Material selection of subsea storage tanks for arctic sea conditions

Arvind Kishor Tirumanur Shanmugavelu[1] and *Muraliraja* Rajaraman[1*]

[1]Vels Institute of Science Technology and Advanced Studies, Chennai, India

Abstract. The Arctic region contains a plethora of recoverable hydrocarbon wealth in the form of oil and gas. The main challenges faced in the Arctic region is the issue of multi-phase flow in the current field operation coupled with the decline of the reservoir. In the early stages of field life, the reservoir pressure is sufficient to allow the natural flow from reservoir formation to surface without additional supporting compression. Unfortunately, the pressure naturally declines throughout the entire life cycle of the field. To achieve a better production profile in the arctic region the idea is to implement a Subsea processing concept employing a Subsea Storage Tank (SST). In this paper the collision analysis will be performed under specified environmental condition in order to provide more realistic simulation of structural behaviour. The determination of the maximum loads to which the SST can survive is analysed and a study of the possible protection systems will be carried out. The incorporation of SST in the subsea system will enhance the production rate by 50% and decrease the oil spill accidents considerably. Keywords: Subsea Storage, Static; Explicit dynamics; Ansys.

1 Introduction

With arctic oil and gas exploration coming to be a new frontier in oil and gas exploration, there is need to bring in innovative ideas capable of confronting this challenge. Consequently, considering this challenge technically and commercially, Engineering has got to strive to give solutions with objectives of minimizing cost of operation and improving reservoir performance. Among these issues in the field of study, are multiphase flow, icing and polar low and this make production quite a serious problem for the industry. In oil and gas Exploration the produced hydrocarbons are transported using the pipelines, shuttle tankers or through the production platform having the storage facilities. The more primary way of transportation is through pipelines since most the production fields are nearer to the shoreline. By this transportation method the produced hydrocarbons are being transported through the underwater laid pipelines as a multiphase flow. In multiphase flow, all the produced hydrocarbons are not separated into oil gas water and CO_2. Once multiphase flow reaches the refineries these hydrocarbons are processed by various

* Corresponding author: muralimechraja@gmail.com

treatment methods and the oil gas condensate water and CO_2 are separated and sent for exportation. The separated carbon-di-oxide got injected back into the well to enhance the production recovery. This multiphase flow through the underwear pipelines have experienced many problems through the past two decades [1,2].

The overall aim of this study, while remaining solution-minded, is to optimally propose and deliver a cost benefit design approach that is most suitable for oil reservoir in the field of study. This proposed design has looked at the possibility of using SST to eliminate the earlier mentioned existing issues associated with the field. This will ensure that condensate is separated from the crude oil by providing a storage solution and thereby providing among others, a good platform for field expansion and eliminate multiphase issue that has since characterized our field of study. Condensate will be separated by a separation unit which will be stored in the SST while the gas can be conveyed through the existing export pipeline [3-6]. As will be shown in details later in this paper, the SST will be incorporated with a flexible bag which collects the condensate and as it expands, seawater in the tank is expelled until the bag is fully filled. After which the condensate is conveyed through a riser from the cap of the structure. To achieved this process, static structural analysis which deals with its response to static loading, explicit analysis which investigates iceberg impact on the structure is being discussed in this paper.

2 Background for Analysis and Design

2.1 SST overview

SST is the subsea storage equipment, a recent innovation by Kongsberg Oil and Gas Company (Figure1), which incorporates a flexible bag to contain the production liquid. It is a gravity-based storage tank that differs from conventional gravity storage systems by the flexible bag, this eliminates contact between sea-water and the stored fluid, thus eliminating the problems with emulsion layer and risk of bacterial growth. The bag is covered by a rigid structure in order to protect the damage of whole fluid containment and considered as the secondary protection containment. The top of the protection structure is designed with a special hatch such that the bag may be easily retracted or installed separately from the protection structure if necessary for repair or replacement. To begin with, the external protection structure can be made with three types of material which are steel, GRP and concrete. All materials provide their own benefit and drawback however stainless steel and concrete are considered as the selected material for fabricating the SST in this analysis. The Figure 2 represents the modelled Subsea Storage Tank.

