ANALYSIS OF PRESSURIZED HORIZONTAL VESSELS UNDER SEISMIC EXCITATION

A. Di Carluccio[1], G. Fabbrocino[2], E. Salzano[3], G. Manfredi[4]

[1] *PhD, Research Associate, Structural & Geotechnical Dynamic Lab StreGa, School of Engineering, Campobasso. Italy*
[2] *Professor, Structural & Geotechnical Dynamic Lab StreGa, School of Engineering, Campobasso. Italy*
[3] *Researcher, Institute of Research on Combustion, National Research Council, Napoli, Italy*
[4] *Professor, Dept. of Structural Engineering, University of Naples Federico II, Napoli. Italy*
Email: antonio.dicarluccio@unimol.it, giovanni.fabbrocino@unimol.it , salzano@irc.cnr.it , gamanfre@unina.it

ABSTRACT :
Codes for design and constructions of pressure-vessel provide a number of loading conditions that have to be considered. Pressures are primary loadings that are applied either internally or externally over the surface of the vessels; applied forces act either at local points or throughout the mass of the vessel.
Among applied loads, inertial forces due to ground motion can be relevant when industrial plants located in seismic areas are of concern. In fact, earthquake represents external hazard that interacts with safety of industrial equipments and systems. It can trigger accidental scenarios as fires, explosion and dispersion of toxic substances from industrial equipment, thus increasing the damages to people, environment and properties. In this context, dynamic behaviour of industrial equipment, as for example pressurized horizontal cylinders, is certainly of interest. An assessment of available technical solutions and design guidelines concerning pressurized equipments has been carried out. This preliminary stage of the work leads to a structural standardisation of components and detailing able to cover the need of knowledge for seismic risk evaluations. The present paper tackles from a structural and seismic engineering perspective, the assessment of seismic performances of pressurised vessels. Dynamic analyses of vessels designed according to National and International Codes are discussed and relevant outcomes for seismic protection of components are highlighted.

KEYWORDS:
Industrial facilities, vessels, seismic vulnerability, seismic design, dynamic analysis.

1. INTRODUCTION

Pressure vessels are probably one of the most widespread equipment within the different industrial sectors. In fact, there is no industrial plant without pressure vessels, steam boilers, tanks, autoclaves, collectors, heat exchangers, pipes, etc. More specifically, pressure vessels represent fundamental components in sectors of paramount industrial importance, such as the nuclear, oil, petrochemical, and chemical sectors. For many years an ISO committee (ISO TC/11, Annaratone 2007) was dedicated to study pressure vessels and provide design guidelines. However, even when the code includes specific regulations to determine the thickness of the different components, facing soma issues related to structural design are exhaustively taken into consideration. In Italy, a specific area of ISPESL (www.ispesl.it) regulations (VSR collection) is dedicated to pressure vessels design and fabrication. A pressure vessel is not an easy structure. Actually it is characterized by a regular and simple shape, but requires special care especially when modern approach to structural design is of concern. A strong effort has been carried out especially in the field of mechanical engineering to analyses such structures, but further work is needed if seismic loads are taken into consideration. The present paper tackles from a structural and seismic engineering perspective, the assessment of seismic performances of pressurised vessels. Dynamic analyses of vessels designed according to National and International Codes are discussed and relevant outcomes for seismic protection of components are highlighted.

2. INDUSTRIAL INSTALLATIONS

Industrial facilities show a large number of constructions and structural components (ASCE 1997). As materials are concerned, it is easy to recognize that both reinforced concrete and steel constructions are commonly used, even in combination like composite structures. Large installation can be characterized by use of prestressed members, especially when long spans are required. However, it is worth nothing that a large variety of functions have to be accomplished by structural components so that the latter can be classified as building like structures and non-building like structures. Building structures typically found in an industrial plant include administration buildings, control buildings, substations, warehouses, firehouses, maintenance buildings, and compressor shelters or buildings. Other structures, whose structural systems do not resemble those of buildings, are classified as non-building-like structures. Above-ground pressurized tanks are examples of such class of constructions. These equipment (Fig. 1), usually present in industrial plants, are used as gas and vapour storage systems. Figure 1 shows an example of pressurized horizontal steel tank. More details about typical industrial facilities can be found elsewhere (Di Carluccio 2007, Fabbrocino et. al. 2007).

