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Finite Element Analysis (FEA) on Conceptual Design of Elliptical Natural Gas Tank for Vehicle Application

Romales Bin Ramli[1], Noorfaizal Bin Dato' Yidris[2]

[1]Centre for Instructor and Advanced Skill Training (CIAST), Shah Alam, Selangor
[2]Universiti Putra Malaysia, Serdang, Selangor.

Abstract

Utilization of Natural Gas for Vehicles (NGV) as an alternative fuel for vehicles has increased after liquid fuel prices such as petrol and diesel have risen due to the instability of crude oil prices in the world market. For the purpose of converting ordinary vehicles to Natural Gas Vehicles (NVGs), several additional components and the pressurized cylinder tank need to be installed on the vehicle. Installation of pressurized cylinder tank can cause the vehicle storage space becomes narrower, increased of vehicle's weight and relatively high installation costs to be incurred. Therefore, this study will develop less expensive elliptical NGV tank, lighter and reduce the use of storage space in the vehicle.

Keywords: *NG, NGV, NGVs, FEA, ABAQUS*

Introduction

Nowadays, more than 17.7 million natural gas vehicles (NGVs) are on the road and 22 162 NG refuelling stations are in operation worldwide (NGVA [1]). Malaysia ranked as one of the countries rapidly promoting the use of NGVs since 2008 due to rising world oil prices. Statistically reported on 2012, 53 783 NGVs being used and 173 refueling stations are in operation in Malaysia (NGVA [1]). Currently, the global increase of petroleum price, resulting in higher prices for petrol and diesel in Malaysia, this situation encourages the use of alternative fuels such as Natural Gas (NG). Thus, widely use of NG as fuel for vehicles will automatically increase the needs of proper shape for NG tanks, whereas safety and meet the international standard is a priority for a consideration in development of NG fuel tanks.

Problem Statements

Globally, Increasing of Natural Gas Vehicles (NGVs) on the road is due to rise of crude oil price. Statistically reported by IANGV 2013, during crude oil prices rose from USD 24.68 per barrel in 2000 to USD 114.6 per barrel in 2008, the number of NGVs also increased from 1,203,100 in 2000 to 9,619,449 in 2008. In Malaysia, since the drastic price rising of liquid fuel such as petrol and diesel in 2008, statistics show that number of NVGs has increase from 24, 988 in the year 2007 up to 40,248 in the year 2008. (IANGV, 2013). However, in Malaysia the increase of NGVs on following years, 2009 to 2012 showed little increments, compared to 2008 (refer **Table 1**). This circumstances may be influenced by several factors that are identified, as described below:

i) High costs for the installation of additional components for NGVs;
ii) CNG (NGV) storage cylinder tank size reduces vehicle's trunk space (vehicle's cargo/ storage); and

iii) Additional components for NGVs increased vehicle's weight.

[20] The CNG (NGV) tank is about 3.8 times larger than a gasoline tank with the same energy content. CNG (NGV) tank also is heavier in order to manage the high pressure. Besides, the cheapest solid steel (Type 1) cylinders weigh 4 to 5 times as much as the same capacity gasoline tank. Practically, the NGV tank about to taking up half of the vehicle's trunk space. For example, the tank on the 2012 Honda Civic NG vehicle holds about 8.0 gge (gallon of gasoline equivalent) of CNG (NGV) at 3600 psi, giving the vehicles a range of 192 miles (EPA city) to 304 miles (EPA highway), while taking up half of the vehicle's trunk space (6.1 cubic feet rather than 12.5 cubic feet). The detail comparison between Honda Civic NG with similar vehicles shown in **Table 2.**

Therefore, this study aims to analyse the development of the cheapest NGV gas tank (type 1-steel), using an ellipse cross-sectional shape than a cylindrical shape which can reduce the use of the vehicle's storage space, while reducing the thickness of the skin of the tank to reduce the weight of the tank. However, the stiffeners are used to maintain the strength of the tank when subjected to the maximum pressure as specified in ISO 11439.

Table 1: NGVs growth in Malaysia (2007-2012)

	2012	**2011**	**2010**	**2009**	**2008**	**2007**
NGVs	51,364	48,946	46,701	42,617	40,248	24,988
Annual Increase	2418	2245	4084	2369	15,260	5988
% Annual Increase	4.94	4.81	9.58	5.89	61.07	31.52

(Sources: IANGV, 2013)

Table 2: Comparison of Honda Civic NG to Similar Vehicles

	Civic NG	Civic LX	Civic Hybrid
MSRP[a]	$26,805	$18,505	$24,200
mpg	27/38	28/39	44/44
Fuel cost	$1,050	$1,800	$1,300
Power	110 HP	140 HP	110 HP
Cargo (cubic feet)	6.1	12.5	10.7
Weight (pounds)	2848	2705	2853
CO_2 (grams/mile)	227	278	202

[a]Manufacturer's suggested retail price.
SOURCE: American Honda Motor Company; available at http://www.honda.com/.

Methodology

The development of the elliptical NGV tank is based upon the Type 1: seamless steel NGV cylinders (CNP 20-30-279A) as specified in ISO11439 standards. The tank design concept using the steel materials 34CrM04, which has a yield strength of 800 N/mm^2 or 650 N/mm^2 (depend on the shell thickness). Finite Element Analysis (FEA) by using ABAQUS software on elliptical NGV tank's concept design, will be carried out by applying 200 bar/ 20 MPa as Working/ Service Pressure. Referring to ISO11439, Minimum Pressure Test to be employed is 300 bar/ 30 MPa (which is 1.5 of Services Pressure). As a reference of the study, analysis of Type 1: NGV cylinder tank (CNP 20-30-279A) and basic elliptical NGV tank without the stiffeners is conducted using ABAQUS. The new design concept will be developed with reference to the change of the elliptical cross-sectional dimensions, the thickness of the shell tank, the thickness of the stiffeners, stiffeners type and the stiffeners pattern used. Different concept design has been analyzed to identify which can produce the lower maximum stresses than the maximum stresses on NGV cylinder tank type 1 (CNP 20-30-279A) or at least lower than the material's yield strength. Finally, the elliptical NGV tank with aspect ratio of 2 and the shell thickness of 10 mm has been analyzed by using ABAQUS, the analysis proves that the combination stiffeners of three solid plates as longitudinal stiffeners (thickness, 8 mm) and 10 additional hoop stiffeners (thickness, 8 mm) able to sustain the test pressure in the tank.

