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Design and Study of Floating Roofs for Oil Storage Tanks

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Floating roofs are widely used to store petroleum products with high volatility. This is to prevent the product loss and to ensure safe environment around the storage tanks. However, small number of researches were accomplished. These researches aim at study the design of the floating roof and the associated risks that it faces during operation. In an effort to compensate the lack of knowledge for this issue and to investigate the behavior of the floating roof during operation, this paper studies the design of deck plate and roof pontoons of the floating roof with especial features.
In this research and in order to study deck plate design, a comparative work was performed of the stress and deflection analyses of deck plate for the floating roofs under the load of accumulated rainfall. Five different loads were applied on the deck plate by using three different analysis methods to study the deflection and stresses. The results show that the nonlinear finite element analysis is the most accurate and applicable one to be used in the design of the floating roof deck, since it simulates the exact loading cases that happen in reality. However, using Roark's Formulas gives higher results but it can be used as a reliable and fast method in the analysis of the deck plate.
To study roof pontoons design, a buoyancy analysis of the floating roof was established with punctured pontoons. In this study, three cases were applied to analyze the buoyancy of the floating roof in each case. The obeyed methodology of this study is by calculating the center of gravity and moment of inertia of the floating roof in each case. Then, to determine the submergence height due to weight and tilt and ensure that the floating roof will keep floating under each case. The results show that the floating roof will remain floating after the puncture of two adjacent pontoons and deck plate according to the design of the physical model; but it will sink if the number of punctured pontoons is increased to three.

Keywords: tanks, floating roof, plate deflection, large displacement, Finite Element Analysis, nonlinear analysis, pontoon.

1. Introduction

Storage tanks are essential part in industry in oil & gas fields. They are mainly used to store different fluid products such as water, oil and gas. To transport fluids from places of production to end users, we need storage tanks to store the products. Storage tanks were a key factor of the development of dozens of industries. Petrochemicals industry is a good example for the importance of storage tanks as it couldn't be developed without the ability to store huge amount of crude and refined oils products in a safe and economic storages. Another example of the usages of storages tanks are the processing plants such as chemicals factory and food processing factories; since production pauses are always occur to allow reactions at different stages. Also, after ending the production process, we need safe and huge storages as the products cannot transport immediate to the customers and end users. The majority of the storage tanks are working under atmospheric pressure. According to API 620 [1] the maximum allowable pressure for storage tanks is 15 psi and if the pressure is larger than this value, it is considered as a pressure vessel [2]. Floating roof tank; as its name; implies the roof to float on liquid surface in the tank. As the liquid level changes due to filling, emptying, contraction and expansion, the roof is designed to move with the liquid. This type of tanks used for 2 main reasons;

1. Minimize the loss of the stored liquid product inside the tank due to evaporation by eliminate the free space above the stored liquid.
2. Minimize the fire hazard by decreasing the volatile gases inside the tank.

2. Main two types of floating roof tanks

2.1. *Single deck floating roof*

In single deck roof, which is also called pontoon roof, the buoyancy is derived by the pontoons, according to API 650 [3]. The deck of single deck floating roofs shall be designed to be in contact with the storage liquid during normal operation, regardless of the service.

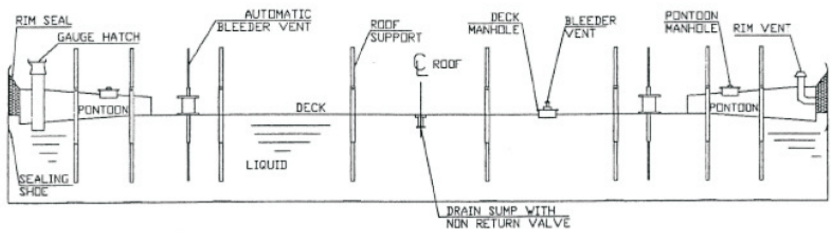

Figure 1 Single deck roof

2.2. *Double deck roof*

It consists of upper and lower steel membranes separated by series of bulkheads, which are subdivided by radial bulkhead. Double deck roof is more rigid than the single deck and the air gap, between the upper deck and bottom deck plates, works as an insulation which reduces the solar heat reaching the product during the hot weather.

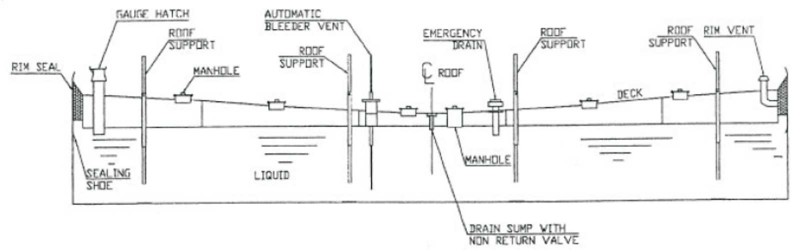

Figure 2 Double deck floating roof

Different researches have been developed to study the design of the floating roof and predict its mechanical behavior of the different parts and analyze its failure mechanism under different loads.

First, the study of stress and deflection analyses of floating roofs under rainfall loads [4]. This paper proposes a load modifying method for the stress and deflection analyses of floating roofs. The formulations of deformations and loads are developed according to the equilibrium analysis of the floating roof. According to these formulations, the load modifying method is generated to conduct a nonlinear analysis of floating roofs with the finite element simulation. The analysis is developed through a series of iterations until a solution is achieved within the error tolerance.

