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SEISMIC DESIGN OF SPHERICAL LIQUID STORAGE TANKS (COMPDYN 2011)

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Abstract: *Spherical storage tanks are widely used for various types of liquids, including hazardous contents; consequently these storage tanks must be adequately designed for seismic actions.*

While very detailed and specific seismic design rules for cylindrical tanks are provided by several codes, such rules are missing for spherical tanks. This paper describes the results of a survey on existing European and American Codes with regard to their applicability to spherical liquid storage tanks and provides comparison of design outcomes according to these codes. The investigations were performed on an example of an existing spherical tank which was selected to be representative for the current practice. The studies comprised numerical FE modelling and calculation as well as simplified models for the estimation of the dynamic properties of the tank structure. The applicability of behaviour factors was discussed based on proposals made by Eurocode 8. Particular attention was paid to the influence of sloshing effects for which no guidance is given in the codes. The sloshing effects were investigated according to the current state of the art based on available publications.

Finally the resistance of the tank was compared to the action effect determined from the European and American codes. The comparison of action effects obtained with and without consideration of sloshing effects showed a rather important influence of these effects on the final results.

1 INTRODUCTION

The contribution describes the results of an investigation of a representative example of a spherical liquid storage tank subjected to seismic actions. The aim of the study was to verify the applicability of existing European and American codes to spherical tanks although no particular design rules for this kind of tanks – neither for the determination of loads nor for the detailing – are provided by the considered codes. Furthermore the influence of sloshing effects was investigated according to the current state of the art [9].

2 OBJECT OF INVESTIGATION

2.1 Dimensions and load cases

The research focused on a spherical pressure vessel (material S 355) with the dimensions given below, see Figure 1. The spherical tank was supported by twelve vertical legs without additional bracings between them.

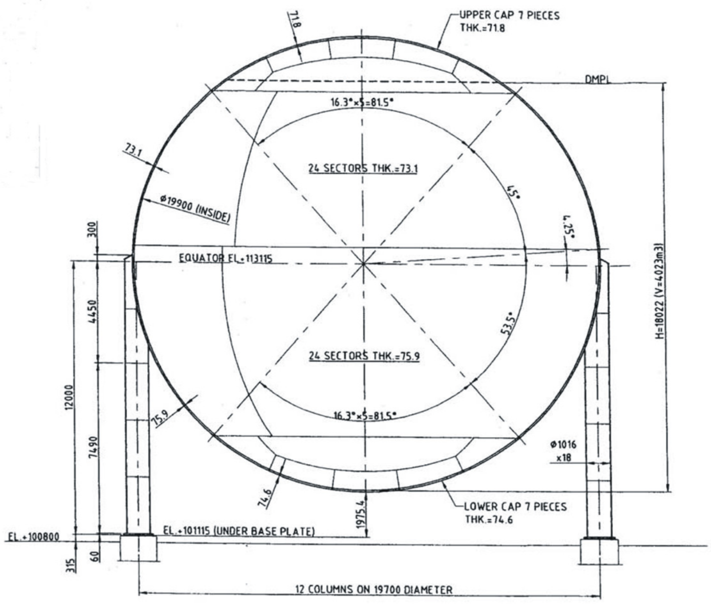

Figure 1: Spherical pressure vessel with 12 columns (inner diameter of the sphere $D_I = 19.9\ m$)

The numerical investigation considered the following load cases:

- self-weight of the structure (columns and sphere) (total weight $m = 879\ t$);
- operating load (density $\rho = 522 kg/m^3$, filling height $h_p = 18.1m$, weight $m = 2104t$);
- seismic load ($a_g = 0.24\ g \approx 2.4\ m/s^2$)

2.2 Seismic actions

In order to compare European and American standards the value of the response acceleration S_d for $T_B \leq T \leq T_C$ according to EN 1998-1:2010 (3.13) [1] was selected to be equal to S_a for $T_0 \leq T \leq T_S$ according to ASCE/SEI 7-05 (11.4-5) [4] (see Figure 2). However, the behaviour factor q is not taken into account at this point (q = 1).

$$S_d(T) = a_g \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2.5}{q} - \frac{2}{3} \right) \right] \quad \text{(according to EN 1998-1 (3.13))} \qquad (1)$$

$$S_a = S_{DS} \cdot \left(0.4 + 0.6 \cdot \frac{T}{T_0} \right) \quad \text{(according to ASCE/SEI 7-05 (11.4-5))} \tag{2}$$

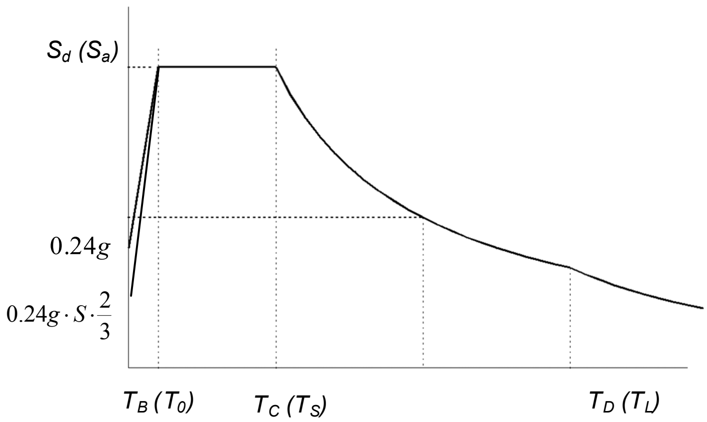

Figure 2: Elastic response spectrum according to EN 1998-1 [1] and ASCE/SEI 7-05 [4]

To consider similar ground conditions for both standards comparable locations were assumed (ground type *C* according to EC 8, part 1 [1] complies with site class *C* according to ASCE 7 [4]).

The model for the determination of the fundamental period T_1 was divided into the following sub-systems:

- ground and foundation (soil-structure interaction effects are not considered here);
- spherical pressure vessel structure;
- fluid, sloshing response, etc.