Results and Discussion

Von Mises Stress and Displacement of Standard Type 1 CNG Tank

Based on Type 1 CNG cylinder tank (Model CNP20-30-279A), manufactured by Wuxi Banner Vessel Co. Ltd., dimension of the tank been constructed in ABAQUS such previous simulation work in mesh convergence analysis. Model CNP20-30-279A has a capacity of 30 Litre with an outside diameter of 279 mm, height of the tank is 680 mm and 6.4 mm wall thickness. The mechanical properties of its material, 34CrMo4 extracted from Sajadi [13], which a value of 200GPa (200000N/mm^2) and 0.3 for the modulus elasticity and Poisson ratio will commonly use in simulation. The simulation have been proceeded by using different pressures of 30 MPa (minimum test pressure) and 45 MPa (minimum burst pressure) to find the maximum stress and displacement occurred on its surface. The Maximum Von Mises stress and displacement occurred due to the both pressure (30 MPa and 45 MPa) compared to material yield strength (800 MPa @ N/mm^2) and allowable minimum elongation (11% of wall thickness). As a result, 300 Bar Test Pressure generated 744.1 N/mm^2 maximum stress in the inside surface of standard tank and the displacement of the surface tank reach a maximum value of 0.4186 mm, which is below than yield strength for 34CrMo4 and a minimum elongation for designated wall thickness (11% of 6.4 mm). However, 450 Bar Burst Pressure generated 1116 N/mm^2 maximum stress in the inside surface of the standard tank, greater than yield strength for 34CrMo4 (800 N/mm^2), vice versa it's still below than maximum tensile strength (1200 N/mm^2). The displacement of the surface tank reaches a maximum value of 0.6279 mm, below than a minimum elongation for designated wall thickness (11% of 6.4 mm). Subsequently, those values will be set as reference datum for a following analysis, where the maximum stress and maximum displacement values will be generated by the conceptual designed tank should be lower than those values.

Elliptical Tank Aspect Ratios

Analysis of elliptical tank aspect ratios is important to determine suitable major axis and minor axis of the conceptual elliptical tank, Wang [18] on his research found that elliptical tank aspect ratio values contributed to the maximum stresses on the elliptical tank. As defined by Wang [18] on equation 1 (shown in **Figure 1**), for the elliptical tank, Aspect Ratio, a/b is equal to the major axis radius dividing by minor axis radius of the tank.For 30 N/mm^2 Test Pressure ABAQUS analysis, the boundary condition was set at the both ends of the elliptical tank (without considering both of semi-ellipsoidal head at the ends of the tank). Thus, the meshing was set at global size 5, which is envisioned to generate the exact result of analysis. The allocated space area in vehicle's trunk space has taken into account while prescribing the elliptical tank dimension for aspect ratios (1.5, 2, 2.5, 3 and 4), where its capacity remain 30 Litre as shown in **Table 2.** As a result, for the same capacity (30 Litre), the maximum stress on the elliptical tank increased due to the rising of aspect ratios. **Figure 2 and Figure 3** shown aspect ratio 2 generated the lowest maximum stress and the lowest displacement for the elliptical tank while simulated on the test pressure (30 N/mm^2).

Table 2: Result for analysis of elliptical tank aspect ratios

Aspect ratio, r_1/r_2	**1.5**	**2**	**2.5**	**3**	**4**
Major axis radius, r_1	270	420	420	420	450
Minor Axis radius, r_2	180	210	168	140	112.5
Height, h	960	480	620	800	960
Thickness, t	6	6	6	6	6
Capacity, Litre	30	30	30	30	30
Test Pressure, N/mm^2	30	30	30	30	30
Global Size	5	5	5	5	5
Number of Element	30720	21480	27032	32640	70500
Von Mises Stress, N/mm^2	9778	5098	12100	29400	78010
Displacement, U (mm)	82.7	23.22	65.2	187.4	3638

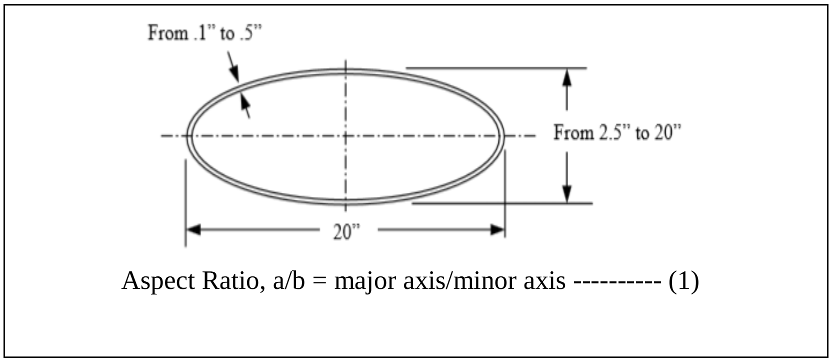

Figure 1: Elliptical Tank Aspect Ratios

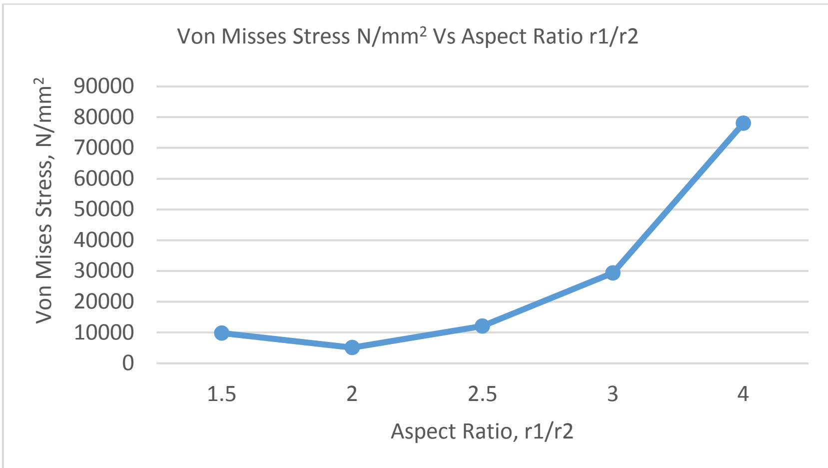

Figure 2: Result of Aspect Ratio analysis - The Von Mises stress

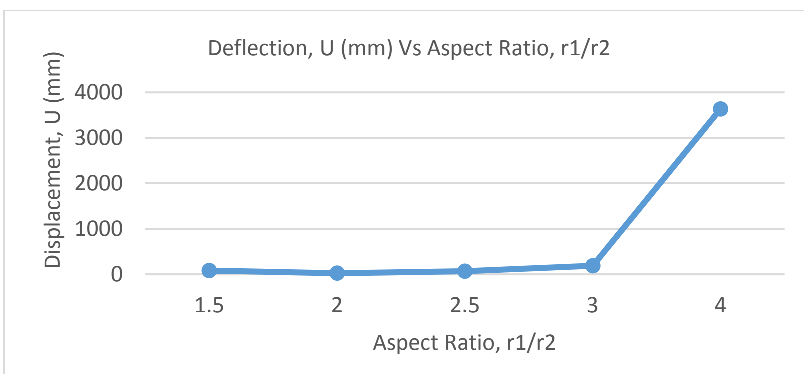

Figure 3: Result of Aspect Ratio analysis – Displacement, U (mm)