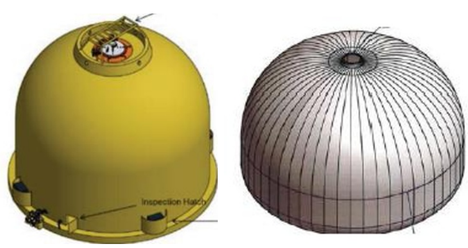

Fig. 1. The external protection structure (Left) and flexible bag (Right)

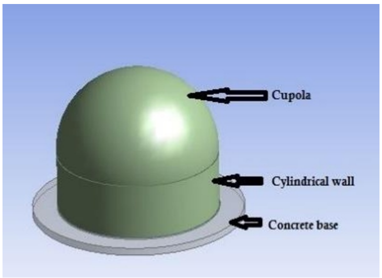

Fig. 2. ISO view of the complete SST

Generally, steel material provides lighter dry weight with ease of fabrication in comparison with other materials though it requires good corrosion protection system and anchoring system during installation phase. The flexible storage bag is a recent innovation which is made with composite materials from combination of coated fabric and woven textile. These materials provide good stress and strain resistance due to the loading and offloading condition. The capacity and main dimensions of the modelled SST are given in Table 1.

Table 1. SST capacity and dimension

Description	Details
Storage Capacity	20,000 cubic metres
Total Height	40 metres
Cupola Diameter	40 metres
Concrete Basement Diameter	56 metres

The stainless steel- Grade 304 (UNS S30400) has been used as the cupola and cylindrical wall. The selection of the SST properties has been carefully selected based on corrosion concern and thorough examination of ideal properties for the area of concern. However, this choice of materials is made because its basic properties are suitable for arctic application. The Table 2 below shows the steel properties according to ASM Handbooks [7].

Table 2. Steel material parameter used

Property	**Value**	**Unit**
Density	7896	kg /m^3
Shear Modulus	7.6923E+10	Pa
Young's Modulus	190	G Pa
Poisson's Ratio	0.265	-
Bulk Modulus	134	G Pa
Gruneisen Coefficient	2.17	-
Tensile Strength	510	M Pa
Compressive Strength	205	M Pa
Ductility	0.3	-
Elastic Limit	205	M Pa
Fracture toughness	119	M Pa. m$^{1/2}$

To provide the weight necessary for keeping the SST in a stable and fixed position the concrete basement is used, therefore assuring the gravity base solution. The main concrete

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properties are listed in the Table 3, and they represent the behavior of an isotropic material. The thickness of the SST wall is a key parameter in the analysis since the stress experienced in the SST depends on the wall thickness.

Table 3. Reinforced concrete properties

Property	Value	Unit
Density	2520	Kg m^{-3}
Shear Modulus	2.206E+09	Pa
Specific Heat	654	J kg^{-1} C^{-1}
Hardening Slope	2	-
Bulk Modulus	3.527E+10	Pa
Elastic Strength/fc	0.53	-
Tensile Strength ft/fc	0.1	-
Compressive Strength fc	1.4E+06	Pa
Shear Strength fs/fc	0.18	-

1.2 2.2 Relevant Offshore Standards, classification and rules

According to SST is under developing equipment, there is no specified code and standard addressing directly to establish limitation of iceberg impact for SST. The overview of SST and ice interaction is mainly complied with ISO 19906:2010 Petroleum and Natural gas industries – Arctic offshore structures. This standard provides a guideline of iceberg properties, region data and also mechanism of ice [8]. For the Abnormal limit states (ALS) allows plastic deformation region of structure which allows safety factor 1.0 of the ultimate tensile strength of material of cupola and wall of SST. While, the SST structural design comply to LRFD design method from DNV design of offshore steel structures which target the safety level of acceptable resistance of the structure material [9]. To consider flat plated structures, stiffened panel and shell structure allowable strength, the material factors of material strength are determined according to AISC LRFD steel manual as shown in Table 4. For this SST stainless steel structure, the limitation is 191.3 MPa.