2.3 Fundamental period of the spherical pressure vessel structure

The fundamental period of the tank structure including maximum filling and neglecting sloshing effects was determined as follows (see Figure 3):

- using FEM-calculations, fundamental period was determined to $T_1 = 1.54\ s$;
- using a strut-and-tie model (single equivalent load in center of gravity) $T_1 = 1.56\ s$.

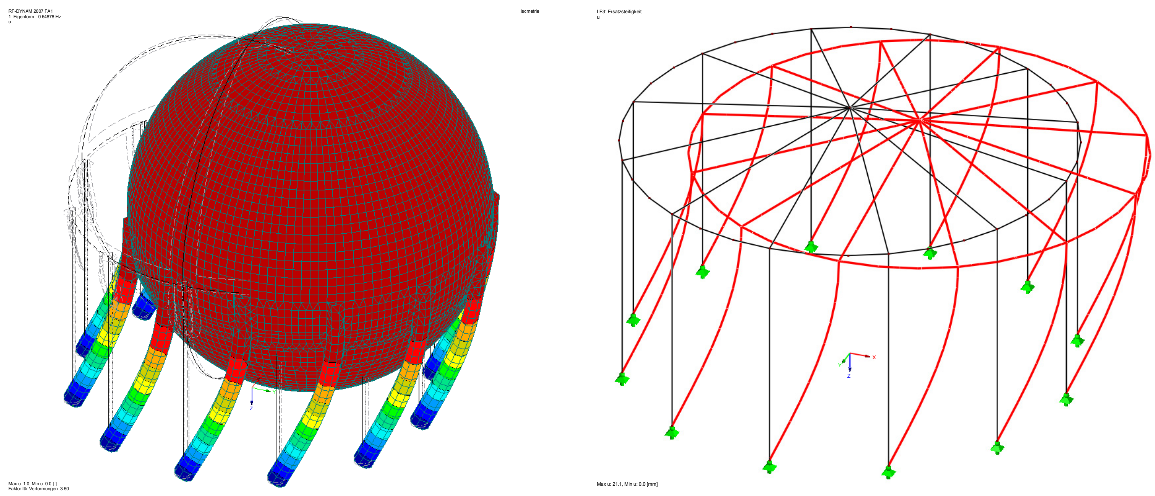

Figure 3: Ascertainment of the fundamental period T_1 based on FEM model (left) and strut-and-tie model (right)

3 SELECTION OF A BEHAVIOUR FACTOR

3.1 Basis of the behaviour factor

In the seismic design of structures the behaviour factor *q* (or response modification factor *R*) represents the dissipation capability of the structure. This dissipation capability depends on the structural type and the type of the construction (e.g.: concrete, steel, composite …). The upper limit value of *q* depends on the ductility class. EC 8, part 1 [1] differentiates between three ductility classes. Structures with small dissipation capability belong to the low ductility class (DCL). Structures belonging to DHM (medium ductility class) or DCH (high ductility class) have to fulfil minimum requirements with regard to plastic deformability (e.g. rotation capacity of the cross-sections) and with regard to detailing (e.g. capacity design of connections). In the following medium ductility class (DCM) was supposed for the steel tanks under investigation.

For structures in Europe basic seismic design rules, including seismic actions, are provided by Eurocode 8 Part 1. In the USA basic rules and seismic actions are provided e.g. by ASCE 7 [4]. With regard to tank structures EN 1998-4 [2] applies in Europe. The American standards API 620 [5] and API 650 [6] are used for the design of ground supported tanks including earthquake. Table 1 shows a compilation of references to the behaviour factor *q* respectively response modification factor *R* available the European and American standards.

Behaviour factor q	**Response modification factor R**
EN 1998-1, chap. 6.3 (steel buildings)	*ASCE/SEI 7-05, tab. 12.2 1 (general systems)*
EN 1998-4, chap. 2.4 (general)	*ASCE/SEI 7-05, tab. 15.4 2 (nonbuilding structures)*
EN 1998-4, chap. 3.4 (silos)	*API 650, tab. E 4 (ground supported, liquid storage tanks)*
EN 1998 -4, chap. 4.4 (tanks)	*API 620, tab. L 1Q and L1 R (ground supported, liquid storage tanks)*
	UBC 1997, Volume 2, tab. 16 N (general systems)
	UBC 1997, Volume 2, tab. 16 P (nonbuilding structures)

Table 1: References of behaviour factor and response modification factor

3.2 Behaviour factor *q* according to European standards

The provisions given by EC 8 for the application of behaviour factor *q* to spherical tanks are of limited precision. For elevated tanks EN 1998-4 [2], Chap. 4.4 refers to Chap. 3.4 (silos) where the application of behaviour factor *q* for an inverted pendulum (see Figure 4) is recommended. Basic definitions of an inverted pendulum system are given in EC8 Part 1. The following definitions given by Eurocode 8 are of interest for assessment of the behaviour factors of spherical elevated tanks:

- EN 1998-1 5.1.2 (1): Inverted pendulum systems – system in which 50% or more of the mass is in the upper third of the height of the structure, or in which the dissipation of energy takes place mainly at the base of a single building element.
  NOTE: One-storey frames with column tops connected along both main directions of the building and with the value of the column normalized axial load ν_d exceeding 0,3 nowhere, do not belong in this category.

- EN 1998-1 6.3.1 (5): Inverted pendulum structures may be considered as moment resisting frames provided that the earthquake resistant structures possess more than one column in each resisting plane and that the following inequality of the limitation of axial force: $N_{Ed} < 0{,}3\ N_{pl}, R_d$ is satisfied in each column.
- EN 1998-4 4.4 (4): behaviour factors specified in 3.4 should be applied also to the part of the response of elevated tanks […]
- EN 1998-4 3.4 (5): For skirt-supported silos, with the skirt designed and detailed to ensure dissipative behaviour; the upper limit values of the q factor defined in EN 1998-1, Sections 5 to 7 for inverted pendulum structures may be used.

