17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Seismic design and assessment of risk-targeted reduction factor for a reinforced concrete pipe rack – piping system

G. Karagiannakis[1], L. Di Sarno[1,2], Jure Žižmond [3], Matjaž Dolšek [3]

[1] *Department of Engineering, University of Sannio, Benevento, ITALY, {karagiannakis, ldisarno@unisannio.it}*
[2] *School of Engineering, University of Liverpool, {Luigi.Di-Sarno@liverpool.ac.uk}*
[3] *Department of Civil and Geodetic Engineering, University of Ljubljana, {jzizmond, mdolsek@fgg.uni-lj.si}*

Abstract

The procedure for estimating a target risk for adverse consequences of earthquakes should be developed in close cooperation with stakeholders and decision-makers who understand the high impact of the potential failure of industrial facilities on society and business state. However, the conventional procedures for earthquake-resistant design of critical infrastructures are not developed to such a level that would make it possible to use a target risk as an input parameter for designing the structures. This issue can be overcome by introducing the risk-based formulation for the evaluation of seismic design action for force-based design. In such an approach, the reduction factor depends on a target probability of exceedance of a designated limit state and takes into account the ground-motion randomness and uncertainty. In general, the formulation of the risk-targeted reduction factor depends on the code format for the reduction of seismic action. In this paper, the Eurocode's format of force-based design is used. Therefore, the reduction of seismic action is accounted for by the behaviour factor.

Several structural parameters have to be assumed in order to estimate the risk-targeted behaviour as discussed in the paper. In virtue of poor knowledge concerning the nonlinear response of pipe rack – piping systems, it is very challenging to appropriately assume these parameters. Thus, a reinforced concrete pipe rack, which represents a part of a liquified natural gas terminal, was firstly modelled and designed according to Eurocode 8 accounting for the low and high probability of earthquake recurrence aimed at designing the system for damage and life safety objective, respectively. The pipe rack, the piping system and the interaction of the pipe rack – piping system with the adjacent storage tank were explicitly considered in the 3D model, which provided full dynamic coupling of the three components of the analysed system.

The seismic performance assessment of the pipe rack and piping system was performed by the incremental dynamic analysis using a set of 11 spectrum compatible ground motions. Based on the results of IDA analysis, the design of pipe rack was evaluated on the safe side, however, the pipelines presented higher vulnerability due to a number of assumptions that are discussed. For the presented example, it was shown that the behaviour factor for the design of the pipe rack – piping system is controlled by the performance of the pipes and not the structure supporting the pipes.

Keywords: seismic design; behaviour factor; pipe rack; pipelines; seismic hazard.

1. Introduction

The concept of global response modification during the design process towards taking advantage of nonlinear material properties is well-known since the beginning of the century. It intends to design a structure for smaller forces than those that it will experience during its reference life by introducing a behaviour (in European or EC8) or response modification (in American or US) factor (hereon simply termed q- or R-factor, respectively). The q-factor depends on the ductility reduction factor and the overstrength factor. The former is relevant to the ability of the structure to deform beyond the yielding point and nonlinear seismic response of a structure with respect to the linear response, whereas the second regards the additional strength beyond the design strength up to yielding one. Comprehensive research endeavours of the deterministic perception of q- or R-factor could be found [1]–[5] in . In the risk-based formulation introduced by Žižmond and Dolšek [6], the behaviour factor account for a target probability of exceedance of the near-collapse limit state, the return period of the elastic acceleration spectrum used for the design, the slope of seismic hazard function and the dispersion of limit state intensity causing exceedance of the near collapse limit state.

Eurocode 8 [7] (EC8) and the National Italian code (NTC) [8] prescribe q-factors that could be characterized as empirical and not strictly risk-targeted for common buildings, let alone non-common building structures. For instance, a design of a non-building structure such as the Reinforced Concrete (RC) Pipe Rack (PR) – Piping System (PS) that the present study addresses should account for a higher return period of earthquake occurrence, not only due to the importance of a process plant but also for the response of critical supported equipment e.g. pipelines that transfer hazardous materials. Thus, selecting common values of q-factor from the codes might not be an utterly justifiable option, since they refer to the commonly adopted return period of 475 years increased by a constant importance factor (γ) depending on the importance of a structure. On the other hand, the US code [9] postulates factors based upon risk-targeted seismic design maps with respect to maximum considered earthquake of 2475 years return period. Higher values of R-factor compared to the values of q-factor from EC8 are partly a consequence of inconsistency of a return period of seismic design action. It is generally accepted that in the US code, the seismic design action could be reduced by 2/3 - this factor is empirical and refers to additional overstrength that damaged structures reserved in the US till collapse - in order to provide the life safety performance level for ordinary buildings (Seismic Design Category II), whereas the collapse prevention performance level is satisfied for the maximum considered earthquake level. Furthermore, the US code [10] prescribes a framework for probabilistic evaluation of system performance factor for all building systems recognizing that this objective may not be fully achievable for certain structural configurations e.g. PRs.

The probabilistic evaluation of q-factor has been gaining ground against the deterministic method after the entrance of risk assessment of structures. Some early approaches for probabilistic q-factor calculation relied on the modelling of uncertainties in the design as well as on the probability of failure. Thomos and Trezos [11] showed that the uncertainties affected the q-factor mean value and Chryssanthopoulos et al. [12] showed that the behaviour factor proposed by the codes is conservative for ordinary buildings design. Finally, Costa et al. [13] proposed a probabilistic methodology that assumes a predefined level of displacement ductility capacity and failure probability towards estimating the optimal q-factor. The study showed among others that the structural irregularity was more considerable compared to regular structures when the ductility demand was greater. Pipe racks are usually irregular both in vertical and horizontal direction (no diaphragmatic behaviour) and are usually modelled with low ductility demand so that to reduce differential displacements at the level of piping systems. However, this construction strategy may lead to high peak floor acceleration which might also be unacceptable for piping safety ([14]). Thus, it is evident that the response of a PR – PS may be governed by the behaviour of nonstructural elements.

