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Analysis on the Influence Factors of Propellant Tank Stress

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Analysis on the Influence Factors of Propellant Tank Stress

T D Xin[1], D P Yang[2,3] and Y S Duan[1]

[1]Space Engineering University, Beijing, 101416, China

[2]Aviation University Air Force, Changchun, 130022, China

[3]Corresponding author: D P Yang, Aviation University Air Force, Changchun, 130022, China.

Email: xyxy0701@163.com

Abstract. The propellant tank is a vital structure for the liquid rocket, and the analysis of influence factors to the propellant tank stress can provide a significant reference to design the propellant tank. Through establishing the ellipsoid cylindrical tank model, the meridian stress and hoop stress distributions of tank roof, cylinder and bottom are analysed. And then the equivalent stress is defined based on the material strength theory. According to the parameters of a certain type tank, the equivalent stresses of tank roof, cylinder and bottom are worked out with different ellipsoidal norms, overload factors, tank radiuses and internal pressurizations, the effects of these influence factors on the tank stress are analysed, and the change laws of tank roof, cylinder and bottom equivalent stresses are determined to provide a reference for the design of propellant tank.

1. Introduction

The propellant tank is not merely used to store the propellant that accounts for about 90% of the launch weight, but the major bearing structure of the liquid rocket. The analysis of the influence factors can provide a reference for the design of propellant tank.

In 1970, Thompson carried out the axial and internal pressure tests to analysis the stress of a certain type propellant tank[1]. In 1993, Ahmed evaluated the strength and buckling performance of tank bottom by comparing the analytical data with the experimental data[2]. And the research reports of the NASA SP-8007[3], TP-218785[4] and TP-219587[5] provide a lot of test data for the structural analysis of the tank. At present, Wyart et al calculated the stress intensity factor of a stiffened plate with a through thickness crack are calculated by using the finite element/extended finite element method[6]. The performance of the tank under elastic and thermoplastic loads is analysed by the means of experiment and finite element analysis[7][8]. Jackson et al analysed, designed and tested the stress of the 2.4m diameter and 5.5m diameter composite cryogenic tank[9]. Zhao, Huang and Wang et al of the state key laboratory for structural analysis of industrial equipment analysed the strength of y-ring of large diameter tank and the stress state of ellipsoid bottom of propellant tank[10][11][12]. These researches provide a significant reference for analysing the influence factors to propellant tank stress.

2. Formulation the equivalent stress

In this section, the ellipsoid cylindrical tank model is established, and then the equivalent stress is determined by analysing the meridian and hoop stress distributions of tank roof, cylinder and bottom. According to the actual force of tank, the tank mathematical model is established （Figure 1）.

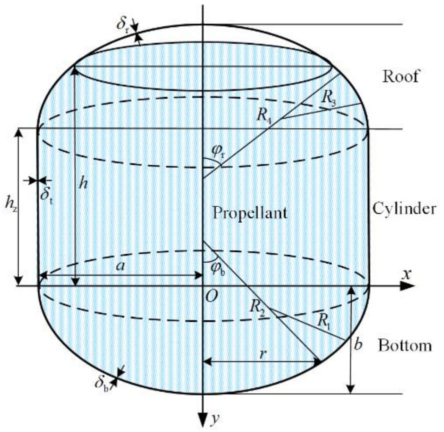

Figure 1. The ellipsoid cylindrical tank model.

where r is the distance between y axis and reference point, b is the height of tank bottom, a is the tank radius, R_1 is the first curvature radius of tank bottom, R_2 is the second curvature radius of tank bottom, φ_{b} is the angle between R_2 and y axis, R_3 is the first curvature radius of tank roof, R_4 is the second curvature radius of tank roof, φ_{r} is the angle between R_4 and y axis, h is the height of liquid level, h_z is the height of tank cylinder, δ_{r}, δ_{t} and δ_{b} are the wall thicknesses of tank roof, cylinder and bottom.

