F2, Guruprasad chs ltd, Pune – 411043, Maharashtra, India | Email: abntechsolutions@gmail.com | Contact: +91-9420495508

FEA Report

Water Storage Tank

Date: 21/03/2024

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1. Introduction

This report documents the Finite Element Analysis performed on a water storage tank. The Software used for the FE analysis is Ansys Workbench 2023 R2. The major focus of this analysis is to assess storage tank through a stress analysis to validate its design with respect to following standards: EN 1993-4-1& EN 1993-1-6. Two load cases have been simulated for the storage tank,

1. Hydrostatic Pressure
2. Vertical Lifting

2. Geometry

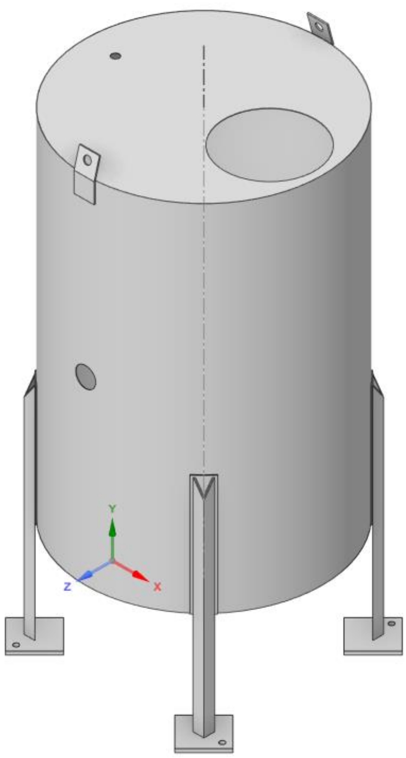


Figure 1 3D CAD geometry

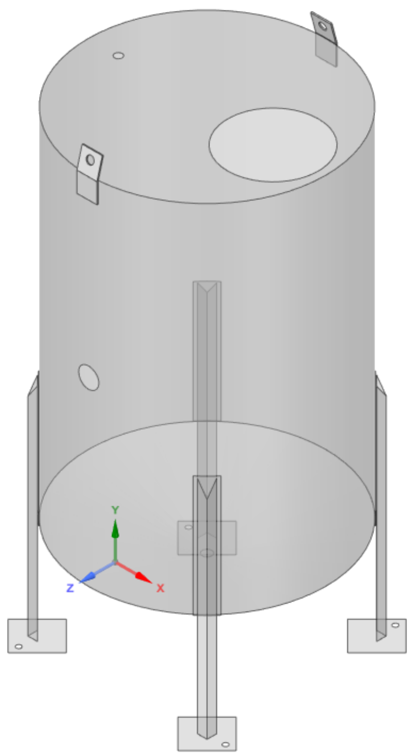
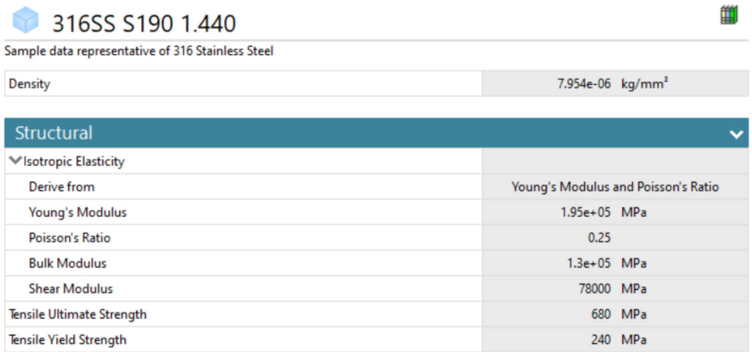


Figure 2 Extracted mid surface for shell meshing.

A mid-surface was extracted from the 3D model so that it can be meshed using Shell Elements. Shell Elements support bending stresses and do not undergo shear locking as solid elements.

3. Materials

An austenitic stainless steel – 316SS S190 1.440 was considered for this simulation. The material model used for the analysis taken from the material library in Ansys with following values:



316SS S190 1.440
Sample data representative of 316 Stainless Steel

Density	7.954e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	1.95e+05 MPa
Poisson's Ratio	0.25
Bulk Modulus	1.3e+05 MPa
Shear Modulus	78000 MPa
Tensile Ultimate Strength	680 MPa
Tensile Yield Strength	240 MPa

Figure 3 316SS S190 1.440 Material Properties

4. Mesh

The geometry was meshed using quadratic shell elements with an element size of 25mm which was able to accurately capture the finer features of the tank geometry as well provide better computational efficiency. Following mesh metrics have been considered to assess the quality of the mesh. The observed values are close to the ideal value of the respective mesh metrics which indicates the mesh is of good quality and will result in higher accuracy of results.

Mesh Metric (Avg.)	Observed Value	Ideal Value
Element Quality	0.96345	1
Aspect Ratio	1.1728	1
Skewness	7.672e-002	0

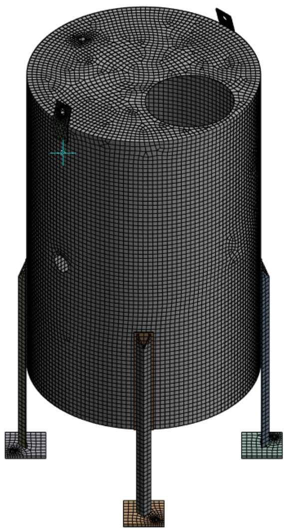


Figure 4 Meshed Geometry

5. Hydrostatic Pressure Condition

This condition simulates the loads on the water tank due to the internal pressure applied by the water stored inside the tank because of gravitational acceleration.