Also, there is a study of damages of a floating roof-type oil storage tank due to thermal stresses [5]. This paper studied whether the thermal stress on the floating roof could cause damage, strain and temperature measured on the actual tank's floating roof by using optical fiber gauges. Thermal stress analysis and fracture estimation were also carried out as additional analysis. As a result, thermal stress on the floating roof turned to be relatively small and could not cause the initial crack. However, the temperature variation in a day could affect the crack propagation.

Another study was for the importance of the flexural and membrane stiffness in large deflection analysis of floating roofs [6]. Applying integrated variational principles on fluid and deck plate to the large deflection analysis of floating roofs, this paper studied the significance of the flexural and membrane components in the formulations of the deck plate. Integrated variational principles facilitate the treatment of the compatibility of deformation between floating roof and supporting liquid.

Analysis results show that different assumptions about deck plate formulation commonly used in the literature, results in considerably different deflection and stress patterns on the floating roof. The results show that modeling of the deck plate as a flexural element rather than the membrane, by eliminating the need for nonlinear analysis, gives reasonable results for deflections and stresses in the deck plate.

As shown in the introduction very few researches done to study the design of floating roof tanks and the effect of buoyancy forces in the deck plate and pontoons. Due to the shortage of researches on floating roof tanks design, we decided to conduct a research to study the design of the deck plate and pontoons of the floating roof with practical methods, which can be used later in the future in the practical life. We start our research with define the physical model used in our study.

3. Physical model

The physical model of our study is shown in Fig. 3. The model consist of an external single deck floating roof operating in a vertical cylindrical oil storage tank, which is filled with oil of density ($\rho = 700$ kg/m^3). The dimensions of the tank are 40 m diameter and 23 m height. The oil occupies 100% of the total tank volume.

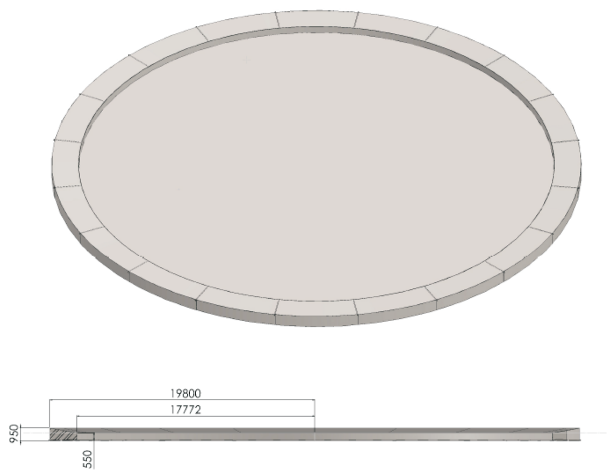

Figure 3 Single deck type floating roof

The components of single deck floating roof are shown in Fig. 4.

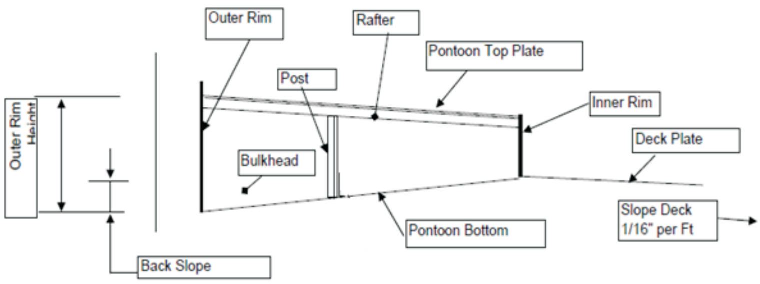

Figure 4 Components of single deck floating roof tank

The details of the properties and dimensions of the physical model are shown in Tabs. 1, 2 and 3.

Table 1 Floating roof design data

Tank Diameter	40 m
Tank Height	23 m
Roof Outside Diameter, Do	39.6 m
Material of Construction	SA 283 Gr.C
Corrosion Allowance	3 mm
Min. Specific Gravity of product	0.7
Max. Specific Gravity of product	1

4. Buoyancy calculations

- Buoyancy acting on deck is related to submergence of the deck above backslope.
- Height of submergence above backslope is related to size of backslope.
- Floatation depth of deck is related to the weight of the deck.
- Ideal condition is for buoyancy forces to equal deck loads, or in terms of floatation for the submergence above backslope to equal floatation depth of deck.
- If the backslope is too large, the floatation depth of the deck is greater than the submergence above backslope (weight of deck is greater than buoyancy forces) this means that the deck floats lower in the product than the pontoon which can create a vapor space.