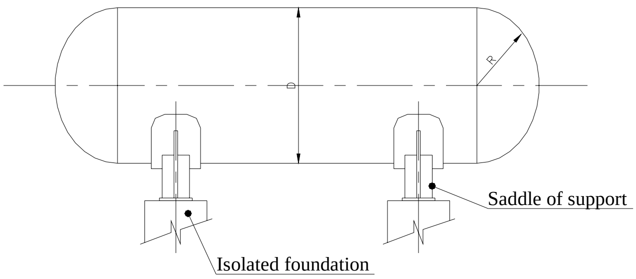


Figure 1 Horizontal pressurized storage steel tank and summary table of structural parameter.

The structural design of most pressure vessels is done in accordance with the requirements contained in the ASME Boiler and Pressure Vessel Code, Section VIII (ASME BPVC 2007). Vessels are usually obtained from the assemblage of different components: covers, heads, nozzle, saddle supports. Paragraph UG-22 of Division 1 specifies the loadings that must be considered to determine the minimum required thicknesses for the various vessel components. These design loadings are: internal or external design pressure, weight of the vessel and its normal contents under operating or test conditions, superimposed static reactions from the weight of attached equipment (e.g., motors, machinery, other vessels, piping, linings, insulation), loads at attached of internal components or vessel supports, wind, snow, and seismic reactions, impact reactions such as those that are caused by fluid shock, and so on. Table 2.1 summarizes the ASME Code equations used to calculate the minimum required thickness for common pressure vessel components.

Table 2.1 Vapour tension and density of liquid ammonia as a function of temperature.

Part	Thickness, t_p in.	Pressure, P, psi	Stress, S, psi
Cylindrical shell	$\frac{\mathrm{Pr}}{(SE_1-0.6P)}$	$\frac{SE_1 t}{(r+0.6t)}$	$\frac{P(r+0.6t)}{tE_1}$
Spherical shell	$\frac{\mathrm{Pr}}{(2SE_1-0.2P)}$	$\frac{2SEt}{(r+0.2t)}$	$\frac{P(r+0.2t)}{2tE}$
2:1 Semi-Elliptical	$\frac{PD}{(2SE-0.2P)}$	$\frac{\mathrm{Pr}}{(2SE_1-0.2P)}$	$\frac{P(D+0.2t)}{2tE}$
Torispherical head with 6% knuckle	$\frac{0.885PL}{(SE-0.1P)}$	$\frac{SEt}{(0.885L+0.1t)}$	$\frac{P(0.885L+0.1t)}{tE}$
Conical section (α=30°)	$\frac{PD}{(2\cos\alpha(SE-0.6P))}$	$\frac{2SEt\cos\alpha}{D+1.2t\cos\alpha}$	$\frac{P(D+1.2t\cos\alpha)}{2tE\cos\alpha}$

where P is the internal design pressure, r is the internal radius, S is the allowable stress, E_1 and E are the longitudinal weld joint efficiency, t_p is the required wall thickness for internal pressure, t is the actual wall

thickness (less corrosion allowance), D is the inside diameter, L is the inside crown radius of torispherical head, $\alpha = \tan^{-1}(0.5(D_l - D_s)/(ConeLength))$, D_L is the cone inside diameter at large end, D_S is the cone inside diameter at small end, in. Add twice the corrosion allowance to specified unworried inside diameter.
These pressurized equipment are usually used to stored hazardous material as ammonia. Ammonia is a colorless gas with a pungent, irritant characteristic odor. Different design for storage equipment are used (Technip 2000), depending on the amount of stored ammonia:
On-ground atmospheric storage tank (cryogenic) – Amount > 5000 tons
Pure ammonia can be stored at atmospheric pressure provided the refrigeration of content at -33°C. Typical layouts are cylindrical vertical tanks, flat bottom, as only the load of liquid is of concern. Normally, cryogenic tanks are economically advantageous for total amount of ammonia larger than 5000 tons, even if it is often used also for amount of 3000 tons, due to the several problems which arise when using other storage tank design or type, as for pressurized sphere.
Pressurized on-ground storage tank - Amount < 3000 tons
Generally, spheres are used for total amounts between 500 and 3000 tons. It should be noted that the design pressure should take account of also the eventual pressure of inert gas injected in the tank or other external loadings. Typical minimum design pressure for cylindrical tank is 15.5 bar.
Semi-refrigerated on-ground pressurized storage tank
Semi-regriferated tanks -33°C < $T_{storage}$ < $T_{ambient}$ < 26°C (P_v = 10.13 bar) are often adopted in order to reduce the design working pressure of tank, hence the wall thickness.
Underground pressurized tank
Typical storage tank have cylindrical shape, atmospheric (non-refrigerated), with typical design pressure of 17.2 bar.

