

The Influence of Radius Ratio and Cross Section Ovality on Limit Pressure of LPG Toroidal Tanks

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Abstract

This paper reports a series of finite element study of the influence of radius ratio and cross-section ovality on limit pressure of LPG toroidal tanks. The tanks were modeled for 45 liter water capacity. The influence of radius ratio of 2, 2.5, 3, and 4 were investigated. For every radius ratio, the ovality of cross section range from 0.4 for in-plane ovality to -0.4 for out-of-plane ovality were investigated. Major axis of oval cross-section was from extrados to intrados for in-plane ovality and from crown to crown for out-of-plane ovality. Shell element type was used in the finite element modeling. The material response to loading was assumed elastic-perfectly-plastic. Limit pressure were obtained via nonlinear analysis using Newton-Raphson algorithm and presented in non-dimensional forms. The results show that for in-plane ovality of cross-section, maximum ovality is 0.2 for radius ratio of 2.5, 3, and 4, and 0.16 for radius ratio of 2. For out-of-plane ovality of cross-section, maximum ovality is -0.3 for radius ratio of 2, 3, and 4, but only -0.24 for radius ratio of 2.5. For radius ratio of 2.5, 3, and 4, circular cross-section toroidal tank has a limit pressure greater than those with ovality. Peculiar behavior was found for radius ratio of 2, where cross-section with out-of-plane ovality of -0.2 and -0.3 produced higher limit pressure than of circular cross section. In general, ovality of 0.2 for in-plane and -0.2 for out-of-plane are the maximum ovality that could be developed for further design of a toroidal tank.

Keywords: toroidal tank, limit pressure, in-plane ovality, out-of-plane ovality, elastic-perfectly-plastic

1. Introduction

In order to reduce the oil fuel (BBM) consumption of passenger cars in Indonesia, and also to reduce the Public Service Obligation (PSO) of BBM for Indonesian's people, the Indonesian's government had planned to limit the usage of oil fuel for passenger cars starting from April 1st, 2012. There are three options that has been considered. The first option is not to allow people having car to use PSO oil fuel (*premium kind*) so they have to use *pertamax* kind oil fuel. The second option is to increase the fixed value of PSO oil fuel. This option has been implemented since June 2013. And the third option is by conversion from using oil fuel to using LPG fuel (BBG) for cars.

For long term, the third option, i.e., conversion of BBM to BBG seems to be a proper option. However, to implement this policy, the government has to build infrastructures and technology such as public LPG filling station (SPBU) and also to provide *conversion kit from BBM to BBG* in combustion system. One of the combustion system components that need to be redesigned is fuel storage tank. Storage tank for LPG is a kind of pressure vessel that needs to be designed carefully against burst-type failure. From engineering and economic point of view, a tank having toroidal in shape is very suitable for LPG fuel tank of passenger cars. It can be placed in spare tire position.

The study of static dan dynamic behaviour of toroidal shell had been carried out by many researchers. Free vibration analysisi of two toroidal shell had been carried out by Tzou dan Wang [1] to control the vibration of toroidal shell structure and to enhance its accuracy and reliability. Jiang dan Redekop [2] carried out analysis of static dan dynamic charecteristics of orthotropic toroidal shells of variable thickness and obtained solution based on the shell equations of Sanders-Budiansky. Experimental limit external pressure tests had been carried out on three toroidal tanks by Btachut [3], two of the tanks were fabricated from mild steel by spinning two part of toroidal and welded at its intrados and extrados, while another one was fabricated by welding circumferentially four 90-degree elbows. Stress and strain analysis of LPG toroidal tanks had been carried out by Velickovic [4] using finite element method. Kisioglu [5] is one of few researcher who had carried out investigation on limit pressure of toroidal tank of LPG storage for vehicle in Turkey. Burst pressure test of toroidal tank having oval cross section had been carried out by Kisioglu [6]. Strength design of circular toroidal tank for LPG 3kg was reported by Lubis [7]. Finite element study of the position of radial and non-radial flush nozzles on circular toroidal shell were reported by Lubis, et.al. [8, 9]. To the best of author's knowledge, it was not found in modern literature a comprehensive study of strength design of oval cross section toroidal tanks using for oil fuel tank for passenger cars in Indonesia. This paper reports results of nonlinear finite element analysis of toroidal tank having various oval cross section in term of limit pressure.