2.1. The stress of tank bottom

According to Figure. 1, we may obtain the elliptic equation of tank bottom generatrix ($0 < y \le b$)

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1, \quad 0 < y \le b \tag{1}$$

The ellipsoidal norm e is the ratio of semi-major axis a to semi-minor axis b . we may obtain

$$\begin{cases} r = x = \left(a^2 - e^2 y^2\right)^{1/2} \\ \sin\varphi_{\mathrm{b}} = \left(\dfrac{a^2 - e^2 y^2}{e^4 y^2 + a^2 - e^2 y^2}\right)^{1/2} \\ R_1 = \dfrac{\left(e^4 y^2 + a^2 - e^2 y^2\right)^{3/2}}{e^2 a^2} \\ R_2 = \left(e^4 y^2 + a^2 - e^2 y^2\right)^{1/2} \end{cases} \tag{2}$$

The mechanical equilibrium equation on y direction can be expressed as

$$\left[P + gn\rho\left(h + y\right)\right]\pi r^2 = \sigma_{\mathrm{b1}} 2\pi r \delta_{\mathrm{b}} \sin\varphi_{\mathrm{b}} \tag{3}$$

where σ_{b1} is the meridian stress of tank bottom, n is the overload factor, g is the gravitational acceleration, ρ is the density of propellant, P is the internal pressurization.

According to equation (3), the σ_{b1} can be obtained

$$\sigma_{\mathrm{b1}} = \frac{\left[P + gn\rho\left(h + y\right)\right] r}{2\delta_{\mathrm{b}} \sin\varphi_{\mathrm{b}}} \tag{4}$$

According to the non-moment theory, the equilibrium equation of tank bottom can be expressed as

$$\frac{\sigma_{\mathrm{b1}}}{R_1} + \frac{\sigma_{\mathrm{b2}}}{R_2} = \frac{P + gn\rho\left(h + y\right)}{\delta_{\mathrm{b}}} \tag{5}$$

where σ_{b2} is the hoop stress of tank bottom.

Using equation (5), the σ_{b2} can be obtained

$$\sigma_{\mathrm{b2}} = \frac{\left[P + gn\rho(h+y)\right]R_2}{\delta_{\mathrm{b}}} - \frac{\sigma_{\mathrm{b1}}R_2}{R_1} \tag{6}$$

2.2. The stress of tank roof

Since the structure of tank roof ($-h_{\mathrm{z}} - b \le y < -h_{\mathrm{z}}$) is same to the structure of tank bottom ($0 < y \le b$), we may obtain

$$R_3 = R_1,\ R_4 = R_2,\ \sin\varphi_{\mathrm{r}} = \sin\varphi_{\mathrm{b}} \tag{7}$$

The elliptic equation of tank roof generatrix is

$$\frac{x^2}{a^2} + \frac{\left(y + h_{\mathrm{z}}\right)^2}{b^2} = 1, \quad -h_{\mathrm{z}} - b \le y < -h_{\mathrm{z}} \tag{8}$$

Similarly, we may obtain when $-h_{\mathrm{z}} - b \le y < -h$, the meridian of tank roof σ_{r1} is

$$\sigma_{\mathrm{r1}} = \frac{PR_4}{2\delta_{\mathrm{r}}} \tag{9}$$

The hoop stress of tank roof σ_{r2} is

$$\sigma_{\mathrm{r2}} = \frac{PR_4\left(2R_3 - R_4\right)}{2\delta_{\mathrm{r}}R_3} \tag{10}$$

When $-h \le y < -h_{\mathrm{z}}$, the meridian stress of tank roof σ_{r1} is

$$\sigma_{\mathrm{r1}} = \frac{R_4\left[P + \rho ng\left(h+y\right)\right]}{2\delta_{\mathrm{r}}} \tag{11}$$

And the hoop stress of tank roof σ_{r2} is

$$\sigma_{\mathrm{r2}} = \frac{\left[P + \rho ng\left(h+y\right)\right]\left(2R_3 - R_4\right)R_4}{2\delta_{\mathrm{r}}R_3} \tag{12}$$

2.3. The stress of tank cylinder

The internal pressurization, axial load and propellant hydraulic pressure are the main forces to tank cylinder ($-h_{\mathrm{z}} \le y \le 0$). The meridian stress of tank cylinder caused by internal pressurization and the axial load is

$$\sigma_{\mathrm{t1}} = \frac{Pa}{2\delta_{\mathrm{t}}} - \frac{Mng}{2\pi a\delta_{\mathrm{t}}} \tag{13}$$

where M is the launch weight.

The hoop stress caused by the internal pressurization and propellant hydraulic pressure can be expressed as

$$\sigma_{\mathrm{t2}} = \frac{\left[P + gn\rho\left(h+y\right)\right]a}{\delta_{\mathrm{t}}} \tag{14}$$

where σ_{t2} is the hoop stress of tank cylinder.