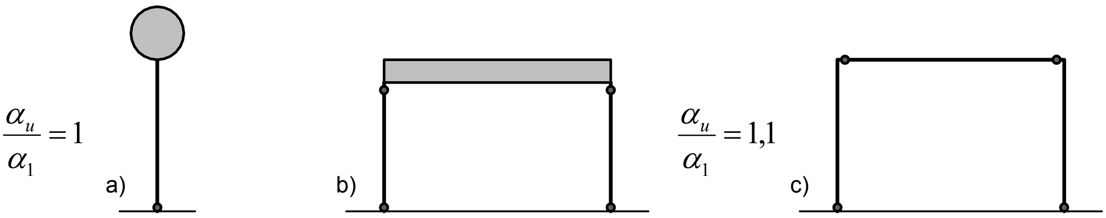

Figure 4: Inverted pendulum (a, b) and MRF (c) according to EN 1998-1, Fig. 6.5 [1]

The modal shapes obtained by the calculations using the FE-model and the strut-and-tie model however, showed that an elevated spherical tank barely behaves like an inverted pendulum as it is intentioned by EN 1998-1. Rather, the spherical tank supported by a number of columns exposes behaviour comparable to a moment resisting frame with a rigid girder. Moreover, two aspects mentioned in EC 8-1 5.2.1 – potential plastic hinges at the top of columns and more than one single resisting element – indicate a possible classification of such structures as a MRF rather than inverted pendulum. The comparison of elevated tanks to skirt-supported structures as given by EC 8-4, however, suggests the presence of one resisting element only and consequently the maximum q-factor of 2,0 (see Table 2), provided that the structural detailing allows for the development of a plastic mechanism.

STRUCTURAL TYPE	Ductility Class	
	DCM	DCH
a) Moment resisting frames	4	$5\alpha_u/\alpha_1$
b) Frame with concentric bracings Diagonal bracings V-bracings	 4 2	 4 2,5
c) Frame with eccentric bracings	4	$5\alpha_u/\alpha_1$
d) Inverted pendulum	2	$2\alpha_u/\alpha_1$
e) Structures with concrete cores or concrete walls	See section **5**	
f) Moment resisting frame with concentric bracing	4	$4\alpha_u/\alpha_1$
g) Moment resisting frames with infills Unconnected concrete or masonry infills, in contact with the frame	2	2
Connected reinforced concrete infills	See section **7**	
Infills isolated from moment frame (see moment frames)	4	$5\alpha_u/\alpha_1$

Table 2: Table 6.2 from EN 1998-1 [1]

In fact, neither of the possible interpretations – inverted pendulum or MRF – seems to be reasonable in order to estimate the real performance of a spherical tank. The classification as inverted pendulum is probably rather conservative whereas for a classification as a frame detailing rules for the achievement of dissipative behaviour are missing.

3.3 Response modification factor R according to American standards

American standards such as ASCE 7 [4] differentiate between building and non-building structures. Table 15.4-2 in [4] contains declarations for the non-building structure types “tank” respectively “vessels”. The response modification factor for an elevated tank supported by non-braced legs yields the value R = 2.0 according to Table 15.4 2 in [4] (see Table 3).

Nonbuilding Structure Type	Detailing Requirements[c]	*R*
Elevated tanks, vessels, bins, or hoppers:		
On symmetrically braced legs (not similar to buildings)	15.7.10	3
On unbraced legs or asymmetrically braced legs (not similar to buildings)	15.7.10	2
Single pedestal or skirt supported		
- welded steel	15.7.10	2
- welded steel with special detailing	15.7.10 and 15.7.10.5 a and b.	3
- prestressed or reinforced concrete	15.7.10	2
- prestressed or reinforced concrete with special detailing	15.7.10 and 14.2.3.6	3
Horizontal, saddle supported welded steel vessels	15.7.14	3
Tanks or vessels supported on structural towers similar to buildings	15.5.5	Use v categ resi
Flat-bottom ground-supported tanks:	15.7	
Steel or fiber-reinforced plastic:		
Mechanically anchored		3
Self-anchored		2.5
Reinforced or prestressed concrete:		
reinforced nonsliding base		2
anchored flexible base		3.25
unanchored and unconstrained flexible base		1.5
All other		1.5

Table 3: Extract from ASCE/SEI 7-05, Table 15.4 2 [4]

Ostensibly there is a good agreement between the European and the American proposal for the behaviour factor to be applied to elevated tanks ($q = R = 2.0$). In fact however, the American provisions are referring to generally shaped tanks. The detailing requirements of chapter 15.7.10 as given in the table above, are also of general nature and do not provide guidance on how to achieve a ductile behaviour in particular with regard to the connection of the legs to the shell of the tank.

3.4 Selected behaviour factor for further investigations

Considering the uncertainties related to the choice of an adequate behaviour factor and the fact that the selected example has been initially designed using elastic calculation methods the behaviour factor used in the following seismic calculations was assumed to be $q = R = 1{,}5$. Since the aim of this study was the comparison of design values resulting from the application of the European and American codes, it was important to select comparable design actions and design resistance by using the same behaviour factor for all code-based calculations. On the other hand selecting the lower bound of the available behaviour factors led to safe-sided results with regard to the intended verification of an existing spherical tank.

A more sophisticated, performance based check of the response of the spherical tank to seismic actions would require either nonlinear time-step calculations. In order to determine a realistic behaviour factor these studies would need to be extended to an incremental dynamic analysis and to other dimensions of the tanks. Such a study however was not included in the working programme of the research project.

4 SEISMIC ANALYSIS ACCORDING TO CODES

4.1 Design spectrum

In order to obtain comparable results using European and American standards the following parameters were chosen (see Table 4). The relevant design spectra according to European and American standards are shown in Figure 5. The spectra were selected such that the "plateau"-values for both codes are the same.

EN 1998-1 [1]		ASCE/SEI 7-05 [4]	
• *ground type C*	*(Table 3.1 in [1])*	• *site class C*	*(Table 20.3-1 in [4])*
$S = 1,0^{1)}$	*(Table 3.2 in [1])*	• *occupancy category III*	
$T_B = 0,2$ s	*(Table 3.2 in [1])*	$S_S = 0,85^{2)}$	*(Fig. 22-1 to 22-14 in [4])*
$T_C = 0,6$ s	*(Table 3.2 in [1])*	$S_1 = 0,25^{2)}$	*(Fig. 22-1 to 22-14 in [4]*
$T_D = 2,0$ s	*(Table 3.2 in [1])*	$T_0 = 0,086$ s	*(Eq. 11.4-6 in [4])*
		$T_S = 0,431$ s	*(Eq. 11.4-6 in [4])*
		$T_L \geq 4,0$ s	*(Fig. 22-15 to 22-20 in [4])*

1) This value does not agree with table 3.2 in [1] and was only chosen to fit the plateau.