2. Finite Element Modeling

The toroidal tanks were modeled for 45 liter water capacity. Effect of radius ratio on limit pressure was studied for 2, 2.5, 3, and 4. For every radius ratio, the influence of cross-section ovality range from 0.4 for in-plane ovality to -0.4 for out-of-plane ovality on limit pressure was studied parametrically. The major axis of oval cross-section was from extrados to intrados for in-plane ovality and from crown to crown for out-of-plane ovality. Table 1 shows the geometry parameter considered. The geometry of a circular toroidal shell is shown in Fig.1.

Table 1. Radius ratio and cross-section ovality

R/r	Cross-section ovality								
2.0	0.4	0.3	0.2	0.1	0.0	-0.1	-0.2	-0.3	-0.4
2.5	0.4	0.3	0.2	0.1	0.0	-0.1	-0.2	-0.3	-0.4
3.0	0.4	0.3	0.2	0.1	0.0	-0.1	-0.2	-0.3	-0.4
3.5	0.4	0.3	0.2	0.1	0.0	-0.1	-0.2	-0.3	-0.4

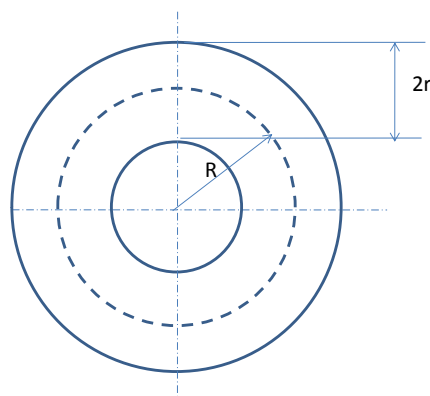


Figure 1. Geometry of a toroidal shell

Volume of a circular toroidal shell can be calculated by the following formula:

$$V = \pi r^2 \cdot 2\pi R = 2\pi^2 r^2 R \quad (1)$$

where, r = radius of cross-section
 R = major radius of toroidal shell

It is common to define a non-dimensional radius ratio ρ , as the ratio of major radius to radius of cross section:

$$\rho = \frac{R}{r} \quad (2)$$

Equation (1) can be further written as

$$V = 2\rho\pi^2 r^3 \quad (3)$$

For toroidal tanks having 45 liter water capacity, the radius of cross-section for radius ratio of 2, 2.5, 3, and 4 are given in Table 2:

Table 2. cross-section radius of toroidal tank having 45 liter water capacity

$\rho = R/r$	2.0	2.5	3.0	4.0
r , mm	104.46	96.97	91.25	82.91

The installation of toroidal tank in passenger cars will be placed in spare tire position. For this reason, various geometries should be available to be chosen. In this study, toroidal tanks having oval cross-section were designed against limit pressure. Limit pressure were examined for various value of radius ratio and ovality. Ovality of cross-section was defined as:

$$\Omega = \frac{2\alpha}{r} \quad (4)$$

where, Ω = ovality of cross-section
 α = radius distortion from circular along extrados
 to intrados

In-plane ovality results in positive radius distortion (major axis of oval cross-section is from extrados to intrados, and vice versa (major axis of oval cross-section is from crown to crown). Table 3 shows radius distortion for every value of ovality:

Table 3 Radius dirtortion of cross section, mm

$\rho = R/r$	$\Omega = 0.4$	0.3	0.2	0.1	0	-0.1	-0.2	-0.3	-0.4
2.0	20.89	15.67	10.45	5.22	0.00	-5.22	-10.45	-15.67	-20.89
2.5	19.39	14.55	9.70	4.85	0.00	-4.85	-9.70	-14.55	-19.39
3.0	18.25	13.69	9.13	4.56	0.00	-4.56	-9.13	-13.69	-18.25
4.0	16.58	12.44	8.29	4.15	0.00	-4.15	-8.29	-12.44	-16.58

The ANSYS SHELL281 element type was chosen in finite element modeling. The element

has six degree of freedom at its node – translation in the x, y, and z direction as well as rotation about the x, y, and z axis. The number of elements in longitudinal and circumferential direction is 180 and 18 respectively. Total number of elements is 3240. In this modeling, nozzle was not included and the tank would exhibits membrane action under internal pressure. Typical finite element model is shown in Figure 2.

