DIMENSIONING STEEL STRUCTURE OF RECTANGULAR TANK ACCORDING TO THE EUROCODE

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Summary: *The main topic of the paper is dimensioning steel liquide storage tank, rectangular in shape, with three compartments. Depending on the investor's request (dimensions required for the tank and maximum use of space) a need arose for structure with atypical shape. Austenitic stainless steel is used in this example what is recommended for use in aggresive environments. Dimensioning of steel plates, stiffened and unstiffened, according to Eurocode is carried out according to EN 1993-1-7, which refers to plates loaded out of their plane. Within the first part of the analysis dimensioning is performed according to Eurocode 3. The second part of the paper represents comparative analysis of results obtained according to Eurocode and results obtained using previous domestic standard SRPS.MZ.3. 054. (1981).*

Keywords: *EC3; SRPS; stainless steel; rectangular tank*

1. INTRODUCTION

The subject of the paper is dimensioning steel tank which does not have a standard, cylindrical or spherical shape. Since these forms of tanks commonly appear in practice, dimensioning of these reservoirs is routine. However, depending on the investor's request (dimensions required for the tank, maximum use of space), there is a need for constructions with atypical forms. Such atypical structure, rectangular in shape with three compartments, is dimensioned in this paper. With a few exceptions in which is available

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a number of examples by national standards with silo and tank cells [1], dimensioning this type of construction, ie dimensioning of flat steel plates loaded perpendicular to the middle plane of plate does not take up an importante place in our literature. Also an entire chapter devoted to Eurocode 3 in our literature can be found in [2], and by [2] with additional parts of Eurocode 3 related to the tanks and stainless steel, dimensioning of the structure that is the subject of this paper is performed. As the first stage of analysis, dimensioning is performed according to the Eurocode, and as the most interesting problem, dimensioning of flat steel plates subjected to bending is analyzed. The second stage is the analysis of the model in the software package ABAQUS. Dimensioning of stiffened or unstiffened steel plates of tanks, according to the Eurocode, is performed according to EN 1993-1-7 [3], which refers to plates subjected to out of plane loading. Details about the dimensioning of all elements of a rectangular tank, are given as a part of the EN 1993-4-2 [4]. In our country, for the calculation of the tanks, currently is in use standard JUS.MZ.3. 054. (1981) [5].

2. BASIS OF DESIGN OF RECTANGULAR TANKS ACCORDING TO THE EUROCODE

Eurocode 3 presents the part of the Eurocode which refers to the dimensioning of steel structures. It is based on the semi-probabilistic concept of design, or on limit states. In order to select the method of structural analysis, it is necessary to define a structure type, or to define a consequence class to which a structure belongs. Therefore EN 1993-4-2 [5] defines a consequence class, according to which it classifies a type of construction in a particular class which defines the level of realibility of the construction. According to [5], the level of realibility of tank construction is defined according to following three consequence classes (Table 1).

Table 1: Consequence classes for tank constructions

Consequence class 3	Tanks storing liquids or liquefied gases with toxic or explosive potential and large size with flammable liquids or water – polluting liquids in urban areas. Emergency loadings should be taken into account for these structures where necessary.
Consequence class 2	Medium size tanks with flammable liquids or water – polluting liquids in urban areas
Consequence class 1	Agricultural tanks or tanks containing water

The term load is presented in the Eurocode with the term action. Actions on the analyzed tank are defined by the requirements that the tank is going to be built indoors, in certain dimensions. Based on this, and according to [5], from the actions which act on tank construction, the only action on the analyzed tank construction is liquid induced load.It is necesarry to observe the tank filled to the maximum level possible and to use the characteristic values of actions in design situations. Liquid induced loads in tanks, according to EN 1991-4 [6], are classified as variable actions.

2.1 PARTIAL FACTORS FOR ACTIONS

The values of partial factors for actions given in Annex A1 of EN 1990 [7], can be used in calculation of tanks. According to [5] for both persistent and transient design situations, it is recommended to use partial factors according to the Table 2.

Table 2: Recommended values of partial factors for actions γ_F on tanks for persistent and transient design situations and for accidental design situations:

Design situation	Liquid type	Recommended values for γ_F in case of variable actions from liquids	Recommended values for γ_F in case of permanent actions
Liquid induced loads during operation	Toxic, explosive or dangerous liquids	1,4	1,35
	Flammable liquids	1,3	1,35
	Other liquids	1,2	1,35
Liquid induced loads during test	All liquids	1,0	1,35
Accidental actions	All liquids	1,0	-

Also, if the maximum depth of the liquid and the heaviest liquid to be stored are precisely defined, the partial factor for actions can be reduced from 1.5 to 1.35. However, although the maximum depth of the fluid and the fluid that is going to be stored are accurately defined, for the example analyzed in this paper partial factor for actions $\gamma_Q = 1.5$ is used.