3. SEISMIC ANALYSES ACCORDIG TO EUROCODE

3.1. Horizontal circular cylindrical tanks

Information about the seismic design of horizontal circular cylindrical tanks are contained in the Eurcocode 8, but they are not actually exhaustive. In particular, EC8 suggests that horizontal tanks need to be analyzed both along the longitudinal and the transverse axis and that an approximate values for hydrodynamic pressures induced by horizontal excitation in either the longitudinal and transversal direction can be obtained from solutions for the rectangular tank of equal dimension at the liquid level and in the direction of motion, and of depth required to give equal liquid volume. This approximation is sufficiently accurate for design purposes over the range of H/R (see Fig. 2) between 0.5 and 1.6. When H/R exceeds, 1.6, the tank should be assumed to behave as if it were full with the total fluid mass rigidly connected to the tank.

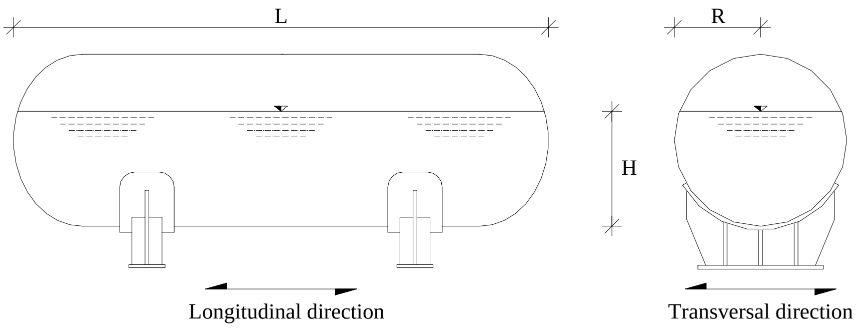


Figure 2 Horizontal circular cylindrical tank.

Regarding the seismic analysis of the rectangular tanks Eurocode distinguishes the case of tank with rigid walls from the one where walls are flexible. Whenever the walls of the tank can be assumed as rigid the total pressure is given by the sum of an impulsive and a convective contribution:

$$p(z,t) = p_i(z,t) + p_c(z,t) \tag{3.1}$$

The convective pressure component is given by the sum of modal terms (sloshing modes), each one having a different variation with time. Dominant contribution comes from the fundamental mode, that is:

$$p_c(z,t) = q_{c1}(z)\rho L A_1(t) \tag{3.2}$$

where $A_1(t)$ is the acceleration response function of a simple oscillator that has the frequency of the first mode, the appropriate value of the damping, and subjected to an input acceleration $A_g(t)$; details about the function $q_{c1}(z)$ can be found elsewhere (Eurocode 8). The period of first sloshing mode is given by:

$$T_{c1} = 2\pi \sqrt{\frac{L/g}{\frac{\pi}{2}\tanh\left(\frac{\pi}{2}\frac{H}{L}\right)}} \tag{3.3}$$

The impulsive component is as follows:

$$p_i(z,t) = q_0(z)\rho L A_g(t) \tag{3.4}$$

where L is the half-width of the tank in the direction of the seismic action, and the function $q_0(z)$ gives the variation of p_i along the height (p_i is constant in the direction orthogonal to the seismic action). The base shear and the moment on the foundation could be evaluated with the same equations calculated for cylindrical tanks (with L replacing R) (Eurocode 8, Malhotra et. Al. 2000). Wall flexibility produces generally a significant increase of the impulsive pressures, while leaving the convective one practically unchanged. From design point of view, an approximation (Priestley, 1986) is to use the same vertical impulsive pressure distribution valid for rigid wall, but to replace the ground acceleration $A_g(t)$ in equation 2.4 with the response acceleration of a simple oscillator having the frequency and damping factor of the first impulsive tank-liquid mode. The period of vibration of the first tank-liquid mode can be obtained approximately by:

$$T_f = 2\pi \sqrt{\frac{d_f}{g}} \tag{3.5}$$

where:

- d_f is the deflection of the wall on the vertical center-line and at the height of the impulsive mass, when the wall is loaded by uniform load in the direction of the ground motion and of the magnitude: $m_i g / 4BH$.
- $2B$ is the tank width perpendicular to the direction of loading.