2) This value was selected such that the plateau-values for both codes are the same

Table 4: Values of parameters describing the design spectrum according to EC 8 [1] and ASCE 7 [4]

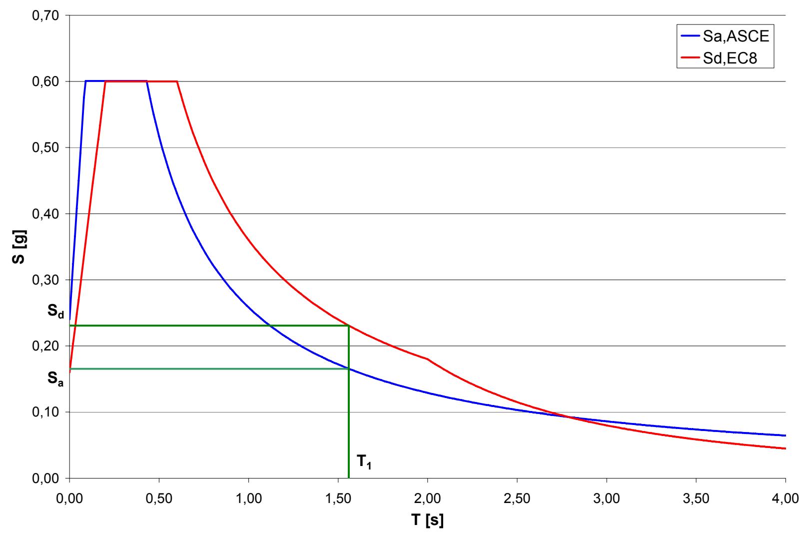

Figure 5: Comparison of the elastic response spectrum for the spherical pressure vessel according to EC 8 [1] and ASCE 7 [4]

The comparison of the spectra shows, that even with a similar plateau of 0.6g, up to T = 2.7 [s] the European spectrum leads to higher values than the American one (see Figure 5). However, the design spectrum of both standards is very dependent on the chosen parameters. Therefore the comparison of the spectra is not discussed further here. In addition for each standard the same importance factor and behaviour factor were chosen:

EN 1998-1 [1]	ASCE/SEI 7-05 [4]
• *importance factor* $\gamma_I = 1.25$	• *importance factor* $I = 1.25$
• *behaviour factor* $q = 1.5$	• *response modification factor* $R = 1.5$

Table 5: Importance factor and behaviour factor according to EC 8 [1] and ASCE 7 [4]

4.2 Seismic base shear force neglecting sloshing effects

A. According to European standards

The design of tanks, silos and pipeline systems is governed by EC 8, part 4 [2]. In order to obtain the seismic action effects the "lateral force method" based on linear-elastic analysis according to EC 8, part 1 [1] was used. This method is applicable for structures that respond to seismic action approximately as a single-degree-of-freedom system. This requirement is considered to be fulfilled, if the structure meets the "criteria for regularity in elevation" given in EC 8, part 1 [1] and if the fundamental periods T_1 for the two main directions are smaller than the following values:

$$T_1 \leq \begin{cases} 4 \cdot T_C \\ 2{,}0\,s \end{cases} \tag{3}$$

When neglecting the influence of sloshing the fundamental mode may be assumed as clearly governing the response. Also, the structure may be assumed as regular in plan and elevation. Thus the seismic base shear force F_b was determined as follows:

$$F_b = S_d(T_1) \cdot m \cdot \lambda \tag{4}$$

where $T_1 = 1.56\,s$ (see chapter 2.3)

$$S_d(T_1) = a_g \cdot S \cdot \frac{2.5}{q} \cdot \left(\frac{T_C}{T_1}\right) = 1.51\,m/s^2$$ (Eq. 13.3 in [1])

$$S_d(T_1) = 0.154\,[1/s]$$ (for $q = 1.5$)

$$S_d(T_1) = 0.231\,[1/s]$$ (for $q = 1.0$)

$$m = 879 + 2104 = 2983\,t$$ (see chapter 2.1)

$$\lambda = 1.0$$ (Ch. 4.3.3.2.2 in [1])

$$F_b = 1.51 \cdot 2983 \cdot 1.0 = 4503.9\,kN$$

$$F_b = \gamma_I \cdot 4503.9 = 5629.8\,kN$$ (for $\gamma_I = 1.25$)

In order to determine the design values for detailed verification of structural elements of the general structure the following application rules must be considered:

- combination of the effects of the components of the seismic action according to EN 1998-1 (4.3.3.5) [1] (here only the horizontal seismic acceleration is considered using the alternative combination E_{Edx} *"+"* $0.3E_{Edy}$, because the vertical acceleration should be taken only for horizontal or nearly horizontal structural members);

- if the accidental eccentricity of EN 1998-1(4.3.2) [1] is not taken into account by a more exact method including a 3D-model, the accidental torsional effects are accounted for by multiplying the action effects for the individual load resisting elements:

$$\delta = 1 + 0.6 \cdot \frac{x}{L_e} \tag{5}$$

where x distance of the element under consideration from the centre of mass of the building in plan, measured perpendicularly to the direction of the seismic action considered

L_e distance between the two outermost lateral load resisting elements, measured perpendicularly to the direction of the seismic action considered

- combination of the seismic action with other actions in accordance with EN 1990:2010 (6.4.3.4) [3] and EN 1998-1 (3.2.4) [1], whereas the combination coefficient for the variable action "snow load" and "wind load" is $\psi_{2,1} = 0$

With regard to the first point – combination of earthquake directions – it shall be mentioned that the initial intension of this rule was the consideration of seismic actions acting "diagonally" on structures usually rectangular in plan. Using this simplified attempt it is permitted to calculate a structure for each orthogonal direction separately and to omit the determination of the most unfavourable direction of the seismic action. Contrary to typical buildings the investigated spherical tank does not have "orthogonal" directions as it is practically rotation-symmetric. Thus there is no "unfavourable" load direction and the necessity of the combination of directions needs to be checked.

