The Stress Analysis and Design Eva]uation on the Acrylic Vessels in the Neutrino Experiment

C.-Y. Wang, Y. Chang, C.-H. Wang, H.-T. Hu, M.-S. Chen, and Y.-B. Hsiung

***Abstract*– This study calculated the stresses and deformations of the acrylic tanks used in neutrino experiment under dynamic loads and evaluated the safety level of those tanks. The diameters of those large t tanks are φ3m and the thickness of their walls are only 10mm. The measured mechanical properties are: E_B=2.95GPa ±8%, S_Y=77.92 ±7%, S_U= 102.13MPa ±12%. The stress distributions of the tanks were simulated by finite element analysis (FEA) software COMSOL and ABAQUS. The dynamic load conditions are vertical upward and horizontal acceleration pulses. The result shows that empty 3m acrylic tank can at least safely sustain 0.3g acceleration. For a 3m tank filled with liquid, the pressure wave of solid-liquid coupled vibration may destroy the tank without reinforced ribs on top lid**

I. Introduction

The antineutrino detector of the Dayabay experiment[1] comprises one stainless steel tank (D=φ5m, H=5m) and two acrylic tanks. One of the tanks with dimensions, D=φ3m, H=3m is fabricated in Taiwan. Fig. 1 shows the geometry of those tanks. In order to keep high optical quality, the surface of the acrylics should be polished and the thickness should be as thin as possible. The thickness of the peripheral wall of the tank is 10 mm. The finished acrylic tank will be transported to the Dayabay on Shenzhen, China. During the transportation, vibration and impact may cause pulsed load. Acrylic is a brittle and low strength material so that it is quite important for the designer to promise the safety of those large thin-walled tanks during transportation and installation operation.

A typical developing procedure for the design of the detector is shown in Figure 2. The stress level and deformation of each important detector component should be evaluated when the geometry of the component is determined and when the main dimension of the component is changed. When lifting or installation plan is changed, the stress level of the component must be evaluated again to ensure the safety.

The purpose of this paper is to investigate the stress and safety of the acrylic tanks under pulsed acceleration load.

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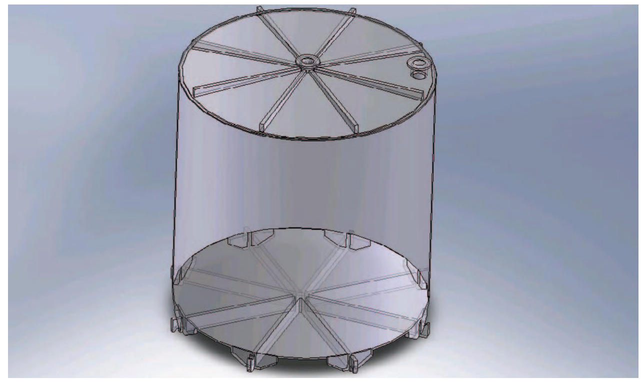

Figure 1. The construction of φ 3m acrylic tank of the anti-neutrino detector in the Dayabay neutrino experiment. This tank is a thin-walled structure.

II. Material properties and Modeling

In Dayabay, the material of two inner tanks of the detector must be transparent for blue-light signal of the wave length around 400 nm. The wall thickness of those tanks should be as thin as possible to minimize the lost of the signal, also for the weight loaded and material costs. Acrylic is the only material that is transparent for the signal and can be glued and polished to fabricate the tanks. However, the strength of acrylic is much lower than that of steel or aluminum and few studies have been done regarding the design and fabrication on large thin-walled acrylic vessel. Hence, all design on the acrylic tanks should be evaluated by experiments and finite element analysis (FEA).