Recently, a framework for the estimation of the risk-targeted reduction (behaviour) factor has been proposed by Žižmond and Dolšek [6]. The methodology utilizes a risk-targeted safety factor proposed in [15] and the assumed values of overstrength and ductility reduction factor for the determination of the risk-targeted reduction factor (behaviour factor). In this paper, the procedure was used for the determination of risk-targeted reduction factor for a RC PR-PS. The obtained reduction factor, either of PR or PS, is compared to the prescribed values in the codes towards highlighting the applicability of force-based design.

2. Behaviour (q) factor for structural and nonstructural elements

The selection of behaviour factor for the design of PR - PSs is not straightforward since apart from the pipe rack type (e.g. concentrically braced or moment-resisting frame and pipelines type of joints), the adequate analysis method should be considered. Therefore, when the dynamic coupling is not considered, separate q-factor could be accounted for the design of structural members and pipelines as prescribed in seismic codes. Otherwise, the q-factor is selected as the minimum between the two. EC8 postulates q-factors for irregular structures that could not be necessarily appropriate for pipe racks. Different types of loading exerted by the equipment as well as the higher risk that they are designed for are parameters that should be considered in a more robust manner. On the other hand, US codes propose values for different types of PRs. The values of q-factor for different ductility classes, namely Ductility Class Low, Medium and High (DCL, DCM and DCH, respectively) as prescribed by EC8 and US codes (the pertinent reference of US codes is ordinary, intermediate and special, respectively) for RC moment frames such as the one that is addressed in the sequel are demonstrated in Table 1. EC8 does not postulate values for low ductility class, and this might be another indication that they are not appropriate for PRs. The values are multiplied by the ratio a_u/a_1, which accounts for the redundancy between the first plastic mechanism of a structural member till structural instability. It is also pointed out that the factor should be reduced by 20% in order to account irregularities, if any. As mentioned previously, the US code values for concrete PRs are considerably greater than those in the EC8, probably because of different seismic demand level, thus a direct comparison between them is not feasible.

Table 1 – Behaviour factors for concrete moment resisting pipe racks (after [7] and [9])

	DCL	DCM	DCH
EN	N.A	$3.0\ a_u/a_1^*$	$4.5\ a_u/a_1$
US	3	5	8

$^*a_u/a_1$=1.1, 1.2 & 1.3 for one storey, multistorey one-bay frame and multistory multi-bay frames, respectively.

When it comes to behaviour factors for non-seismic isolated pipelines, EC8 postulates values that depend on the radius over thickness ratio (r/t). As shown in Table 2, the less the sensitivity of pipe to buckling failure is, the greater the behaviour factor is, varying from 3 to less than 1.5. On the contrary, the US code proposes values that are considerably higher in comparison with EN and are not categorised as previously. The EN q-factors may refer to above grade pipelines and not necessarily pipelines mounted on complex supporting structures, where the seismic amplification is expected to be higher. Also, the US code clearly states that nonstructural components are designed for design earthquake ground motions and not the risk-targeted maximum considered earthquake as structural systems, since there are no implicit performance goals associated with the last seismic intensity for nonstructural components. The R-factor ranges from 6 to 12 for code and non-code conforming steel pipelines. The high values might stem from the fact that steel pipelines are designed as flexible enough to accommodate high displacements and are intended to reflect the rigorous design requirements and intensified stresses postulated in [16]. When pipelines are analysed as coupled with PRs, it is obvious that the latter cannot be designed for such a high q-factor value since there is a clear need to restrict differential displacements on pipelines level and the absence of diaphragmatic behaviour cannot ensure a great involvement of dissipative elements.

Table 2 – Behaviour factors for non-seismic isolated pipelines (after [9] & [17])

q (EN)			**R (US)**		
r/t<50	r/t<100	r/t>100	Welded connections	Welded connections (non-code conforming)	Non-welded connections
3	2	<1.5	12	9	6

A closed-form solution that correlates the q-factor of a PS with the ductility of the supporting structure was proposed by Okeil et al [18]. The factor is also dependent on the piping to seismic action frequency ratio. It was deduced that the more flexible configuration of piping system requires less support ductility demand than the stiffer system and the q-factor increases with the ductility μ. However, the value of pipe q-factor was never greater than 3-4. Finally, a piping system was analysed in [19] accounting for gap and friction. The nonlinearity between the PR and pipelines (friction) caused the reduction of the acceleration by the order of 2-3 with respect to the elastic case. The aforementioned deductions come in disagreement with the values proposed in US code [9], however, they belong into the range proposed by EC8 [7].

3. Description of the pipe rack and piping system

The present study examines the seismic response of a regasification sub-plant that consists of a RC PR-PS and a storage tank (Fig. 1). Several pipelines are mounted on the rack in order to distribute ethylene from the tank into the nearby process units. Since the modelling of the entire pipelines is impossible from the computational point of view and time constraints, only the pipe rack PR1 and corresponding PS are analysed along with the storage tank.