The consideration of accidental torsional effects by the simplified model was assumed to cover all eccentricities resulting from external installations, connected pipes, inspection ladders etc. and selected due to its applicability to a SDOF-model. The effects of the applied eccentricity however (+30%, see chapter 4.2 C), seem to be very much safe-sided as indicated by the results presented in Table 6.

Further investigations according to EC 8 were carried out using the strut-and-tie model in Figure 3 (right side). The results are shown and discussed in chapter 4.2 C.

B. According to American standards

The Appendix E of API 650 [6] provides only requirements for the seismic design of cylindrical tanks. Therefore the equivalent lateral force procedure of ASCE/SEI 7-05 (12.8) [4] was applied. For the investigated spherical pressure vessel the seismic base shear force V was determined as follows:

$$V = C_S \cdot W \tag{6}$$

where $T = 1.56\ s$ (see chapter 2.3)

$F_a = 1.06$ (Tab. 11.4-1 in [4])

$F_v = 1.55$ (Tab. 11.4-2 in [4])

$S_{MS} = F_a \cdot S_S = 0.901$ (Eq. 11.4-1 in [4])

$$S_{M1} = F_v \cdot S_1 = 0.388 \qquad \text{(Eq. 11.4-2 in [4])}$$

$$S_{DS} = \frac{2}{3} \cdot S_{MS} = 0.601 \qquad \text{(Eq. 11.4-3 in [4])}$$

$$S_{D1} = \frac{2}{3} \cdot S_{M1} = 0.258 \qquad \text{(Eq. 11.4-4 in [4])}$$

$$S_a(T) = \frac{S_{D1}}{T} = 0.165\left[1/s\right] \qquad \text{(Eq. 11.4-6 in [4])}$$

$$C_S = \frac{S_{DS}}{R/I} = 0.5 < \frac{S_{D1}}{T \cdot \left(R/I\right)} = \underline{0.138} \qquad \text{(Eq. 12.8-3 in [4])}$$

$$W = 879 + 2104 = 2983\,t \cong 29830\,kN \qquad \text{(see chapter 2.1)}$$

$$V = 0.138 \cdot 29830 = 4116.6\,kN$$

Finally the horizontal seismic load effect E_h shall be determined in accordance with ASCE/SEI 7-05 (12.4.2) [4] as follows:

$$E_h = \rho \cdot Q_E \qquad (7)$$

where $\rho = 1.3$ (Ch. 12.3.4 in [4])

for Seismic Design Category D (Tab. 11.6-2 in [4])

$Q_E = V = 4116.6\,kN$ (Ch. 12.4.2.1 in [4])

$$E_h = 1.3 \cdot 4116.6 = 5351.5\,kN$$

To determine the design values for detailed verification of structural elements of the general structure the following application rules must be considered:

- according to ASCE/SEI 7-05 (12.5) [4] for structures assigned to Seismic Design Category D, the design seismic forces are permitted to be applied independently in each of two orthogonal directions and orthogonal interaction effects are permitted to be neglected;
- according to ASCE/SEI 7-05 (12.7.2) [4] a minimum of *25%* of the filling live load shall be include within the effective seismic weight (here: *100%* of the filling live load);
- according to ASCE/SEI 7-05 (12.8.4.2) [4] accidental torsion should be taken into account by assumed displacement of the centre of mass by a distance equal to 5 percent of the dimension of the structure perpendicular to the direction of the applied forces. This approach is exactly the approach according to EN 1998-1(4.3.2) [1] and was not implemented here;
- combination of the seismic action with other actions in accordance with ASCE/SEI 7-05 (12.4.2.3) [4]: $(1.2 + 0.2\,S_{DS})\,D + \rho\,Q_E + L + 0.2\,S$, whereas the dead load D is equal to the self-weight of the tank, the live load L is equal to the filling and the snow load is zero.

This investigation is carried out using the strut-and-tie model in Figure 3 (right side). The results are shown and discussed in chapter 4.2 C.

C. Comparison of the design value

The static seismic equivalent loads are determined and combined following the rules given above. They are applied as single equivalent loads in centre of gravity of the strut-and-tie model and the action effects are calculated using linear elastic analysis. The results are given in the following Table 6, listing action effects (separated for the individual load cases) and design values (of the load combination) for both column base and column head according to European standards and American Standards respectively. The table also shows results for seismic action in 0°-direction as well as in 15°-direction. Although the static seismic equivalent loads according to European standards are approximately 5% higher than the ones taken from the American standards, the correlation of those results is good. This good correlation is due to the combination of the seismic action with other actions in accordance with ASCE/SEI 7-05 (12.4.2.3) [4].

		column base				column head			
		Eurocode		ASCE		Eurocode		ASCE	
		$\alpha = 0°$	$\alpha = 15°$	$\alpha = 0°$	$\alpha = 15°$	$\alpha = 0°$	$\alpha = 15°$	$\alpha = 0°$	$\alpha = 15°$
self-weight	N	*-732.3*		*-966.6*[1]		*-686.5*		*906.2*[1]	
	$V_x = V_y$	*0.0*				*0.0*			
	$M_y = M_x$	*0.0*				*0.0*			
operating-load	N_K	*-1753.5*				*-1753.5*			
	$V_x = V_y$	*0.0*				*0.0*			
	$M_y = M_x$	*0.0*				*0.0*			
seismic-load	N	*-1335.6*	*-1288.8*	*-1086.6*	*-1049.6*	*-1335.6*	*-1288.8*	*-1086.6*	*-1049.6*
	V_x	*609.9*		*446.0*		*609.9*		*446.0*	
	V_y	*183.0*		*0.0*		*183.0*		*0.0*	
	M_y	-				*6313.4*		*4616.4*	
	M_x	-				*1894.0*		*0.0*	
load combination	N_d	*-3821.5*	*-3774.6*	*-3806.8*	*-3769.8*	*-3553.0*	*-3514.0*	*-3746.2*	*-3709.2*
	$V_{x,d}$	*609.9*		*446.0*		*609.9*		*446.0*	
	$V_{y,d}$	*183.0*		*0.0*		*183.0*		*0.0*	
	$M_{y,d}$	-				*6313.4*		*4616.4*	
	$M_{x,d}$	-				*1894.0*		*0.0*	