Table 2 Geometry data

Outer Rim Height, H_{or}	950 mm
Inner Rim Height, H_{ir}	550 mm
Pontoon width, w	2000 mm
Rim Gap	200 mm
No. of Pontoons, N	20
Outer Rim Diameter, $Ø_{or}$	39600 mm
Inner Rim Diameter, $Ø_{ir}$	35544 mm
Bulkhead Outer height, B_{oh}	935 mm
Bulkhead Inner height, B_{ih}	535 mm
Bulkhead Width, W_b	1972 mm
Outer Rim T_{hk}, T_{or}	10 mm
Corroded Outer Rim T_{hk}, T_{or}	7 mm
Inner Rim T_{hk}, T_{ir}	16 mm
Top Pontoon T_{hk}, T_{tp}	5 mm
Bottom Pontoon T_{hk}, T_{bp}	8 mm
Outer Rim Height, H_{or}	950 mm
Height above deck level, H_{sub}	550 mm
Corrosion allowance	3 mm

Table 3 Material properties, SA283 Steel, grade C

Tensile Strength, Ultimate	380 - 485 MPa
Tensile Strength, Yield	205 MPa
Design Yield strength	136 MPa
Elongation at Break	25%
Bulk Modulus	160 GPa
Shear Modulus	80 GPa
Poisson's ratio	0.25
Density	7850 Kg/m^3

- If the backslope is too small, the floatation depth of the deck is smaller than the submergence above backslope (weight of deck is less than buoyancy forces). This means that the deck floats higher in the product than the pontoon which can cause rainwater drainage towards the pontoon.

Case 1: Normal operation case with no rain above the roof

Calculate the Floatation level for roof pontoon (corroded):

H_{fl} = (V displacement - V under deck level)/Area roof,

V displacement = (W roof) / ρ product

W roof = 74,000 Kg, so V displacement = (74000)/700 = 105.7 m^3, V Backslope = 50 m^3

Area roof = 1232 m^2, so H_{fl}= (105.7 – 50) /1232 = 0.045 m = 45 mm

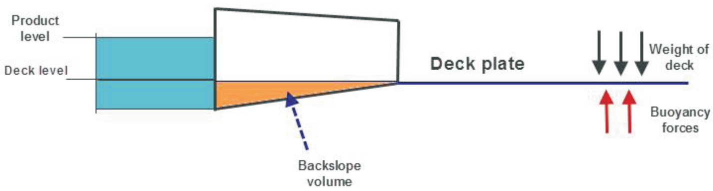

Figure 5 Normal operation case

The maximum submerged height above deck level H_{sub} = 550 mm, so the design is safe in this condition.

Case 2: 250 mm rain above the roof:

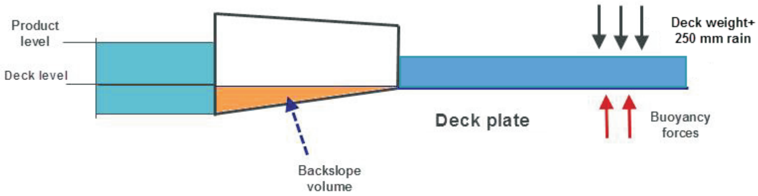

Figure 6 250 mm rain operation case

Calculate the Floatation level for roof pontoon (corroded):

H_{fl} = (V displacement - V under deck level)/Area roof,
V displacement = (W roof + W rain) / ρ product
W roof = 74,000 Kg,
W rain = ρ water x H rain x Deck Area = 1000x0.25x992 = 248,000 Kg
so V displacement = (74000 + 248000)/700 = 460 m^3,
V under deck level = 50 m^3
Area roof = 1232 m^2, so H_{fl} = (460 – 50) /1232 = 0.332 m = 332 mm
The maximum submerged height above Deck level H_{sub} =550 mm, so the design is safe in this condition.

5. Comparative study of stress and deflection of floating roof subjected to the load of accumulated rainfall

In this comparative study, 5 different loads are applied on the corroded deck plate by using 3 different analysis methods to study the deflection and stresses. First method is using the equations of stresses and deformations on thin plates which derived according to (Roark's formulas for stress and strain, 7th edition – Effect of large deflection, diaphragm stresses) [7]. Second method is the numerical nonlinear

finite element analysis by applying the load gradually and study the effect of the large displacement on the material behavior in deformation and stress. The third method is the numerical application of linear finite element analysis by applying 100% of the load on the deck without consideration of the large deflection effect on the material.
The 5 different load cases are:

- Case 1: Normal Case with no rain above the roof
- Case 2: 50 mm of rain above the roof
- Case 3: 100 mm of rain above the roof
- Case 4: 200 mm of rain above the roof
- Case 5: 250 mm of rain above the roof

H = (V displacement - V under deck level)/Area roof
q = unit lateral pressure = (Downward force - Buoyancy force) x g/ Deck area.
Tab. 4 shows the values calculated of (H) and (q) for each case (corroded):

Table 4 H and q values after corrosion

Case number	H [mm]	q [N/m^2]
1	45	422
2	103	514
3	160	613
4	275	805
5	332	904

5.1. *Effect of large deflection, diaphragm stresses (Roark's formulas for stress and strain)*

When Plate deflection becomes larger than one–half the Plate thickness, as may occur in thin plates, the surface of the middle becomes strained and the stresses in it cannot be ignored because it changes the behavior of the plate deflection. That stress is called diaphragm stress; it allows the plate to carry a part load as a diaphragm in direct tension. This tension balanced by radial tension at the edges if the edges are held or by circumferential compression if the edges are not horizontally restrained. In thin plates, this circumferential compression can lead to buckling. When the condition of large deflection accrues, the plate is stiffer than calculates by the ordinary theory of small deflection and the load–stress relations and the load–deflection are nonlinear. Stresses for a certain load are less than the ordinary theory of small deflection indicates. Formulas, for stress and deflection in circular plates when middle surface stress is taken into account, are given in the below equations.