2.2 PARTIAL FACTOR FOR RESISTANCES

The values of partial factors for resistance, recommended for tanks according to [5], are given in the Table 3.

Table 3: Partial factors for resistance γ_M recommended for tanks

Resistance to failure mode	Relevant γ	Numerical values recommended for tanks
Resistance of welded or bolted shell wall to plastic limit state, cross-sectional resistance	γ_{M0}	1,00
Resistance of shell wall to stability	γ_{M1}	1,10
Resistance of welded or bolted shell wall to rupture	γ_{M2}	1,25
Resistance of shell wall to cyclic plasticity	γ_{M4}	1,00
Resistance of welded or bolted connections or joints	γ_{M5}	1,25
Resistance of shell wall to fatique	γ_{M6}	1,10

2.3 LIQUID INDUCED LOADS

The liquid which is intended to be stored in the tank analyzed is wine. According to [6] a characteristic value of pressure p is $p(z)=\gamma z$

where

z - is depth of the liquid and

γ - is density of the liquid.

Densities of liquids are given in EN 1991-1-1 [8], in Annex A, which contains tables of nominal values of densities for construction materials, among which is the specified value of density of wine, which is: $\gamma=10.0\left[kN/m^3\right]$

2.4 MODELLING OF THE BOX STRUCTURE OF THE RECTANGULAR TANK

As noted above, when modelling a rectangular tank it is necessary to follow the instructions given in [4] concerning the resistance and stability of flat plates loaded out of plane, but the instructions given in [5] can also can be considered sufficient. During dimensioning stiffeners, it is necessary to determine the effective plate width. The effective plate width on each side of he stiffener should not be higher than $n_{ew}t$, where t is local plate thicknes. Recommended value for n_{ew} is 15ε.

2.5 DIMENSIONING OF RECTANGULAR AND PLANAR – SIDED TANKS

Rectangular tank should be dimensioned as a stiffened box in which the structural action is dominantly bending, or as a structure composed of thin membranes in which is dominant membrane stress state.

<u>Types of tanks</u>:

Unstiffened tanks – represent a construction that is designed with flat unstiffened steel plates (unstiffened box). (Fig.1-left [9]) Stiffened tanks – represent a construction to which stiffeners are attached so that one part of a stiffener is within the plate (stiffened box). The stiffeners can be circumferential, vertical or orthogonal. (Fig.1-right,2,3 [9]) Tanks with ties – can be squere or rectangular.

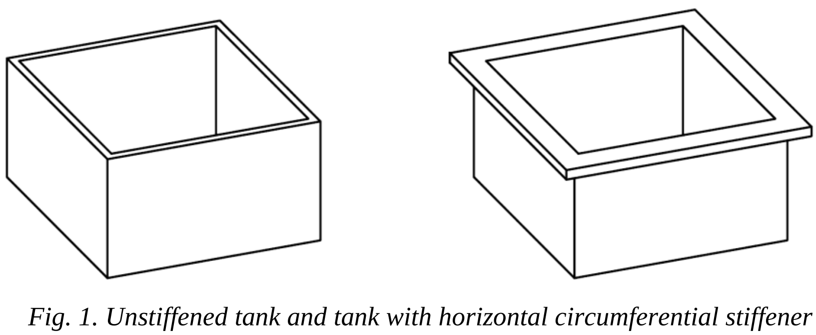

Fig. 1. Unstiffened tank and tank with horizontal circumferential stiffener

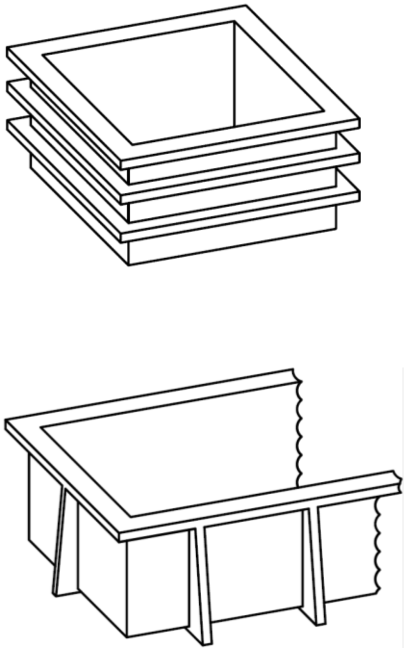

Fig. 2. Tank with horizontal circumferential stiffeners, and tank with vertical, "U" stiffeners

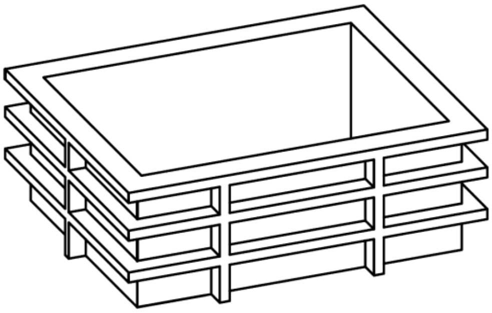

Fig.3. Tank with orthogonal stiffeners

Unstiffened plates, during the design of unstiffened tanks, are necessary to design as two – dimensional plates, under the liquid induced load, pressure above the liquid, stresses resulting from diaphragm action, and due to local influence of pipes of additional elements on the tank. Stiffened plates can be corrugated or trapezoidal and these plates are designed to the same load as unstiffened plates.