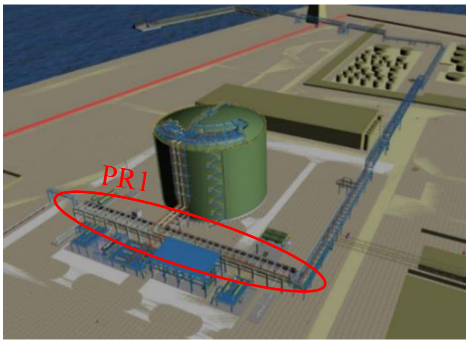


Fig. 1 – Ethylene terminal layout and the RC pipe rack under consideration next to the storage tank

3.1 Pipe rack – storage tank

The short and long part of PR1 in front of the storage tank are made of concrete C40/50 due to fire resistance requirements but the concrete could also be a preferable solution against steel due to time constraints and costs. The reinforcing steel grade B500C was adopted for the reinforcing steel. More information about the geometrical and mechanical characteristics of the PR can be found in [20].

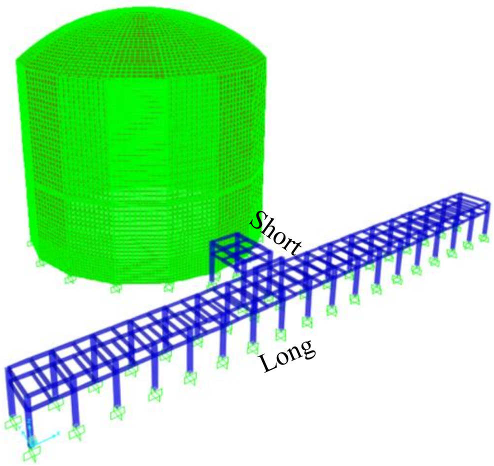


Fig. 2 The RC pipe rack (short and long) and the storage tank as modelled in [21]

The tank serves to store ethylene at low temperature and has a maximum capacity of 29000 tonnes. The tank is 38 m tall, has 24.5 m inner radius and 65 cm wall thickness. The tank dome has an average thickness of 600 mm and reaches an overall height of 47.4 m. Since the tank is full of containment, only one predominant mode was considered during the seismic design. The impulsive mass was placed at 42% of total cylindrical tank height as noted in [22] and [23].

3.2 Piping system

The PS is supported on PR for maintenance, operational and safety reasons. The layout of 7 pipelines is shown in Fig. 3 and strongly depends on the position of surrounding process units that pipelines run to. The pipes have different diameters ranging from 16” to 4” and transfer ethylene. The pipes are made of A312/TP304L steel with 0.2% proof stress equal to 250 MPa.

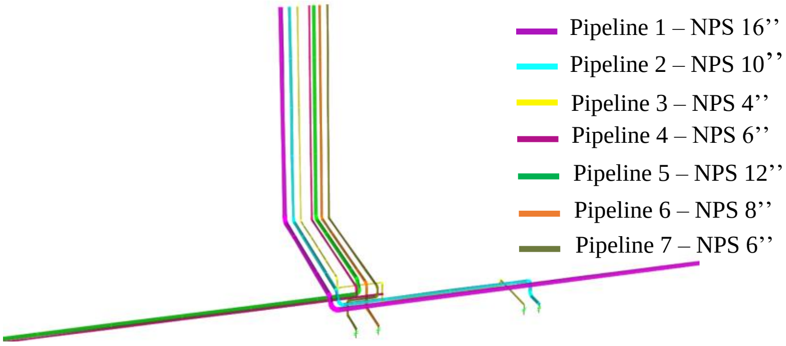


Fig. 3 – The piping system layout as modelled in [21] by using beam elements

4. Seismic design of pipe rack and piping system

The model for the seismic design was prepared by considering the dynamic coupling between the pipe racks and pipelines. According to EC 8 [7] and NTC [8], nonstructural elements that are expected to influence the behaviour of the primary structure should be accounted for in the analysis. Also, industrial equipment that may impose risk within critical facilities should be designed to resist the design seismic action with appropriate response spectra stemming from the supporting structural elements. Thus, the seismic codes do not stipulate clearly criteria for accounting or neglecting the dynamic interaction between primary structure and nonstructural elements. To this effect, common industrial practice analyses separately industrial equipment with a supporting structure, thus neglecting interaction phenomena and facilitating modelling difficulties that could arise particularly when using software that does not involve e.g. special pipe supports or pipe plasticity models. When the decoupled case is considered, several concerns should be addressed. For example, the use of the in-structure spectrum method might not account for differential movements of pipe supports within a rack or between adjacent ones. Therefore, as mentioned previously, for the design of the structure presented in this study, the coupled case was considered.

Three main parameters have to be examined when modelling and designing piping systems. It is obvious that the type of pipe elements is of paramount importance for describing the seismic response of pipes and fittings. During the design, beam elements were used for both straight and pipe bends. In particular, the elbows were modelled by discretising the curved part into 20 elements, which was found accurate enough when comparing the resistance of the elbow with beam and shell elements.

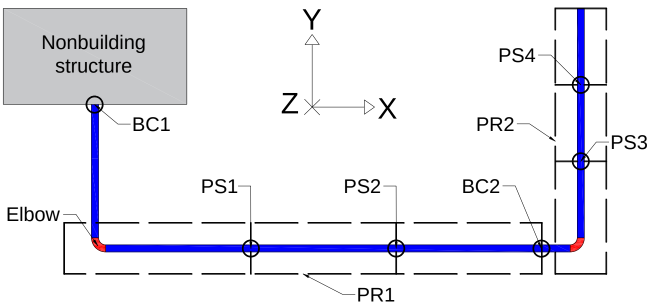


Fig. 4 Flexibility/rigidity of pipelines connection with a pipe rack or adjacent structures

Apart from the type of pipe elements, the type of pipe connection to the PR is also important for a robust modelling of pipes. Since the PR is located in a high seismicity area, there is a high need for attributing flexibility to the PS in order to absorb high displacements. Also, the pipe-to-pipe support friction is omitted in order to stay on the safe side. Consequently, the pipelines are usually unrestrained in the longitudinal direction, and all the rotations are free as well. In case of our piping system, it was decided that the pipe supports PS1 and PS2 of pipelines supported on pipe rack PR1 (Fig. 4) are restrained only in the Y and Z direction. To this effect, the failure is concentrated mainly on pipe bends (elbows) and pipe supports e.g. PS1 or connections e.g. BC1, in case there are considerable differential displacements between two adjacent structures e.g. pipe rack and storage tank (nonbuilding structure).