A. Boundary Conditions

A fixed support was provided to the bottom plates of the tank. A hydrostatic Pressure Boundary condition was applied to the inner faces of the cylindrical shell. As per the 2.9.2.2 in EN 1993-4-1 code, a partial factor of 1.25 is recommended for resistance to failure mode and is multiplied in the hydrostatic pressure calculation. The hydrostatic pressure is calculated as,

P = Rho*g*d

P = 998*9.81*1.95(approx.) *1.25

P = 23864.05 Pa

P = 0.023864 MPa.

Where,

Rho = Density of water in kg/m3

g = Acceleration due to gravity in m/s2

D = depth of fluid in m

The hydrostatic pressure boundary condition in Ansys considers the depth of water at multiple points and applies the pressure as variable load throughout the depth with highest load at the bottom of the tank and lowest at the top.

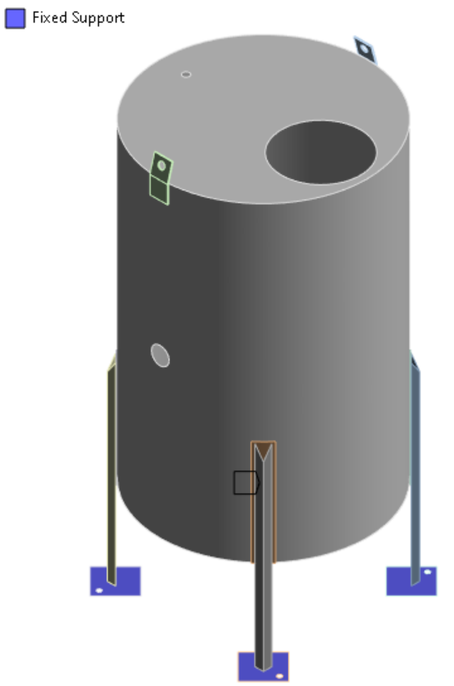


Figure 5 Fixed Support boundary condition

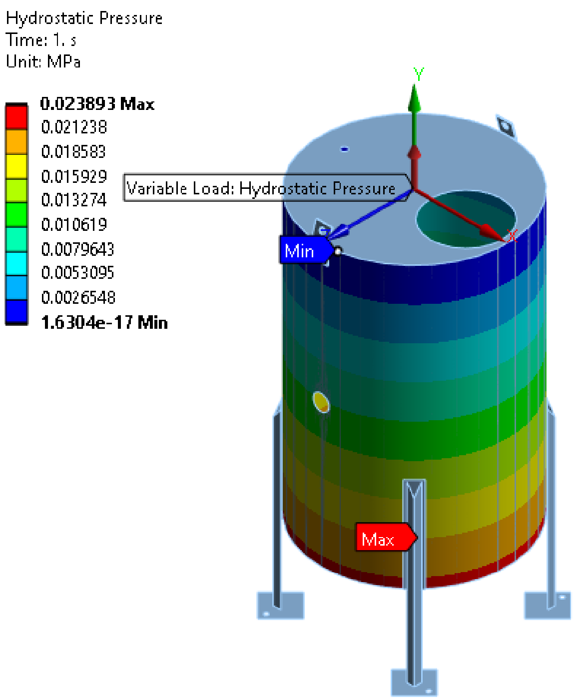
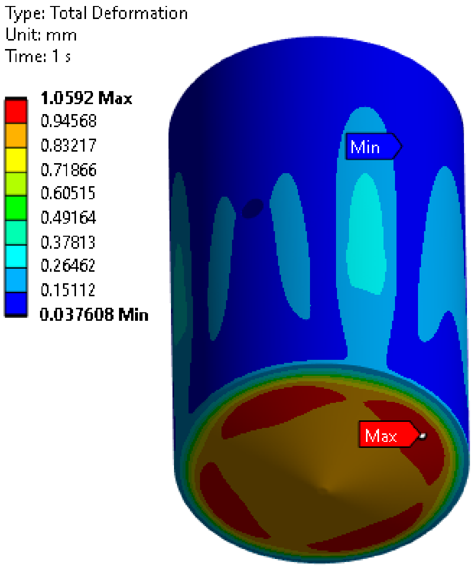


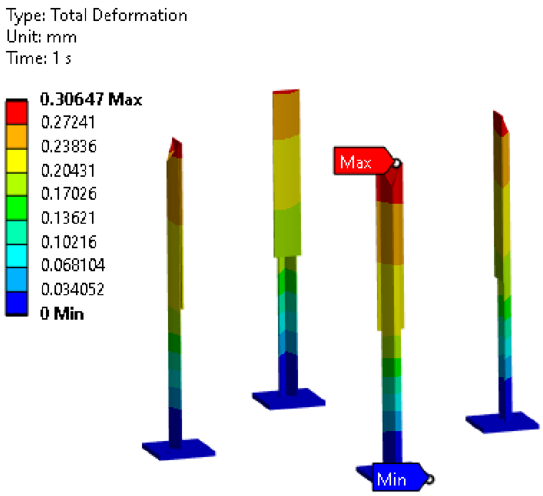
Figure 6 Hydrostatic boundary condition

B. Results discussion

1. Total Deformation

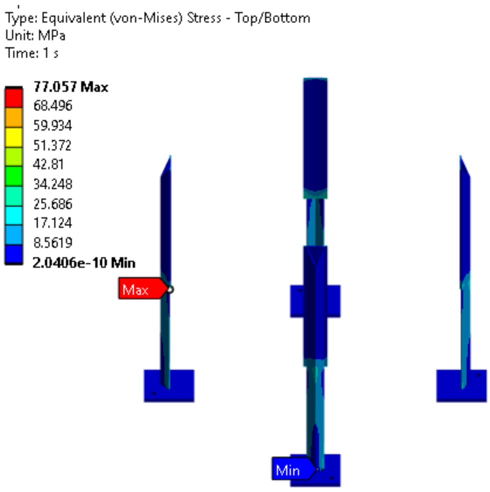
A maximum deformation of **1.059 mm** is observed in the **tank shell** and **0.3 mm** deformation is observed in the **mounting structure** (Stiffening plates, legs & base plates).