Tank Reference Analysis and Result

Analysis on initial design parameter conducted for a basic elliptical tank to gain basic picture on area that need to improvise for the conceptual elliptical tank design. Based on aspect ratio analysis, 30 Litre elliptical tank with aspect ratio of 2 been referred, for a simulation with a different thickness of the tank wall, which is a minimum 6 mm thick (below than current standard CNP20-30-279A CNG tank) and 8 mm thick (maximum thickness for the group ($3<t\leq 8$ mm) of 34CrMo4 plate, Sajadi [13]) and maximum 10 mm thick (thickness for the group ($8<t\leq 20$ mm) of 34CrMo4 plate, Sajadi [13]). Using ABAQUS, the end part of the elliptical tank were removed and boundary condition was set at the both ends. The material applied was 34CrMo4 with elastic modulus of 200Gpa (200000 N/mm^2) and Poisson ratio of 0.3, which is the same material for the current standard CNP20-30-279A CNG tank. This analysis will proceed with

30 MPa (N/mm^2) Test Pressure and 45 MPa (N/mm^2) Burst pressure to determined maximum stress and displacement occurred in the tank surface. This simulation has applied test pressure (30 N/mm^2) and burst pressure (45 N/mm^2) on the elliptical tank with aspect ratio of 2, for a different tank shell thickness (6 mm, 8 mm and 10 mm) to generate maximum stress and the maximum displacement as shown in **Table 3.** However, Maximum stress on the tanks was greater than 34CrMo4 yield strength (800 N/mm^2 for the group ($3<t\leq8$ mm) and 650 N/mm^2 for the group ($8<t\leq20$ mm)) as well as maximum stress on reference current standard tank CNP20-30-279A (744.1 N/mm^2 for test pressure analysis and 1116 N/mm^2 for burst pressure analysis). For the test pressure analysis and the burst pressure analysis, the maximum stress on tank with 10 mm shell thickness is lower than 6 mm/ 8 mm shell thickness tank and the maximum displacement also decreased due to the increment of the shell thickness as shown in **Table 3.** Due to the high maximum stress and high maximum displacement of elliptical tank compared to reference current standard tank CNP20-30-279A, a stiffener should be added to elliptical tank to increase the strength of the tank and also decreasing the maximum displacement on the surface of the tank. The critical area should be concerned in this study is on the curve of major axis of the tank, where predicted area as conclude by Wang [18] on his paper 'Stress Analysis of an Elliptical Pressure Vessel under Internal Pressure'.

Table 3: Result of the elliptical tank (aspect ratio 2) analysis (reference)

	Shell Thickness, t = 6 mm		**Shell Thickness, t = 8 mm**		**Shell Thickness, t = 10 mm**	
Pressure, P	Von Misses Stress, (N/mm^2)	Displacement, U (mm)	Von Misses Stress, (N/mm^2)	Displacement, U (mm)	Von Misses Stress, (N/mm^2)	Displacement, U (mm)
Test Pressure 300 Bar (30 N/mm^2)	5098	23.22	3857	11.74	2560	10.47
Burst Pressure 450 Bar (45 N/mm^2)	7647	238	5785	17.61	3840	15.71

Elliptical Tank Concept

The simulation analysis been proceed for a main stiffener on the elliptical tank with a different type of main stiffener and its location inside internal area of the tank. Theoretically, the additional main stiffener will increase the rigidity of the tank structure by increasing the moment inertia of the combined section. Three different types of main stiffener were created and the part will be a constraint on the inner surface of the tank. Furthermore, additional stiffener has been introduced to reduce hoop stress generated by internal pressure in the elliptical tank.

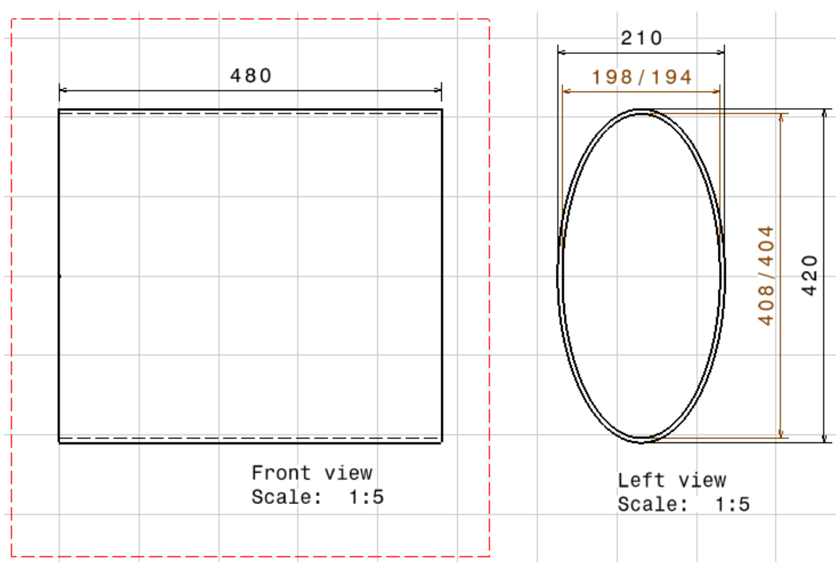

Figure 4: Basic dimension for elliptical tank

Table 3: Geometries dimension for elliptical tank with stiffener

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Major Axis, a (mm)	420	420	420	420	420	420
Minor Axis, b (mm)	210	210	210	210	210	210
Height, h (mm)	480	480	480	480	480	480
Aspect Ratio, a/b	2	2	2	2	2	2
Tank's Shell Thickness, (mm)	6/8/10	6/8/10	6/8/10	6/8/10	6/8/10	6/8/10
Number of Stiffeners	1	2	3	3	3	3
Number of Additional Stiffeners	0	0	0	10	10	30
Stiffener's thickness, (mm)	8	8	8	8	8	8

Result of Conceptual Design Analysis

Concept 1: Single Steel Plate (Thickness = 8 mm)

This concept of stiffener is applying 8 mm steel plate on the middle of internal surface of elliptical tank (major axis). By using an elliptical tank with a different shell thickness (6 mm and 8 mm), this concept of stiffener has been analyzed to look at the effect of stiffener on the maximum stress and the maximum displacement generated by test pressure (30 N/mm^2) and burst pressure (45 N/mm^2). Based on simulation on 6 mm shell thickness elliptical tanks due to test pressure (30 N/mm^2), maximum stress in an internal surface of the tank decreased 25% compared to basic elliptical tank. While, the maximum displacement on its surface decreased 39.2% compared to the basic elliptical tank as shown in **Table 4 & 5.** The stiffener location indirectly produces a critical point area of stress on the curve at the end of the ellipse major axis shown on **Figure 6**.