[1] $(1.2+0.2\ S_{DS})\ D$ (combination of the seismic action with other actions according to ASCE/SEI 7-05)

Table 6: Action effects and design values for load directions of $\alpha = 0°$ and $\alpha = 15°$ according to European and American standards

In addition a closer look at the results leads to the following recognitions:

- the methods to calculate the seismic base shear force according to European and American standards are identical, so that the differences in the results only come from the different design spectra;

- the adding of the redundancy factor ρ = 1.3 increased the static seismic equivalent load according ASCE 7 [4]; after this step the seismic loads according to Eurocode and ASCE are quite equal
- because of the accidental eccentricity, which was simplified taken into account according to the EC-8 [1], the difference between the results increased again. This becomes apparent by calculating the shear force V_x resulting from the seismic load:

$$V_x = \delta \cdot \frac{F_b}{n} = 609.9\,kN \qquad \text{(Eurocode)}$$

$$V_x = \frac{E_h}{n} = 446.0\,kN \qquad \text{(ASCE)}$$

where $n = 12$ (number of columns, see chapter 2.1)

$$\delta = 1 + 0.6 \cdot \frac{x}{L_e} = 1.3 \qquad \text{(see Eq. 5)}$$

with $L_e = 19700\,mm$ (see chapter 2.1)

$$x = \frac{19700}{2} = 9850\,mm \qquad \text{(see chapter 2.1)}$$

To design columns, bases and joints of the columns to the spherical pressure vessel the design values for α = 0° according to EC 8 are relevant. The verification of the individual members as well as the ULS verification of the vessel skin is not discussed here since the focus was only on the comparison of the different action effects.

4.3 Seismic base shear force taking into account sloshing effects

In the European as well as the American standard rules for the consideration of sloshing effect for liquids are provided for cylindrical (EC 8 und ASCE 7) respectively for rectangular (ASCE 7) tanks only. Thereby the maximum height of the sloshing wave is calculated (see equation 8 and 9) which pretend the minimum height of the freeboard. Neither in the European nor in the American standard a calculation of a seismic design shear force due to the sloshing effect is regulated.

$$d_{\max} = 0.84 \cdot R \cdot \frac{S_d(T_{c1})}{g} \qquad \text{(EC 8)} \qquad (8)$$

$$\delta_S = 0.5 \cdot D_i \cdot I \cdot S_{ac} \qquad \text{(ASCE 7)} \qquad (9)$$

For this reason the published procedure of KARAMANOS et al. [9] was used to consider the sloshing effect in seismic design of the investigated spherical tank.

e	[%]	M_{1C}/M_L	M_{2C}/M_L	M_{3C}/M_L	M_{4C}/M_L	M_{nC}/M_L	M_I/M_L
-1.0	0.0	1.00000	0.0000	0.00000	0.00000	1.00000	0.00000
-0.95	25	0.98315	0.00010	0.00000	0.00000	0.98326	0.01674
-0.90	5.0	0.96594	0.00039	0.00000	0.00000	0.96634	0.03366
-0.80	0.0	0.9338	0.00137	0.00007	0.00001	0.93184	0.06816
-0.60	20.0	0.85437	0.00434	0.00052	0.00014	0.85947	0.14053
-0.40	30.0	0.77117	0.00785	0.00140	0.00046	0.78136	0.21864
-0.20	40.0	0.67990	0.01140	0.00253	0.00094	0.69619	0.30381
0.00	50.0	0.57969	0.01458	0.00372	0.00150	0.60594	0.39406
0.20	60.0	0.46981	0.01687	0.00472	0.00202	0.49844	0.50156
0.40	70.0	0.35009	0.01753	0.00525	0.00235	0.38440	0.61560
0.60	80.0	0.22222	0.01542	0.00490	0.00228	0.26162	0.73838
0.80	90.0	0.09363	0.00919	0.00310	0.00150	0.12608	0.87392
0.90	95.0	0.03655	0.00439	0.00154	0.00076	0.05586	0.94414
0.95	97.5	0.01364	0.00185	0.00067	0.00034	0.01810	0.98190
1.00	100.0	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000

Table 7: Variation of Sloshing Masses with respect to Liquid height in a Spherical Container [9]

The calculation of the relevant seismic design shear force due to the sloshing effect was performed assuming a liquid fill height of 90% which was determined to be the most unfavourable condition. The convective and impulsive masses follow from Table 7:

$$M_{nC} = 652.6[t] \tag{10}$$

$$M_I = 1239.4[t] \tag{11}$$

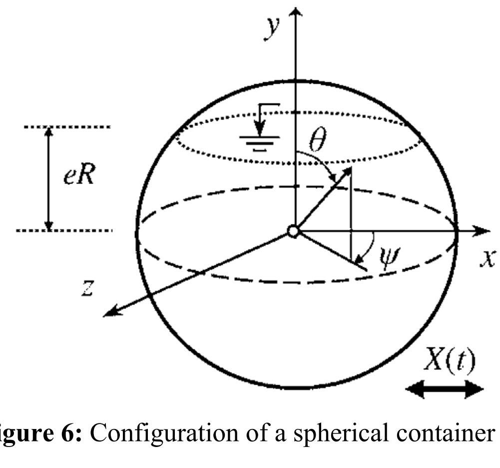

Figure 6: Configuration of a spherical container [9]

The relevant acceleration was calculated with the same assumptions regarding to the design spectrum described in Chapter 2.1.

For the convective part of the sloshing effect the periods are shown in Table 8. The angular frequencies were determined according to Table 9.