Table 4. AISC LRFD Steel Manual

Material factor	Value
Flat plated and stiffened panel structure	1.15
Girder, beams stiffener on shell	1.15
Shell of single curvature (Cylindrical shells, conical shells)	1.15 – 1.45

1.3 2.3 Static structural analysis

The pressure exerted by a fluid at equilibrium at a given point within the fluid, due to the force of gravity. Hydrostatic pressure increases in proportion to depth measured from the surface because of the increasing weight of fluid exerting downward force from above. The only external fluid pressure is sea water with the density of 1025 kg/m3. Internal pressure is a measure of how the internal energy of a system changes when it expands or contracts at constant temperature. Generally, internal fluid in SST is seawater and crude oil which has density 1025 and 800 kg/m3. Actually, crude oil density ranges between 800 – 1000 kg/m3 but in this analysis low crude density is selected to calculate the maximum different pressure applied on shell structure [10].

In this static analysis, it is separated into two scenarios condition in SST. Firstly, the hydrostatic pressure of fluid applies on the SST considering with external fluid and internal fluid. Two internal fluids which are crude oil and water with density 800 kg/m3 and 1025 kg/m3 respectively are chosen to analyse. In the second case, load of iceberg is applied on the structure at the centroid of cupola of SST. The magnitude of this force is assumed by the research in base case and high case assumption as shown in Table 5. In High case, it is assumed that the strength of ice is significantly high which 4.0 MPa.

Table 5. base case and high case of static load analysis

Case	Design load (MN)
Base case	367
High case	1269

2.4 Collision Analysis

2.4.1 Environmental Conditions

Although the iceberg impact is improbable in Arctic field, it is been realizes that the essence of implementation of SST in Arctic region is to analyse and design the structure to withstand iceberg impact. The collision analysis is performed under specified environmental conditions in order to provide most realistic simulation of structural behaviour. In this model, the environmental loads are determined from Grand Banks offshore Newfoundland data.

For Environmental data, Program of Energy Research and Development (Canada), Canadian Hydraulics Centre, National Research Council Canada has collected wind, wave and Iceberg data. Due to the depth at which the tank is placed there is significantly no influence from the wave forces. However, current provides impacts on the tank as it is placed firmly on the seabed. Water Depth – 100-120 m, Wind Speed – Not applicable as tank is on seabed, Wave Height – 4.5-12.0 m, Water current – 0.25 -2 m

2.4.2 SST-Iceberg Collision Mechanics

It is observed experimentally that when iceberg and ship collide, the energy absorbed by the ship is proportional to their kinetic energies before impact. Though this describes iceberg-ship collision however since it explains the whole idea about an iceberg impact with a structure and, it has been used for our system behaviour. If it is assumed that the total energy is transferred to the structure then iceberg can be considered to be totally rigid. The first scenario has to do with ductile strength of the structure and this happens when the impact is totally inelastic and iceberg is assumed to come to a stop after impact.

Second scenario which is when the energy is shared between the colliding bodies i.e., iceberg kinetic energy is conserved. The last possible scenario is when the total energy is absorbed by the iceberg which explains strength design of a structure. In our analysis, a shared energy scenario is used since it is the best realistic scenario for an iceberg-structure collision. Based on this, a proper material selection can be achieved. It should be added that only internal energy has been considered for our analysis and this deals only with the local damage of the colliding bodies

2.4.3 Iceberg load calculation

In Grand Banks region, there are mainly two production structure which are Gravity base structure and ship-shape FPSO. This paper has considered the iceberg force collision for GBS in Grand Banks region in 95m of water depth and also provides several cases scenarios for iceberg loading. However, in deeper depth, the probability of larger iceberg is raised. Based on the conditions, several cases and its assumptions are given in the Table 6.

Table 6. Assumption of case scenario

Case	Assumption
A	No iceberg management capability The impact model is based on geometry of contact point and the shape distribution
B	Define constant strength of iceberg at 0.25 MPa
C	Define constant strength of iceberg at 1.0 MPa
D	Define constant strength of iceberg at 4.0 MPa
E	Define the ice nominal pressure as $p(a)= 3\ a^{-0.4}$
F	Reduce velocity to 0.75 of base case
G	No rotation model
H	Including management and detection system

Modelling of iceberg is complicated, hence before modelling, various article on iceberg modelling were consulted to effectively model an iceberg that can give reasonable results, but all these shapes were not realistic. However, the chosen iceberg has been modelled with every possible irregularity so as to get best realistic result possible. The sizes have been taken from the field of study and to get a realistic result. It is therefore important to mesh the iceberg. Two different icebergs are modelled, according to Smith [11] measured iceberg from Newfoundland has the dimensions and mass as shown in Table 7.