Also, the consideration of boundary conditions at pipe edges is of paramount importance for achieving a robust and adequate model of PS. Usually, pin or fixed connections are assumed, overlooking the flexibility of pipes that might bend upwards or downwards after running out of the main pipe rack frame. For example, it might be necessary due to the process layout of a plan, a pipeline to run from a storage tank to an adjacent PR1 and PR2 (Fig. 4). If only the PR1 is modelled due to time-constraints, appropriate boundary conditions (BC2) are adopted to account for the flexibility of pipe on PR2. In this study, the remaining part of pipelines is taken into account by calibrating springs for each degree of freedom and placing them at pipe edges. In order to calibrate the springs, a finite element analysis model was created on ABAQUS for the remaining part of each pipeline shown in Fig. 3 and subjected under axial, shear and bending deformation keeping each time all the other degrees of freedom constant. Then, the elastic stiffness of the force-deformation curve was obtained and assigned at the pipe edge for each degree of freedom.

The RC PR had originally been designed for a low-seismicity area, but in order to acquire a better insight into the seismic response of the most critical components, in the framework of this study, it was placed to one of the most seismic-prone areas in Italy (Priolo Gargallo, Sicily, Italy) and re-designed. The PR was designed according to the NTC [8] for the Damage Limitation State (DLS) and the Safe Life Limit State (SLLS) requirement. The design parameters for both LSs are summarized in Table 3. Although NTC [8] and EC8 [7] do not prescribe values of q-factor for pipe racks, a value equal to 3.3 was assigned considering that the rack does not have significant irregularities and is one storey moment frame (a_u/a_1=1) (see also Table 1).

Table 3: Design parameters for the RC rack

	Location	Priolo Gargallo, Sicily
	Soil	Type C
DLS	PGA	0.08g
	q-factor	3.3
	T_R	75 yrs
SLLS	PGA	0.30g
	q-factor	3.3
	T_R	713 yrs

Table 4: Design parameters for the RC rack

SLS	Characteristic combination (irreversible)	$G_1 + G_2 + \gamma_Q \cdot Q_k = 1.0G_1 + 1.0G_2 + 1.0 \cdot Q_{k1}$
ULS	Fundamental combination	$\gamma_{G1} \cdot G_1 + \gamma_{G2} \cdot G_2 + \gamma_Q \cdot Q_k = 1.3 \cdot G_1 + 1.3 \cdot G_2 + 1 \cdot Q_{k1}$
SLS+ULS	Seismic combination	$G_1 + G_2 + \psi_{21} \cdot Q_{k1} + E = G_1 + G_2 + 0.8 \cdot Q_{k1} \pm 1.0(0.3)EQX \pm 0.3(1.0)EQY$

G: permanent load for structural (1) and nonstructural elements (2), Q: variable load for future installation of equipment on the rack, γ_G(1,2): permanent load factor, γ_Q: variable load factor for semi-permanent load regarding industrial equipment.

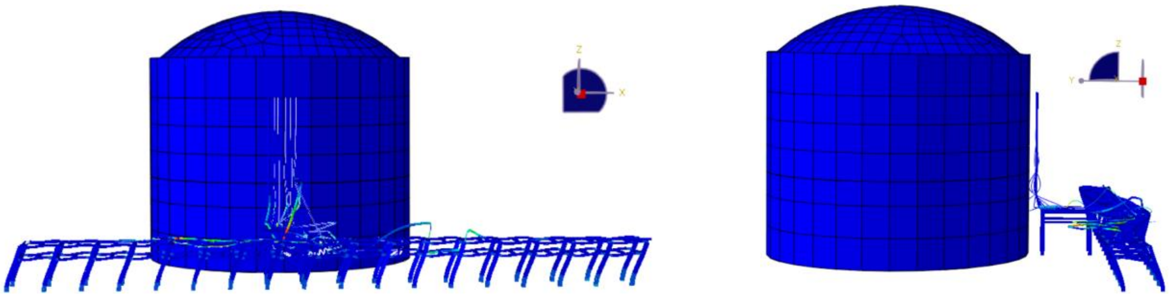
The RC PR was analysed with response spectrum analysis coupled with the pipelines and 4 main load combinations, with and without an earthquake, as stipulated in NTC [8] (Table 4). In the design, the dead load of the RC PR and PS was considered as permanent load, whereas the weight of pipelines due to future installation was accounted as variable load. The weight of the pipes was applied to the beam by adding the additional uniform load of 4kN/m at the location of the pipes supports. Note that the internal pressure in pipelines is neglected in order to be on the safe side, since it has been found that the bending resistance increases due to pressure. Also, appropriate load factors that regard to industrial equipment were considered. The mass of ethylene inside the pipelines was considered by increasing the density of steel material.

The design of the PS was based on NTC [8] as well. The EN13480-3 [24], which covers the design and calculation of metallic industrial piping, describes two seismic levels, namely the Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE), in contrast with ASME B31.3 [16] that accounts only for the former. In the framework of this study, the OBE seismic level regarded the seismic design action and the SSE was correlated with the Safe Life Limit State (SLLS). The PS was also designed with response spectrum analysis accounting for the maximum strains for both OBE and SSE level, which are quoted in Table 5. The pipes were designed to remain below the yielding point for both seismic levels. Note that the maximum strain was observed on elbows, as it was expected.