T_{1C}	T_{2C}	T_{3C}	T_{4C}
3.18	2.06	1.65	1.41

Table 8: Frist four sloshing periods for a liquid height of 90%

with:

$$T_{nC} = T_{nC} = \frac{2\pi}{\omega} \tag{12}$$

e	[%]	$\lambda_1 = \omega_1^2 R/g$	$\lambda_2 = \omega_2^2 R/g$	$\lambda_3 = \omega_3^2 R/g$	$\lambda_4 = \omega_4^2 R/g$
-1.00	0.0	1.0000	7.0000	17.0000	31.0000
-0.9	5.0	1.0347	6.5638	13.8911	26.7570
-0.80	10.0	1.0723	6.2008	11.8764	17.0320
-0.60	20.0	1.1583	5.6742	9.8543	13.8660
-0.40	30.0	1.2625	5.3683	8.9418	12.4210
-0.20	40.0	1.3924	5.2406	8.5509	11.8000
0.00	50.0	1.5602	5.2756	8.5045	11.6840
0.20	60.0	1.7882	5.4930	8.7793	12.0210
0.40	70.0	2.1232	5.9729	9.4763	12.9380
0.60	80.0	2.6864	6.9574	10.9566	14.9180
0.80	90.0	3.9595	9.4551	14.7598	20.0330
0.90	95.0	5.7615	13.1776	20.4520	27.7020
0.95	97.5	8.3121	18.5527	28.6891	38.8160
1.00	100.0				

Table 9: Variation of the first four sloshing frequencies with respect to liquid height in a spherical vessel **[9]**

The impulsive angular frequency was calculated with the stiffness of the support systems K_{bs}.

$$\omega_{(2)}^2 = \omega_I^2 = \frac{K_{bs}}{M_I} \tag{13}$$

For the evaluation of the impulsive period the support systems stiffness was determined by using the FE-model of the spherical tank. To obtain the same stiffness by hand calculation (see equation 14) the effective column height had to be h_L = 10.39 [m].

$$K_{bs} = \sum_{j=1}^{N} \frac{3 \cdot EI_L}{h_L^3} \tag{14}$$

This resulted in a period for the impulsive part of T_I = 1.48 [s]. Table 10 shows the masses and periods neglecting the sloshing effect and with consideration of sloshing. The comparison shows that the impulsive Eigen period T_I is approximately equal to the Eigen period T_1 without sloshing. In contrast, the value of the convective Eigen period T_{1C} is more than twice as large.

without sloshing				
	total mass M [t]		period T_I [s]	
dynamic analysis	2919.2		1.54	
inverted pendulum	2919.2		1.56	
sloshing considered				
	convective mass M_C [t]	impulsive mass M_I [t]	period T_{1C} [s]	period T_I [s]
sloshing response	263.96	2644.64	3.18	1.48

Table 10: Comparison of Natural periods

Table 11 shows the ordinates S_d which were evaluated with the periods T_{1C} and T_I as well as the design spectrum according to Chapter 2.1. For the convective part the behaviour factor was set to q = 1.0 according to EN 1998-4, Chap. 4.4(4) [2].

$S_d(T_{1C})$	$S_d(T_I)$
0.80	2.74

Table 11: Comparison of the design response spectrum

In the calculation of the seismic design shear force F_D (equation 15) only the first convective period was taken into account. The convective and impulsive parts of the sloshing effect were combined by the "square root of the sum of the squares"-rule (SRSS):

$$F_D = \sqrt{\left(M_C \cdot S_d\left(T_{1C}\right)\right)^2 + \left(M_I \cdot S_d\left(T_I\right)\right)^2} \tag{15}$$

For the investigated spherical pressure vessel the seismic design shear force according equation 15 resulted to F_D = 7240 [kN]. The comparison with the seismic base shear force F_b = 5629.8 [kN] from Chapter 4.2 A shows that the consideration of the sloshing effect provides significantly higher earthquake loads. Thus the seismic design shear force F_D according equation 15 was used in the following stress analysis.

It needs to be mentioned, that in particular in cases where the convective period is significantly longer than the impulsive period, the application of the SRSS-rule may lead to non-conservative results because of the increased probability of the co-occurrence of the maxima of both modes (see Figure 7).

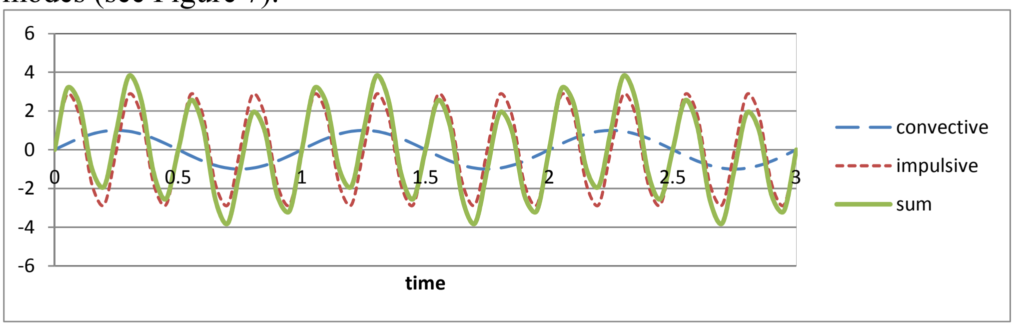

Figure 7: Simplified combination of convective and impulsive modes

4.4 Stress analysis

The stress analysis was performed using a finite element model of the spherical pressure vessel (see Figure 8). Thereto the following load cases from case study 4 were applied.