The design of unstiffened plates is derived according to the EN 1993-1-3.
Dimensioning of elements is carried out to bending in horizontal plane, where bending is the result of pressure of the liquid which is acting perpendicular to the tank wall. In design is necessary to consider the membrane tensile stresses occurring in the walls as a result of hydrostatic pressure on the walls perpendicular to the wall that is being analyzed.
It is also necessary to consider membrane compression stresses occuring in the walls as a result of a wind load on the walls perpendicular to the wall that is being analyzed. In case analyzed in this paper, the influence of the wind will not be considered according to the claim that the construction is going to be located indoors.
Local bending effects from additional elements or pipes on the tanks should be avoided as much as possible. If this is not possible, it is necessary to examine the stress and strain state near the hole. In case analyzed in this paper, the stress and strain state near the hole is not analyzed.

2.6 STAINLESS STEEL CONSTRUCTION

Material used for the tank that is analyzed in the next chapter is austenitic steel 1.4301. According to [10], properties of stainless steel for material used (nominal values) are:
Yield strength: $f_y = 21.0 kN/cm^2$
Ultimate tensile strength: $f_u = 52.0 kN/cm^2$
The values of the coefficient of elasticity for stainless steel used are:
Modulus of elasticity: $E = 200000 N/mm^2$
Poisson's ratio: $\nu = 0.3$.
Coefficient ε for stainless steel 1.4301 is:

$$\varepsilon = \left[\frac{235}{f_u} \cdot \frac{E}{210000} \right]^{0.5} = 1.03$$

Recommended values of partial factors for resistance, according to [10], for stainless steel are given in Table 4:

Table 4: Partial factors for resistance γ_M - recommended for stainless steel

Resistance to failure mode	Relevant γ	Recommended value for stainless steel
Resistance of cross – sections to excessive yielding including local buckling	γ_{M0}	1,1
Resistance of members to instability assessed by member checks	γ_{M1}	1,1
Resistance of cross – sections in tension to fracture	γ_{M2}	1,25
Resistance of bolts, rivets, welds, pins and plates in bearing	γ_{M2}	1,25