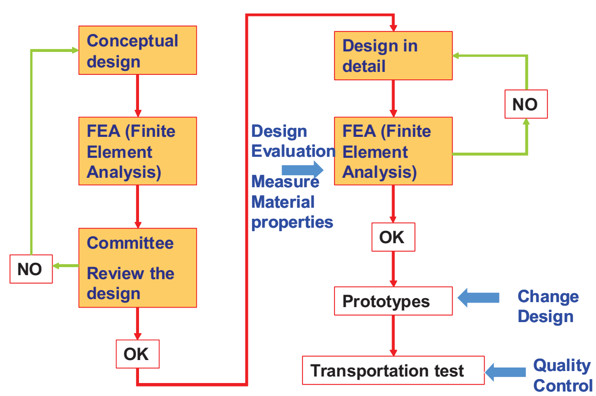

Figure 2. The developing procedure for the detector .components

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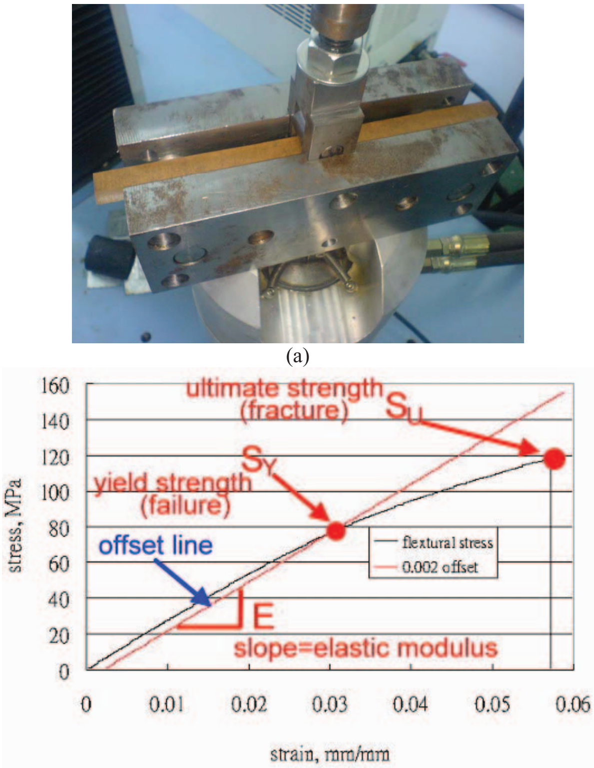

(a)

(b)

Figure 3. (a) Apparatus and specimen of ASTM D790 test, (b) stress-

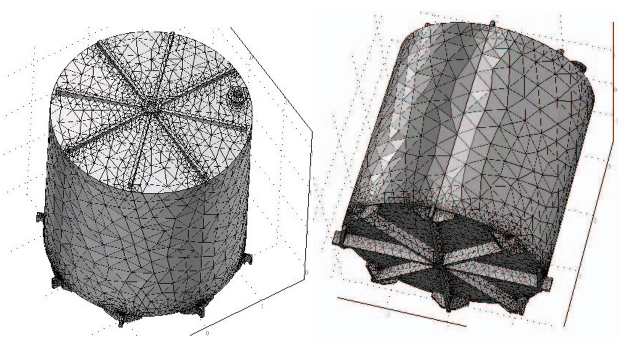
Figure 4. The FEA model for the φ 3m acrylic tank. The ribs and flanges are with solid elements and the body is with shell element.

A. *Mechanical Properties and ASTM D790 Test*

The mechanical properties of the acrylic were measured by ASTM D790 test. ASTM D790 states two methods, 3-points and 4-point loading types, to measure the flexural properties of material. As 3-point test is suit for plastic material, this arrangement was adopted in this experiment. The arrangement of the test is a simple beam supported at two points, as shown in Fig. 3a. When the punch head with force P depresses the specimen downward, the maximum stress in the outer fibers occurs at midspan. Figure 3b shows a typical stress-strain curve obtained from the test. In some materials, the stress at which the material changes from elastic to plastic behavior is not easily detected. In this case, we may determine "offset yield strength". We can construct a line parallel to the initial portion of the stress-strain curve but offset by 0.002 mm/mm from the origin. The 0.2% offset strength is the stress at which our constructed line intersects the stress-strain curve, as shown in Fig. 3b.

The average data for acrylic are: offset E_B=2.95GPa ±8%, S_Y=77.92 MPa ±7%, S_U= 102.13MPa ±12%. If we take the safety factor as 2, the maximum stress for the tank should be less than $S_Y/2$= 38.96 Mpa.