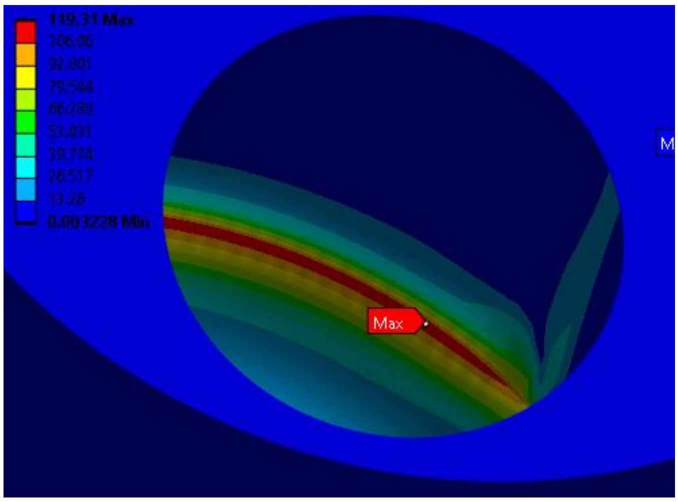




2. Equivalent Von-Mises Stress

A maximum of **119.31 MPa** of equivalent von-mises stress in the **tank shell** is observed at the joint between shell wall and the conical hopper and maximum of **77.057 MPa** is in the **mounting structure** (Stiffening plates, legs & base plates).





3. EN code verification

a. Cylindrical Shell Wall

Membrane Theory

As per 2.2 (2) Reliability differentiation in EN 1993-4-1 code, the storage tank is considered as consequence class 1: Silos with capacity between 10 tonnes and 100 tonnes.

As per 4.2.2.4 - Methods of Analysis for Consequence class 1 in EN 1993-4-1, Membrane theory analysis is adopted for this case.

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As per 6.2.3 in EN 1993-1-6, In every verification of this limit state, the design stresses shall satisfy the condition: $\boldsymbol{\sigma_{eq.Ed}} \leq \boldsymbol{f_{eq.Rd}}$. Where $\sigma_{eq.Ed}$ is Equivalent stress at the design load & $f_{eq.Rd}$ is von-mises equivalent strength which is yield strength of the material.

Point (5) in 6.2.1 – Design values of stresses Where Membrane Theory is used in EN 1993-1-6, $\sigma_{eq.Ed}$ can be represented as,

$$\sigma_{eq,Ed} = \frac{1}{t}\sqrt{n_{x,Ed}^2 + n_{\theta,Ed}^2 - n_{x,Ed} \cdot n_{\theta,Ed} + 3n_{x\theta,Ed}^2}$$

Where,

$\sigma_{eq.Ed}$ is Equivalent stress at the design load;

t is thickness of the shell

$n_{x,Ed}$ is meridional membrane stress resultant;

$n_{\theta,Ed}$ is circumferential membrane stress resultant;

$n_{x\theta,Ed}$ is membrane shear stress resultant;

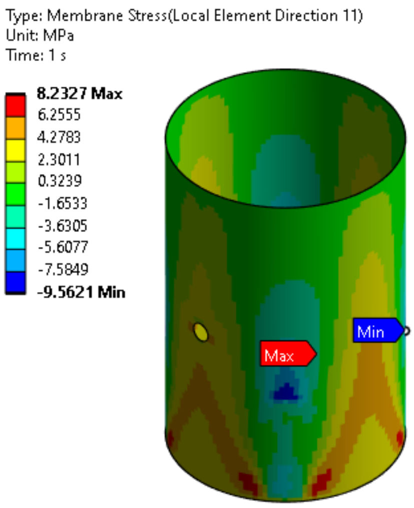

Figure 7 Meridional membrane stress in shell

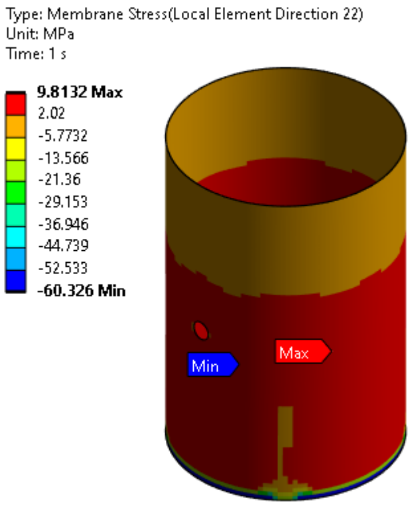

Figure 8 Circumferential membrane stress in shell

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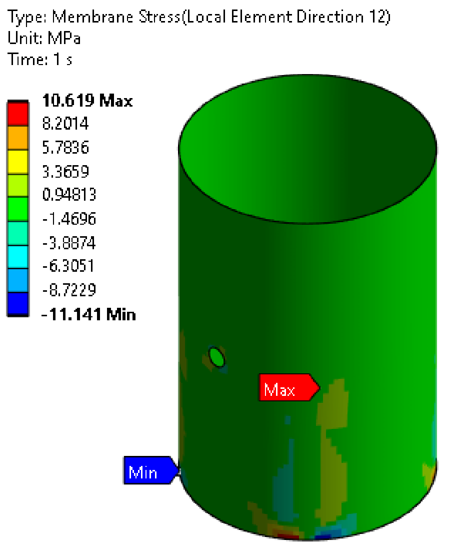