3 DIMENSIONING STRUCTURAL ELEMENTS OF A TANK FOR WINE - ($100m^3$)

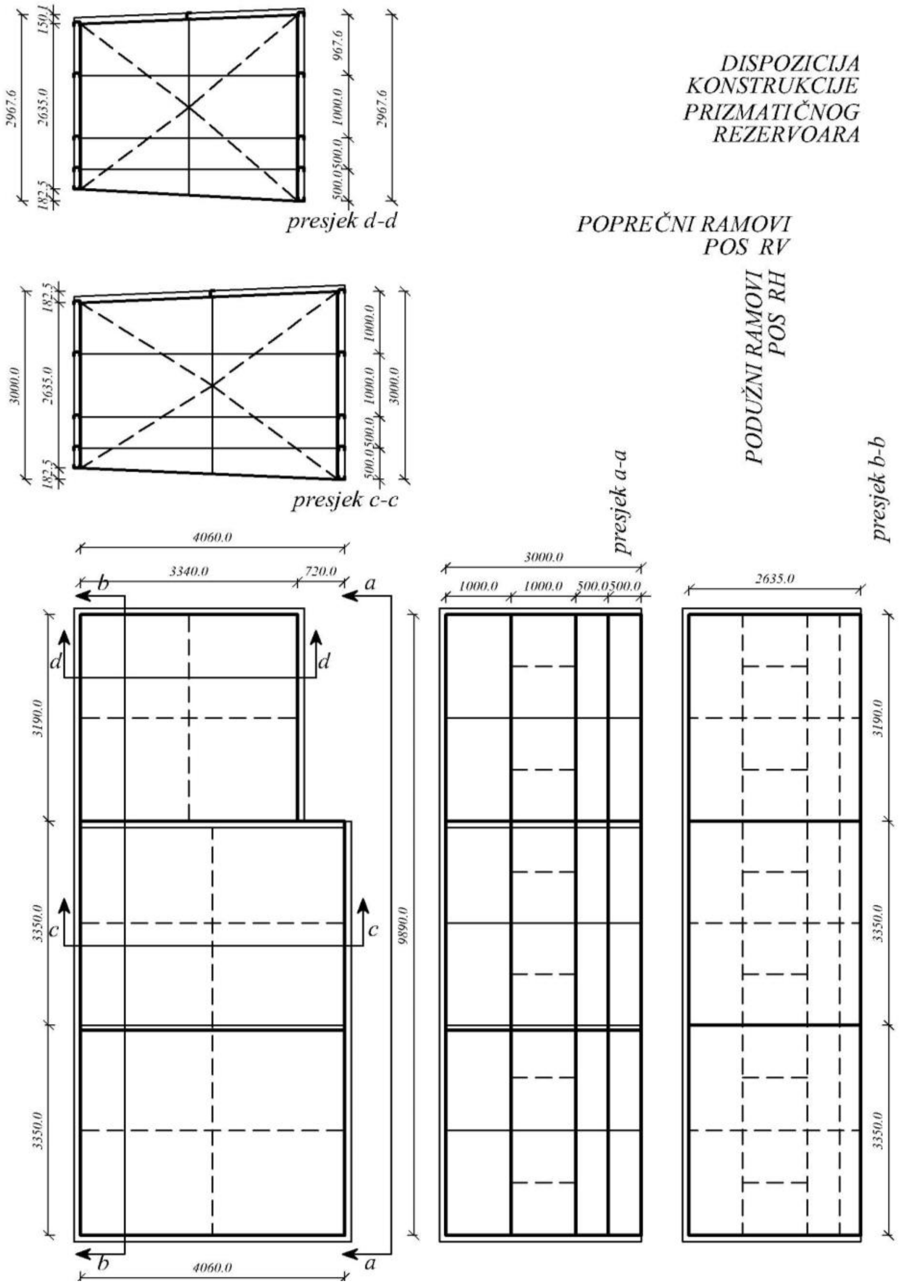

Fig.4 Disposition of the prismatic tank

3.1 CALCULATION OF THE TANK SHELL (BOX)

Calculation of the box tank is done due to liquid induced load (Fig.5)

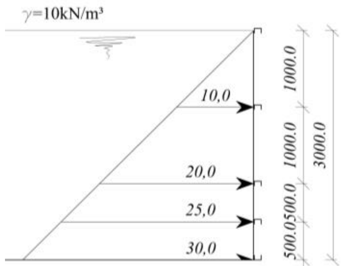

Fig.5 Liquid induced load on the box of the tank q

Design values of actions obtained from $q_{Ed} = \gamma_Q \cdot q$ are given in Figure 6:

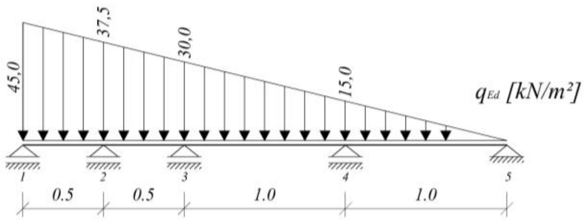

Fig. 6 Design values of actions on the tank shell

Parts 1-2 and 2-3 of tank shell are calculated as equivalent beam girders, while parts 3-4 and 4-5 are calculated by [4], Annex C. While dimensioning equivalent beam girders, it has been established that the bending resistance of cross-section is satisfied.

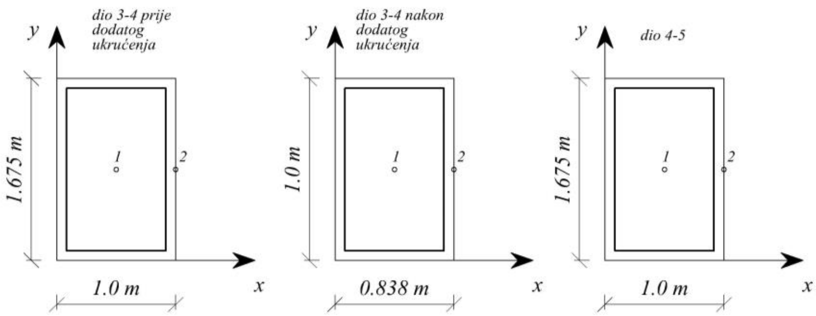

Fig. 7 Segments of shell dimensioned as unstiffened plates with all edges clamped, with labels of points: 1. – The point in the middle of the segment; 2. – The point on the edge of the longer side ,For part 3-4, according to [4], detailed calculation of a tank shell segment is shown:

Part 3-4:

Design value of action:

$q_{Ed} = 22.5 kN/m^2$

Parameter Q:

$$Q = \frac{q_{Ed} \cdot a^4}{E \cdot t^4} = 439,453;$$

$Q > 400 \rightarrow$ vertical stiffener is adopted on $\lambda = \frac{1}{2} l = 0.838m$.