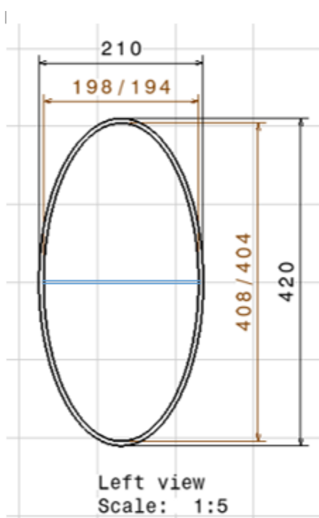

Figure 5: The elliptical tank with single stiffener

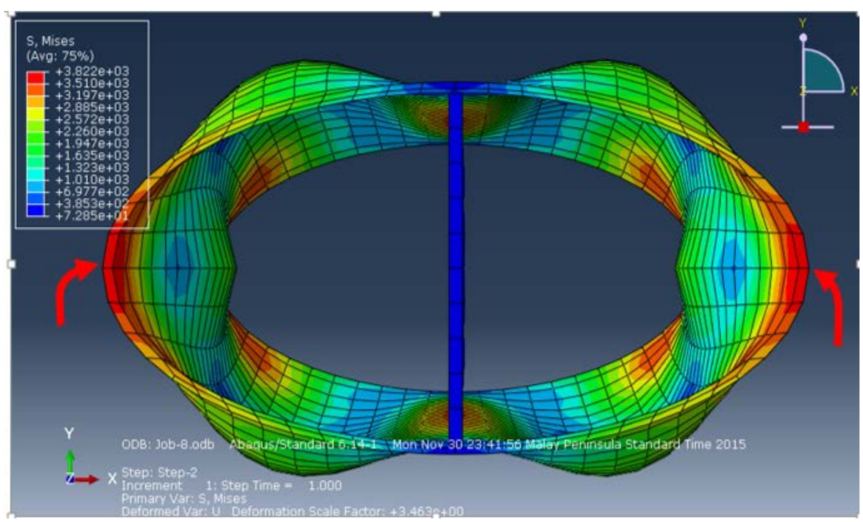

Figure 6: Stress critical point area of concept 1: single stiffener (test pressure, 6mm shell thickness)

Concept 2: Two Steel Plate (Thickness = 8 mm)

Concept 2 stiffener comprise two of 8 mm steel plate, which located 100 mm from the center of the elliptical tank **(Figure 7).** By using an elliptical tank with a different shell thickness (6 mm and 8 mm), this concept of stiffener has been analyzed to look at the effect of stiffener on the maximum stress and the maximum displacement generated by test pressure (30 N/mm^2) and burst pressure (45 N/mm^2). Based on simulation, due to the burst pressure (45 N/mm2) on the elliptical tanks with shell thickness of 8mm, maximum stress in an internal surface of the tank decreased 42% compared to basic elliptical tank. While, the maximum displacement on its surface increased

0.04% compared to the basic elliptical tank as shown in **Table 4 & 5.** Throughout this analysis, the stiffener indirectly produces a critical point area of stress on the curve at the end of the ellipse minor axis as shown on **Figure 8.** The location of its critical point area occurred on the middle the tank, where is totally different from the previous analysis on Concept 1: single stiffener.

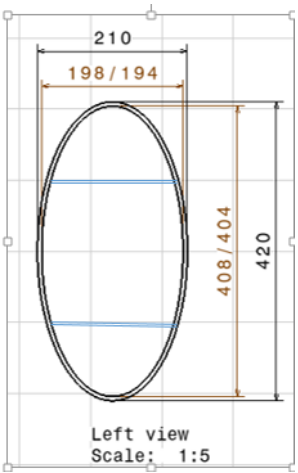

Figure 7: The elliptical tank with 2 stiffeners

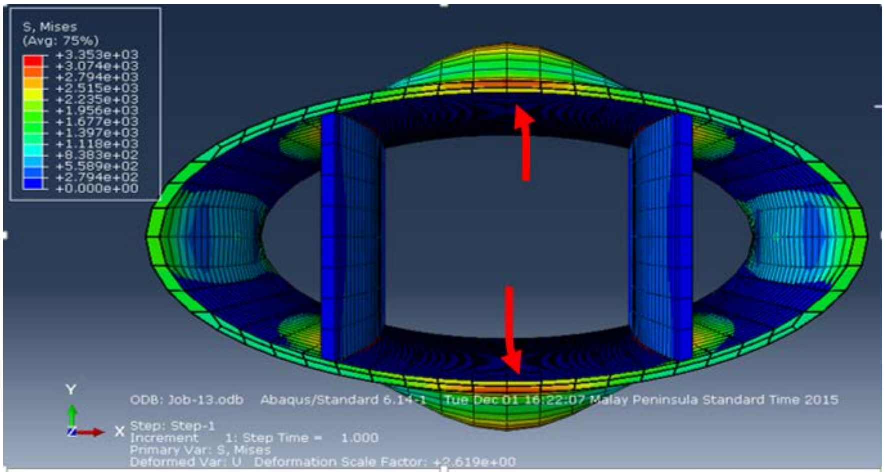

Figure 8: Stress critical point area of concept 2: two stiffener (burst pressure, 8 mm shell thickness)

Concept 3: Three Steel Plate (Thickness = 8 mm)

Concept 3 stiffener comprise three of 8 mm steel plate, which is combination of concept 1 stiffener and concept 2 stiffener **(Figure 9).** By using an elliptical tank with a different shell thickness (6 mm and 8 mm), this concept of stiffener has been analysed to look at the effect of stiffener on the maximum stress and the maximum displacement generated by test pressure (30 N/mm^2) and burst pressure (45 N/mm^2). Based on simulation on 8 mm shell thickness elliptical tanks due to test pressure (30 N/mm^2), maximum stress in an internal surface of the tank decreased 67.7% compared to basic elliptical tank. While, the maximum displacement on its surface decreased 53.8% compared to the basic elliptical tank as shown in **Table 4 & 5.** The combination of previous concept of stiffener produces a critical point area of stress on the curve at the end of the ellipse major axis shown on **Figure 10.** Thus, the next analysis will focus on the critical point area for enhancing the strength of the elliptical tank.