B. *Numerical Modeling on the φ 3m Acrylic Tank*

The main body of the φ 3m acrylic tank is a thin-walled vessel. The thickness of the top lid and bottom plate are 15 mm and that of the peripheral wall is 10 mm. As the diameter of the tank is much greater than the thickness, the body can be modeled as shell element [2]. Eight reinforced ribs are mounted on top lid and bottom plate. Those parts should be modeled as solid element. The numerical model of the φ 3m acrylic tank is shown in Figure 3.

The loading conditions simulated in this work were stationary lifting and dynamic conditions in which an empty and a filled tank with acceleration pulse were simulated. The stationary lifting condition was simulated as four lifting hooks supporting the weight of tank. The stationary condition was calculated by COMSOL. The upward acceleration pulse width is 0.001 second. The density of acrylic is 1190 kg/m^3. The liquid in the tank is simulated as EC3D8R water element in ABAQUS. EC3D8R water element can not simulate the flow of the liquid but simulate the pressure distribution of the liquid. Hence, the computation of the simulation can much faster than that of real liquid case [3][4]. The calculation of each dynamic case has two stages: first is static simulation for 1sec, and than an acceleration pulse is applied on the tank.

III. Result and Discussion

A. *Stationary Load*

This condition simulates the lifting condition that the tank is lifted by four slings mounted on four bottom hooks. The Figure 5 shows the deformation of the tank under this load condition. The center portion of top lid deflects downward 0.0878 mm. The peripheral wall is just with little deformation. The Von Mises stress, a failure criterion for the elastic material, of entire tank is small, as shown in Figure 6. The maximum Von Mises stress is at the lifting rib near the peripheral wall and the value of the stress is 4.408 MPa. As this maximum stress is much less than the yield strength S_Y so that the tank is very safe for the lifting process.

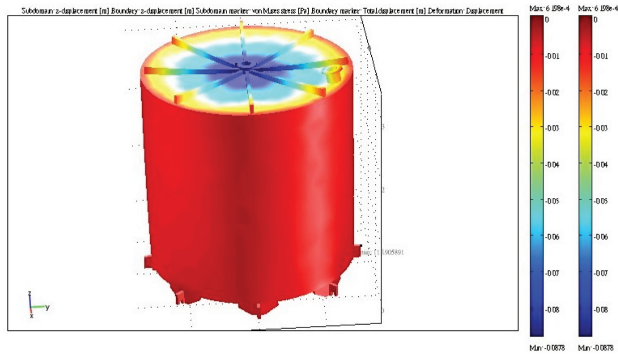

Figure 5. Deformation of the φ 3m arcylic tank with stationary lifting load. The maximum deflection of the center flange on the top lid is 0.0878 mm.

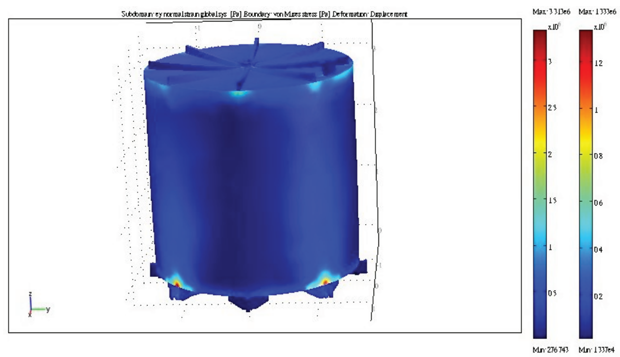

Figure 6. Von Mises stress of the φ 3m arcylic tank with stationary lifting load. The maximum stress is 4.408 MPa.

B. Dynamic Loading: Empty Tank

The designed strength of the acrylic vessel in the dectector should endure a maximum dynamic load of 0.2g. Hence, all vibrations during installation and transportation must be controlled below 0.2g. This acceleration level is similar to the vibration of a car travelling on the highway and normal low speed lifting process.