Parameter Q:

$$Q = \frac{q_{Ed} \cdot a^4}{E \cdot t^4} = 216.8$$

$$\frac{b}{a} = 1.2$$

For $Q = 200$ and $\frac{b}{a} = 1.5 \rightarrow$ $k_{\sigma bxp} = 0.0876$;

$k_{\sigma mxp} = 0.0259$;

Stresses at point 1:

$$\sigma_{bx,Edp} = k_{\sigma bx} \cdot \frac{q_{Ed} \cdot a^2}{t^2} = 8.65kN / cm^2$$

$$\sigma_{mx,Edp} = k_{\sigma mx} \cdot \frac{q_{Ed} \cdot a^2}{t^2} = 2.558kN / cm^2$$

$$\sigma_{x,Edp} = \sigma_{bx,Edp} + \sigma_{mx,Edp} = 11.208kN / cm^2$$

Design resistance :

$$\sigma_{Rd} = \frac{f_y}{\gamma_{M0}} = 19.09kN / cm^2$$

$$\frac{\sigma_{x,Edp}}{\sigma_{Rd}} = 0.587 < 1$$

Deflection at point 1:

$$w_1 = k_w \cdot \frac{q_{Ed} \cdot a^2}{Et^3} = 0.0102289m$$

<u>Part 4-5:</u>

Stresses at point 1:

$$\sigma_{bx,Edp} = k_{\sigma bxp} \cdot q_{Ed} \cdot a^2 / t^2 = 5.981kN / cm^2$$

$$\sigma_{mx,Edp} = k_{\sigma mxp} \cdot q_{Ed} \cdot a^2 / t^2 = 1.116kN / cm^2$$

$$\sigma_{x,Edp} = \sigma_{bx,Edp} + \sigma_{mx,Edp} = 7.1kN / cm^2$$

$$\frac{\sigma_{x,Edp}}{\sigma_{Rd}} = 0.372 < 1$$

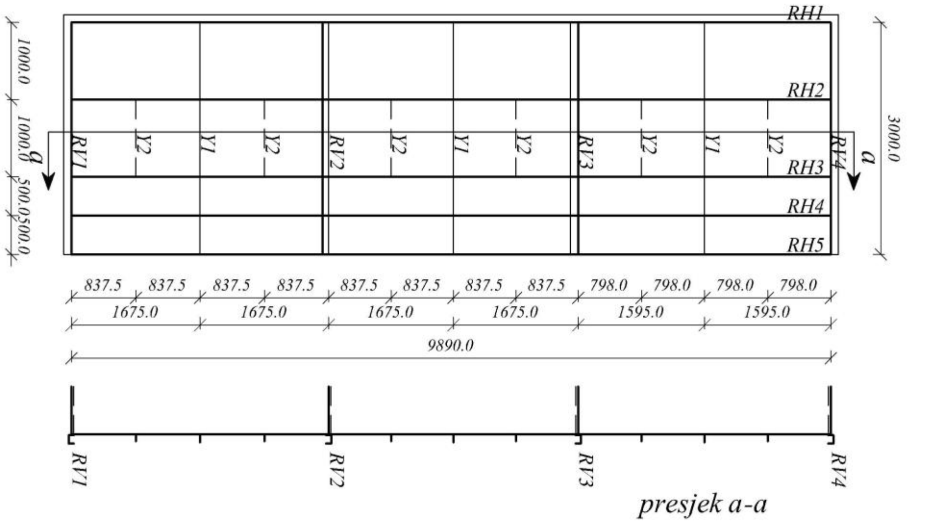

Fig.7 The position of the stiffeners of tank shell, the horizontal and vertical frames

Vertical stiffener Y2:

Vertical stiffener Y2 which is located at part 3-4 of a tank shell segment is a vertical plate welded to the tank shell. The vertical stiffener is dimensioned as a T-section consisting of vertical plate and effective width of a tank shell. For a static system, the simply supported beam is adopted, with equivalent continuous design value of action. It has been established that the bending resistance of cross-section is satisfied.

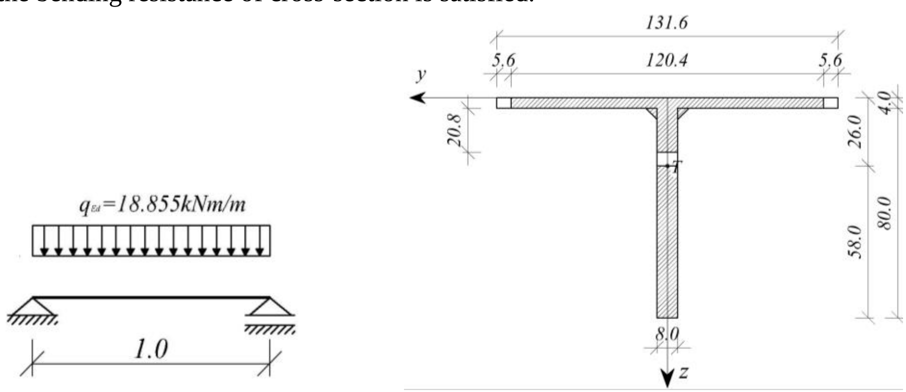

Fig.8 Static system (left) of a part of a stiffener between two horizontal stiffeners, and dimensiones of the stiffener (right)

Vertical stiffener Y1:

Vertical stiffener Y1 of a tank shell segment is composed of vertical plate welded to the tank shell as well as Y2. On the parts 1-2, 2-3 and 4-5, one hight of a rib of the T-section is adopted, while at part 3-4 it was necessary to adopt a greater hight of a rib (Fig. 9). The calculation is performed as for stiffeners Y2, and it has been established that the bending resistance of cross-section is satisfied.