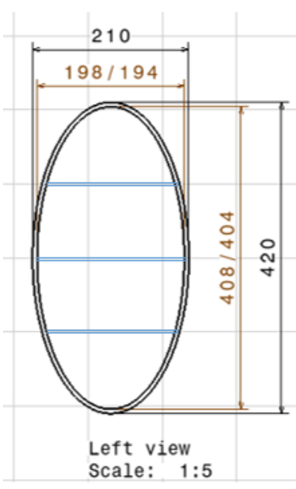

Figure 9: The elliptical tank with 3 stiffeners

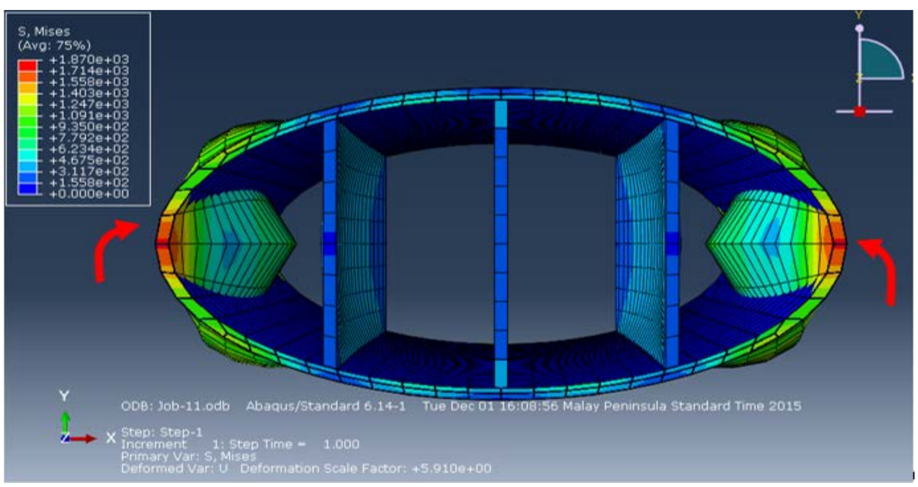

Figure 10: Stress critical point area of concept 3: three stiffener (test pressure, 8 mm shell thickness)

Concept 4: Three Steel Plate and Type 1 Additional Stiffeners (Width = 20 mm, Thickness = 8 mm)

By using concept 3 stiffener comprise three of 8 mm steel plate, 10 pieces of 20 mm width additional stiffener (illustrated as **Figure 11**) tied on the tank internally at the end of the major axis curve, which is a critical point area of the tank. Due to test pressure (30 N/mm^2)

on 6 mm elliptical tank, the additional stiffener reduces 8.5% of maximum stress in the tank structure compared to the elliptical tank with concept 3 stiffener. Beside, maximum displacement on the tank surface decreased 73.7%. The type 1: additional stiffener on the 8 mm elliptical tank affects the maximum stress and the maximum displacement generated by the burst pressure (45 N/mm^2) as shown on **Table 4 & 5.** Due to the burst pressure, the maximum stress has been decrease 5.13% compared to the elliptical tank with concept 3 stiffener, as well as maximum displacement on the tank surface decreased 81.3%. The concept 4 stiffener effectively reducing maximum displacement on the tank due to the internal pressure applied.

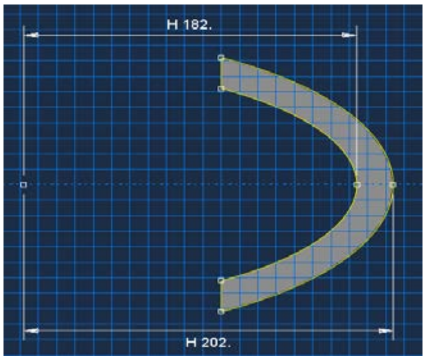

Figure 11: Type 1 Additional stiffener for elliptical tank (thickness = 8 mm, width = 20 mm)

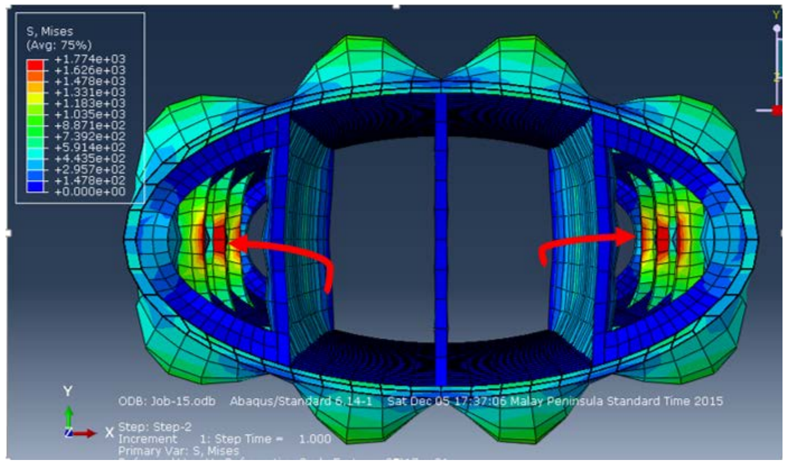

Figure 12: Stress critical point area of Type 3: three stiffener with Type 4 additional stiffener (burst pressure, 8 mm shell thickness)

Concept 5: Three Steel Plate and Type 2 Additional Stiffeners (Width = 40 mm, Thickness = 8 mm)

Type 2 additional stiffener was an extension of the width stiffener to 40 mm instead of 20 mm in the previous design. The extension of the width is to study its effect on the maximum stress and the maximum displacement resulting in the tank due to internal pressure. Due to test pressure (30 N/mm^2) on 8 mm the elliptical tank, the additional stiffener reduces 23% of maximum stress in the tank structure compared to the elliptical tank with Concept 3 stiffener. Beside, maximum displacement on the tank surface decreased 80%. The value of maximum stress on this combination of stiffeners approaching the yield strength of the 34CrMo4 (800 N/mm^2).