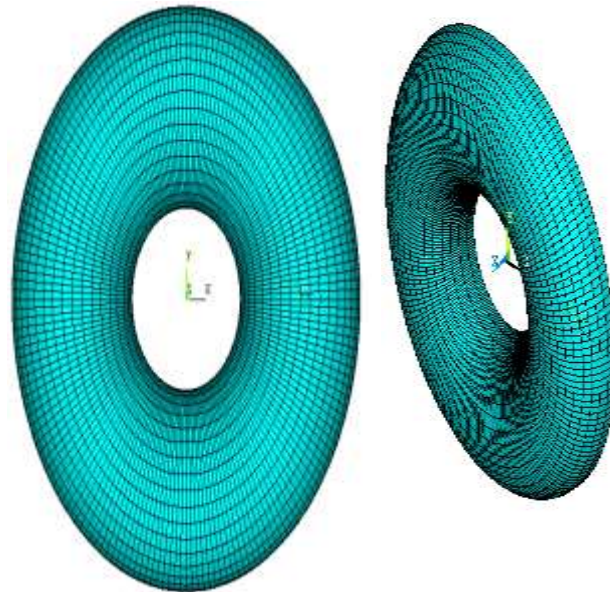


Figure 2. Typical finite element model for a toroidal tank

The advantage of symmetry was taken into consideration in finite element modeling. Boundary conditions were applied such as the shell free to expand in radial direction but restraint in longitudinal direction.

Material properties used in this analysis was the properties of Pertamina LPG 3kg tank used in Indonesian’s household as reported by Winarto and wahyuadi [10]. These are Young’s modulus of 207000 MPa and Yield strength of 295 MPa.

Internal pressure load was applied as ramp load and limit pressure were obtained using the well-known Newton-Raphson algorithm for solution of nonlinear problem. The applied loads were set for 1.5 times p_Y , where p_Y is the pressure to yield for a circular toroidal tank as calculate from equation (5). Table 4 summarizes the pressure to yield as a function of radius ratio ρ . Limit pressure would be expected somewhat above these values.

$$p_Y = \frac{2t\sigma_Y}{r} \frac{\rho - 1}{2\rho - 1} \quad (5)$$

Table 4. pressure to yield for toroidal tanks

$\rho = R/r$	2.0	2.5	3.0	4.0
p_Y , MPa	4.330	5.248	5.948	7.014

3. Results and Discussion

Figure 3 shows non-dimensional limit pressure of toroidal tank having in-plane ovality. They were obtained from the last convergence solution of Newton-Raphson algorithm for non-linear problem and normalized by pressure to yield as given in Table 4. It can be seen that toroidal tank of circular cross-section produced the highest limit pressure and decrease as cross-section becomes oval for every radius ratio. Limit pressure becomes lower than the

pressure to yield for ovality greater than 0.2. Maximum ovality is only 0.16 for radius ratio of 2. Toroidal oval cross-section of radius ratio 2.5, 3, and 4 and maximum ovality of 0.2 can be chosen for further design development.

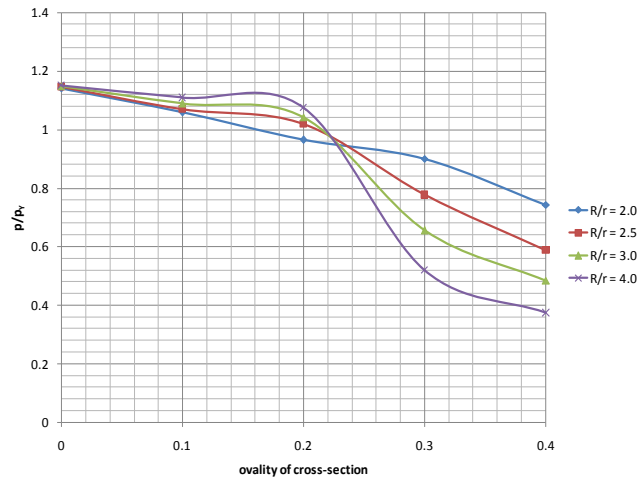


Figure 3. Limit pressure of toroidal tanks having in-plane oval cross-section

Figure 4 shows limit pressure of toroidal tank having out-of-plane oval cross-section. For radius ratio of 2, limit pressure becomes lower than pressure to yield for ovality greater than 0.34. For radius ratio of 2.5, limit pressure becomes lower than pressure to yield for ovality greater than 0.22. For radius ratio of 3 and 4, limit pressures becomes lower than pressure to yield for ovality greater than 0.3. Figure 4 revealed that maximum ovality of 2 would be the best choice for further development of toroidal tank.