4. NUMERICAL ANALYSIS

The structure analyzed in the present study, shown in Figure 3, is a typical small horizontal circular cylindrical liquid storage tank with a volume of $5\ m^3$. The tank is filled halfway with liquid ammonia at a pressure of *10.13 bar* with a density of $680\ kg/m^3$. The cylinder has an inner diameter of *1300 mm*, a thickness of *6 mm* and is made of a steel plate with $E=210\ GPa$, $\nu=0.3$ and $\rho=7850\ kg/m^3$.
The equator of the cylinder is *1000 mm* above ground. The cylinder, *3100 mm* long, is closed with two semisphere with same diameter of cylinder and with a total length of *4400 mm*. The cylindrical tank is supported by two vertical plate with a thickness of *13 mm*.
Additional details on geometry dimension can be found in Figure 3.

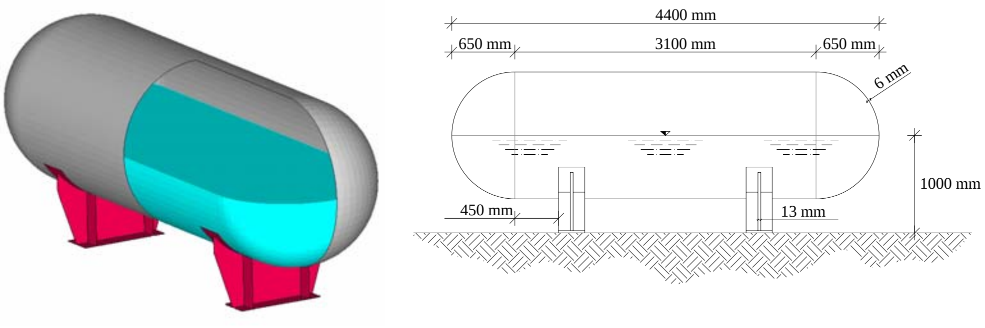
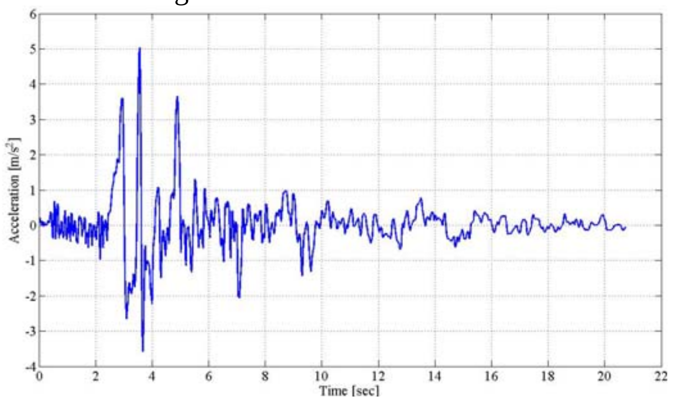


Figure 3 LsDyna Finite Element models and geometry details.

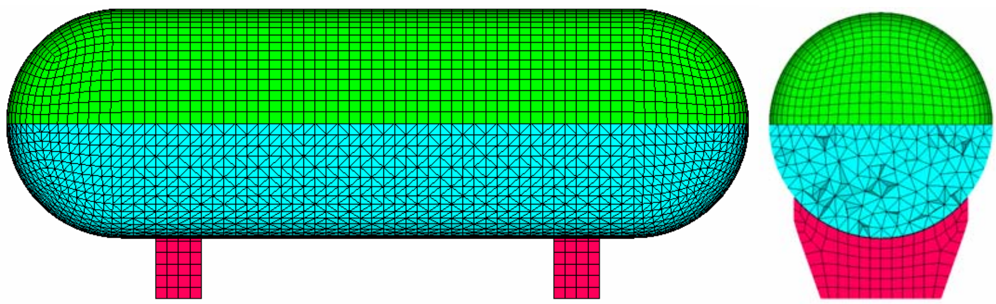
A time history analysis with LsDyna's finite element program has been carried out in longitudinal and transversal direction. The record used for time history analysis presented in the paper is an stiff soil European record and showed in Figure 4.