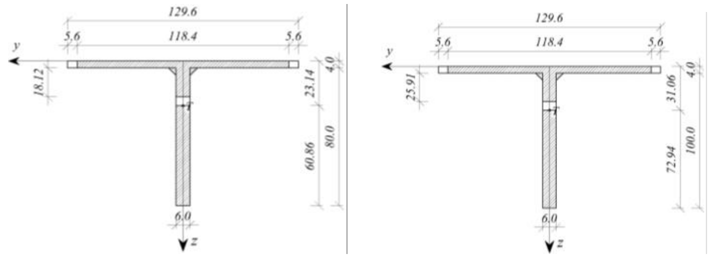

Fig. 9 Dimensions of stiffeners of parts 1-2, 2-3, i 4-5 (left) and 3-4 (right)

3.2 DESIGN OF HORIZONTAL FRAMES RH

While dimensioning horizontal frames, for one horizontal frame cross-sectional forces for unit load $q_0=10kN/m$, are first calculated and based on the maximum value of the bending moment obtained *max* $M_0=13.85kNm$, and the reduction factor η, which defines the amount of load that belongs to each horizontal frame, the profiles given in Table 6 are adopted. Dimensioning is performed with effective width of a tank shell and additional steel plates between the profile and the shell. Horizontal frames are presented in Figure 7.

Table 6. Reduction factor, design value of bending moments, adopted profiles, plastic section modulus, design moment of resistance and required ratio to define bending resistance, respectively.

RH	η	$\max M_{Ed}$ $[kNm]$	Adopted profiles	$W_{pl,y}$ $[cm^3]$	$M_{c,y,Rd}$ $[kNcm]$	$\frac{\max M_{Ed}}{M_{c,y,Rd}}$
RH1	0.125	2.597	UPE 80	42.091	803.561	$0.323 < 1$
RH2	1.0	20.775	IPE 140	115.67	2208.24	$0.941 < 1$
RH3	1.4063	29.2159	IPE 160	157.675	3010.15	$0.971 < 1$
RH4	1.25	25.9688	IPE 160	157.675	3010.15	$0.863 < 1$
RH5	0.719	14.9372	UPE 120	90.245	1722.85	$0.867 < 1$

3.3 DESIGN OF VERTICAL FRAMES RV

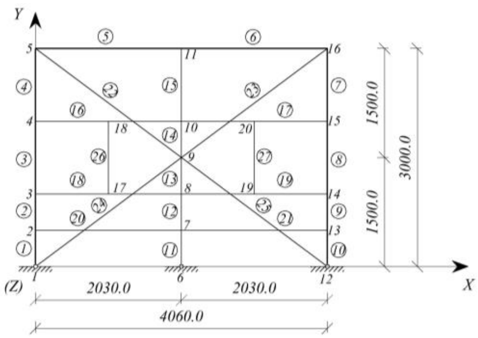

Fig.10 Vertical frame

While dimensioning elements of vertical frames, the profiles given in the Table 7 are adopted, wherein the combined cross-section resistance is examined, where cross-sections are obtained by combining the adopted profiles with effective width of a tank shell and an additional steel plate between them. It has been examined and satisfied beding, shear and axial resistance of cross-section. The resistance of cross-section on the interaction of actions was checked, and found that there is no need for interaction examination.

Table 7. Adopted profiles for elements of vertical frames

RV	Adopted profiles
Elements 1-10	UPE 120
Elements 11-15	UPE 160
Elements 16-27	∦ 60.6

3.4 DESIGN OF UPPER SHELL

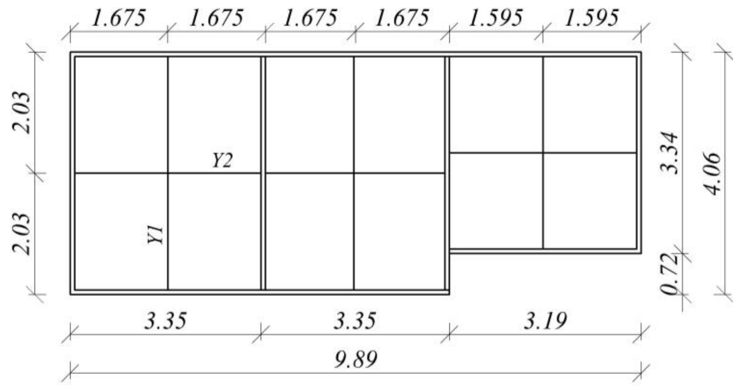

Fig.11 Dimensions of upper shell and stiffener positions

Dimensioning of the upper shell is also performed. While determining the design values of load, considering that the load is self-weight, the partial factor for actions is adopted as $\gamma_G = 1.35$. For stiffeners of the upper shell is adopted:

Y1 – || 60.1,5...