2.4. The equivalent stress of tank

The equivalent stress of tank σ_{e} can be expressed as[13]

$$\sigma_{\mathrm{e}} = \begin{cases} \max\left(\sigma_1, \sigma_2\right) & \sigma_1 > 0, \sigma_2 > 0 \\ \left|\sigma_1\right| + \left|\sigma_2\right| & \text{else} \end{cases} \tag{15}$$

where σ_1 represents the meridian stress, σ_2 represents the hoop stress.

3. The influence factors analysis

According to the parameters of a certain type tank, as shown in table 1, the equivalent stresses of tank roof, cylinder and bottom are analysed with different ellipsoidal norms, overload factors, tank radiuses and internal pressurizations.

Table 1. Parameters of a certain type tank

Parameter	Value	Parameter	Value
e	1.6	a /m	1.6
ρ /kg·m^{-3}	793	h_z /m	6.922
p/Pa	151987	g / m·s^{-2}	9.8
M /t	202	δ_b, δ_t, δ_r /mm	4
h /m	7.5	n	2

3.1. The equivalent stress of tank

According to the Table 1, and when the ellipsoidal norm e are 1.5, 1.6, and 1.7 respectively, the equivalent stresses of tank roof, cylinder and bottom σ_{re}, σ_{te} and σ_{be} on y direction can be worked out, as shown in Figure 2.

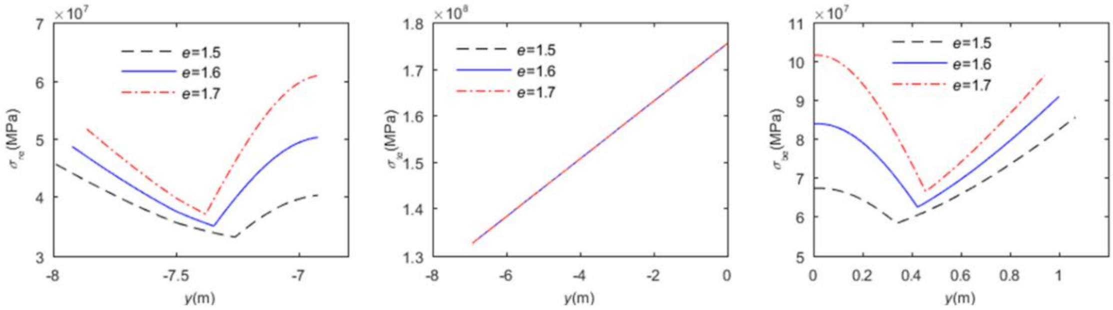

Figure 2. The effect of ellipsoidal norm.

Figure 2 shows that e has no effect on the equivalent stress of tank cylinder. However the equivalent stresses of tank roof and bottom increase with e increasing. And the change rates of tank roof and bottom equivalent stresses increase with e increasing.

3.2. The effect of overload factor

When the overload factor n are 1, 2, and 3 respectively, the σ_{re}, σ_{te} and σ_{be} on y direction can be worked out, as shown in Figure 3.

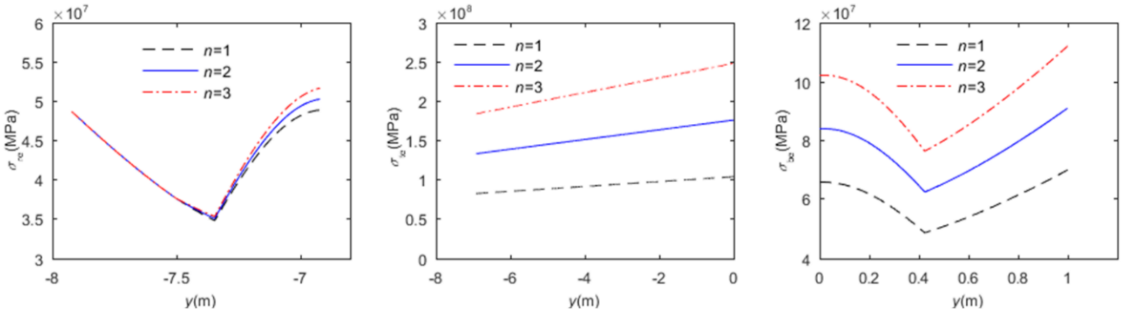

Figure 3. The effect of overload factor.