Table 7. Ice Dimensions

Ice mass (kilo tonne)		Total height (m)	Maximum diameter (m)
Average	620	118	100
Extreme	2100	111	180

The accuracy of the data was ±5% above water and ±10% below water. The size and shapes of icebergs depends on their region. Based on 2006-0672, DNV iceberg is simplified into three shapes, cube, sphere and cone. However, curved shapes demonstrated realistic simulation in compare with flat ones. Figures 3 and 4 illustrate the shape of two icebergs, which are modelled.

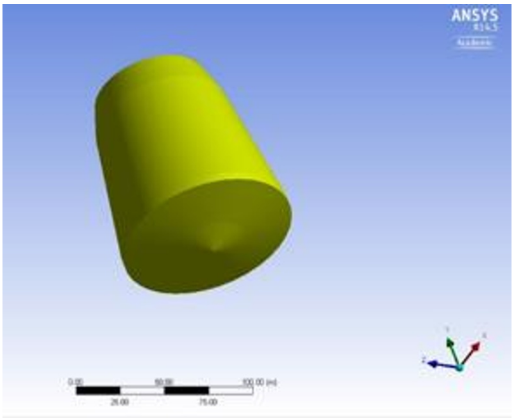

Fig. 3. Iceberg 1

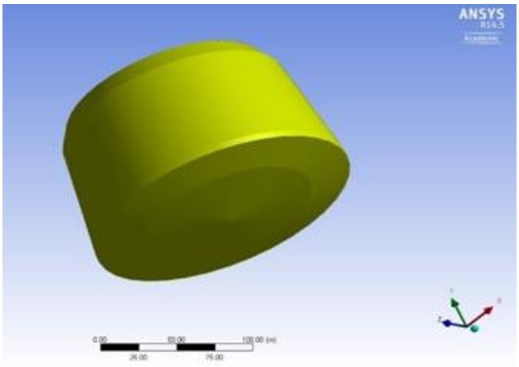

Fig. 4. Iceberg 2

The parameters used for the ice material in Modelling part is given in the Table 8. So, while considering the geometry and mass of iceberg in our field, an irregular shape but isotropic property has been assigned to the iceberg for the analysis in order to get realistic result.

Table 8. Iceberg material used

Property	Value	Unit
Density	915	Kg/m^3
Shear Modulus	3.7109E+09	Pa
Young's Modulus	9.50E+09	Pa
Poisson's Ratio	0.28	-
Bulk Modulus	7.197E+09	Pa
Absorption Coefficient	0	m^{-1}
Tensile Ultimate Strength	6.9E+05	Pa
Compressive Ultimate Strength	3.45E+06	Pa
Maximum Principal Strain	0.01	m/m
Maximum shear Strain	0.01	m/m

Meshing is considered to be one of the most critical aspects in analysis that approximates the geometric domain. The Coarse, Medium and Fine are the three available

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meshing types in ANSYS® Workbench™ 2.0 Framework. The fine mesh (Figure 5) is used for getting very few cell domains whereas the coarse mesh provides too many cells.

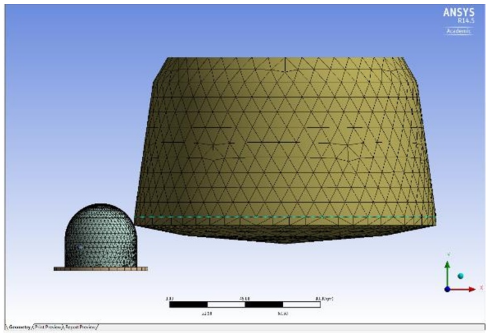

Fig. 5. Meshing

From statistic data of iceberg drifting velocity, the velocity ranges between 0.5 to 1.50 m/s in Newfoundland region which is influenced by both wind and current velocity. However, the speed of iceberg also depends on the iceberg size which smaller size is generally relatively faster. To simply this analysis, it is considered that velocity is applied on every iceberg sizing. Three velocities are selected for analysing structural responses which are 0.5, 1.0 and 1.5 m/s.