Figure 9 Shear membrane stress in shell

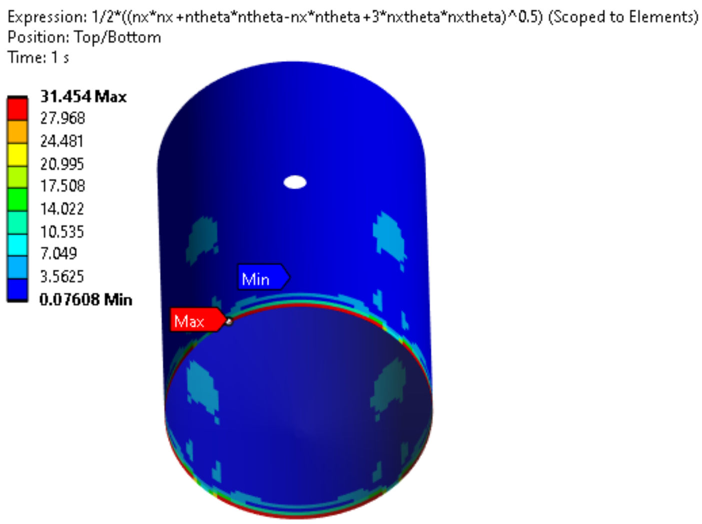


Figure 10 σ_(eq.Ed) in shell

The values of $n_{x,Ed}$, $n_{\theta,Ed}$, $n_{x\theta,Ed}$ are obtained for the cylindrical shell from Membrane stress result object in Ansys. All the 3 stress values vary from positive to negative. The positive value indicates the tensile stress while negative value denotes the compressive stress. **The maximum $\sigma_{eq.Ed}$ is calculated to be 31.454 MPa. Which satisfies the condition $\sigma_{eq.Ed} \leq f_{eq.Rd}$**

Plastic Limit State

As per 5.1.2 – Wall Design in EN 1993-4-2, the shell wall of the water tank shall be tested for a) Plastic Limit. As per 4.1.1 Plastic Limit & 4.2.2.2 – Primary Stresses in EN 1993-1-6, Plastic limit is considered as yield strength of the material. The **maximum equivalent von mises stress value in the shell is observed as 119.31 MPa** at the joint between shell wall and conical hopper. This indicates that the **stresses in the shell do not cross plastic limit state.**

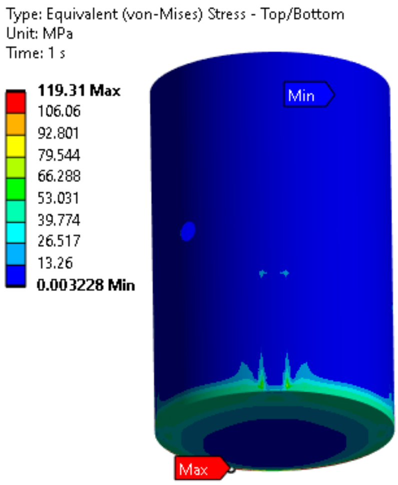


Figure 11 Equivalent Von-Mises stress in shell

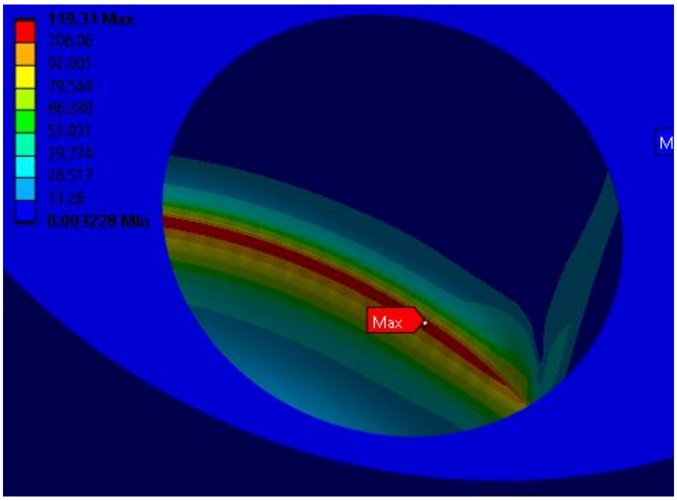


Figure 12 Equivalent Von-Mises stress in shell

Linear Eigenvalue Buckling/Bifurcation analysis

As per (17) in 5.3.2.4 – Buckling under axial compression in EN 1993-4-1, At every point in the structure the design stress resultants should satisfy the condition:

$$\boldsymbol{n_{x.Ed} \leq t \times \sigma_{x.Rd}}$$

Where,

$\boldsymbol{n_{x.Ed}}$ is meridional membrane stress resultant

t is thickness of shell wall

$\boldsymbol{\sigma_{x.Rd}}$ Design buckling membrane stress is calculated as, (16) in 5.3.2.4. in EN 1993-4-1

$$\sigma_{x,Rd} = \sigma_{x,Rk} / \gamma_{M1}$$

γ_{M1} is taken as 1.1 from 2.9.2 in EN 1993-4-1.

And, $\boldsymbol{\sigma_{x.Rk}}$ is Characteristic buckling membrane stress and is calculated as,

$$\sigma_{x,Rk} = \chi_x f_y$$

…equation 5.29 in (14) 5.3.2.4 in EN 1993-4-1

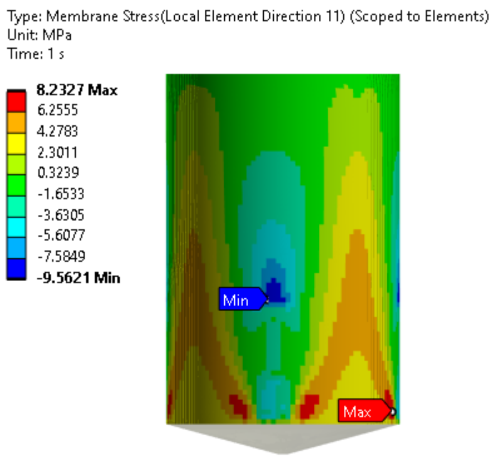
Where, X_x is calculated as 0.32 as per equation 5.32 in (15) 5.3.2.4 in EN 1993-4-1 and f_y is yield strength of the material which is 240 MPa.