Table 5: Max design strain of elbows and straight pipes

Max strain ε (‰)	Response Spectrum	
	Elbow	Straight
OBE	0.5	0.4
SSE	0.7	0.5

The two principal modes in the X and Y direction are shown in Fig. 5a and 5b, respectively. From the Figure, it can be clearly seen that differential displacement of the long part of PR1 with the short one as well as with the storage tank could govern the seismic response.


a) b)
Fig. 5 The two principal modes of the system in a) X and b) Y direction

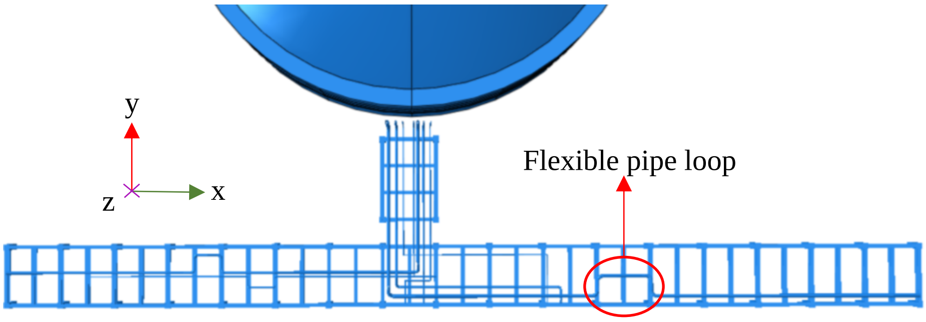


Fig. 6 Seismic code-conforming piping system configuration with flexible loops

The structural member sections of PR increased considerably in comparison to the original structure, since it was necessary to reduce the differential displacement at piping system-level particularly in the Y direction due to the differential displacement with the adjacent rack (Fig. 6). The final cross-sections of beams and columns for the PR1 are demonstrated in Fig. 7. The layout of pipelines was also changed in comparison to the original structure in order to comply with the code requirements. In particular, flexible pipe loops were created for some pipes in the longitudinal direction in order to reduce pipe overstressing at the edges as shown in Fig. 6.

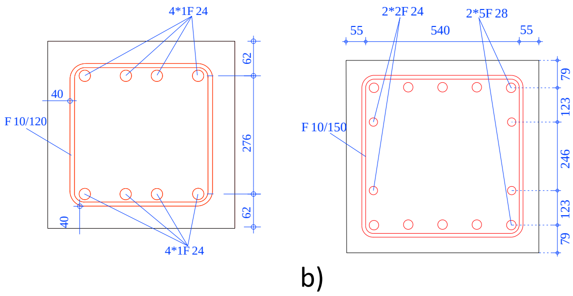


Fig. 7 Reinforcement layout for a) beam and b) column member

5. Assessment of the seismic response of the pipe rack and piping system and calculation of risk-targeted reduction factor

The PR - PS was assessed to estimate the risk-targeted reduction factor according to the procedure proposed by Žižmond and Dolšek [1]. Incremental Dynamic Analysis (IDA) method offers a thorough understanding of response – intensity measure relation, record-to-record variability and global system capacity at collapse region ([25]). Thus, 11 spectrum compatible records were selected (Fig. 8) according to [26] for the assessment of the structural system. The number of runs per each record was dependent on the record. The initial run was determined roughly at 0.05g and step increments of 0.1g was employed, whereas additional analyses were conducted close to collapse for higher accuracy. The scaling factor was applied both for the horizontal (H) and vertical (V) component in order to keep the ratio V/H constant.

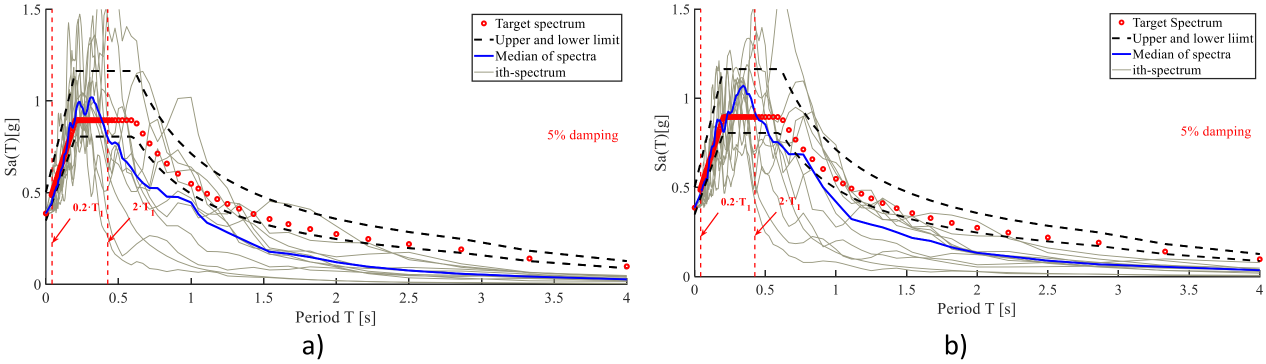


Figure 8: Selection of 11 records for the a) X, b) Y component through the uniform hazard method as prescribed in [26]

The analyses of the seismic response were performed on ABAQUS. The PR and tank were modelled as linear elastic since the preliminary analysis on the PR showed that no plastic deformation was observed even at high values of PGA. On the other hand, the PS was modelled using nonlinear elements. In particular, the PR was modelled with the 3-node B32 beam element as described in [27], whereas the response of pipelines was examined with stick pipe models, and the special purpose element ELBOW32 was adopted for the pipe bends for higher accuracy. The material of pipe steel was described with a bilinear curve with 277 MPa yielding strain and 352 ultimate one at 5% plastic strain. The material density increased to account for the ethylene in the same manner as during the design phase.