The caluating conditions are vertical accelerations 0.1g, 0.2g, and 0.3g applied on the bottom of the tank. The vertical displacement of the center of top lid is shown in Figure 7. The mumximum vertical alternative deformation for 0.3g is 0.22 mm.The result shows that the maximum stress exists at the top centeral hole of the center flange. The maximum stress is 0.0626 MPa for 0.3g, as shwn in Fig 8. The stress distribution

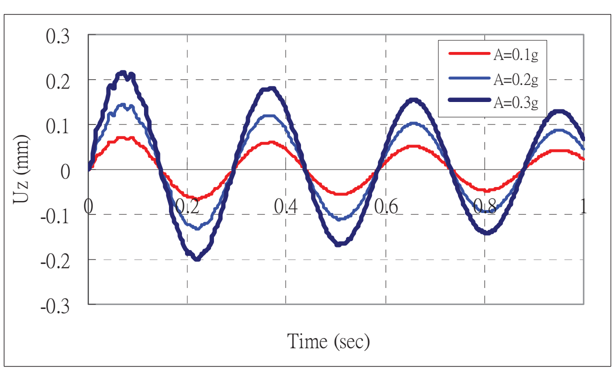

Figure 7. The vertical displacement of the center of top lid of the empty tank.

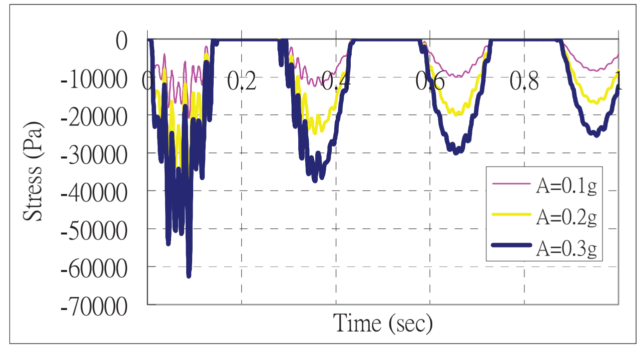

Figure 8. Stress fluctuation on the location of the max. Von Mises stress of the empty tank.

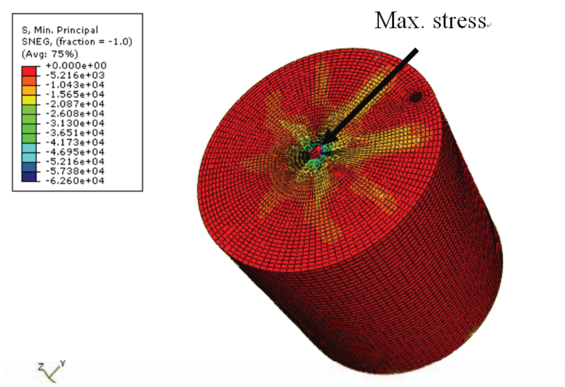

Figure 9. The maximum stress of empty tank under upward acceleration (0.3g) is at the top lid near the center flange.

of Von Mises stress is shown in Figure 9.

C. Dynamic Loading: Filled Tank

The case calculated a 3m acrylic tank filled with water and a vertical acceleration 0.2g upward is acted on it. This condition simulates the transportation process of a detector filled with liquid scintillater. When the tank lifted and transported in the Daybay tunnel, the dynamic solid-liquid couple vibration may generate severe pressure fluctuation and may break the tank.

The model first calculates the stationary condition for one second to ensure the liquid and the tank are in equilibrium and then a pulse of acceleration is acted on the acrylic tank.

Figure 10 shows deformation of a filled tank without reinforced ribs and flanges. The deflection fluctuation at the center of the top lid is as large as 2m. Severe pressure fluctuation makes the acrylic wall crash, as shown in Figure 11. The cause of this situation may be the stiffness of the tank without reinforce ribs is too low to support the pressure impact.