2.4.5 Analysis Case Test Matrix

To analyse iceberg impact on SST, the structural analysis is performed according to the below test matrix cases in Table 9 in order to simulate the SST response in various conditions.

Table 9. Analysis Cases for explicit dynamic

	SST Material	**Wall Thickness (m)**	**SST - Storage**	**Iceberg Collision**
Case 1	Steel	0.15	Oil	Cupola
	Subcase	**Mass of the Iceberg (Mkg)**	**Velocity of Iceberg (m/s)**	
	1a	2100	1.5	
	1b	2100	1.0	
	1c	2100	0.5	
	1d	600	1.5	
	1e	600	1.0	
	1f	600	0.5	
Case 2	Steel	0.15	Water	Cupola
Case 3	Steel	0.15	Oil	Sidewall
Case 4	Steel	0.15	Water	Sidewall
Case 5	Steel	0.30, 0.40, 0.50	Oil	Cupola
Case 6	Steel	0.30, 0.40, 0.50	Water	Cupola
Case 7	Concrete	0.50	Oil	Cupola
Case 8	Concrete	0.50	Oil	Sidewall
Case 9	Steel	0.15, 0.30, 0.40, 0.50	Oil	Cupola

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3 Results and Discussion

3.1 Structural Analysis

From structural analysis part, it can be categories into two parts which are static and explicit analysis. The modelling was done using ANSYS® Workbench™

3.1.1 Member structural analysis

The collision static analysis is by specifying a best possible point load that can be applied on the structure by the iceberg. This analysis method provides significantly short time analysis to acquire the results of collision analysis. Table 10 presents the related interaction of hydrostatic pressure on the structure and its corresponding deformation behavior.

Table 10. Hydrostatic and iceberg impact force on SST

Hydrostatic pressure			
Internal pressure	Deformation (mm)	Stress (x 10^7 Pa)	Strain (m/m)
Oil	2.09	2.00 (Cupola) 2.93 (Wall)	1.01E-04 (Cupola) 1.48E-04 (Wall)
Water	2.59 (Cupola)	2.10 (Cupola) 2.59 (Wall)	1.02E-05 (Cupola) 1.30E-05 (Wall)
Iceberg impact (367 MN)			
Internal pressure	Deformation (mm)	Stress (x10^7 Pa)	Strain (m/m)
Oil	2.09	6.28 (Cupola) 6.33 (Wall)	1.22E-02 (Cupola) 3.17E-04 (Wall)
Water	2.14	6.27 (Cap) 6.33 (Wall)	3.13E-04 (Cupola) 3.17E-04 (Wall)
Iceberg impact (1269 MN)			
Internal pressure	Deformation (mm)	Stress (x10^7 Pa)	Strain (m/m)
Oil	7.2	2.17E+01(Cupola) 2.21E+01 (Wall)	1.08E-03 (Cupola) 1.10E-03 (Wall)
Water	7.2	2.16E+01 (Cupola) 2.18E+01 (Wall)	1.08E-03 (Cupola) 1.09E-03 (Wall)

This comparison is presented in order to evaluate the adequacy and reliability of the chosen structure design parameters in applying code provisions. The main stress and deformation concentration is in the red area. It can be seen that in only applied pressure force the stress distribution increase along the radius of SST. The lower section of structure experience higher stress load [12]. While the deformation also acts similar behavior as shown in Figure 6 (a)&(b).

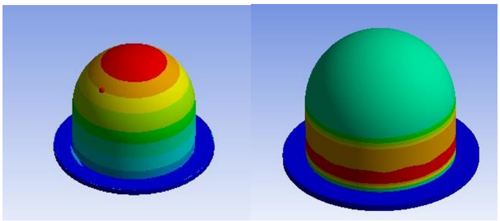

Fig. 6. (a) Stress distribution on SST (b) Deformation distribution on SST

The most deformed area is the top part of the hatch of the structure. Moreover, effect of different types of internal fluid does not provide significant effect on the structure. The maximum total deformation is in the large iceberg impact force which deforms 7.2 mm of the structure shape.