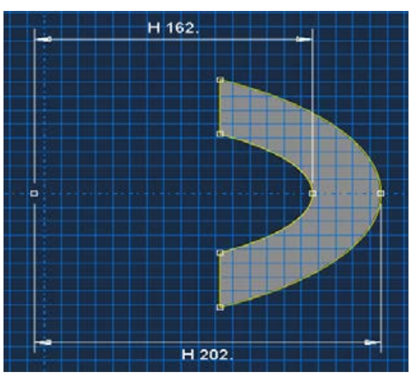

Figure 13: Type 2 Additional stiffener for elliptical tank (thickness = 8 mm, width = 40 mm)

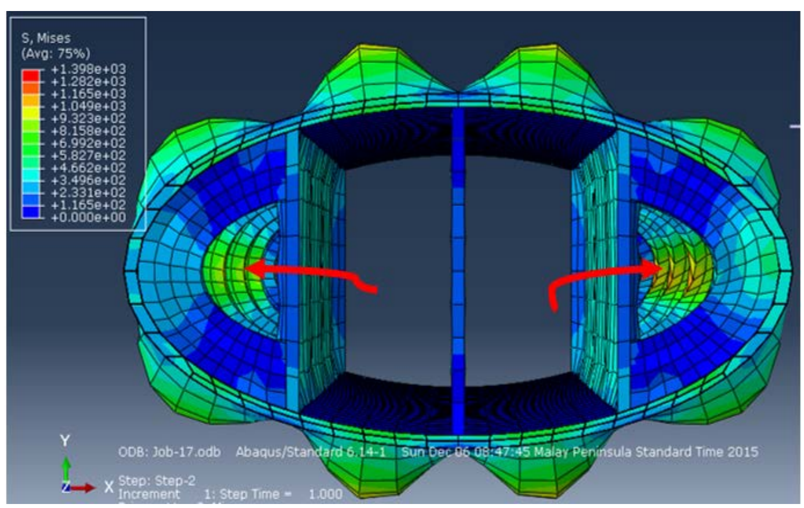

Figure 14: Stress critical point area of Type 3: three stiffener with Type 5 additional stiffener (burst pressure, 8 mm shell thickness)

Concept 6: Three Steel Plate, Type 2 Additional Stiffeners and Type 3 Additional Stiffeners (Width = 40 mm, Thickness = 8 mm)

This concept is combination of steel plate, type 2 and type 3 additional stiffeners inside the elliptical tank to reduce maximum stress and maximum displacement on its surface. Based on analysis of this concept, test pressure (30 N/mm2) generates 948.2 N/mm2 of maximum stress, which is only 0.2% below than maximum stress being generated on concept 5. However, the maximum displacement on this concept reduce 31.5% compared to the concept 5.

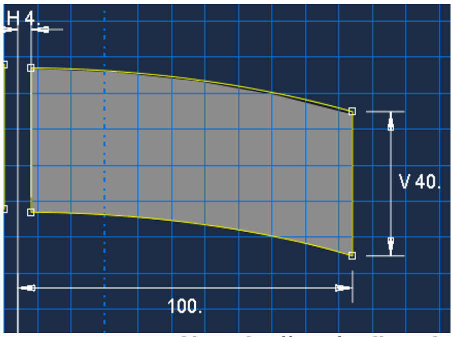

Figure 15: Type 3 Additional stiffener for elliptical tank (thickness = 8 mm, width = 40 mm)

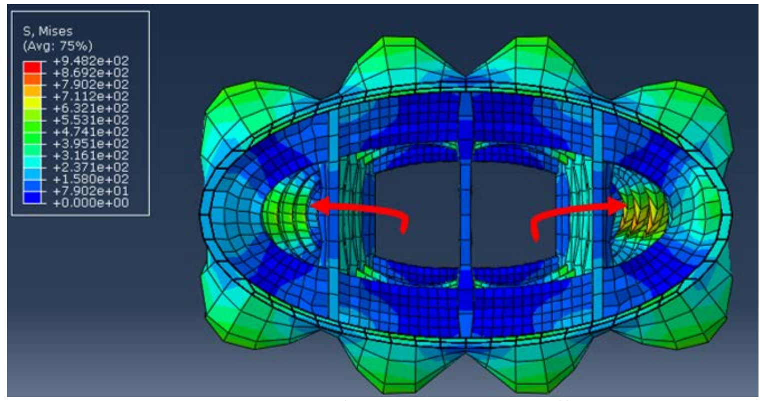

Figure 16: Stress critical point area of 10 Type 2 additional stiffeners and 20 Type 3 additional stiffeners (test pressure, 8 mm shell thickness)

Obviously, the combination of steel plate longitudinally attached on internal tank surface as concept 3 effectively reducing the maximum stress generated by internal pressure in the elliptical tank. Whereas, type 2: additional stiffener seems more capable to sustain the elliptical tank with reducing maximum displacement of the surface. Thus, the combination of three steel plates as a main stiffener and type 2: additional stiffeners as concept 5 stiffener will be my further analysis on this paper.

Table 4: Result of the elliptical tank (aspect ratio 2) analysis (6 mm)

		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Test Pressure 300 Bar (30 N/mm^2)	**Von Misses Stress, (N/mm^2)**	3822	3016	1762	1612	1536	1319
	Displacement, U (mm)	14.11	19.28	8.043	2.112	2.198	1.057
Burst Pressure 450 Bar (45 N/mm^2)	**Von Misses Stress, (N/mm^2)**	5732	4524	2642	2257	2299	1381
	Displacement, U (mm)	21.16	28.92	12.06	3.146	2.679	1.584

Table 5: Result of the elliptical tank (aspect ratio 2) analysis (8 mm)

		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Test Pressure 300 Bar (30 N/mm^2)	**Von Misses Stress, (N/mm^2)**	2763	2235	1247	1180	**950.5**	948.2
	Displacement, U (mm)	9.659	12.22	5.415	1.01	**1.072**	0.7342
Burst Pressure 450 Bar (45 N/mm^2)	**Von Misses Stress, (N/mm^2)**	4144	3353	1870	1774	1398	1033
	Displacement, U (mm)	14.49	18.33	8.122	1.515	1.607	1.10