The pipelines were checked for two limit states (i.e. yielding (Y) and near-collapse (NC)). The definition of limit states for pipelines is commonly based on engineering judgment and the degree of conservativeness. However, there are three main failure modes of the pipeline, i.e. the failures under tension, compression (local buckling) and fatigue. Regarding the failure under tension, usually, the values of yielding strain (ε_y) equal to 0.12% and strain equal to 0.5% (e.g. [28]) are adopted for the yielding and near-collapse limit state, respectively. The failure under fatigue has been reported as equally crucial for pipelines [28], and is correlated with the buckled area of the pipe due to compressive strain and occurs due to strong repeated loading in that area after reaching the compressive strain resistance (ε_{Cu}). In this study, the values proposed by Vathi et al. [28] are adopted. In particular, the yielding limit state is correlated with the yielding strain, whereas the near-collapse limit state is associated with the compressive strain resistance ε_{Cu}. Assuming ε_{Cu} as the ultimate strain resistance of pipes is on the safe side, considering that a buckled pipe is rather vulnerable and needs replacement. Even if the loss of containment event has not occurred, the pipe poses an immediate threat to plant safety, since failure may occur due to future earthquakes of lower magnitude. The ε_{Cu} strain for NC limit state for all pipelines, which are calculated based on the proposal of Vathi et al. [28] are presented in Table 6 (the strain refers to the lower bound). Note that since the PR – PS was analysed on rigorous finite element analysis program ABAQUS ([27]), the plasticity development on pipes was examined by using the scalar measure PEMAG (plastic strain magnitude).

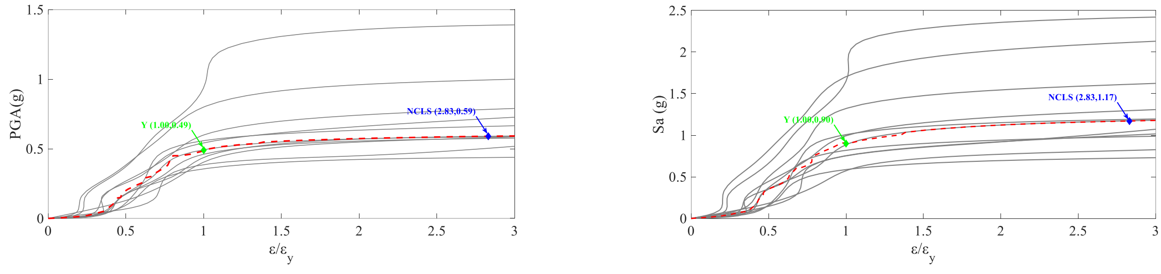
Table 6: Plastic strain (ε_{Cu}) of elbows and straight pipes assessment for NC limit state

ID	P1	P2	P3	P4	P5	P6	P7
SLLS	0.34%	0.52%	1.08%	0.76%	0.46%	0.61%	0.76%

The relationship between the maximum strain of the pipelines normalised to yielding strain and PGA (IDA curves) are presented in Fig. 9a. The median PGA that regarded the NC limit state of pipes was nearly 2 times greater than the design PGA. The IDA curves were also plotted against S_e (Fig. 9b) for the estimation of the reduction factor r_{NC}, which takes the overstrength and ductility reduction factor of a structure into account and is given by ([6]):

$$r_{NC} = \frac{S_{e,NC}}{S_{e,D}} \qquad (1)$$

where the numerator refers to the spectral acceleration that causes a NC limit state of the pipelines, (i.e. $S_{e,NC}$ =1.17g), and the denominator regards the design spectral acceleration $S_{e,D}$, which is equal to 0.26g. Thus, r_{NC} was estimated equal to 4.5.



a) b)

Figure 9: The IDA curves of pipelines plotted against a) PGA and b) S_a(T_x=0.19 sec, 5%)

In order to calculate the risk-targeted reduction factor (q_a), Dolšek et al. [15] introduced a risk-targeted safety factor γ_{im} that divides the reduction factor r_{NC} and intends to connect the intensity associated with target probability of collapse of the structures with the elastic spectral acceleration $S_{e,713}$ (Figure 10). Apart from a closed-form solution and a simple model that was developed in [15], the γ_{im} can be calculated as a ratio between risk-target spectral acceleration causing near-collapse limit state $S_{e,NC,a}$ and the elastic spectral acceleration $S_{e,TR}$ (i.e. $S_{e,713}$), which is obtained from hazard maps, from hazard curve or from elastic spectrum. The $S_{e,NC,a}$ can be calculated as a ratio between risk-target spectral acceleration causing collapse limit state $S_{e,C,a}$ and limit state reduction factor γ_{ls} which was introduced in [15]. There are several ways to calculate $S_{e,C,a}$. However, in general, it can be assessed by numerical solution of risk-equation:

$$P_{C,a} \approx \lambda_{a,C} = \int_0^\infty P\left(C \middle| S = S_e; S_{e,C,a}, \beta_C\right) \cdot \left|\frac{dH(S_e)}{dS_e}\right| \cdot dS_e \qquad (2)$$

where H is a known hazard curve (for the location of a structure) for spectral acceleration S_e at the first fundamental period of the rack, P(·) is targeted-collapse fragility function, which is unknown and should be estimated. For this purpose, the median values (in our case $S_{e,C,a}$) and the dispersion $\beta_{C,a}$ should be defined. The value of $\beta_{C,a}$ is not so sensitive with respect to $P_{C,a}$, and thus the target $\beta_{C,a}$ can be assumed equal to β_C. Since the target probability of collapse is defined, the only unknown parameter of Eq. 2 is $S_{e,C,a}$, which can be calculated numerically.