Figure 3 shows that, n has no effect on the equivalent stress of tank roof no-filling part, however with n increasing the equivalent stress of tank roof filling part increases slightly. And the equivalent stresses of tank cylinder and bottom increase with n increasing.

3.3. The effect of tank radius

When the tank radius a are 1m, 1.669m and 2.338m respectively, the σ_{re} , σ_{te} and σ_{be} on y direction can be worked out, as shown in Figure 4.

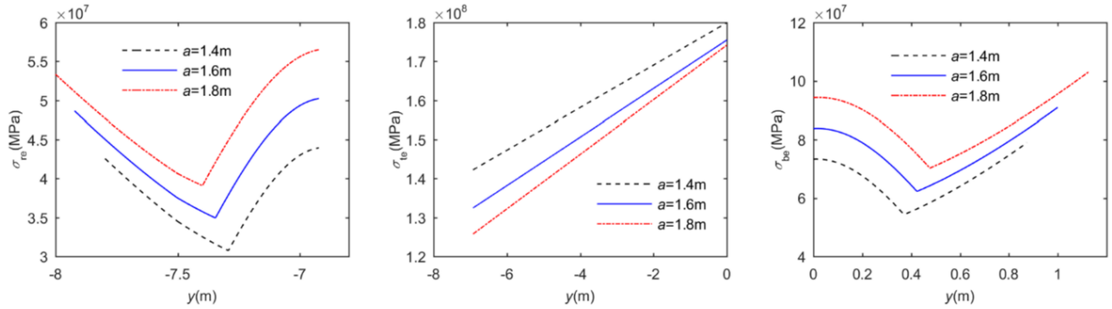

Figure 4. The effect of tank radius.

Figure 4 shows that the equivalent stresses of tank roof and bottom increase, and the equivalent stress of tank cylinder decrease with a increasing. Moreover, the change rate of tank cylinder equivalent stress increases with a increasing.

3.4. The effect of internal pressurization

When the internal pressurization P are 0Pa, 151987Pa and 303974Pa respectively, the σ_{re}, σ_{te} and σ_{be} on y direction can be worked out, as shown in Figure 5.

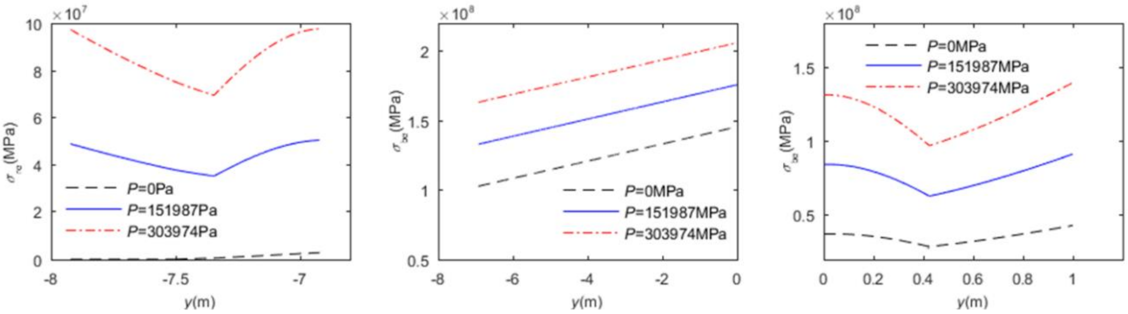

Figure 5. The effect of internal pressurization

Figure 5 shows that, the equivalent stresses of tank roof, cylinder and bottom increase significantly with P increasing, and the change rates of tank roof and bottom equivalent stresses increase with P increasing. However, P has no effect on the change rate of tank cylinder equivalent stress.

4. Conclusion

In this paper, the effects of the influence factors on the propellant tank stress are analyzed, the main conclusions are as follows:

(1) The ellipsoidal norm e has no effect on the stress of tank cylinder, the equivalent stresses of tank roof and bottom increase with e increasing.

(2) The overload factor n has no effect on the equivalent stress of tank roof no-filling part, and the equivalent stress of tank other parts increase with n increasing.

(3) The equivalent stresses of tank roof and bottom increase with the tank radius a increasing. However, the tank cylinder equivalent stress decreases and the change rate of tank cylinder increases with a increasing.

(4) The equivalent stresses of tank roof, cylinder and bottom increase with the internal pressurization P increasing.

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