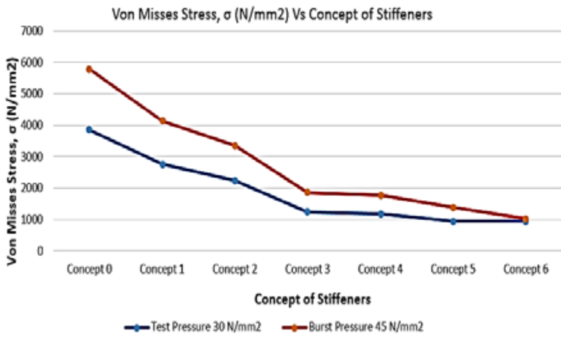

Figure 17: Comparison of Maximum Stress

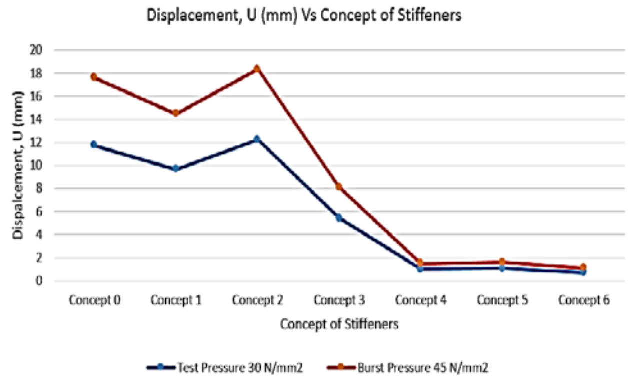

Figure 18: Comparison of Maximum Displacement

Optimization Process

The Concept 5 of the elliptical tank was further being optimized according to its simulation result. Basically, the optimization process involved changing of the main stiffeners and the additional stiffeners. Firstly, the shell thickness be retained on 8 mm, because 8 mm was the maximum shell thickness in its group and the mechanical properties of material such as yield strength and minimum elongation will change above that value (refer to Sajadi [13]). Initially, the optimization process mainly focuses on the main stiffeners and the additional stiffeners of the concept 5 elliptical tank to get better results on the maximum stress and the maximum displacement. However, the optimization process on the main stiffeners and the additional stiffeners fail to reduce the maximum stress and maximum displacement below the material yield strength. Consequently, for the next optimization process involved changing the shell tank thickness to reduce the maximum stress and maximum displacement of the tank. The shell thickness of the concept 5 tank was changed to 9 mm and being simulated. The process was being repeated with 1 mm increment of the shell tank thickness up maximum of 10 mm thickness.

Optimization of Shell Tank

As discussed above, the shell thickness of the Concept 5 elliptical tank was changed to 9 mm and being simulated. The process was being repeated with 1 mm increments of the shell tank thickness up maximum of 10 mm thickness. Sajadi [13], the yield strength value for the 9 mm shell thickness elliptical tank and above, was decreased to 650 N/mm^2, which below than the yield strength of 8 mm shell thickness elliptical tank (800 N/mm^2). **Table 6** show the result of optimization process for the tank shell thickness, which is **the suitable value for the shell thickness was 10 mm** instead of 8 mm according to its maximum stress value. Based on simulation on 10 mm shell thickness tank, test pressure (30 N/mm^2) generates 628.9 N/mm^2 as the maximum stress in the tank, which is below than the yield strength value for 34Crmo4. Furthermore, the maximum displacement on its surface was decreased to 0.6892 mm, below than 12% of its shell thickness (1.2 mm). Simultaneously, burst pressure (45 N/mm^2) generates 943 N/mm^2 maximum stress and 1.034 mm as the maximum displacement on its surface. Thus, 10 mm shell thickness tank was the suitable value for the elliptical tank design. While, the combination of 3 main stiffeners and 10 additional stiffeners was effectively reduced the maximum stress and maximum displacement generated by internal pressure in the elliptical tank.

Table 6: Result of optimization process on the Shell Thickness (Main Stiffener Thickness, t_{st} = 8 mm, additional stiffener thickness, ta_{st} = 8 mm)

	Test Pressure 300 Bar (30 N/mm^2) Main Stiffeners Thickness, t_{st} = 8 mm Additional Stiffener Thickness, t_{ast} = 8 mm		**Burst Pressure 450 Bar (45 N/mm^2)** Main Stiffeners Thickness, t_{st} = 8 mm Additional Stiffener Thickness, t_{ast} = 8 mm	
Shell Thickness, t_s (mm)	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**
8	950.5	1.072	1398	1.607
9	751.5	0.8088	1127	1.214
10	**628.9**	**0.6892**	**943**	**1.034**

Optimization of Main Stiffeners

For the next optimization process, the thickness of three steel plate was changed to 9 mm and being simulated. The process was being repeated for 1 mm increments of the steel plate thickness up to a maximum of 11 mm thickness. Following that, simulation process will apply test pressure and burst pressure to generate maximum stress and maximum stress in the elliptical tank. Based on **Table 7,** the increment of the main stiffener thickness value increases the maximum stress on the 8 mm tank shell thickness. Thus, the process being repeated by using different values of the shell tank thickness (9 mm and 10 mm). Based on simulation result data, the most suitable thickness of steel plate as the main stiffener for the tank has been identified during analysis on 10 mm shell thickness (refer to **Table 9**). **The suitable value for the main stiffeners thickness was 8 mm** instead of 10 mm because the maximum displacement of the tank increased due to increment of the main stiffener thickness. The increment of the maximum displacement of the tank cannot be tolerated because the increment of the main stiffener thickness contributed to the total volume and the weight of the tank.

Table 6: Result of optimization process on the Shell Thickness (Main Stiffener Thickness, t_{st} = 8 mm, additional stiffener thickness, ta_{st} = 8 mm)

	Test Pressure 300 Bar (30 N/mm^2) Shell Thickness, **t_s** = 8 mm Additional Stiffener Thickness, t_{ast} = 8 mm		**Burst Pressure 450 Bar (45 N/mm^2)** Shell Thickness, **t_s** = 8 mm Additional Stiffener Thickness, t_{ast} = 8 mm	
Main Stiffeners Thickness, t_{mst} (mm)	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**
8	950.5	1.072	1398	1.607
9	951.3	1.038	1381	1.557
10	954.8	1.079	1364	1.618
11	958.3	0.9684	1332	1.445

Table 8: Result of optimization process on the main stiffeners thickness (Shell Thickness, t_s = 9 mm, Additional Stiffener Thickness, t_{ast} = 8 mm)

	Test Pressure 300 Bar (30 N/mm^2) Shell Thickness, **t_s** = 9 mm Additional Stiffener Thickness, t_{ast} = 8 mm		**Burst Pressure 450 Bar (45 N/mm^2)** Shell Thickness, **t_s** = 9 mm Additional Stiffener Thickness, t_{ast} = 8 mm	
Main Stiffeners Thickness, t_{mst} (mm)	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**
8	751.5	0.8088	1127	1.214
9	741.7	0.7784	1112	1.168
10	733.0	0.7473	1096	1.121
11	735.2	0.7206	1080	1.078

Table 9: Result of optimization process on the main stiffeners thickness (Shell Thickness, t_s = 10 mm, Additional Stiffener Thickness, t_{ast} = 8 mm)