Earthquake Code	000535ya
Event Name	Erzincan
Country	Turkey
Date	13/03/1992
Station Name	Erzincan-Meteorologij Mudurlugu
Duration [sec]	20.75
PGA [m/s^2]	5.0275

Figure 4 Natural earthquake used in the time history analysis.

The finite element analyses (Fig. 5) presented have been performed with LsDyna code using a Lagrangian approach.



Shell Elements	4945
Solid Elements	39677
Total Joint	13416

Figure 5 LsDyna Finite Element models details.

The Finite Element program used in the analysis is LsDyna (Hallquist 1998, Hallquist 2001, LSTC 2003). LsDyna uses an explicit Lagrangian numerical method to solve nonlinear, three dimensional, dynamic, large displacement problems (Ferziger 1997, Zienkiewicz 2000). Implicit, arbitrary Lagrangian-Eulerian, Smoothed Particle Hydrodynamics (also known as SPH (Lacome 2001)) are also available; Lagrangian, ALE and SPH numerical method can be used for liquid storage tank (Vesenjak et. al. 2004). For the modeling of tank wall four joints shell elements has been used; the liquid has been modeled with solid elements. Details on the analyzed models are shown in Figure 5.
The tank and bases were modeled with four-noded Belytschko-Tsay shell (Belytschko 1981) elements with two

integration points. The material models used for steel is MAT_1. The MAT_1 in LsDyna is an isotropic elastic material and is available for beam, shell, and solid elements. In this elastic material the code compute the co-rotational rate of deviatoric Cauchy stress tensor and pressure as follows:

$$S_{ij}^{\nabla^{n+\frac{1}{2}}} = 2G\dot{\varepsilon}_{ij}^{'n+\frac{1}{2}} \quad (a) \qquad p^{n+1} = -K \ln V^{n+1} \quad (b) \qquad (4.1)$$

where G and K are the elastic shear modulus and bulk modulus and V is the relative volume, i.e., the ratio of the current volume to the initial volume. For analyses presented in the paper a MAT_1 fluid option was used for the liquid. In fluid option of MAT_1 only bulk modulus must be defined. In this case fluid-like behaviour is obtained where bulk modulus, *K*, and pressure rate, *p*, are given by:

$$K = \frac{E}{3(1-2\nu)} \quad (a) \qquad p = -K\dot{\varepsilon}_{ii} \quad (b) \qquad (4.2)$$

and shear modulus is zero. A tensor viscosity is used which acts only the deviatoric stresses, S_{ij}^{n+1}, given in terms of damping coefficient as:

$$S_{ij}^{n+1} = VC \cdot \Delta L \cdot a \cdot \rho\dot{\varepsilon}_{il} \qquad (4.3)$$

where *p*, is a characteristic element length, *a* is the fluid bulk sound speed, ρ is the fluid density, and $\dot{\varepsilon}_{il}$ is the deviatoric strain rate. As contact type a Contact Node to Surface is used. For analyses presented a dynamic relaxation of 1 second has been considered, as clearly shown in the time histories reported in Figures 7-8.
The latter reports for longitudinal and transversal seismic action the comparison between the base shear evaluated according to EC8 procedure discussed in section 3.1 and the full stress LsDyna FEM analysis. According to EC8, when H/R is between 0.5 and 1.6, the horizontal tanks can be analysed as the rectangular tank of equal dimension at the liquid level and in the direction of motion, and of depth required to give equal liquid volume. Figure 6 shows the equivalent rectangular tank configuration for longitudinal and transversal seismic action respectively.

