were modelled using straight elements with pipe sections. Mass of the water present inside pipes was considered by increasing the mass density of the pipe material. Although elbows were modelled using straight elements in the FE model, flexibilities (see [7]) of these elements were adjusted based on an ABAQUS-based [27] FE analysis. Each elbow had a radius equal to 1.5 times the outer diameter of the connecting pipe; moreover, we considered that the effect of flexibility of an elbow spreads across a distance, L equal to two times the mean diameter of the pipe as illustrated in Fig. 4. The adjusted geometry and properties of elbow elements including the dimensionless flexibility factor, k_B, considered in the piping system model are reported in Table 4.

Table 3. Some design parameters of the support structure.

Location	High Seismic-prone region
pga	0.33g
q factor	3.2
Ground type	C
Return Period	712 years
Importance Class	III*

*Industries with dangerous activities; Reference life, Vr = 75 years

As discussed before, these types of structures with piping systems are normally modelled elastically. However, in order to exploit ductility of the support structure, some nonlinearity was introduced in the model, but only in some brace members. In a greater detail, plastification was allowed only in the some vertical cross and k-bracings of the structure by introducing nonlinearities to those members based on the US standard [28]; see Fig. 5 in this respect which shows the nonlinear model adopted for the vertical cross bracing x3 as shown in Fig. 3(c).

Table 4. Elbow properties considered in the piping system model

Property	8" Elbow		6" Elbow	
	Original	Modified	Original	Modified
Thickness, e_n (mm)	8.18	6.61	7.11	4.35
Flexibility factor, k_B	6.84	1.35	5.97	2.46
Moment of inertia, J^* (mm^4)	3.02 x 10^7	2.49 x 10^7	1.17 x 10^7	7.53 x 10^6

The support structure was placed in Sicily, a high seismic region in the south of Italy. As can be noted from Table 3, soil type C and an important class III was considered for the support structure. Thus, the support structure was designed for an earthquake with a return period T_R equal to 712 years corresponding to the Safe Life Limit State (SLLS) suggested in the Italian standard [29] which, differently from EN 1998-1, prescribes four limit states, as listed in Table 5, in the spirit of performance-based earthquake engineering. Corresponding pga values are also reported in Table 5.

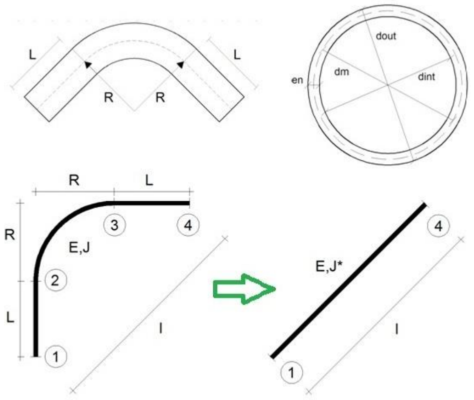


Figure 4. Elbow geometry and equivalent straight elbow element

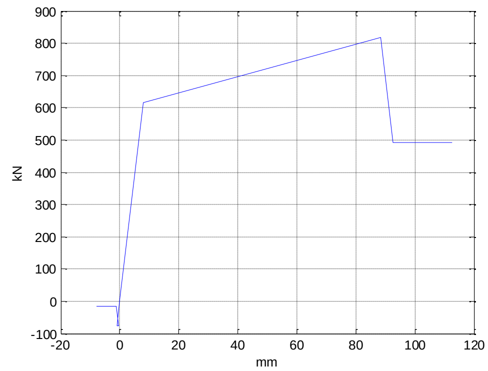


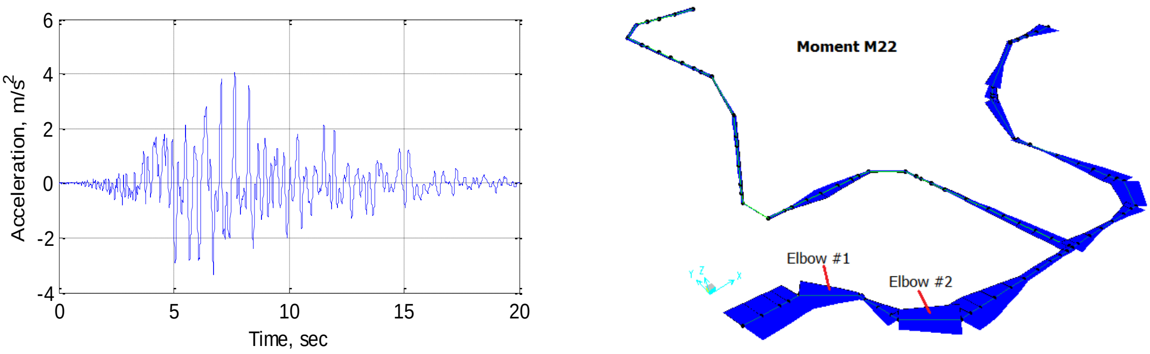
Figure 5. Nonlinear model for cross bracing x3.