These formulas used whenever the maximum deflection exceeds half the thickness if accurate results are desired [7].

$$\frac{qa^4}{Et^4} = K_1\frac{y}{t} + K_2\left(\frac{y}{t}\right)^3 \tag{1}$$

$$\frac{\sigma a^2}{Et^2} = K_3\frac{y}{t} + K_4\left(\frac{y}{t}\right)^2 \tag{2}$$

Get the deflection (y) from Eq. 1 and then get the stresses in center and edge from Eq. 2 where:
t – thickness of plate,
a – outer radius of plate,
q – unit lateral pressure = (Downward force - Buoyancy force) x g/ Deck area
K_1, K_2, K_3 and K_4 – constants.
Downward force = Weight on roof,
Buoyancy force = Deck area x Floatation height x ρ product.

Summary of results obtained by Roark's formulas for stress and strain shown in Tab. 5.

Table 5 Summary of results obtained by Roark's formulas – corroded condition

Case number	Max. deflection [mm]	Stress at center [MPa]	Stress at edge [MPa]
1	251	41	72
2	264	45	80
3	280	51	90
4	307	61	107
5	319	66	116

5.2. *Non–linear large displacement analysis*

In this study, Solidworks simulation program were used to study the deflection and stresses on the deck plate using finite element method [8].

Basic integral formulations of Finite Element Analysis:

The concept behind the FEA is to replace any complex shape with the summation of a large number of very simple shapes that are combined to model the original shape as shown in Fig. 7. The smaller shapes are called finite elements as each one occupies a small but finite sub–domain of the original shape [9].

Alternatively, we could split the area into a set of triangles (cover the shape with a mesh) and sum the areas of the triangles:

$$A = \sum_{e=1}^{n} A^e = \sum_{e=1}^{n} A^e \int_{A^e} dA$$

The kinetic energy of the planar body, of ”t” thickness, in Fig. 7 is obtained by integrating over the differential masses:

$$KE = \frac{1}{2}\int v^2 dm = \frac{1}{2}\int v^2 \rho dv = \frac{t}{2}\int v^2 \rho dA$$

where: $v\,(x, y) = v^{e\,T}[N\,(x, y)]^T$

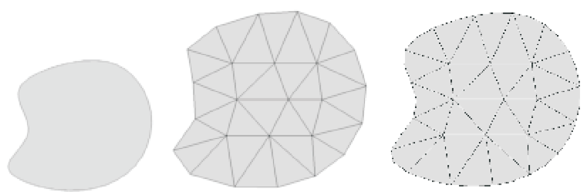

Figure 7 An area meshed with quadratic and linear triangles

The linear theory assumes small displacements. It also assumes that the normal to contact areas do not change direction during loading. Hence, it applies the full load in one step. This approach may lead to inaccurate results or convergence difficulties in cases where these assumptions are not valid. A large displacement solution takes more time and resources than the small displacement solution but gives more accurate results. The large displacement solution is needed when the acquired deformation alters the stiffness (ability of the structure to resist loads) significantly. The small displacement solution assumes that the stiffness does not change during loading. The large displacement solution assumes that the stiffness changes during loading so it applies the load in steps and updates the stiffness for each solution step as shown in Fig. 8.

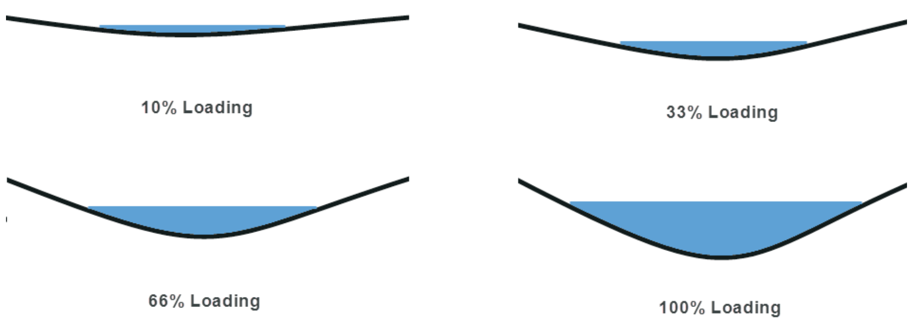

Figure 8 Non–linear large displacement analysis

Summary of results obtained by non–linear large displacement analysis:

Case 1: Normal Case with no rain above the roof

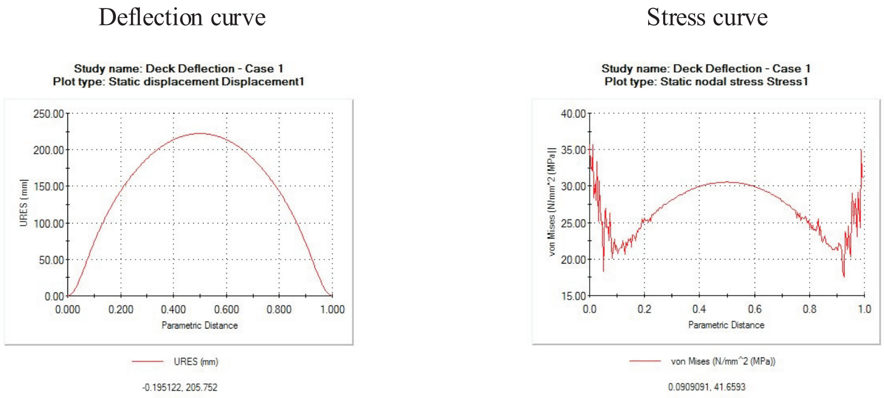

Figure 9 Case 1 – corroded condition curves

Case 2: 50 mm of rain above the roof

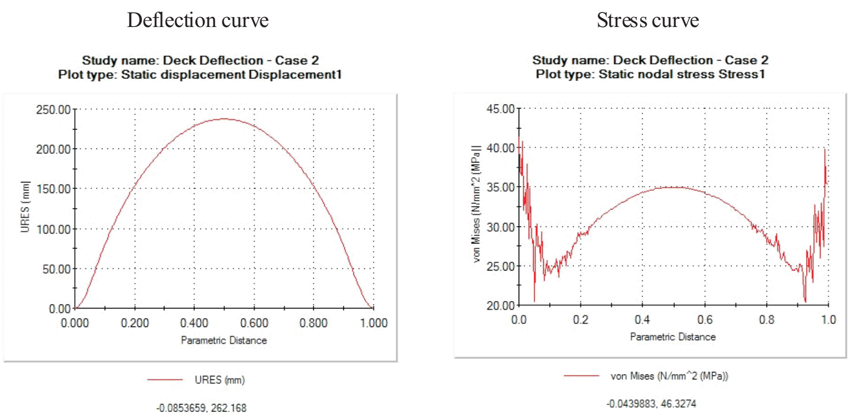

Figure 10 Case 2 – corroded condition curves

Case 3: 100 mm of rain above the roof

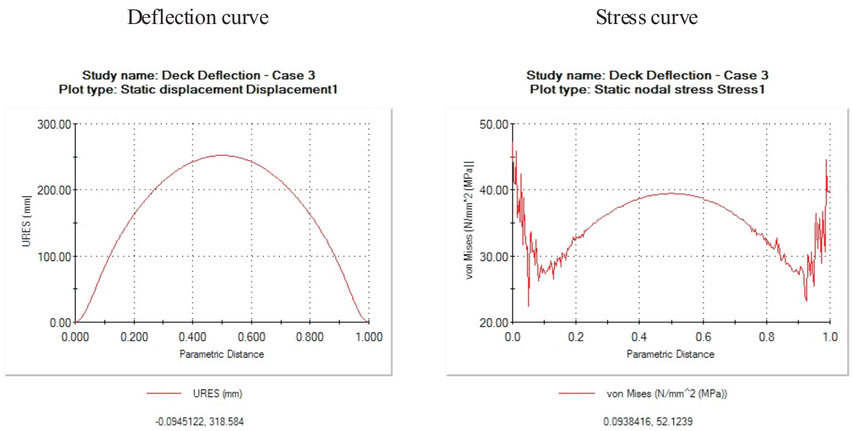

Figure 11 Case 3 – corroded condition curve

Case 4: 200 mm of rain above the roof

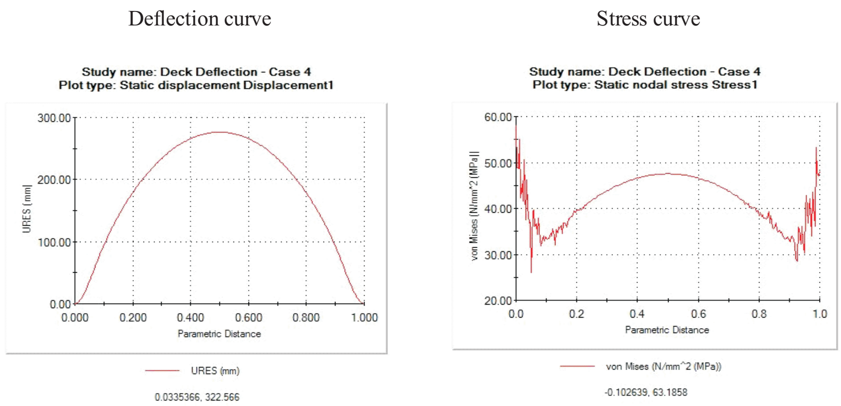

Figure 12 Case 4 – corroded condition curves

Case 5: 250 mm of rain above the roof

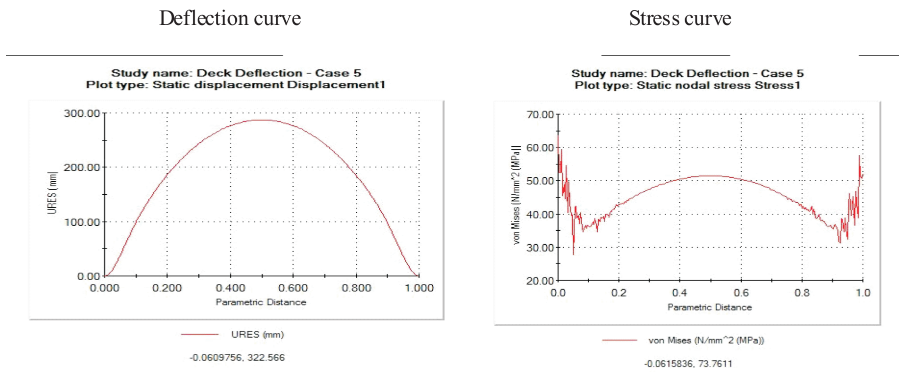

Figure 13 Case 5 – corroded condition curves

5.3. *Linear static analysis*

All loads are applied slowly and gradually until they reach their full magnitudes. After reaching their full magnitudes, loads remain constant (time–invariant). This assumption allows us to neglect inertial and damping forces due to negligibly small accelerations and velocities. Time–variant loads that induce considerable inertial and/or damping forces may warrant dynamic analysis. Dynamic loads change with time and in many cases induces considerable inertial and damping forces that cannot be neglected. The relationship between loads and induced responses is linear. For example, if you double the loads, the response of the model (displacements, strains, and stresses), will also double. You can make the linearity assumption as all materials in the model comply with Hooke's law. The stress is directly proportional to strain, the induced displacements are small enough to ignore the change in stiffness caused by loading. Boundary conditions do not vary during the application of loads. Loads must be constant in magnitude, direction, and distribution.

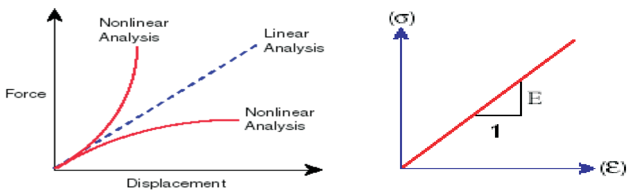

Figure 14 Linear static analysis

Summary of results obtained by linear static analysis:

Table 6 Summary of results obtained by (linear static analysis) – corroded condition

Case number	Max stress [MPa]
1	1050
2	1280
3	1520
4	2000
5	2250

6. Buoyancy Study of Floating Roof with punctured pontoons

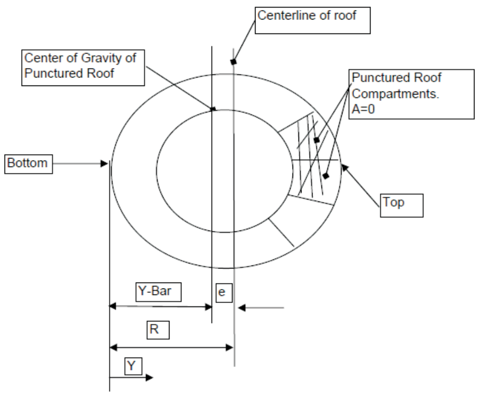

Figure 15 Properties of the punctured roof