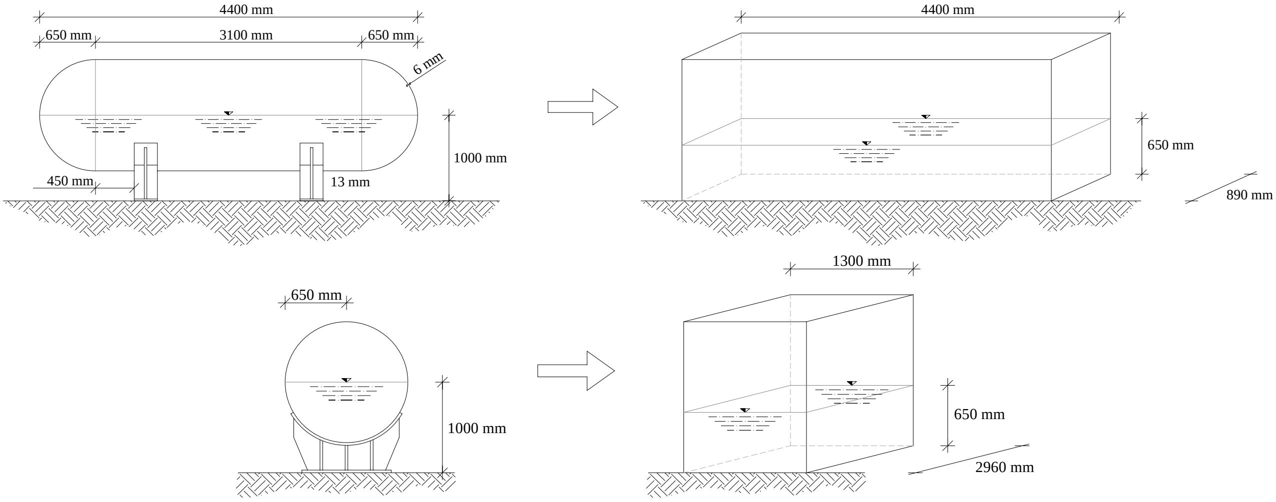


Figure 6 Equivalent rectangular storage tank for longitudinal and transversal seismic action.

On the right hand side of the Figures 7 and 8, FEM results are given in terms of liquid displacements along the earthquake direction. In particular, the surfaces characterised by the same vertical displacement are shown. As base shear is concerned, direct evaluation of the peak base shear according to EC8 seems to be in good agreement with FEM analyses results.