Y2 – 30.60.30.1,5

4 MODEL OF A TANK CONSTRUCTION

ABAQUS 6.7 software package based on FEM (Finite Element Method) consists of a number of engineering programs. It was developed by Hibbitt, Karlsson & Sorensen Inc. ABAQUS represents one of the comprehensive programs, intended to address a wide range of problems, both related to the mechanics, and the other fields of science. Model of a tank is composed of thin plates (*3D shell deformable part*), where all the parts, tank shell and all stiffeners are modeled as thin plates connected with tie constrains. The model consists of 95 parts, connected with 94 tie constrains.

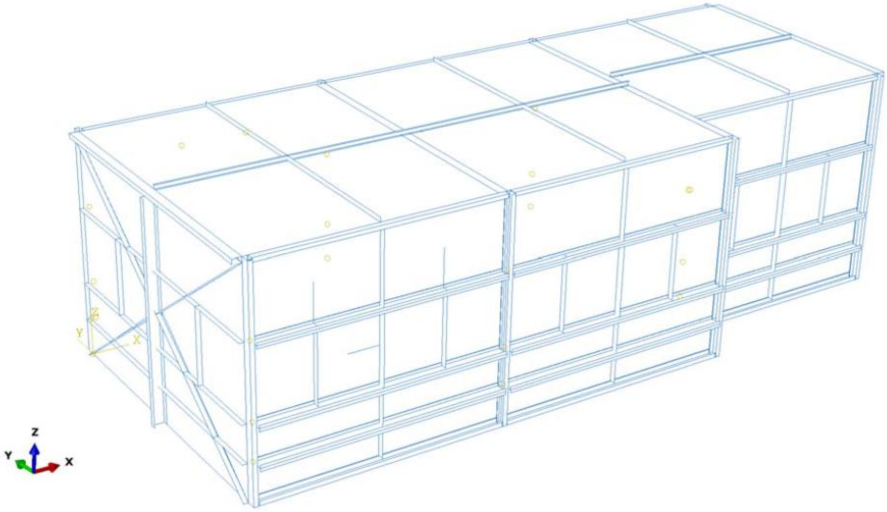

Fig. 12. Model of a rectangular tank with three chambers

The tank is clamped per lower edge, thereby boundery conditions with the bottom of the tank and welding are simulated. Since all parts are modeled as thin plates, for all parts of the tank was used je *STRI3* element, triangular plane element of thin plate with three nodes, each of which has 6 degrees of freedom.
This is the only element in ABAQUS library (according to [11]) designed to solve thin plates. While modeling the plates, the width of elements used was approximate 0.1m. Considering that the geometry of the elements of tank demanded denser mesh of finite elements in certain places, densifying of a mesh was performed. For purposes of numerical modeling, the study of convergence was performed, in which the results of a several numerical models were compared.
The models differed among themselves by the number and the density of the finite element mesh. The convergence of the results of such a complex numerical model requires significant computing resources, particularly working memory.
Since these devices are currently not available to the authors, the listed mesh was adopted. It is observed that the results obtained are of the same order of magnitude as those obtained by calculation according to the Eurocode.

4.1 DISCUSSION OF THE RESULTS

Table 8: Deflections of points of plates

Part	Point	Calculation by the EC	ABAQUS	Difference
3–4 of vertical plate	1	0.0102289*m*	0.0132377*m*	22.7%
	2	0	0.00726218*m*	-
4– of vertical plate	1	0.00949*m*	0.0103487*m*	8.3%
	2	0	0.00557701*m*	-

Table 9: Normal stresses at point 1

Part	Point	Calculation by the EC	ABAQUS	Difference
3 – 4 of vertical plate	1	$11.208 kN/cm^2$	$7.42157 kN/cm^2$	33.7%
4 – 5 of vertical plate	1	$7.10 kN/cm^2$	$5.44576 kN/cm^2$	23.3%

In Tables 8 and 9, deflections in the middle (point 1) and at the site of support (point 2) of the segment of stiffened plate of tank are compared.
A comparison of the absolute deflections is obtained in both cases. In the first case, in design according to the Eurocode, the segment is treated as a plate with all edges clamped (according to [1], Anex C), wherein the obtained plate deflections are deflections obtained so that the edges of segment are treated as immovable parts of plates out of their planes, which is definitely not the case in a real model.
In the latter case, in a model made in Abaqus, the absolute displacements of points in respect to the undeformed position of construction elements are obtained. Comparision of the results obtained from the Eurocode and those obtained in Abaqus showed significant differences.
Bearing in mind that the numerical model in Abaqus is geometrically identical, spatial, structural model, these differences are expected. That is, it is assumed that these differences are a consequence of a greater displacements of observed cross sections in the spatial model, unlike the model in Eurocode in which the supporting elements are hardwired.
These displacements caused a more favorable redistribution of stresses and therefore less intensity of a maximum of stresses.Displacements of all points of construction are shown in Figure 13. Values of displacements in the legend are given in meters.