3.1.2 Explicit analysis

Explicit analysis covers SST-Iceberg impact behavior. It should be added that this analysis provides more accurate results for impact analysis but it required longer computational time. In this analysis the collision of iceberg with subsea storage's cupola are considered with two scenarios, when SST is filled with oil and when it is filled with water. Also, two icebergs of different geometry and mass are chosen for analysis and velocity of 0.5 m/s to 1.5 m/s for each one. Although, for the storage thickness more than 0.15m the reaction is the same, however the 0.30m and 0.05m thickness are tested to compare with the main thickness of 0.15 meter of Stainless steel.

The results of this analysis include

- Total deformation
- Equivalent Stress
- Equivalent Strain

Case 1: In this Explicit Dynamic analysis, the different case studies are carried out in order to understand the behavior of SST during the Iceberg collision [13]. In case 1 the initial analysis is carried out in order to find the stress behavior and deformation of SST having a thickness of 0.15m. The case 1 is subdivided into two cases based on the mass of iceberg colliding with SST. In case 1.1a the extreme condition which is 2100Mkg of Ice with 1.5 m/s drifting velocity was used for the analysis. The result of this case is negative since there is a severe stress experienced in the collision part which is cupola. In order to find the limit case small velocities (1.0m/s & 0.5m/s) are used for case 1.1b (Figure 7): and 1.1c, but still there is deformation in the cupola part of SST. The same set up is carried out in cases 1.1d, case 1.1e (Figure 8), and case 1. 1f using the average mass (600Mkg) with the respective velocities of 1.5m/s, 1m/s, 0.5m/s. In this case the results are negative which means the stress level exceeds the allowable stress limit [13].

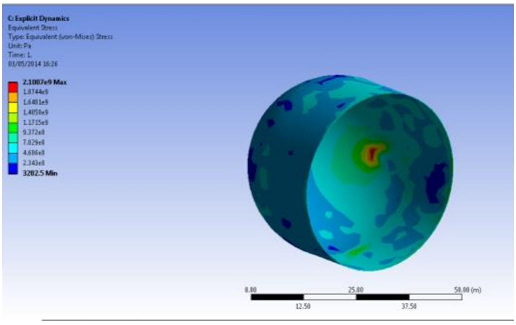

Fig. 7: Internal Equivalent Stress

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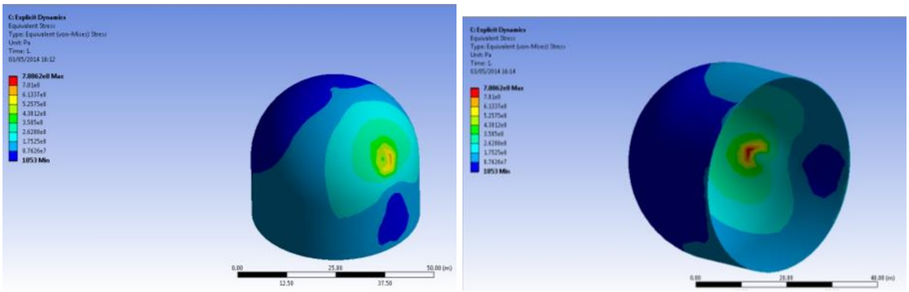

Fig. 8. Equivalent Stress External & Internal View

Case 2 The same steps are carried out using water instead of oil inside in case 2 (Figure 9), but the deformation is very severe when compared to case 1.