Roof buoyancy is designed based on the elastic flexure formula [10], were buoyant forces acting on the effective area of roof resist the weight of the roof. The properties of the punctured roof are determined as shown in (Fig. 15). It shows the center of gravity of the punctured roof and the moment of inertia of the punctured roof. The buoyancy of the floating roof are studied in this research in three cases. First case is study the buoyancy of the floating roof with the puncture of the deck plate and one pontoon. Second case is study the buoyancy of the floating roof with the puncture of the deck plate and two pontoons. The third case is study the buoyancy of the floating roof with the puncture of the deck plate and three pontoons.

1. First calculate the centroid of the floating roof by: A = effective area of individual roof compartments. A = 0 when the compartment is punctured.

   Total Area = Sum of A, W = Weight of roof, R = Roof radius,
   Y = distance from "bottom" to center of gravity of each compartment,
   Y–bar = Sum of A*Y / Sum of Areas, e = R - Y–bar

2. Second calculate the Second moment of inertia by: d – distance from center of gravity of punctured roof to center of gravity of compartment
   d = Absolute (Y - Y–bar),
   I = Second moment of inertia = sum of A * d^2 for all compartments

3. Third calculate the maximum and minimum pressure acting on the floating roof due to punctured roof:
   S_{bot} = I/Y–bar, S_{top} = I / (R + e) = I / (Roof Diameter - Y–bar),
   Moment = W * e, Maximum Pressure = W/ Total Area + M/Stop,
   Minimum Pressure = W/ Total Area - M/S_{bot}

4. Fourth calculate the maximum and minimum submerged height of the floating roof due to its weight and tilt:
   H = submergence due to weight = W / (Total area * Density of Liquid),
   H_{max} due to tilt & weight = h + M/(Stop*Density of Liquid),
   H_{min} due to tilt & weight = h - M/(S_{bot} * Density of Liquid)

6.1. *First Case results: (one pontoon and deck plate are punctured)*

Table 7 Case 1 results - one pontoon and deck plate are puncture

pontoon	Area	centerline degree	Y	Area*Y	D	A*d^2
1	0.0	9.0	38.5	0.0	19.6	0.0
2	11.8	27.0	36.6	432	17.8	3738
3	11.8	45.0	33.2	392	14.3	2413
4	11.8	63.0	28.4	335.0	9.6	1087
5	11.8	81.0	22.8	269	3.9	179
6	11.8	99.0	16.8	198	2.0	47
7	11.8	117.0	11.2	132	7.6	681
8	11.8	135.0	6.4	76	12.4	1814
9	11.8	153.0	3.0	35	15.8	2946
10	11.8	171.0	1.1	13	17.7	3697
11	11.8	189.0	1.1	13	17.7	3697
12	11.8	207.0	3.0	35	15.8	2946
13	11.8	225.0	6.4	76	12.4	1814
14	11.8	243.0	11.2	132	7.6	681
15	11.8	261.0	16.8	198	2.0	47
16	11.8	279.0	22.8	269	3.9	179
17	11.8	297.0	28.4	335.0	9.6	1087
18	11.8	315.0	33.2	392	14.3	2413
19	11.8	333.0	36.6	432	17.8	3738
20	11.8	351.0	38.5	454	19.6	4553.0
Deck	0.0		19.8	0.0	0	0.0
	$\sum = 224.4$			$\sum = 4192$		$\sum = 37757$