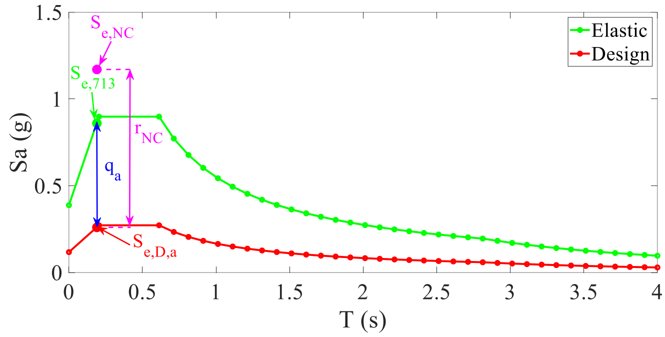
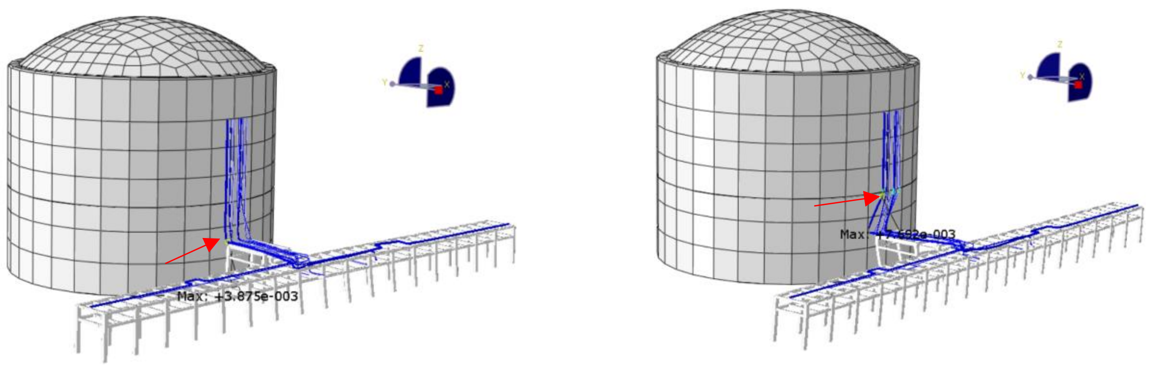


Figure 10: The concept of q-factor estimation using the indirect method as introduced in ([6])

For the analysed pipeline, it was decided to set the target probability of collapse equal to $1 \cdot 10^{-4}$. Since the literature is scarce on the fragility of pipelines supported on pipe racks and codes do not stipulate values as for common building structures, a value of β_C equal to 0.26 was assumed based on the model proposed by Dolšek et al. [15]. Using the previously-defined parameters and hazard curve for the location of the structure, the $S_{e,C,a}$ was estimated to be equal to 3.60 g. The $S_{e,NC,a}$ (3.44 g) was calculated as the ratio between $S_{e,C,a}$ and limit state reduction factor γ_{ls} (1.05), which was calculated based on model proposed in [15]. In order to calculate γ_{im}, the $S_{e,713}$ had to be assessed. In our case, the $S_{e,713}$ (0.86 g) was obtained from elastic spectrum defined based on PGA for return period 713 years (i.e. 0.30g), since this spectrum was used in the design of the system. After doing so, the γ_{im} was estimated as 3.44/0.86=4.00. The risk-targeted reduction factor is then calculated as follows ([6]):

$$q_a = \frac{r_{NC}}{\gamma_{im}} = \frac{r_{NC}}{S_{NC,a}/S_{e,713}} = \frac{4.50}{3.44/0.86} = \frac{4.50}{4.00} = 1.13 \tag{3}$$



a) b)

Figure 11: Critical point of pipes failure at a) pipe bend, and b) attachment on the tank (PGA=2·OBE)

The calculated risk-targeted q-factor for pipelines is considerably lower than the code-based values proposed and values proposed in Table 2 by seismic codes. This is an intriguing outcome that concerns particularly the design of PRs that support flexible pipelines. Pipelines were more vulnerable than the structure because the pipelines were flexible in the longitudinal direction, and thus differential displacements due to the tank and the adjacent short rack caused pipe failure mainly on pipe bends and at the attachment point of pipes to the tank. The pipeline with the greatest diameter (P1) was the most vulnerable and the corresponding critical pipe locations are demonstrated in Fig. 11.

The outcome of this study is in unison with the conclusions of [18]. The pipe supporting system was considered as rigid, and the pipes were flexibly supported in the longitudinal direction, resulting in low ductility demand of pipe supports and low q-factor of pipes, afterwards. If the pipe supports were considered with higher ductility (e.g. flexible springs) and the piping system was more rigidly supported (e.g. special pipe fasteners), the q-factor of pipes could be greater as it was proved in [18].

6. Conclusions

The modelling, risk-targeted force-based design and assessment of a selected RC pipe rack – piping system was addressed in this paper. According to the results and the findings of the study, the following conclusions can be made:

- the seismic vulnerability of the pipeline is higher than that of the pipe rack. The estimated risk-targeted reduction factor was by 66% lower than then behaviour factor by EC8. This is an idiosyncrasy of this kind of systems, where the response is governed by displacement-sensitive pipelines and not by the response of the structure. Therefore the force-based design, which is by the code prescribed for the design of the structure, may not be totally applicable to the pipe rack – piping system;
- the analysis methods of pipelines in seismic codes that do not account for dynamic coupling with pipe racks may underestimate the seismic demand in the pipes, which may not be solved by assuming higher values of reduction factor;
- the definition of near-collapse acceptance criterion is rather considerable for the estimation of risk-targeted behaviour factor of pipelines, however, it is still based on engineering judgment. This may lead to conservative assumptions.