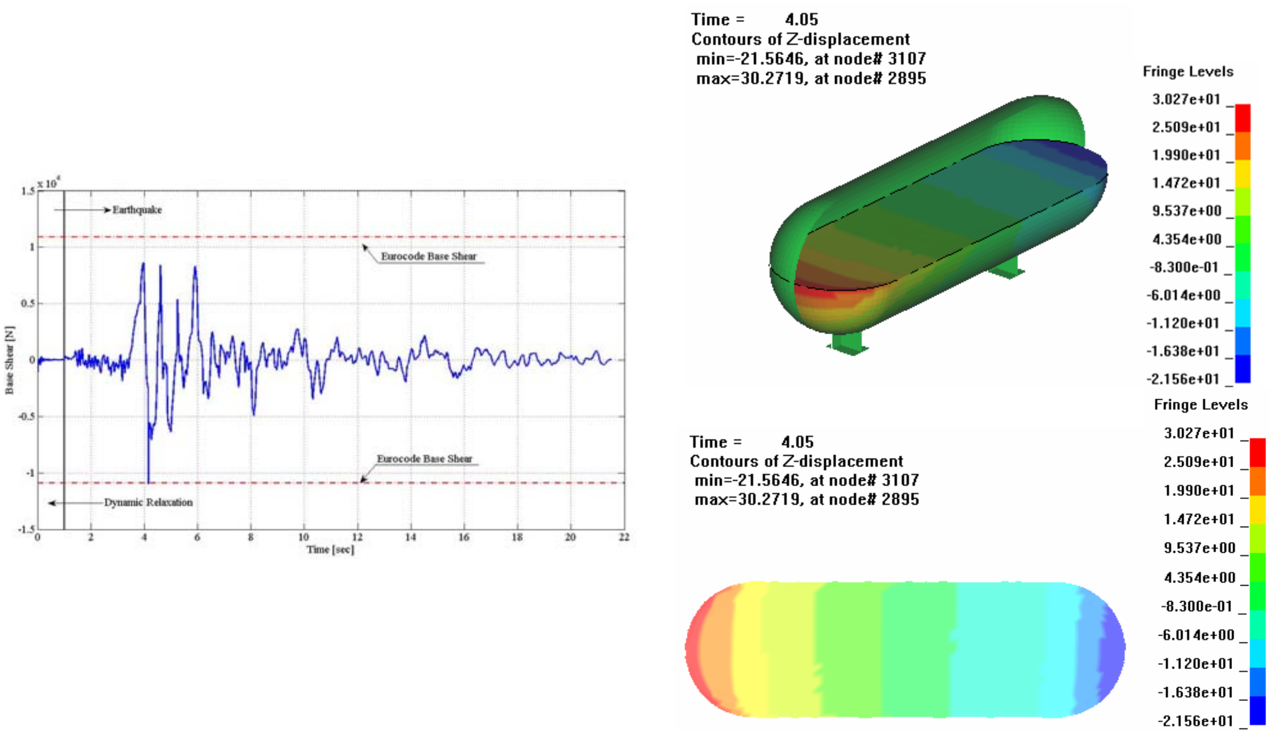


Figure 7 Comparison of results in terms of Base Shear and z-displacement for longitudinal seismic action.

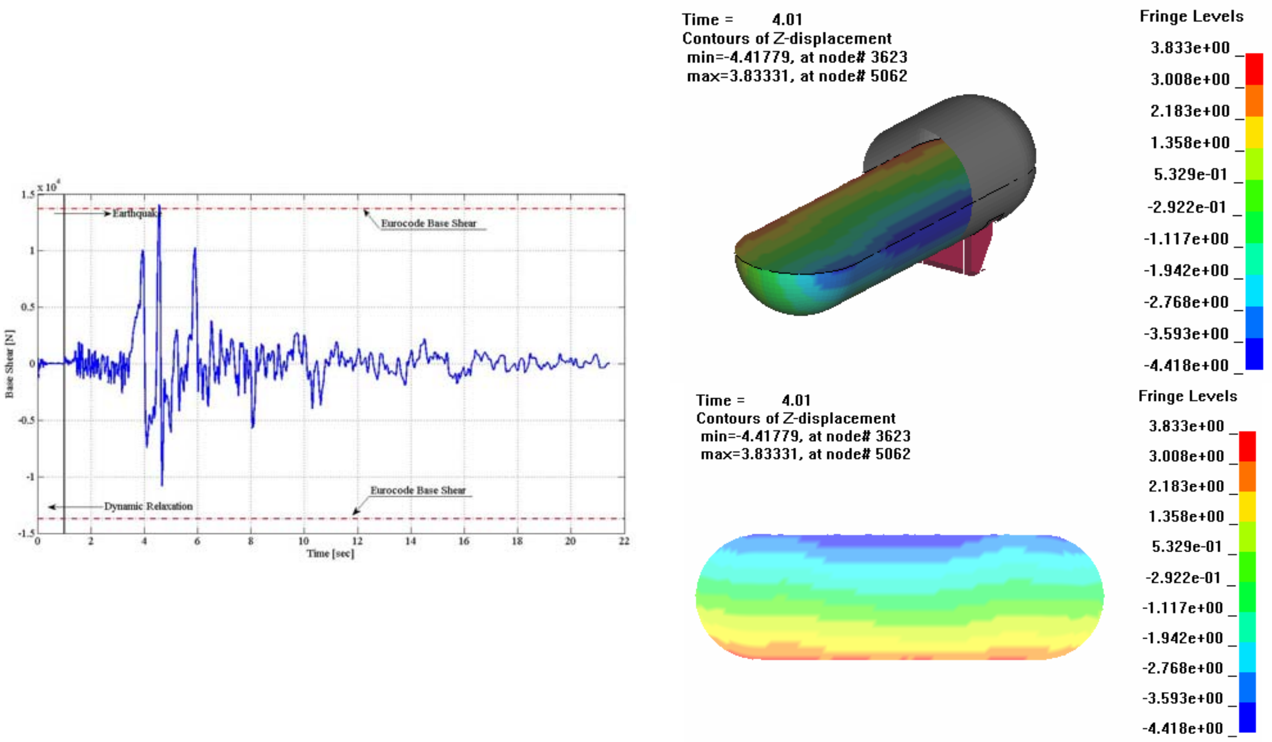


Figure 8 Comparison of results in terms of Base Shear and z-displacement for transversal seismic action.