	Test Pressure 300 Bar (30 N/mm^2) Shell Thickness, **t_s** = 10 mm Additional Stiffener Thickness, t_{ast} = 8 mm		**Burst Pressure 450 Bar (45 N/mm^2)** Shell Thickness, **t_s** = 10 mm Additional Stiffener Thickness, t_{ast} = 8 mm	
Main Stiffeners Thickness, t_{st} (mm)	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**
8	**628.9**	**0.6892**	**943**	**1.034**
9	624.3	0.6952	932.4	1.043
10	619.8	0.7034	924.7	1.055
11	624.2	0.7064	931.7	1.059

Optimization of Additional Stiffeners

The thickness of additional stiffeners has been through the same optimization process as the main stiffeners. In this process, the thickness of 10 additional stiffeners was changed to 9 mm and being simulated. The process was being repeated for 1 mm increments of the additional stiffeners thickness up to a maximum of 11 mm thickness. Based on simulation result data, **the suitable value for the additional stiffener thickness was 8 mm** for the same reason as the main stiffener analysis. Besides, the increment of the additional stiffener thickness was not much contribute to reduce the maximum stress and the maximum displacement.

Table 10: Result of optimization process on the additional stiffener thickness (Shell Thickness, t = 8 mm, Main Stiffener Thickness, t_{st} = 8 mm)

	Test Pressure 300 Bar (30 N/mm^2) Shell Thickness, t_s = 8 mm Main Stiffeners Thickness, t_{st} = 8 mm		**Burst Pressure 450 Bar (45 N/mm^2)** Shell Thickness, t_s = 8 mm Main Stiffeners Thickness, t_{st} = 8 mm	
Additional Stiffener Thickness, t_{ast} (mm)	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**	**Von Misses Stress, (N/mm^2)**	**Displacement, U (mm)**
8	**950.5**	**1.072**	**1398**	**1.607**
9	933.6	1.076	1400	1.614
10	933.7	1.077	1401	1.638
11	933.3	1.077	1400	1.616

As a conclusion, from the simulation of **the Concept 5 elliptical tank** with the combination of the shell tank thickness of 10mm, 8 mm main stiffeners and 8 mm additional stiffeners can reduce 75.4% of maximum stress as well as 93.4% of deflection on its surface compared the basic 10 mm elliptical tank (without stiffeners). However, the shell tank thickness has been enlarged to 10mm, which is greater than the current cylinder tank thickness to reduce the maximum stress below than the yield strength of 34Crmo4. The maximum stress generated at the test pressure (30 MPa @ N/mm^2) was only 628.9 N/mm^2 with 0.6892 mm deflection. Whereas, the burst pressure (45 MPa @ N/mm^2) generates 943 N/mm^2 and 1.034 mm deflection on its surface. Thus, the comparison of the elliptical tank and the current cylinder tank (CNP20-30-279A) summarized as below:

<u>At Test Pressure (30 N/mm^2)</u>

Maximum Stress:

Max. Stress < Max. Stress of current cylinder tank (CNP20-30-279A)
628.9 N/mm^2 < 744.1 N/mm^2

Max. Stress < yield strength (8mm<t<20mm, 34CrMo4)
628.9 N/mm^2 < 650 N/mm^2

Maximum Displacement:

Max. Displacement > Max. Displacement of current cylinder tank (CNP20-30-279A)
0.6892 mm > 0.4186 mm

Max. Displacement < Max. Displacement (12% of the shell thickness)
0.6892 mm < 1.2 mm

<u>At Burst Pressure (45 N/mm^2)</u>

Maximum Stress:

Max. Stress < Max. Stress of current cylinder tank (CNP20-30-279A)
943 N/mm^2 < 1116 N/mm^2

Max. Stress < yield strength (8mm<t<20mm, 34CrMo4)
943 N/mm^2 < 650 N/mm^2

Maximum Displacement:

Max. Displacement > Max. Displacement of current cylinder tank (CNP20-30-279A)
1.034 mm > 0.6279 mm

Max. Displacement < Max. Displacement (12% of the shell thickness)
1.034 mm < 1.2 mm

Conclusion

Initially, this conceptual design of the NGV/ CNG elliptical tank being developed to minimize the use of vehicle‘s storage space and allowing for under chassis installation. This design uses a fully 34CrMo4 steel (see NGV/ CNG cylinder tank type 1) as a material to reduce the cost of the tank. Consequently, the changing of the NGV tank to the elliptical shape instead of the cylindrical tank shape led to drastically increased of the maximum stress and the maximum displacement compared to current cylindrical tank (CNP 20-30-279A). Thus, to maintain the maximum stress and the maximum displacement on the elliptical NGV tank below than permissible values, the following approach has been taken for that purpose, such as:

i. Analysis the effect of Aspect Ratio, r_1/r_2 of the cross-sectional elliptical tank;
ii. Analysis the effect of the shell tank thickness;
iii. Introduction of various types of stiffener and its composition affixed inside the tank.

Finite Element Analysis was employed using ABAQUS to get visualization of the structural behavior due to the test pressure (30 MPa) as well as the burst pressure (45 MPa) acting inside the tank. Based on the result and discussion, the conceptual design of the elliptical tank has been finalized as follow:

i. The aspect ratio, r_1/r_2 for the elliptical tank = 2
ii. The radius for the tank major axis, r_1 = 210 mm
iii. The radius for the tank minor axis, r_2 = 105 mm
iv. The tank length ,h (without ellipsoid head) = 480 mm
v. The radius for the tank ellipsoid, r_3 = 60 mm
vi. The shell tank thickness, t_s = 10 mm
vii. The main stiffeners thickness, t_{mst} = 8 mm
viii. The additional stiffeners thickness, t_{ast} = 8 mm

The conceptual design sustain the test pressure (30 MPa) with the maximum stress generated was **628.9 N/mm^2**, lower than the material yield strength of 650 N/mm^2 (allowable value for the 8<t<20 34CrMo4 steel). Besides, the maximum displacement of **0.6892 mm** due to the test pressure (30 MPa), lower than 1.2 mm (12% of tank shell thickness, allowable value for the 8<t<20 34CrMo4 steel). As a conclusion, the project successful in identifying the conformable shape and size of the NGV storage tank that are less used of vehicle's trunk space, compared to the existing NGV cylinder tank with the same capacity (30 Litre). However, the application of the cheapest material (steel 34CrMo4) has increased total weight of the tank due to the increasing of the tank shell thickness and the use of the stiffeners. In other words, the total weight of the tank can be lightened by using different type of tank which is having varies value of the tank mass to water capacity according to its material.

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