The intensity of the stress fluctuation of the rib-reinforced tank is much lower than that of the tank without reinforce, as shown in Figure 12. The intensity of the stress fluctuation decreases in 1.5 seconds.The result shows that the location where the maximum stress occurs is the same as that of empty

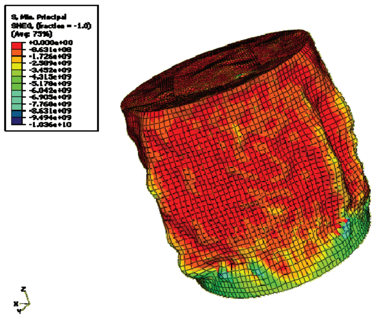

Figure 10. A non-reinforced filled tank can not sustain dynamic load 0.2g. Severe pressure impact may crash the peripheral wall of the tank.

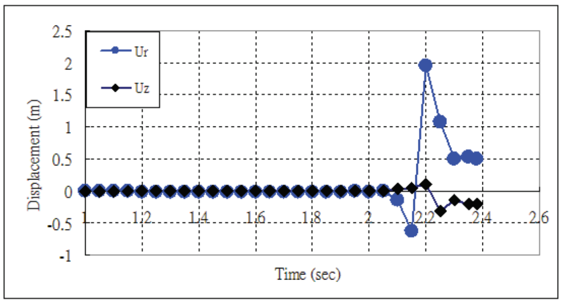

Figure 11. The displacement at the location of the max. stress of the non-reinforced filled tank is too large to normal elastic material. Hence, the tank is crashed by pressure fluctuation.

tank. The value of the maximum stress is 16.03 MPa. Although this value is much higher than that of empty tank, the stress is still much less the yield strength of acrylic, 77.9 MPa. As the safety factor of the main components of the dectector is 2.0, we can ensure that the acrylic tank can be lifted and transported safely.

The vertical deformation is much less than that of non-reinforced case; the maximum vertical deformation is only 8.9 cm. The horizontal deformation is very small so that it can be neglected. In this case the mass of the ribs on the top lid can damp the vibration of the top lid; hence, minimize the hazard of the pressure wave.

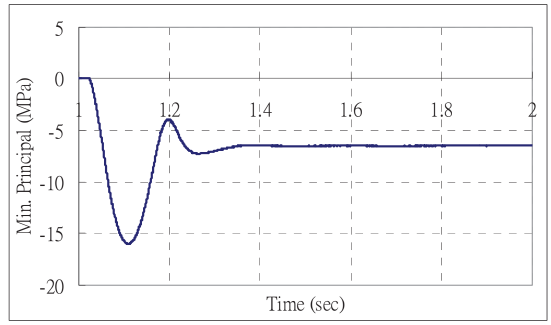

Figure 12.

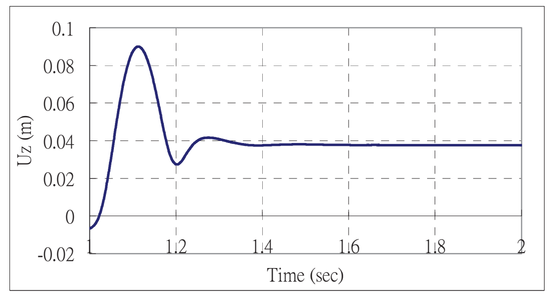

Figure 13.

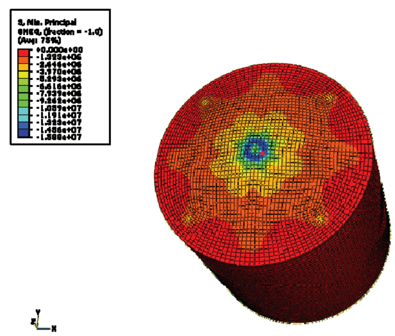

Figure 14.

IV. Conclusion

- The stress and deformation of empty φ3m acrylic tank with stationary lifting load are very small and the tank is very safe for lifting process.
- The empty tank can safely sustain pulsed acceleration up to 0.3g.
- The severe pressure wave of solid-liquid coupled vibration may destroy a filled tank without reinforced ribs on top lid.
- The filled tank reinforced by ribs on top lid can sustain 0.2g dynamic loading. The maximum stress , 16.03 MPa, is much less than the yield strength of acrylic 77.9 MPa. The mass of the ribs can effectively damp the solid-liquid coupled vibration.

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