- dead load (empty weight): 815 [t]
- operating load (90% fill height): 2130 [t]
- internal pressure: 1650.0 [kN/m²]
- external pressure: 101.325 [kN/m²]
- seismic design shear force: 7240 [kN]

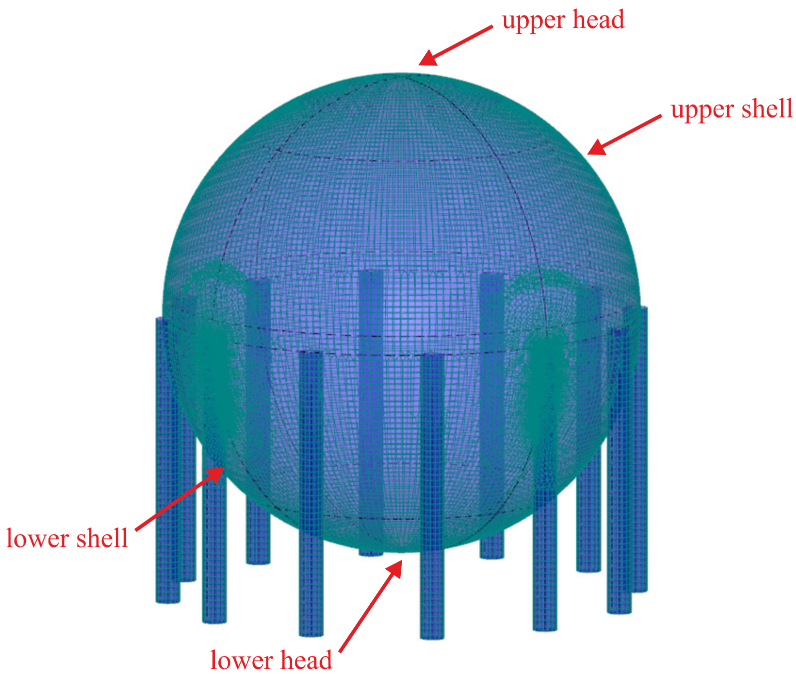

Figure 8: FE-model of the spherical pressure vessel

The tank was modelled with shell thicknesses of $t_1 = 71.8$ [mm], $t_2 = 73.1$ [mm], $t_3 = 75.9$ [mm] and $t_4 = 74.6$ [mm] (see Chapter 2.1). The vessel stresses were determined at the upper head, at the lower head as well as a two undisturbed areas of the shell. In addition stresses of the connection column-shell were determined in load direction and transverse to the load direction. The results are shown in Table 12 and Table 13.

load cases	**dead load**	**operating load**	**internal pressure**	**external pressure**	**seismic load**
	[kN/cm²]	[kN/cm²]	[kN/cm²]	[kN/cm²]	[kN/cm²]
upper head	-0.16	0.00	11.58	-0.70	0.03
upper shell	0.05	0.00	11.30	-0.69	0.09
column-shell (in load direction)	2.02	1.63	**12.68**	-0.70	**27.43**
column-shell (transverse load direction)	1.95	1.30	**12.68**	-0.68	3.98
lower head	0.17	0.42	10.96	-0.68	0.05
lower shell	0.16	0.45	11.16	-0.68	0.03

Table 12: Stresses due to load cases in different points

combination	**EN 1990,** Chap. 6.4.3.4 [3] $\Sigma G_{k,j} + A_{ed} + \Sigma 0{,}8\ Q_{k,i}$	**ASCE/SEI 7-05,** Chap. 2.4.1 [4] D + F + 0,7E	**ASME II Part-D,** Tab. 5A [7] allowable stress
upper head	9.13	11.44	
upper shell	9.18	11.41	
column-shell (in load direction)	**40.90**	**35.53**	
column-shell (transverse load direction)	17.11	18.72	34.5
lower head	9.32	11.59	
lower shell	9.48	11.79	

Table 13: Load case combination

With	$G_{k,j}$	=	D	=	dead load
	A_{Ed}	=	E	=	earthquake load
	$Q_{k,i}$	=	F	=	live load

5 OVERALL CONCLUSIONS AND FUTURE PROSPECTS

With regard to the design of spherical liquid storage tanks the seismic provisions of Eurocode as well of the ASCE Code can be described as similar. The main differences in the results obtained by the application of both codes result from different input data for seismic actions. Nevertheless there are some differences within the calculation rules for spherical tanks:

- The ASCE Code provides more detailed data on the choice of a response modification factor, tanks are not classified as simple inverted pendulum systems;
- Distinction is made between braced and unbraced supports;
- Eurocode proposes the assumption of an inverted pendulum system for the behavior factor

Both codes however do not provide methods for the calculation and consideration of sloshing effects in spherical tanks. Furthermore some rules which are used in the practice design of spherical tanks need clarification or enhancement:

- Realistic assessment of the behavior factor – in fact a sphere supported by a number of legs behaves like a frame rather than like a inverted pendulum;
- The assessment of a behavior factor shall be detailing rules allowing for the achievement of a dissipative behavior; this applies in particular to the connection of the legs to the shell as well as to the foundations;
- The application of the simplified eccentricity, which was selected to allow for a simple modelling of the spherical vessel, leads to very conservative results. The application of a severe method to systems, which are obviously symmetric, shall be allowed whithout the formal requirement of a 3D-investigation;
- The need of application of the 100%-x and 30%-y seismic action with regard to rotation-symmetric structures or components shall be verified;
- Conditions for the consideration of sloshing effects shall be defined together with methods for the calculation of these effects and for the combination of the convective and impulsive modes.

6 ACKNOWLEDGEMENT

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REFERENCES

[1] EN 1998-1:2010-12: "Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings", European Committee for Standardization, Brussels, 2010

[2] EN 1998-4:2007-07: "Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines", European Committee for Standardization, Brussels, 2007

[3] EN 1990:2010-12: "Basis of structural design", European Committee for Standardization, Brussels, 2010

[4] ASCE/SEI 7-05: "Minimum Design Loads for Buildings and Other Structures", American Society of Civil Engineers, Reston, 2006

[5] API Standard 620: "Design and Construction of Large, Welded, Low-pressure Storage Tanks", 11th Edition, American petroleum Institute, Washington D.C., 2009

[6] API Standard 650: "Welded Steel Tanks for Oil Storage", 11th Edition, American petroleum Institute, Washington D.C., 2007

[7] ASME Boiler & Pressure Vessel Code, Section II Material, Part D – Properties (Metric), The American Society of Mechanical Engineers, New York, 2007

[8] ECCS – TC 13 Seismic Design: "ECCS Manuel on Design of Steel Structures in Seismic Zones", No. 76, First Edition, 1994

[9] KARAMANOS, S.A.; PATKAS, L.A.; PLATYRRACHOS, M.A.: „Sloshing Effects on the Seismic Design of Horizontal-Cylindrical and Spherical Industrial Vessels", Journal of Pressure Vessel Technology, ASME, Volume 128, Issue 3, pp. 328-340, 2006ly