5. CONCLUSIONS

This paper reports an evaluation of the seismic response of typical horizontal steel components used in the process industry. In particular, attention has been focussed on the seismic design and analysis of tanks for storage of hazardous materials, as ammonia. They are very common worldwide and can help to develop methods of seismic analysis able to take account of fluid/structure interactions. Advanced FEM analyse have been carried out and a comparison between procedures proposed by Eurocode 8 has been discussed. A satisfactory capacity of simplified models to fit the overall response of tanks has been shown. This circumstance is by far more relevant, since computational efforts for full stress analyses are huge compared to those required by Eurocode procedures. Another interesting aspect is related to the capacity of procedures suggested by Eurocode to give good estimates of the peak base shear. Further investigations are needed to confirm such results and extend them to relevant industrial facilities.

6. ACKNOWLEDGEMENTS

The present study has been carried out in the framework of activities of the assessment and reduction of seismic risk to large infrastructural systems FIRB Project, task 7 "Assessment of the seismic risk of tanks and pipelines" coordinated by Prof. G. Manfredi.

REFERENCES

Annaratone D., Pressure Vessel Design, ANCC-VSG, Springer; March 12, 2007.

ANCC, Associazione Nazionale Controllo Combustione, Raccolta VSR, ed. July 1978

ASCE American Society of Civil Engineers (ASCE), Petrochemical Energy Committee Task Report, Guidelines for Seismic Evaluation and Design of Petrochemical Facilities, ASCE publication, 1997.

ASCE, Guidelines For Seismic Evaluation and Design of Petrochemical Facilities, Task committee on seismic evaluation and design of petrochemical facilities, *The American Society of Civil Engineers Petrochemical Energy Committee*.

ASME, Boiler and Pressure Vessel Code, Sect. I, III, VIII, 2007.

Belytschko, T., Tsay, C.S., Explicit Algorithms for Nonlinear Dynamics of Shells, AMD-Vol. 48, ASME, 209-231, 1981.

Di Carluccio, A., Structural Characterization and Seismic Evaluation of Steel Equipment in Industrial Plants, *PhD Thesis* in Seismic Risk, 2007.

Eurocode 8, Design provisions for earthquake resistance of structures, Part 1-General rules and Part 4–Silos, tanks and pipelines, European committee for Standardization, Brussels, 1998.

Fabbrocino, G., Di Carluccio, A., Manfredi, G., Iervolino, I, Salzano, E., Structural Characterization of Industrial Facilities in the Framework of Seismic Risk Analysis, *XXI Congresso CTA*, Catania, 2007.

Ferziger,J., Peric,M., Computational Methods for Fluid Dynamics, Springer Verlag, Berlin, 1997.

Hallquist, J.O., LS-DYNA Theoretical Manual, *Livermore Software Technology Corporation*, 1998.

Hallquist, J.O., LS-DYNA Keyword User's Manual, *Livermore Software Technology Corporation*, 2001.

ISO TC/11, Pressure vessel Code Petroleum Refinery Piping, ASA B31,ASME, New York.

Lacome, J.L., Smoothed Particle Hydrodynamics - Part I, 2001.

Livermore Software Technology Corporation, LS_DYNA Keyword User's Manual, Version 970, Livermore, 2003.

Malhotra, P.K., Wenk, T., Wieland, M., Simple procedure for seismic analysis of liquid storage tanks, *Structural Engineering*, IABSE, Vol. 10, No.3, 197-201, 2000.

Priestley, M.J.N., Seismic Design of Storage Tanks. *Recommendations of a Study Group of the New Zealand National Society for Earthquake Engineering*, 1986.

Technip, Serbatoi di stoccaggio ammoniaca: analisi delle misure progettuali di prevenzione e protezione da perdite incidentali in relazione alle diverse configurazioni adottabili, Prog. 1968, *CNR Consiglio Nazionale delle Ricerche*, Maggio 2000.

Vesenjak, M., Mullerschon, H., Hummel, A., Ren, Z., Simulation of fuel Sloshing – Comparative Study, LS-DYNA Answenderforum, Bamberg 2004.

Zienkiewicz, O., C., Taylor, R., L., The Finite Element Method – Volume 1 and 3, McGraw-Hill Ltd., London, 2000.