Therefore,

$\boldsymbol{\sigma_{x.Rd}}$ **= 70 MPa.**

$\boldsymbol{t \times \sigma_{x.Rd}}$ **= 2 x 70 = 140 MPa.**

The **maximum compressive meridional stress in the shell is obtained as -9.5621 MPa** (negative value indicates compressive stress) from Ansys. And it satisfies the condition, $\boldsymbol{n_{x.Ed} \leq t \times \sigma_{x.Rd}}$



b. Conical Hopper

Membrane Theory

As per (3) in 6.3.1 in EN 1993-4-1 Resistance of conical hoppers, the stress resultants arising in the body of the hopper may generally be found using the membrane theory of shells. **The maximum $\sigma_{eq.Ed}$ is calculated to be 34.388 MPa. Which satisfies the condition,**

$$\sigma_{eq.Ed} \leq f_{eq.Rd}$$

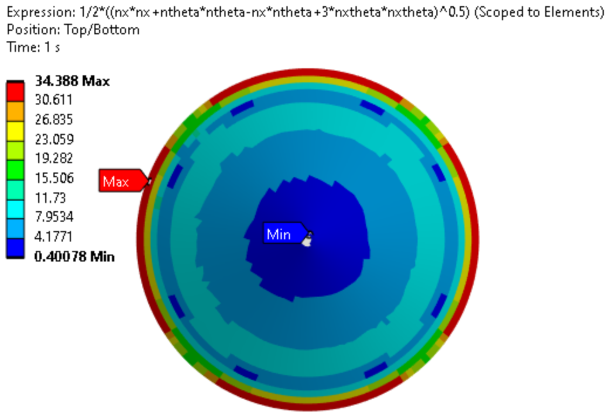


Figure 13 σ_(eq.Ed) in conical hopper.

Rupture at the transition joint

As per (2) – 6.3.2.3 in EN 1993-4-1 – Rupture at the transition junction,

$$n_{\emptyset h,Ed} \leq n_{\emptyset h,Rd}$$

Where,

$n_{\emptyset h,Ed}$ = The design value of the local meridional force per unit circumference allowing for the possible non-uniformity of the loading and is obtained by,

$$n_{\phi h,Ed} = g_{asym}\, n_{\phi h,Ed,s}$$

Where,

g_{asym} is the unsymmetrical stress augmentation factor. The value of g_{asym} 1.2 is recommended.

$n_{\emptyset h,Ed,s}$ is the design value of the meridional membrane force per unit circumference at the top of the hopper obtained assuming the hopper loads are entirely symmetrical. **$n_{\emptyset h,Ed,s}$ is obtained as 18.758 MPa** from Ansys.

Hence, $n_{\emptyset h,Ed}$ is calculated as, 22.5 MPa, which satisfies the condition,

$n_{\emptyset h,Ed} \leq n_{\emptyset h,Rd}$

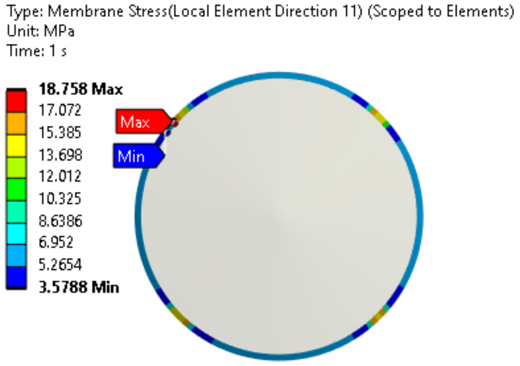


Figure 14 n_(Øh,Ed,s)

The $n_{\emptyset h,Rd}$ can be calculated as,

$$n_{\phi h,Rd} = k_r \, t f_u / \gamma_{M2}$$

Where,

The value of k_r is recommended as 0.9.

t is the thickness of the shell

f_u is ultimate tensile strength of the shell and is considered as 680 MPa.

& γ_{M2} is enhanced partial factor and is taken as 1.4 as per (3) in 6.1.2 Hopper wall design in EN 1993-1-4.

The value of $n_{\emptyset h,Rd}$ is calculated to be 874.28 MPa.

This satisfies the condition $n_{\emptyset h,Ed} \leq n_{\emptyset h,Rd}$.

C. Welds

As per 4.5.3.3 'Simplified method for design resistance of fillet weld' in EN 1993-1-8, at every point along weld length, the resultant of all the forces per unit transmitted by the weld satisfy the following criterion:

$$F_{w,Ed} \leq F_{w,Rd}$$

Where,

$F_{w,Ed}$ is the design value of the weld force per unit length.