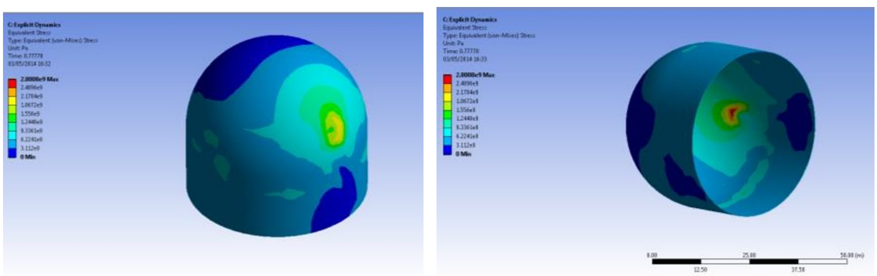

Fig. 9. Equivalent Stress External & Internal View

Case 3 & 4: The side wall of the SST is tested in Case 3 and 4 using the big mass of Iceberg (2100Mkg) and the extreme condition velocity (1.5m/s) to test the sidewall of the SST. In case 3 (Figure 10), oil is stored inside and in case 4 (Figure 11), water is stored during the analysis. The stress limits exceed in both the case 3 and 4.

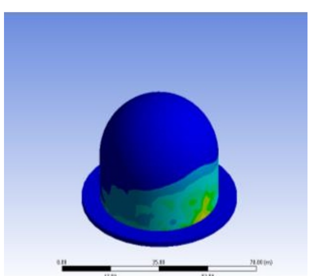

Fig. 10. Equivalent Stress

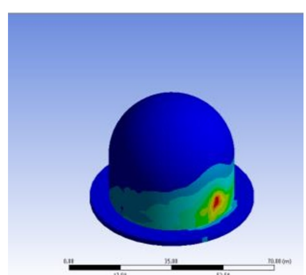

Fig. 11. Equivalent Stress

Case 5 & 6: Since the cases until 4 are failed, in case 5 (Figure 12) and Case 6 (Figure 13) the thickness of the SST is increased to 0.30m, 0.40m and 0.5m and checked in both oil and water stored condition. The results show that the stress concentration reduces as the thickness of the SST wall increases.

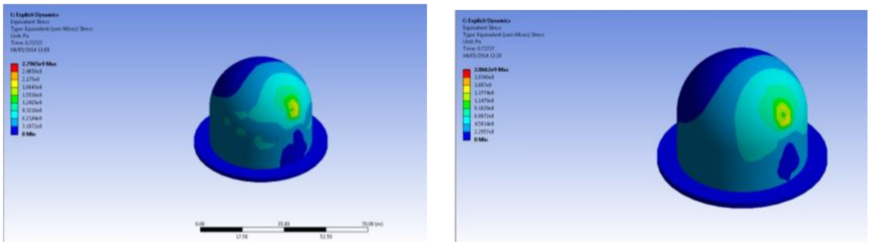

Fig. 12. Equivalent Stress (0.3m t) (0.4m t)

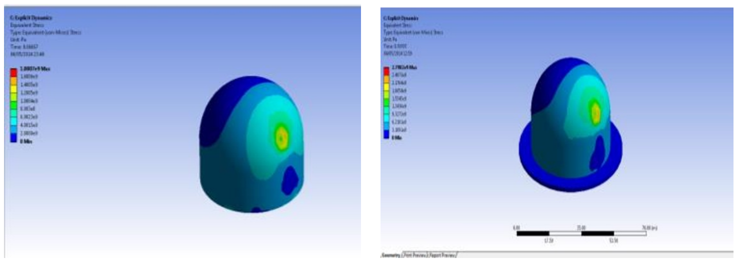

Fig. 13. Equivalent Stress (0.3m t) (0.4m t)

Case 7: The case 7 (Figure 14) results shows that the usage of concrete as a fabrication material is strictly avoidable. The analysis result shows that there is a possible of cracks on the top of the SST tank

Case 8 The case 8 results (Figure 15) shows that the usage of concrete is very dangerous when there is collision occurs with the side wall of the SST. In this case the SST is complety deformed due to the collision

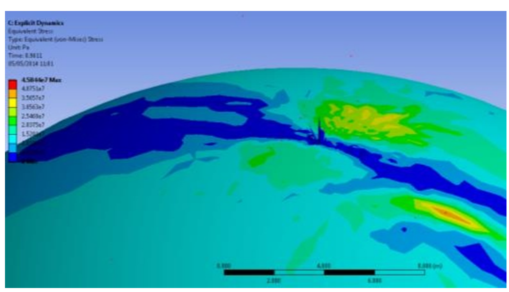

Fig. 14. Equivalent Stress (0.5m thickness)