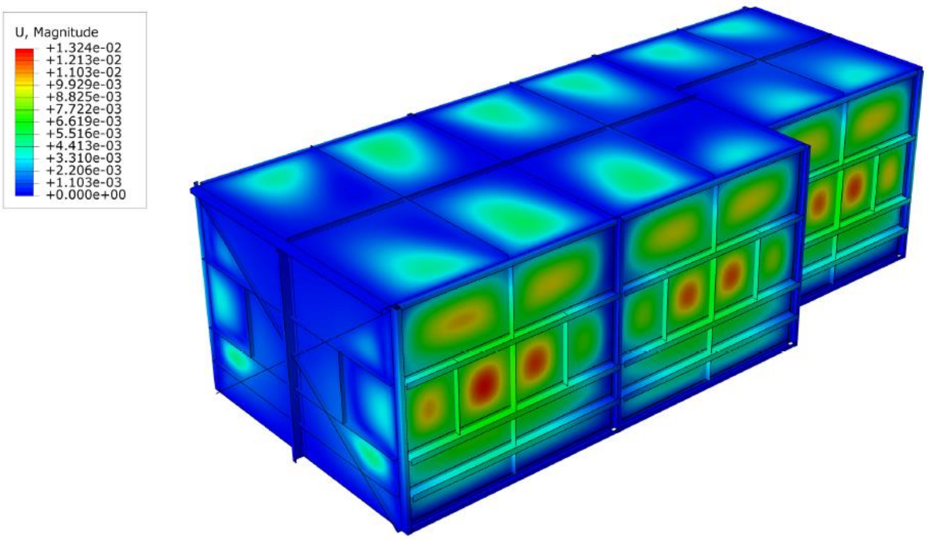

Fig. 13 Model of tank with values of displacements perpendicular to the plane of plate, of points of elements

5 CONCLUSION

In this paper the design of elements of a rectangular tank construction by the Eurocode was performed. With obtained dimensions of elements, tank was modeled in the software package ABAQUS, and displacement (perpendicular to the plane of plates) values, and values of maximum stresses were compared. Due to the need for making the rational numerical model that can be used in practical calculations in project design companies with standard computer equipment, the model of a given mesh size is adopted. Deviations in the results of two very different approaches applied are expected, given the complexity of the structure. These differences are partly a consequence of the adopted mesh size, and a lot more are consequence of displacements of cross sections observed in the model that represents the real structure in relation to the adopted model for the dimensioning by the Eurocode. The difference in results, that occur in design by Eurocode compared to the results obtained from the numerical model in Abaqus, are up to 22.7%, which was obtained at the largest segment of the tank shell, while the difference in the normal stresses are up to 33.7%. The results showed that there is a lot of reserves in the construction, ie may be submitted more load. A clearer picure of this could be obtained conducting experimental analysis on a model whose dimensions are aproximate real-size for this objects which, in the case of potential savings, which order of magnitude is about 20% or more, is certainly justified.

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DIMENZIONISANJE ČELIČNE KONSTRUKCIJE PRAVOUGAONOG REZERVOARA PREMA EVROKODU

Rezime: *Predmet rada je dimenzionisanje čeličnog rezervoara za tečnosti pravougaonog oblika sa tri komore. S obzirom na zahteve investitora (gabarit na koji je potrebno postaviti rezervoar i maksimalnu iskorištenost prostora) javila se potreba za konstrukcijom netipičnog oblika. U primeru je korišten austenitni nerđajući čelik koji se preporučuje za upotrebu u agresivnim sredinama. Dimenzionisanje čeličnih ploča rezervoara, ukrućenih i neukrućenih, prema Evrokodu je izvršeno u skladu sa SRPS EN 1993-1-7 koji se odnosi na ploče opterećene van svoje ravni. U prvom delu rada rezervoar je dimenzionisan prema Evrokod-u 3. Drugi deo rada predstavlja uporednu analizu rezultata dobijenih dimenzionisanjem prema Evrokod-u u odnosu na rezultate dobijene upotrebom prethodnog domaćeg standarda SRPS.MZ.3. 054. (1981).*

Ključne reči: *EC3; SRPS; nerđajući čelik; pravougaoni rezervoar*