$F_{w,Rd}$ is the weld resistance per unit length and is calculated as,

$$F_{w,Rd} = f_{vw.d} \, a$$

Where,

a is throat thickness of the fillet weld and is considered as 6mm,

$F_{vw,d}$ is the design shear strength of the weld and is determined from,

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$$f_{vw.d} = \frac{f_u / \sqrt{3}}{\beta_w \gamma_{M2}}$$

Where,

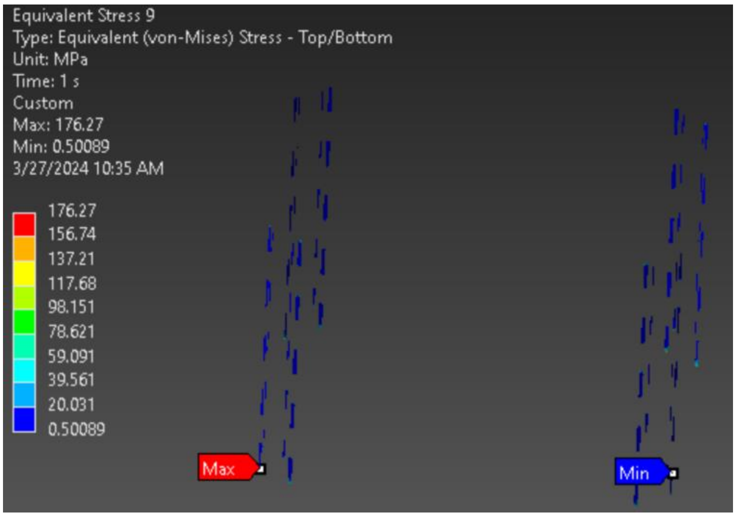
f_u is ultimate tensile strength of the shell and is considered as 680 MPa.

β_w is considered as 1, as per Table 4.1, 4.5.3.2 in EN 1993-1-8

And, γ_{M2} is considered as 1.25 as per 2.9.2 in EN 1993-4-1

$F_{vw,d}$ is calculated as 314.087 MPa. & $F_{w,Rd}$ is calculated as 1884.526 MPa.

$F_{w,Ed}$ is obtained as 176.27 MPa from Ansys



This satisfies the condition $F_{w,Ed} \leq F_{w,Rd}$.

d. Column Bases

As per 6.2.8.2 & 6.2.5 in EN 1993:1-8, the design resistance of symmetric column base plates subject to an axial compressive force applied concentrically $F_{C,Rd}$ can be calculated as,

$F_{C,Rd} = F_{jd}\, b_{eff}\, l_{eff}$

Where:

b_{eff} is the effective width of the T-stub flange and is taken as 208.28mm

l_{eff} is the effective length of the T-stub flange and is taken as 208.28mm

F_{jd} is the design bearing strength of the joint and is calculated as per 6.2.5 – (7) in EN 1993:1-8,

$F_{jd} = \beta_j\, F_{Rdu} / (\, b_{eff} \,.\, l_{eff})$

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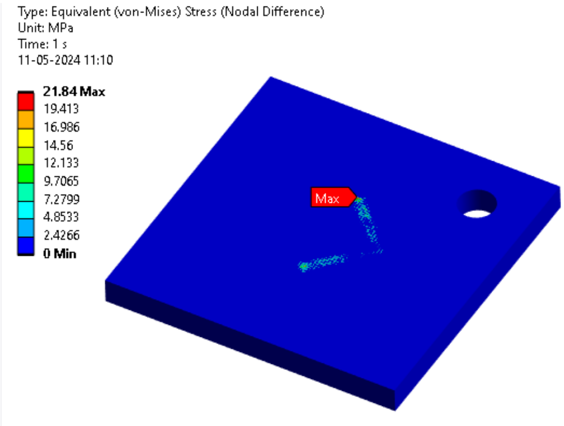

Figure 21 Equivalent Von Mises Stress in Base Plates

Where:

β_j is the foundation joint material coefficient, which is taken as 2/3

F_{Rdu} is the concentrated design resistance force given in 6.7 of EN 1992:1-1 and is calculated as,

$\boldsymbol{F_{Rdu}}$ **= 3 x** $\boldsymbol{f_{cd}}$ **x** $\boldsymbol{A_{c0}}$

Where:

A_{c0} is the loaded area, which is 598.47 mm2,

f_{cd} is design concrete compressive strength and is considered as 41 MPa. (Ansys Engineering data material database)

The

$\boldsymbol{F_{Rdu}}$ is calculated as **73,611.81 N.** & $\boldsymbol{F_{jd}}$ is calculated as **1.12 MPa.**

Hence,

$\boldsymbol{F_{C,Rd}}$ is calculated as **48,583.8 N.**

The **force** exerted at **each base plate** is obtained from Ansys simulation is, **6313.2 N.**

Since, the force exerted at each base plate from simulation is **lower** than the **calculated design resistance** of the column base plates $\boldsymbol{F_{C,Rd}}$ **,** the design criteria is satisfied**.**

6. Vertical Lifting Condition

This condition simulates the loads acting on the water tank when the tank is lifted during the installation by attaching the rope/chain/belt fixes to the lugs attached to the shell.

A. Boundary Conditions

An acceleration boundary condition was applied to the whole assembly to simulate the self-weight stresses due to gravity. As per the 2.9.2.2 in EN 1993-4-1 code, a partial factor of 1.25 is recommended for resistance to failure mode and is multiplied in the gravitational acceleration value.
A remote displacement of 500 mm was applied to the holes in the lugs with remote point at the meridian axis of the shell to simulate lifting by rope, chain, belt, etc.

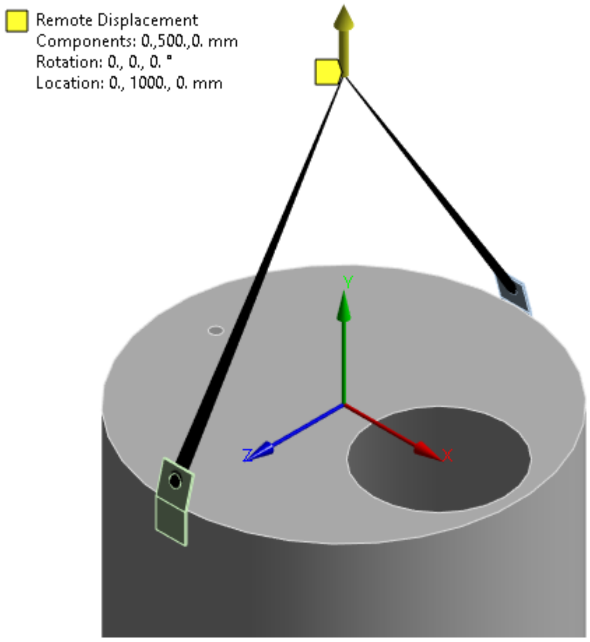

Figure 15 Remote displacement boundary condition

Figure 16 Gravitational acceleration boundary condition

B. Results Discussion

1. Equivalent Von-Mises Stress

A maximum equivalent von-mises stress of **24.682 MPa** is seen in the **tank shell** at the connection point of tank and the lug. Maximum von-mises stress of **38.5 MPa** is observed in the **lugs at the bend.**