Calculation of floating roof centroid:
Y–bar = Sum of A*Y / Sum of Areas = 18.7 m, R = 19.8 m,
e = R - Y–bar = 1.1 m

Calculation of the Second moment of inertia:
I = sum of A * d^2 for all compartments = 37757 m^4

Calculation of the maximum and minimum pressure:
S_{bot}= I/Y-Bar = 2019 m^3,
Stop = I / (R+e) = I / (Roof Diameter - Y-Bar) = 1806 m^3
Weight= 105000 kg, Moment = W * e = 115500 kg*m,
Maximum Pressure = W/ Total Area + M/Stop = 532 kg/m^2,
Minimum Pressure = W/ Total Area - M/S_{bot} = 411 kg/m^2

Calculation of the maximum and minimum submerged height:
H =W / (Total area * Density of Liquid) = 0.668 m,
H_{max} = h + M/(Stop*Density of Liquid) = 0.759 m,
H_{min} = h - M/(S_{bot} * Density of Liquid) = 0.587 m
H_{max} = 759 mm < Floating roof height = 950 mm, safe

6.2. *Second Case results: (Two pontoons and deck plate are punctured)*

Table 8 Case 2 results - Two pontoons and deck plate are punctured

pontoon	Area	centerline degree	Y	Area*Y	D	A*d^2
1	0.0	9.0	38.5	0.0	20.7	0.0
2	11.8	27.0	36.6	432	18.9	4215
3	11.8	45.0	33.2	392	15.4	2798
4	11.8	63.0	28.4	335.0	10.6	1326
5	11.8	81.0	22.8	269	5.0	295
6	11.8	99.0	16.8	198	0.9	10
7	11.8	117.0	11.2	132	6.5	499
8	11.8	135.0	6.4	76	11.3	1507
9	11.8	153.0	3.0	35	14.8	2585
10	11.8	171.0	1.1	13	16.6	3252
11	11.8	189.0	1.1	13	16.6	3252
12	11.8	207.0	3.0	35	14.8	2585
13	11.8	225.0	6.4	76	11.3	1507
14	11.8	243.0	11.2	132	6.5	499
15	11.8	261.0	16.8	198	0.9	10
16	11.8	279.0	22.8	269	5.0	295
17	11.8	297.0	28.4	335.0	10.6	1326
18	11.8	315.0	33.2	392	15.4	2798
19	11.8	333.0	36.6	432	18.9	4215
20	0.0	351.0	38.5	0.0	20.7	0.0
Deck	0.0		19.8	0.0	2.1	0.0
	$\sum$=212.6		$\sum$=415.7	$\sum$=3738		$\sum$=32974

Calculation of floating roof centroid:
Y–bar = Sum of A*Y/Sum of Areas = 17.6 m, R = 19.8 m, e = R - Y–bar = 2.2 m
Calculation of the Second moment of inertia:
I = sum of A * d^2 for all compartments = 32974 m^4
Calculation of the maximum and minimum pressure:
S_{bot} = I/Y–bar = 1873 m^3,
Stop = I/(R + e) = I/(Roof Diameter - Y–bar) = 1499 m^3
Weight = 105000 kg, Moment = W * e = 231000 kg.m,
Maximum Pressure = W/ Total Area + M/Stop = 648 kg/m^2,
Minimum Pressure = W/ Total Area - M/S_{bot} = 371 kg/m^2
Calculation of the maximum and minimum submerged height:
H = W/(Total area * Density of liquid) = 0.706 m,
H_{max} = h + M/(Stop*Density of liquid)= 0.926 m,
H_{min} = h - M/(Sb_{ot} * Density of liquid)= 0.523 m
H_{max} = 926 mm < Floating roof height = 950 mm, safe.

6.3. *Third Case results: (Three pontoons and deck plate are punctured)*

Table 9 Case 3 results - Three pontoons and deck plate are punctured

pontoon	Area	centerline degree	Y	Area*Y	D	A*d^2
1	0.0	9.0	38.5	0.0	21.8	0.0
2	11.8	27.0	36.6	432	20.0	4720
3	11.8	45.0	33.2	392	16.5	3213
4	11.8	63.0	28.4	335.0	11.8	1643
5	11.8	81.0	22.8	269	6.1	439
6	11.8	99.0	16.8	198	0.2	0.5
7	11.8	117.0	11.2	132	5.4	344
8	11.8	135.0	6.4	76	10.2	1228
9	11.8	153.0	3.0	35	13.6	2183
10	11.8	171.0	1.1	13	15.5	2835
11	11.8	189.0	1.1	13	15.5	2835
12	11.8	207.0	3.0	35	13.6	2183
13	11.8	225.0	6.4	76	10.2	1228
14	11.8	243.0	11.2	132	5.4	344
15	11.8	261.0	16.8	198	0.2	0.5
16	11.8	279.0	22.8	269	6.1	439
17	11.8	297.0	28.4	335.0	11.8	1643
18	11.8	315.0	33.2	392	16.5	3213
19	0.0	333.0	36.6	0.0	20.0	0.0
20	0.0	351.0	38.5	0.0	21.8	0.0
Deck	0.0		19.8	0.0	3.2	0.0
	$\sum$=200.8		$\sum$=415.7	$\sum$=3306		$\sum$=28491