The literature is still scarce on the design of pipe racks. In future research, it is necessary to further develop practice-oriented design approaches that might account for the stress-based design of pipes in conjunction with pipe racks displacement, which might lead to less stiff pipe racks (material saving) and even safer pipelines design. In virtue of a number of assumptions made and the idiosyncrasies of the system, the results presented in this study may not be generalised for other pipe racks.

7. Acknowledgements

The work presented herein has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No 721816. This support is gratefully acknowledged.

8. References

[1] M. Fischinger and P. Fajfar, “On the response modification factors for reinforced concrete buildings,” in *4th US NCEE. Palm Springs. 1990;2:249-258.*

[2] M. Fardis, E. Carvalho, P. Fajfar, and A. Pecker, “Seismic Design of Concrete Buildings to Eurocode 8. 1st ed. Boca Raton: CRC Press; 2015.”

[3] E. Miranda and V. V. Bertero, “Evaluation of Strength Reduction Factors for Earthquake-Resistant Design,” *Earthq. Spectra*, vol. 10, no. 2, pp. 357–379, 1994.

[4] C. M. Uang, “Establishing R (or Rw) and Cd factors for building seismic provisions,” *J. Struct. Eng.*, vol. 117, no. 1, pp. 19–28, 1991.

[5] A. S. Elnashai and L. Di Sarno, *Fundamentals of Earthquake Engineering: From Source to Fragility*, Second. Wiley, 2015.

[6] J. Žižmond and M. Dolšek, “Formulation of risk-targeted seismic action for the force-based design of structures.,” *Earthq. Eng. Struct. Dyn.*, vol. 1–23, 2019.

[7] EN1998-1, *Eurocode 8: Design of structures for earthquake resistance - Part 1 : General rules, seismic actions*

and rules for buildings, vol. 1, no. English. 2004.

[8] NTC, *"Norme Tecniche per le costruzioni", DM Infrastructure, 14 January*. (in Italian), 2018.

[9] ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. 2017.

[10] FEMA P695, *Quantification of building seismic performance factors. Prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, DC. 2009.* 2009.

[11] G. C. Thomos and C. G. Trezos, "Behaviour factor of RC structures: A probabilistic approach," in *WIT Transactions on the Built Environment*, 2005.

[12] M. K. Chryssanthopoulos, C. Dymiotis, and A. J. Kappos, "Probabilistic evaluation of behaviour factors in EC8-designed R/C frames," *Eng. Struct.*, 2000.

[13] A. Costa, X. Romão, and C. S. Oliveira, "A methodology for the probabilistic assessment of behaviour factors," *Bull. Earthq. Eng.*, 2010.

[14] A. D. L. Di Roseto, A. Palmeri, and A. G. Gibb, "Performance-based seismic design of a modular pipe-rack," in *Procedia Engineering*, 2017.

[15] M. Dolšek, N. Lazar Sinković, and J. Žižmond, "IM-based and EDP-based decision models for the verification of the seismic collapse safety of buildings," *Earthq. Eng. Struct. Dyn.*, vol. 46, no. 15, pp. 2665–2682, 2017.

[16] ASME B31.3, "ASME Code for Pressure Piping, B31 - ASME B31.3-2008 (Revision of ASME B31.3-2006)," *Chem. Eng.*, vol. 76, no. 8, pp. 95–108, 2008.

[17] EN1998-4, *Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]*. 2006.

[18] A. M. Okeil and C. C. Tung, "Effects of ductility on seismic response of piping systems and their implication on design and qualification," *Nucl. Eng. Des.*, 1996.

[19] H. Kobayashi, M. Yoshida, and Y. Ochi, "Dynamic response of piping system on rack structure with gaps and frictions," *Nucl. Eng. Des.*, 1989.

[20] L. Di Sarno and G. Karagiannakis, "On the seismic fragility of pipe rack—piping systems considering soil–structure interaction," *Bull. Earthq. Eng.*, Feb. 2020.

[21] CSI, "SAP2000. Analysis Reference Manual v.18.1.1," *CSI: Berkeley (CA, USA): Computers and Structures INC.* p. 496, 2018.

[22] ACI 350.3, "ACI 350.3 - Seismic Design of Liquid-Containing Concrete Structures and Commentary," *Struct. Concr.*, 2004.

[23] EN 1998-4, *Design of Structures for Earthquake Resistance-Part 4: Silos, Tanks and Pipelines*, vol. 1. 2004.

[24] EN13480-3, "EN 13480-3, 2002, Metallic Industrial Piping–Part 3: Design and Calculation, CEN, Brussels.," 2012.

[25] D. Vamvatsikos and C. Allin Cornell, "Incremental dynamic analysis," *Earthq. Eng. Struct. Dyn.*, vol. 31, no. 3, pp. 491–514, 2002.

[26] I. Iervolino, C. Galasso, and E. Cosenza, "REXEL: Computer aided record selection for code-based seismic structural analysis," *Bull. Earthq. Eng.*, vol. 8, no. 2, pp. 339–362, 2010.

[27] ABAQUS, "ABAQUS 6.17 Analysis User's Manual'. Online Documentation Help: Dassault Systèmes.," 2017.

[28] M. Vathi, S. A. Karamanos, I. A. Kapogiannis, and K. V. Spiliopoulos, "Performane criteria for liquid storage tanks and piping systems subjected to seismic loading," *J. Press. Vessel Technol.*, 2017.