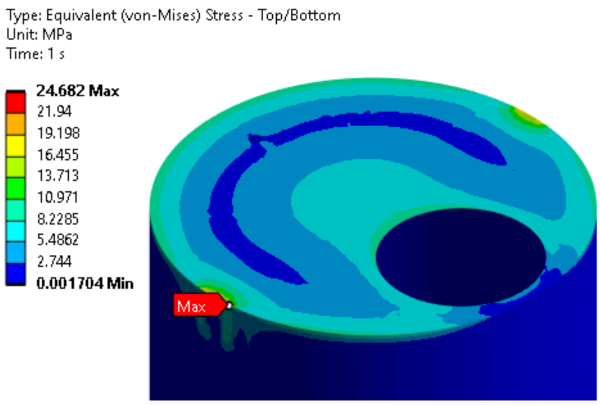

Figure 17 Eq. von-mises stress - shell

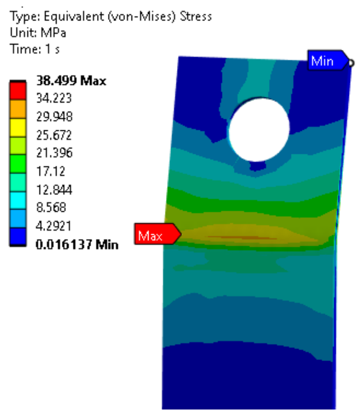

Figure 18 Eq. von-mises stress - lugs

2. EN code verification

a. Cylindrical Shell Wall

Membrane Theory analysis

The maximum $\boldsymbol{\sigma_{eq.Ed}}$ is calculated to be **4.8482 MPa** at the joint between lug and the cylindrical shell, which satisfies the condition, $\boldsymbol{\sigma_{eq.Ed}} \leq \boldsymbol{f_{eq.Rd}}$

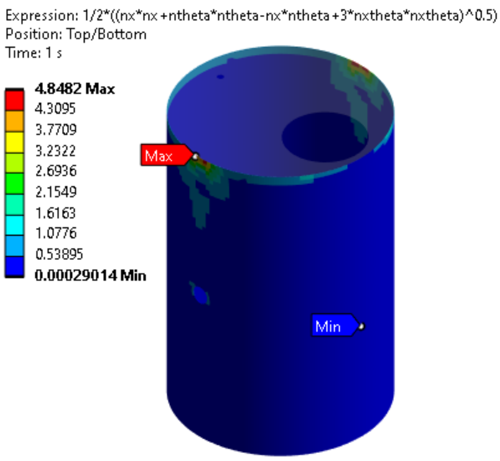

Figure 19 σ_(eq.Ed) in shell

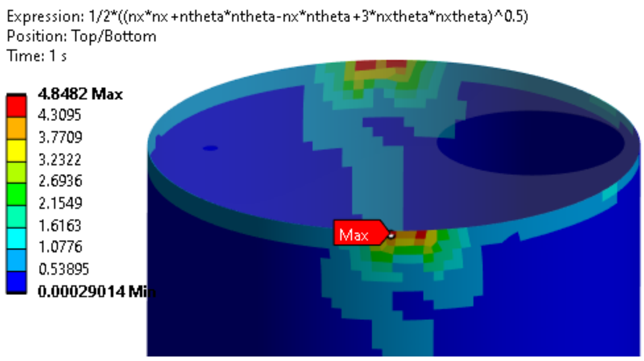

Figure 20 σ_(eq.Ed) in shell

Plastic Limit State

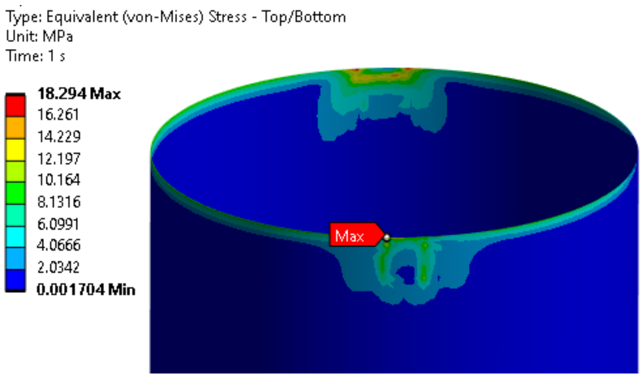

Figure 21 Eq. von-mises stress shell

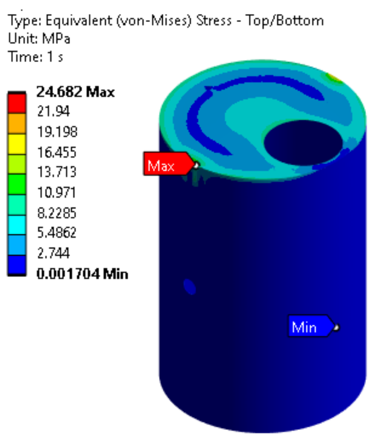

Figure 22 Eq. von-mises stress roof

The maximum value of equivalent von-mises stress in the **cylindrical shell wall** is **18.294 MPa** and the **roof is 24.682 MPa.** This indicates that the **stresses in the shell wall do not exceed plastic limit state.**

Linear Eigenvalue Buckling analysis

A linear Eigenvalue Buckling analysis was performed on the storage tank under vertical lifting condition, And the significant load multiplier values were found to be **-30.149** & **-18.068**.