Calculation of floating roof centroid:
Y–bar = Sum of A*Y / Sum of Areas = 16.5 m, R = 19.8 m,
e = R- Y-bar = 3.3 m

Calculation of the Second moment of inertia:
I = sum of A * d^2 for all compartments = 28491 m^4

Calculation of the maximum and minimum pressure:
S_{bot}= I/Y–Bar = $1727 m^3$,
Stop = I / (R+e) = I / (Roof Diameter - Y–Bar) = 1233 m^3
Weight = 105000 kg, Moment = W * e = 346500 kg.m,
Maximum Pressure = W/ Total Area + M/Stop = 804 kg/m^2,
Minimum Pressure = W/ Total Area - M/S_{bot} = 322 kg/m^2

Calculation of the maximum and minimum submerged height:
H =W / (Total area * Density of Liquid) = 0.747 m,
H_{max} = h + M/(Stop*Density of Liquid)= 1.148 m,
H_{min} = h - M/(S_{bot} * Density of Liquid)= 0.460 m
H_{max} = 1148 mm $>>$ Floating roof height = 950 mm, unsafe

7. Results conclusions

1. The results of deck plate deflection show that there are wide differences between using the first two methods (Roark's Formulas and nonlinear finite element analysis) the third method (linear finite element analysis) as shown in Fig. 16. Since using the numerical linear finite element analysis in this application is not applicable because it ignores the effect of the large displacement and deformation in the material behavior in strain, deflection and stresses, due to that wrong behavior, the results in the third method is too much higher than the results in the other two method.

2. Nonlinear finite element analysis is the most accurate and applicable to use in the design of the floating roof deck, since it simulate the exact loading cases that happen in reality, however using Roark's Formulas gives higher results but it can be used as a fast method in the analysis of the deck plate. Therefore, as a conclusion of the results comparison, the linear finite element analysis method is not applicable to our study and cannot be used to study the behavior of the floating roof deflection.

3. According to API 650 (section 5, Tab. 5-2) the product design stress of materiel A283 Gr.c is 137 MPa So to protect the floating roof from failure the maximum stress on the roof must not exceed this value. The graph in (Fig. 17) shows that our design is valid to carry the 5 different load cases without failure. Also, it shows that it will handle the stress on its corroded condition without any failure on the floating roof.

4. The results show difference in results from using Roark's Formulas of large deflection method and non–linear finite element method because the accuracy of the non-linear method is much higher than the Roark's Formulas which is simpler analysis method. In spite of this difference, our study shows that the design is safe using both methods at different study cases and conditions.

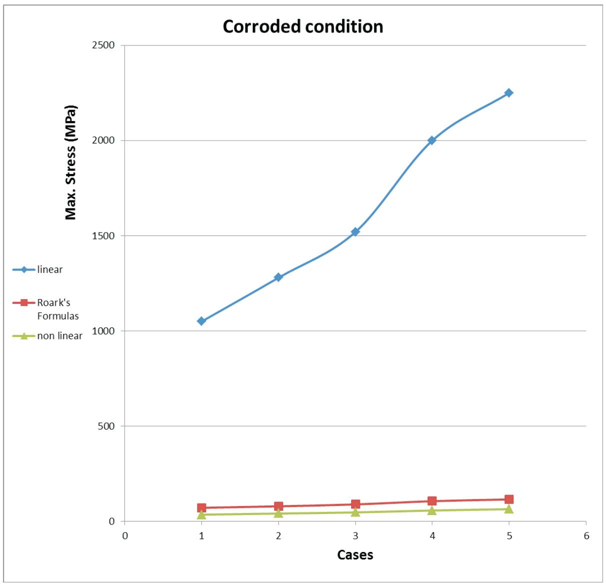

Figure 16 Comparison between Roark's formulas, nonlinear finite element analysis and linear finite element analysis

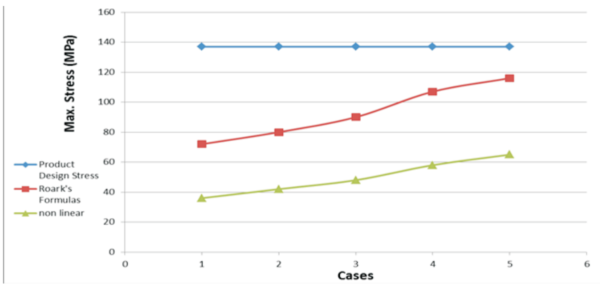

Figure 17 Comparison between the results and product design stress (corroded condition

To increase the safety factor of the floating roof deck:

- use another materiel with higher product design stress value as A516 Gr.70 or A573 Gr.70,
- increase the deck plate thickness,
- apply suitable coatings to prevent corrosion.

5. Floating roof will remain floating after the puncture of two adjacent pontoons and deck plate according to the design of the physical model but it will sink if the number of punctured pontoons increased to three.

6. To increase safety factor against floating roof sinking, it is better to reduce section area of pontoons by increase number of pontoons inside the floating roof. However, the design must take on consideration that area of pontoons is limited with space required for welders to enter inside it.

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