Since the piping system considered herein represents a moderately hazardous facility, the SLLS was considered equivalent to the OBE earthquake. However, as discussed above the SSE ground motion would be too severe. Nonetheless and in order to consider a ground motion beyond the OBE, the one associated with the CLS earthquake reported in Table 5 - corresponding to a T_R equal to 1462 years- was considered. Along this line, the input earthquake for the analysis was generated using the Italian spectrum specific of the place where the structure was placed; see in this respect Fig. 6(a) that shows the input accelerogram corresponding to the CLS.

Table 5. pga values corresponding to different limit states

Limit States			pga (g)
Serviceability limit state	Operational limit state	OLS	0.05
	Damage limit state	DLS	0.08
Ultimate limit state	Safe life limit state	SLLS	0.29
	Collapse limit state	CLS	0.41

The piping system was analysed with the four levels of earthquakes listed in Table 5. Seismic loadings were applied in the horizontal x direction (see Fig. 3(b)) adopting a Rayleigh damping considering a 4% damping for the structure suggested in [30]. The maximum stresses and strains in pipes at SLLS and CLS were then compared to the $M_{a,OBE}$ and $M_{a,SSE}$, respectively. Analysis were also carried out at OLS and DLS level earthquakes to check the performance of piping systems at those levels.



(a) (b)

Figure 6. (a) Input earthquake accelerogram and (b) Moment about z axis in the piping system at CLS.

Moments about z axis, M_z in the piping system at CLS is presented in Fig. 6(b); the maximum moment was observed in Elbow #1. Stresses and strains were then compared with corresponding allowable values (see Table 8) calculated according to Eq. (1) and (2) listed in Table 6 and 7. One can see from Table 8 that both the maximum stress and strain at SLLS were below the allowable stress at OBE, $\sigma_{a,OBE}$, while these values at CLS were below the allowable stress at SSE, $\sigma_{a,SSE}$. One may note that while the maximum stress levels are below the allowable limits by a lower margin, maximum strains were found to be far below the allowable limits suggested by standards. In fact, a higher level of plastification is allowed by the strain based design methods. Nevertheless, the above analysis indicates that the piping system remains below its nominal yield strength, i.e. 418 MPa, under an OBE or SSE level earthquake.

Table 6. Allowable stress at OBE, $\sigma_{a,OBE}$ and at SSE, $\sigma_{a,SSE}$

	Stress limit	
Code	$\sigma_{a,OBE}$ (MPa)	$\sigma_{a,SSE}$ (MPa)
EN 13480-3	195.99	293.99
ASME B31.1 & B31.3	217.23	-

Table 7. Allowable strain in pipes

	Strain limit	
Code	Tension limit	Compression limit
CSA-Z662 (2007)	2.5%	1.6%
DNV-OS-F101 (2000)	2.0%	-
ASCE (2005)	2.0%	-

Table 8. Maximum stresses and strains in the piping system at SLLS and CLS

Limit States	Elbow	Stress (MPa)	Strain
SLLS	Elbow #1	186.46	0.093%
	Elbow #2	184.02	0.092%
CLS	Elbow #1	251.53	0.126%
	Elbow #2	248.11	0.124%

4. CONCLUSIONS

Due to the scarcity of adequate and uniform seismic design guidelines for petrochemical, oil & gas piping systems, designers are compelled to follow standards conceived for other structures, such as buildings and nuclear plants. In this paper, a performance-based seismic analysis of petrochemical piping systems through two realistic case studies was presented. Several issues related to the seismic design and analysis of piping systems were addressed, and relevant design/analysis rules suggested by international codes and standards were discussed. Current allowable stress- and strain-based verification methods were commented. In this respect, a discussion on the selection of proper seismic inputs was offered showing the limits of current guidelines. Two realistic piping systems were analysed in the nonlinear regime for limit states suggested by modern performance-based earthquake standards; and a comparison between computed stresses and strains and allowable code-based design values were made. A favourable performance of both the piping systems under chosen limit states was found. It was found maximum stress and strain values in both the piping systems remained below their yield strengths and allowable limit values even at the collapse limit state.

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