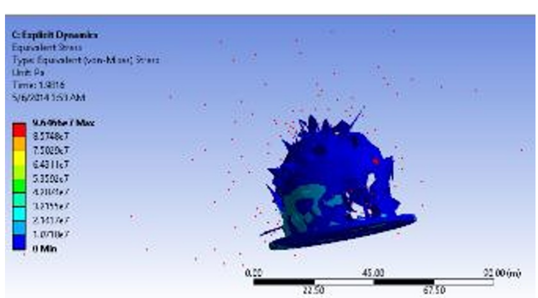

Fig. 15. Equivalent Stress (0.4m thickness)

Case 9: The case 9 results Figure 16 (a, b, c, d, e, f) shows that there is a significant drop in the stress value when the mass of the iceberg reduces. The stress range reduces when the momentum of the iceberg decreases.

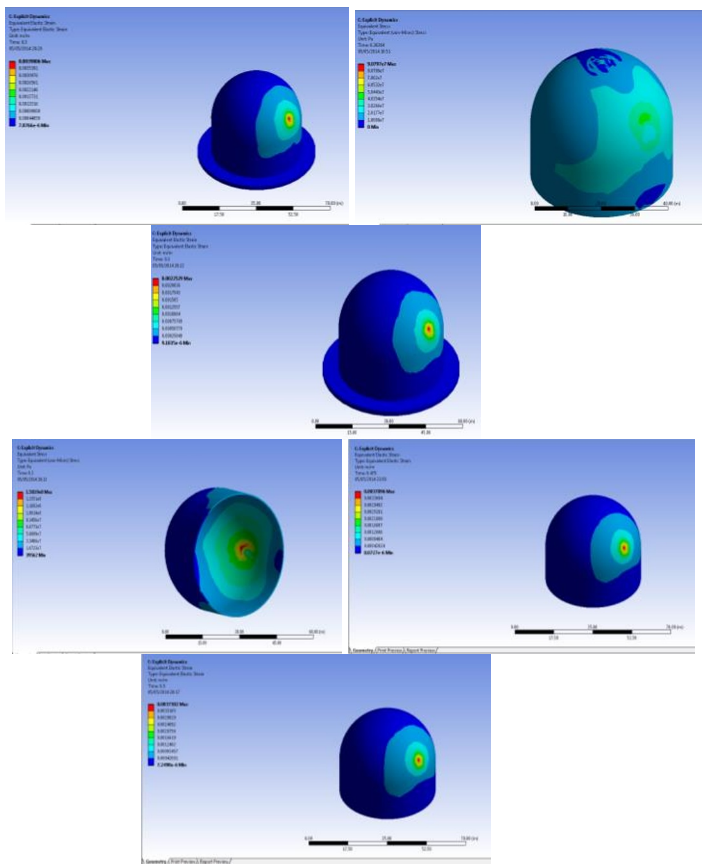

Fig. 16. Equivalent Stress (a) (23 Mkg, 0.15m) (b) (23 Mkg,0.30m) (c) (23 Mkg, 0.40m) (d) (23 Mkg, .40m) (e) (100 Mkg, 0.40m) (f) (100 Mkg, 0.50m)

4 Conclusions

The analysis on SST in artic condition is done successfully and the following data are derived based on the analysis,

- When considering stress due to numerical ice impact loading, it can be seen that equivalent stress seems to be increased linearly due to the raising of ice impact force. However, the allowable stress of material is limited at 191 MPa according to offshore steel structure guideline from DNV.
- The contact point of equivalent stress and allowable stress seems to reach when the iceberg impact force reaches 1100 MN.
- The explicit analysis gives brief knowledge about the ice interaction with the SST Structure. The different scenarios considered provide belter knowledge about the collision mechanism.

- From the case 9, it is concluded that the SST stress limit depends on the mass of the iceberg and the velocity of the iceberg. The modelled SST can withstand the stresses until the momentum of iceberg shouldn't be exceeding 34.5 Mkg.m/s.

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