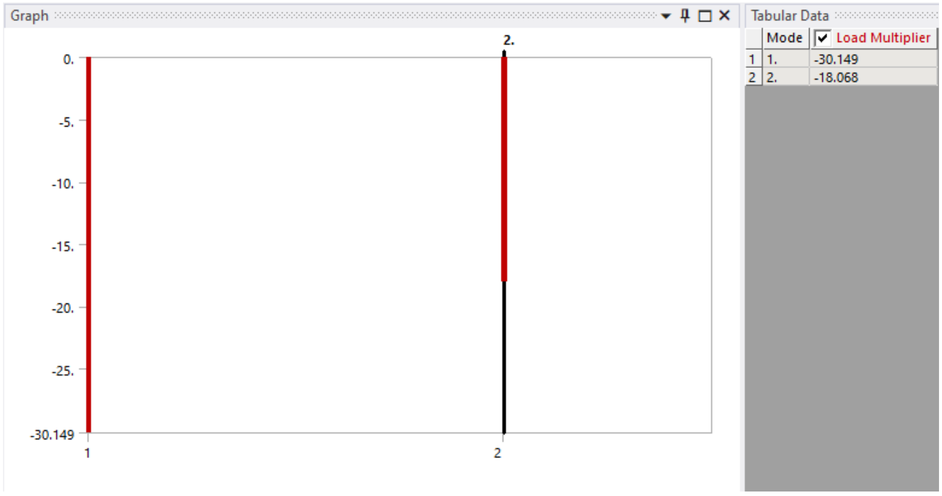

Figure 23 Load multipliers – Linear Eigenvalue Buckling

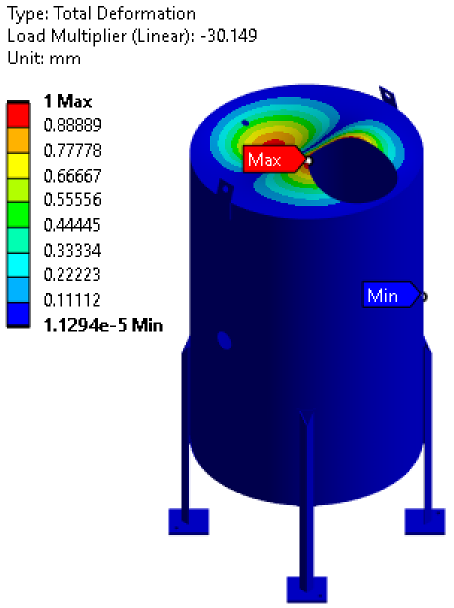

Figure 24 Mode shape for Load multiplier 1

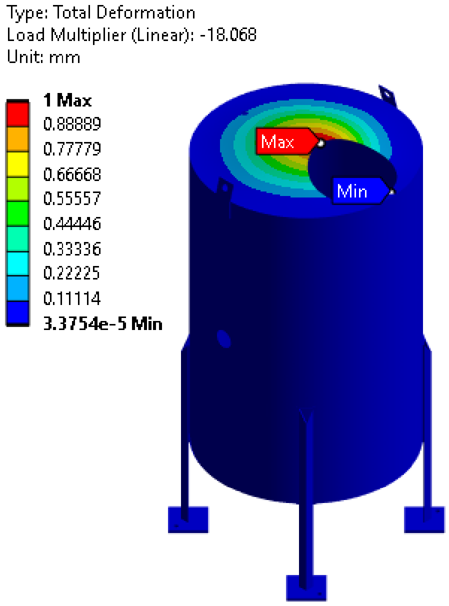

Figure 25 Mode shape for load multiplier 2

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7. Conclusion

1. The water storage tank has been assessed for 2 loading conditions: i) Hydrostatic Pressure condition & ii) Vertical Lifting condition.
2. Results of membrane theory analysis satisfy the conditions mentioned in the EN 1993-4-1 & EN 1993-1-6. Hence, the storage tank can be considered safe from failure.
3. Results of Plastic Limit State analysis satisfy the conditions mentioned in the EN 1993:4-1 & EN 1993-1-6. Hence, the storage tank can be considered safe from failure due to yielding.
4. Results of Linear Buckling analysis satisfy the conditions mentioned in the EN 1993-4-1 & EN 1993-1-6. Hence, the storage tank can be considered safe from failure due to buckling.

8. Specific questions from safety officer:

1. Material properties are not indicated. Is S190 1.4301? Please, integrate the report with the mechanical property values adopted in the FEA.
   Please refer to this link
2. Shell buckling behaviour investigation, especially for the roof under lifting conditions, is not presented. Please, integrate the report with the results of a linear buckling analysis, showing that the maximum load multiplier is higher than 10, as per EN 1993-1-1.
   Please refer to this link
3. The lower conical hopper shall be verified in accordance with the indications given in the section 6 of EN 1993-4-1, considering the additional requirements from EN 1993-1-4. Please, integrate the report with these verifications.
   Please refer to this link
4. The verifications of fillet welds, as per EN 1993-1-8 (section 4.5) and EN 1993-1-4, are not presented. Please, integrate the report with these verifications.
   Please refer to this link
5. GD Loaded Tank Eurocode verification.pdf :
   Pillar base plates shall be assessed in accordance with the indications given in the section 6.2.8.2 of the EN 1993-1-8 (and EN 1993-1-4). Please, integrate the report with these verifications.
   Please refer to this link