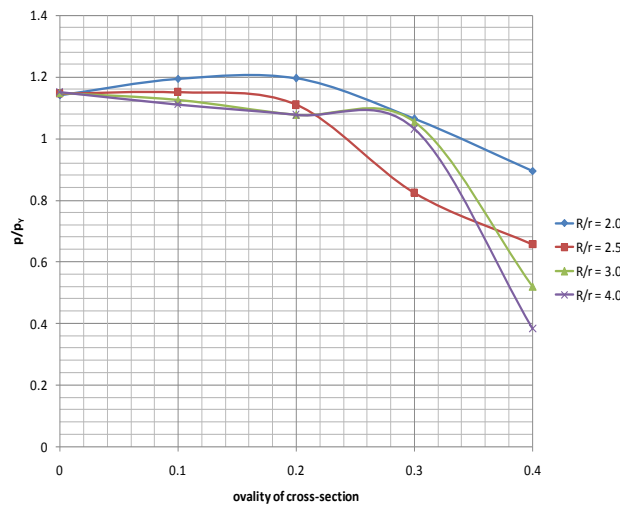


Figure 4. Limit pressure of toroidal tanks having in-plane oval cross-section

Figure 5 shows non-dimensional limit pressure for radius ratio 2, 2.5, 3, and 4. It was plotted to show the effect of ovality orientation. It can be seen in general that toroidal tank having out-of-plane ovality of cross-section stiffer than those of in-plane ovality, indicated by higher limit pressure.

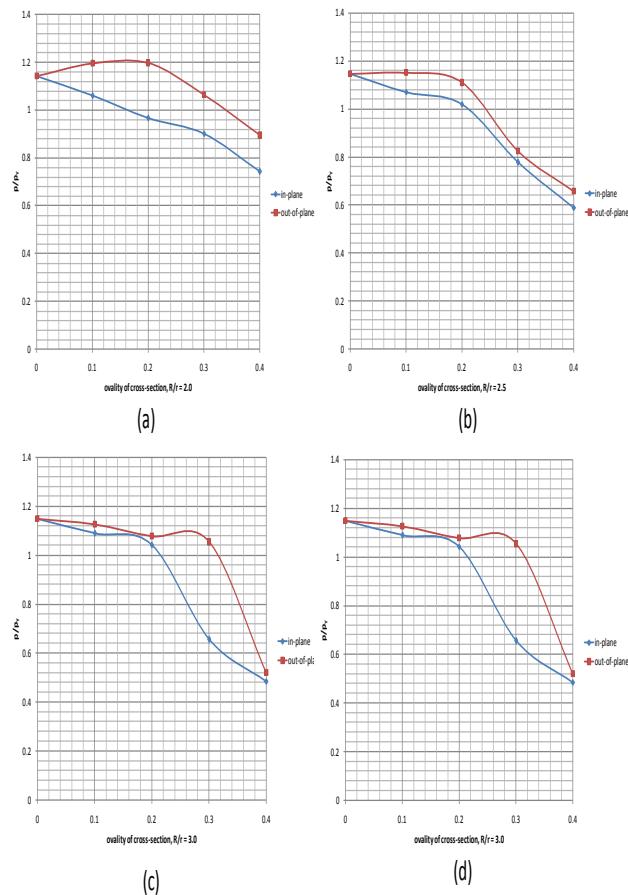


Figure 5. Limit pressure of toroidal tank having in-plane and out-plane ovality of cross section, (a) $R/r = 2$, (b) $R/r = 2.5$, (c) $R/r = 3.0$, and (d) $R/r = 0.4$

4. Conclusion

Finite element study of the limit pressure of toroidal tank having oval cross-section were performed. It can be concluded that toroidal tank having out-of-plane ovality are stronger than those having in-plane ovality and more prominent for very short radius ratio, in this study, 2 and 2.5. Limit pressure were compared to pressure to yield, and by this comparison show that maximum ovality of 2 for all radius ratio would be chosen for further design of toroidal tank. Choosing toroidal tank having out-of-plane or in-plane ovality needs further consideration with main constraint of space available for spare tire in a vehicle. Choosing out-of-plane ovality will reduce ground clearance of a vehicle, while choosing in-plane ovality would need more space. This will be the subject of further study and would be presented elsewhere.

5. Acknowledgement

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